NASA/CP-97-206241

# Government-Sponsored Programs on Structures Technology

*Compiled by*
*Ahmed K. Noor and John B. Malone*

November 1997

## *The NASA STI Program Office . . . in Profile*

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part or peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that help round out the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- Email your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Phone the NASA Access Help Desk at (301) 621-0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  800 Elkridge Landing Road
  Linthicum Heights, MD 21090-2934

NASA/CP-97-206241

# Government-Sponsored Programs on Structures Technology

*Compiled by*
*Ahmed K. Noor*
*University of Virginia*
*Center for Advanced Computational Technology, Hampton, Virginia*

*John B. Malone*
*Langley Research Center, Hampton, Virginia*

Proceedings of workshops sponsored by the National Aeronautics
and Space Administration, Washington, D.C., the American Institute of
Aeronautics and Astronautics Structures Technical Committee, Reston, Virginia, and
the University of Virginia Center for Advanced Computational Technology, Hampton, Virginia,
and held in Kissimmee, Florida
April 6, 1997
and in Hampton, Virginia
September 4, 1997

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 1997

## CONTENTS

# Introduction and Highlights of the Workshop

Ahmed K. Noor
Center for Advanced Computational Technology
University of Virginia
Hampton, VA

# INTRODUCTION AND HIGHLIGHTS OF THE WORKSHOP

Ahmed K. Noor
Center for Advanced Computational Technology
University of Virginia
NASA Langley Research Center
Hampton, VA

## OUTLINE

Structures technology encompasses a wide range of component technologies from materials development to analysis, design, testing, production, and maintenance. Materials and structures have been largely responsible for major performance improvements in many aerospace systems. The maturation of computational structures technology and the development of advanced composite materials, witnessed during the past thirty years, have improved structural performance, reduced operational risk, and shortened development time. The design of future aerospace systems must meet additional demanding challenges. For aircraft, these include affordability, safety and environmental compatibility. For military aircraft, there will be a change in emphasis from best performance to low cost at acceptable performance. For space systems, new challenges are a result of a shift in strategy from long-term, complex and expensive missions to those that are small, inexpensive and fast.

Materials and structures, in addition to being enabling technologies for future aeronautical and space systems, continue to be key elements in determining the reliability, performance, testability and cost effectiveness of these systems. This will be discussed further in subsequent presentations. The focus of the workshop is on current government sponsored programs in the structures area. The outline for the introductory remarks is given in Fig. 1.

First, some of the characteristics and design drivers of future aerospace systems are described; second, the component technologies that can improve the vehicle performance, advance the technology exploitation process, and reduce system life-cycle costs are identified; third, the changes in the activities and operations of the AIAA Structures Technical Committee are discussed; and fourth, the objectives and format of the workshop are outlined.

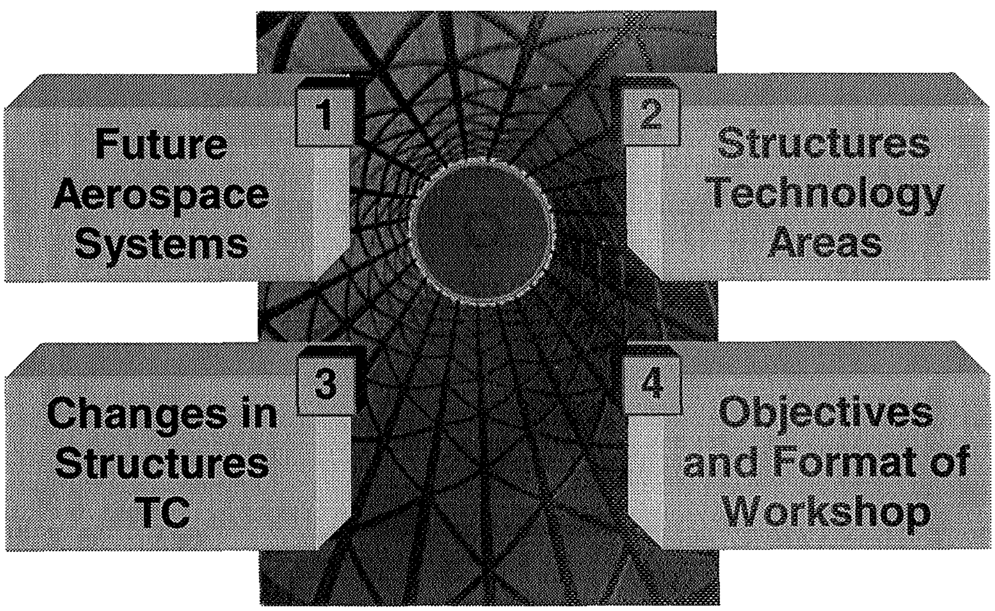
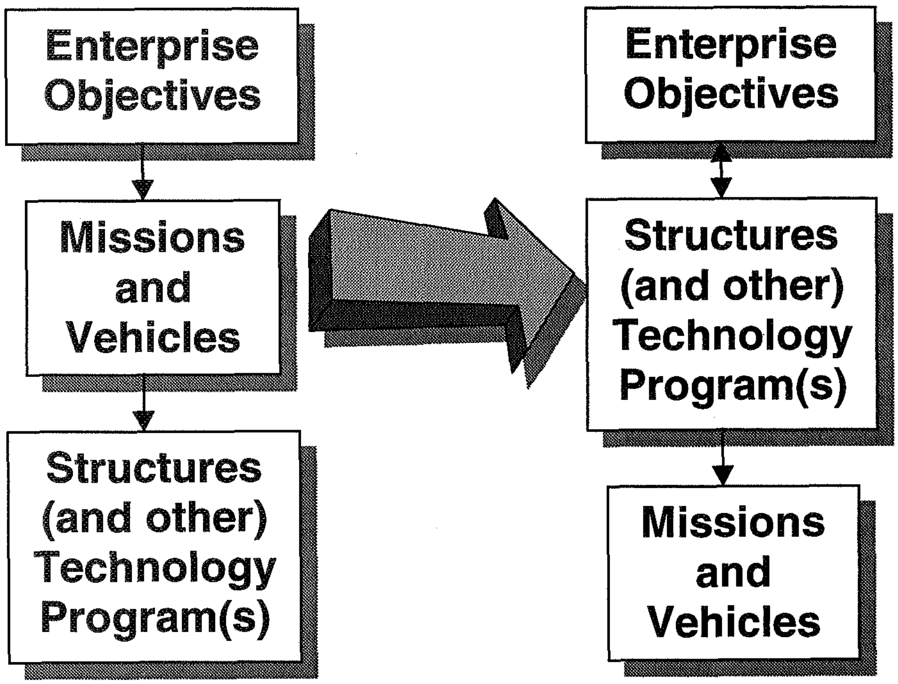



**Figure 1**

## PARADIGM CHANGE IN STRUCTURES TECHNOLOGY

In the past, the structures and other technology programs were derived from missions and vehicles selected to meet the enterprise objectives. In the future the enterprise objectives will drive the structures technology which in turn will expand the mission horizons. The missions and vehicles will evolve from the convergence of objectives and technology.



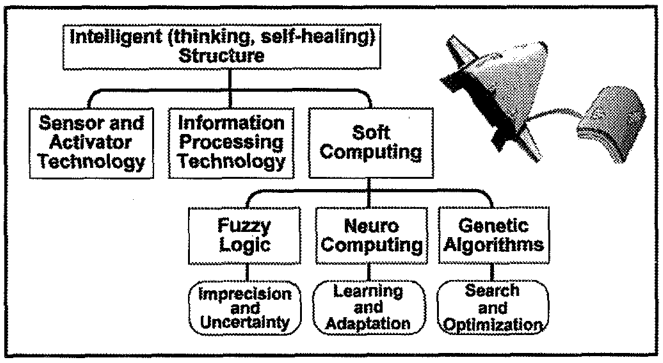

- Enterprise objectives drive structures technology
- Structures technology expands mission horizons
- Missions and vehicles evolve

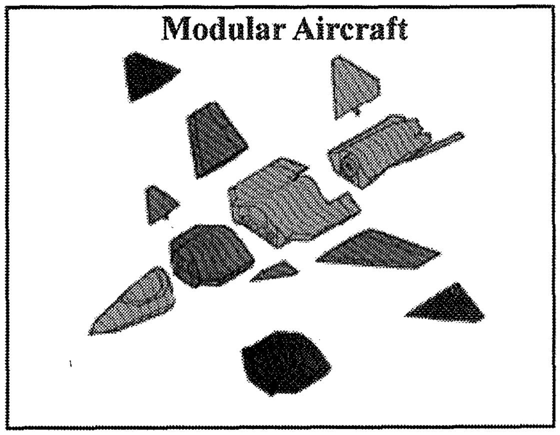
**Figure 2**

## CHARACTERISTICS OF FUTURE AEROSPACE SYSTEMS

Some of the major characteristics of future aerospace systems that will affect their design are:

- a high degree of autonomy - thinking, self-healing vehicles will feature embedded sensors, actuators, and elaborate information processing systems
- miniaturization of subcomponents and/or the entire vehicle
- engineered multifunctional materials
- modularity - using modules to tailor vehicle capabilities to specific mission needs.



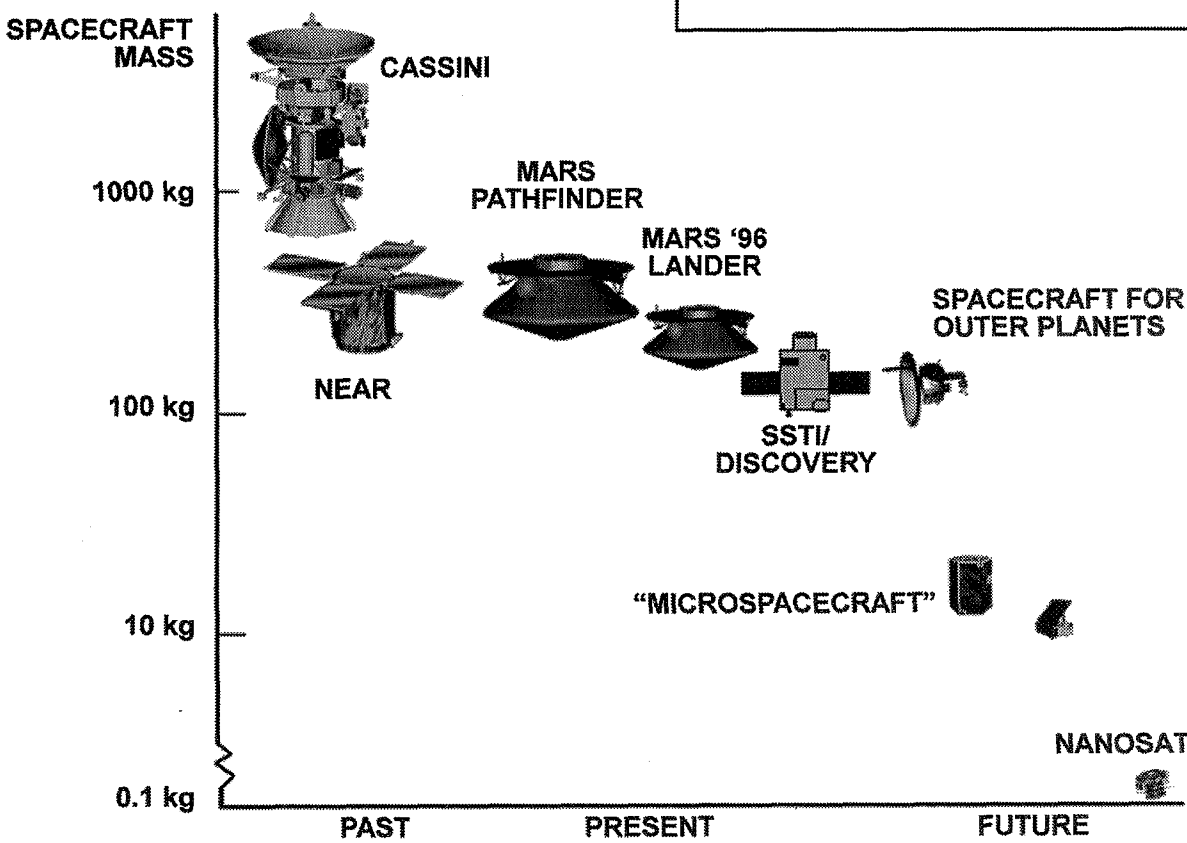




Figure 3

## DESIGN DRIVERS

The design drivers for future aerospace systems include:

- affordability, with emphasis on reducing life-cycle cost;
- improved performance via insertion of new technologies; and
- rapid prototyping which reduces both the design and development times.

The design objectives can be achieved through the use of intelligent simulation-based design environment which is described subsequently (Fig. 11).

**Affordability**

reduce life-cycle cost

**Rapid prototyping**

reduce design and development times

**Improved performance**

rapid insertion of new technologies

**Achieved through...**

intelligent synthesis environment

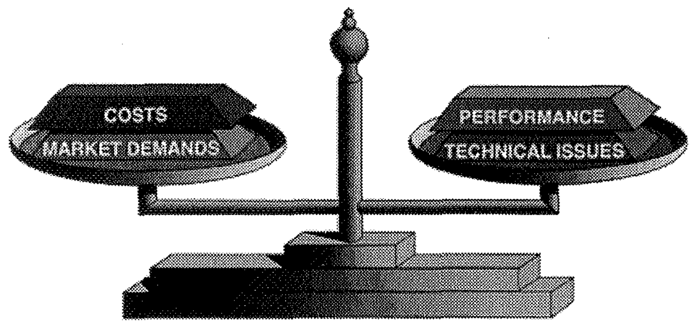
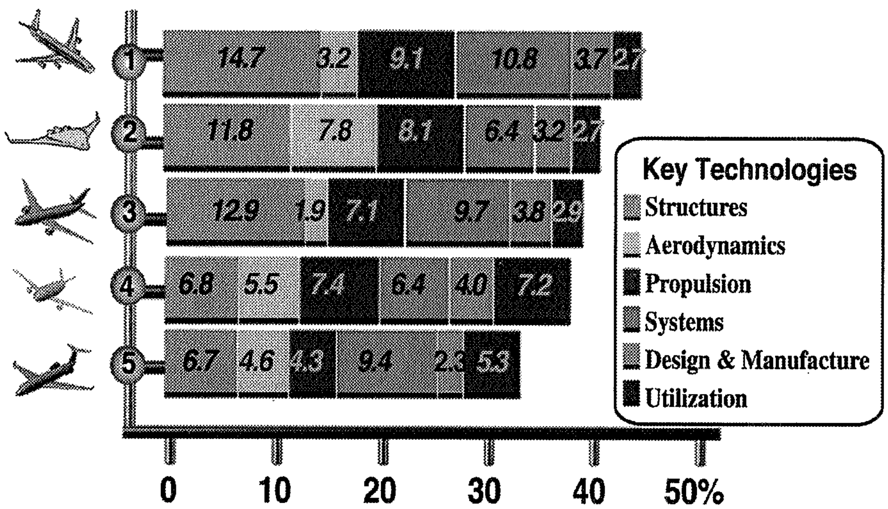


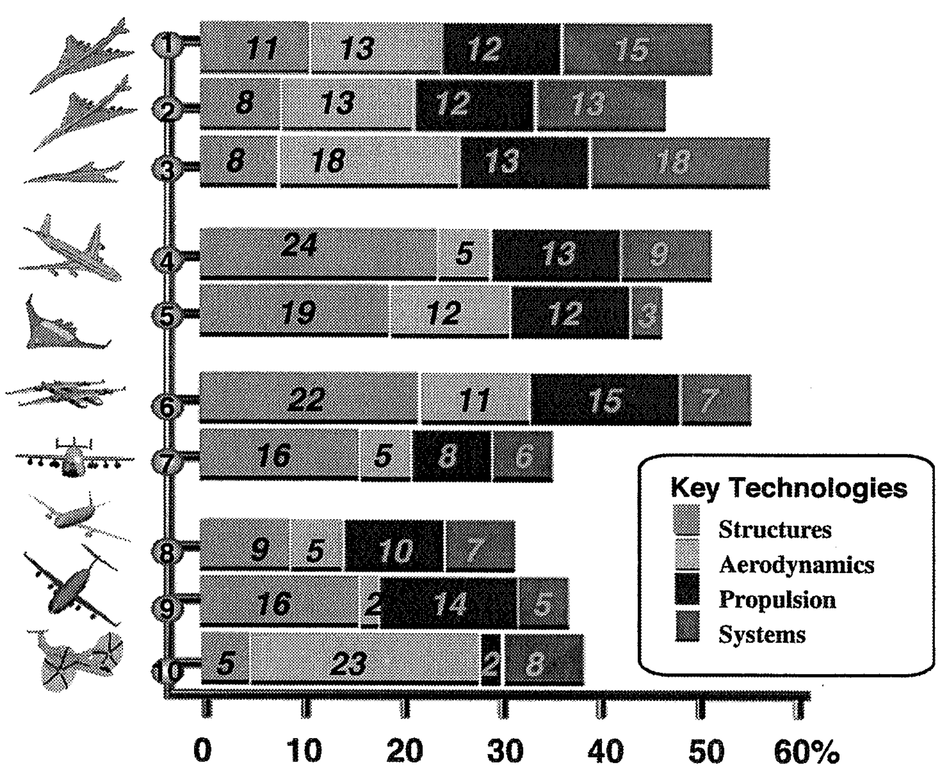

**Figure 4**

## IMPACT OF STRUCTURES TECHNOLOGY ON FUTURE AIRCRAFT

For some of the future air vehicles, the development and deployment of new structures technologies can have more impact on reducing the operating cost and the gross weight than any other technology area. This is depicted in Fig. 4.




*Projected percentage reduction in subsonic transport operating cost in 2020 resulting from deploying new technologies. Long_haul/high capacity (1. conventional, 2. Blended wing body); 3. Long_haul capacity conventional; 4. Medium range intracontinental; 5. Regional jet (courtesy of NASA Langley Research Center).*




*Projected vehicle total gross weight reduction percent. Supersonic (1. Long_Haul, 2. premium service, 3. business jet); Long_haul, high capacity subsonic (4. conventional, 5. blended wing body); global air cargo (6. long haul, 7. short haul); STOL (8. medium range intercontinental, 9. short haul high capacity); short haul/vertical lift, 10. tiltrotor. (courtesy of NASA Langley Research Center).*

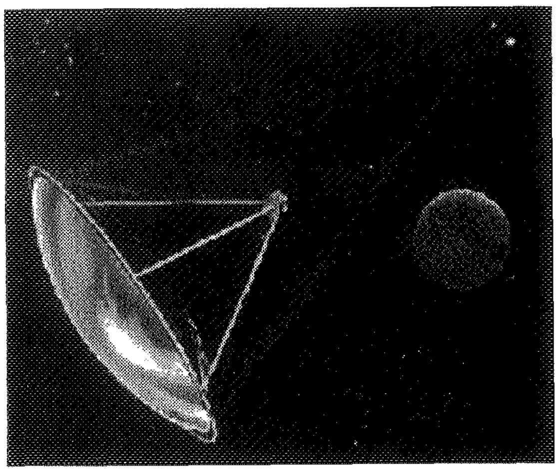
**Figure 5**

## STRUCTURES TECHNOLOGY AREAS

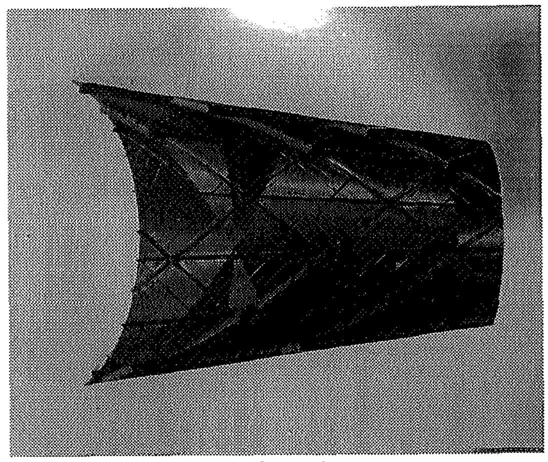
The component technologies that can improve the vehicle performance, advance the technology exploitation process, and reduce system life-cycle costs can be grouped in six categories, namely:

- smart materials and structures
- multifunctional materials and structures
- affordable composite structures
- extreme environment structures
- flexible load-bearing structures
- computational methods and simulation-based design.

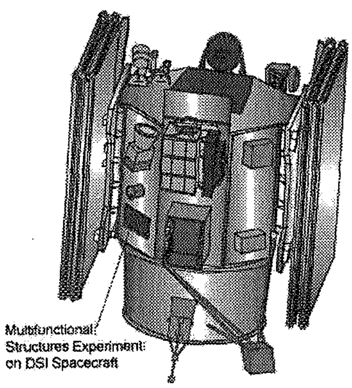
The development of each of the component technologies is a multidisciplinary activity which involves tasks in other disciplines.



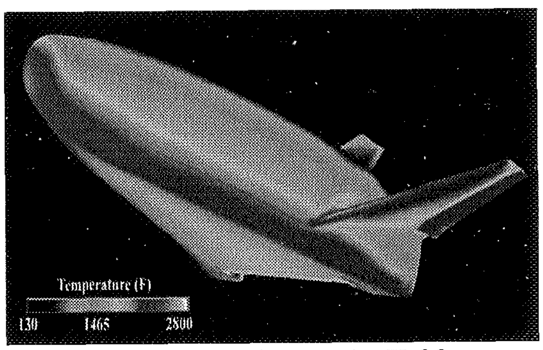
*Inflatable solar concentrator*



*Advanced grid stiffened structure*




*Technology flight demonstration of MFS DS-1*



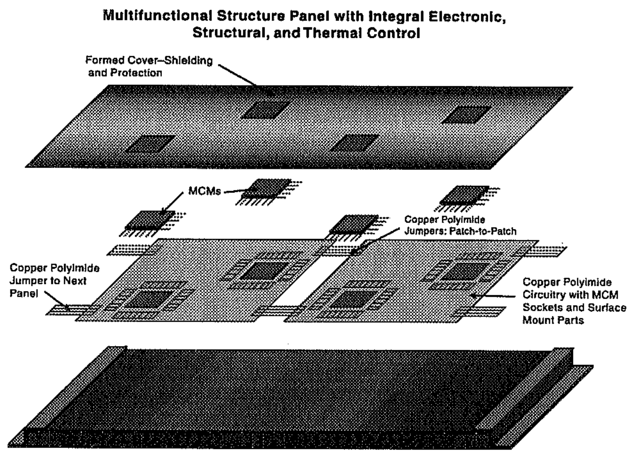

*Temperature distribution in X-33 reusable launch vehicle*

**Figure 6**

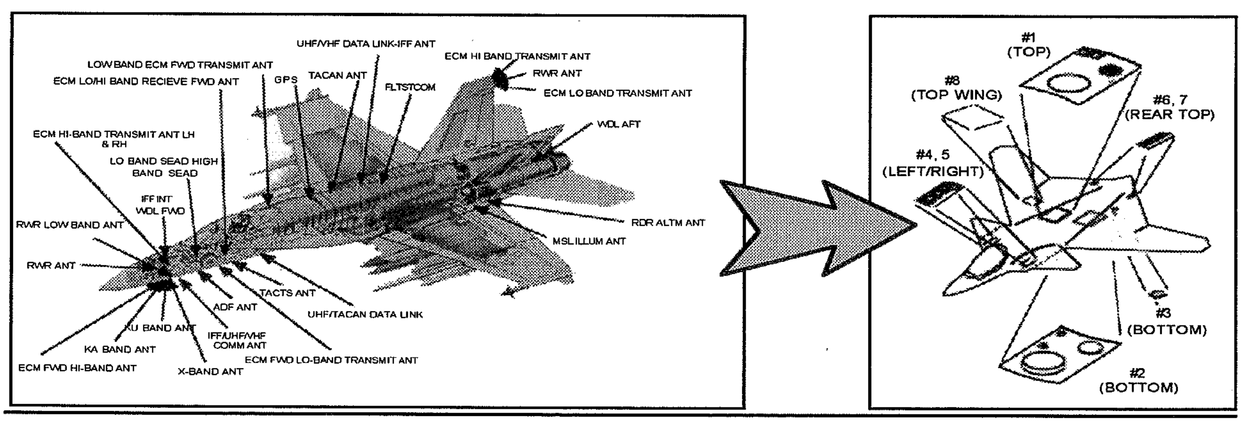
## SMART AND MULTIFUNCTIONAL MATERIALS AND STRUCTURES

Smart structures sense external stimuli, process the sensed information, and respond with active control to the stimuli in real or near-real time. The response to external stimuli can be through deforming or deflecting the structure, or through communicating the sensed information to another control center. Smart materials enact a deformation or deflection of the structure by changing their physical properties when subject to either an electric, magnetic or thermal load.

Multifunctional structures (MFS), in addition to supporting loads, incorporate sensors to detect and evaluate loads or failure, and to interact with the surrounding electromagnetic environment. MFS represent a new manufacturing and integration technology by which communications and electronics equipment are integrated into conformal load-bearing structures. The technology is enabled by advances in large-scale integrated electronics packaging, lightweight composite structures and high-conductivity materials. In multifunctional structures, electronic assemblies (multichip modules), miniature sensors and actuators are embedded into load-carrying structures, along with associated cabling for power and data transmission. This level of integration effectively eliminates traditional boards, boxes, large connectors, bulky cables, and thermal base plates, thereby yielding major weight, volume and cost savings, over traditional structural and electronic packaging techniques.




***The MFS design concept multifunctional structure panel with integrated electronic, structural and thermal control***

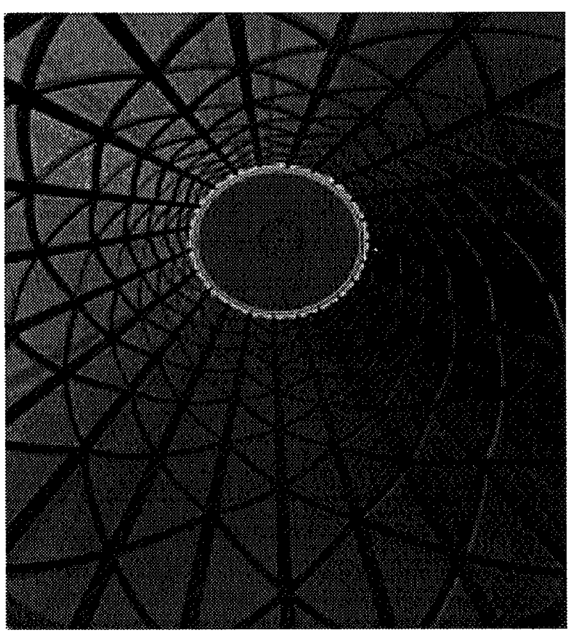



*Multifunctional aircraft structure*
**Figure 7**

## AFFORDABLE COMPOSITE STRUCTURES

For many of the future air vehicles, the use of composite primary structures, along with other structures technology improvements, can have more impact on affordability than any other technology area. While composite design opportunities continue to be explored, the cost to manufacture composite structures has proved to be the biggest obstacle to their widespread use. This is due to design and manufacturing approaches that utilize composite materials in the conventional "metals fashion" of assembling large numbers of mechanically-fastened parts. Affordable composite aerospace structures can be achieved by proper material selection, changing load paths, using robust low-cost manufacturing processes and joining/assembly techniques, and developing approaches for subsystem integration. A fully-coordinated design approach involving larger, integrated components to maximize producibility, quality, and design efficiency is needed in order to fully exploit the weight and cost benefits of composites. This will require composites to be considered as early in the conceptual design process as possible so that load paths are defined that offer manufacturability and do not penalize the efficiency of the composite structure. Among the low-cost composite manufacturing processes are tow placement, resin transfer molding, resin film infusion, pultrusion and nonautoclave processing. An example of promising structural concepts for low-cost automated manufacturing is the Advanced Grid Stiffened (AGS) structure which evolved from early isogrid stiffening concepts, and are characterized by a lattice of rigid, interconnected ribs.

Several government and industry programs have focused on affordable composite structures. Noteworthy among these are the Advanced Composites Technology (ACT) Program; Composites Affordability Initiative (CAI) in the U.S.; and the Affordable Manufacture of Composite Aircraft Primary Structures (AMCAPS) Program in the U.K.



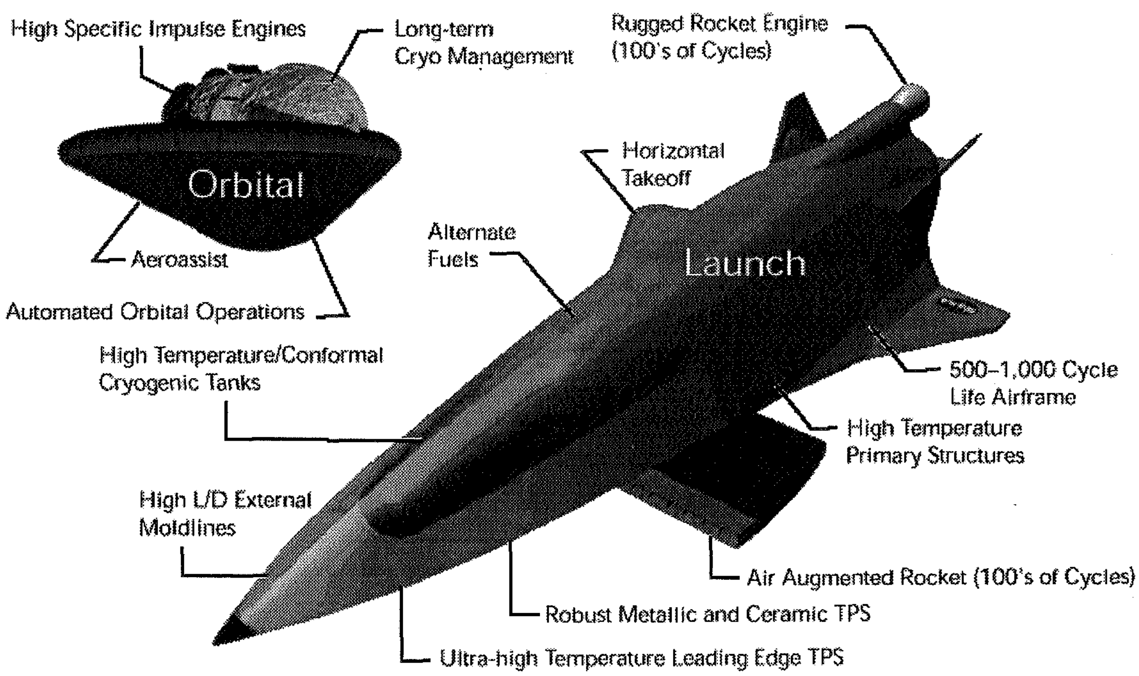
***A look inside the first composite grid stiffened flight structure. The structure, a payload shroud, is composed primarily of high-tech carbon fiber and is filament wound as one continuous piece (courtesy of Air Force Research Lab., Kirkland Air Force Base).***

**Figure 8**

## EXTREME ENVIRONMENT STRUCTURES

Hot structures is an enabling technology for airframes and engines operating in the high-speed flight regime required for future transpacific and transatmospheric vehicles (TPV and TAV), as well as for space transportation systems. For airframes, new and lightweight structural concepts will be needed that can accept high temperatures (400°F through 1500°F) and high acoustic content (noise levels up to 170 dB). This creates an entirely new environment within which large areas of the vehicle will now be exposed, simultaneously, to extreme thermal and acoustic load levels.

For future space transportation systems, advanced materials and structural concepts are needed for the primary structure, leading edges/nose caps, cryotanks and thermal protection systems (TPS). For the primary structure, candidate materials are high-temperature polymeric matrix and advanced metal matrix composites. Reliable bonded and bolted joint concepts are needed for these materials. For the leading edges/nose caps, refractory composites, active cooling and reusable ablators are considered. Composite and metallic sandwich construction are candidates for the cryotanks. The tanks need to be integrated with the vehicle and with a global health monitoring system during design. For TPS, candidate materials include ultra high-temperature ceramic composites and long-life, low-cost carbon-carbon and ceramic matrix composites. The use of refractory composite hot structures concepts in the primary structure can eliminate the requirement for TPS.



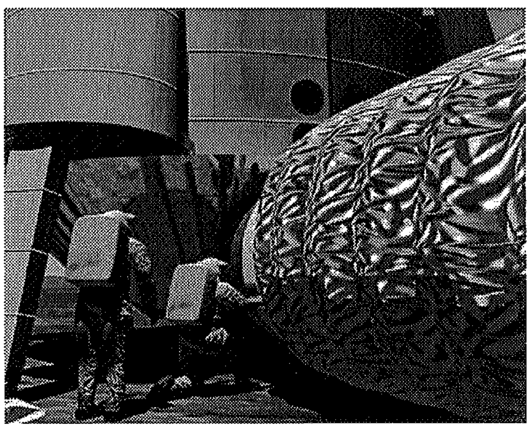

*Affordable, Operable, Reliable High Performance Systems*

**Figure 9**

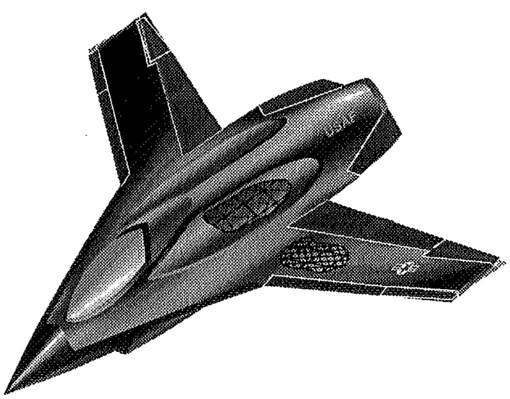
## FLEXIBLE LOAD-BEARING STRUCTURES

Future flexible load-bearing aerospace structures include inflatable deployable aperture structures for antennas, radars, solar sails and reflectors; flexible wall multilayer structures for lunar and Mars habitats; and novel flexible load-bearing concepts for aircraft structures. Inflatable deployable structures combine the advantages of low-launch volume and mass.

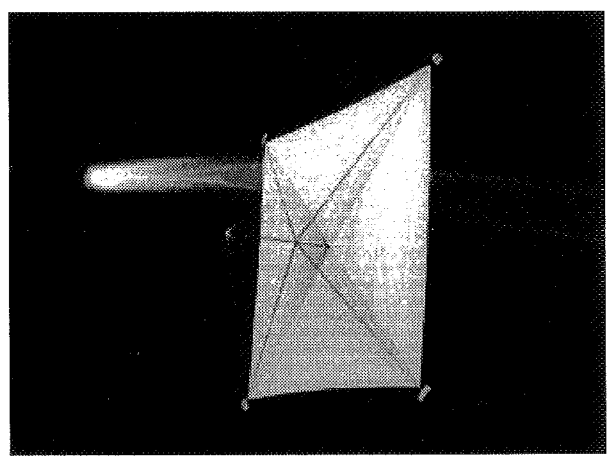
Among the novel flexible load-bearing concepts considered for aircraft structures are the expandable fuel cell (EFC) and the compliant trailing edge. The EFCs are located on the external surface of the vehicle, are conformal to the outer moldline of the vehicle when they are empty, and are inflated when filled with fuel. The EFCs can significantly increase the range capability of the aircraft over that achieved by conventional methods.



***Inflatable laboratory being attached to Mars lander to increase the internal pressurized volume for the crew (courtesy of NASA Johnson Space Center and John Frassanito & Associates).***



***Future tailless military aircraft using smart materials, twisting wing, expandable fuel cell, and compliant trailing edge (courtesy of Air Force Research Labs., Wright Patterson Air Force Base).***



***Inflatable solar sail***

**Figure 10**

## COMPUTATIONAL METHODS AND SIMULATION-BASED DESIGN

High-fidelity finite element models are routinely used to predict the loads and the response of aerospace vehicles. However, the realization of future aerospace systems and missions require advances in a number of areas of computational technology including:

- computational development of new materials and processes;
- accurate prediction of damage initiation and propagation as well as the safe life of the vehicle;
- intelligent simulation-based design which refers to the seamless process of simulating the entire life cycle of the aerospace system before physical prototyping.

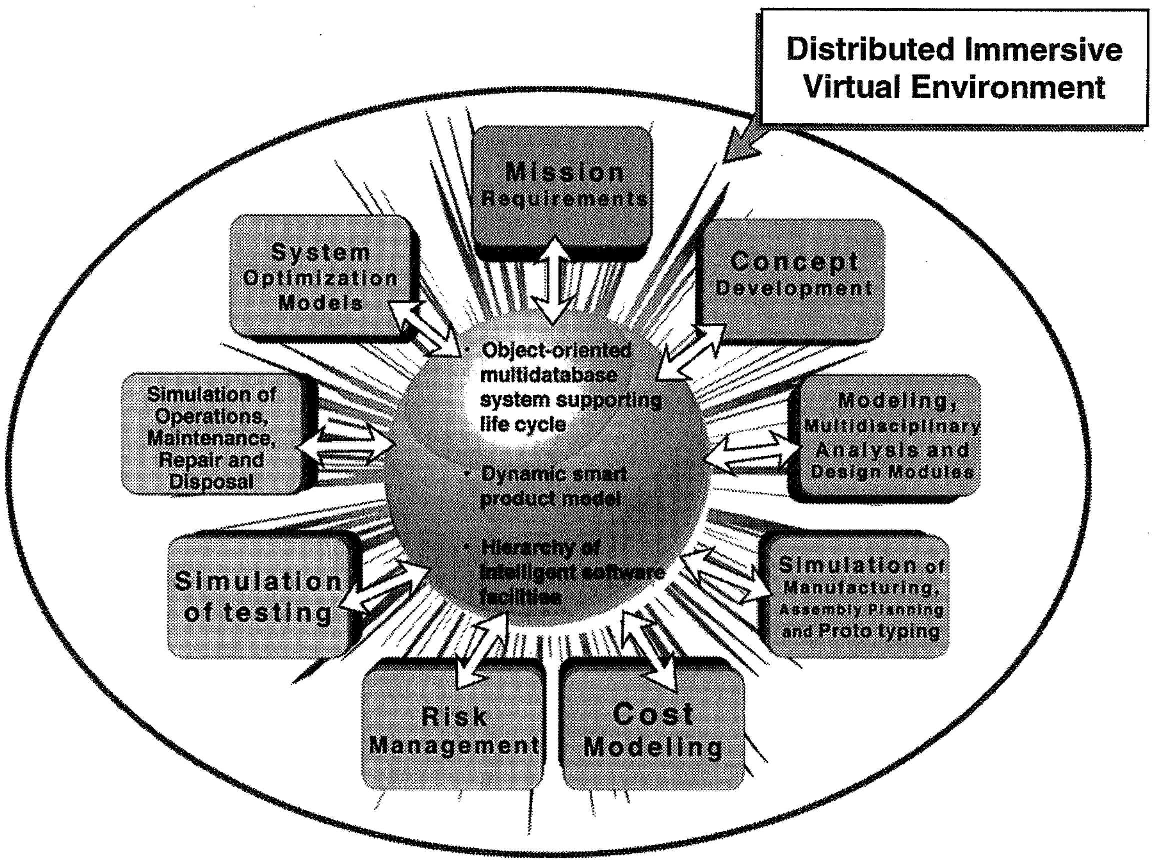



**Figure 11**

## GOALS OF AIAA STRUCTURES TECHNICAL COMMITTEE

The three major goals of the AIAA Structures Technical Committee are:

- serve as a focal point for new developments in aerospace structures;
- develop and deploy innovative approaches for the rapid dissemination of technical information to professionals; and
- help in identifying future directions of research in support of aerospace systems.

A number of changes have been implemented in the operations and activities of the Technical Committee. The changes aim at insuring responsiveness to changes in the aerospace community via innovative approaches and relevance of the activities.

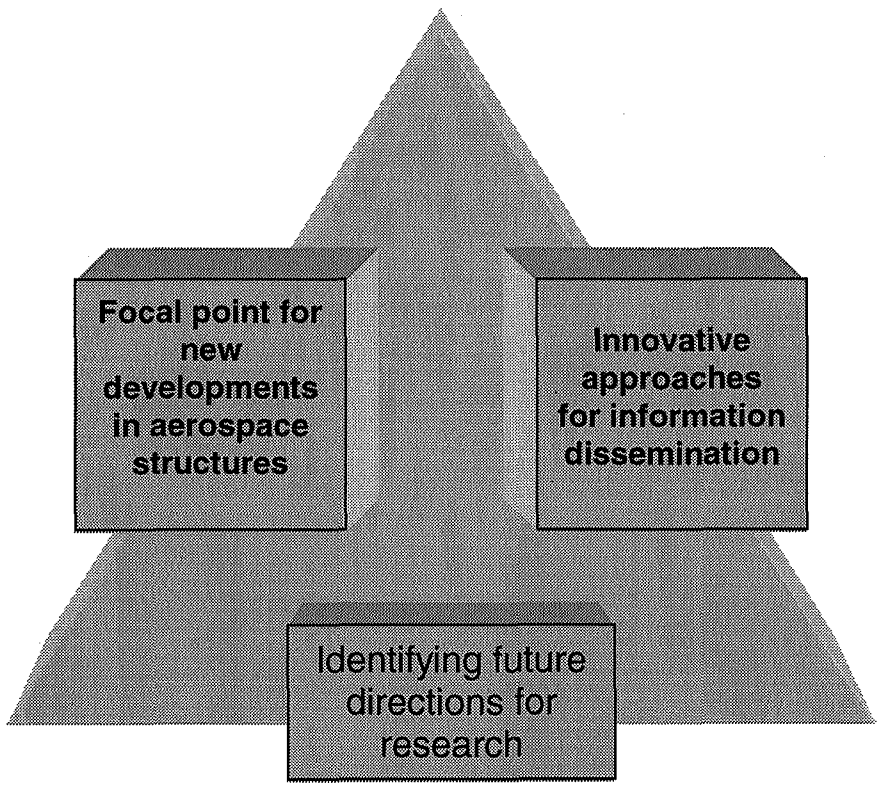



**Figure 12**

# NEW DIRECTIONS AND CHANGES IN THE OPERATION OF AIAA STRUCTURES TECHNICAL COMMITTEE

Among the changes in the operation of the AIAA Structures Technical Committee are:

- Development and maintenance of an elaborate web page. The URL address is:

**http://www.swri.org/aiaa_struct/**

The web page will serve as a source of information for recent developments in the aerospace structures area, and as a communication infrastructure for Structures TC members (frequent meetings on the web) and other professionals in related areas.

- Coordination of activities with AIAA Technical Committee and other professional societies active in the aerospace structures area (ASME, ASCE, SAE, AHS).

- Insuring timeliness and relevance of technical subcommittees.

- Writing a report on "Structures Technology for Future Aerospace Systems" (similar to National Research Council/National Academy of Engineering reports).

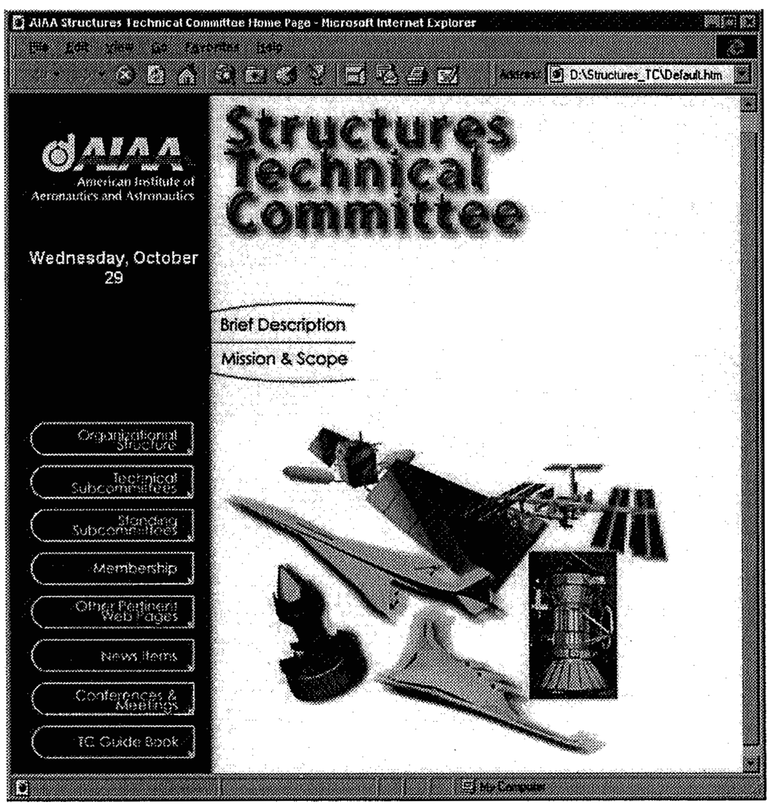
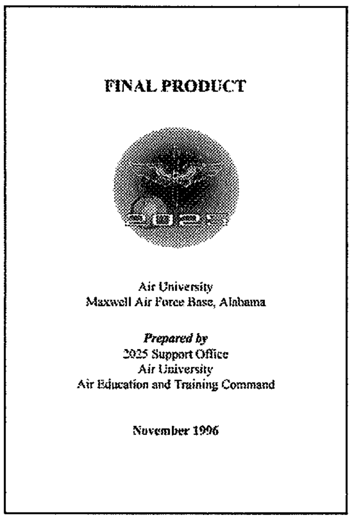


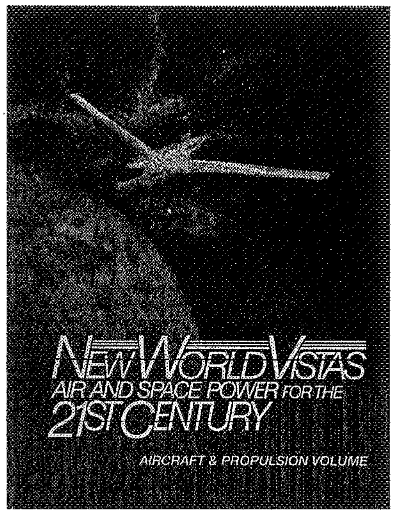

**Figure 13**

## OBJECTIVES AND FORMAT OF THE WORKSHOP

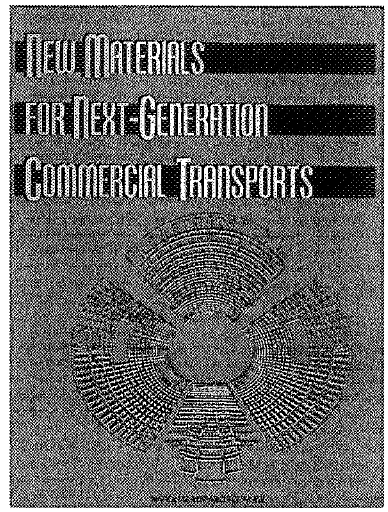
The objectives of the workshop are: a) provide a forum for discussion of current government-sponsored programs in the structures area; b) identify high-potential research areas for future aerospace systems; and c) initiate suitable interaction mechanisms with the managers of structures programs. Four sessions were held on April 6, 1997 and two sessions were held on Sept. 4, 1997. Thirteen presentations are included in the proceedings. Some recent reports pertaining to future aerospace systems are shown below.



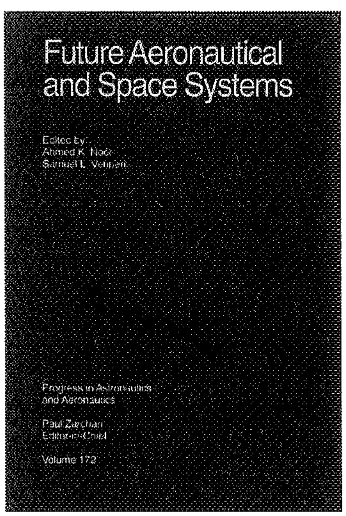

*2025 Final Report (Nov. 1996)*



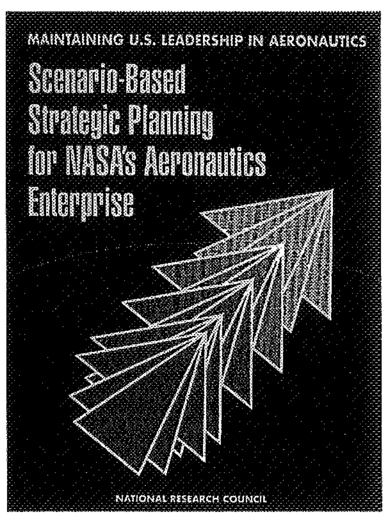

*New World Vistas: Air and Space Power for the 21st Century (1996)*



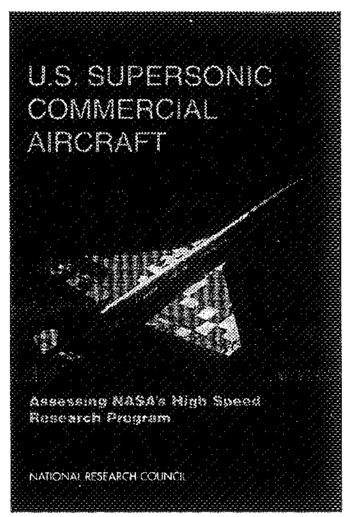

*New Materials for Next-Generation Commercial Transports (1996)*




*Future Aeronautical and Space Systems (1997)*




*Scenario-Based Strategic Planning for NASA's Aeronautics Enterprise (1997)*




*U. S. Supersonic Commercial Aircraft (1997)*

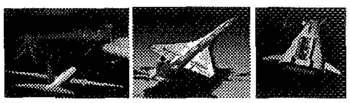
**Figure 14**

# Airframe Systems Research and Technology Base Program

Woodrow Whitlow, Jr.
NASA Langley Research Center
Hampton, VA

# AIRFRAME SYSTEMS
# RESEARCH AND TECHNOLOGY BASE PROGRAM

Dr. Woodrow Whitlow, Jr.
Deputy Director
Airframe Systems Program Office
NASA Langley Research Center
Hampton, Virginia 23681



*Office of Aeronautics and Space Tranportation Technology*

## Airframe Systems
## Research and Technology Base Program

**Dr. Woodrow Whitlow, Jr.**
**Deputy Director, Airframe Systems Program Office**
**April 6, 1997**

## THREE PILLARS FOR SUCCESS

The goals of the Aeronautics Enterprise are framed by three technology *pillars*:

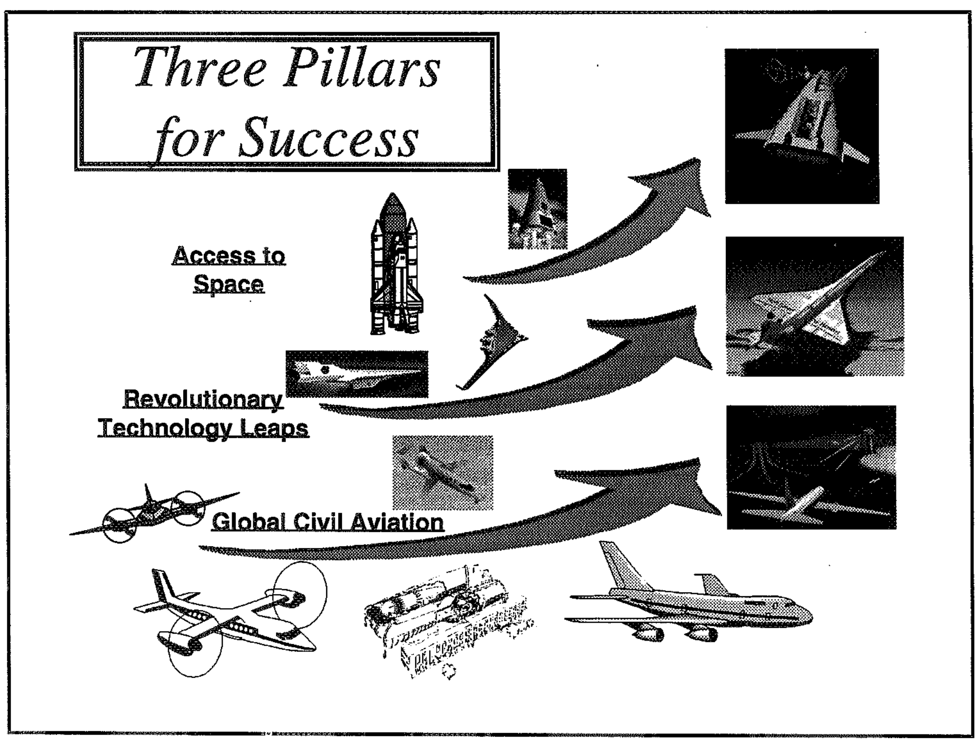
- Global Civil Aviation;
- Revolutionary Technology Leaps; and
- Access to Space.

Global Civil Aviation focuses on our goals for safety, affordability, and the environmental compatibility of subsonic aircraft.

Revolutionary Technology Leaps addresses high-risk, innovative concepts and technology applications that break old operating paradigms, creating new tools and capabilities that open the door to new products and markets for U.S. industry.

In Access to Space, we will merge aeronautics technologies and operating principles with revolutionary new launch vehicle technologies. Again, this is about how new transportation systems will open the doors for economic growth in new sectors such as space.

The goals are framed in terms of a final outcome, which is something that NASA does not control. We have stated the goals as the anticipated benefits of our technology once it has been incorporated by industry. We cannot achieve these goals alone. To accomplish this will require partnership and coordination with manufacturers, airlines, industry, DoD, and the FAA.



## SYSTEM BENEFIT FRAMEWORK FOR THE NATIONAL GOALS

The Aeronautics Enterprise works closely with it customers and partners to ensure that its technology, products and services are developed to levels where customers can confidently make decisions regarding the application of those technologies. This strategy allows the enterprise to support the national aeronautics goals:

- Maintain the superiority of U.S. aircraft and engines;
- Improve safety, efficiency and affordability of the global air transportation system;
- Ensure the long-term environmental compatibility of the aviation system; and
- Achieve aircraft-like operations and costs for launch systems.

Research programs are in place to develop technology that provides benefits in the following areas:

- Performance
- Efficiency and affordability
- Survivability
- Safety and security
- Capacity and efficiency
- Environment, and
- Cost per pound to place payload into low-earth orbit.

### System Benefit Framework for the National Goals

***National Goals***

<table>
<tr><th colspan="2">Revolutionary Technology Leaps</th><th colspan="4">Global Civil Aviation</th><th>Access to Space</th></tr>
<tr><td colspan="3">Maintain the Superiority of U.S. Aircraft and Engines</td><td colspan="2">Achieve an Efficient, Safe, and Affordable Global Air Transportation System</td><td>Ensure the Long-Term Environmental Compatibility of the Aviation System</td><td>Achieve Aircraft-like Operations and Costs</td></tr>
<tr><td>Performance</td><td>Survivability</td><td>Efficiency & Affordability</td><td>Safety & Security</td><td>Capacity & Efficiency</td><td>Environment</td><td>Cost per Pound to LEO</td></tr>
</table>

## AIRFRAME SYSTEMS PROGRAM LINKED TO NASA STRATEGIC PLAN

The NASA Strategic Plan establishes a framework for making management decisions by separating the agency's programs into four externally focused Strategic Enterprises. These enterprises, shown at the upper right of the figure are as follows:

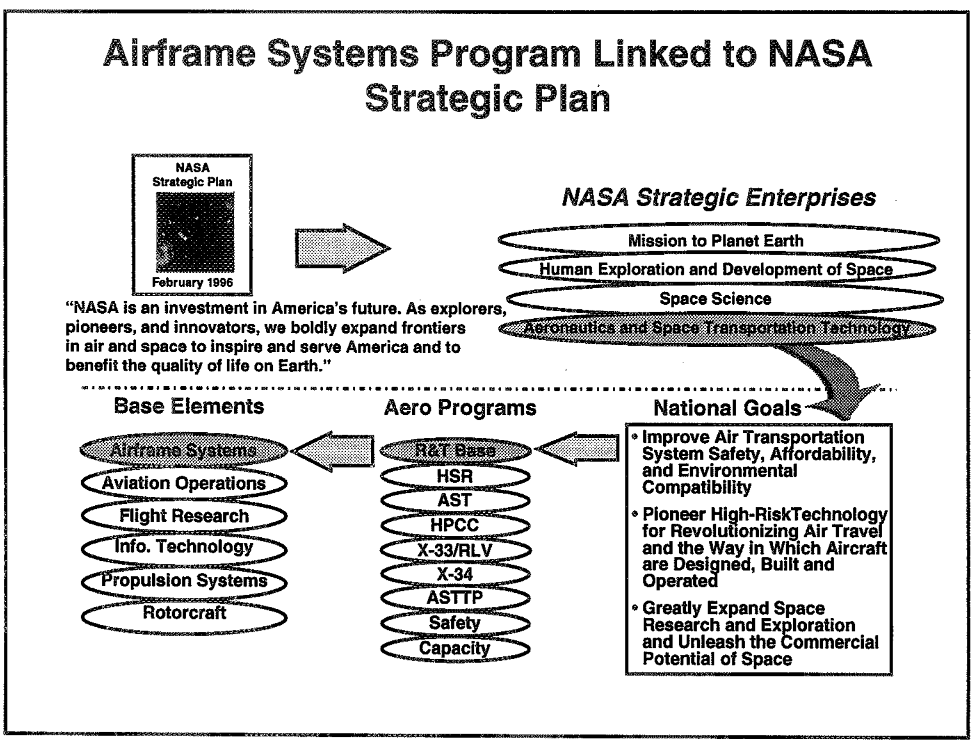
- Mission to Planet Earth;
- Human Exploration and Development of Space;
- Space Science; and
- Aeronautics and Space Transportation Technology.

Research conducted under the Airframe Systems Program supports the mission of the Aeronautics Enterprise.

The Aeronautics Research and Technology (R&T) Base supports the national goals by providing a foundation to do the following:

- Develop advanced technology concepts and methodologies for application by industry;
- Build focused programs to address selected national needs;
- Respond quickly to critical safety and other issues; and
- Provide facilities and expert consultation for industry during their product development.

The Airframe Systems Program develops breakthrough, innovative technologies related to those systems that either determine or characterize the performance of aircraft.



## NASA R&T BASE LEAD ROLES

To take advantage of the unique capabilities that exist at each of the research centers, the Aeronautics Research and Technology Base consists of six programs:

- Airframe Systems
- Aviation Operations Systems
- Flight Research
- Information Technology
- Propulsion Systems, and
- Rotorcraft.

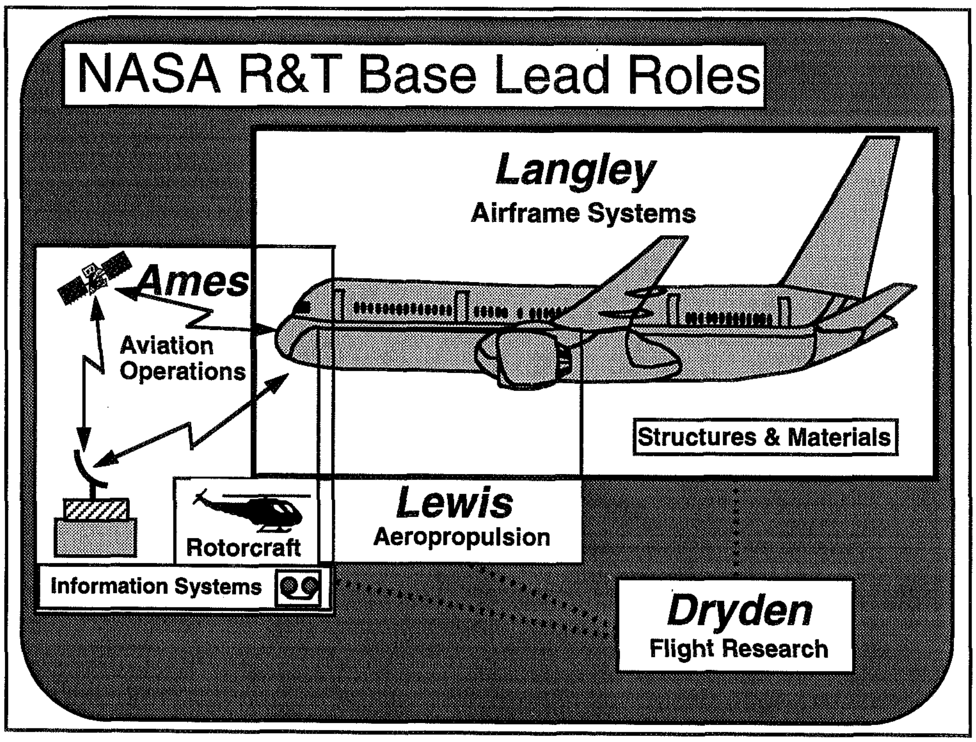
Each element is led where the center of gravity of relevant expertise exists. The Airframe Systems Program is led at Langley Research Center.

Airframe systems are those systems that determine or characterize the performance of an aircraft, including airframe-propulsion system integration.

Key elements of airframe systems include the following:

- Conceptual design
- Aerodynamic design, development, and testing
- Structural design, development, and testing (including airframe materials)
- Flight crew station design, integration, and testing, and
- Airborne systems (including flight mechanics, controls, electromagnetics, and flight-crucial systems) design, integration, and testing.

The Agency Center of Excellence for Structures and Materials, one of the key elements of airframe systems, is located at Langley Research Center.



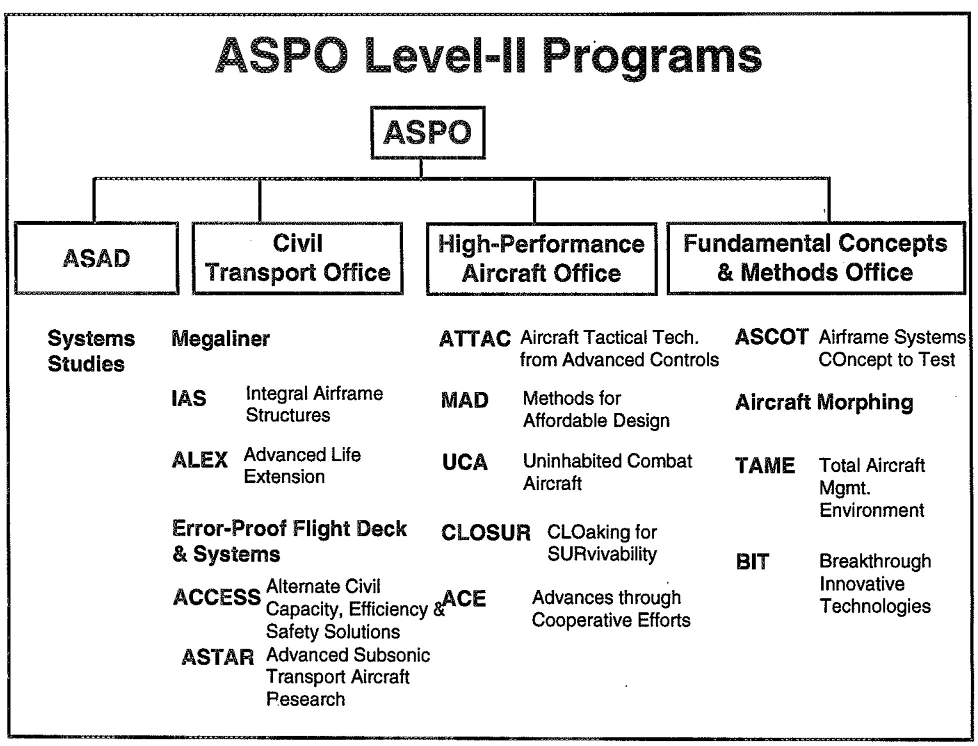
## ASPO LEVEL-II PROGRAMS

Airframe systems technology development for some specific vehicle classes are addressed in other Aeronautics Enterprise programs. The Advanced Subsonic Technology (AST) Program has focused technology efforts for general aviation, civil tiltrotor, and subsonic transport aircraft. In addition, Ames Research Center leads the Research and Technology Base portion of the Rotorcraft Research Program. The High-Speed Research (HSR) Program is developing technologies that will allow the decision on the feasibility of building an economically viable supersonic civil transport aircraft. Reusable launch vehicle (RLV) technology is being developed in the X-33 Program.

While technology developments in the focused programs are aimed at relatively near-term applications, the Airframe Systems Program has the following characteristics:

- Breakthrough technologies
- High-risk/High-payoff
- Revolutionary
- Expanding Frontiers
- Pioneering research for the twenty-first century
- Requires paradigm shifts
- A sound investment in America's aeronautics future, and
- Complemented by focused programs.

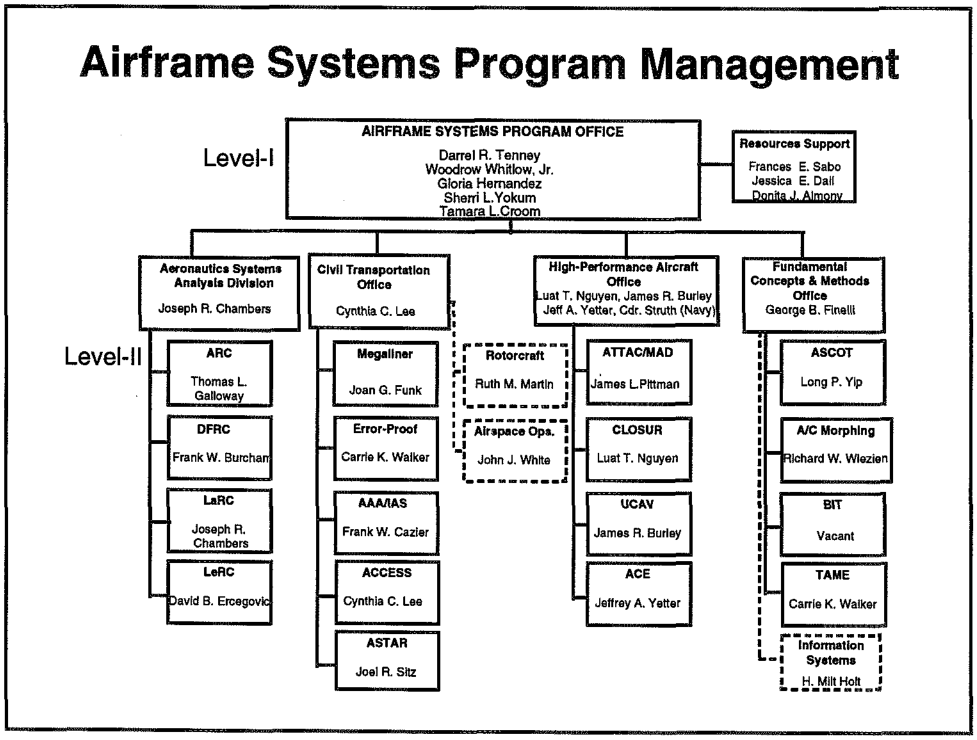
The Airframe Systems Program Office (ASPO) has planned a set of innovative Level-II research programs that are focused along advanced conceptual (systems) studies, transport aircraft, high-performance aircraft, and fundamental aeronautical concepts and methods. These programs are shown in the figure.



## AIRFRAME SYSTEMS PROGRAM MANAGEMENT

In order to assure that the research planning and implementation is responsive to customers' needs, the management of the Airframe Systems Program centers around vehicle classes and long-term aeronautics research needs. A Systems Studies and Analysis element provides independent assessments, high-payoff research and concepts, and data for deciding investment strategies.

The Level-II programs are managed within the Aeronautics Systems Analysis Division, the Civil Transportation Office, the High-Performance Aircraft Office, and the Fundamental Concepts and Methods Office. The Rotorcraft, Airspace Operations, and Information Systems managers serve as the Langley points of contact for those programs.



# R&T BASE: AIRFRAME SYSTEMS

The figure shows how the Airframe Systems Level-II programs align with the national goals.

## R&T Base: Airframe Systems

| | Maintain the Superiority of U.S. Aircraft and Engines | | | Achieve and Efficient, Safe, and Affordable Global Air Transportation System | | Ensure the Long-Term Environmental Compatibility of the Aviation System |
|---|---|---|---|---|---|---|
| System Benefits / Veh./ Cust. Classes | Performance | Efficiency & Affordability | Survivability | Safety & Security | Capacity & Efficiency | Environment |
| Subsonic Transports | | IAS, ACCESS, ASTAR | | ALEX, Error-Proof Flight Deck | Megaliner | |
| High Performance Aircraft | ATTAC, ACE | MAD, UCA | CLOSUR | | | |
| Hypersonic Vehicles | Hyper-X | | | | | |
| Tools & Test Techniques | Aircraft Morphing | Airframe Sys. Concept to Test | | TAME | | |
| Basic X-Cutting Research | Breakthrough Innovative Technologies (BIT) Systems Studies | | | | | |

## AIRFRAME SYSTEMS PROGRAMS

This slide presents a brief description of the following Level-II programs:

- Megaliner
- Error-Proof Flight and Aircraft Electronic Systems
- Advanced Life Extension (ALEX)
- Integral Airframe Structures (IAS)
- Alternate Civil Capacity, Environment, Efficiency, and Safety Solutions (ACCESS), and
- Advanced Subsonic Transport Aircraft Research (ASTAR).

This presentation contains details about the following programs:

- Megaliner
- ALEX
- IAS.

These programs involve a significant amount of structures research.

### Airframe Systems Programs

| Program | Research Thrust |
|---|---|
| Megaliner | Revolutionary subsonic long-haul transports |
| Error-Proof Flight Deck & Aircraft Electronic Systems (Error-Proof) | Error-Proof flight deck and mission critical systems |
| Advanced Life Extension (ALEX) | Airworthiness of thick, metallic structural components typical of wing structure, in the aging commercial transport fleet |
| Integral Airframe Structures (IAS) | Low cost large, integral, metallic structures |
| Alternate Civil Capacity, Environment, Efficiency, & Safety Solutions (ACCESS) | Cooperative activities with industry or other government agencies |
| Advanced Subsonic Transport Aircraft Research (ASTAR) | Intelligent Adaptive Control System and Adaptive Performance Optimization |

## AIRFRAME SYSTEMS PROGRAMS

This slide presents a brief description of the following Level-II programs:

- Aircraft Tactical Technology from Advanced Controls (ATTAC)
- Methods for Affordable Design (MAD)
- Cloaking for Survivability (CLOSUR)
- Uninhabited Combat Aircraft (UCA)
- Advances through Cooperative Efforts (ACE), and
- Hyper-X.

This presentation contains details about the ATTAC program since it involves a significant amount of structures research.

### Airframe Systems Programs

| Program | Research Thrust |
|---|---|
| Aircraft Tactical Technology from Advanced Controls (ATTAC) | Advanced control technologies for performance and survivability |
| Methods for Affordable Design (MAD) | Accelerated aircraft design process and reduced aircraft life-cycle costs |
| Cloaking for Survivability (CLOSUR) | System survivability |
| Uninhabited Combat Aircraft (UCA) | Technologies for revolutionary mission capabilities and affordability |
| Advances through Cooperative Efforts (ACE) | Military focused cooperative activities with DoD, and industry |
| Hyper-X | Design and performance predictions of hypersonic aircraft |

## AIRFRAME SYSTEMS PROGRAMS

This slide presents a brief description of the following Level-II programs:

- Airframe Systems Concept to Test (ASCOT)
- Aircraft Morphing
- Breakthrough Innovative Technologies (BIT)
- Total Aircraft Management Environment (TAME), and
- Systems Studies and Analysis.

This presentation contains details about the Aircraft Morphing program since it involves a significant amount of structures research.

### Airframe Systems Programs

| Program | Research Thrust |
|---|---|
| Airframe Systems Concept to Test (ASCOT) | High fidelity modeling and analysis tools for airframe and propulsion systems |
| Aircraft Morphing | Self-adaptive flight via smart systems technologies |
| Breakthrough Innovative Technologies (BIT) | Fundamental research into revolutionary technology concepts |
| Total Aircraft Management Environment (TAME) | Integrated control of aircraft |
| Systems Studies & Analysis | Maintain systems analysis capability |

## ADVANCED LIFE EXTENSION (ALEX)

**Program Statement, Objective:**

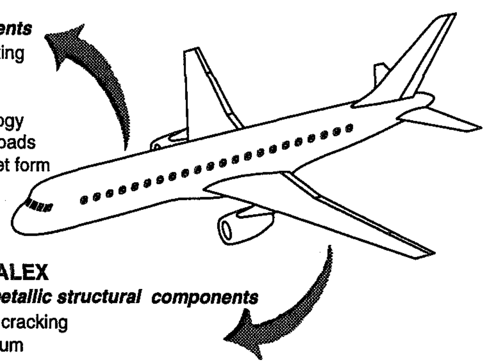
NASA's ALEX program will focus on technology issues associated with assuring the continued airworthiness of thick, metallic structural components subjected to spectrum fatigue loading, typical of wing structure, in the aging commercial transport fleet. The program will focus on structural integrity analysis methodology and NDE of these components. This research also will provide advanced technology to support the design of new subsonic aircraft.

**Technical Approach:**

The ALEX Program will build upon and leverage results from the Advanced Subsonic Technology Program, where appropriate, and develop new structural integrity analysis and NDE technologies that are unique to thick metallic structural components, such as the wing. The main areas of technology development will be prediction methodology for fatigue crack growth and residual strength in thick metallic structural components, and NDE methods for thick components and damage in hidden structures. The structural integrity analysis methodology development will focus on the effects of three-dimensional plasticity and variable spectrum fatigue loading in thick structures. The NDE activity will focus on methodologies for detecting and sizing fatigue cracks in multilayer complex structures and imaging methodologies for mapping corrosion in hidden structures, such as ribs, spars, forgings, and fittings.

**Relationship Between AST Aging Aircraft Element and Airframe Systems ALEX Program**

**AST Aging Aircraft**
***Thin sheet metallic fuselage components***
- NDE for disbond, corrosion, and cracking
  - Riveted lap splice joints
  - Riveted thin skin structure
- Structural Integrity Analysis Methodology
  - Nonlinear effects due to combined loads
  - 2000 series aluminum alloys in sheet form
  - Widespread fatigue damage



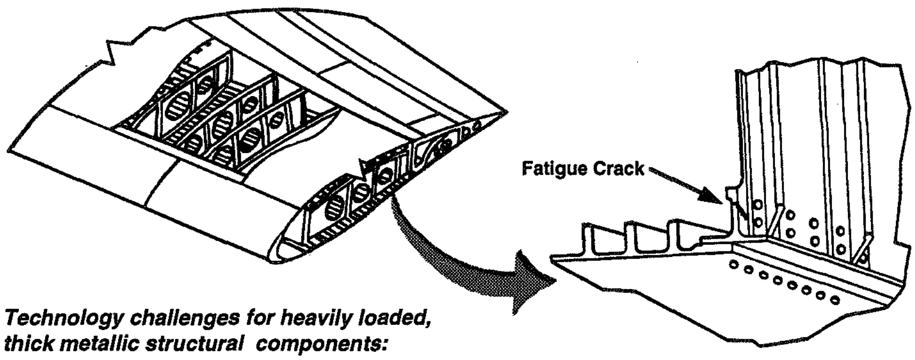
**Airframe Systems - ALEX**
***Heavily loaded, thick metallic structural components***
- NDE for corrosion and cracking
  - Thick section aluminum
  - Hidden components
  - Multilayer, complex geometry components
- Structural Integrity Analysis Methodology
  - Spectrum loading effects on fatigue behavior
  - Various aluminum alloys in plate, extrusion and forging forms
  - Mutilayer, complex geometry components
  - Corrosion fatigue effects

## ALEX FOCUSES ON TECHNOLOGY CHALLENGES FOR DAMAGE IN THICK AND HIDDEN STRUCTURE

Research within the ALEX Program focuses on technology challenges for heavily loaded, thick metallic structural components:

- Reliable, inexpensive nondestructive evaluation methods for detecting corrosion and cracking; and
- Rigorous fracture mechanics based on fatigue crack growth and residual strength analysis methodology.

### ALEX Focuses on Technology Challenges for Damage in Thick and Hidden Structure




***Technology challenges for heavily loaded, thick metallic structural components:***

- Reliable, inexpensive NDE methods for *corrosion* and cracking
  - Thick section aluminum
  - Hidden components
  - Multilayer, complex geometry components
- Rigorous, fracture mechanics based *fatigue crack growth* and residual strength analysis methodology
  - Spectrum loading effects on fatigue behavior
  - Various aluminum alloys in plate, extrusion and forging forms
  - Mutilayer, complex geometry components (3-D plasticity effects)
  - Corrosion fatigue effects

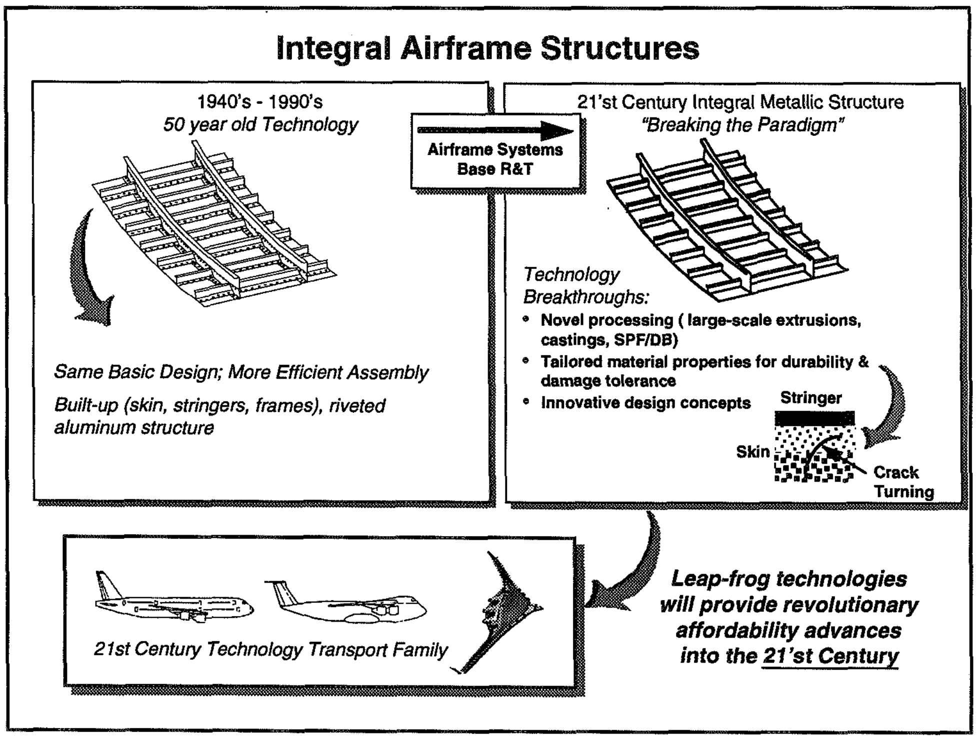
# INTEGRAL AIRFRAME STRUCTURES (IAS)

**Program Statement, Objective:**

The airframe industry has identified reductions in the ownership cost of airplanes as a critical factor in maintaining and increasing the market share of U.S. aircraft companies. There are significant technical challenges that must be overcome before these cost savings can be realized. The challenges that must be overcome to realize cost reductions include scale-up of advanced metallic materials processing technologies, and the durability and damage tolerance of large integral structural components. The IAS program will develop and demonstrate the technologies required to meet these challenges.

**Technical Approach:**

The IAS program will develop technologies required to demonstrate the feasibility of manufacturing large, integral, metallic structures for reducing the cost of manufacturing airframes. The key issues that will be addressed in the initial three-year activity (FY96-FY98) are application and scale-up of advanced materials processes, analysis methodology development and demonstration of the durability and damage tolerance of integrally stiffened structures, and verification of cost assessment tools. The results will be validated through the fabrication and evaluation of an integrally stiffened panel component.



## MEGALINER

**Program Statement, Objective:**

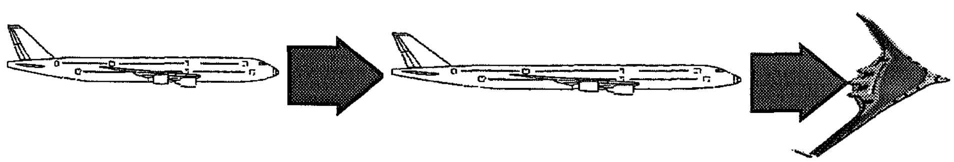
The goal of the Megaliner Program is to address barrier technology issues that inhibit the development of a new generation of aircraft. The potential application is to a range of aircraft configurations from super affordable derivatives of current transport configurations to the next generation of subsonic transport configurations. These transports include very large (800 passenger), long-range (8000-12000 nmi) commercial/cargo configurations. The Megaliner Program seeks to provide technology advancements in the areas of capacity, environment, safety, and affordability.

**Technical Approach:**

The Megaliner Program will address barrier technologies in structures and materials, aerodynamics, airframe/propulsion integration, and acoustics to significantly expand design options for future subsonic transports. The technical approach will involve developing and validating improved analysis methods and advanced concepts integrated with ground, and potentially flight, experiments.

**Megaliner Program Responds to National Capacity Issues**

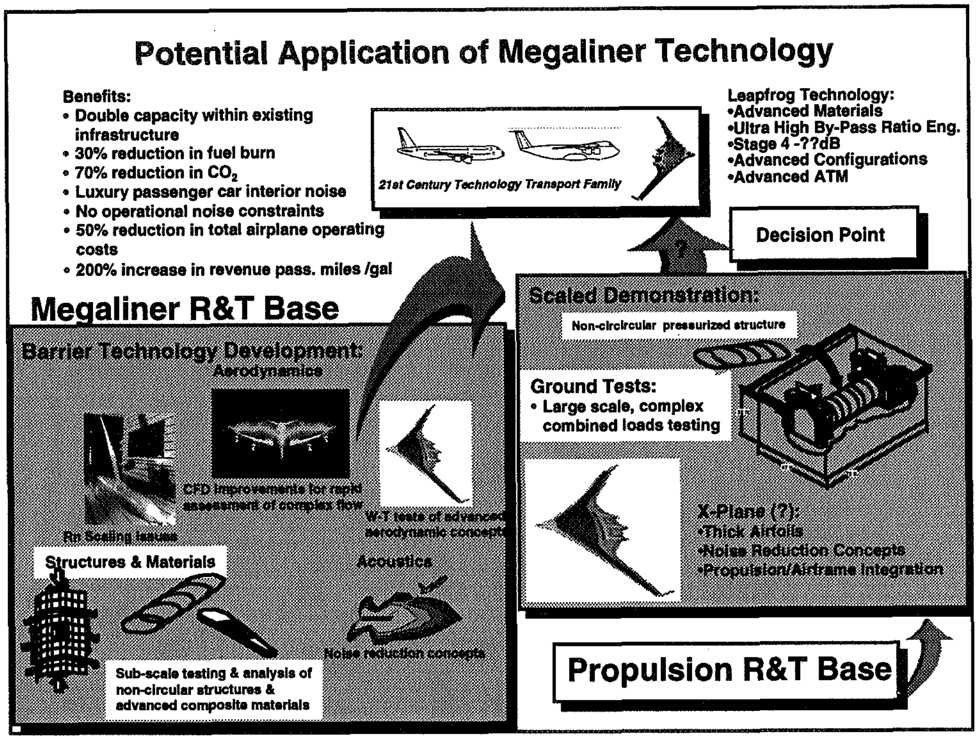
*Goal: Develop breakthrough technologies that dramatically expand design options to enable more efficient very large transport aircraft*



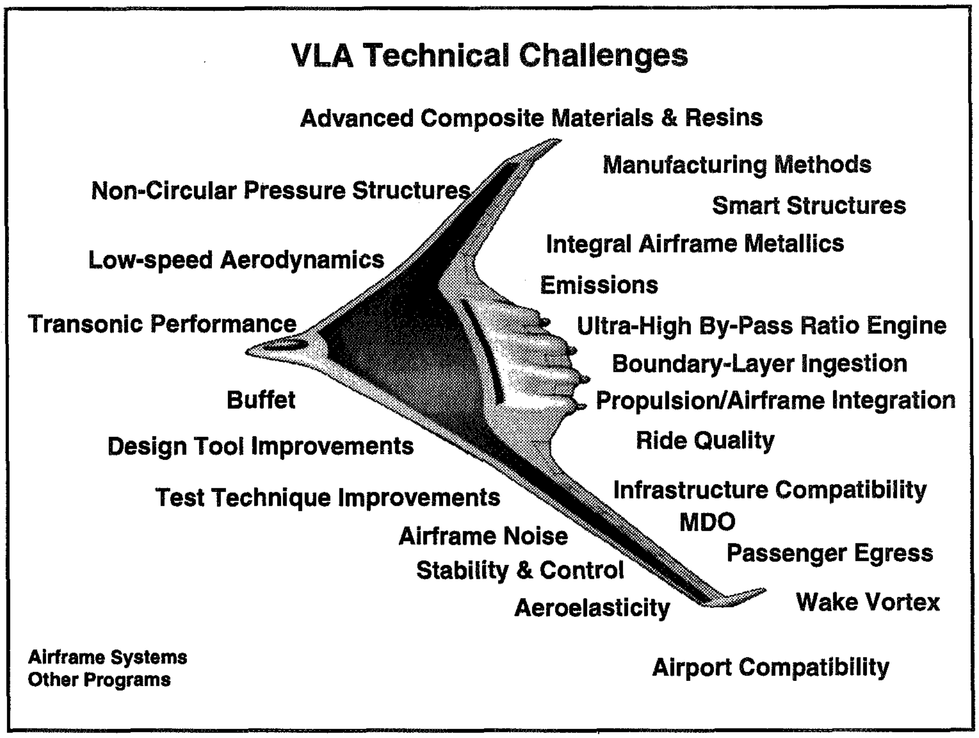
*Objective: Address barrier technology issues for future subsonic, very large, long range commercial/cargo transports*

- **Advanced composite materials and resins**
- **Sub-scale component test of non-circular pressure structures**
- **Test technique improvements for high Reynold's number testing of VLT's**
- **Improved design tools for rapidly assessing complex flows**
- **Thick, high-subsonic cruise Mach airfoil performance**
- **Noise reduction for VLT's**

# POTENTIAL APPLICATION OF MEGALINER TECHNOLOGY



## VLA TECHNICAL CHALLENGES



## AIRCRAFT TACTICAL TECHNOLOGY FROM ADVANCED CONTROLS

**Program Statement, Objective:**

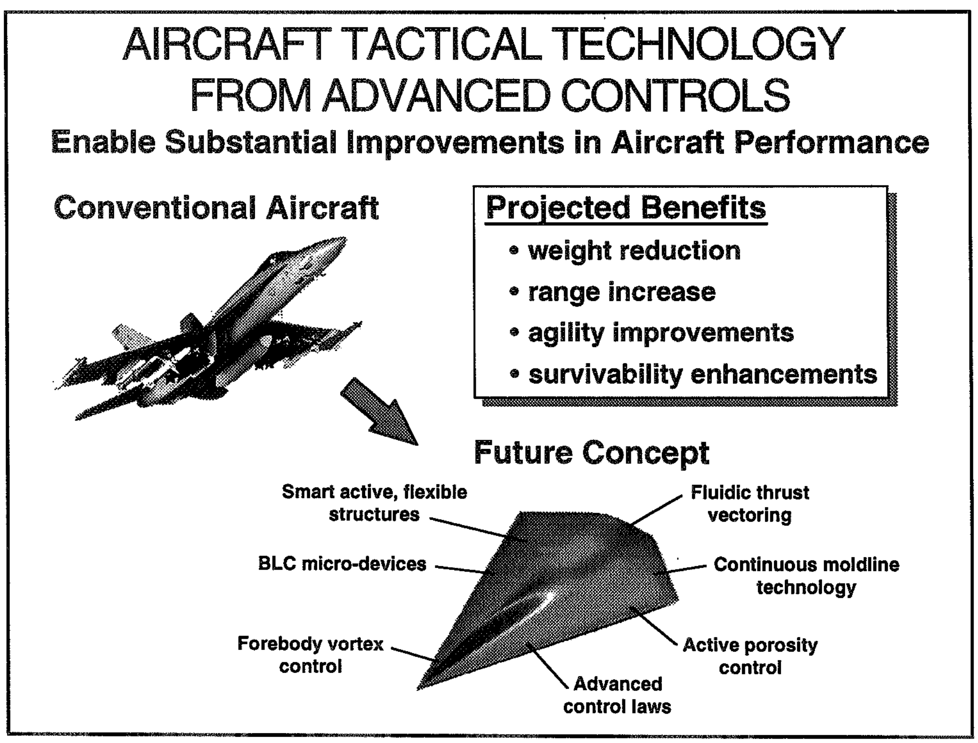
Future high-performance aircraft requirements are driven by the war fighter's needs and mission requirements as derived from studies of future conflict scenarios. These studies indicate that mission requirements will continue to push the performance envelope of high-performance aircraft. The goal of the ATTAC program is to develop advanced control technologies that contribute to a 20 percent decrease in aircraft takeoff gross weight and a 30 percent increase in agility while being compatible with survivability requirements. In order to accomplish this goal, unconventional control concepts will be explored along with advanced control law design methodology and optimization techniques.

**Technical Approach:**

There are two elements within the ATTAC program:

Innovative Control Concepts. This element will explore unconventional control concepts such as passive porosity, synthetic jets, fluidic thrust vectoring, and active structures.

Multi-Element Control Law Design Methodology. A variety of control law methodologies and optimization algorithms will be evaluated for robustness and flexibility when dealing with a large number of control effectors with widely varying characteristics in a highly constrained design space.



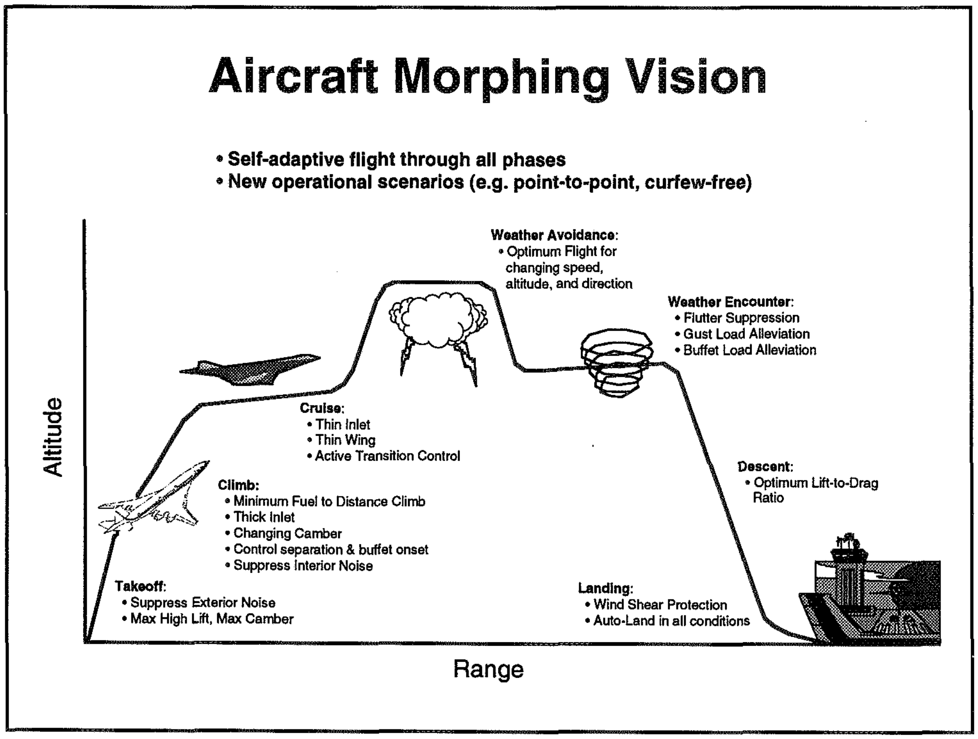
## AIRCRAFT MORPHING

**Program Statement, Objective:**

The Aircraft Morphing program will pursue achievement of self-adaptive flight for the purposes of achieving better performance, agility, and/or safety. The approach is to use smart, self-initiated, real-time modification and reconfiguration of aircraft structural, material, electronic, surface and aerodynamic properties to achieve optimal performance.

**Technical Approach:**

Within Aircraft Morphing, three elements are planned: Smart Materials, Devices and Systems; Aeroelasticity and Flight Dynamics; and Active Airframe Systems Control.



# Conclusions

- **Aeronautics Research and Technology Base has shifted from a discipline focus to a program focus**
- **Program planning is progressing**
  - Level-I plans are complete
  - Detailed Level-II plans are under development
  - Significant inter-center planning and coordination
- **Programs are addressing problems that are important to the nation**
  - Access to Space
  - Global Civil Aviation
  - Revolutionary Technology Leaps

# An Overview - NASA LeRC Structures Program

Erwin V. Zaretsky
NASA Lewis Research Center
Cleveland, OH

# AN OVERVIEW - NASA LERC STRUCTURES PROGRAM

Erwin V. Zaretsky, P.E.
Chief Engineer
Structures and Acoustics Division
NASA Lewis Research Center
Cleveland, OH

**AN OVERVIEW -**

**NASA LERC STRUCTURES PROGRAMS**

by

Erwin V. Zaretsky, P.E.
Chief Engineer for
Structures and Acoustics
NASA Lewis Research Center
Cleveland, Ohio 44135

## LERC STRUCTURES AND ACOUSTICS DIVISION CAPABILITY

The Structures and Acoustics Division of the NASA Lewis Research Center has its genesis dating back to 1943. It has been an independent Division at Lewis since 1979. Its two primary capabilities are performance and life analysis of static and dynamic systems such as those found in aircraft and spacecraft propulsion systems and experimental verification of these analyses. Research is conducted in-house, through university grants and contracts, and through cooperative programs with industry. Our work directly supports NASA's Advanced Subsonic Technology (AST), Smart Green Engine, Fast Quiet Engine, High-Temperature Materials and Processing (HiTEMP), Hybrid Hyperspeed Propulsion, Rotorcraft, High-Speed Research (HSR), and Aviation Safety Program (AvSP).

### LeRC Structures & Acoustics Division Two Primary Capabilities

- Analysis capability
- Experimental capability

## LERC STRUCTURES AND ACOUSTICS DIVISION CORE COMPETENCIES

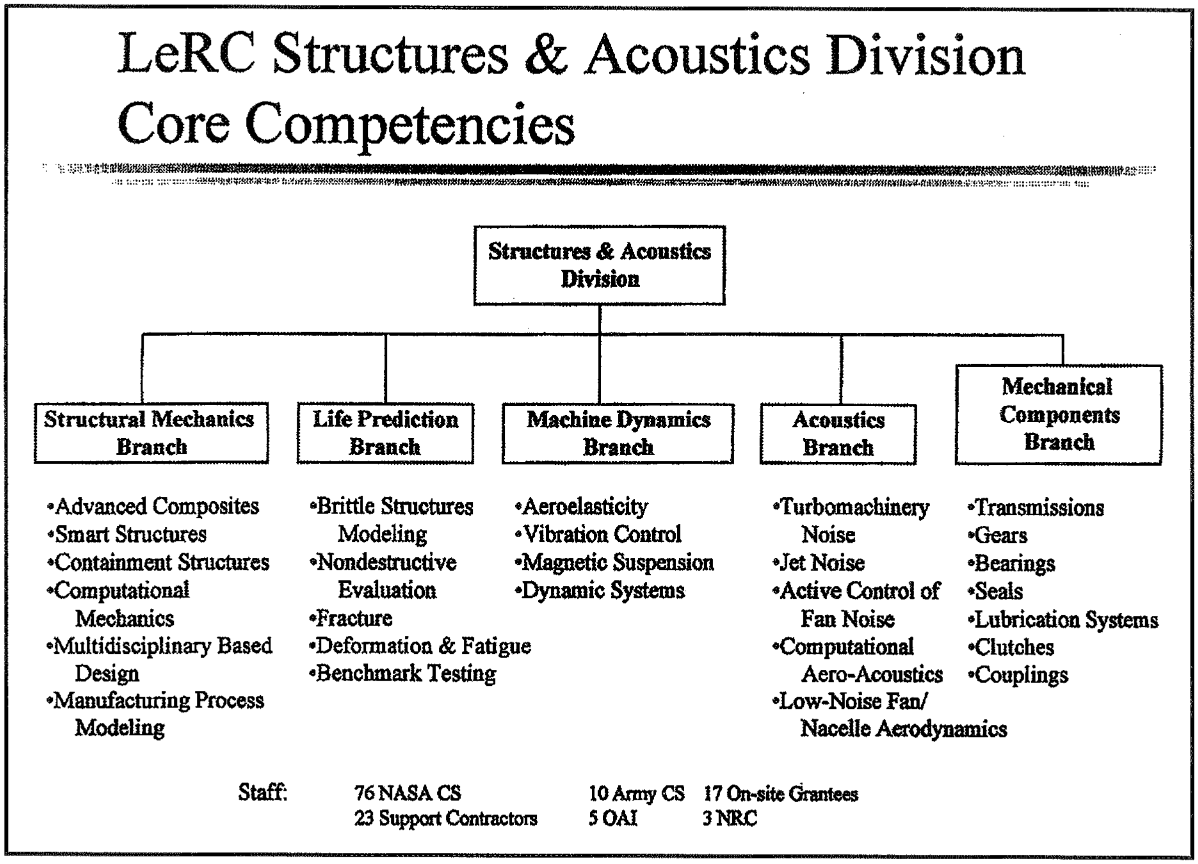
There are eight core competencies of the Structures and Acoustics Division. These are listed below. A primary focus of the Division has been the design application of new composite materials into advanced aerospace structures. In addition, research is being performed on drive systems for helicopters and turboprop aircraft. Work is performed on aeroelasticity and aircraft engine noise suppression. Current goals emphasize lighterweight, more reliable aeropropulsion structures operating at higher temperatures.

### LeRC Structures & Acoustics Division Core Competencies

- Computational tools
- Experimental methods and test techniques
- Structural concepts
- Advanced materials applications
- Mechanical drive systems
- Vibration control
- Aeroelastic codes
- Noise Suppression

## LERC STRUCTURES AND ACOUSTICS DIVISION ORGANIZATION

The Structures and Acoustics Division comprises five branches consisting of 134 engineers, scientists and support personnel. The staff consists of NASA Lewis civil servants and personnel from universities and private support organizations which are listed. The breakdown of the Division programs are shown under their respective branches.



## LERC STRUCTURES AND ACOUSTICS DIVISION CONTACTS

The Structures and Acoustics Division welcomes inquiries from industry, universities and other government organizations as well as private individuals. There exists many collaborative research and technology projects between outside organizations and the various branches. Contacts for each of the organizational entities are shown.

### LeRC Structures & Acoustics Division Contacts

**Structures & Acoustics Division (5900)**
**L. James Kiraly**
**Acting Division Chief**
**433-6023**

**Structural Mechanics Branch (5910)**
**Dale A. Hopkins**
**Acting Branch Chief**
**433-3260**

**Acoustics Branch (5950)**
**Valerie Lyons**
**Acting Branch Chief**
**433-5728**

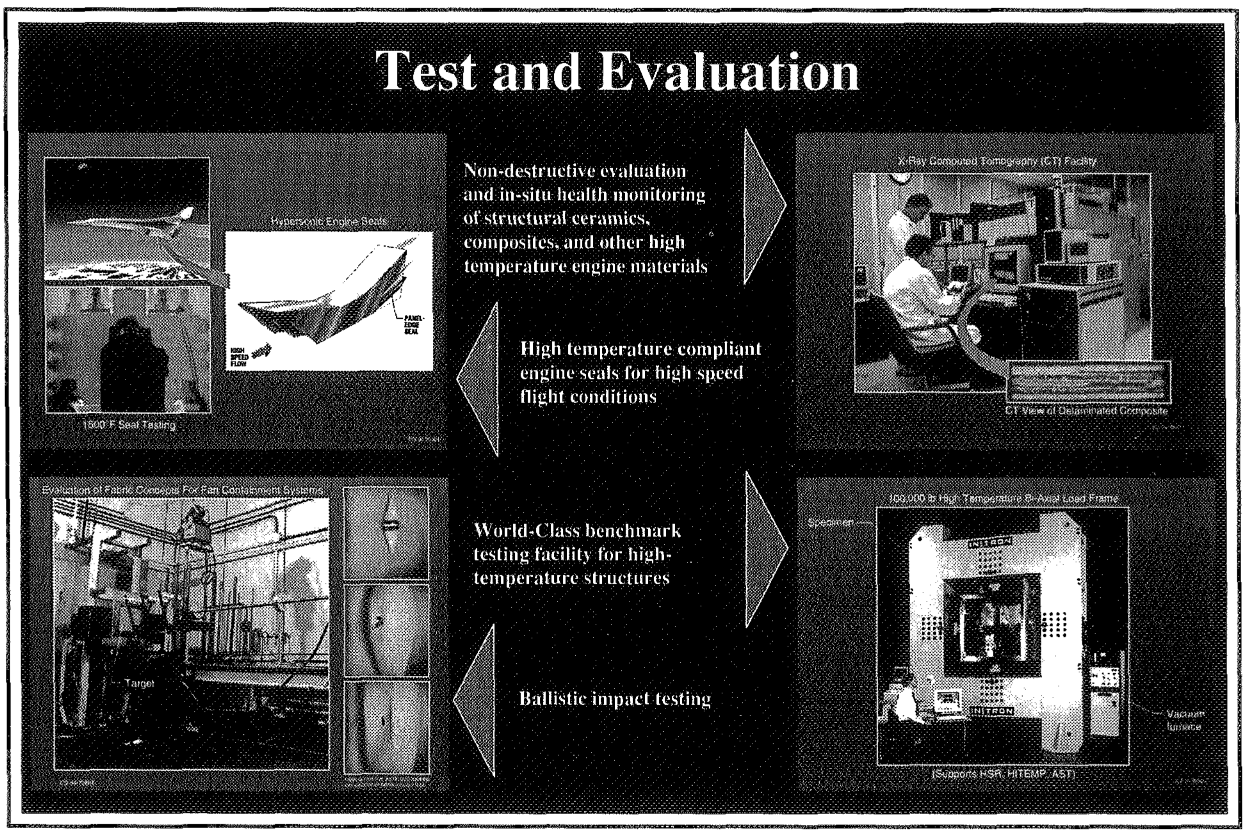
**Life Prediction Branch (5920)**
**John P. Gyekenyesi**
**Branch Chief**
**433-3210**

**Mechanical Components Branch (5940)**
**John J. Coy**
**Branch Chief**
**433-3915**

**Machine Dynamics Branch (5930)**
**George L. Stefko**
**Acting Branch Chief**
**433-3920**

## TEST AND EVALUATION

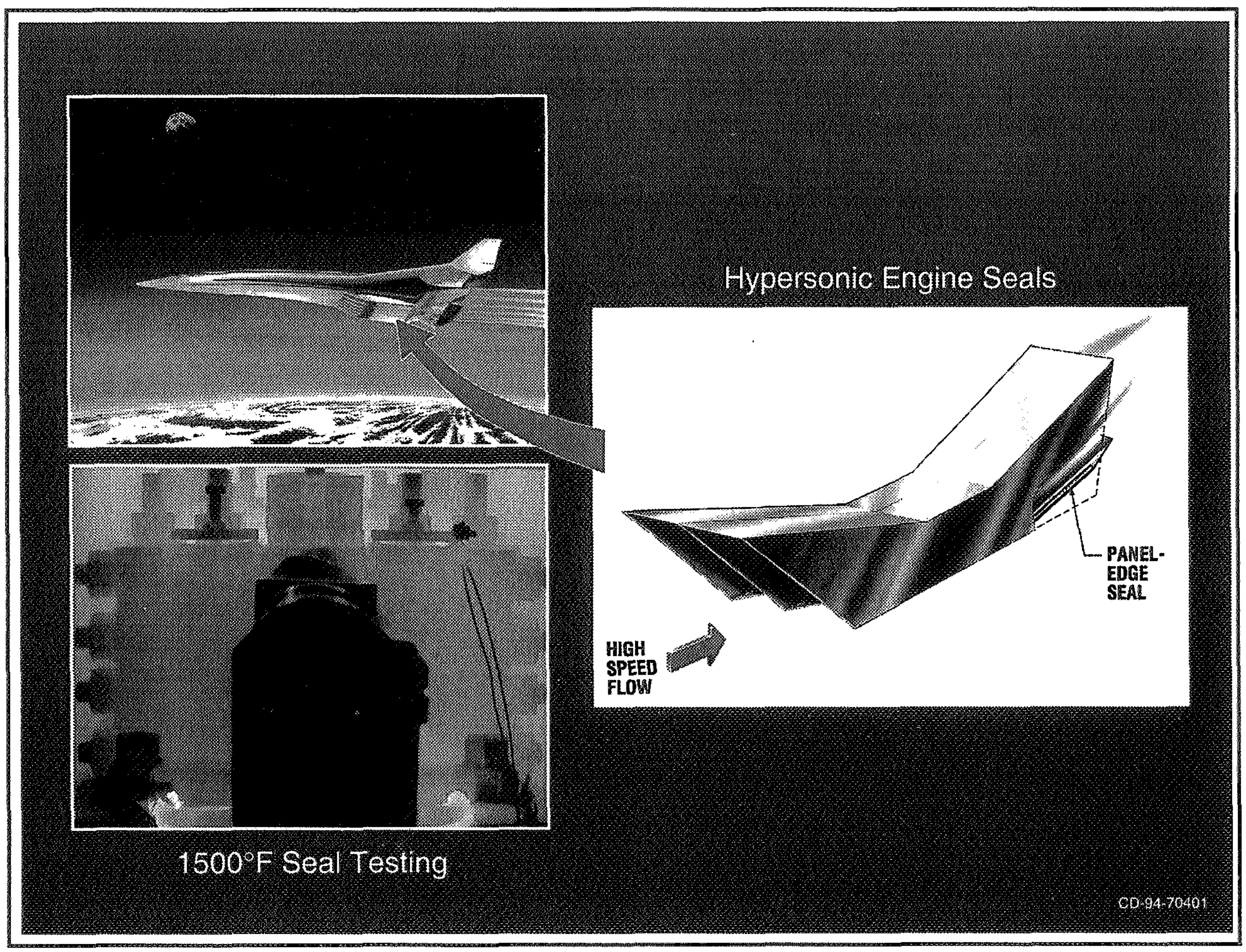
Unique mechanical testing and nondestructive evaluation techniques are being developed to make global civil aviation and access to space more competitive and affordable. A state-of-the-art computed tomography facility was developed to characterize critical manufacturing problems in advanced composite materials and engine subscale components. This facility provides rapid re-engineering and reduction in product development cycle time. A world-class benchmark testing facility for high temperature structures was established. This facility is used to verify and validate structural analyses methods for aeropropulsion systems operating at 1500°C and to produce reliable test data for advanced materials in scale-up form subjected to prototypical operating conditions. The ballistic impact facility was built for testing light weight fan containment systems and other jet engine systems where impact strength is of concern. High temperature compliant engine seals are being developed to survive temperatures up to 1100°C, to have low leakage, to exhibit resilience with cycling, and to resist scrubbing damage.




CD-96-72981

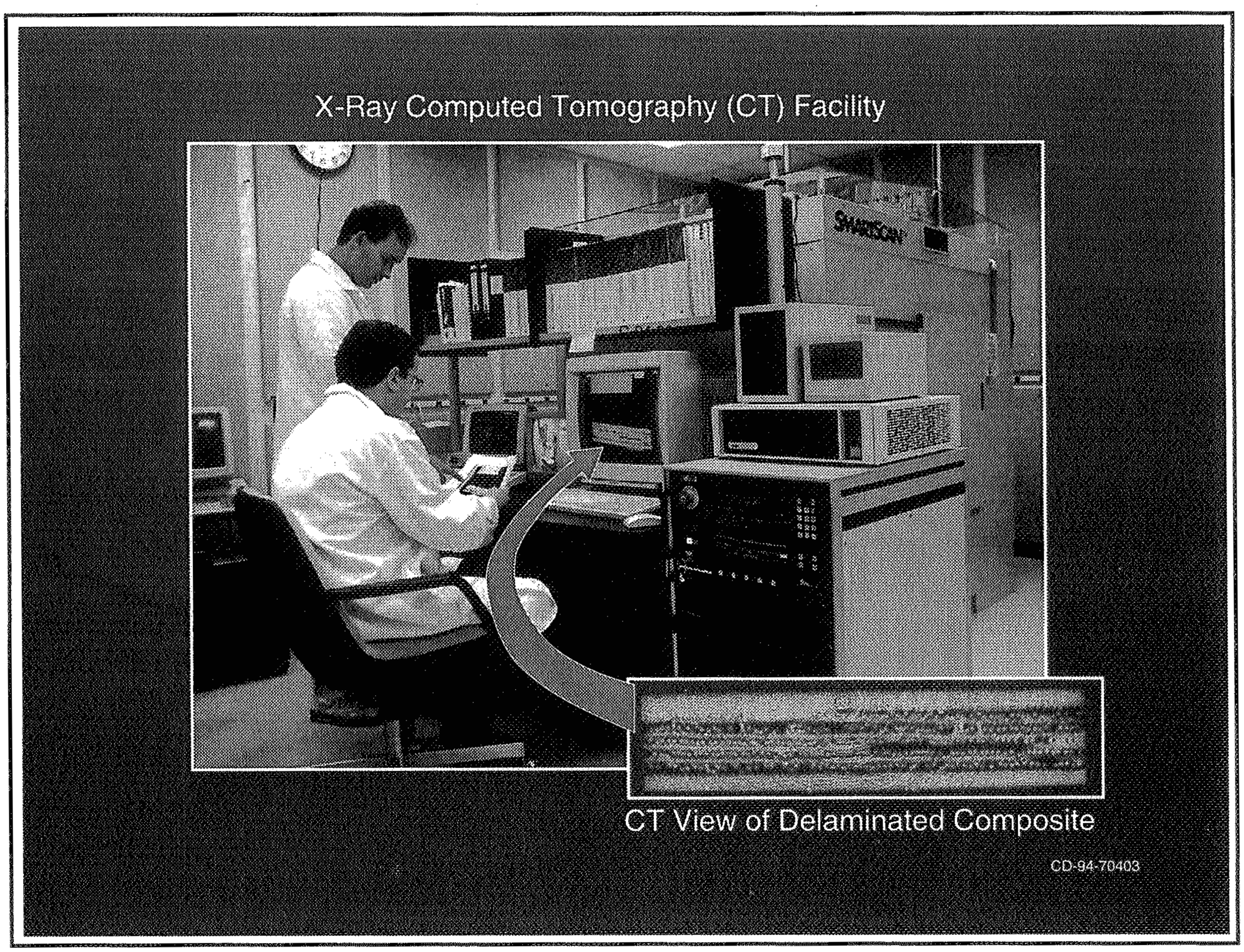
## HIGH TEMPERATURE SEALING

The National Aerospace Plane Project identified a critical need for seals that could operate at or above 2000°F. This temperature was in excess of conventional graphite and metal seal temperatures. A need existed for a seal that exhibits low leakage to limit parasitic losses; remains flexible at temperature; resists hydrogen embrittlement and oxidation; and be fabricable using available materials. In order to accommodate these requirements, research and development of braided seals made from high-temperature ceramics and super alloy fibers into leak resistant, abrasion resistant structures are being performed. This seal follows and seals significant engine sidewall distortions. This NASA potential seal concept was awarded the NASA 1997 Invention of the Year Award.



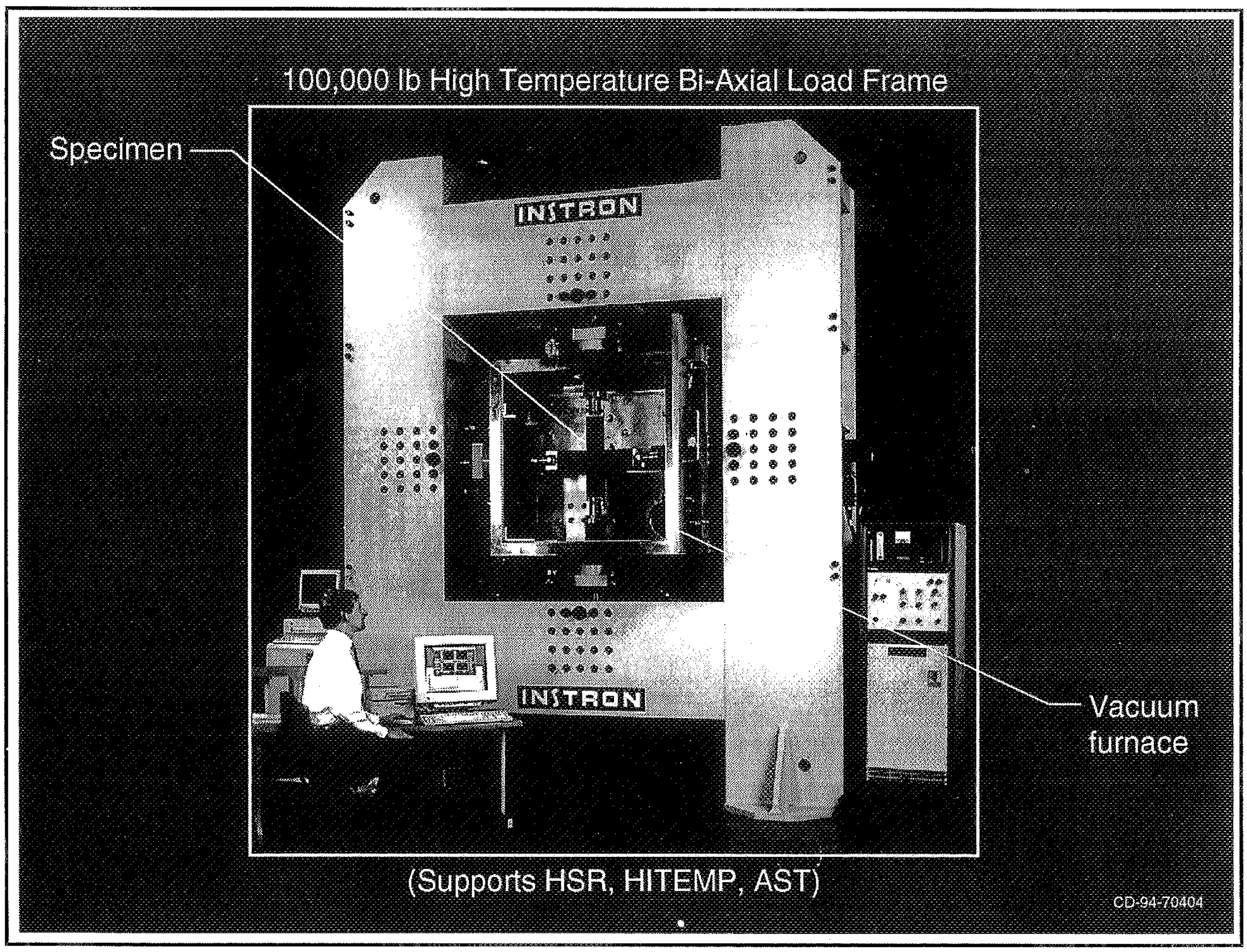
## X-RAY COMPUTED TOMOGRAPHY

A state-of-the-art computed microtomography facility was established. This facility is used to characterize critical manufacturing problems in advanced composite materials and engine subscale components as well as to provide rapid re-engineering and reduction in product development cycle time. This facility is a modularized digital x-ray system that produces digital radiographic, tomographic and laminographic images. It is unique for quality assurance of composites because it resolves volumetric flaws as small as 25 × 25 × 25 mm (1 mill) in a cross section of up to 5 × 5 cm (2 in).



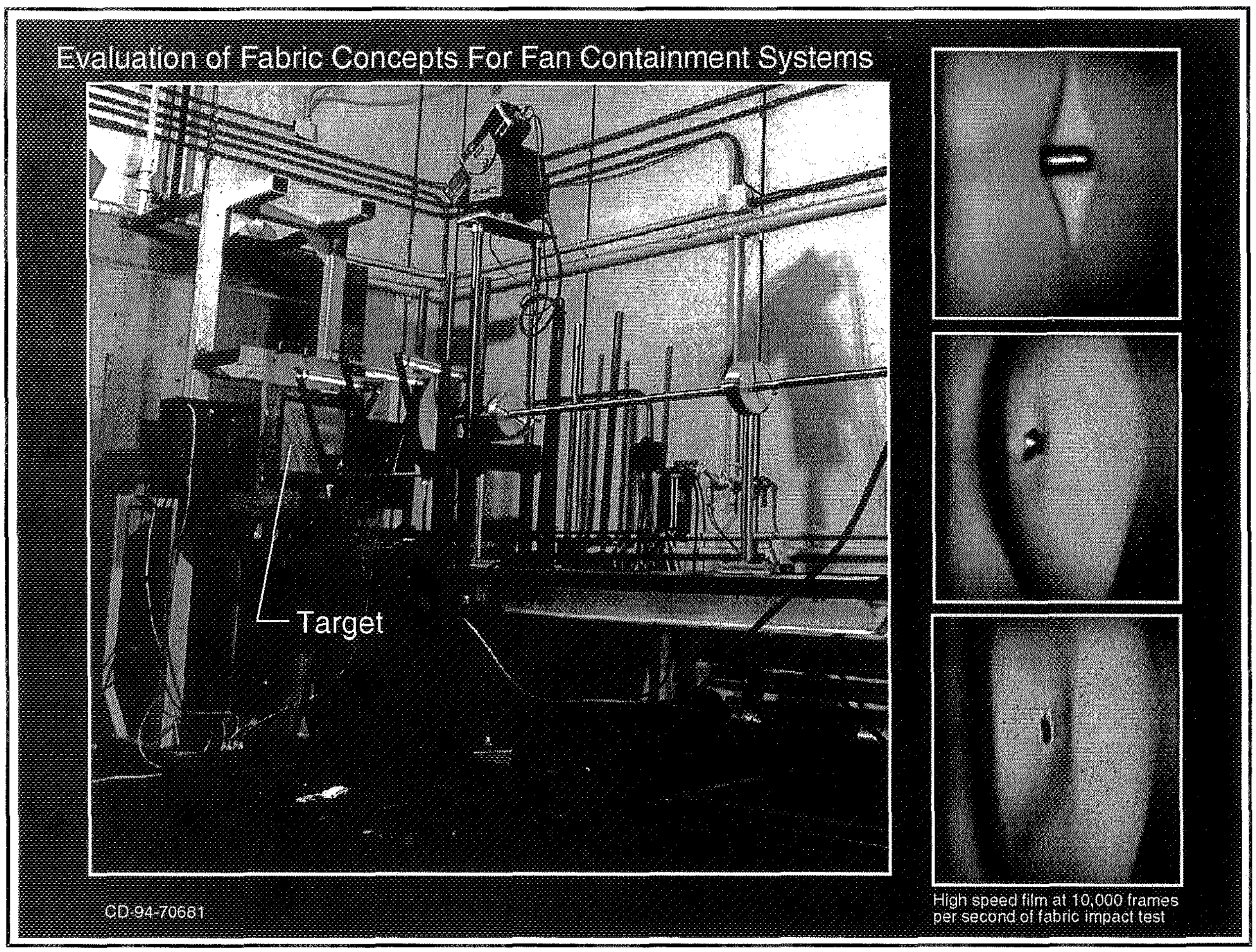
STRUCTURAL TESTING

A difficulty with most advanced materials is that the behavior of those materials at the test coupon level can be significantly different from that at the full-scale component level. A benchmark structural test facility has been developed to address scale-up issues by testing materials at the sub-element level. This facility can be used to verify and validate structural analysis methods. Experimental conditions are generated under prototypical loading conditions including complex stress states. The experimental results are compared to those analytically predicted.



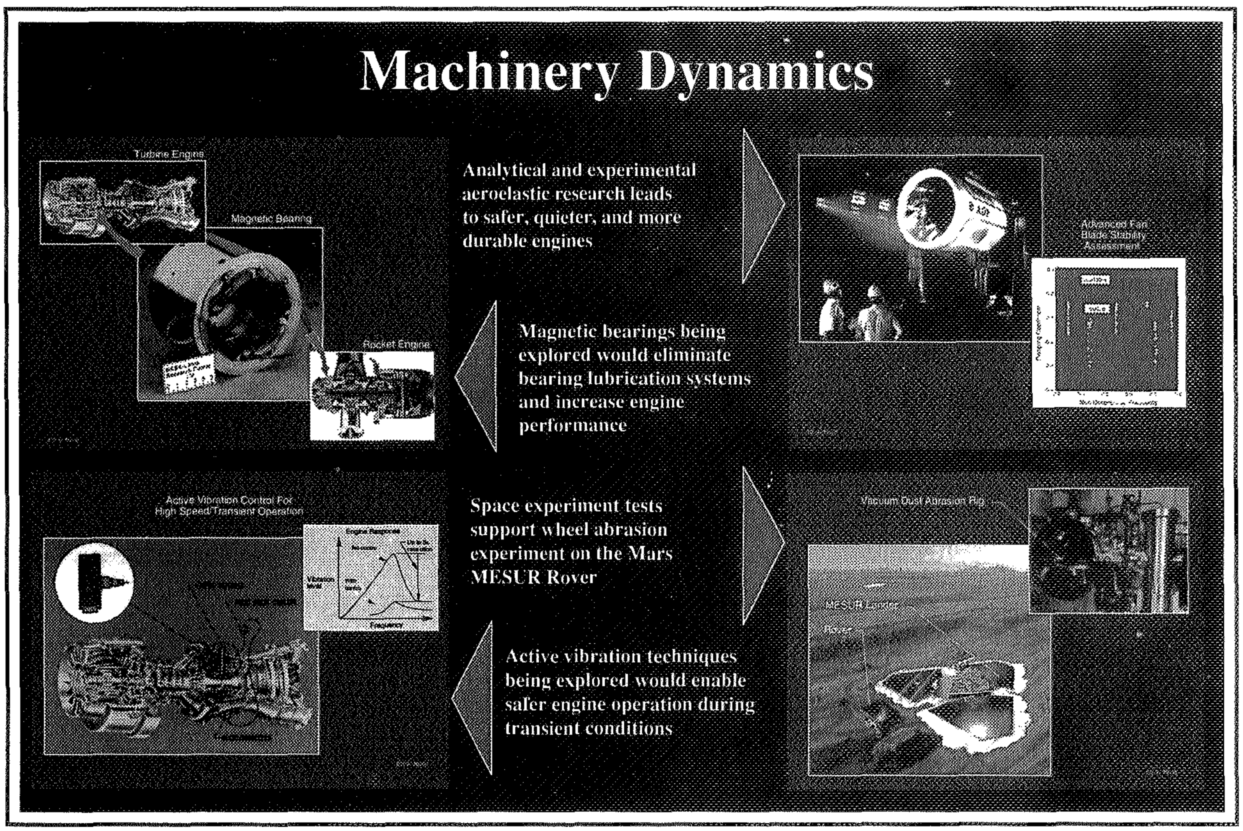
## BALLISTIC IMPACT RESEARCH

Impact research is being conducted to reduce the weight of jet engine fan containment systems for future aircraft, assess the impact resistance of new turbine blade materials, and improve the ability of the material models in DYNA-3D to predict damage and failure. The work is both experimental and computational in nature. The ballistic impact laboratory currently has several gas guns ranging in size from 1/16" to eight inches in diameter. Projectiles weighing up to five pounds at velocities up to 1200 ft/sec. can be shot from these guns. Gun barrels range in size from 0.15 cm to 20 cm in diameter and can shoot projectiles weighing up to 2.5 Kg at speeds of 350 m/sec. A computational capability exists complementing the experimental effort. The LS-DYNA-3D explicit finite element analysis code is used to predict deformation and damage of the impact events.



## MACHINERY DYNAMICS

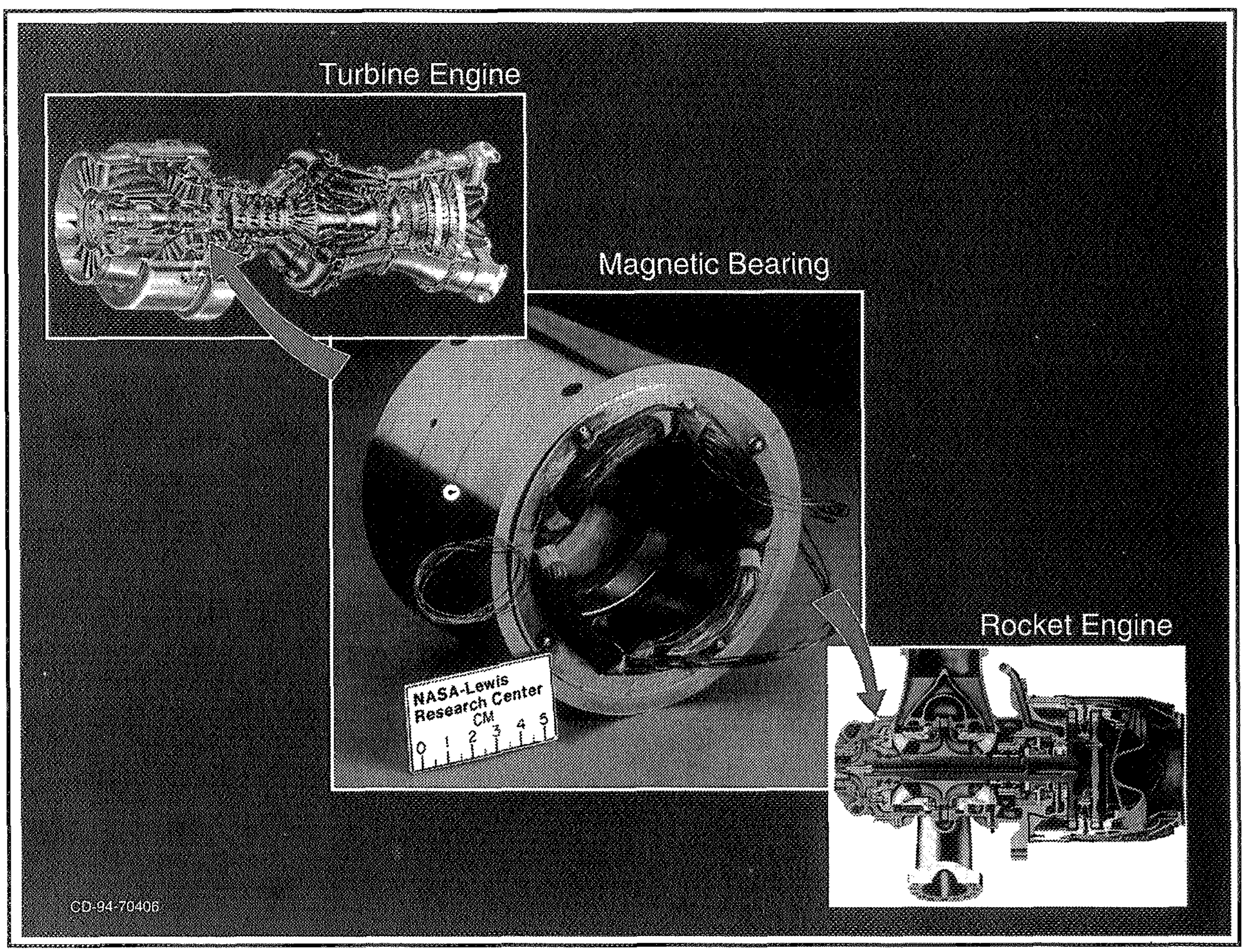
Our machinery dynamics research can be broadly classified into four major activities: turbomachinery aeroelasticity, vibration control, dynamic systems response and analysis, and computational structural methods. This work is applicable to turboprop, turbofan, turbopumps, compressors, and advanced engine core technology. We are developing improved analytical and experimental methods for avoiding flutter and minimizing forced vibration response of aerospace systems. In dynamic systems response and analysis, we are analyzing and verifying the dynamics of interacting systems as well as developing concepts and methods for controlling motion in space and microgravity environments. We are developing advanced computer programs for analyzing, predicting and controlling the stability and dynamic response of aerospace propulsion and power system components such as rotating bladed structural assemblies, engine rotors, high-speed shafting, and the coupled interactions of blade-disk-shaft-casting structural systems.




CD-96-72982

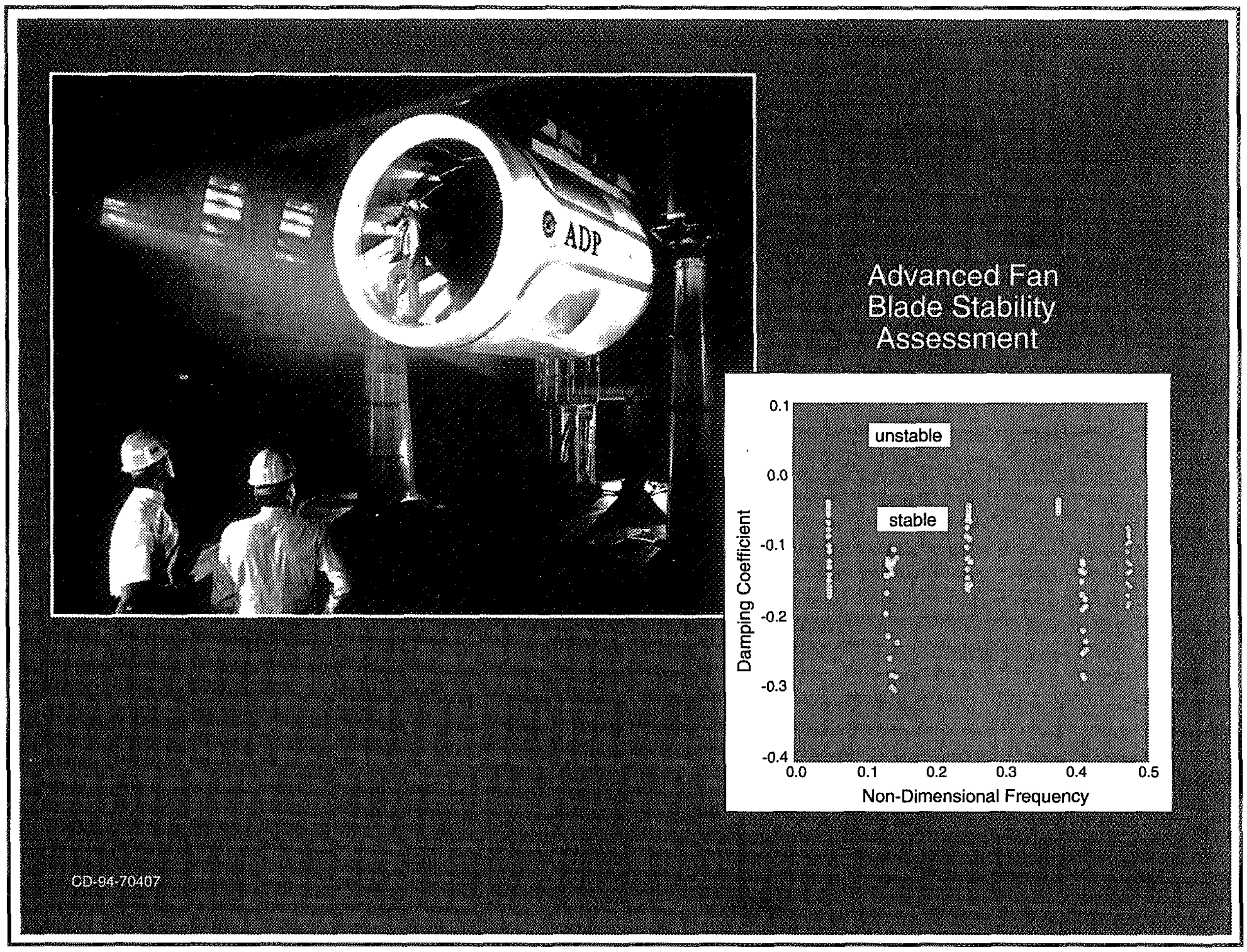
MAGNETIC SUSPENSION SYSTEMS

Research is being conducted to study the feasibility of magnetic suspension system or magnetic bearings for both high temperature and cryogenic applications. The application of magnetic bearings to aircraft and rocket engines could improve the efficiency of these systems by increasing the rotor speed and controlling the rotor vibrations. It can also improve the reliability by using magnetic bearings as a health monitoring device. A magnetic bearing is similar to an electric motor. The magnetic bearing has a laminated rotor and stator made out of cobalt steel. The stator has a series of coils of wire wound around it. These coils form a series of electric magnets around the circumference. These magnets exert a force on the rotor and coupled with displacement probes keeps the rotor in the center of the cavity.



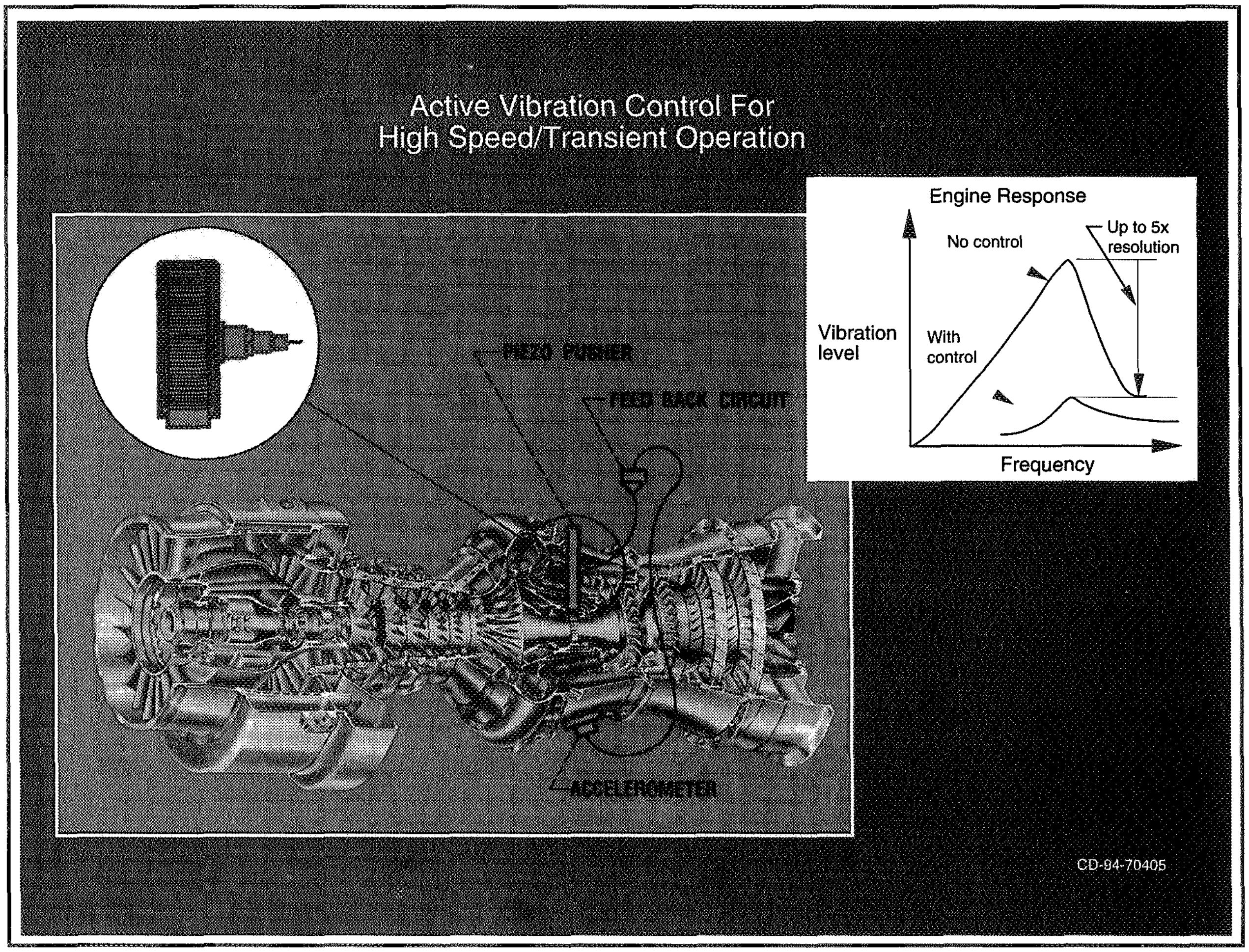
ENGINE DYNAMIC ANALYSIS

Analysis and model testing are being conducted as part of a program to develop low noise advanced wide chord and engines in cooperation with the major U.S. engine manufacturers. A demonstrator advanced wide chord fan engine from Pratt & Whitney is shown in the larger frame. The engine is in the Ames 40-by-80 wind tunnel. An analysis was performed by the Structures and Acoustics Division to assess the dynamic stability of a wind tunnel model fan that will be tested at Lewis this year.



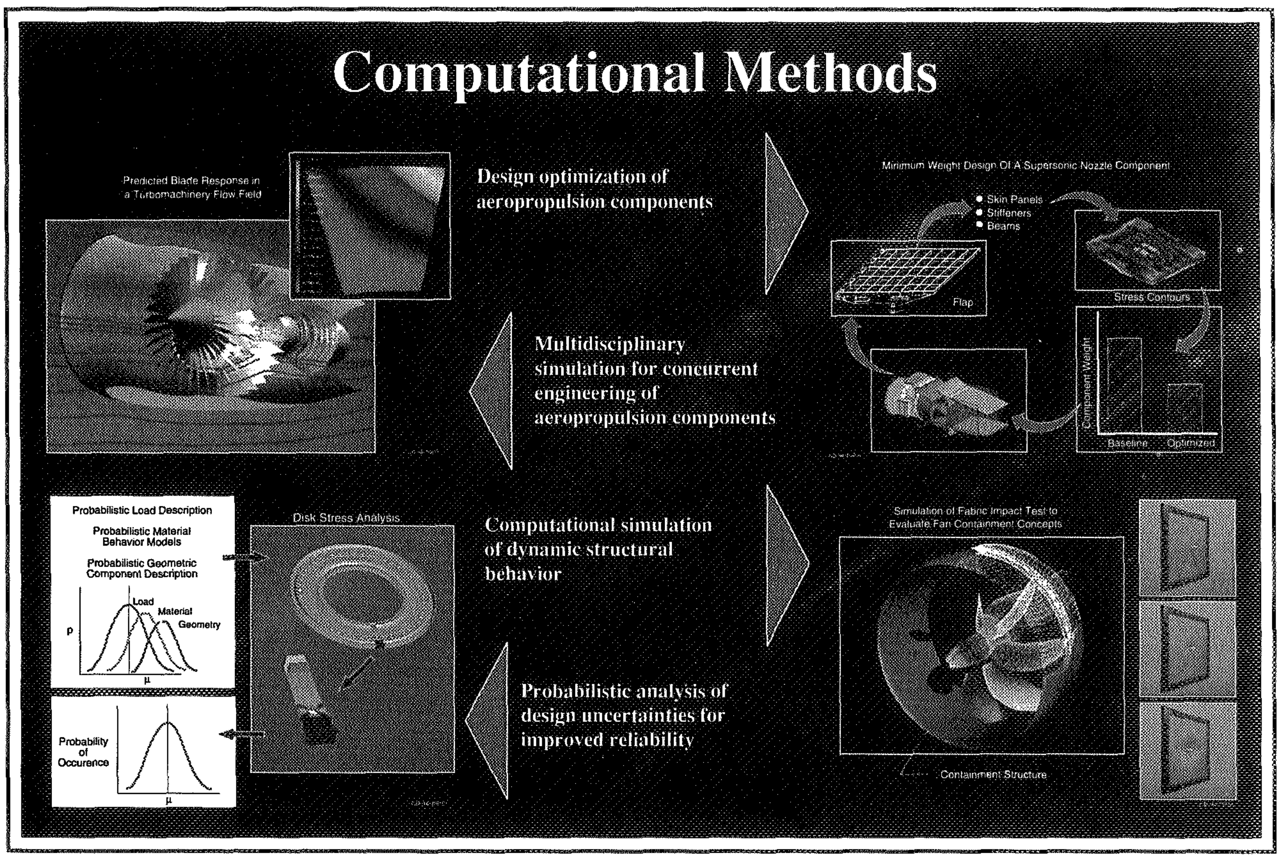
ACTIVE VIBRATION CONTROL

Our research in vibration control includes developing real-time, actively controlled bearing support systems for advanced aircraft turbine engines. Such support systems will reduce advanced aircraft turbine engine weight and rotor vibrations, improve efficiency, and possibly increase stall margins. Expert system controllers are being studied that use advanced computer architectures to adaptively change flight conditions and to monitor the health of the support systems. Gas turbine engine seal efficiency is affected by rotor vibrations which causes the seals to open. Our research is conducted in order to develop a system which senses the vibrations and applies a correction force at the support bearing to cancel them.



# COMPUTATIONAL METHODS

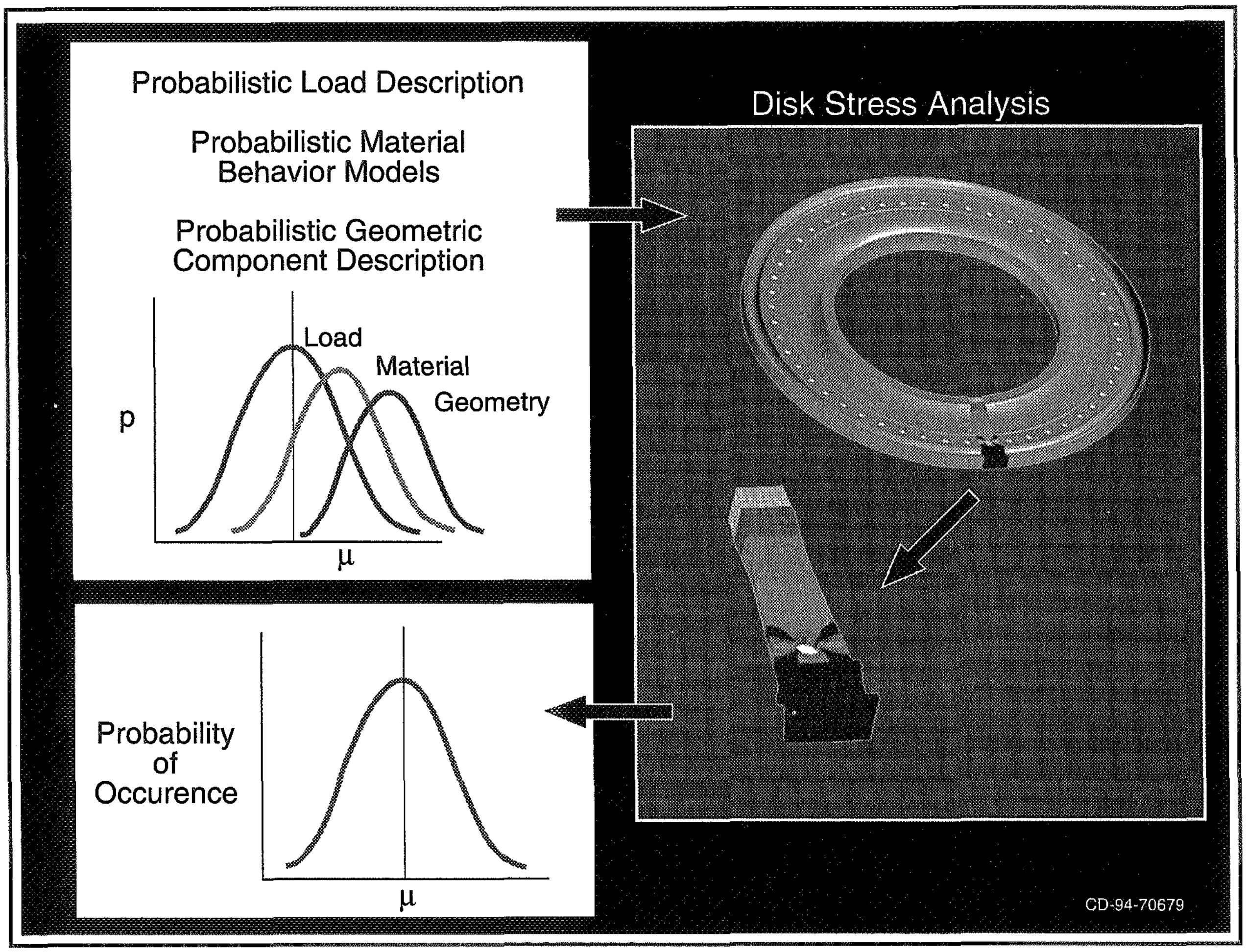
In computational structural methods, we are developing advanced programs for analyzing, predicting and controlling the stability and dynamic response of aerospace propulsion and power system components such as rotating bladed structural assemblies, engine rotors, high-speed shafting, and the coupled interactions of blade-disk-shaft-casing structural systems. In particular, we are developing and employing computational methods to analyze the complex interacting dynamic of advanced turbo-machinery and engine components such a fans, compressors, turbines and turbopumps. Analytical methods include both deterministic as well as probabilistic methods. Modeling includes new materials such as metal matrix composites and ceramic matrix composites.




CD-96-72983

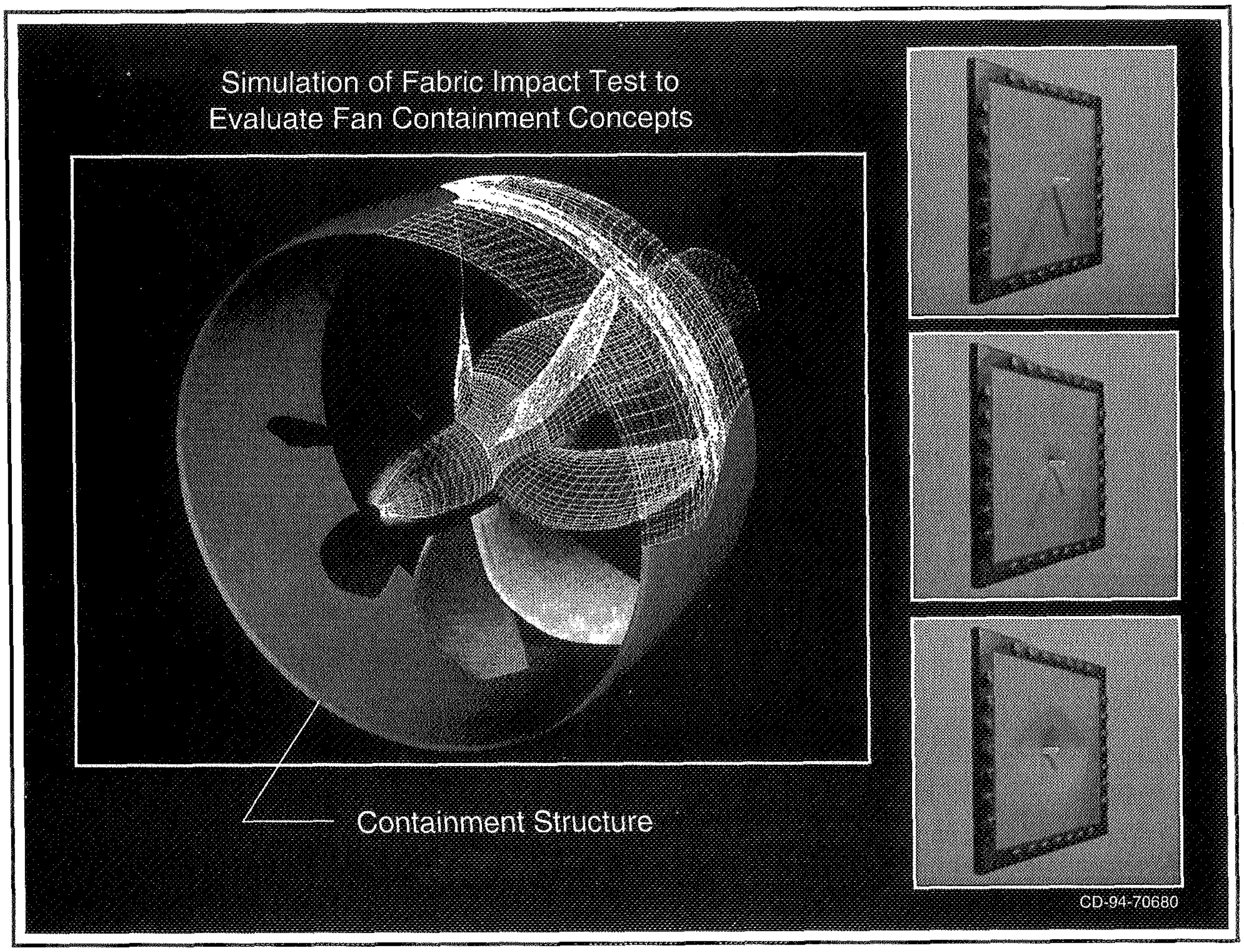
## PROBABILISTIC DESIGN FOR STRUCTURAL RELIABILITY AND RISK

Deterministic structural analysis methods are not always sufficient to evaluate critical structural components properly for life-rated structural systems. Analysis of aerospace structures are formulated based on: (1) loading conditions; (2) material behavior; (3) geometric configuration; and (4) supports. These four fundamental aspects are uncertain in nature. One formal way to account for these uncertainties is to develop probabilistic structural analysis methods where the uncertainties in all participating variables are described by appropriate probabilistic functions. The objective of this research is to develop a methodology for computational simulation of uncertainties applied to specific aerospace components. We also exercise the methodology whereby it can be credibly applied to actual product design practice to quantify risk and reliability in life-rated structures.



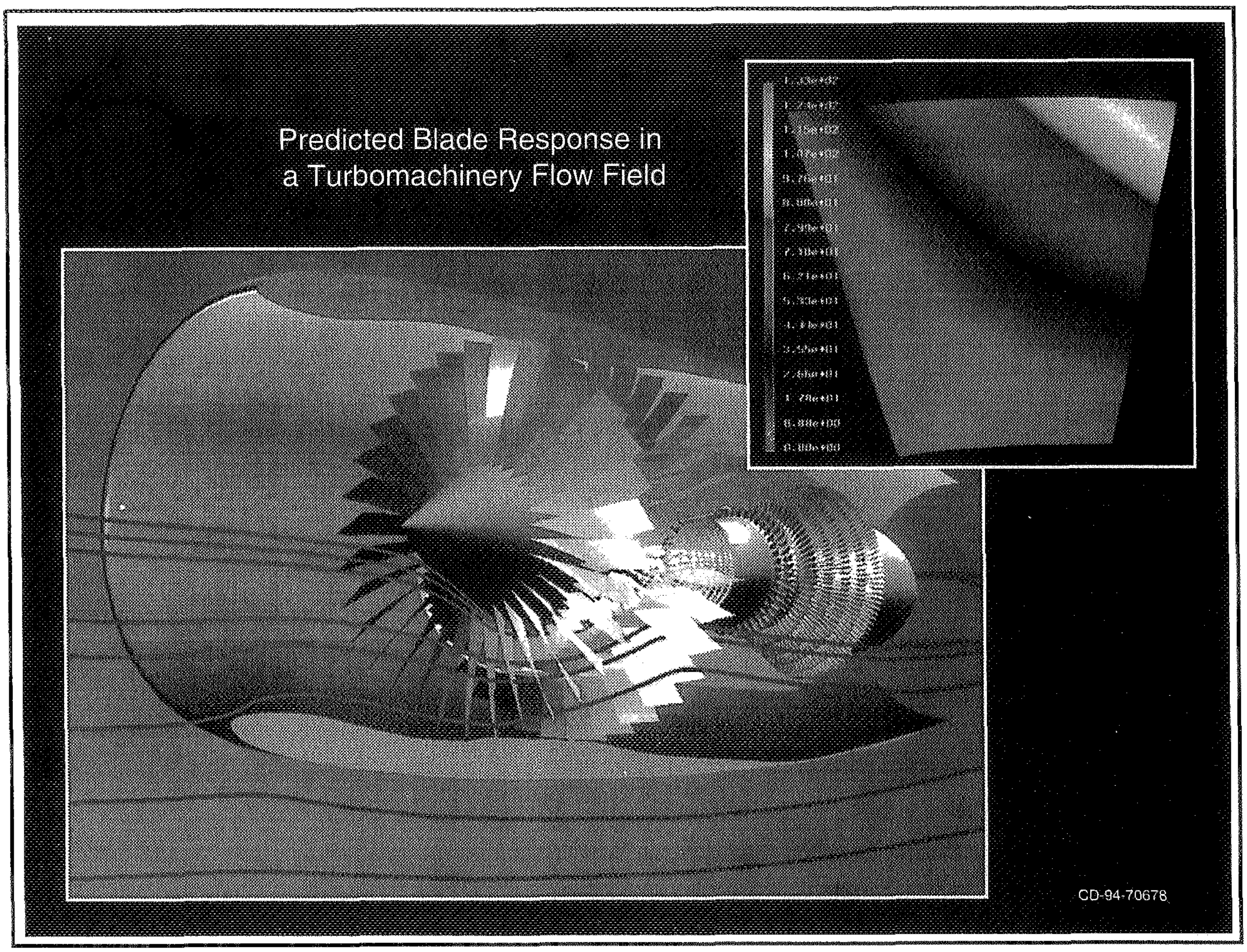
## CONTAINMENT STRUCTURES

In addition to the ballistic impact research program previously described, analytical work is proceeding which uses the results of the experimental program to evaluate fan containment concepts. The LS-DYNA-3D explicit finite element analysis code is used to predict deformation and damage of full-scale containment concepts.

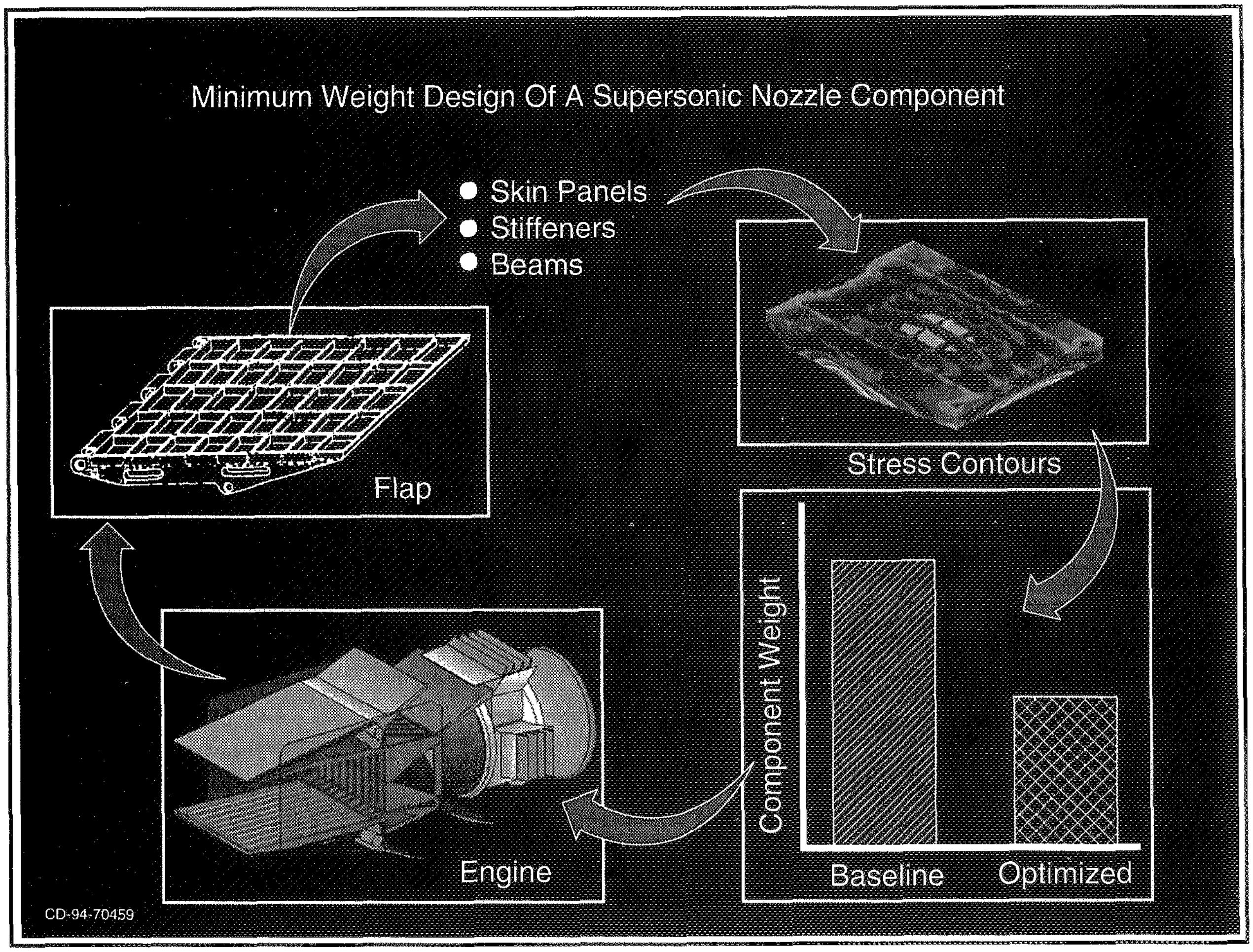


## DYNAMIC SYSTEM RESPONSE

We are analyzing and verifying the dynamics of interacting systems. This is illustrated in the figure where compressor and turbine blade responses are predicted in a computer simulation of a full-scale turbine engine. Analyses of this type can be used to optimize engine designs and operation thereby eliminating trial and error experimental methods.

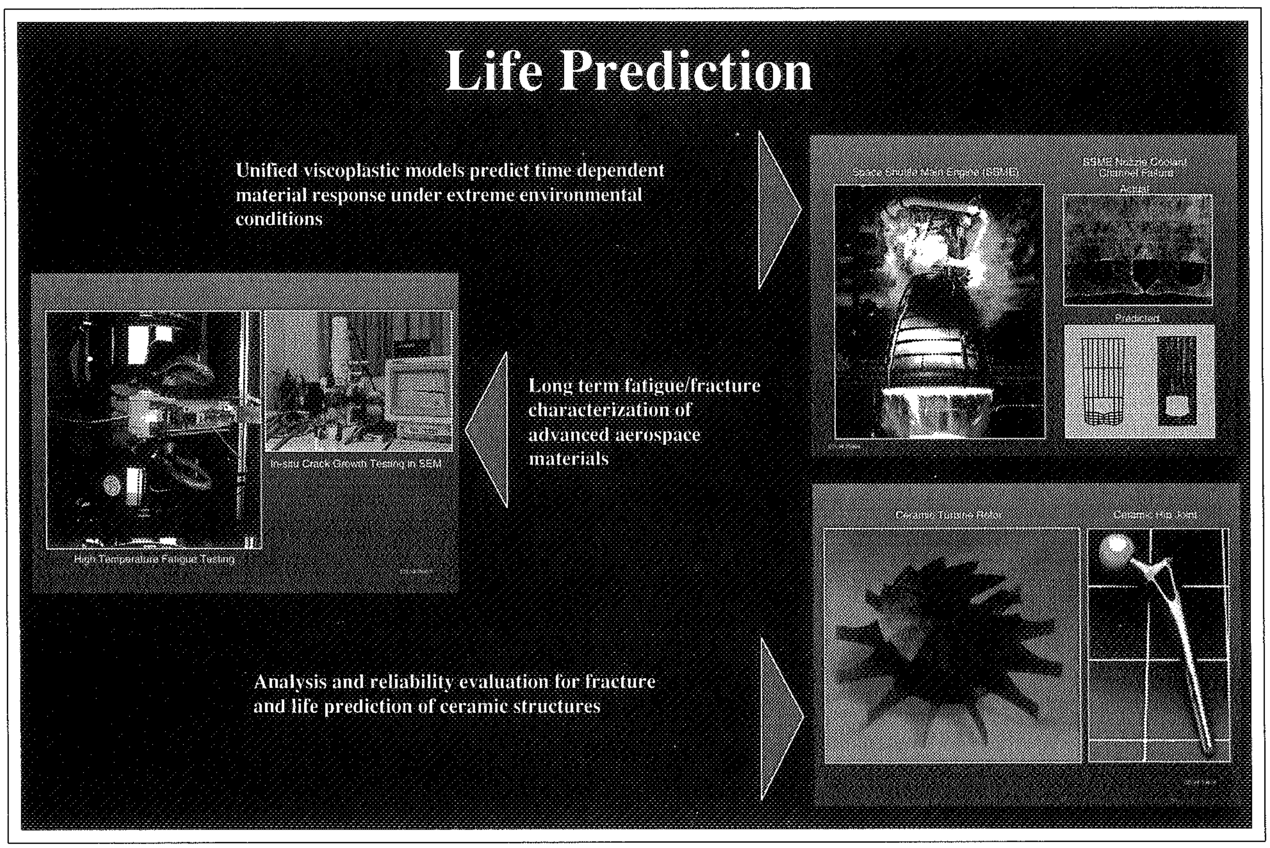


Various computer codes developed by us, or for NASA, are used for design optimization. An example of such aerospace component optimization is illustrated for a mixed flow turbofan engine exhaust nozzle system for the High-Speed Civil Transport. The nozzle is fabricated out of several components such as rear and forward divergent flaps, rear and forward sidewalls, bulkheads, duct extensions, about six disk supports, etc. Design complexity of the nozzle increases with flight mach number, pressure ratios, temperature gradients, dynamic response, and degradation of material properties at elevated temperatures. Design optimization of a rear divergent flap of the downstream mixing nozzle was attempted through the design code CometBoards (an acronym for comparative evaluation test bed of optimization and analysis routines for the design of structures). The static as well as dynamic analyses for the flap were carried out utilizing two analysis codes (LEHOST and MSC/NASTRAN). A qualitative behavior of the flap was explored through its dynamic animation. Scrutiny of the animation revealed that skin panel, stiffeners, tapered sidewall and edge beams can be potential candidates for the purpose of design optimization of the flap. The flap was optimized for minimum weight condition for static and dynamic constraints for the potential design variables.



## LIFE PREDICTION

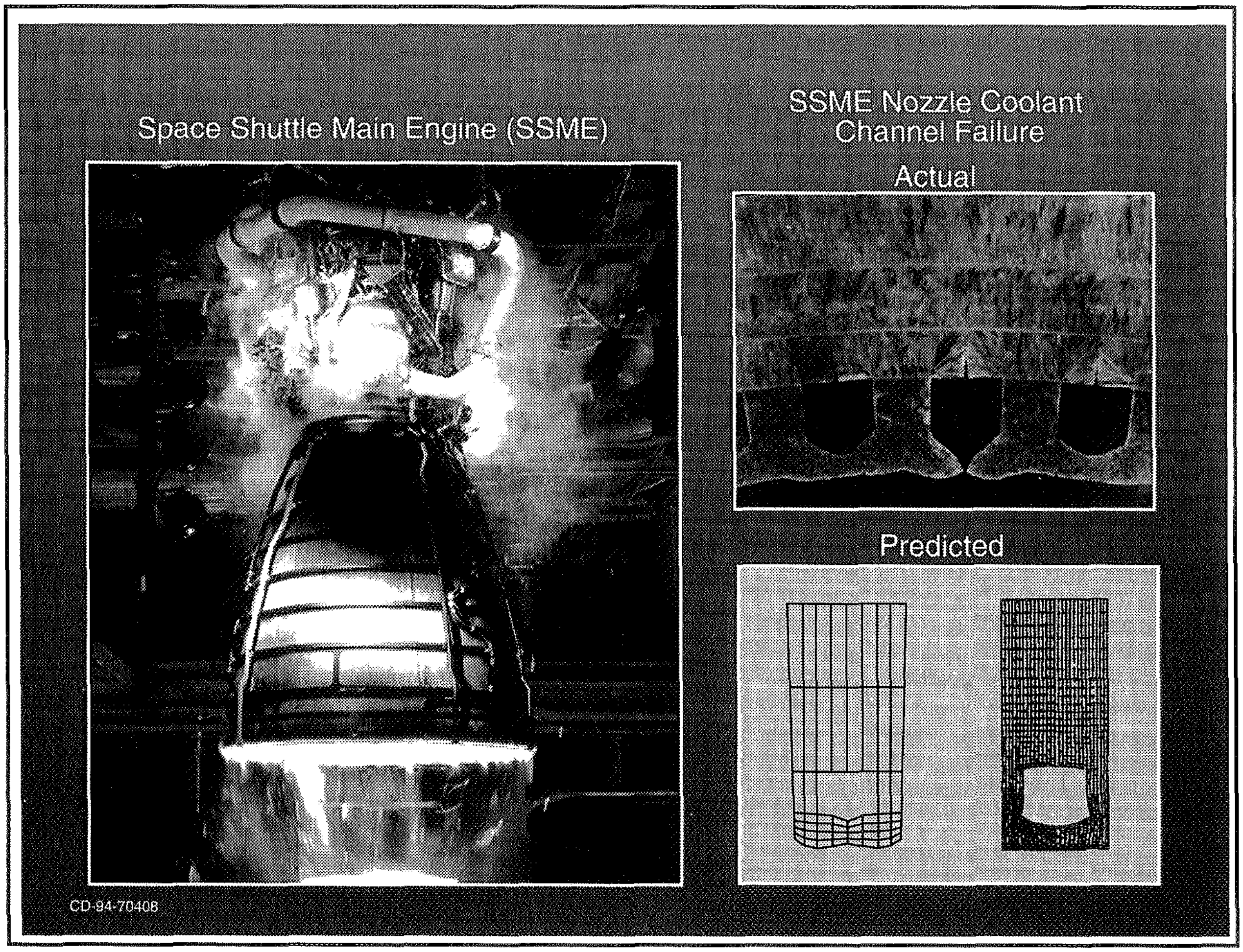
The development of verified and validated life prediction models for components experiencing extreme thermomechanical loading conditions such as rocket engine nozzles presents a major challenge. Research is coordinated in a number of technical areas. One such activity is the development of unified viscoplastic constitutive models which are capable of treating plasticity, creep and their interactions. Another area of research is the development of fatigue, fracture and reliability models which are tailored specifically for a particular class of materials.




CD-96-72984

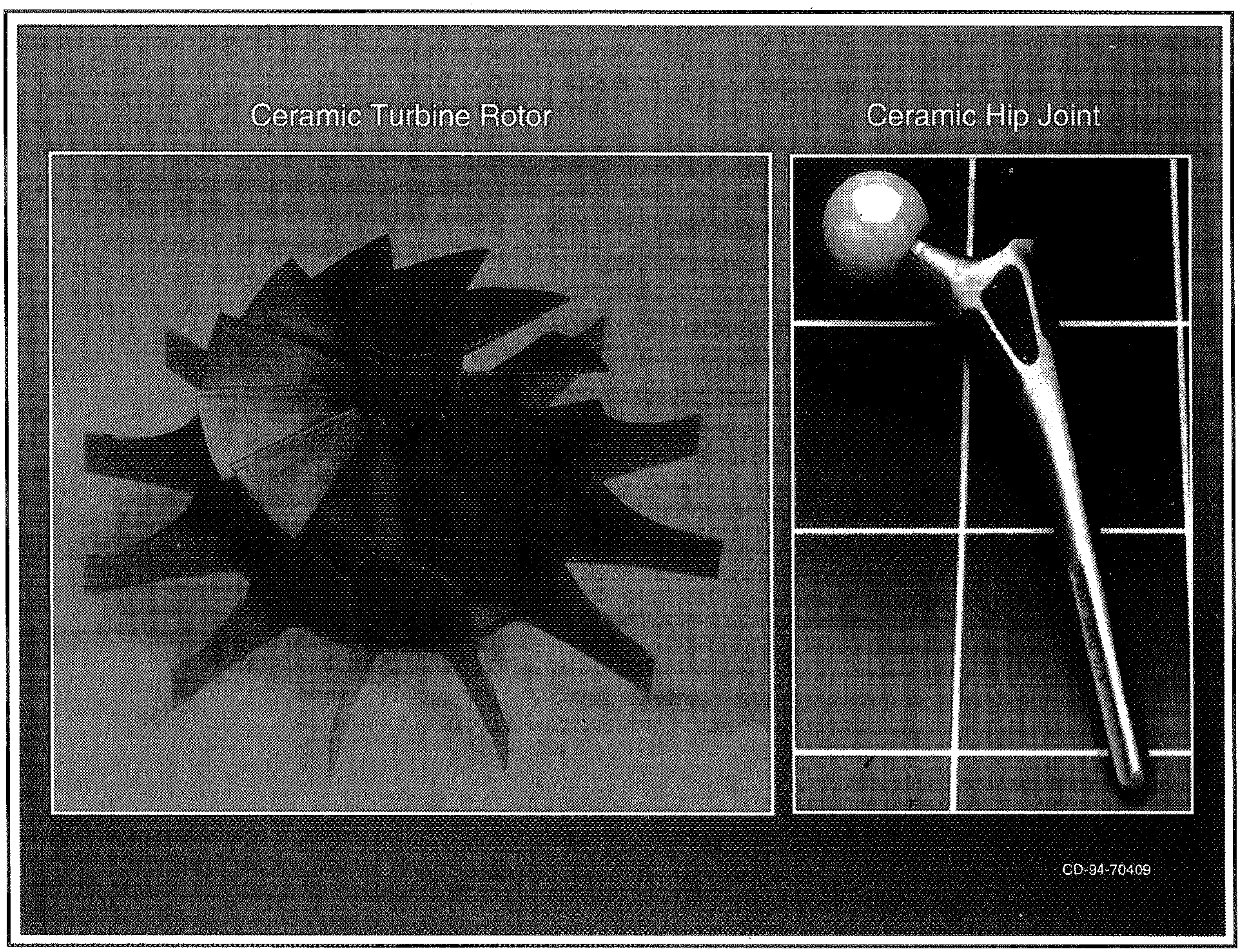
SPACE SHUTTLE MAIN ENGINE (SSME)

The viscoplastic constitutive models we developed and applied to the nozzle coolant channel of the SSME was successful in predicting the failure of the channel under launch conditions and provide a correction to eliminate the failure mode. These models have been successful in predicting the "large" strains which can accumulate at critical locations in actually cooled structures as a result of creep ratchetting.



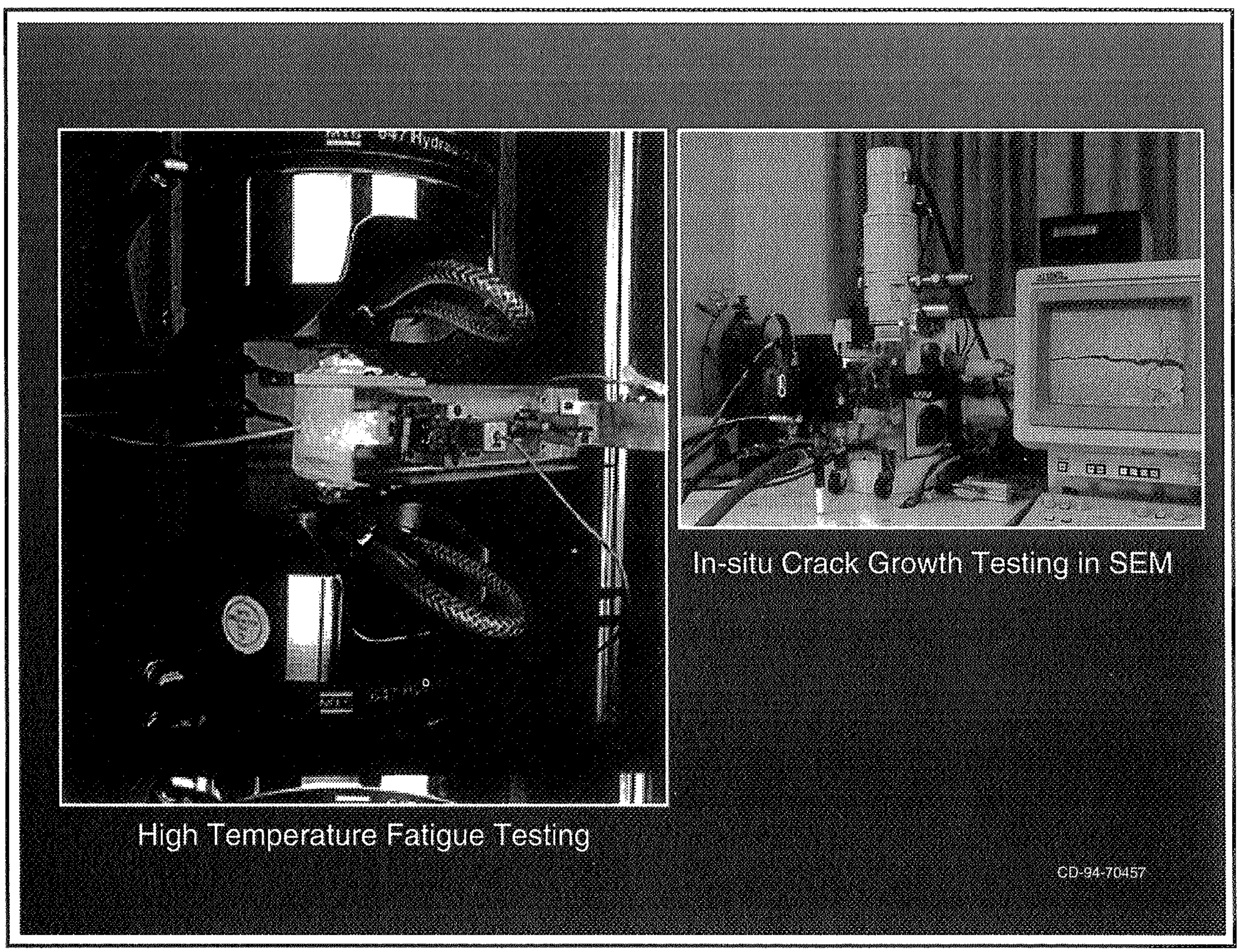
## CERAMIC COMPONENTS ANALYSIS

A Structures and Acoustics Division developed code, CARES/*Life* (Ceramic Analysis and Reliability Evaluation of Structures *Life* prediction) is an integrated package that predicts the probability of a monolithic ceramic component's failure as a function of time in service. It couples commercial finite element programs, which resolve a component's temperature and stress distribution, to reliability evaluation and fracture mechanics routines for modeling strength-limiting defects. These routines are based on calculations of the probabilistic nature of the brittle material's strength. CARES/*Life* is used world-wide. Success stories can be cited in several industrial sectors including aerospace, automotive, biomedical, electronic, glass, nuclear and conventional power generation industries.



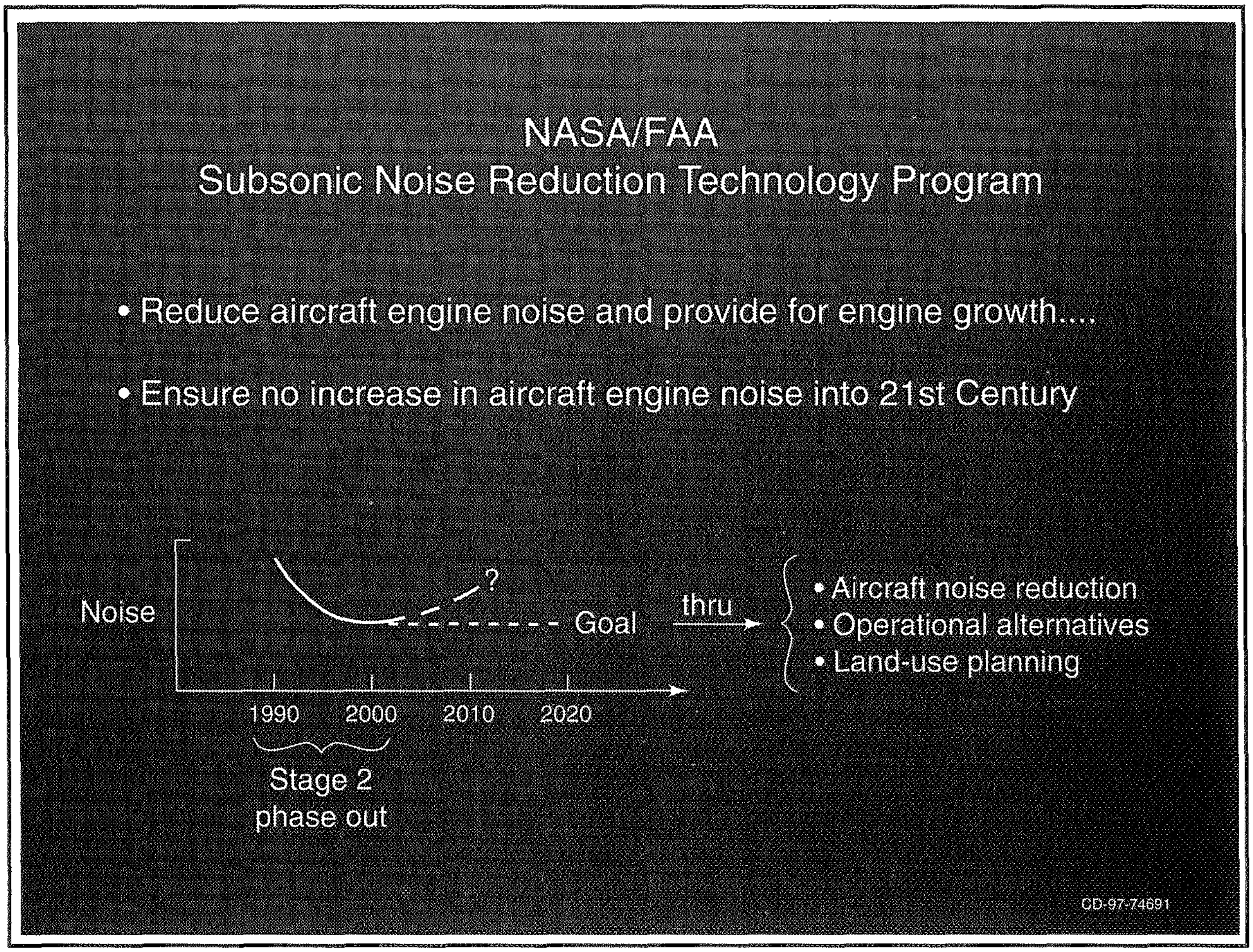
## BENCHMARK STRUCTURES FACILITY

For many advanced materials considered for aerospace application, the results from coupon testing can be significantly different from that at the component level. A benchmark structures test facility has been developed to address scale-up issues by testing material at the sub-element level. This facility can be used to verify and validate structural analysis methods by generating experimental data under prototypical loading conditions including complex stress states. The results are compared to those predicted by structural analysis.



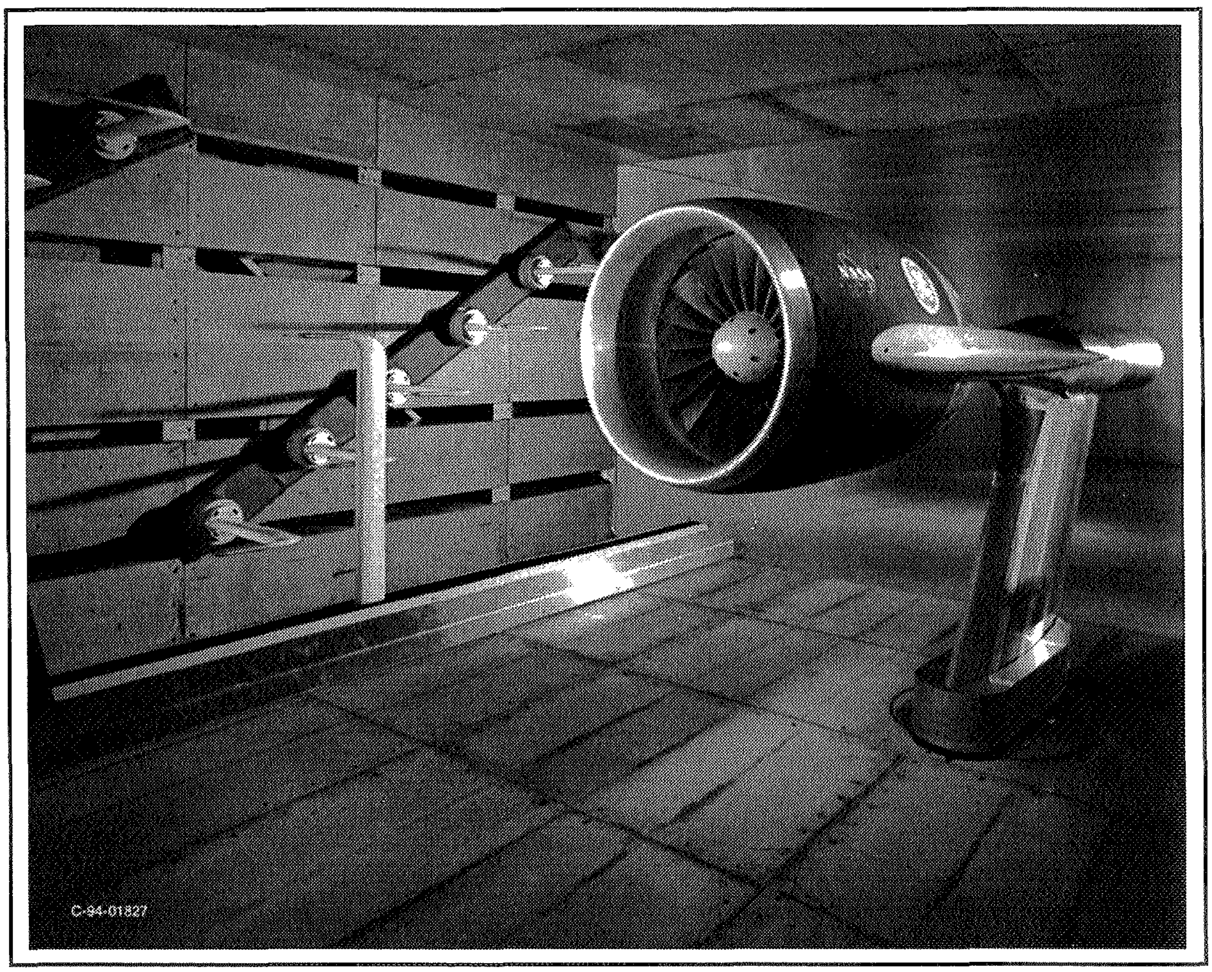
# ENGINE NOISE REDUCTION

The AST Noise Reduction Program started in 1994 to provide technology for reducing subsonic aircraft noise 10 dB relative to 1992 technology. Even though Stage 2 aircraft will be phased out by the end of the decade, increases in the number of flights will cause the noise impact to increase if there is no new technology available. The goal of the AST Noise Reduction Program is to keep the impact of aircraft noise constant after all Stage 2 aircraft are phased out. This will be done through the combination of source reduction for the airplanes (engine and airframe), identifying alternate operations for aircraft, and land-use planning for airports. Lewis is leading the effort to reduce the engine noise by 6 dB as a part of the total 10 dB goal.



## HIGH-BYPASS ADVANCED ENGINE FANS

The major U.S. engine manufacturers, General Electric, Pratt & Whitney, Allison and Allied Signal, bring their advanced design fans to NASA Lewis for testing. As part of joint programs between NASA and the engine companies, fan models are tested in the 9-by-15 wind tunnel to determine their performance, acoustic and structural characteristics. The picture shows a NASA/GE model being tested. The microphones used to collect acoustic data are seen against the tunnel wall. Results from experiments have indicated that significant noise reductions can be achieved across the normal fan operating range with modification of the stator vane geometry. Further experimentation will be conducted later in the program to verify the effects of stator vane geometry on fan tone noise at different fan pressure ratios. These encouraging results have stimulated industry into addressing how these new types of stator vane technologies could be incorporated into the next generation of high bypass turbofan engines.



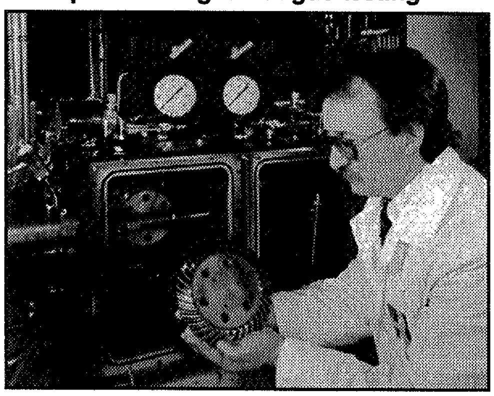
## MECHANICAL COMPONENTS

Life and failure prediction of drive train components such as rolling-element bearings, gears, clutches and seals is an integral part of the research performed by the Structures and Acoustics Division. Most of this research is directed towards helicopter transmission systems. The work is both experimental and analytical. Unique test facilities include spiral level gear endurance testers and spur gear endurance testers.

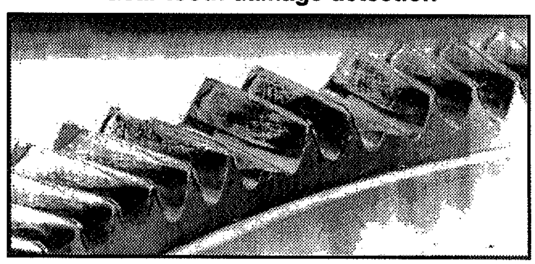
**Health and Usage Monitoring and Fatigue and Crack Propagation**

**Health and usage monitoring and fatigue and crack propagation research to improve safety and reduce maintenance of rotating machinery**

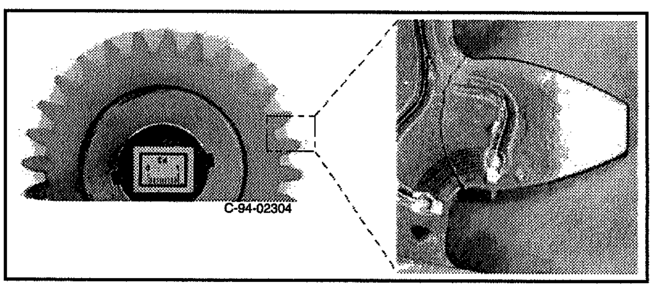
**Spiral bevel gear fatigue testing**



**Gear tooth damage detection**



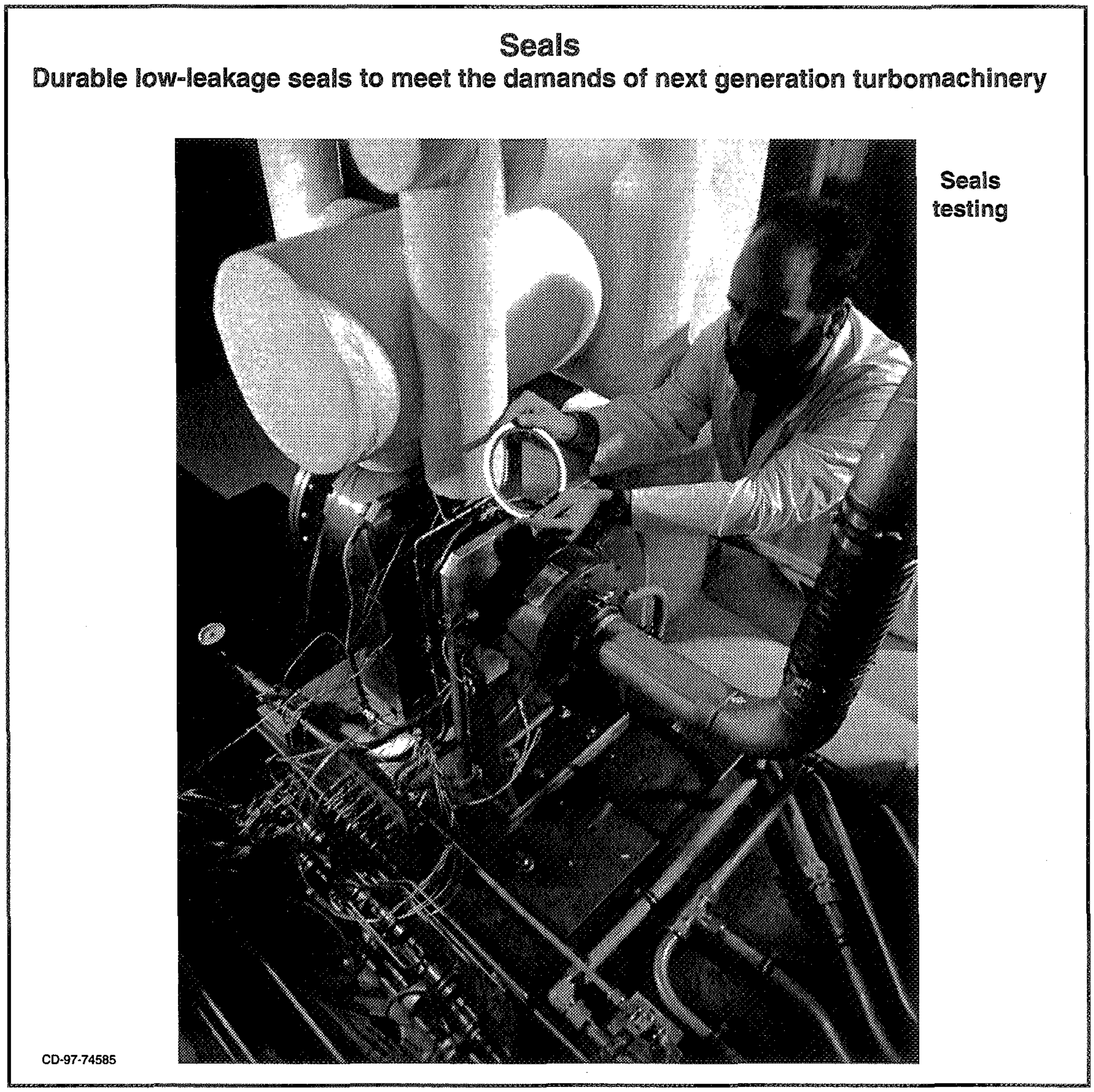
**Gear crack propagation and life**




CD-97-74583

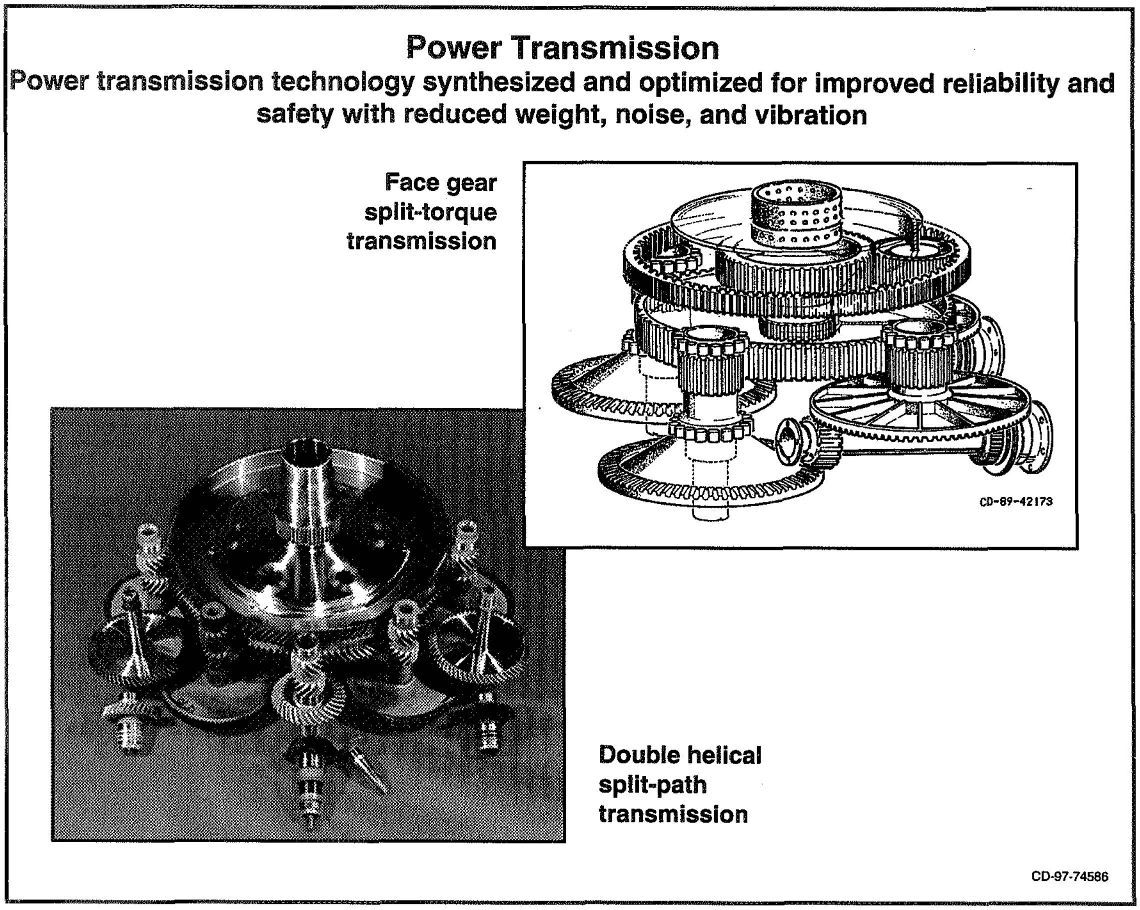
## ENGINE SEALS

As engine designers are faced with continued challenges to increase aircraft engine performance, reduce engine specific fuel consumption (SFC), and increase engine "time on the wing," they must exploit improvements in many components, including engine seals. With the advent of new concepts such as brush seals, large improvements in engine performance (greater than three-quarters of one percent reduction in SFC) are now being realized. The relatively small investment required to mature these new seal technologies, coupled with appreciable gains in engine performance, makes seal technology development a high technical return on investment.



## HELICOPTER DRIVE TRAINS

If the criteria used to design terrestrial gear boxes were applied to helicopter and turboprop power transmission systems, these aircraft would be too heavy to carry any significant payload. In addition, as the applied load is increased for a given size box, the life and reliability of the transmission decreases by cubic power of load. In order to improve the power to weight ratio of these gear boxes as well as to increase their life and reliability, new design concepts, materials and lubrication concepts are studied and tested by the Structures and Acoustics Division. These concepts include high-contact ratio gearing and split-torque designs.

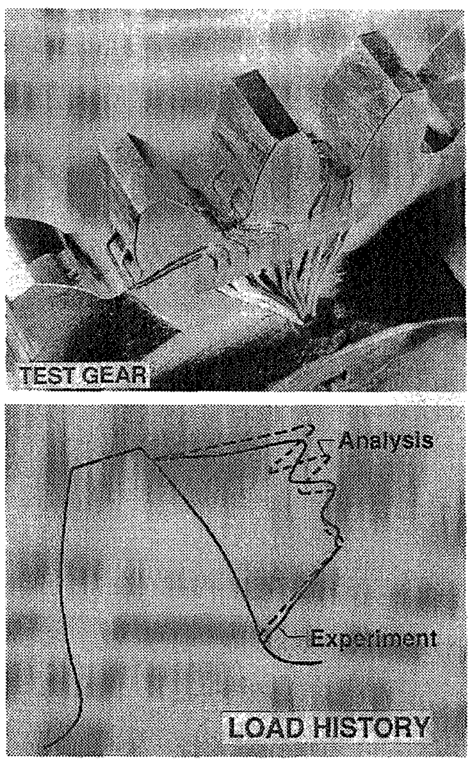


# GEARS, BEARINGS AND CLUTCHES

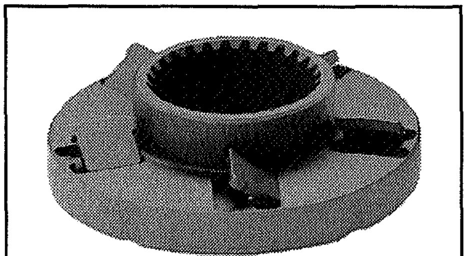
In addition to full-scale transmission research, component work is also performed on an individual scale to develop and verify analytical prediction codes. The essence of this code development and benchmarking is to apply these analytical tools to optimize mechanical transmission systems to obtain minimum power loss with maximum life and reliability. Trade-off studies are performed and are verified experimentally. This work has resulted in bevel gears with lower noise and improved performance prediction methods for gear boxes.

## Gears, Bearings, and Clutches

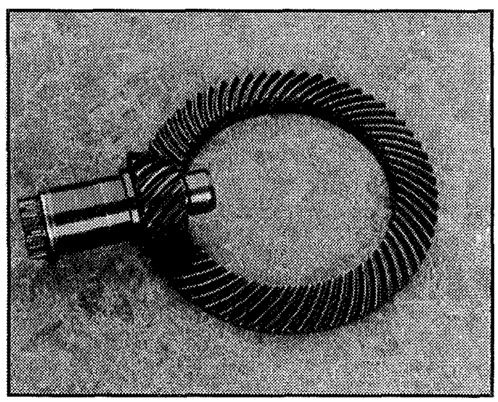
**Advanced mechanical components realized through use of new materials, concepts, and analytical tools**




**Experimentally validated analysis methods**



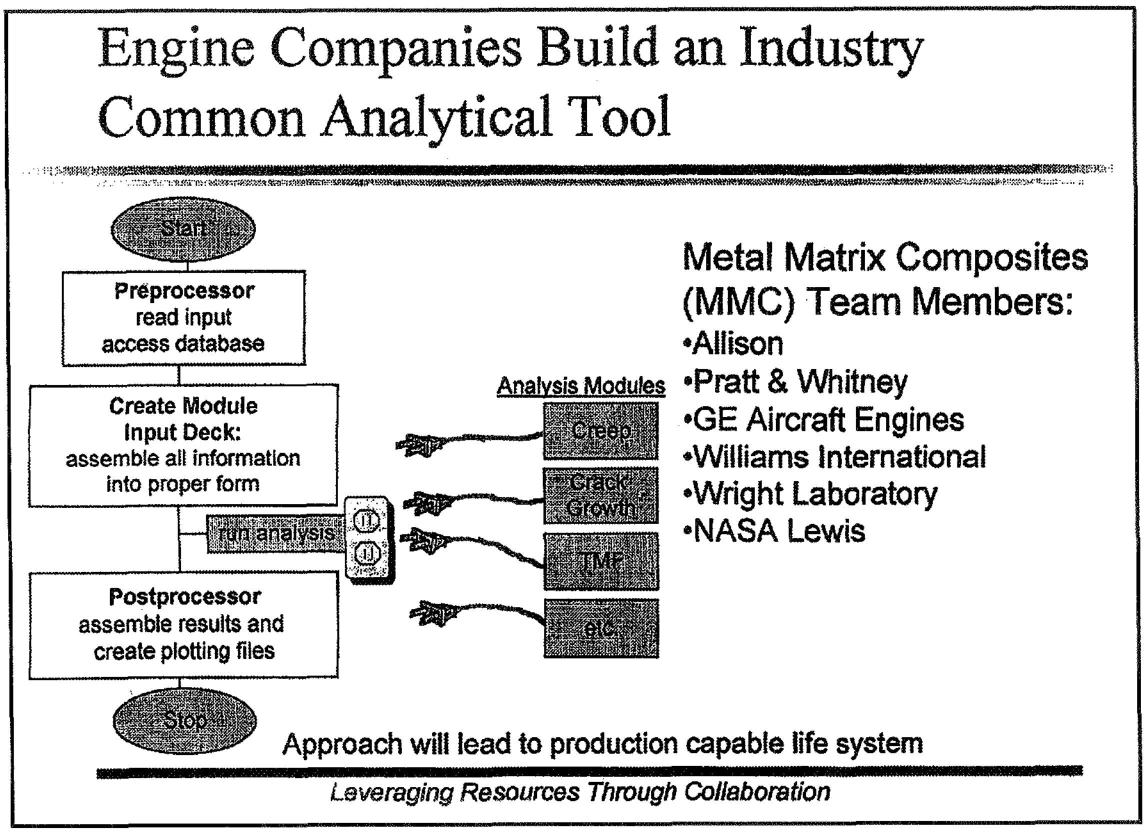
**Mechanical diode clutch**



**Low-noise, high-strength spiral bevel gear**

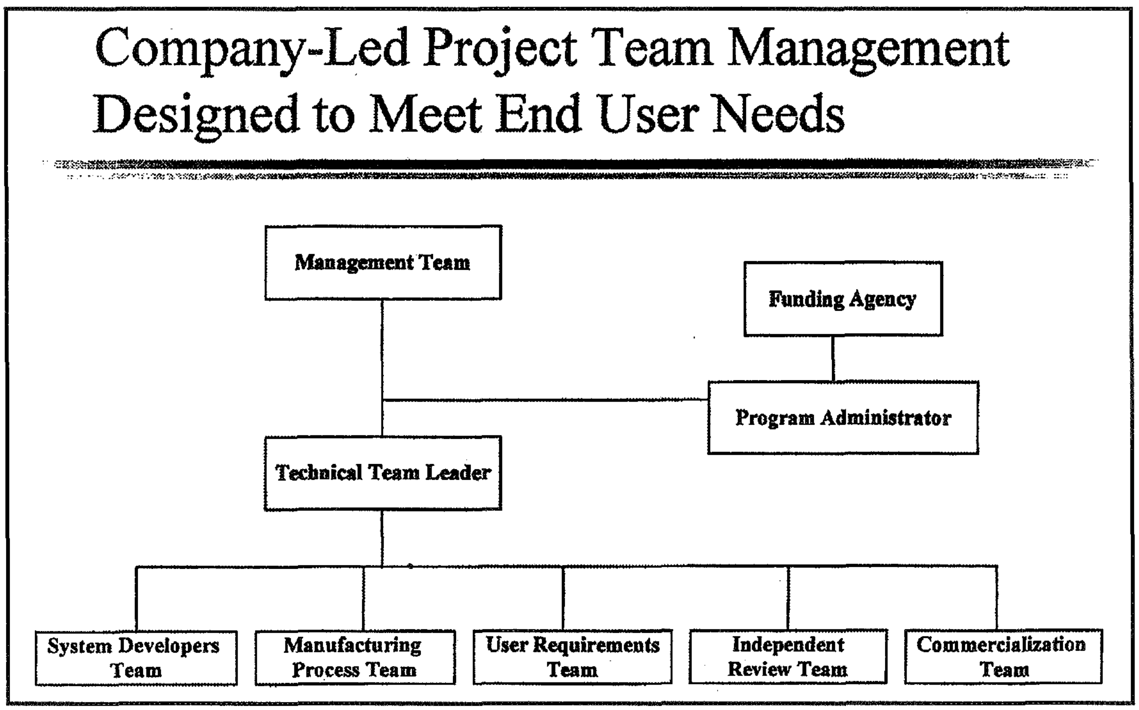
## COOPERATIVE PROGRAMS

The Structures and Acoustics Division has been instrumental in organizing industry-government consortiums to undertake cooperative pre-competitive technology programs. These programs are organized to consolidate talent and facilities between industry and other government laboratories to accomplish a specific and well defined goal. The advantage of this effort is gathering a critical mass of talent which does not exist at a single organization to accomplish a single well defined goal. A prime example of this effort is shown in the figure with a combined effort of the named organizations to develop a common life prediction code for metal matrix composite materials.



## MANAGEMENT STRUCTURE FOR COOPERATIVE PROGRAMS

In order to manage the cooperative programs a virtual company is organized between industry and government participants. The management team is made up of members of participating industry and government organizations. A technical team leader is selected by the management team. The technical team leader together with the technical team manages the day-to-day operation of the program. A program administrator is selected by the management team to act as an administrator facilitator and primary contractor for the work being performed. The program administrator is usually a nonprofit organization. Funding can be from both government and non-government fund sources.



# Habitats and Surface Construction Technology and Development Roadmap

Marc Cohen
NASA Ames Research Center
Moffett Field, CA

and

Kriss J. Kennedy
Johnson Space Flight Center
Houston, TX

# Habitats & Surface Construction Technology & Development Roadmap

Presented to the
AIAA Structures Technical Committee
Hampton, VA

*September 4, 1997*

*Marc Cohen / NASA ARC*
mcohen@mail.ARC.nasa.gov
*Kriss J. Kennedy / NASA JSC*
kriss.j.kennedy1@jsc.nasa.gov





## Top Level Strategy for Habitats & Surface Construction

- GOAL: Sustain human presence on Mars.
- TARGET: Provide habitation and surface infrastructure to support humans on Mars on a long term basis.
- PLAN: Provide the capability to produce and construct habitats and surface facilities using indigenous resources.
- RATIONALE: Open Mars to long-term planetary exploration by humans with the eventual settlement of humans on Mars.
- INITIAL PRODUCTS: Initial human mission using relevant habitation technologies. ISRU resource demonstrations, i.e. material extraction and benefaction for processing.

# Executive Summary

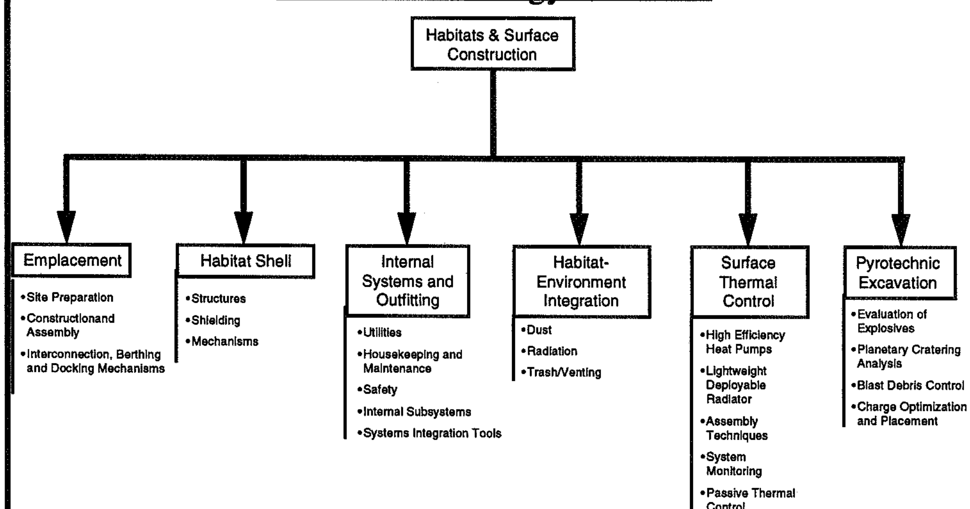
- Vision

  Provide the capability for automated delivery and emplacement of habitats and surface facilities.
- Benefits
  - Composites and Inflatables: 30 - 50% (goal) lighter than Al Hard Structures
  - Capability for Increased Habitable Volume, Launch Efficiency
  - Long Term Growth Potential
  - Supports initiation of commercial and industrial expansion.
- Key H&SC Technology Issues
  - Habitat Shell Structural Materials
  - Seals and Mechanisms
  - Construction and Assembly: Automated Pre-Deploy Construction Systems
  - ISRU Soil/Construction Equipment: Lightweight and Lower Power Needs
  - Radiation Protection (Health and Human Performance Tech.)
  - Life Support System (Regenerative Life Support System Tech.)
  - Human Physiology of Long Duration Space Flight (Health and Human Performance Tech.)
  - Human Psychology of Long Duration Space Flight (Health and Human Performance Tech.)
- What is Being Done?
  - Use of composite materials for X-38 CRV, RLV, etc.
  - TransHAB inflatable habitat design/development
  - Japanese corporations working on ISRU-derived construction processes.
- What Needs to be Done for 2004 Go Decision
  - Characterize Mars Environmental Conditions: Civil Engineering, Material Durability, etc.
  - Determine Credibility of Inflatable Structures for Human Habitation
  - Determine Seal Technology for Mechanisms and Hatches, Life Cycle, Durability

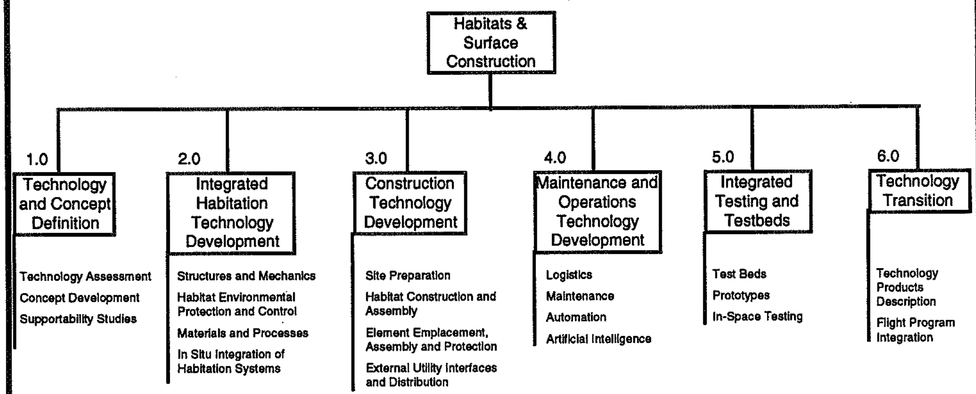




# H&SC Technology Structure



# H&SC WBS




H&SC Team 09/02/97



## WBS 2.0 Integrated Habitation Technology Development

- Develop Habitat Technologies
  - Materials
  - Processes
  - Structures
  - Mechanisms
  - Radiation Protection
  - Passive Thermal Control
  - Dust Control
  - Habitat Internal Subsystem In-Situ Integration
- This Technology Development Area Addresses Items Such As:
  - Inflatable and Composite/Carbon Structures
  - Constructible Habitats
  - Water Jacket Radiation Shielding
  - Natural and Artificial Lighting
  - Joining Processes and Interfaces
  - Interior Utility Interfaces

H&SC Team 09/02/97

## WBS 2.0 Integrated Habitation Technology Development
## Typical Products

- Pressure Shell
  - Rigid Pressure Shell Components
  - Flexible/Inflatable Pressure Shell Components
  - ISRU Product Pressure Shell Components
- Habitat Structures
  - Deployable Trusses
  - Deployable Columns
  - Quick Connect Bracing
  - Quick Release Structural Connectors
  - Mechanical Fastening Materials and Devices
- Interior Structures and Mechanisms
  - Bulkheads
  - Rack Support Structure and Components
  - Subsystem Equipment Support Structure and Components
  - Floor Support Structure
  - Foldable Decking
  - Deployable Stairs, Ramps and Elevators
- Radiation Protection
  - Loose Regolith/Soil Shielding
  - Pressure Shell Integrated Shielding
  - Sintered/Cast Basalt Shielding
  - Prefabricated Shielding
- Micrometeoroid Protection
  - Loose Regolith/Soil Shielding
  - Pressure Shell Integrated Shielding
  - Sintered/Cast Basalt Shielding
  - Prefabricated Shielding
- Ejecta Protection
  - Loose Regolith/Soil Shielding
  - Constructed Blast Shields
  - Sintered/Cast Basalt Shielding
  - Prefabricated Shielding
- Thermal Control
  - Internal Thermal Insulation
  - Reflective Coverings and Coatings
  - Integral Shielding
- Lighting
  - Natural Lighting Techniques and Equipment
  - Artificial Lighting
- Vibration Control
  - Vibration Isolation Techniques and Components
  - Vibration Dampening/Reduction Techniques and Components
  - Noise Prevention Techniques and Components
  - Noise Reduction Techniques and Components





## Robotic Construction Technology (WBS 2.5)

- Survey existing approaches to robots and their capabilities - automobile assembly, housing, etc.
- Evaluate potential for adapting construction components for robotic assembly.
- Use CAD/VR to experiment with simulated robotic construction.
- Determine appropriate levels of modularity, assembly and component packaging.
- Develop virtual user interface for directing robotic/teleoperated construction.
- Build experimental construction system with components.
- Conduct integrated robotic construction ops tests.

## Robotic Construction Technology Products (WBS 2.5)

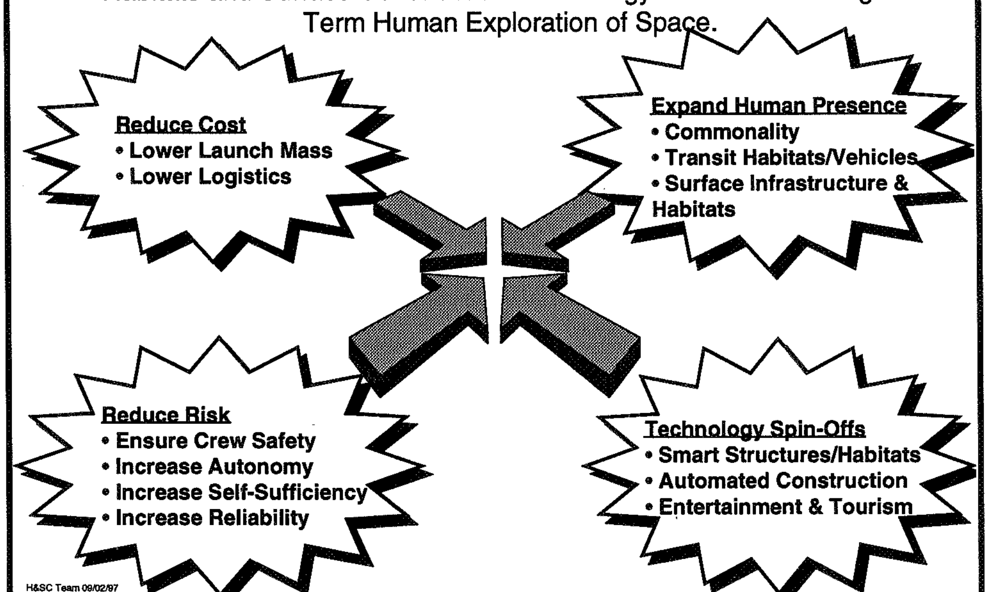
- System studies of approaches to robotic/teleop construction techniques.
- Evaluation of potential for robotic methods to assemble a Lunar/ Mars base.
- Develop requirements for capabilities, software, expert systems, user interface, training, hardware, end effectors, and construction components such as grapple fixtures, hard points, joints, connectors, etc.
- Design experimental prototype robotic construction system.
- Adapt hardware and software for robotic construction field testing.

H&SC Team 09/02/97

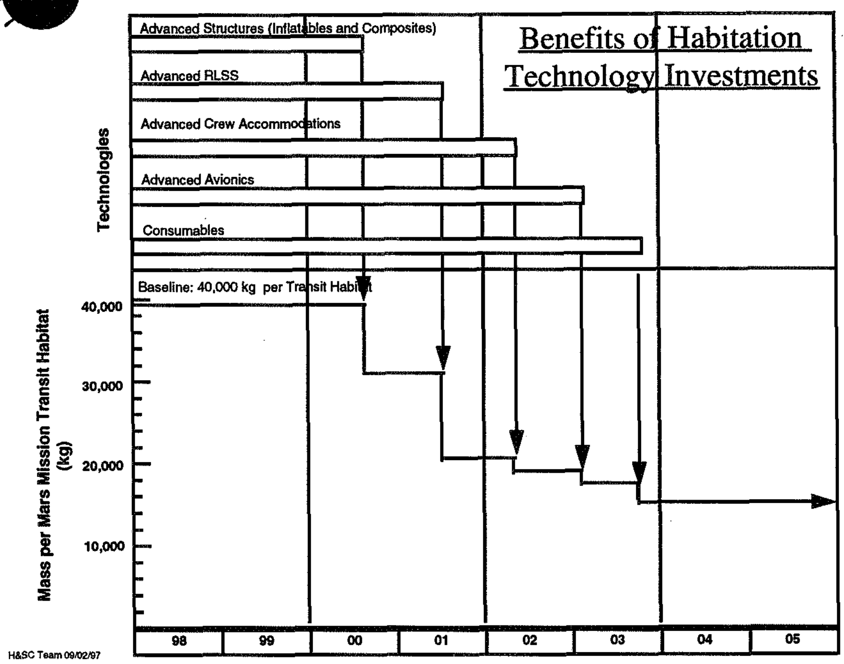
*HEDS Technology Planning* *Habitats & Surface Construction*

## Purpose and Benefits of H&SC

Habitats and Surface Construction Technology is Crucial for Long-Term Human Exploration of Space.




H&SC Team 09/02/97




H&SC Team 09/02/97



# 2004 Go Decision Criteria

| Technology | 2004 Go/ No Go Criteria | Rationale |
|---|---|---|
| Inflatable Structures | • Meet Human-Rating Standards<br>• Long-Duration Environmental Tests / Survivability<br>• Maintain Pressure Integrity | • Habitats: In Space and Surface |
| Advanced Composite Structures | • Meet Human-Rating Standards<br>• Long-Duration Environmental Tests / Survivability<br>• Maintain Pressure Integrity | • Habitats: In Space and Surface |
| Seals/Mechanisms | • Capability to Maintain Seal in Dust Environment<br>• No Leaks<br>• Long Duration Service | • Must Maintain Integrity and Long-Life in Lunar/ Mars Environmental Conditions |
| ISRU-Derived Structures | • Prove ISRU Structural Technology<br>• Prove Manufacturing Process<br>• Prove Soil Moving & Mining Processing<br>• Prove Construction Technique Under Simulated Conditions<br>• Prove Autonomous/Telerobotic Equipment Capability<br>• Prove Power Efficient Techniques/ Equipment | • Support Mars Mission with ISRU Capability<br>• Support Humans as Habitats: In Space and Surface |
| Artificial Intelligent Structures (Smart Structures) | • Proven Ability to Integrate A.I. Nano Technology into Pressure Shell Skin/Structure<br>• Proven Capability for Self Diagnostics and Repair | • Habitats: In Space and Surface<br>• Alleviate Direct Human Activities |

**Assumes Human Factors and Radiation Shielding by Health & Human Performance Technology.**

H&SC Team 09/02/97

# Criticality of Technology

| Technology | Criticality | Justification/Value |
|---|---|---|
| Inflatable Structures | • Unproven Technology for Habitat Space Structures<br>• Requires longer lead time and funding to meet 2003 Go Time to answer critical technology issues about materials and shell integration | Save $ • Can reduce the number of ETO Launch Vehicles by 2-3 Launches: ≈ $150 - 300 M<br>√Health† • Provides the Habitability Volume Required for Long Duration Spaceflight: Crew Psychological Health<br>Save $ • Does Not Require New HLLV /Shuttle C to meet Volume Capability<br>Save $ • Lower IMLEO (mass) thus Mission Cost<br>• Impact to Mission Architecture Design and Operations |
| Seals | • Critical Link of Providing Contamination Control<br>• Crew Health<br>• System Life-Cycle, Failures | √System† • Pressure Integrity of Connections<br>√System† • Ensures Life Cycle of Pressure Connections, Hatches & Mechanisms<br>√System† • Protection of Lubricants and Mechanisms<br>√Health† • Protect Humans from Dust |
| Advanced Composites | • Unproven Technology for Habitat Space Structures<br>• Requires time and funding to meet 2003 Go Time to answer critical technology issues about materials and shell integration | Save $ • Can reduce the mass of a HAB by ≈ 30%, thus IMLEO<br>Save $ • Lower IMLEO (mass) thus Mission and Transportation Cost |
| Soil Moving Machinery | • Requires High Power and Energy Efficient Equipment<br>• Required for Site Preparation and Clearing, Habitat Emplacement, and Radiation/ Blast Ejecta Berming | • Ensures Cleared Site for Landing, Habitat Emplacement, and Surface Mobility<br>• Mission Failure Due to Inability to Land or Link Surface Facilities due to surface conditions<br>• Support Long-Term Objectives of Sustained Human Presence |
| Mass Handling Equipment | • Requires High Power and Energy Efficient Equipment<br>• Required for Loading and Unloading of Payloads, and Moving/Connecting Elements | • Ensures Cleared Site for Landing, Habitat Emplacement, and Surface Mobility<br>• Mission Failure Due to Inability to Land or Link Surface Facilities due to surface conditions<br>• Support Long-Term Objectives of Sustained Human Presence |

H&SC Team 09/02/97

HEDS Technology Planning — Habitats & Surface Construction

# Enabling H&SC Technology

| Technology | Enables | Rationale |
|---|---|---|
| Inflatable Structures | • Larger HAB Volume<br>• Inflatable Aerobrake<br>• Inflatable Airlock | • Smaller ETO Launch Vehicles<br>• No LEO Assembly Ops<br>• Save HAB Vol and Packaging Vol |
| Seals | • Integrity of Connections<br>• Long Life Connections, Hatches, and Mechanisms<br>• Contamination Control | • Pressure Integrity of Connections<br>• Ensures Life Cycle of Pressure Connections, Hatches and Mechanisms<br>• Protection of Lubricants and Mechanisms<br>• Protect Humans from Dust |
| Shell Materials | • Tolerant of Environment | • Tolerant of Long Duration Exposure to Space and Mars Environment |
| Advanced Composites | • Lightweight Strong Structures | • Lower Initial Mass in LEO |
| Soil Moving Machinery | • Site Preparation and Clearing<br>• Habitat Emplacement<br>• Radiation/Blast Ejecta Berming | • Ensures Cleared Site for Landing, Habitat Emplacement, and Surface Mobility |
| Mass Handling Equipment | • Loading and Unloading of Payloads<br>• Moving/Connecting Elements | • Required for Base Assembly |
| Self-Deploying and Automated Systems | • External Shelters/Facilities<br>• Internal System Assembly<br>• Unmanned Cargo Pre-deployment | • Limit EVA Crew Time for Construction/ Assembly Operations |

H&SC Team 09/02/97

*HEDS Technology Planning* *Habitats & Surface Construction*

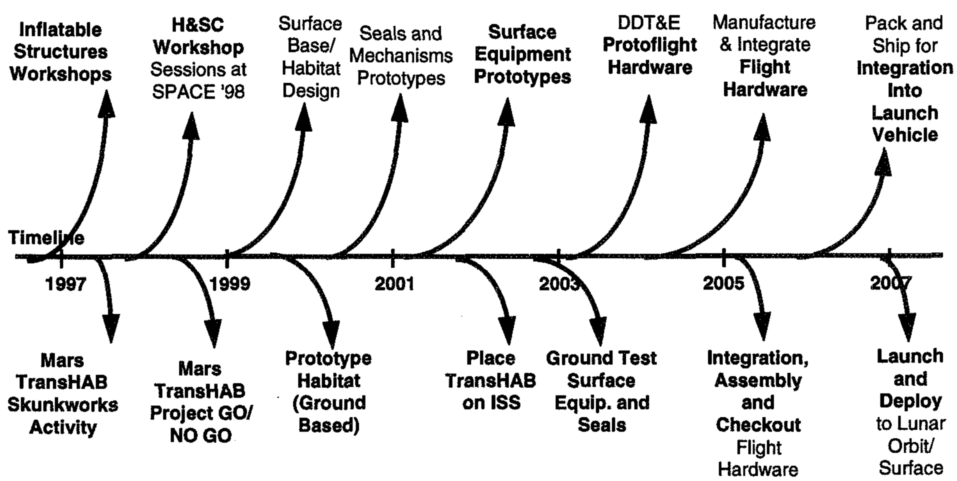
# Breakthrough H&SC Technology

| Technology | Enables | Rationale |
|---|---|---|
| AI. Smart Structure | • Integrated and Self Diagnostics<br>• Self Repair | • Alleviate Crew Maintenance and Repair Time<br>• Automation and Several Yrs Unmanned |
| ISRU-LSS Living Shell | • Process CO2 Through Shell to Produce O2 for Interior Use<br>• Integration of Nano Life Support System into Skin | • Self Sufficiency, Lower Weight<br>• Applicable to Hostile Terrestrial Environments |
| Bio-Structure | • Bio-Technology Integration with Shell Skin Enables Self-Healing Capability | • Alleviate Crew Servicing and Maintenance |
| Tunneling/ Mining Mole | • Enables Underground Habitation Facilities Analogous to Oil Industry Siberia (Hostile Environment) Facilities | • Create Underground Facilities for Mars Evolution/Civilization<br>• Constant Thermal Environment<br>• Radiation Protection |
| ISRU-Derived Structure | • Use of In-Situ Materials to Process, Manufacture and Assemble Structures | • Supports Long-Term Plan for Human Expansion into Solar System<br>• Breaks Dependency of Earth Supplies |
| | | |

H&SC Team 09/02/97

*HEDS Technology Planning* *Habitats & Surface Construction*

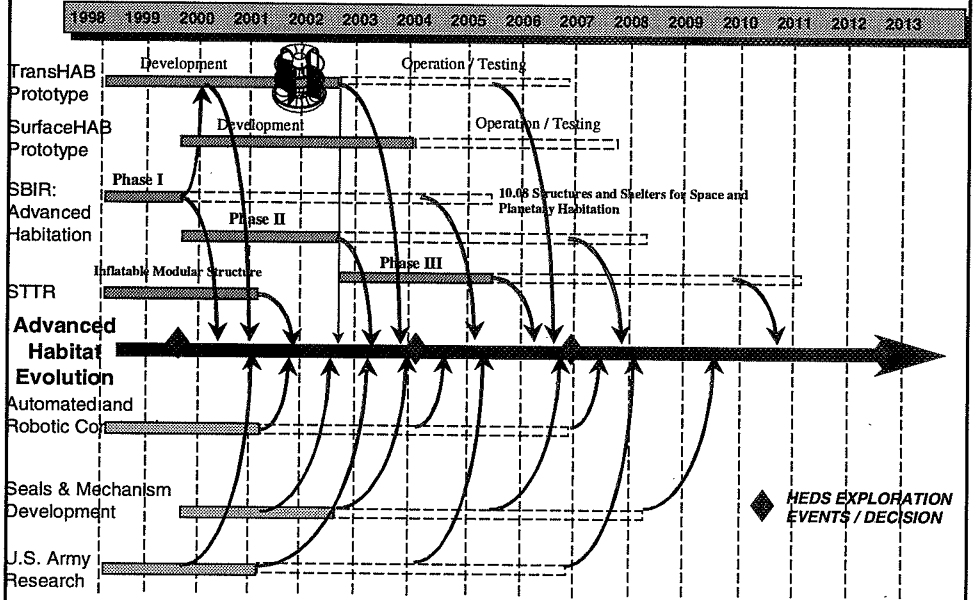
# Habitats and Surface Construction Roadmap




H&SC Team 09/02/97

*HEDS Technology Planning* *Habitats & Surface Construction*

## Habitats & Surface Construction Roadmap

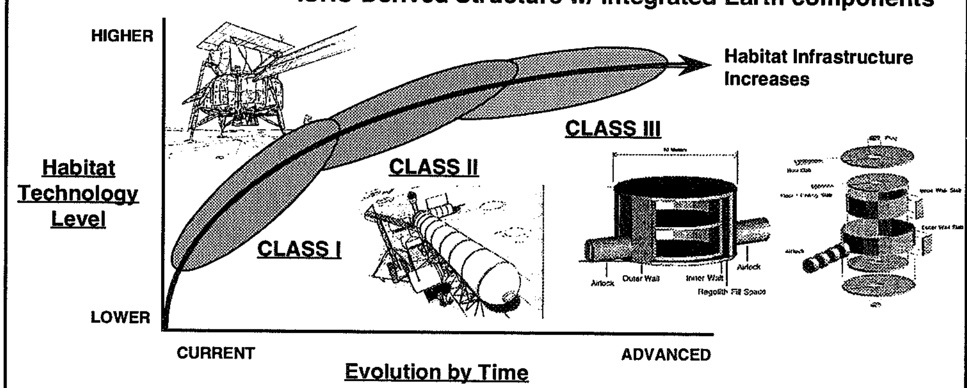



H&SC Team 10/27/97

*HEDS Technology Planning* *Habitats & Surface Construction*

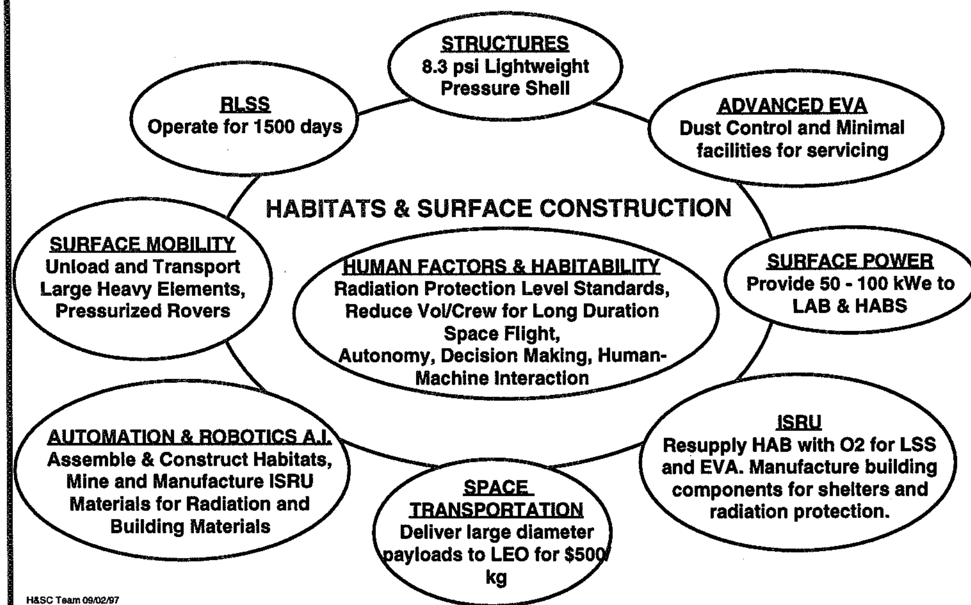
## Habitation Technology Strategy (Options)

- **CLASS I:**
  - **Preintegrated, Hard Shell Module**
- **CLASS II:**
  - **Prefabricated, Surface Assembled**
- **CLASS III:**
  - **ISRU Derived Structure w/ Integrated Earth components**




H&SC Team 10/27/97

# H&SC Technology Requirements








# Key Structural Issues

- Metal Alloy Structures
  - Environmental Degradation, Manufacturability, $ to Manuf., Achieve tbd% weight savings, robustness, maintainability and repair.
- Composite Structures
  - Environmental Degradation, Manufacturability, $ to Manuf., Achieve 30% weight savings, robustness, maintainability and repair.
- Inflatable Structures
  - Environmental Degradation, Manufacturability, $ to Manuf., Achieve weight savings, robustness, reliability, deployability: automated/robotic assisted surface deployment, maintainability and repair.
- ISRU-Derived Structures
  - Environmental Degradation, Manufacturability, $ to Manufacture HAB units, Complexity of mining, benefaction and processing ISRU material to make structures, robustness, reliability, automated/robotic assisted manufacturing, maintainability and repair.

## Habitats and Surface Construction
### *Man-Rated Pressure Structure*

- Technology: Advanced Structures
- Application: In-Space and Planetary Pressurized Structures for Human Exploration
- Benefits:
  - 30-50% (goal) lighter than Al Hard Structures
  - Capability for Increased Habitable Volume, Launch Efficiency
  - Long Term Growth Potential
  - Compatible with Technology Developments for Current Space Craft.
- Current Technology Status:

Composites: TRL 6-7
- Used for pressure tanks: DC-X
- Incorporated into X-33 Demonstration
- Incorporated into X-38 CRV
- Planned for Space Craft Upgrades

Inflatables: TRL 4-5
- Concepts Developed
- Impediment Defined
- EMU Suit Materials
- Materials Selection for HAB
- Full-Scaled Prototype Planned FY98-99
- '96 Space Demo of IAE

ISRU Derived: TRL 1-2
- Resources Identified
- Extraction Techniques Defined
- Material Processing and Manufacturing Defined
- Structural Concepts

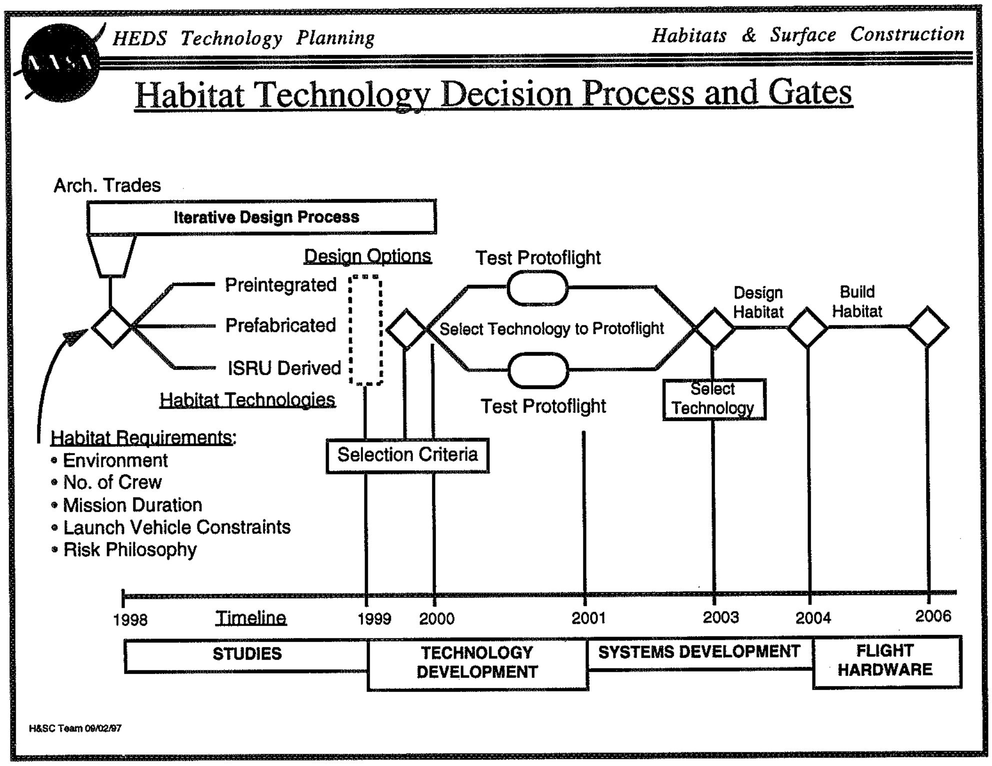
H&SC Team 09/02/97

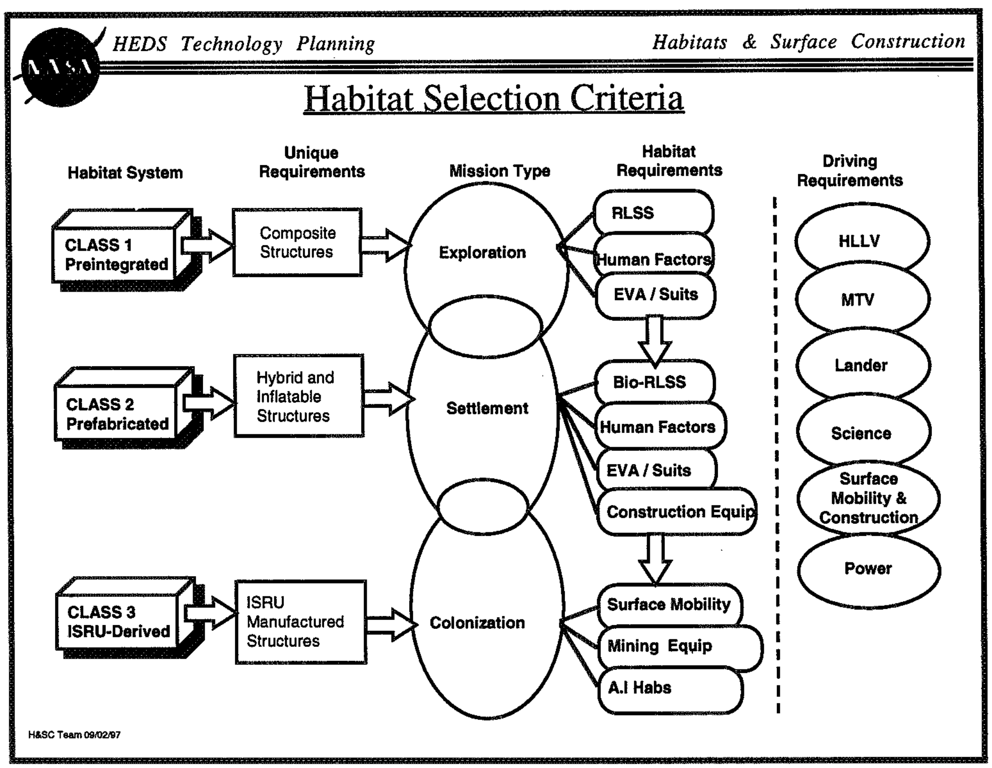


## Material Requirements for Habitats

- Large Volumes, i.e. 300-500 $m^3$
- High Strength Materials
  - Internal Operating Pressure 8.3 psia
- Durability
  - 10-15 Years
- Reliability
  - Fail Op/Fail Safe
- Low Cost
  - Orders of Magnitude Less ($M NOT $B)
- Low Mass
  - Orders of Magnitude Less (100s kg NOT 10s Mt)
- Autonomous Deployment
- Low Vibration
- Withstand Radiation: GCR and SPE
- No Off-gassing to Internal HAB
- Withstand Debris/Micrometeoroid Hits
  - 1/4" d @ 7 km/s, Self-repair?
- Low Risk
  - Deployment
  - Pressure Integrity
  - Puncture/Tear Resistant
  - No Off-gassing
- Pre-integrated Support Systems
  - Life Support, Communications
  - Deployable Floors and Walls
  - Smart Structures: self diagnostic
- Human Support
  - Radiation Shelters
  - Medical Treatment
  - EVA Support
  - Living and Working Facilities
  - Autonomous Operations

H&SC Team 09/02/97


HEDS Technology Planning
Habitats & Surface Construction
Habitat Technology Decision Process and Gates
Arch. Trades
Iterative Design Process
Design Options
Preintegrated
Prefabricated
ISRU Derived
Habitat Technologies
Habitat Requirements:
• Environment
• No. of Crew
• Mission Duration
• Launch Vehicle Constraints
• Risk Philosophy
Test Protoflight
Select Technology to Protoflight
Test Protoflight
Selection Criteria
Design Habitat
Build Habitat
Select Technology
1998
Timeline
1999
2000
2001
2003
2004
2006
STUDIES
TECHNOLOGY DEVELOPMENT
SYSTEMS DEVELOPMENT
FLIGHT HARDWARE
H&SC Team 09/02/97


HEDS Technology Planning
Habitats & Surface Construction
Habitat Selection Criteria
Habitat System
Unique Requirements
Mission Type
Habitat Requirements
Driving Requirements
CLASS 1 Preintegrated
Composite Structures
Exploration
RLSS
Human Factors
EVA / Suits
CLASS 2 Prefabricated
Hybrid and Inflatable Structures
Settlement
Bio-RLSS
Human Factors
EVA / Suits
Construction Equip
CLASS 3 ISRU-Derived
ISRU Manufactured Structures
Colonization
Surface Mobility
Mining Equip
A.I Habs
HLLV
MTV
Lander
Science
Surface Mobility & Construction
Power
H&SC Team 09/02/97

## Interaction Between H&SC and Other Technologies

| | | |
|---|---|---|
| ISRU:<br>- Development of ISRU processes<br>- ISRU processing technologies<br>- Mining technologies<br>- Development of ISRU structural materials | ISRU and H&SC:<br>- Dust control technologies<br>- Regolith movement technologies | H&SC:<br>- Construction technologies<br>- Excavation technologies<br>- Maintenance technologies<br>- Assembly of ISRU structural materials |
| Planetary Rover:<br>- Rover technologies<br>- Sample collection technologies<br>- Navigation technologies | Planetary Rover and H&SC:<br>- Vehicle chassis utilization | H&SC:<br>- Robotic construction technologies<br>- Robotic maintenance technologies<br>- Robotic surveying technologies |
| BLSS:<br>- Life support technologies<br>- Plant growth technologies | BLSS and H&SC:<br>- Artificial lighting technologies<br>- Radiation filtering materials | H&SC:<br>- Greenhouse construction technologies<br>- Natural lighting technologies |



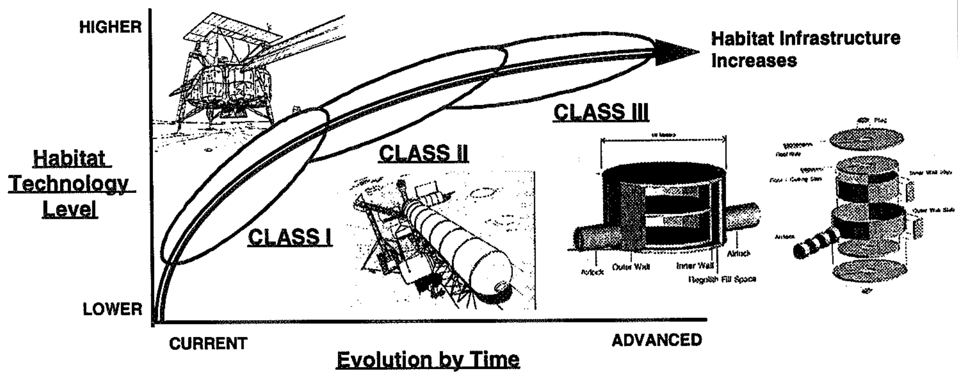


## Summary

- Need Advanced Structures Research
- SBIR/STTR Innovative Technology Opportunities
- Technology Development Strategy
- Return-on-Investment Potential is Enormous
- Paradigm Shift from "Traditional" Habitat Concepts
- Need to Move Technology from Earth Applications to Space Applications
- Need Continued Material Testing for Human Spaceflight Use

# Habitation Technology Strategy (Options)

- **CLASS I:**
  - **Preintegrated, Hard Shell Module**
- **CLASS II:**
  - **Prefabricated, Surface Assembled**
- **CLASS III:**
  - **ISRU Derived Structure w/ Integrated Earth components**







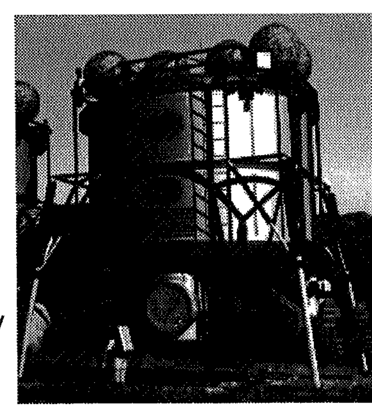

# Class 1: Preintegrated Habs

**Vision**

- A **composite structure** that can be autonomously predeployed and operated on the Moon and Mars surface. Fully integrated. The capability for A.I. smart hab for failure detection, analysis and self repair.

**Benefits**

- Low mass.
- High reliability and easy to repair.
- Near-current technology.
- Add larger modules to ISSA and Lunar Orbit.



**Current Status**

- Technology demonstrated to TRL 6-7.
- Manufacturing techniques being perfected by aircraft and launch vehicle industry.
- Incorporated into CRV skin.

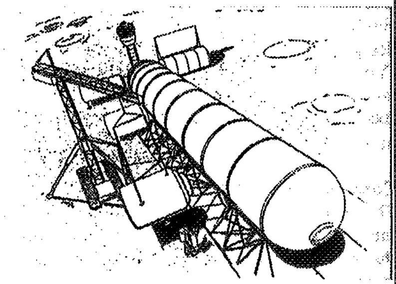
# Class 2: Prefabricated Habs

**Vision**

- An **inflatable structure** that can be autonomously predeployed and operated on the Moon and Mars surfaces. Partially integrated and flexible. The capability for A.I. smart hab for failure detection, analysis and self repair.

**Benefits**

- Larger usable habitable volume
- Lower mass
- Higher crew productivity
- Higher crew moral and quality of life (lower stress)
- High reliability and easy to repair
- Taking the steps toward building new civilizations



**Current Status**

- Technology demonstrated to TRL 4-5 by NASA-LaRC and DoD/U.S. Army.
- Industry established "smart" houses and integrated systems.
- Workshops on Space Inflatable Structures are planned (2 in '96).
- Shannon Lucid's experience of 6 months in space (Zero G).
- Long term habitability studies completed by ARC & JSC.
- Early Human Testbed preparing for 90 day test.





# Impediments of Inflatable Structures

- Technical
- High Strength Material
- Seaming/Stress Points
- Connection Points
  - Hard Points for Internal/External Connections
- Reliable and Autonomous Deployment
- Material Degradation
  - Radiation, Dust, Thermal, Atomic O2, Micrometeoroid
- Hatches and Interconnects
- Off-gassing
- Durability/Life Span
- Flexibility/Packaging
- Human Rating

Social

- In-Space/Surface Flight Experience
- "Unknown" Factor
- Lack of Skilled Work Force at NASA with Inflatable Structures
  - Understanding not Building
- Balloon (Pop) Theory
- Cost is so low compared to hard space structures, no one believes it.
- Credibility
- Confidence
  - Comes from in-space demonstrated experience
- Complexity Factor

# Class 3: ISRU-Derived Habs

**Vision**

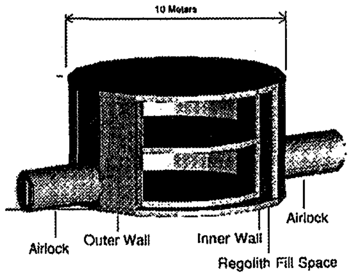
- An **ISRU-derived structure** that is manufactured using indigenous resources and constructed autonomously. It is autonomously operated and maintained utilizing A.I. and V.R. The capability for A.I. for failure detection, analysis and self-repair.

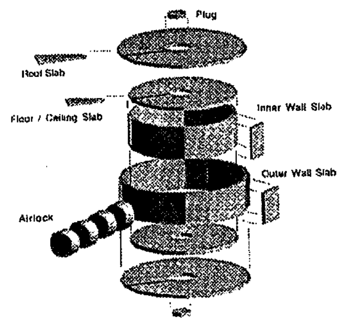
**Benefits**

- Larger usable habitable volumes.
- Can build colony infrastructure to support sustained human presence and evolution.
- Self sufficiency from Earth.
- Higher level of society.
- Ability to manufacture, service and repair.

**Current Status**

- Technology demonstrated to TRL 2-3 for Lunar-crete. Other technologies possible.




H&SC Team 09/02/97

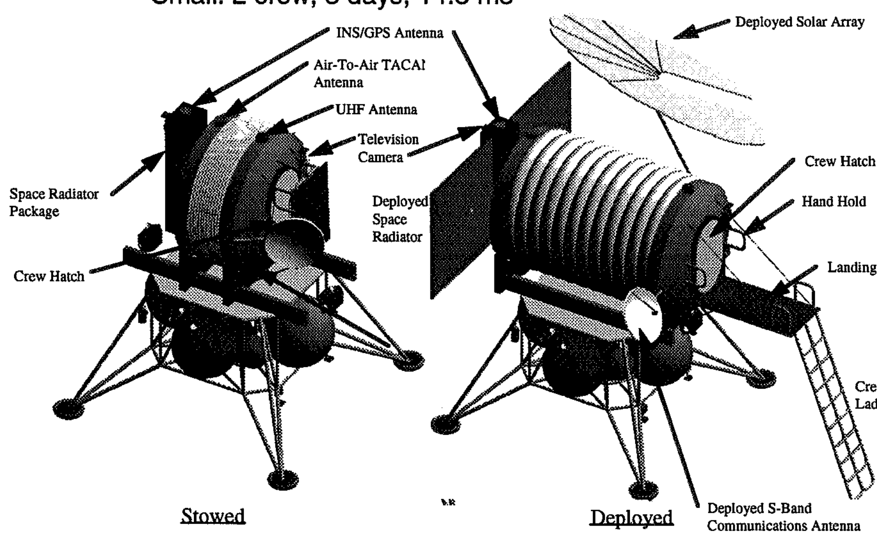
# Concepts & Development





## Inflatable Habitat Concept for Short Surface Mission Duration

- Small: 2 crew, 3 days, 14.5 m3



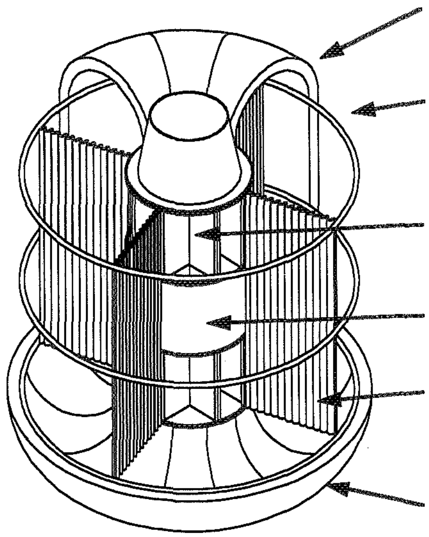

**Human Lunar Return Concept**

**Hybrid Structure: Inflatable Mid-Section with Composite End Domes**

*HEDS Technology Planning* — *Habitats & Surface Construction*

## Mars Transit Internal Configuration

- **Section TransHAB into Four Quadrants**
- **Run Length of HAB**
- **Horizontal Orientation**
- **Deployable Core Fairing for Floor/ Partition System**



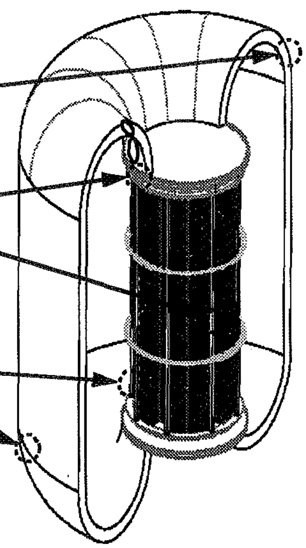

H&SC Team 09/02/97

*HEDS Technology Planning* — *Habitats & Surface Construction*

## TransHAB Structural Configuration

**Engineering Directorate**
*Horacio M. de la Fuente*

- Configuration Topics:
  - Multi-Layer Meteoroid/Orbital Debris Protection
  - Main Structural Attachments
    - Central Core - Inflatable Shell Interface
    - Central Core Shelves
  - Structural Optimization
    - Central Core Longerons
    - Inflatable Shell Aspect Ratio
  - Configuration Summary

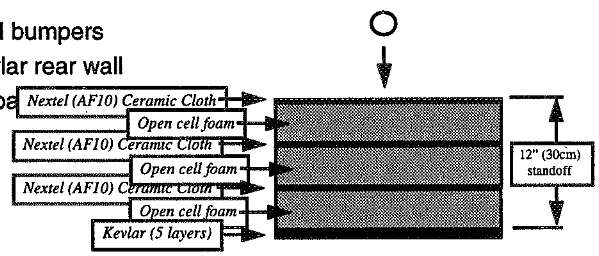


H&SC Team 09/02/97

**Engineering Directorate**
***Horacio M. de la Fuente***

## TransHAB
## Main Structural Attachments

- Meteoroid/Orbital Debris Protection
  - JSC Hypervelocity Testing Results:
    - >98% No leak, while in Earth orbit for ~ 6Mths (threat is orbital debris driven)
    - >99.5% No leak, during to/from Mars transit (threat is meteoroid driven)
    - Impacts up to 0.25 in. (0.63cm) Dia. Aluminum projectile, V=~7 km/s, $0^{0}$ impact angle
  - Main components:
    - Multi-shock Nextel bumpers
    - High-strength Kevlar rear wall
    - Large, open cell foa

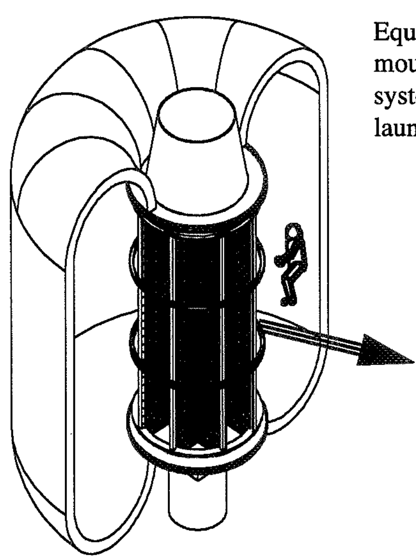


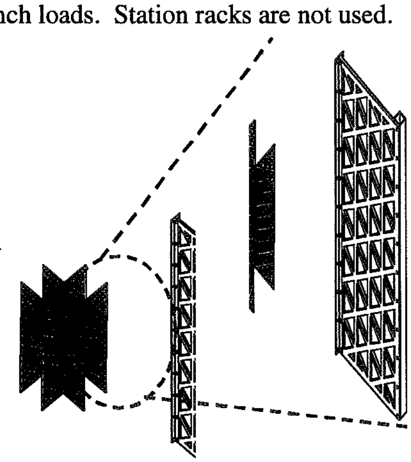




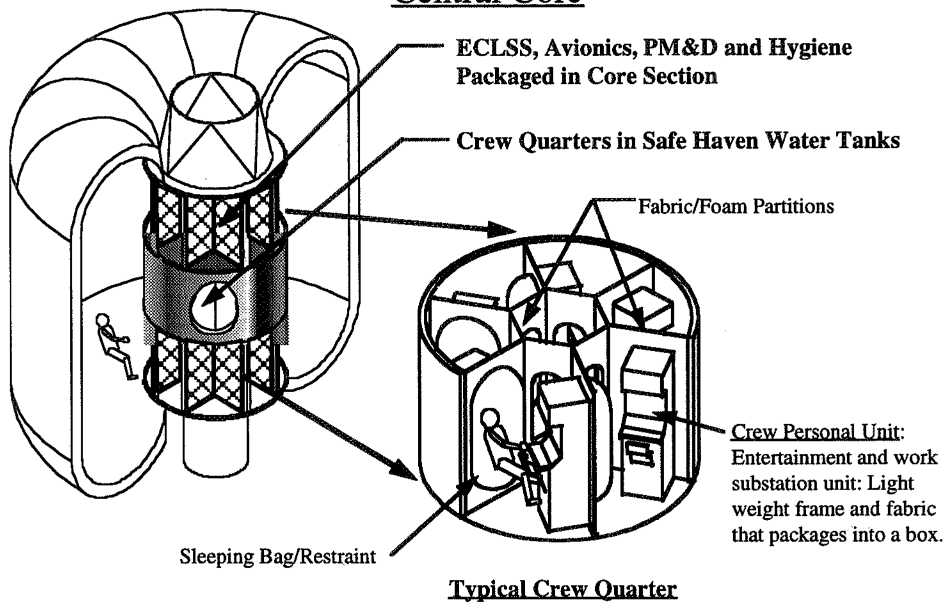

## Central Core Shelf System

Equipment and subsystems are directly mounted/installed on to central core shelf system to optimize structural design to take launch loads. Station racks are not used.





## Central Core




H&SC Team 09/02/97

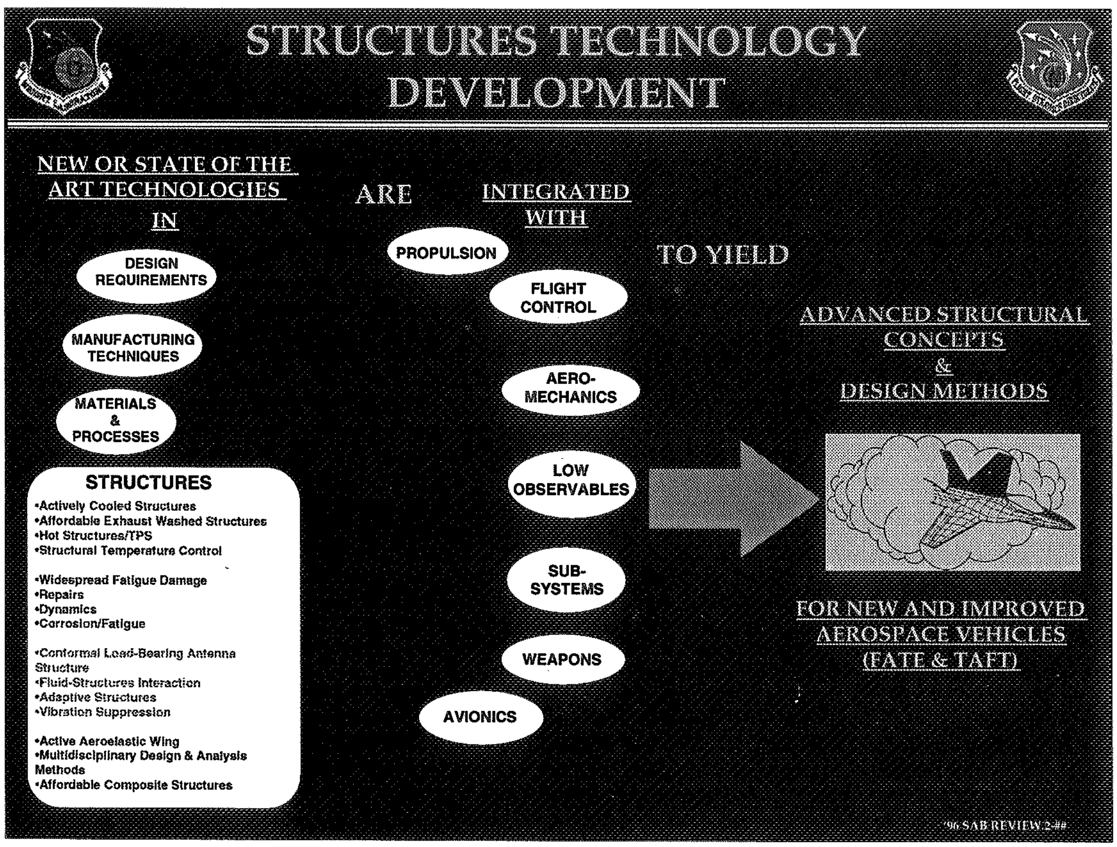
# Structures Technology Development

Donald B. Paul
Flight Dynamics Directorate
Wright Patterson Air Force Base, OH

# STRUCTURES TECHNOLOGY DEVELOPMENT

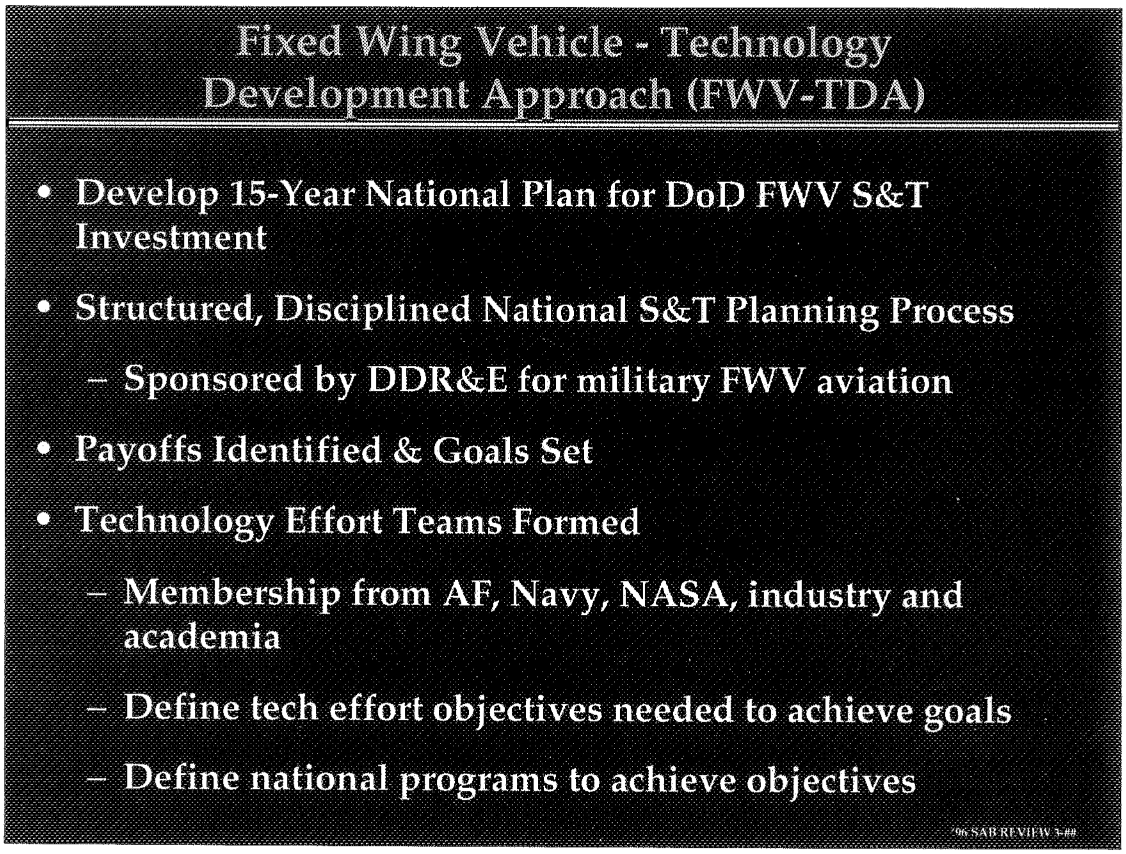
Donald B. Paul
Flight Dynamics Directorate
Wright Patterson Air Force Base, OH

The Flight Dynamics Directorate develops Air Force structures technology by integrating new or state-of-the-art technologies in design requirements, manufacturing techniques, materials, and processes with requirements for propulsion, flight controls, aeromechanics, low observables, subsystems, weapons and avionics. The results are advanced structural concepts and design methods for new and improved aerospace vehicles (FATE & TAFT).



## FIXED WING VEHICLE-TECHNOLOGY DEVELOPMENT APPROACH (FWV-TDA)

The FWV-TDA process is a structured, disciplined, national S&T planning process sponsored by DDR&E for military FWV aviation. The result is a fifteen-year national plan for DoD FWV S&T investment, in which payoffs are clearly identified and challenging goals are established. Technology effort teams, consisting of members from the Air Force, the Navy, NASA, industry, and academia, were formed to define the technology effort objectives necessary to achieve the goals, and national programs to achieve these objectives.



## FWV-TDA AIRCRAFT AND TIMELINE

Military aircraft have been divided into three families to serve a baseline for the FWV-TDA process: fighter/attack aircraft (F-22, F-18E/F); airlift, patrol, and bomber aircraft (C-17, P-3, B-2); and Special Operations Forces (SOF) aircraft (H/MC-130J). The process is to be completed in three phases, with estimated completion dates of 2001, 2006, and 2011 for Phases I, II, and III, respectively.

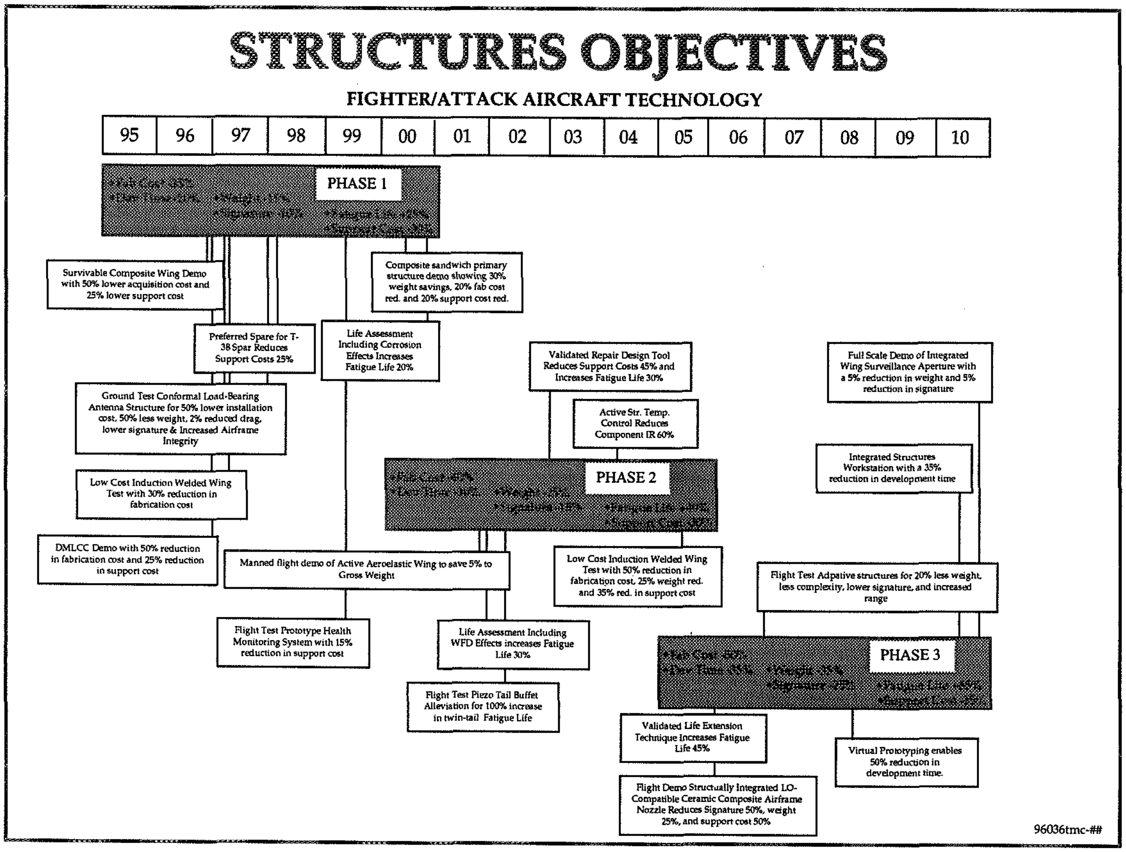
### FWV-TDA

- 3 Families of A/C (Baseline A/C)
  - Fighter/Attack (F-22, F-18E/F)
  - Airlift/Patrol/Bomber (C-17, P-3, B-2)
  - SOF (H/MC-130J)
- 3 Timeframes
  - Phase I ~ 2001
  - Phase II ~2006
  - Phase III ~2011

'96 SAB REVIEW 3-##

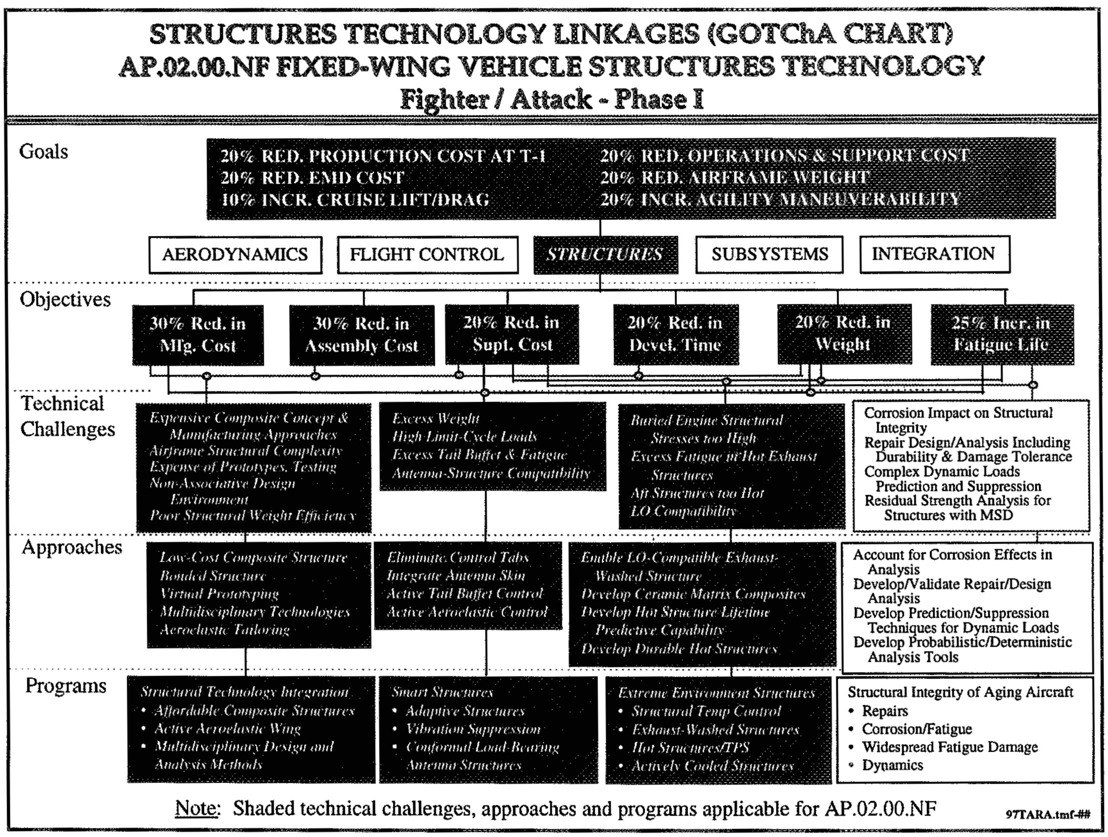
## STRUCTURES OBJECTIVES

This chart shows the FWV-TDA structures objectives for fighter/attack aircraft technology. Similar objectives exist for transports, bombers and special forces aircraft.



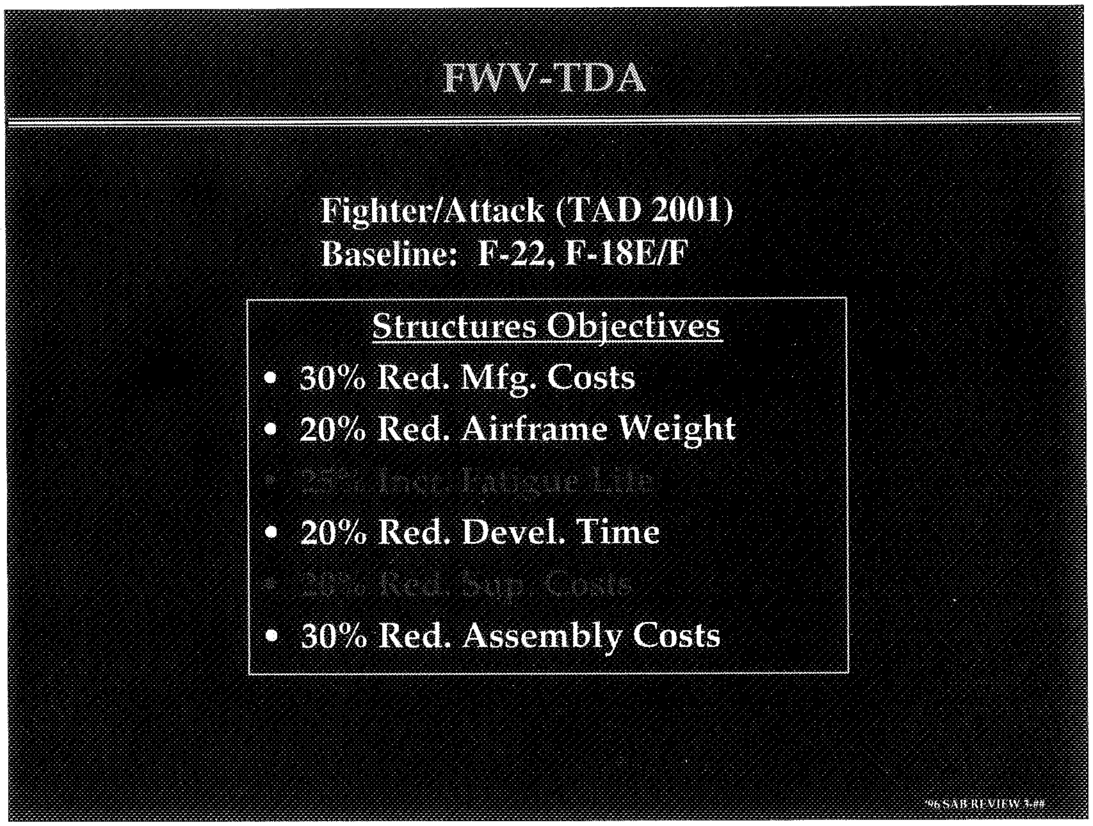
## STRUCTURES TECHNOLOGY LINKAGES

This chart shows the FWV-TDA Phase I goals for fighter/attack aircraft and the objectives necessary to achieve these goals. In order to meet these objectives, many challenging technical obstacles must be overcome. The Structures Division will approach these challenges through its four core technology programs, as shown on the chart.



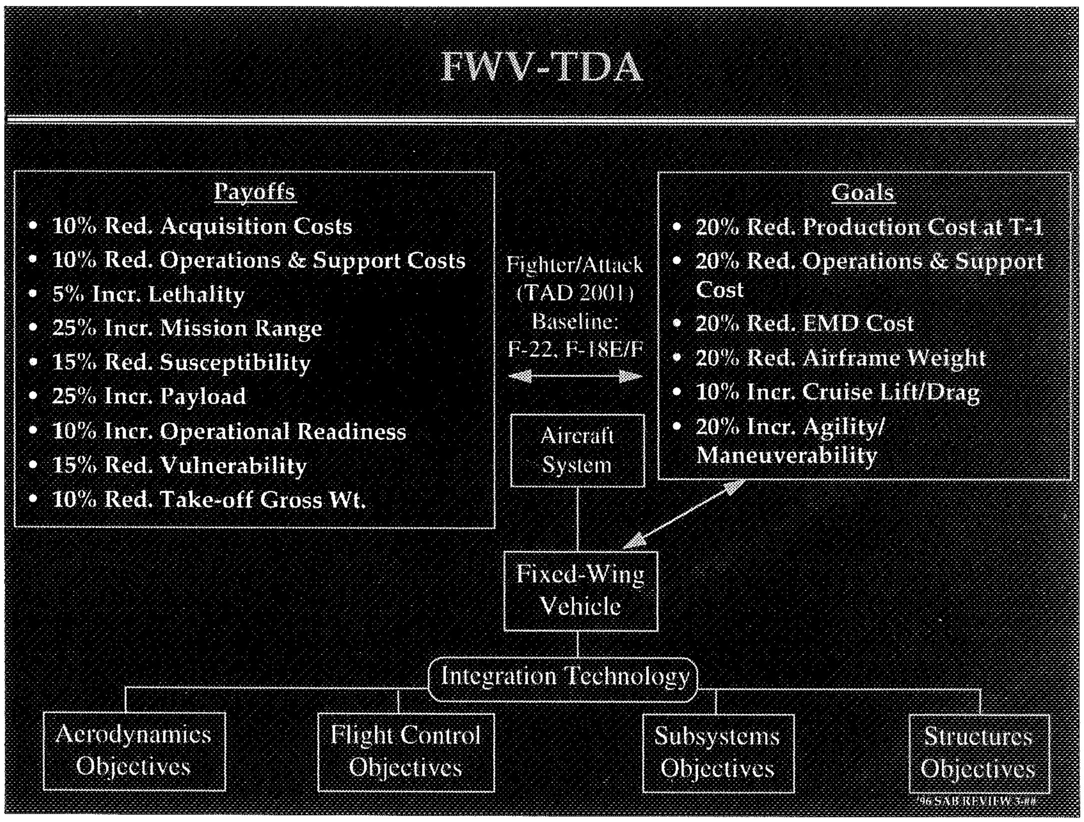
## FWV-TDA STRUCTURES OBJECTIVES FOR FIGHTER/ATTACK AIRCRAFT

Using the F-22 and F-18E/F as baseline aircraft, the FWV-TDA Phase I objectives are to reduce weight, development time and costs, and to increase fatigue life, by the quantitative amounts shown.



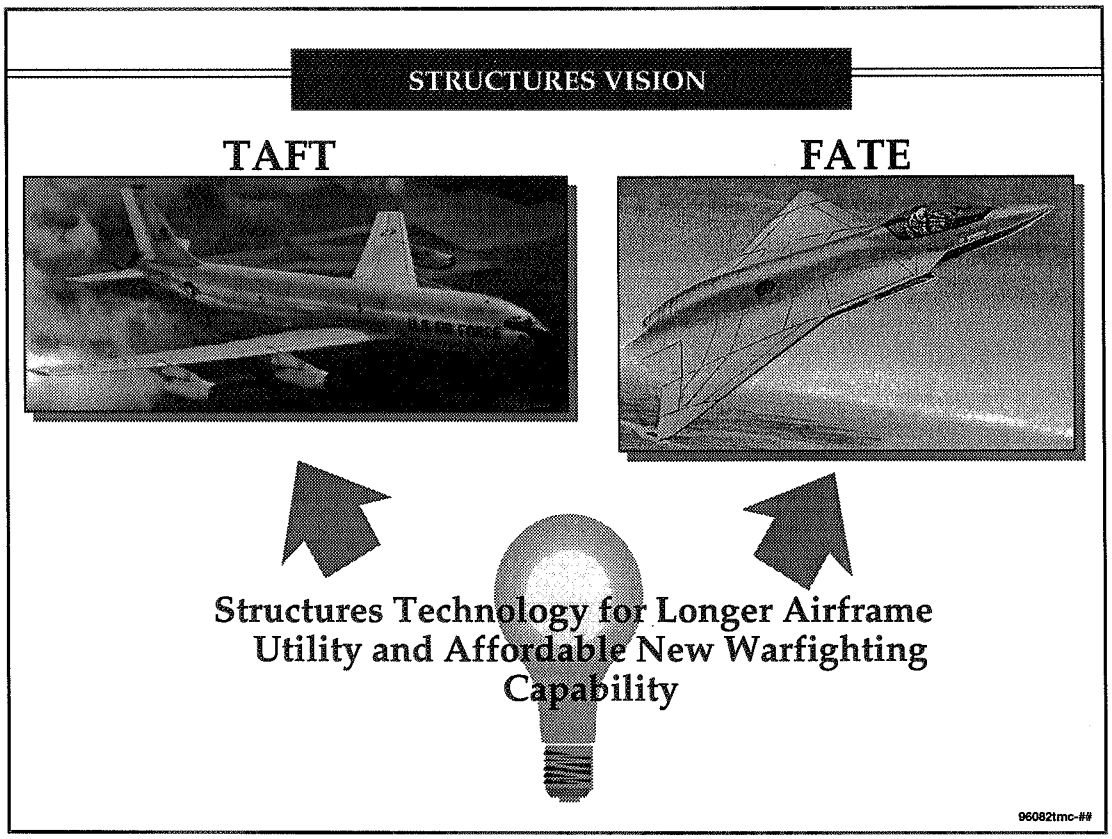
## FWV-TDA GOALS AND PAYOFFS

This chart shows the payoffs associated with achieving the FWV-TDA Phase I goals for fighter/attack aircraft. Structures, subsystems, flight control, and aerodynamics objectives must be integrated in order to deliver the payoffs to actual aircraft systems.



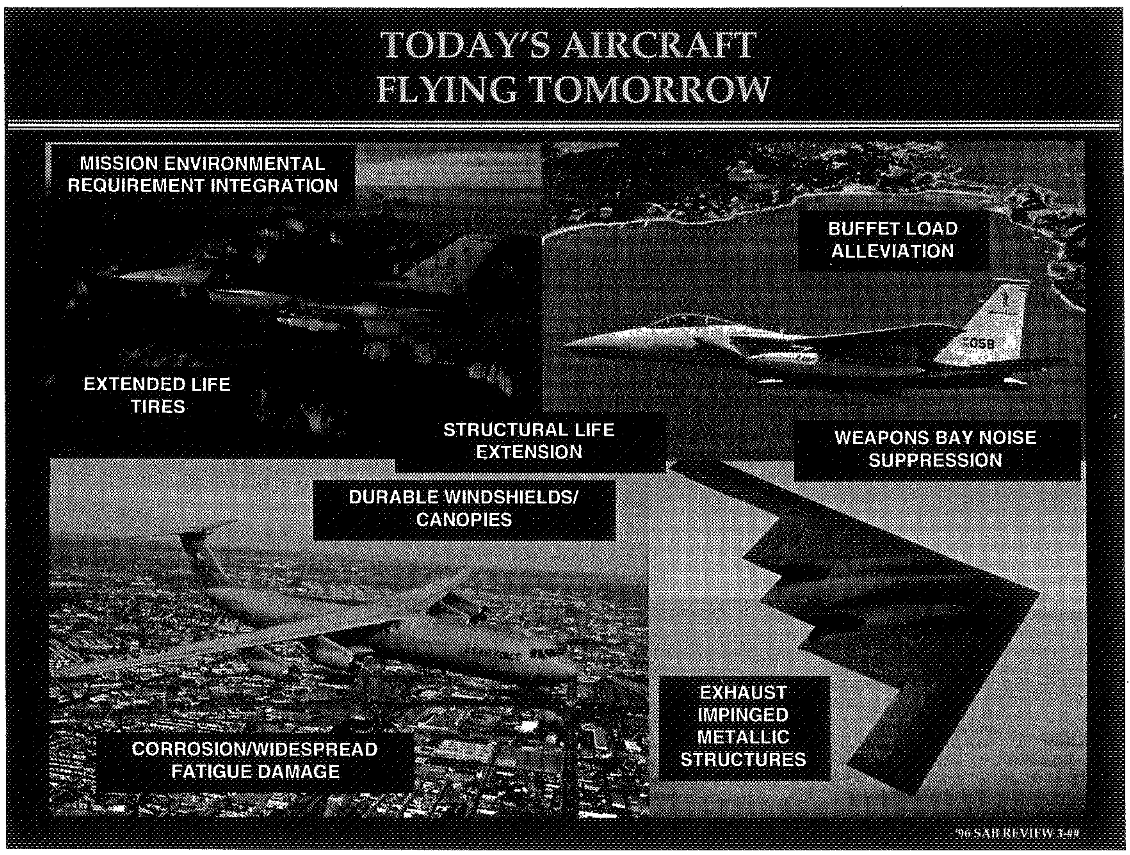
# STRUCTURES VISION

The Structures Division's research emphasis is derived from the Air Force structures vision of making old airframes last longer and building new airframes with significant technology improvements and enhanced warfighting capability. We must keep Today's Aircraft Flying Tomorrow (TAFT) and be sure that Future Aircraft Technology Enhancements (FATE) happen.



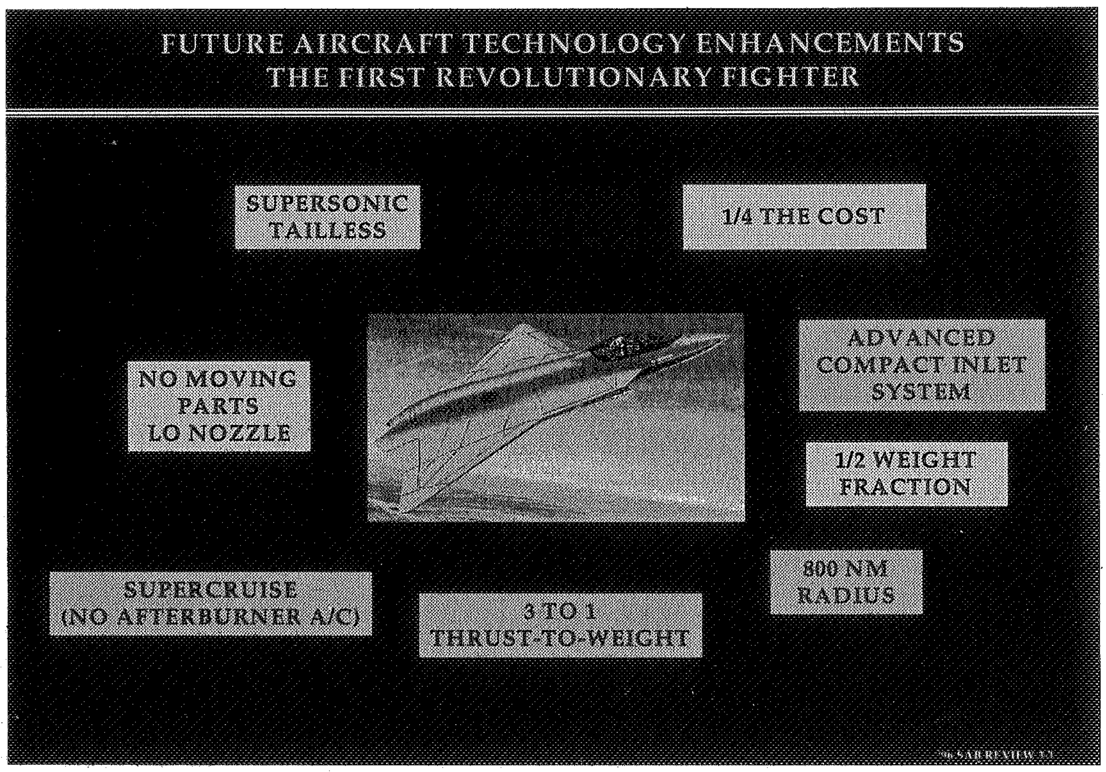
## TODAY'S AIRCRAFT FLYING TOMORROW (TAFT)

In light of the reality that we are buying fewer new aircraft systems, it is critical that we develop technologies to ensure that we can keep Today's Aircraft Flying Tomorrow (TAFT). In order to do this we need: longer-life tires; buffet load alleviation systems; corrosion and widespread fatigue damage prevention, arrest, and repair techniques; more durable windshields and canopies; more durable exhaust impinged metallic structures; as well as other improvements not shown on this slide.



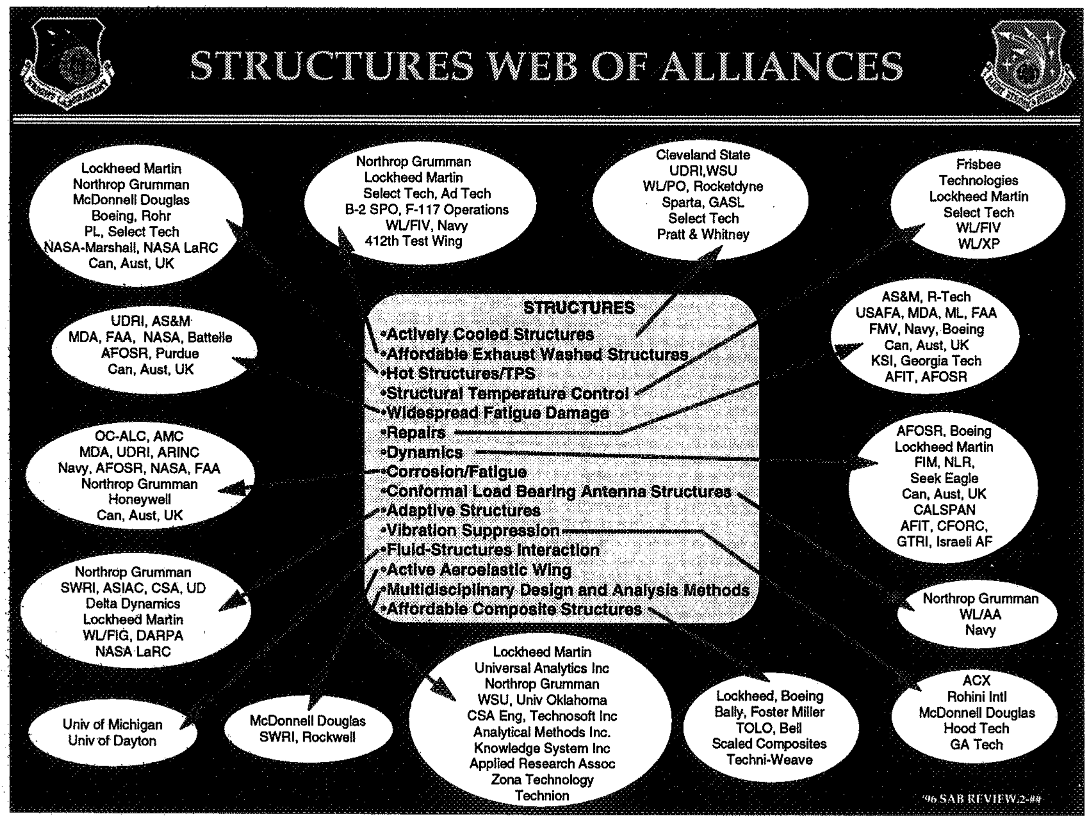
## FUTURE AIRCRAFT TECHNOLOGY ENHANCEMENTS (FATE)
## THE FIRST REVOLUTIONARY FIGHTER

The FATE aircraft is truly revolutionary, as shown by the goals in this chart. A supersonic tailless aircraft at only a quarter of the current system cost—revolutionary! This aircraft will have an advanced compact inlet system, only half of the conventional weight fraction, an 800 NM radius, a 3-to-1 thrust-to-weight ratio, a low-observable nozzle with no moving parts, and will achieve supercruise without an afterburner.



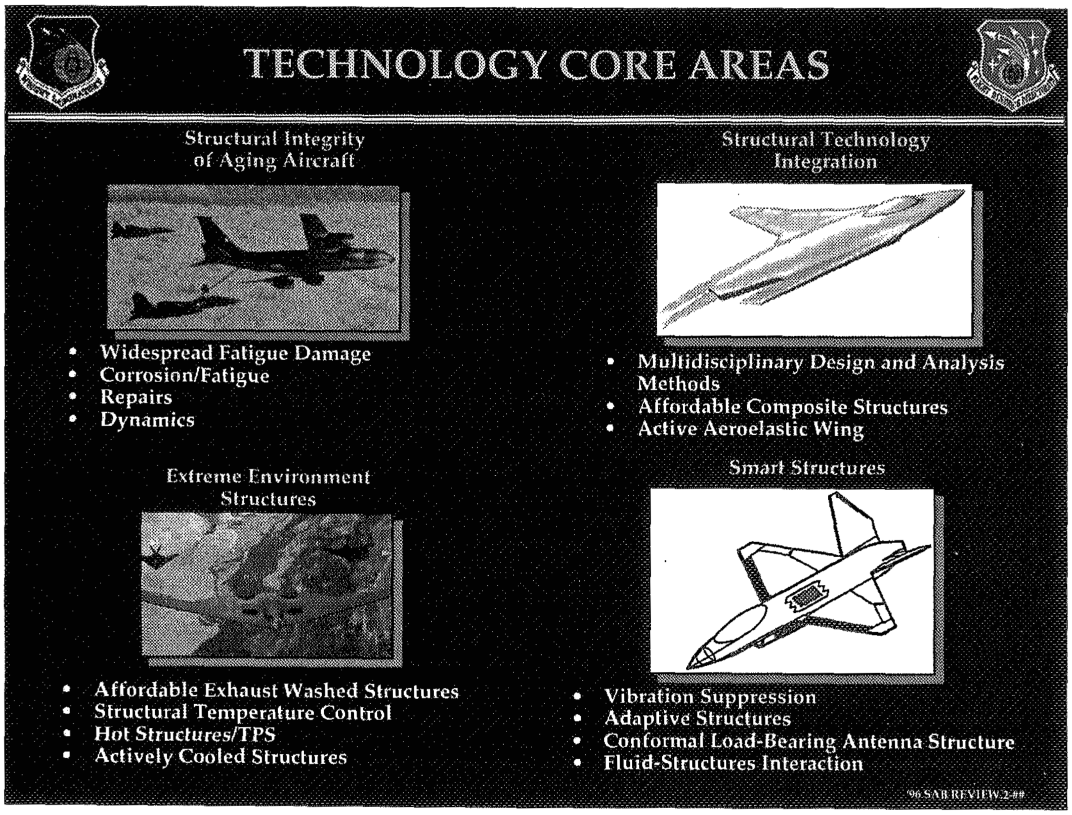
## STRUCTURES WEB OF ALLIANCES

This chart reveals the extensive cooperation between the Air Force, the Navy, NASA, industry, and academia in order to develop new Air Force structures technologies. Specifically, Structures Division's partners are broken down by sub-core competency area. For example, McDonnell Douglas, SWRI, and Rockwell are allied with the Structures Division to develop active aeroelastic wing technology.



## TECHNOLOGY CORE AREAS

Structures Division is advancing the state-of-the-art in aircraft technology by streamlining its research in four core competency areas: Structural Integrity of Aging Aircraft (AA); Structural Technology Integration (TI); Extreme Environment Structures (EE); and Smart Structures (SS). Each of the core competency areas is further divided into sub-core competency areas, as shown on the chart.



## STRUCTURAL INTEGRITY OF AGING AIRCRAFT

Aging Aircraft core area research is focused into four competency areas: corrosion/ fatigue, repairs, widespread fatigue damage, and dynamics. Research efforts range from basic research (6.1) to advanced research (6.3), and is conducted via collaboration with other DoD, industry, and academic partners.

### *Structural Integrity of Aging Aircraft*

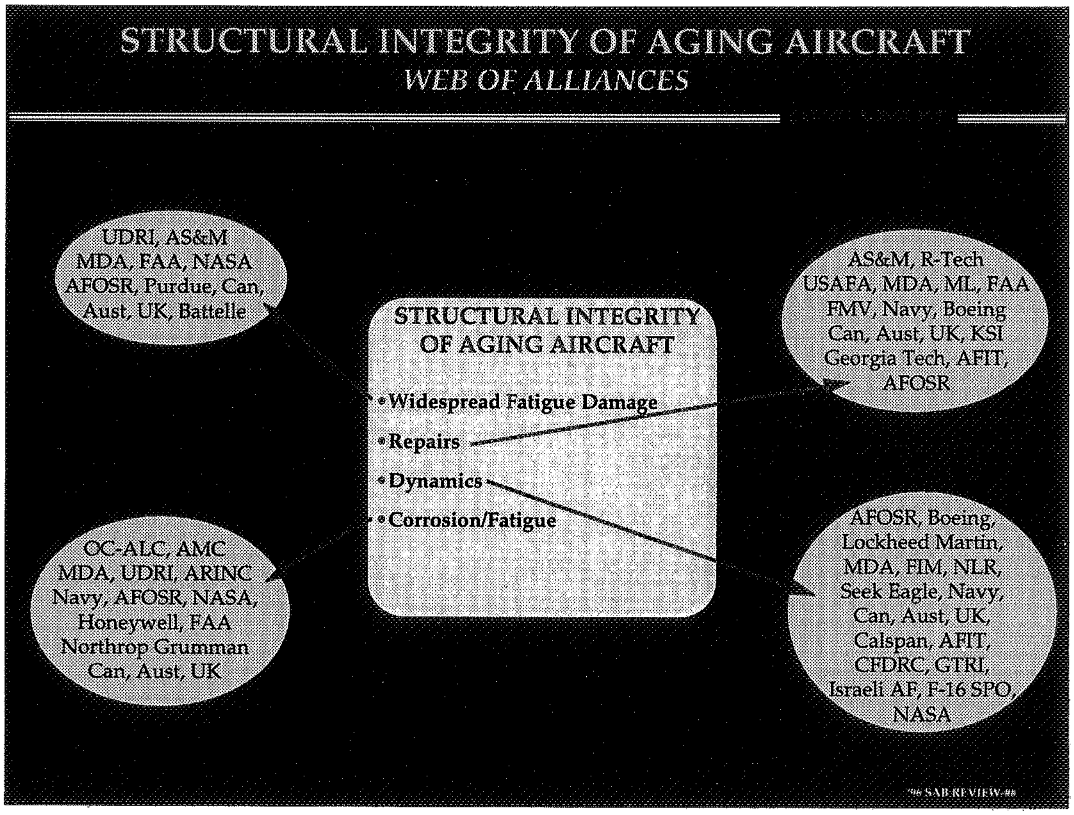
**Wright Laboratory**

**Approach**

- Focus Areas
  - Corrosion/Fatigue
  - Repairs
  - Widespread Fatigue Damage
  - Dynamics
  - 6.1/6.2/6.3 programs
- Collaborative Teaming

## AGING AIRCRAFT WEB OF ALLIANCES

This chart shows how the Aging Aircraft core is allied with its partners in the DoD, industry, and academia in order to accomplish its mission.



## CORROSION/FATIGUE COMPETENCY AREA

The impact of corrosion damage on structural integrity is not yet a well-understood area. Aging Aircraft's goal is to develop and provide the necessary tools to determine the effects of corrosion/fatigue on structural integrity, including the interaction with widespread fatigue damage (WFD).

# *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

### Corrosion/Fatigue

**PROBLEM**

The impact of corrosion damage on structural integrity is not well understood

**GOAL**

Provide the necessary tools to determine the effects of corrosion/fatigue on structural integrity

- Interaction with WFD

## CORROSION/FATIGUE

Several structural integrity issues surface when we consider corrosion/fatigue. Identification and quantification is a problem, as well as measurement techniques, test methodology, and validation. Corrosion/fatigue contributes to WFD by causing pitting and pillowing.

### *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

- Corrosion/Fatigue
  - Structural integrity issues
    - Identification/Quantification
    - Metrics/Transformations
    - Test Protocol/Validation
  - Contribution to widespread fatigue damage
    - Pitting
    - Pillowing

## AGING AIRCRAFT
## WIDESPREAD FATIGUE DAMAGE (WFD)

Over time the onset of WFD due to multisite damage degrades an aircraft's structural integrity. Aging Aircraft's goal is to develop, proof-test, and implement probabilistic tools which can be used to quickly perform accurate risk assessments on aging aerospace vehicles.

***Structural Integrity of Aging Aircraft***

**Wright Laboratory**

**Widespread Fatigue Damage**

**PROBLEM**

The onset of widespread fatigue damage due to multisite damage degrades aircraft structural integrity

**GOAL**

Provide probabilistic tools for risk assessment

## WIDESPREAD FATIGUE DAMAGE

The Air Force is collaborating with the FAA and NASA on both deterministic analysis/validation and probabilistic analysis. Wright Laboratory is teamed with the Air Force Office of Scientific Research (AFOSR) and Purdue University on WFD research.

### *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

- Widespread Fatigue Damage
  - AF is collaborating with FAA/NASA
    - Deterministic analysis/validation
    - Probabilistic analysis
  - WL/AFOSR/Purdue

## AGING AIRCRAFT DYNAMICS RESEARCH

Aging aircraft experience damage due to the interaction of dynamic loads with aircraft structures. For example, buffet loads, limit cycle oscillations, and cavity acoustics are all problem loads. Aging Aircraft's goal is to develop and validate methods to characterize dynamics-induced damage, and to develop and demonstrate suppression techniques capable of negating potential damage.

### *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

**Dynamics**

**PROBLEM**

Damage due dynamic loads interacting with structures

-Buffet, Limit cycle oscillation, cavity acoustics

**GOAL**

Develop/validate analysis methods

Demonstrate suppression techniques

## DYNAMIC LOADS

Excessive or repeated dynamic loads lead to aircraft structure cracking, which in turn contributes to premature aging, and costly repair and replacement. Aging Aircraft personnel are aggressively pursuing methods to predict and suppress these effects by performing research in aeroelasticity, buffet, limit cycle oscillations, and acoustics.

### *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

- Dynamics
  - Excessive/repeated dynamic loads - Cracking
    - Premature aging leads to costly repair/replacement
  - Prediction and Suppression
    - Aeroelasticity, buffet, LCO, Acoustics

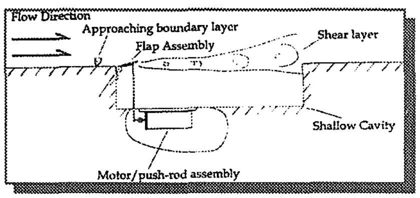
## DYNAMICS-ACOUSTICS

The Air Force has been compelled to solve dynamic and acoustic induced problems throughout its history. Structures Division is currently developing analytical prediction techniques for both subsonic and supersonic free stream flow conditions. The resulting code will predict frequency and amplitude, and will run on a personal computer. An analytical study is under way to evaluate active suppression methods. Wind tunnel tests are currently being performed to evaluate two of the most promising techniques, oscillating flap and blown air. The best concept will be flight-tested.

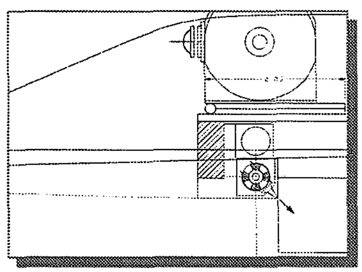
# DYNAMICS - ACOUSTICS

### Solutions

- **Long History in Field:**
  - 60's - prediction of frequencies/pressure amplification
  - 70's - reduction of pressure oscillations in cavities
  - 80's - supersonic flow
  - 90's - active control concepts
- **Develop Analytical Prediction**
  - Subsonic/supersonic free stream flow
  - PC based code to predict frequency, amplitude
- **Evaluate Active Suppression Methods**
  - Analytical study
- **Wind Tunnel Tests - evaluate most promising**
  - Oscillating Flap (in tunnel now!)
  - Blown Air
- **Flight Test Best Concept**




Oscillating Flap



Blown Air

97TARA.tmf-##

## REPAIRS

Bonded composite repair technology is not fully developed, especially in the areas of design criteria, durability and damage tolerance. Aging Aircraft's goal is to develop and validate design and analysis tools for design criteria and structural integrity.

# *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

## Repairs

**PROBLEM**

Bonded composite repair technology is not fully developed

-Design criteria, durability/damage tolerance

**GOAL**

Develop and validate design/analysis tools

- Design criteria, structural integrity

## REPAIRS

The Aging Aircraft Repairs sub-core area develops on design criteria, designs, and analysis tools for bonded repairs, performs experimental verification, identifies manufacturing and producibility needs, and NDI/E requirements.

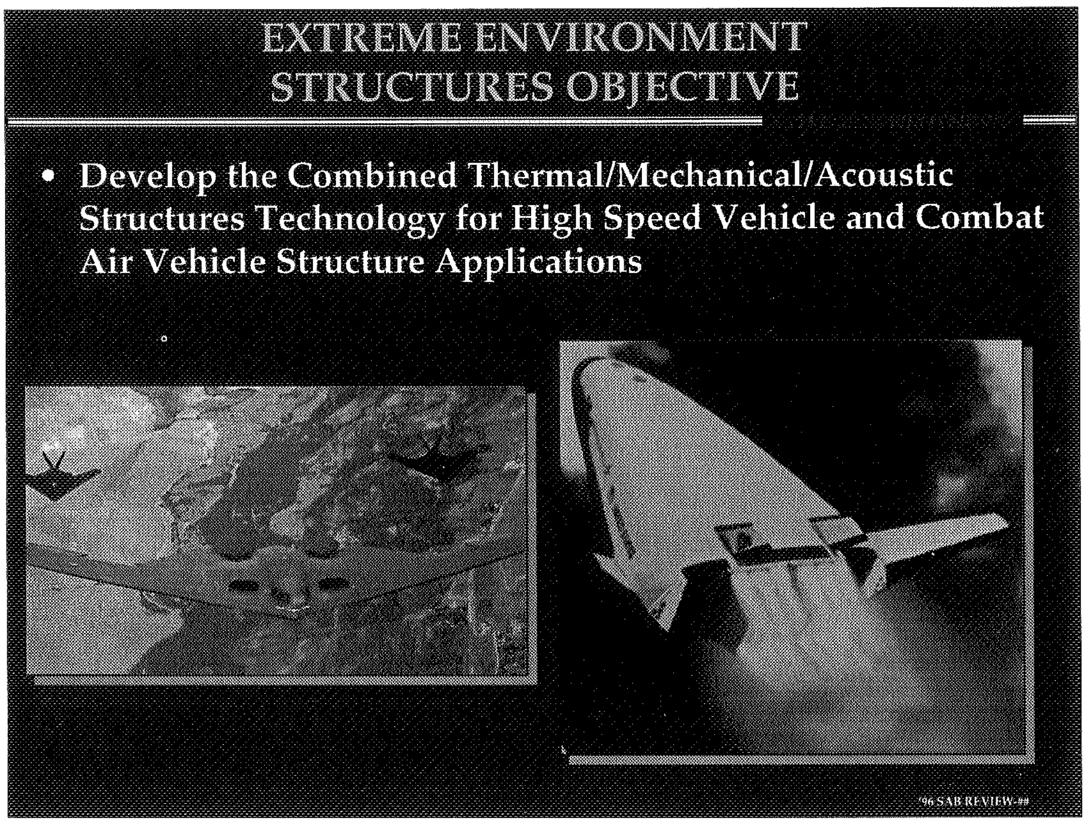
### *Structural Integrity of Aging Aircraft*

**Wright Laboratory**

- Repairs
  - Design criteria
  - Develop design and analysis tools for bonded repairs - User oriented
    - FEM-based to Engineering solutions
    - Damage Tolerance Analysis
  - Experimental verification
  - Identify M&P needs, NDI/E requirements

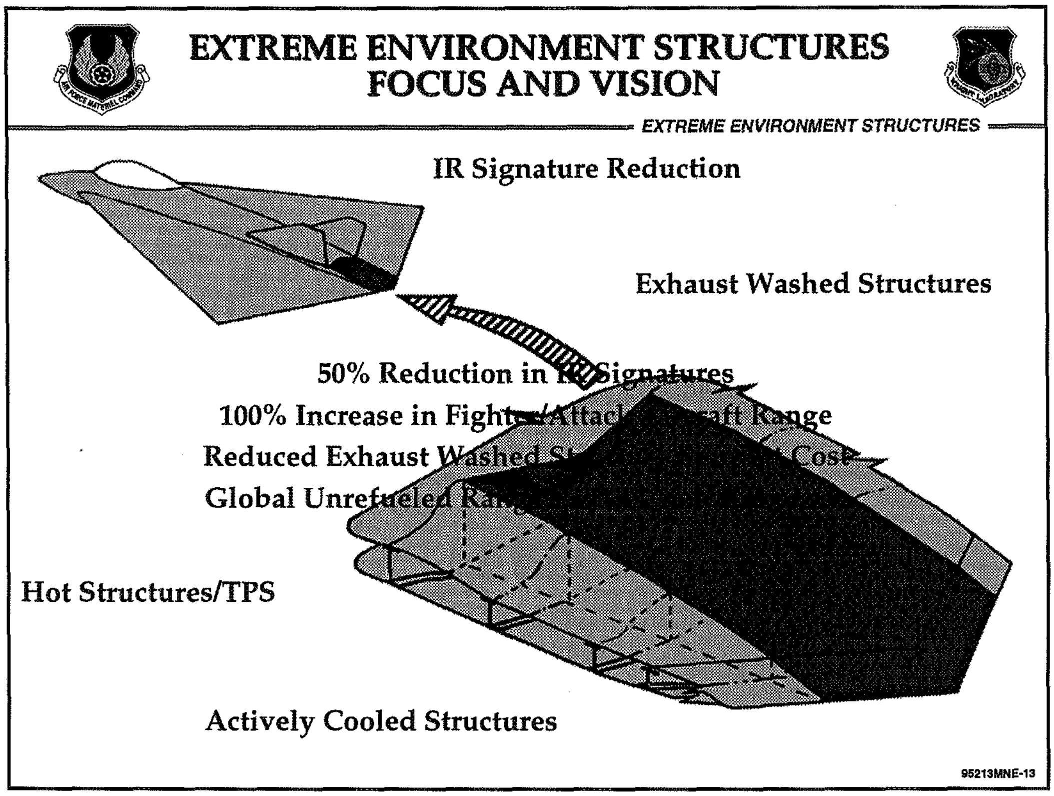
## EXTREME ENVIRONMENTS STRUCTURES

The Extreme Environments core area develops the combined thermal, mechanical, and acoustics structures technology for high speed vehicles, such as spaceplanes and reentry vehicles, and for combat air vehicles, such as stealth fighters and bombers with embedded engines.



## EES FOCUS AND VISION

Extreme Environment Structures has four sub-core areas: two aimed at current and next-generation stealth vehicles: Structural Temperature Control and Exhaust Washed Structures; as well as two aimed at next-generation high speed vehicles such as spaceplanes: Hot Structures/Thermal Protection Systems and Actively Cooled Structures. Many of the technologies under study have application across several of the sub-core areas. These efforts support increasing structural fatigue life while addressing both RCF and IR signature constraints.



## STRUCTURAL TEMPERATURE CONTROL

The objective of Structural Temperature Control is to develop techniques to reduce the IR signature of advanced stealthy aircraft structures. Our approach to reach that objective is to develop advanced heat transfer modeling methods, design, fab, analyze and test advanced cooled structure concepts and to develop coolant flow minimization techniques. The impact of Structural Temperature Control is 35 percent IR signature reduction over F-22/B-2 baselines and enhanced vehicle survivability in high threat environments.

## STRUCTURAL TEMPERATURE CONTROL

*EXTREME ENVIRONMENT STRUCTURES*

### OBJECTIVE

- To develop techniques to reduce the IR signature of advanced stealthy aircraft structures

### APPROACH

- Develop advanced heat transfer modeling methods
- Design, fab, analyze and test advanced cooled structure concepts
- Develop coolant flow minimization techniques

### IMPACT

- 35% IR signature reduction over F-22/B-2 baselines
- Enhanced vehicle survivability in high threat environments

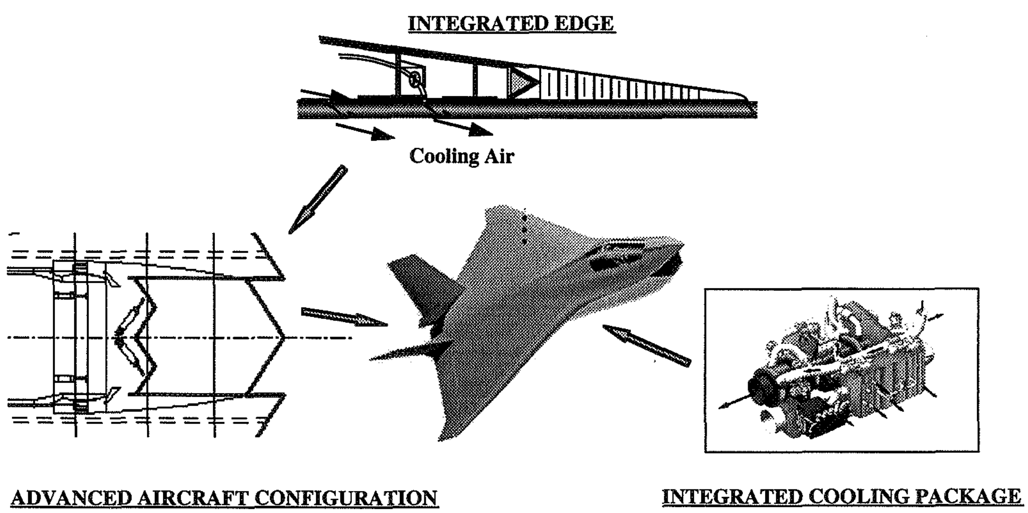
94093-##

## SITE-M

The showcase program in Structural Temperature Control is Structurally Integrated Thermal Energy Management (SITE-M). This program will develop and verify the design of cooling systems for exhaust washed structures. This program is the first attempt to enhance aircraft survivability with efficient use of cooling while still addressing life and maintenance concerns.

### Structurally Integrated Thermal Energy Management (SITE-M)

Current and Developing Air Defense Systems Pose an IR Threat to All Missions



## SITE-M APPROACH AND CHALLENGES

The SITE-M approach is to: develop new analytical modeling capabilities; develop new conceptual designs and prototypes; evaluate thermal management systems; perform aircraft level penalty analysis and sensitivity studies; verify design techniques; and fabricate and test new test components. The technical challenges include integrating thermal management systems with structural and propulsion systems, as well as dealing with weight, affordability and supportability constraints.

### Structurally Integrated Thermal Energy Management (SITE - M)

**•APPROACH**

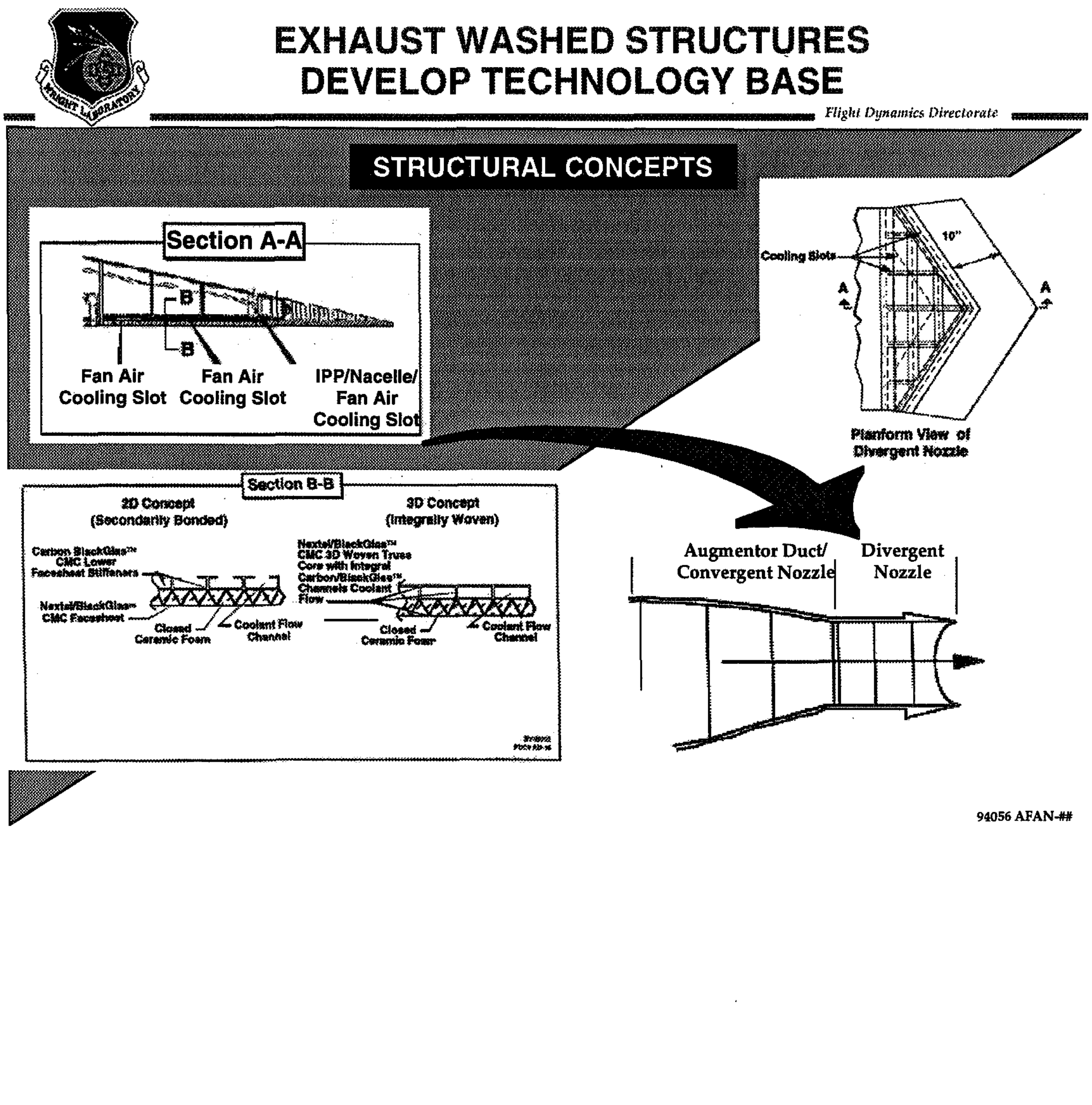
- **Evaluate various structural and thermal management cooling concepts**
- **Develop analytical model of selected concepts**
- **Develop Conceptual Level Design of prototype structural cooling system**
- **Perform aircraft level penalty analysis and technology sensitivity studies**
- **Verify Design of Critical Technologies with representative subelements**
- **Evaluate supportability & repair issues**
- **Fabricate and test Subcomponent**
- **Validate design and develop roadmap to 6.3 program**

**•TECHNICAL CHALLENGES**

- **Integration of thermal management, structural, and propulsion subsystems**
- **System weight and affordability**
- **Structural integrity and thermal life**
- **Availability of adequate heat sinks**
- **Supportability of system**

## EWS-TECHNOLOGY BASE

This sub-core is taking a building block approach to developing the use of ceramic matrix composites (CMC) for structurally integrated nozzles. It starts from characterizing vibration induced fatigue data for CMC's, develops joint design criteria for bonded and bolted joints between CMC's and high temperature polymers, continues through development of sub-component integrated nozzle panels, and concludes with the demonstration of a fully-integrated fixed nozzle.



## EXHAUST WASHED STRUCTURES

Extreme Environment's exhaust washed structures research is aimed at developing and demonstrating durable exhaust washed structures for advanced stealth vehicles. The approach is to establish conceptual design criteria, and then design, fabricate, analyze and test advanced metallic and ceramic composite structures with representative stealth vehicle requirements. Impacts of this research include increasing fatigue life and making significant reduction in RF and IR emissions.

## EXHAUST WASHED STRUCTURES

*EXTREME ENVIRONMENT STRUCTURES*

### OBJECTIVE

- To develop durable exhaust washed structures for advanced stealth vehicles

### APPROACH

- Establish structural design criteria
- Design, fab, analyze and test advanced metallic and ceramic composite structures with representative stealth vehicle requirements

### IMPACT

- 100% Increase in fatigue life over F-22 baseline
- 125% Increase in fatigue life over MC-130 baseline
- 60% Increase in fatigue life over B-2 baseline
- 50% Reduction in support costs over B-2/F-22 baseline
- Significant RF and IR reductions

94093-##

# HOT STRUCTURES/TPS

The objective of Hot Structures/TPS is to develop metallic and ceramic composite structures for high-speed applications and to develop ceramic composite TPS for advanced vehicles. Our approach to reach that objective is to leverage access-to-space launch vehicle technology advancements for high speed aircraft, leverage ARPA and French (DEA) CMC characterization efforts to produce design criteria and validate advanced structural concepts for high speed fighter and bomber operational environments. The impact of Hot Structures/TPS is the enabling of rapid crisis response and reconnaissance, global reach, and low cost access-to-space, 75% reduction in support cost and a 100% increase in fatigue life over SR-71 baseline, 100% increase in range over F-15E baseline and global unrefueled bomber operations.

## HOT STRUCTURES/TPS

*EXTREME ENVIRONMENT STRUCTURES*

### OBJECTIVE

- To develop durable metallic and ceramic composite structures for high speed applications
- To develop ceramic composite TPS for advanced vehicles

### APPROACH

- Leverage Access-to-Space launch vehicle technology advancements for high speed aircraft
- Leverage ARPA & French (DEA) CMC characterization efforts to produce design criteria
- Validate advanced structural concepts for high speed fighter/bomber operational environments

### IMPACT

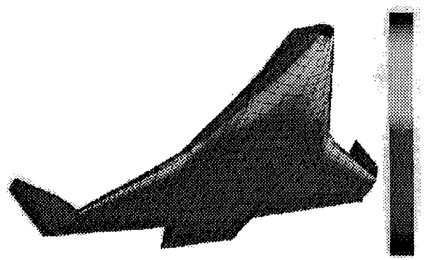
- Enable rapid crisis response and reconnaissance, global reach, and low cost access-to-space
- 75% reduction in support cost and a 100% increase in fatigue life over SR-71 baseline
- 100% increase in range over F-15E baseline
- Global unrefueled bomber operations

94093-##

## RLV/SPACEPLANE SUPPORT

Extreme Environments is working with Phillips Laboratory to support development of advanced RLV and spaceplane technologies. Our objectives are to make operability improvements over the current X-33 program and to provide alternative concepts for mass fraction improvements. Structures Division's emphasis is on thermal protection systems (TPS) and the military utility of these vehicles. Current programs include the Mini-Spaceplane Technology (MiST) program, Carbon-Carbon TPS coating repairs, high temperature sandwich and blanket structures development, and demonstration of durable, flexible TPS.

### *RLV/SPACEPLANE SUPPORT*



***Objectives***

- Focus on operability improvements over current X-33 program
- Provide alternative concepts to improve mass fraction
- Emphasis on thermal protection systems and tanks
- Look at military utility of these vehicles

***Funding Source***

- PL/VT-X Funded: $4.8M(FY96) $500K(FY97)
- Additional programs will follow at direction of AFMC/AFSMC Military Spaceplane Integrated Concept Team
- FI LDDF FY98 - $500k
  FY99 - $1.0M

***Current Programs***

- Mini-Spaceplane Technology(MiST)
- MiST Wingbox & Center Fuselage Demo
- Coating Repair of Carbon-Carbon TPS
- High Temp Comp Sandwich with Blanket TPS
- Titianium Sandwich with Blanket TPS
- Durable Flexible TPS Demo

WL/FIMA
HAK 9/96

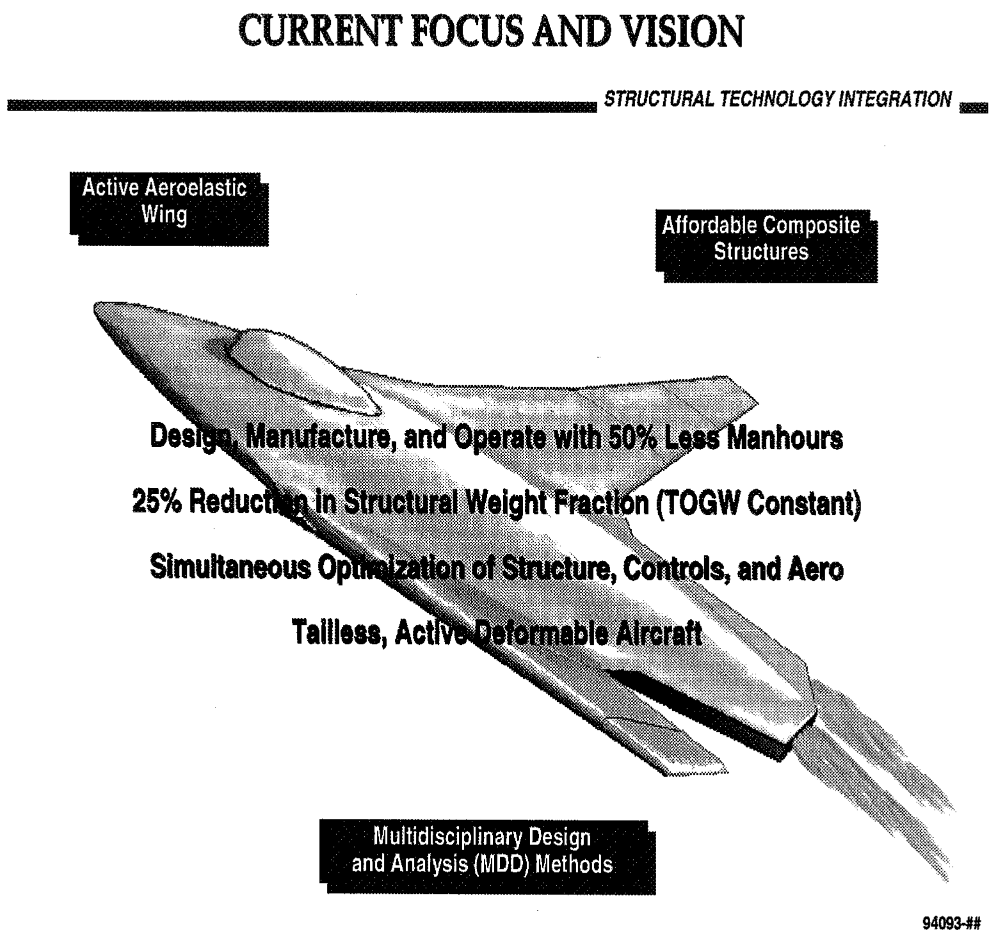
## RLV/SPACEPLANE SUPPORT

Extreme Environments is working with Phillips Laboratory to support development of advanced RLV and spaceplane technologies. Our objectives are to make operability improvements over the current X-33 program and to provide alternative concepts for mass fraction improvements. Structures Division's emphasis is on thermal protection systems (TPS) and the military utility of these vehicles. Current programs include the Mini-Spaceplane Technology (MiST) program, Carbon-Carbon TPS coating repairs, high-temperature sandwich and blanket structures development, and demonstration of durable, flexible TPS.

No Figure Available.

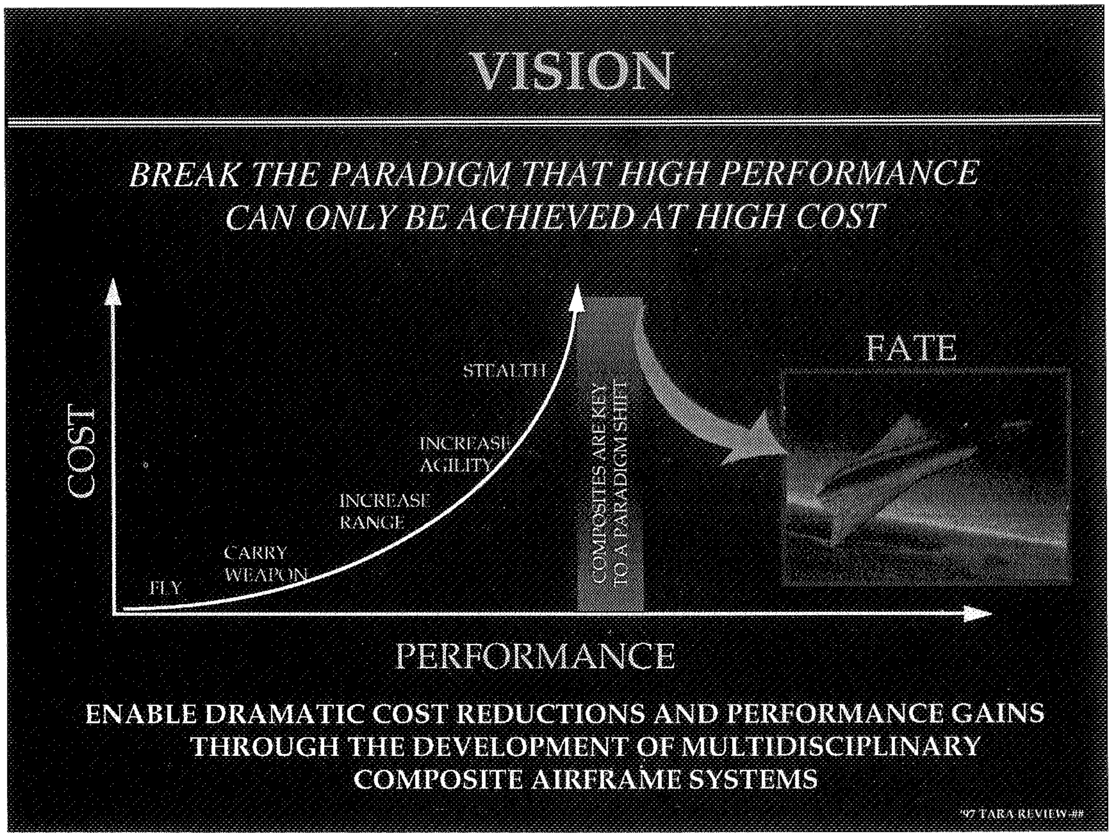
## STRUCTURAL TECHNOLOGY INTEGRATION (TI)

The TI core area focus and vision is to design, manufacture and operate aircraft with half the current required man-hour investment, a 25% reduction in structural weight fraction (maintaining constant TOGW), while simultaneously optimizing structures, controls, aerodynamics, and active aircraft deformation. The TI core research is divided into three sub-core competency areas: Active Aeroelastic Wing, Affordable Composite Structures, and Multidisciplinary Design and Analysis (MDDA) Methods.



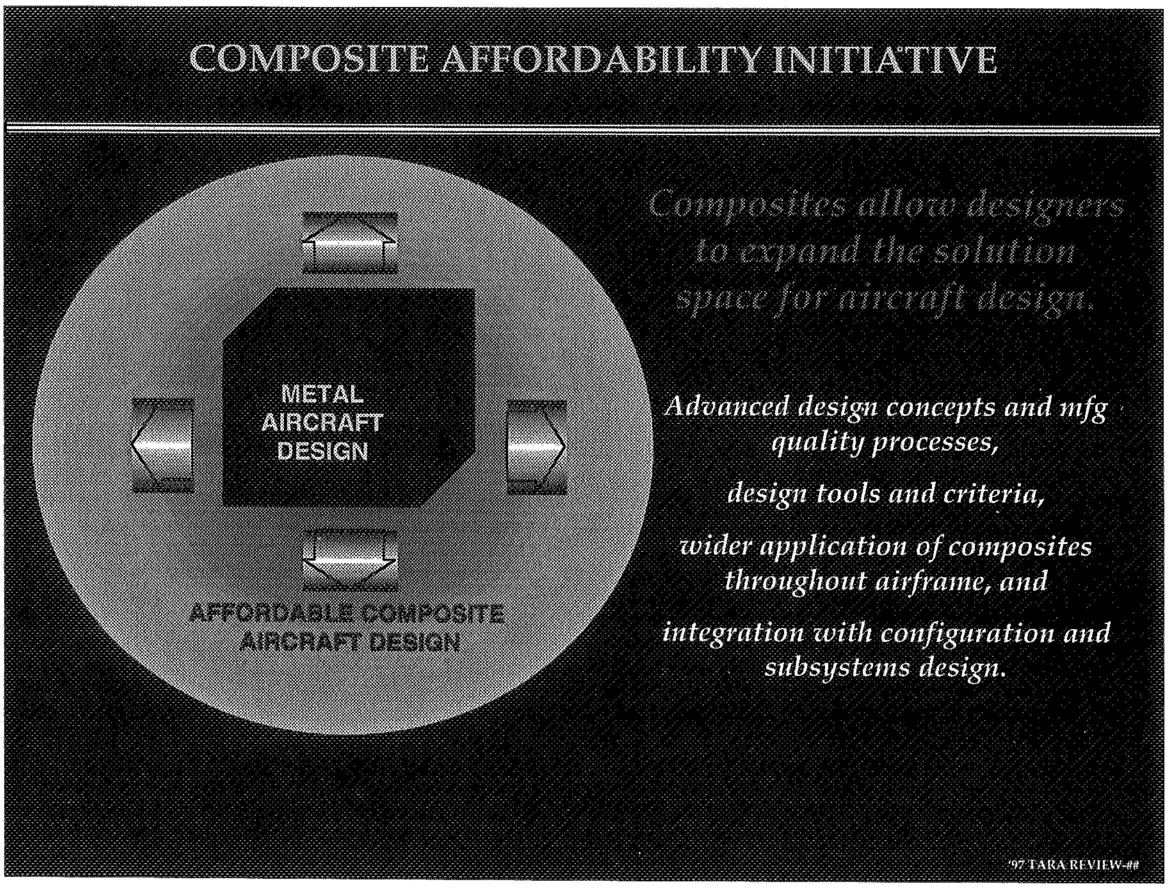
## AFFORDABLE COMPOSITES-VISION

High performance aircraft structures to meet future demands seem to be available only at very high cost. We must break the paradigm that high performance can only be achieved at high cost. Structures Division's goal is to enable dramatic cost reductions and performance gains through the development of multidisciplinary airframe systems.



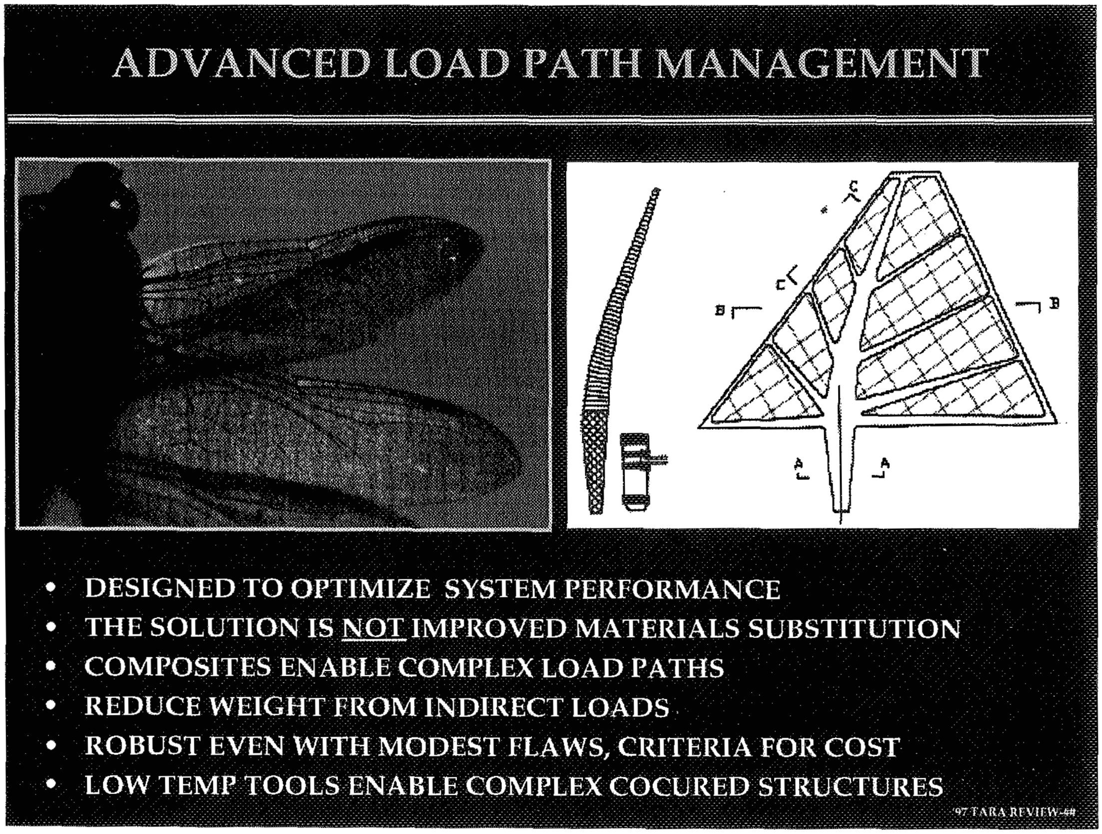
## COMPOSITES AFFORDABILITY INITIATIVE

Composite materials allow designers to expand the solution space for aircraft design. However, we must come "out of the box" of metal aircraft design. To do this, we must start thinking outside of the box. The keys to affordable composite solutions are: advanced design concepts and manufacturing quality processes; proper design tools and criteria; wider application of composites throughout airframe structures; and integration with configuration and subsystems designs.



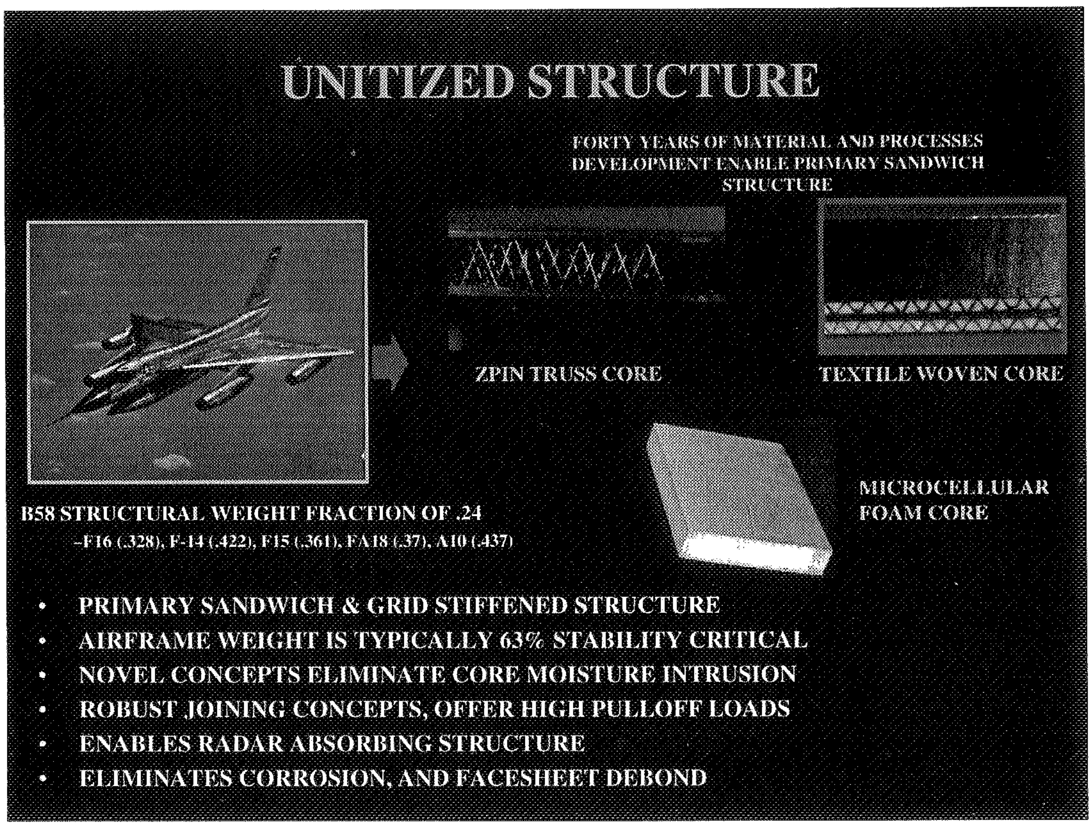
## ADVANCED LOADPATH MANAGEMENT

Composite materials enable optimal design of structures to support complex load paths. Currently, 30-40% of airframe weight is from indirect loads. Through advanced load path management, structures are designed to optimize system performance which cannot be done merely by improved materials substitution. These designs can be robust even when there are modest flaws, enabling lower-cost construction.



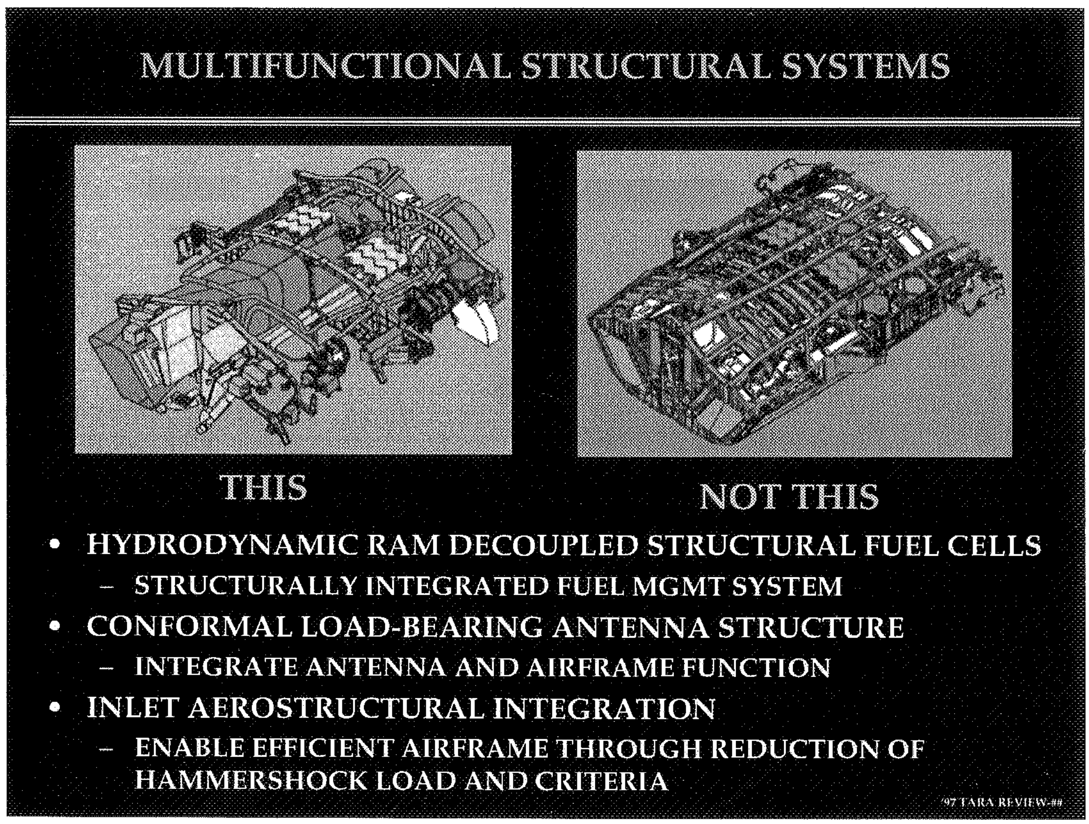
## UNITIZED STRUCTURES

Unitized structures offer the benefits of increased structural weight fraction, elimination of core moisture intrusion, higher pulloff loads, and radar absorbing structures.



## MULTIFUNCTIONAL STRUCTURAL SYSTEMS

It is intuitively obvious that multifunctional structural systems are desirable in order to reduce weight, complexity, etc. For example: hydrodynamic ram decoupled structural fuel cells integrate the fuel management system into the structural support system; conformal load-bearing antenna structures integrate antenna and airframe support functions; and, inlet aerostructural integration enables more efficient airframes through reduction of hammershock load and criteria.

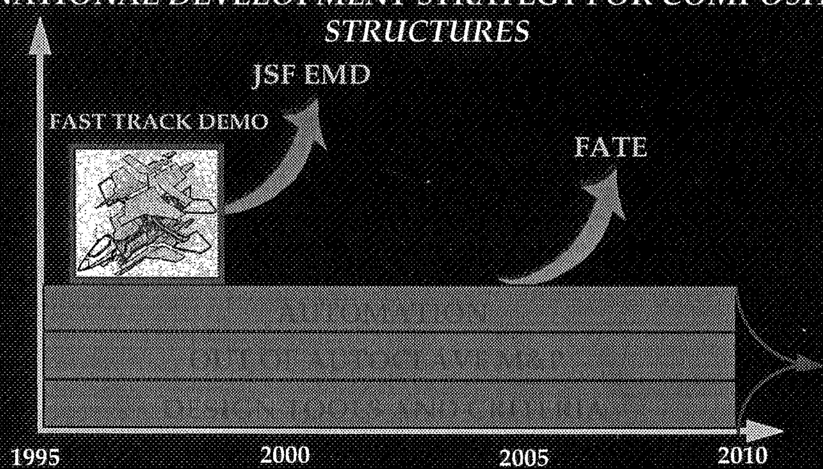


## COMPOSITE AFFORDABILITY INITIATIVE (CAI)

The CAI is a national development strategy for composite structures, which encompasses developing new design tools and criteria, making manufacture and production possible straight out of the autoclave, and automates processes. This technology will be used on the Joint Strike Fighter (JSF) Engineering Management and Development (EMD) as a fast-track demo and will be a major factor in fielding the FATE aircraft.

### COMPOSITE AFFORDABILITY INITIATIVE

*A NATIONAL DEVELOPMENT STRATEGY FOR COMPOSITE STRUCTURES*



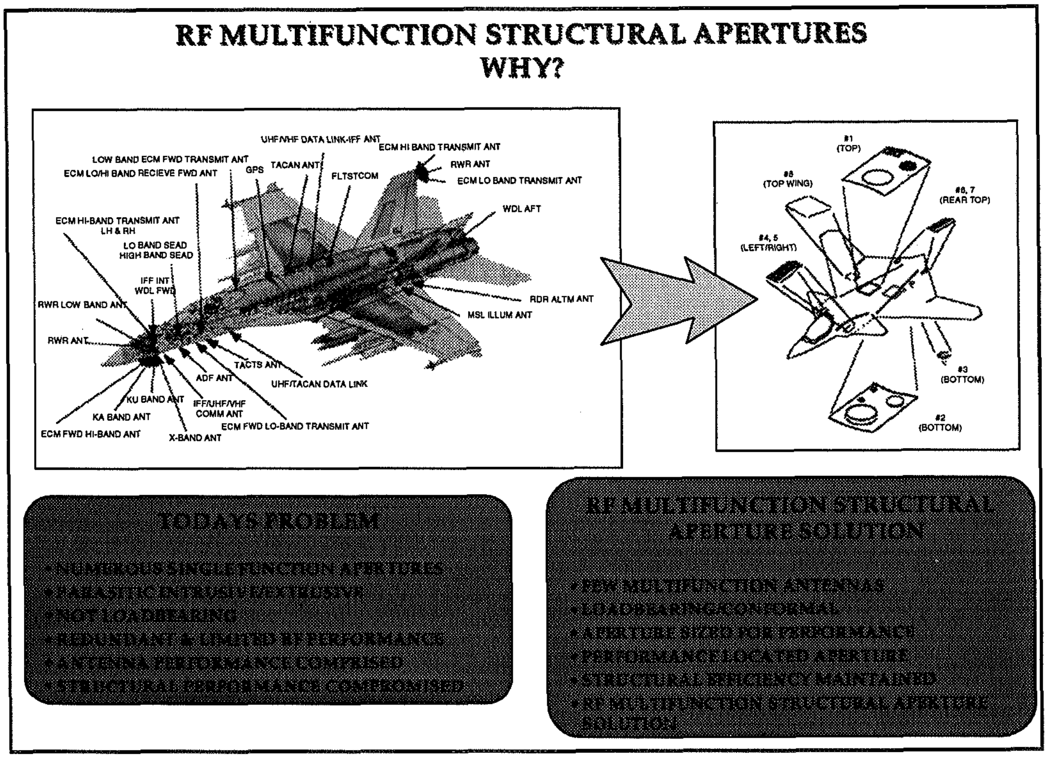

| | | FY97 | FY98 | FY99 | FY00 |
|---|---|---|---|---|---|
| Pervasive Technology | AF/Navy | 7.95 | 10.5 | 10.5 | 16.0 |
| | Industry | 7.95 | 10.5 | 10.5 | 16.0 |
| Tech Transition T1* | AF/Navy | 1.00 | 3.00 | 2.00 | 0.0 |
| Tech Transition T2* | AF/Navy | 1.00 | 3.00 | 2.00 | 0.0 |
| Demonstration | JSF PO | 2.0 | 9.3 | 4.5 | 0.0 |

* Industry resource cost share to be determined

'97 TARA REVIEW-##

## CONFORMAL LOAD BEARING ANTENNA STRUCTURE

This chart illustrates the differences between current airframe technology, in which there are numerous antennae which do not bear any load, and a Conformal Load-Bearing Antenna Structure (CLAS) in which the antennae serve both to transmit/receive/transport signals and to carry flight loads. Not only does CLAS force the antennae to become dual-purpose, but it also greatly reduces the aircraft complexity.



# STRUCTURES SUMMARY

- Structures Technology Focused to Support Broad DoD/USAF/FI Goals
  - FWV - TDA
  - New World Vistas
  - FATE & TAFT
  - 4 Technology Core Areas: Structural Technology Integration, Smart Structures, Extreme Environment Structures, and Structural Integrity of Aging Aircraft

'96 SAB REVIEW.2-##

# Structures TC Goals/Responsibility/Opportunity and AFOSR

Jim C. I. Chang
Air Force Office of Scientific Research
Washington, D.C.

## Structures TC Goals/ Responsibility/Opportunity and AFOSR

**AIAA Structures Committee Meeting**

**6 April 1997**
**Orlando, FL**

**Briefed by:** Dr Jim C. I. Chang, Director

Aerospace and Materials Sciences Directorate

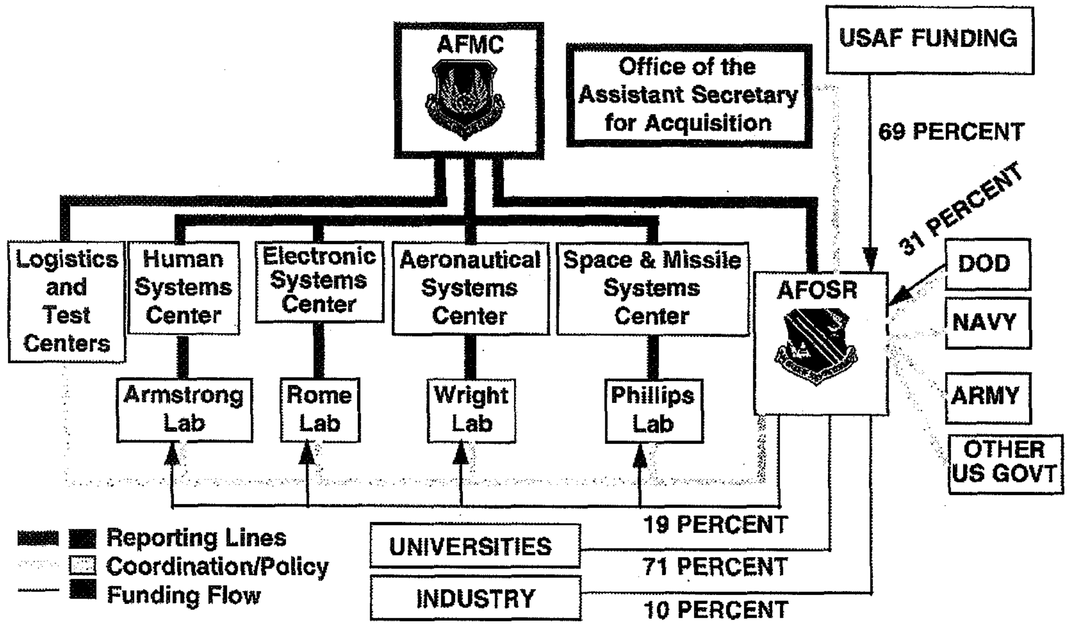
AFOSR/NA

110 Duncan Avenue, Suite B-115

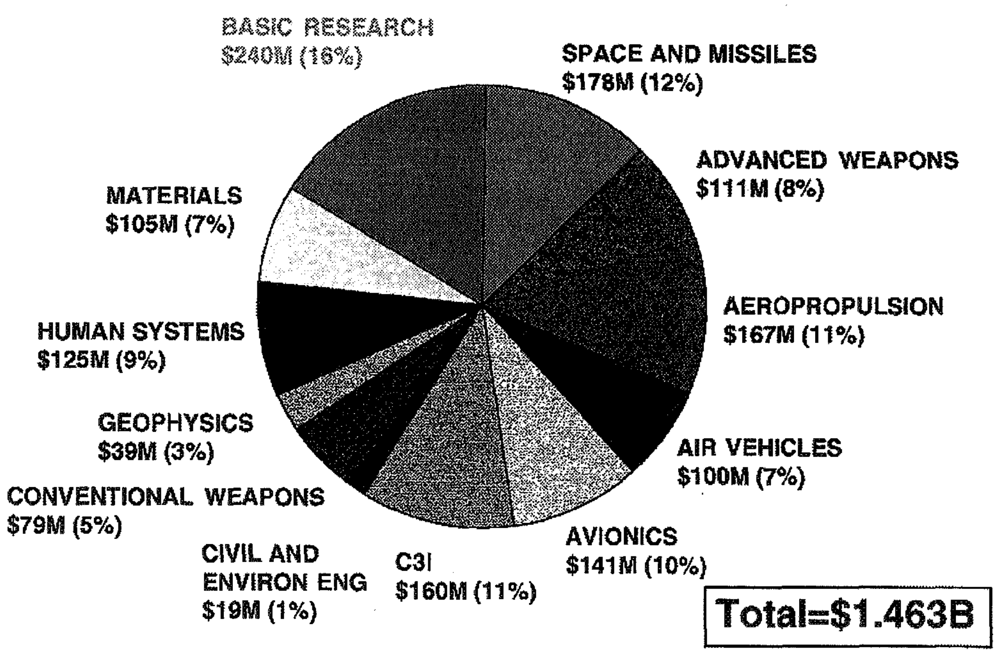
Bolling AFB DC 20332-0001

(202) 767-4987

# USAF S&T ORGANIZATIONAL STRUCTURE



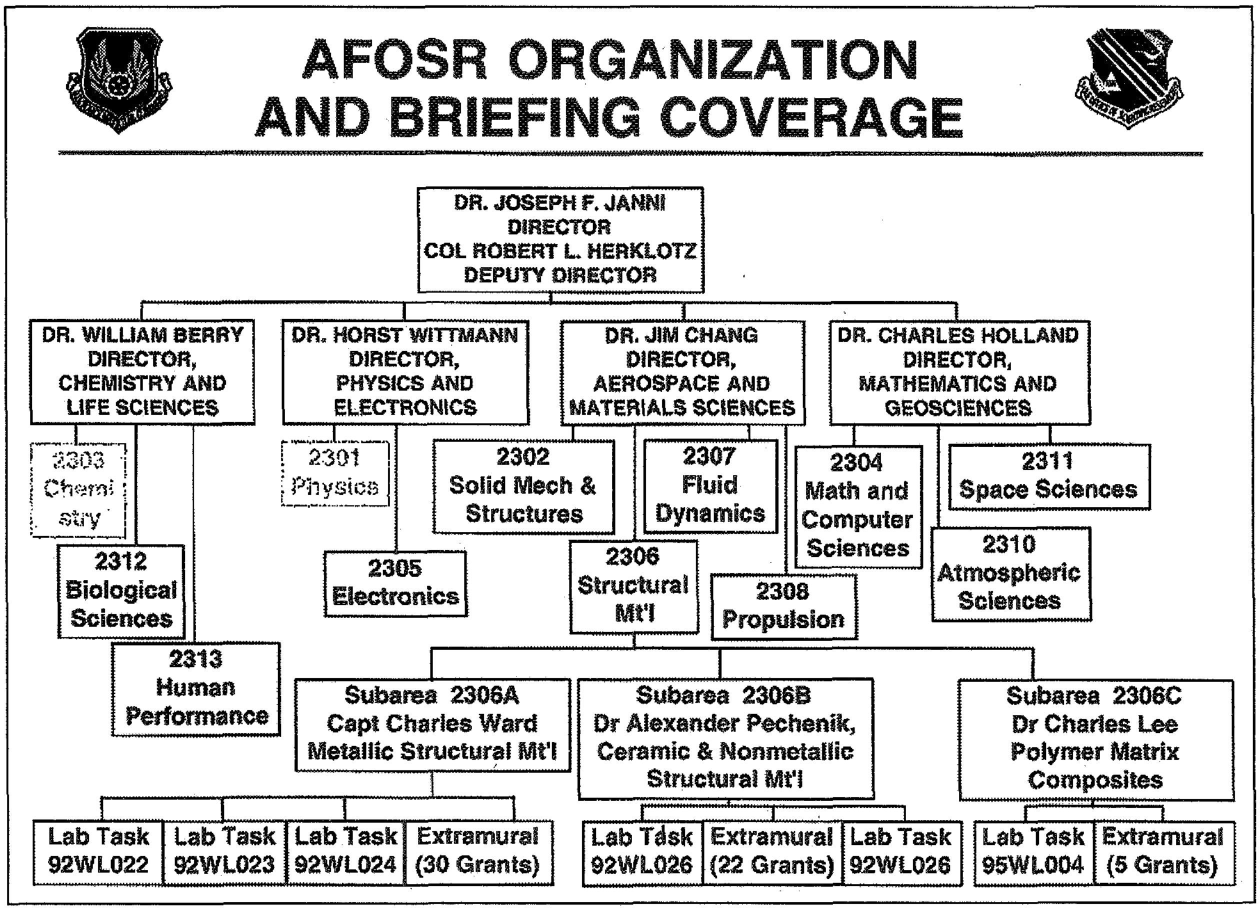

# FY 96 AF S&T INVESTMENT BY TECHNOLOGY AREA



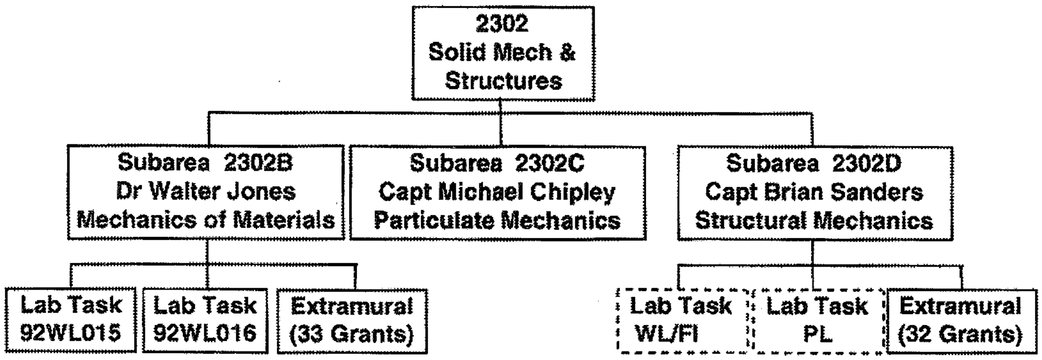
## AEROSPACE AND MATERIALS SCIENCES DIRECTORATE

## MISSION OBJECTIVE

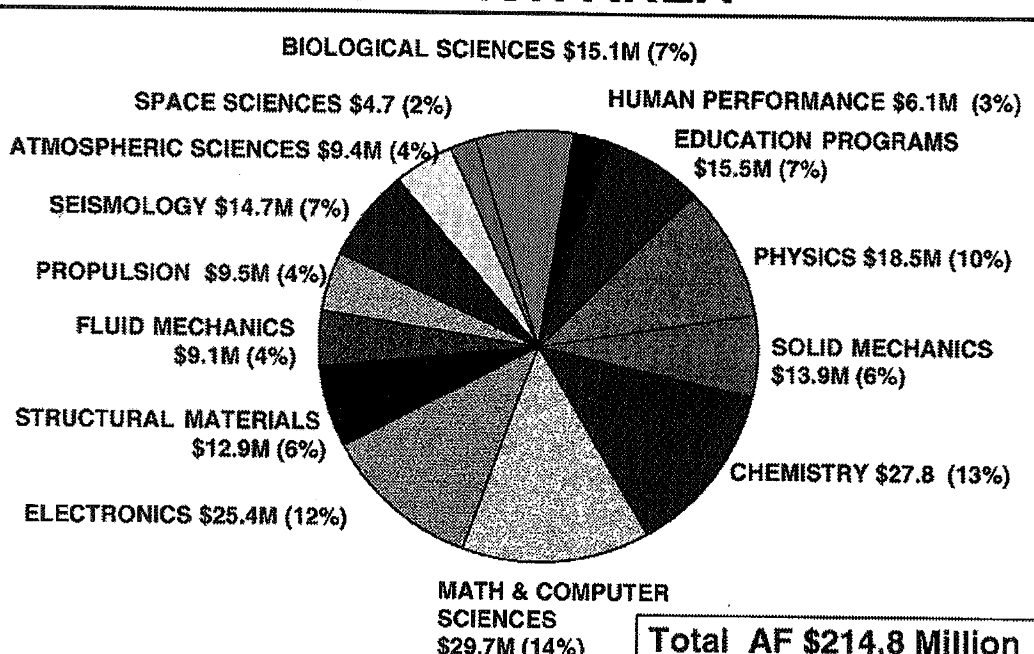
- Manage the Air Force's basic research in Aerospace, Engineering, and Materials Sciences
- Provide leadership and resources to Air Force laboratories, industrial research institutions and universities in conducting Air Force-relevant research, and carrying out multi-discipline cross-directorate science and engineering integration efforts in developing technologies for the design and operation of the current and future Air Force aircraft, tactical and ballistic missiles, space platforms and systems, and field facilities.
- Function as a technology broker to facilitate transitioning between the producers--universities, Air Force laboratories and industry--and the users--Air Force engineering, test and evaluation, logistics organizations and major commands.



# AEROSPACE AND MATERIALS SCIENCES
# JIM CHANG




# FY 96 AF 6.1 INVESTMENT BY RESEARCH AREA




Total AF $214.8 Million

**Table 4.7.2. Service Specific Interests and Commonality in Mechanics**

| Subarea | Army | Navy | Air Force |
|---|---|---|---|
| **SOLID AND STRUCTURAL MECHANICS**<br>Structural dynamics | Finite deformation, impact, and penetration | Structural acoustics<br>Thick composites<br>Micromechanics of electronic devices and solids | Hypersonic aeroelasticity<br>Mechanics of high temperature materials<br>Particulate mechanics |
| Composites<br>Aeroelasticity<br>Acoustics | **Areas of Common Interest**<br>Structural dynamics and control (A, N, AF) | Damage and failure mechanics/QNDE (A, N, AF) | "Smart" structures (A,N,AF) |
| **FLUID DYNAMICS**<br>Aerodynamics<br>Turbulence<br>Unsteady flow | Rotorcraft aerodynamics<br>Rotorcraft aeropropulsion<br>Projectile aeroballistics | Free-surface phenomena<br>Hydrodynamic wakes<br>Hydroelasticity and hydroacoustics | Turbomachinery aerothermodynamics<br>Fixed wing aerodynamics<br>Hypersonic aerothermodynamics |
| | **Areas of Common Interest**<br>Unsteady separated flow (A,N,AF) | | Turbulence (N, AF) |
| **PROPULSION AND ENERGY CONVERSION**<br>Gas turbines | Reciprocating engines<br>Gun propulsion<br>Small gas turbines | Underwater propulsion<br>Missile propulsion<br>Explosives | Large gas turbines<br>Supersonic combustion<br>Spacecraft and orbit propulsion |
| Explosives,<br>Soot formation | **Areas of Common Interest**<br>High-energy materials combustion/hazards (A,N) | Soot formation (A, N, AF)<br>Turbulent flows(A,N,AF) | Spray combustion (A, AF) |

**Table 4.6.2. Service Specific Interests and Commonality in Materials Science**

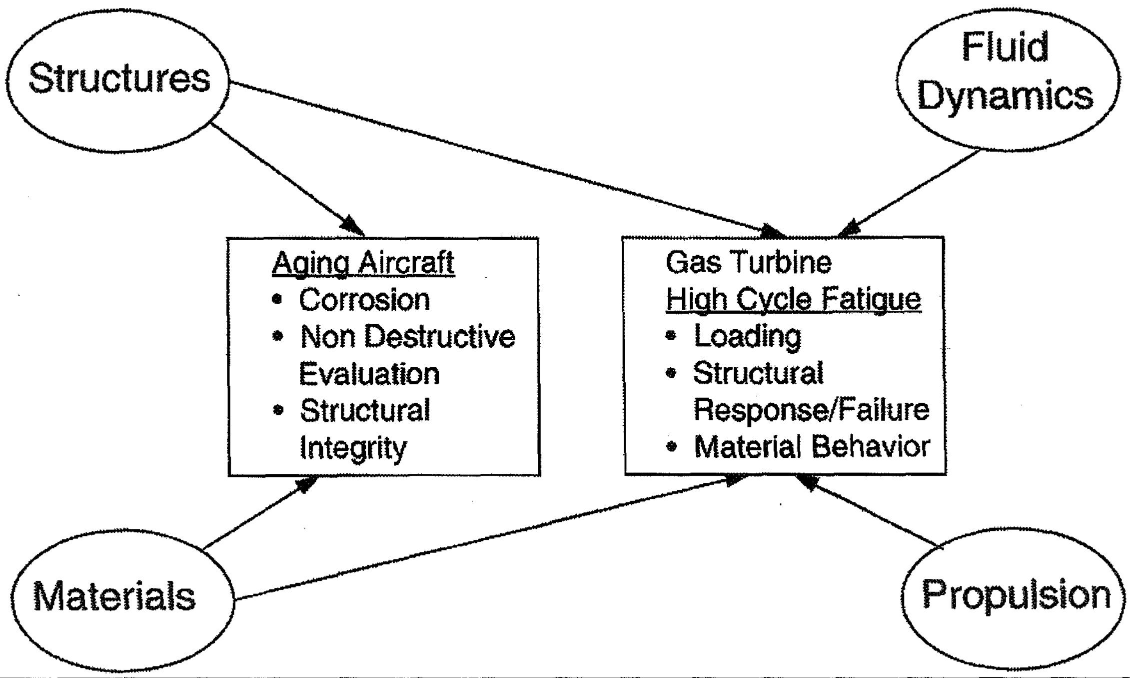
| SUBAREA | Army | Navy | Air Force |
|---|---|---|---|
| **STRUCTURAL MATERIALS**<br>Synthesis<br>Processing<br>Theory<br>Properties<br>Characterization<br>Modeling | Manufacturing science (land/rotocraft systems, armaments)<br>Armor/anti-armor materials<br>Diesel engine materials<br>Gun liner materials | Marine corrosion, oxidation, and fatigue<br>Advanced materials for ships and submarines<br>Acoustically damped structures<br>Layered designed materials | High-temperature fatigue and fracture<br>Aerospace skin materials<br>Aging aircraft<br>Functionally graded materials<br>Hypersonic skin<br>Balanced material properties |
| | **Areas of Common Interest**<br>Advanced composites (A, N, AF)<br>Adhesion /Joining (A, N) | Tribology (A, N, AF)<br>Ceramics (A, N, AF) | Intermetallics (N, AF) |
| **FUNCTIONAL MATERIALS**<br>Synthesis<br>Processing<br>Theory<br>Properties<br>Characterization<br>Modeling | Defect engineering<br>Gradient index optics<br>IR detectors<br>CBD materials<br>Smart materials | Ferrite films<br>Ferroelectrics<br>Diamond<br>Acoustics/active materials<br>Electronic packaging materials<br>Superconductivity | (Topics addressed under chemistry, electronics, physics, and mechanics SPGs) |
| | **Areas of Common Interest**<br>Optoelectronics (A, N) | | Magnetic materials (A, N) |

## AFOSR MATERIALS/STRUCTURES PROGRAM

- Innovative and Responsive to Air Force Need
  - Science Based Frontier Research to Provide Options for Future Air Force
  - Well Integrated With 6.2/6.3 And Industrial Effort to Address Air Force Technology Issues i.e. Aging Aircraft, HCF, and etc...
- Well Managed Process
  - Select Thrusts/Topics
  - Choose and Motivate Performers
  - Program Initiation and Exit Dynamics

## Air Force Basic Research Aerospace and Materials Sciences

SELECTED CURRENT RESEARCH THRUSTS



## Integrated AF S&T Technology Objectives (Selected Examples)

- AF High Cycle Fatigue (HCF) Steering Committee
  - AFOSR/NA, WL/CV, WL/PO, SA-ALC/LR, ASC/LP
  - Manage AF HCF IPT
  - Focus Area - $100M/5 years (6.1-6.3)
- AF Aging Aircraft Steering Group
  - AFOSR/NA, WL/CD, AFMC/EN, ALC
  - Manage AF Aging Aircraft IPT
  - Focus Area - $250M/5 years (6.1-6.3)
  - Working on 6.4 funds

**TOTALLY INTEGRATED PROGRAM**

## *Turbomachinary Component Design Tools Are Inadequate*

- Validity of Goodman Diagram (1899)
- Does not account for HCF/LCF interactions or damage (i.e., FOD)
- Safety Margin loss from higher performance engines
- Large variability in predicting vibratory stresses
- HCF Failure on high performance engines

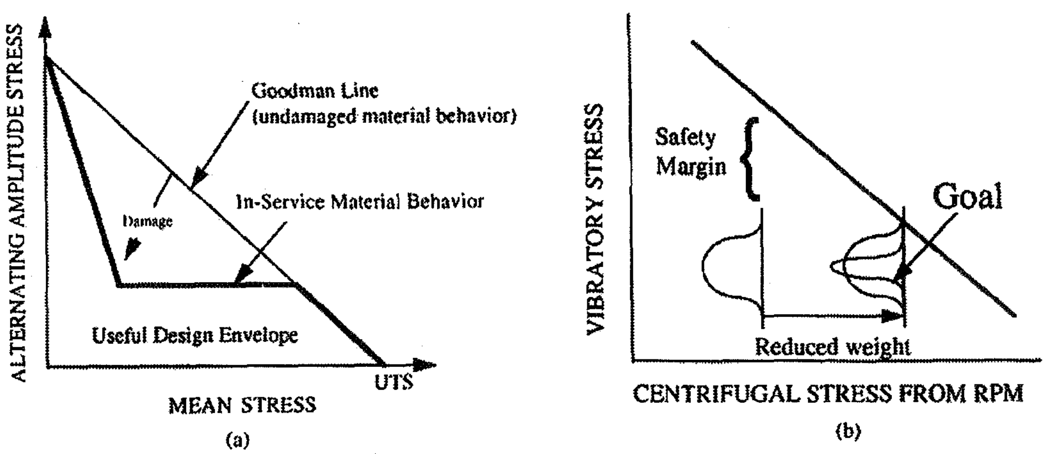



Fig. 3

## ISSUES IN AERODYNAMICS, STRUCTURAL DYNAMICS, AND CONTROL

*Conclusions of Workshop, 10-11 Oct 95, MIT*

Participation from:

- Industry: Allison, Allied Signal, General Electric, Pratt & Whitney
- Universities: CMU, Duke, GIT, NPS, MIT, OSU, Purdue, UC-Davis
- Government: ASC/LP, NASA, WL/ML, WL/PO

*Basic Research Focus Areas:*

- Unsteady aerodynamic forcing functions and multistage effects
- Low order and overall system models
- Characterization and prediction of damping
- Active and passive control of HCF
- Real time sensing instrumentation and experimental techniques

## ISSUES IN MATERIALS AND MECHANICS

***Conclusions of Workshop, 7 Jun 95, WPAFB***

**Participation from:**

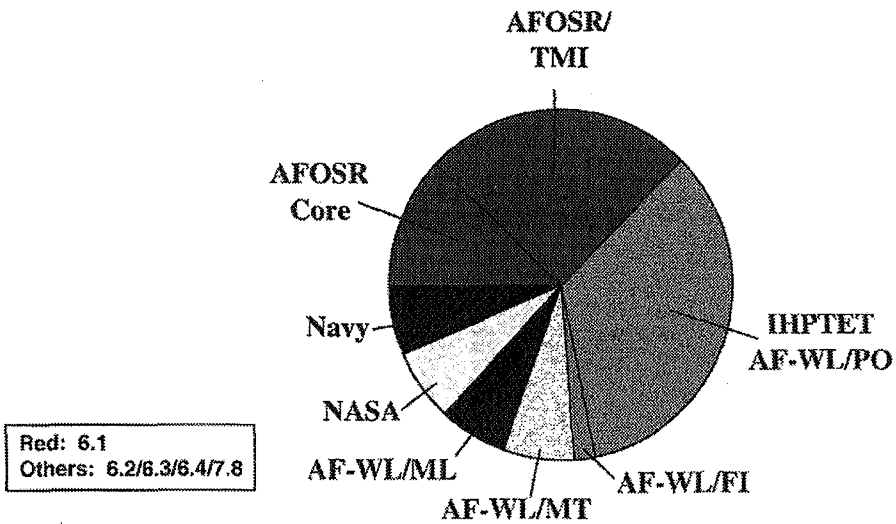
- **Industry: Allied Signal, General Electric, Pratt & Whitney, SWRI**
- **Universities: CalTech, GIT, U. Ill., UVa, Purdue, UCLA, U. Mich.**
- **Government: ASC/LP, NASA, WL/ML, WL/PO**

***Basic Research Focus Areas:***

- **Initiation and Propagation of Small Fatigue Cracks**
- **Cumulative Damage, Variable Amplitude Loading and HCF/LCF Interaction**
- **Mechanics of Fretting and Surface Wear Mechanisms on HCF**
- **Modeling Effects of Surface Treatment and Foreign Object Impact on HCF**
- **Distribution Effects and Stochastic/Probabilistic Aspects of HCF**
- **Novel Experimental and Small Crack Detection/Monitoring Techniques**

# HIGH CYCLE FATIGUE (HCF) S&T PROGRAM

Contributors to Program Funding




AFOSR IS THE MAJOR CONTRIBUTOR

---

## AEROSPACE AND MATERIALS SCIENCES DIRECTORATE

<u>INTEGRATED-PROACTING MATERIALS RESEARCH</u>

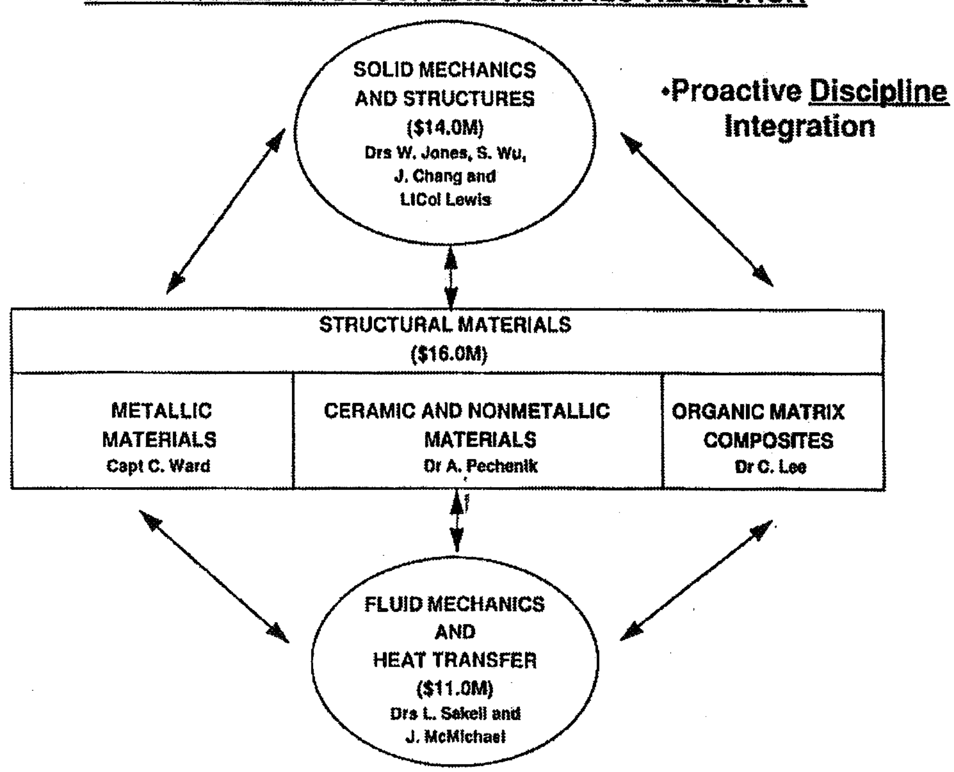
| | |
|---|---|
| <u>IS</u> | TO DESIGN MATERIALS FOR A PURPOSE |
| | TO PREDICT MATERIALS PERFORMANCE |
| <u>IS NOT</u> | TO MAKE THE <u>BEST</u> MATERIALS POSSIBLE |
| | TO CHARACTERIZE <u>AS IS</u> MATERIALS |

## AFOSR MATERIALS/STRUCTURES RESEARCH

| $10^{-10}$ | $10^{-9}$ | $10^{-6}$ | $10^{0}$ |
|---|---|---|---|
| Physics/Chemistry (2301/2303) | Material Science (2306) | Solid Mechanics (2302) | Structures (2302) |

- Full Spectrum/Fully Integrated: Atomic to Micro to Macro to Structural Systems
- Fundamental Understanding/Technology Objectives - Near Term
  - Aero Propulsion & Power (WL)
  - Air Vehicle (WL)
  - Materials and Processing (WL)
  - Conventional Armament (WL)
  - Space and Missile (PL)
- Innovation - Future

## AEROSPACE AND MATERIALSCIENCES DIRECTORATE
## INTEGRATED-PROACTIVE MATERIALS RESEARCH

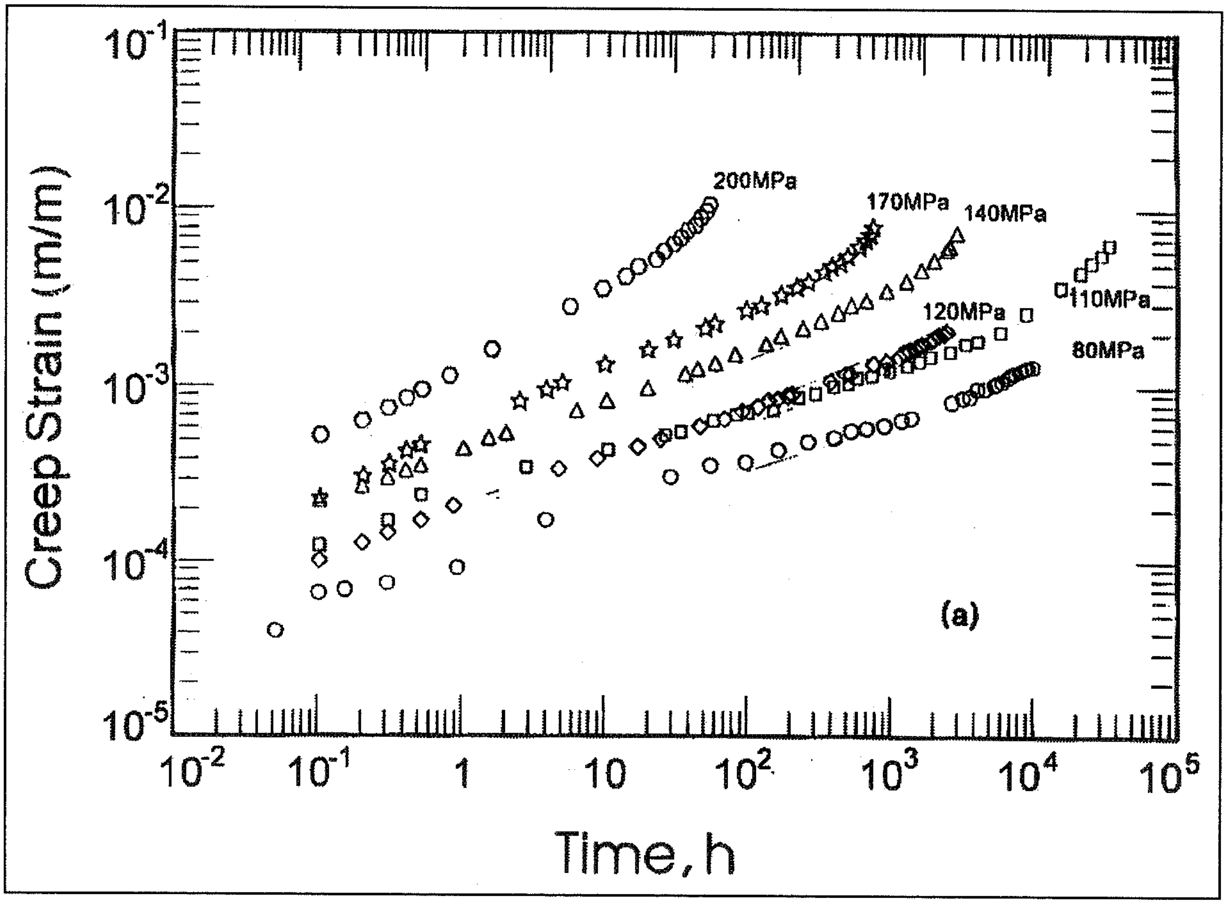


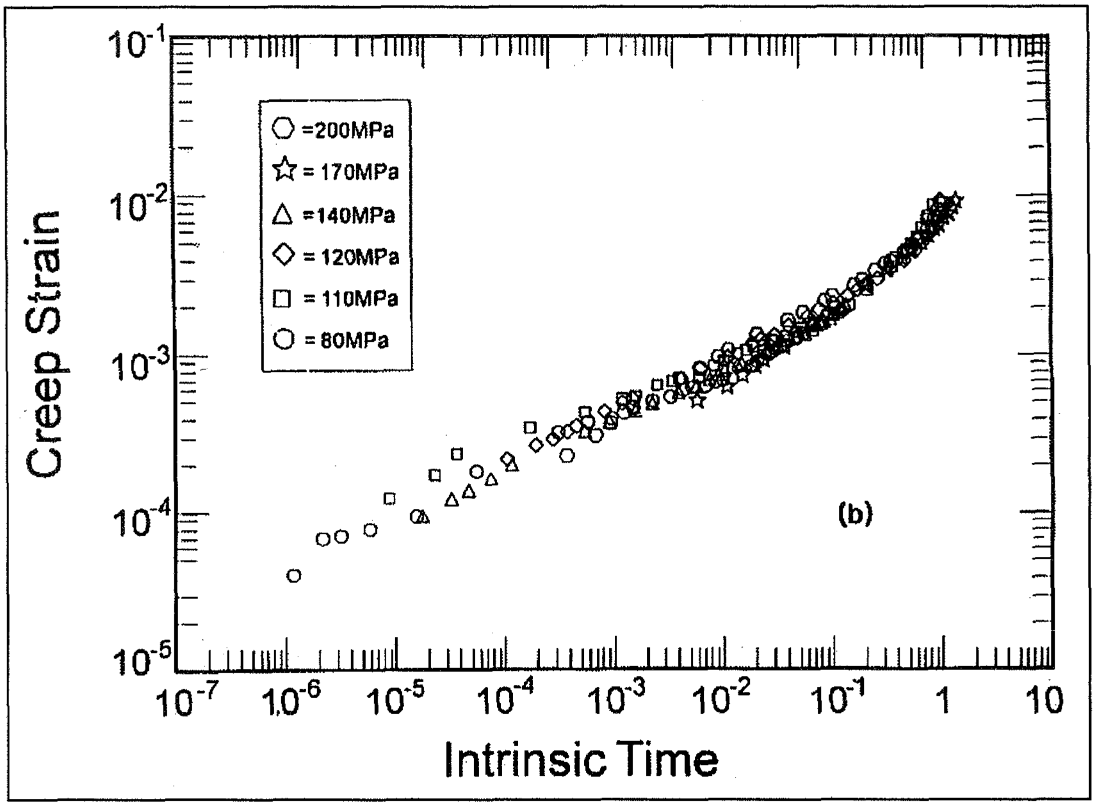
<u>**RENEWAL CREEP THEORY**</u>

- **The theory is based on approximations of dislocation (crystal imperfection) kinetics**
- **The theory reveals that stress and temperature regulate the "effective" passage of time as the material deforms**

$$\dot{\varepsilon}_c = N_1 (1-e^{-\upsilon t})^{\beta} + N_2 \upsilon t \qquad \upsilon(\sigma) = \text{Time Scale Factor}$$

- **The "effective" time is expressed mathematically as an "internal" or "intrinsic" time that describes how quickly load and temperature produce deformation on the master curve**






## Partnership for Research Excellence and Transition (PRET)

***Cooperative program between academia and industry***

- Targets TiAl as an emerging material, nearing application
- Addresses industry-defined technological barriers to application
- Spans materials processing to mechanical design methodology
- Students/faculty spend 2-3 months at industry each year

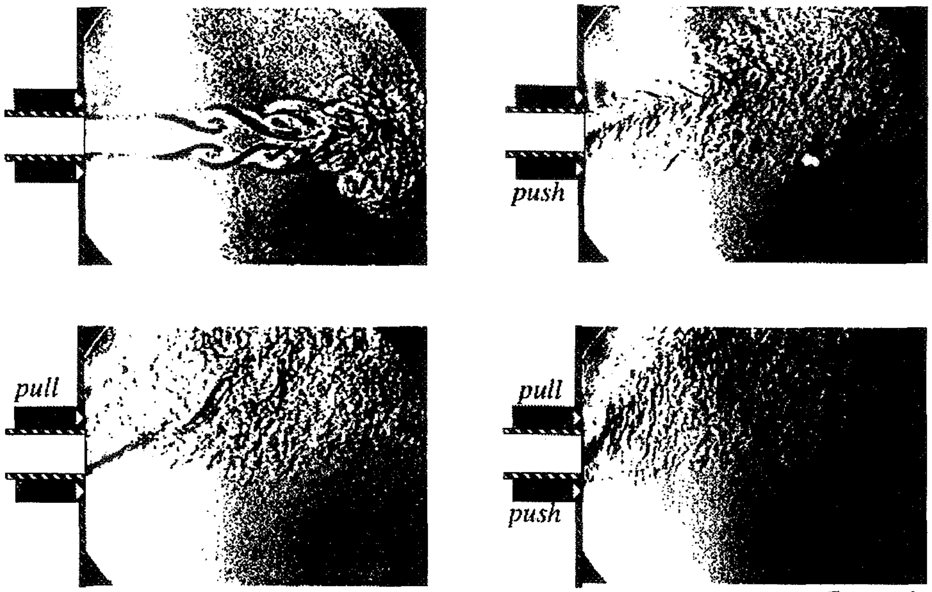
***Awarded to Carnegie Mellon University (1 May 1995)***

- Materials Sci. and Eng. and Mechanical Eng. Departments
- University of Michigan
- Ohio State University
- Michigan State University

***Industrial Partners:***

- General Electric Aircraft Engines
- Allison Engine Company
- Howmet Corporation
- Rockwell International Corporation
- Precision Castparts Corporation

## *push/pull* Vectoring




Georgia Tech

### Air Force Office of Scientific Research
### Aerospace and Materials Sciences Directorate
### Dr Jim C. I. Chang (202/767-4987)

| Project | Subarea | Program Manager |
|---|---|---|
| 2302<br>Solid Mechanics<br>and Structures | B Mechanics of Materials<br>C Particulate Mechanics<br>D Structural Mechanics | Dr W. Jones (70470)<br>Capt M. Chipley (70468)<br>Capt B. Sanders (76963)<br>Dr S. Wu (74989) |
| 2306<br>Structural<br>Materials | A Metallic Structural Materials<br>B Ceramic and Nonmetallic Structural Materials<br>C Polymeric Composites | Capt C. Ward (74960)<br>Dr A. Pechenik (74962)<br>Dr C. Lee (75022)* |
| 2307<br>Fluid<br>Mechanics | A External Aerodynamics and Hypersonics<br>B Turbulence and Internal Flows | Dr L. Sakell (74935)<br>Dr J. McMichael (74936) |
| 2308<br>Propulsion | A Space Power and Propulsion<br>B Air-Breathing Propulsion<br>C Propulsion Diagnostics | Dr M. Birkan (74938)<br>Dr J. Tishkoff (70465)<br>Dr J. Tishkoff (70465) |

*NL

## NWV Areas and Subareas

Global Awareness
- Network Data Fusion for GA
- Light Weight Antenna Structures
- Low Cost, LtWt Membrane Structures
- In situ Sensors
- Global Awareness Virtual Testbed
- Low Noise/Hi Unif Broadband Sensors

Power Projection
- Family of UAV
- Hypersonics
- Lethal/Sublethal DEW
- Energy Coupling Modeling & Simulation

People
- Human Machine Interface
- Team Decision Making
- Cognitive Engineering

Space
- Micro Satellites
- Distributed Functionality
- Precision Deployable Lrg Ant/Optics
- High Efficiency Electrical Laser Sources
- Space Object ID and Orbit Prediction
- High Energy Density Propellants
- Jam-Proof Area-Deniable Propagation
- Nanosecond Global Clock Accuracy
- Hypervelocity Dynamics
- Low Cost LtWt Structures & Materials
- Power Generation and Storage

Dynamic Planning
- Planning & Scheduling
- Communications
- Knowledge Bases
- Intel Agents for AF Btlfld & Ent Info Assts
- Information Warfare
- New Models of Computation
- Domain Spec Component-Based S/W

Mobility
- Precision Air Delivery
- Composite Materials and Structures
- Low SFC Propulsion
- Aerodynamics and Controls
- Subsystem Integ/Pwr
- Advanced Landing Gear
- MicroElectromechanical Sys (MEMS)
- Active Defense Systems
- Battlefield Awareness/Wx Predictions
- Human Sys Interface/Tng

## Structures TC General Goals/Responsibility

- Conferences - AIAA
- Educational - Outreach
- Advocacy
  - Inside the Community - Preaching to the Choir
  - Outside the Community - Program Support, (congressional, government, industry, etc.)
- Jointness
  - Structure TC
  - other AIAA Committees
  - Other Professional Committees - ASME etc.

## Structures TC General Goals/Responsibility

- Technology Advancement/Opportunities/Expectations
  - Near Term - Smartness
  - Far Term - Multifunctional
- Existing Committee Structures
- Jointness
- AFOSR Programs/Directions

## Recommendations

- Establish special subcommittee/task group/blue-ribbon panel to:
  - Identify structures and structure related technology advancement/opportunities/expectations
  - Look at existing structures TC committees - technologies
  - Look at other AIAA committees & other society structures and structures related activities
  - Produce assessment and recommendations
  - Report back to structures TC for deliberation
- Structural TC follow-up actions (?)

# Structural Mechanics

Brian P. Sanders
Air Force Office of Scientific Research
Washington, D.C.

# AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

## STRUCTURAL MECHANICS

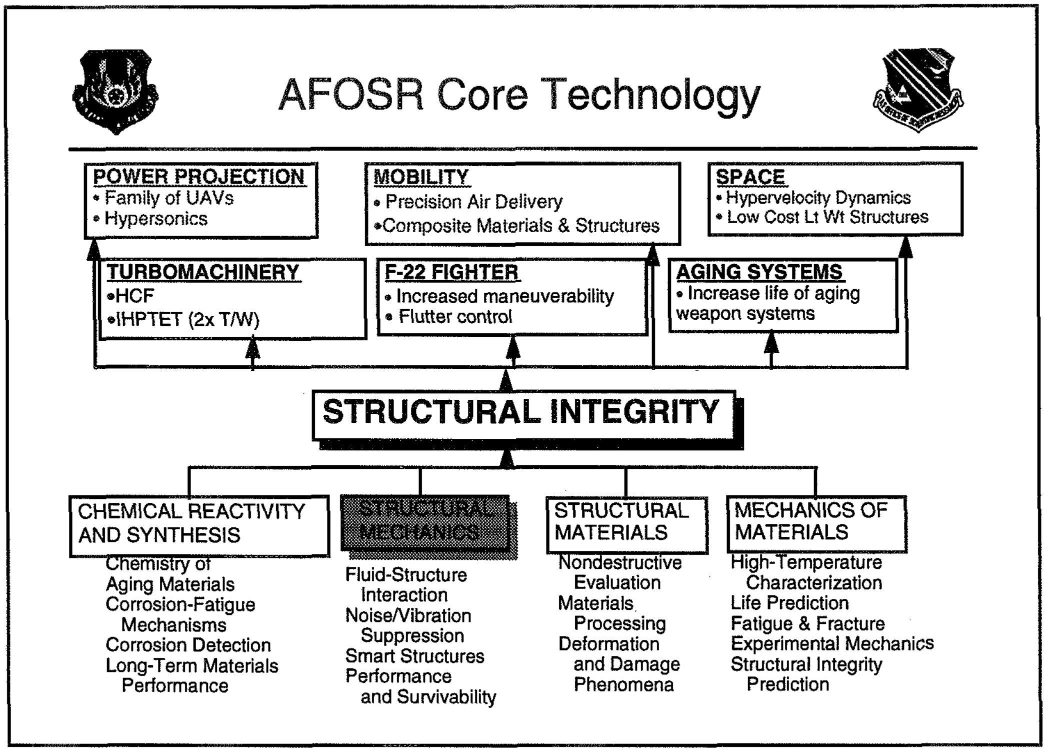
PRESENTED TO
AIAA STRUCTURES TECHNICAL COMMITTEE
AT THE WORKSHOP
ON
GOVERNMENT PROGRAMS IN STRUCTURES

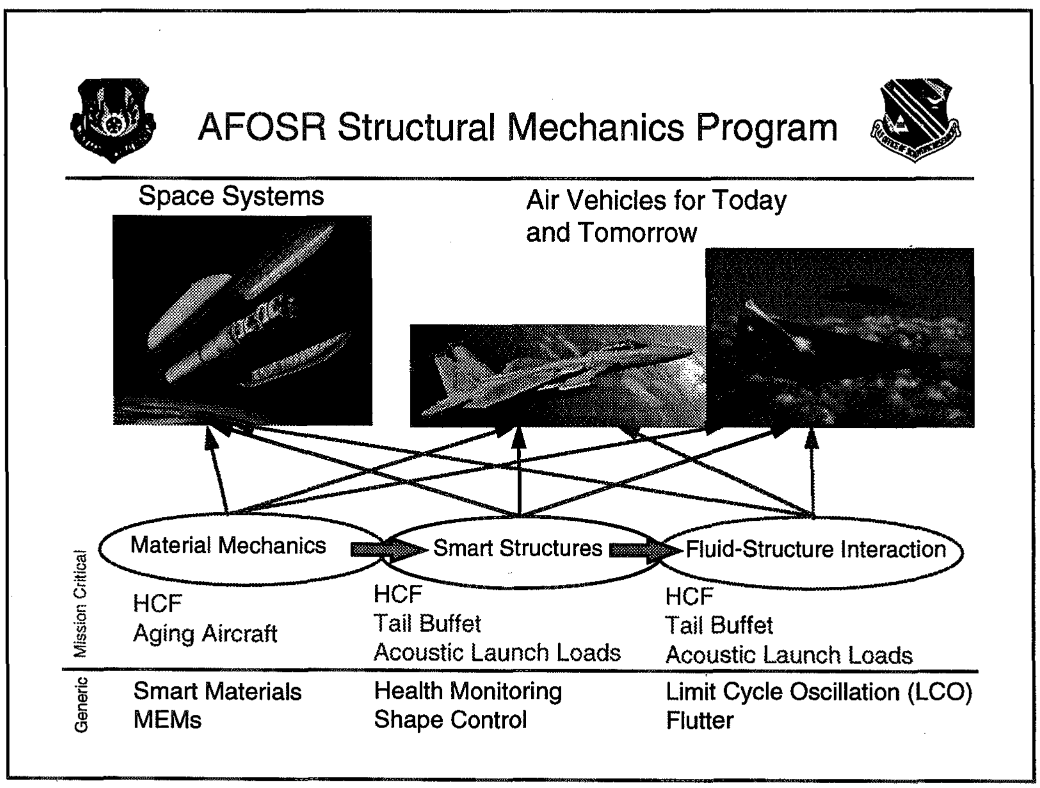
BRIEFER
PROGRAM MANAGER
CAPT. BRIAN P. SANDERS, Ph.D.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NA
6 April 1997

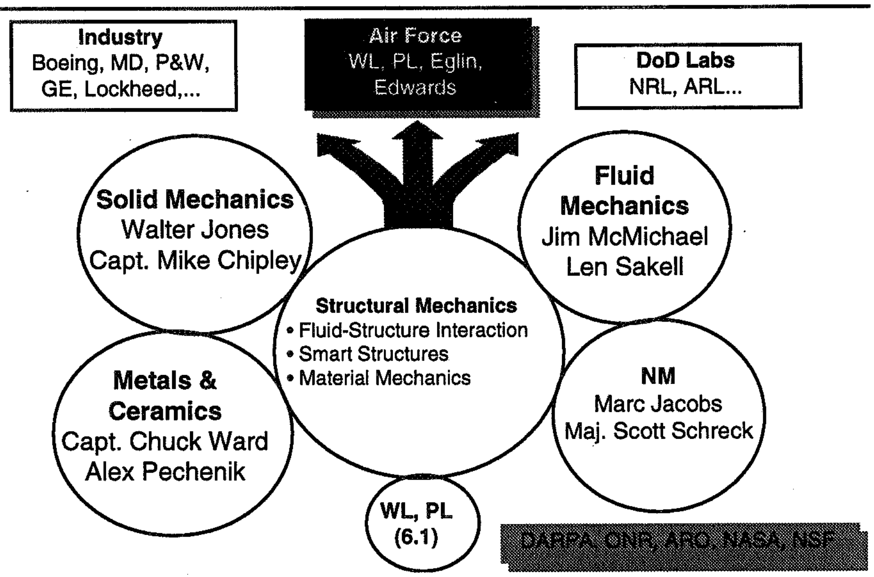
## Outline

- Programmatic Issues
- Subarea Review
- UAV Program
- Summary and Future Plans

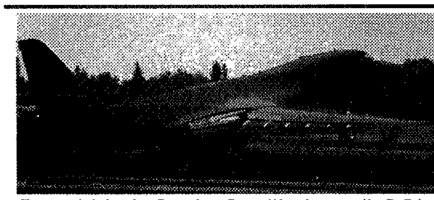

AFOSR Core Technology
POWER PROJECTION
• Family of UAVs
• Hypersonics
MOBILITY
• Precision Air Delivery
•Composite Materials & Structures
SPACE
• Hypervelocity Dynamics
• Low Cost Lt Wt Structures
TURBOMACHINERY
•HCF
•IHPTET (2x T/W)
F-22 FIGHTER
• Increased maneuverability
• Flutter control
AGING SYSTEMS
• Increase life of aging weapon systems
STRUCTURAL INTEGRITY
CHEMICAL REACTIVITY AND SYNTHESIS
Chemistry of Aging Materials
Corrosion-Fatigue Mechanisms
Corrosion Detection
Long-Term Materials Performance
STRUCTURAL MECHANICS
Fluid-Structure Interaction
Noise/Vibration Suppression
Smart Structures
Performance and Survivability
STRUCTURAL MATERIALS
Nondestructive Evaluation
Materials Processing
Deformation and Damage Phenomena
MECHANICS OF MATERIALS
High-Temperature Characterization
Life Prediction
Fatigue & Fracture
Experimental Mechanics
Structural Integrity Prediction


AFOSR Structural Mechanics Program
Space Systems
Air Vehicles for Today and Tomorrow
Material Mechanics
Smart Structures
Fluid-Structure Interaction
Mission Critical
HCF
Aging Aircraft
HCF
Tail Buffet
Acoustic Launch Loads
HCF
Tail Buffet
Acoustic Launch Loads
Generic
Smart Materials
MEMs
Health Monitoring
Shape Control
Limit Cycle Oscillation (LCO)
Flutter

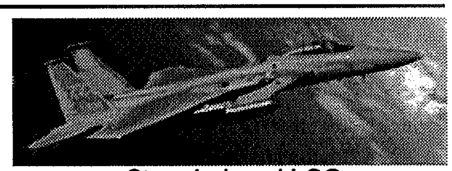
## Program Synergism




## USAF Issues Driven by Fluid-Structure Interaction

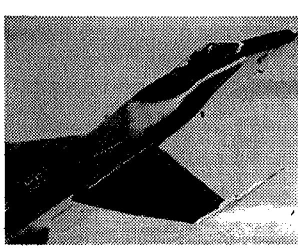


Panel Limit Cycle Oscillations (LCO)



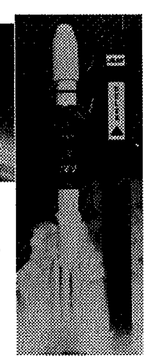
Store Induced LCO

UAV's



Tail Buffet

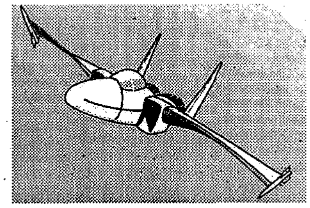
Vibroacoustic issues related to space bound payloads



## Fluid-Structure Interaction

**Technology Opportunity/Payoff**

- Major improvements in airframe and turbomachinery performance
- Substantial risk and cost reduction in design



**Research Barriers**

- Insufficient understanding of the nonlinear
  - aero-structural interaction
  - structural-acoustic interaction

**Research Objectives**

- Improve understanding of physical mechanisms driving instabilities & oscillations
- Investigate aeroelastic behavior of passive & actively controlled flexible structures
  - Control or remove instabilities & oscillations
- Investigate sensitivity of aeroelastic instabilities

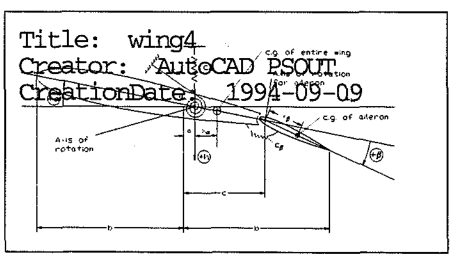
## Nonlinear Dynamics and Control of Wings and Panels (Clark, Dowell & Virgin/Duke)

Objective

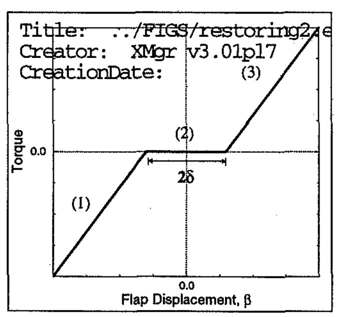
Investigate nonlinear effects on control of aeroelastic systems

Basis Research Issue

Are nonlinear effects on the aeroelastic response significant (yes)

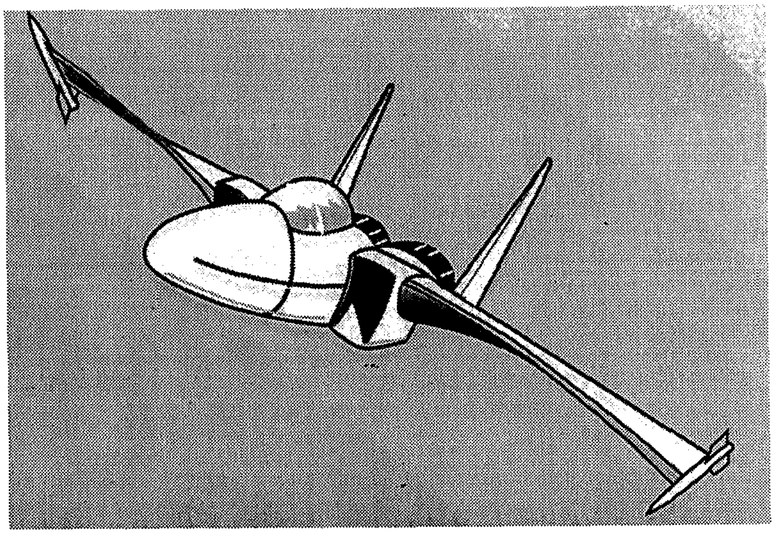



Typical aeroelastic section with control surface




Control surface restoring moment with free play

# Deformation Control for Enhancing Vehicle Performance (Eastep, UD & Khot, WL/FI)



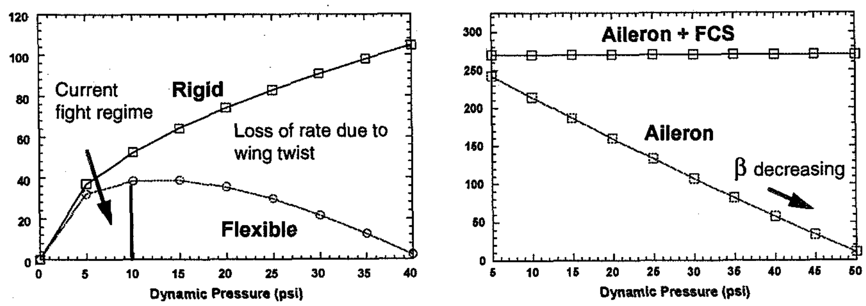
# Deformation Control for Enhancing Vehicle Performance (Eastep, UD & Khot, WL/FI)

**Objective**

- Use wing flexibility as an asset and deform the wing to enhance vehicle performance

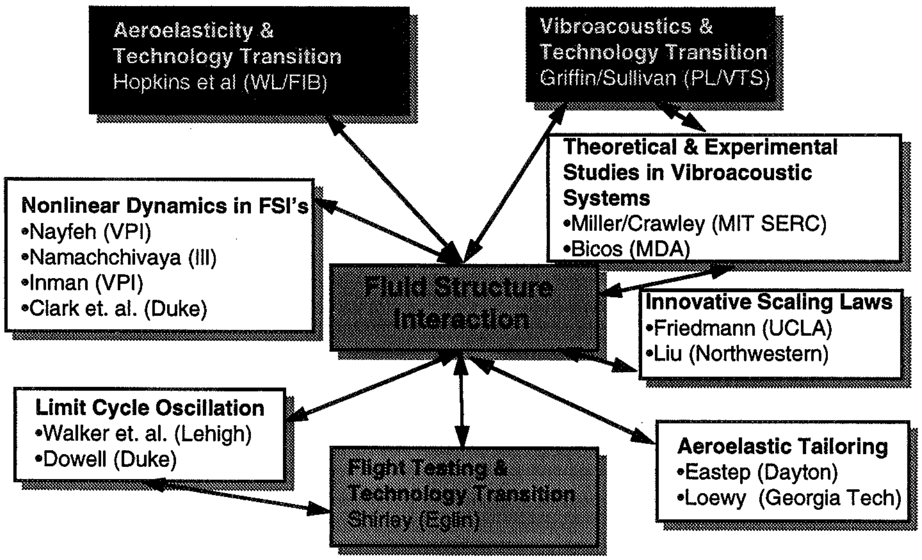
**Basic Research Issue**

- Modeling an air vehicle with prescribed wing deformations



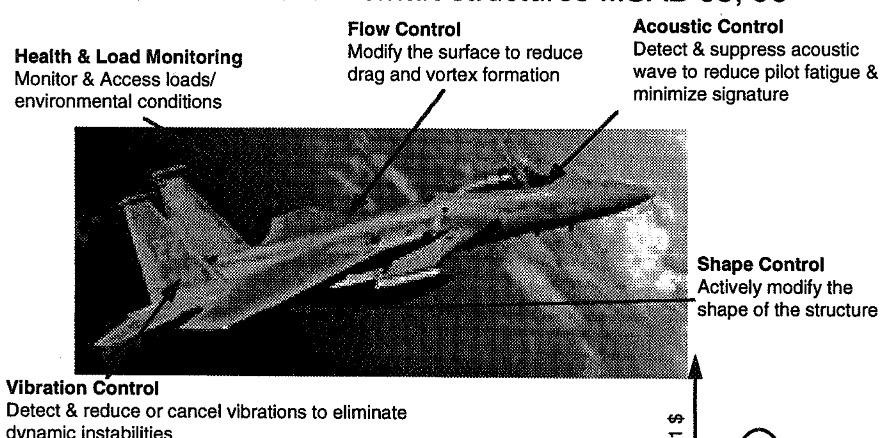

- Retwist the wing using fictitious control surfaces (FCS)
- Roll performance is improved by retwisting the wing
- Demonstrates that roll is feasible w/o control surfaces

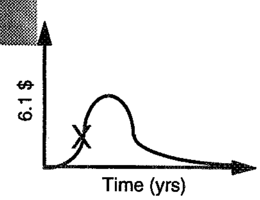
# Fluid Structure Interaction Collabogram




# Smart Composite Structures

- Continue to invest in smart structures ...SAB 95, 96




•Wealth of applications for air and space structures

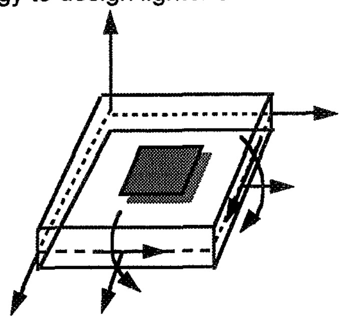
## Smart Composite Structures

**Technology Opportunity/Payoff**

- Smart structures enhance structural performance
- Composite materials are an enabling technology to design lighter & more flexible air & space structures

**Research Barriers**

- Current analysis tools & methodologies do not
  - adequately address structures designed with *smart materials*
  - adequately address scaling issues



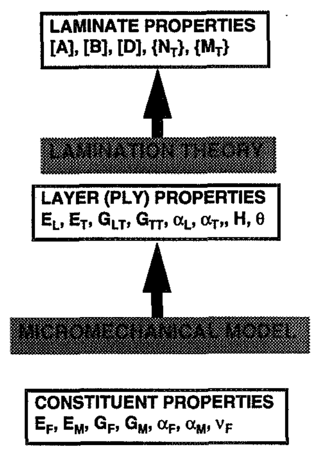
**Research Objectives**

- Improve understanding of mechanics of structures with *smart materials*
- Investigate scaling laws for design of structures with complex geometry and damage

## Hierarchical Adaptive Modeling

(Noor, U Va)

- Objective is to develop a set of nested (or multiscale) mathematical models for different regions
  - two-dimensional continuum models
  - three-dimensional continuum models
  - micromechanical models
- Automated (or semiautomated) methods for treating interfaces between different regions
  - criteria for adaptive refinement (or derefinement) of the mathematical and discrete models based on hierarchical sensitivity coefficients
- Hierarachical adaptive modeling couples the physics of the problem with the computational strategy



# Higher Order Theory Laminates

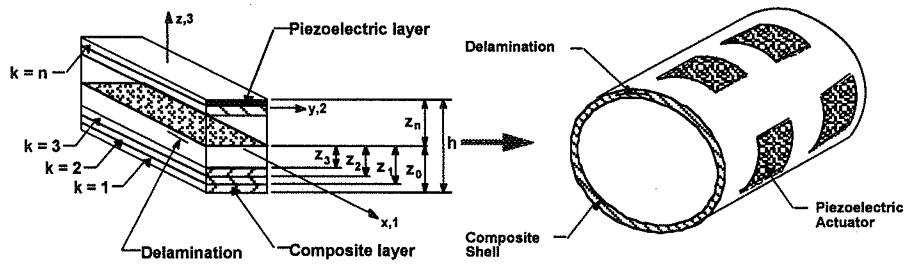
(Chattopadhyay, ASU)

Objective

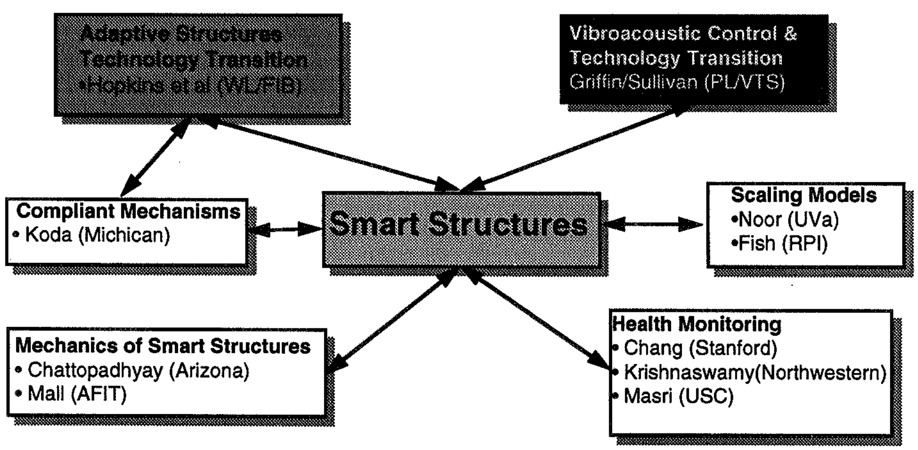
Develop general framework incorporating unique properties of active composites with embedded and/or bonded actuators/sensors

Basic Research Issue

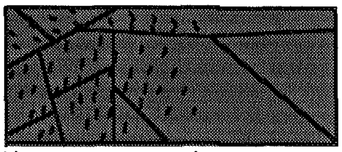
Development of a general & accurate theory for modeling smart composites with and without delaminations




# Smart Composite Structures Collabogram

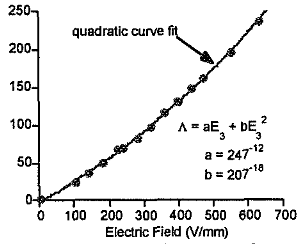


# Issues Driving Research in Material Mechanics

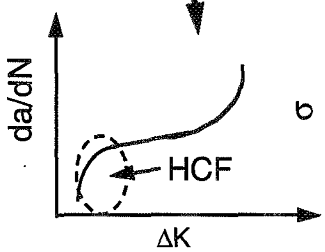


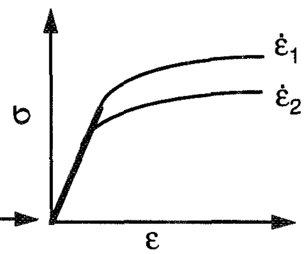
Heterogeneous microstructures

Scaling issues




Nonlinear behavior of smart materials




Damage & deformation are not coupled

# Material Mechanics

**Technology Opportunity/Payoff**

- Improved mechanics techniques for understanding the behavior or
  - New structural materials (i.e., ceramics & metallics)
  - Functional materials (i.e., PZTs, SMAs)

**Research Barriers**

- Current mechanics principles are:
  - Homogeneous, isotropic theories
  - Inadequately deal with scaling issues related to microstructure
  - Fail to capture fundamental behavior of advanced materials in regions of interest

**Research Objectives**

- Improve understanding of fundamental mechanisms that affect material properties and material response
- Develop physics-based material mechanics principles to understand and predict the behavior of advanced materials

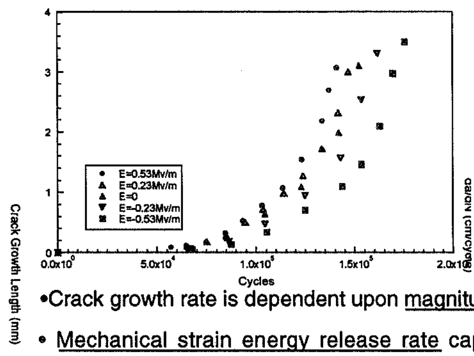
## Fatigue & Fracture Behavior of Piezoceramics (Sun, Purdue)

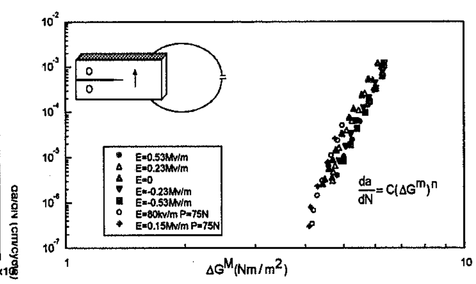
Objective

Investigate the fundamental fatigue and fracture behavior of piezoceramics under combined mechanical and electrical loading

Basic Research Issue

Are conventional fracture mechanics criteria valid?

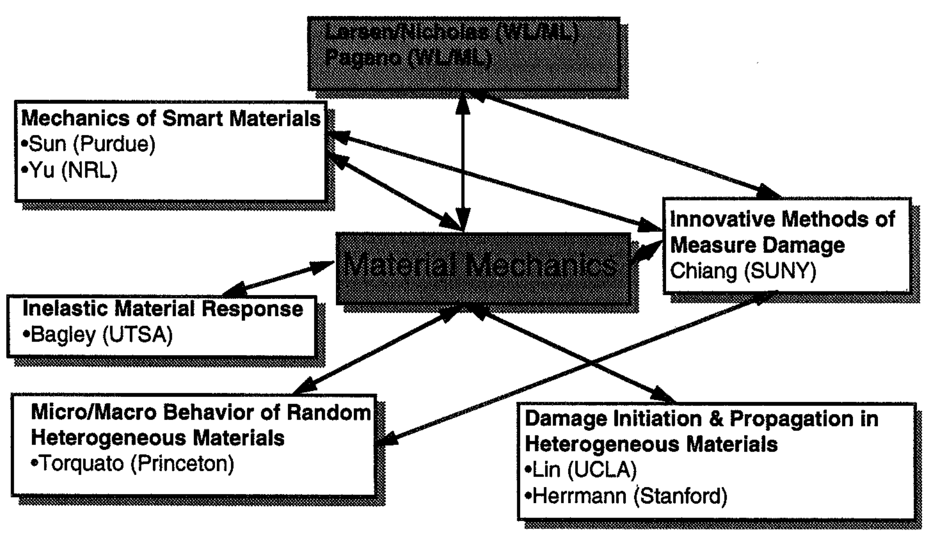



•Crack growth rate is dependent upon magnitude and polarity of the applied electric field

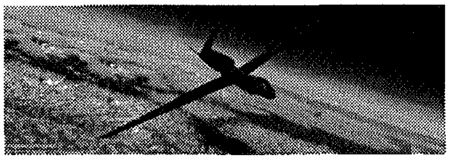
• Mechanical strain energy release rate captures the fracture and fatigue behavior of piezoceramics in the presence of electric fields.

## Material Mechanics Collabogram

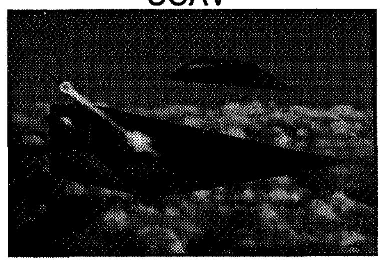


# 6.1 Research in UAVs

High Altitude Long Endurance (HALE)



Unmanned Combat Air Vehicles UCAV



Weaponization

Distributed Architecture & Control Algorithms

Structures & Materials for Increased Survivability & Low Cost

High Efficiency Propulsion Systems

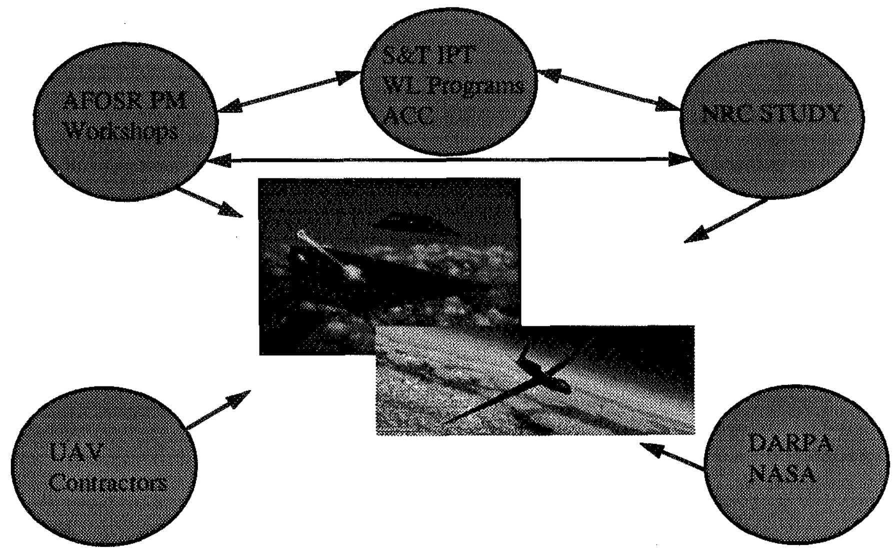
Aerodynamic & Stability Analysis

# AFOSR UAV Team

| | |
|---|---|
| • Dr Julian Tishkoff | Propulsion |
| • Dr Mark Jacobs | Dynamics & Controls |
| • Dr Charles Lee | Materials |
| • Capt Brian Sanders | Structural Mechanics |
| • Dr Len Sakell | Aerodynamics (CFD) |
| • Dr Mark Glauser | Aerodynamics (Unsteady) |
| • Capt Scott Schreck | Computational Mechanics |
| • Capt Mike Chipley | Particulate Mechanics |

• May want to consider same blend of disciplines for UAV TC

## Program Synergism




## Summary & Future Plans

### Summary

- AFOSR Structural mechanics program has three focus areas
  - Fluid-Structure Interaction
  - Smart Structures
  - Material Mechanics

### Future Plans

- Increase emphasis in mechanics of smart structures
- Build extramural program for NWV technology goals
- Investigate potential for mechanics research in MEMs
- Investigate research topics in nanoscience

# The DARPA Smart Materials and Structures Program

C. Robert Crowe
Advanced Research Projects Agency
Arlington, VA

# The DARPA Smart Materials and Structures Program

presented at
NASA Langley Research Center
14 May 1996

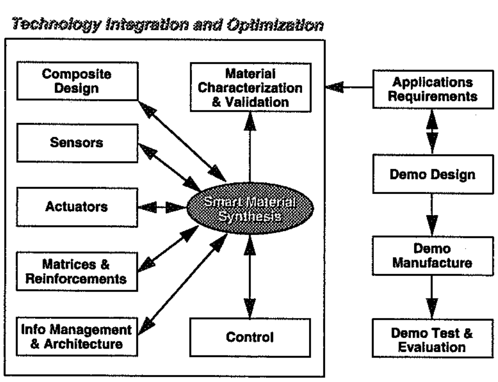
C. R. Crowe
Defense Sciences Office
Advanced Research Projects Agency

## Smart Materials & Structures
## Objectives

Develop a new class of materials that use systems of embedded sensors and actuators to:

- Sense and constructively respond to their environment with active control
  - Noise and Vibration Suppression
  - Shape Adaptive Structures
  - Aerodynamic and Hydrodynamic Fluid/Structure Control
- Systems demonstrations
  - Military aircraft
  - Submarines

## THE ARPA SMART MATERIALS AND STRUCTURES PROGRAM
### *Approach*




- **Research focus:**
  - New materials
  - New components
    - Sensors
    - Actuators
    - Devices
  - Design tools
  - Integration technology
  - Manufacturing technology
    - Embedment technology
    - IPM technology
  - Product definition

3083-5-9-95-2

# Funding

Dollars in Millions

| | FY 93 | FY 94 | FY 95 | FY 96 | FY97 | FY98 | FY 99 | FY 00 | FY 01 |
|---|---|---|---|---|---|---|---|---|---|
| Core | 0.50 | 5.90 | 8.40 | 9.30 | 6.39 | 11.32 | 13.20 | 7.00 | 5.00 |
| Partnerships | 5.00 | 5.80 | 0.65 | 0.60 | | | | | |
| Industry | 5.00 | 5.80 | 0.60 | 0.60 | | | | | |
| SBIR's | 0.50 | 0.60 | 0.60 | 0.65 | 1.00 | | | | |
| Totals | 11.00 | 18.10 | 10.25 | 11.15 | 7.39 | 11.32 | 13.20 | 7.00 | 5.00 |

Nine Year Program...$89.51M

## Smart Materials & Structures

### Sensor / Actuator Integration & Control

- Fiber Optic Sensors
- Piezoelectrics
- Electrostrictors
- FE-AFE Phase Change
- Shape Memory Alloys
- Magnetostrictors
- PVDF
- Electrorheological Elastomers
- Information Management
- Control Theory
- Design Tools
- Manufacturing Technology
- Miniature Power Supplies
- Integration Technology

### High Authority Actuators

- High Performance SMA
- Active Fiber Composites
- Terfenol Optimization
- Injection Molded Actuators
- Relaxor Ferroelectric Actuators
- Single Crystal Perovskites
- Polymeric Muscles

### Demonstrations

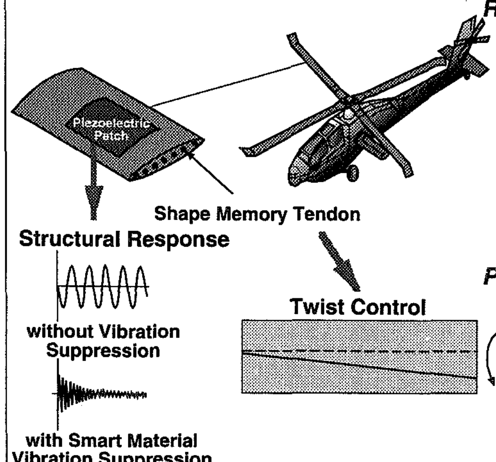
- Shape Adaptive Wing
- Smart Helicopter Rotor
- Shape Adaptive Inlet
- Multifunctional Satellite
- Low ω Active Acoustic Tiles
- Conformal Mid ω Active Acoustic Tiles
- Vortex Leveraging
- Submarine Stern

# MATERIALS

- Electroactive Ceramics
  - Piezoelectric (PZT)
  - Electrostrictor (PMN)
  - FE–AFE Phase Transition (PLZT)
  - Single Crystal Piezoelectrics
- Alloys
  - Shape Memory (Nitinol)
  - Magnetostrictive (Terfenol)
  - Magneto Shape Memory (Heusler)
- Fiber Optic
  - Extrinsic Fabry-Perot
  - Bragg Gratings
  - Long Period Gratings
- Polymers
  - Electroactive
  - Electrorheological Elastomers

# SMART MATERIALS AND STRUCTURES

## Helicopter Blade Vibration Suppression and Twist Control




*Requirements*

Vibration Suppression:
- Response: 1-100 Hz
- Displacement: $\mu$

Twist Control: (Blade Trimming)
- Response: Static to 12 Hz
- Displacement: mm

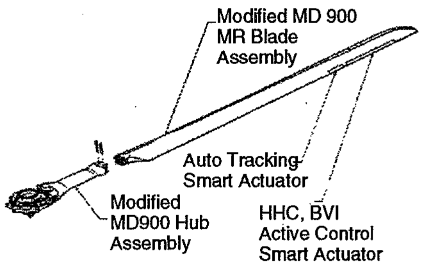
*Payoffs*

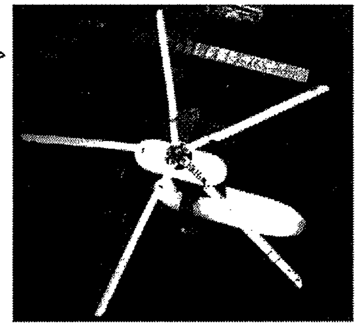
- Increased Speed (from 160 to 200 Knots
- Increased Readiness of at least 15%
- Increased Range
- Increased Maneuverability

3083-11-9-94-6

## Vibration Suppression: Active Rotor Blades

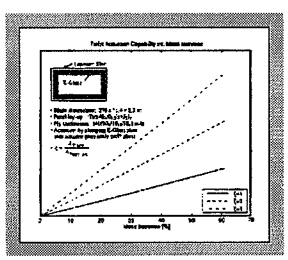
MD900 helicopter



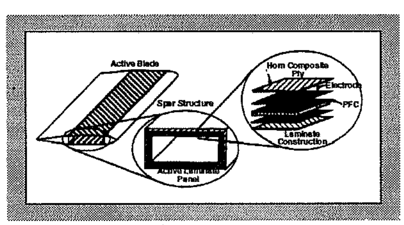



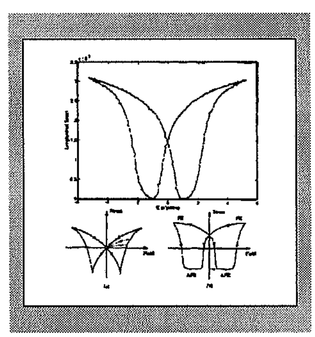
Expected performance improvements for active rotor blade concepts include 10 dB reduction in BVI noise, 80-90% reduction in airframe vibrations, 10% gain in rotor performance (lift/drag), improved maneuverability from stall alleviation

## SMART MATERIALS FOR ROTOCRAFT STRUCTURES



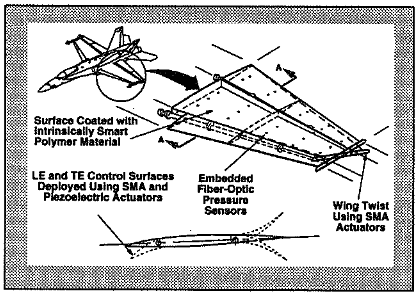
- SHAPE MEMORY CERAMIC MATERIALS DEVELOPMENT
- STRUCTURAL DESIGN/ANALYSIS OF SMART BLADE
- DEVELOP INTEGRAL BLADE APPLICATION



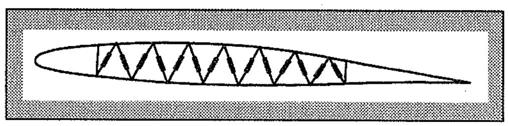



3083-10-6-94-31

# SMART WING AND STRUCTURES DEVELOPMENT

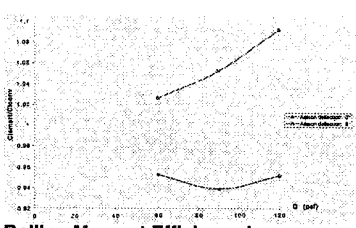



- Develop Shape Memory, Piezoelectric and Magnetorestrictive Actuators
- Develop Fiber Optic Sensor System
- Design Smart Wing
- Demonstrate Wing Subelements
- Perform Wind Tunnel Tests on Scaled Models

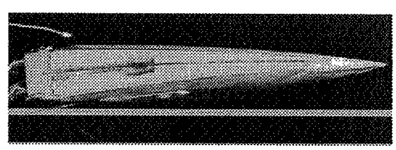


3083-10-6-94-8
R9-8-95

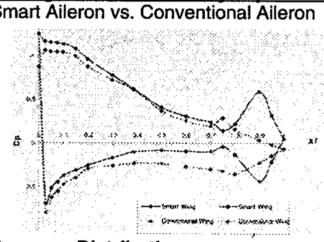
# SMART MATERIALS AND STRUCTURES SMART WING



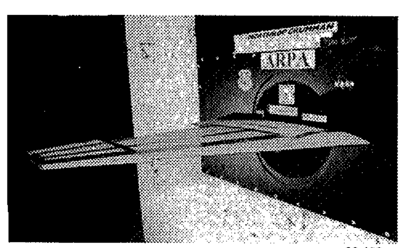
**Rolling Moment Efficiency Improvement**
Smart Aileron vs. Conventional Aileron



Smart Aileron



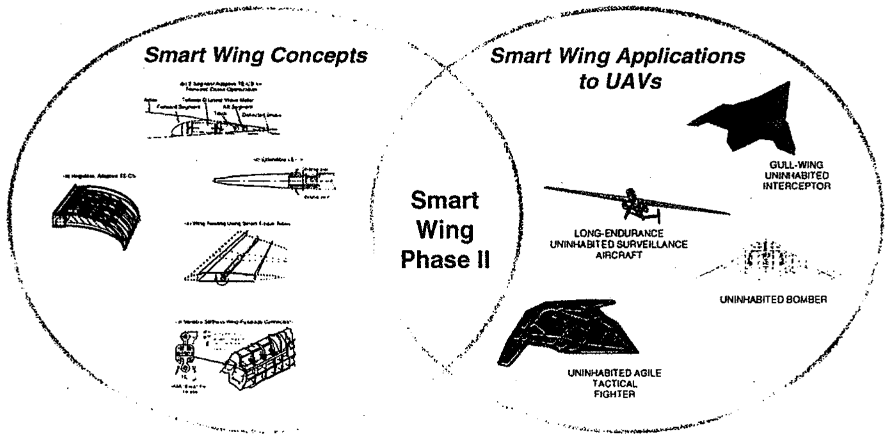
**Pressure Distribution**
Improved Pressure Profile




96-152

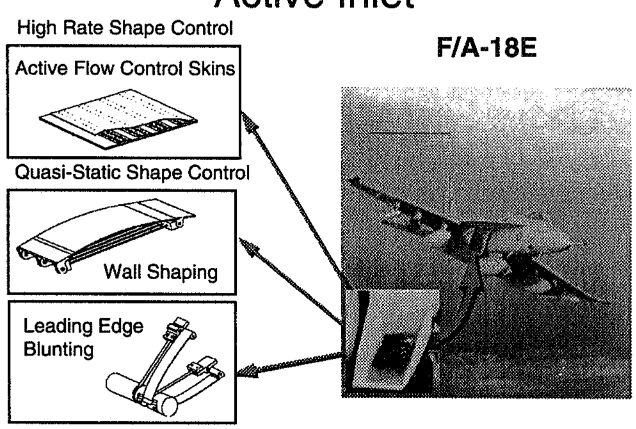
Smart Wing

## Smart Wing Phase II Demo




**Re-direction of Phase II to UAVs For Near Term Technology Transition**

## Shape-Adaptive Structures: Active Inlet




Expected benefits include 20% improved range for tactical aircraft, improved maneuverability, flutter and buffet control, and reduced signature

## SMART MATERIALS & STRUCTURES
*Major Issues*

- SENSORS
  - Optimization of Figures of Merit re Processing and Microstructures
  - Environmental Robustness
  - New Sensor Materials
- ACTUATORS
  - Maximization of Deliverable Energy re Processing and Microstructures
  - New Actuator Materials
- COMPOSITE
  - Mechanical Behavior
  - Microstructure Production
  - Interfaces
  - On-Board Data Processing
  - Calibration
  - Manufacturability
  - Economical
  - Durability

3083-4-25-95-2

## SMART MATERIALS & STRUCTURES
*Major Issues*

- THEORIES
  - Micromechanics
  - Non-Linear Mechanics
  - Cross-Coupled Systems
  - Control
- DESIGN TOOLS
  - Materials Response Simulators
  - Multidimensional Data Visualization
  - Interfaces
- CHARACTERIZATION OF COLLECTIVE BEHAVIOR
  - Strength
  - Fatigue
  - Durability
- INTEGRATION
  - Concurrent Engineering
  - Local/Global Optimization

3083-4-25-95-3

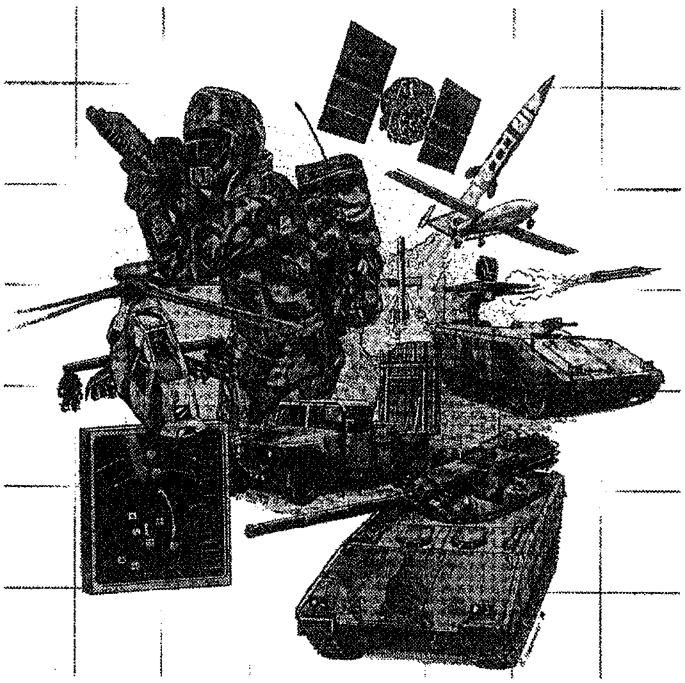
## SMART MATERIALS AND STRUCTURES
### *Manufacturing Issues*

- Smart Materials and Component Synthesis
  - Materials Processing
    - Material/component architecture
      - Models for component placement
      - Fixing of component placement during synthesis
    - Manufacturing techniques and automation
    - Compatibility of sensor/actuator systems with matrices and reinforcements
    - Interconnects
      - Embedded sensor/actuators must be designed and fabricated for part edges
      - Linking sensor /actuators with signal processing system

3083-5-9-95-5

# Structural Dynamics Program
# Army Research Office

Gary L. Anderson
U.S. Army Research Office
Research Triangle Park, NC



# Army Research Office

# STRUCTURAL DYNAMICS PROGRAM


**Dr. Gary L. Anderson**
US Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
Tel. (919) 549-4317
Fax: (919) 549-4310
E-Mail: anderson@aro-emh1.army.mil


**6 April 1997**

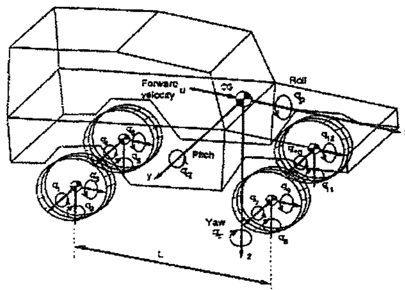
*Engineering and Environmental Sciences Division*

## ARO's Structural Dynamics Program

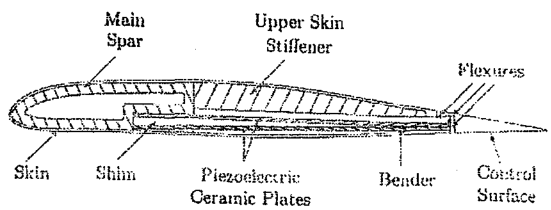
*TOPIC 1: Structural Dynamics*

**Thrusts:**

- **Land vehicle and multi-body dynamics**
- **Structural damping**
- **Smart structures and structural control**
- **Statics and dynamics of inflatable structures**



*A simple model for the multi-body dynamics analysis and simulation of military land vehicles*




*A rotor blade trailing edge flap actuated by a piezoceramic bimorph to suppress vibrations and reduce blade-vortex interaction noise*

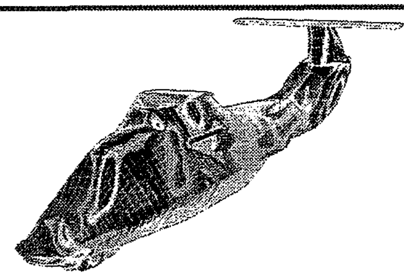
*Engineering and Environmental Sciences Division*

## ARO's Structural Dynamics Program

*TOPIC 2: Air Vehicle Dynamics*

**Thrusts:**

- **Integrated aeromechanics analysis**
- **Rotorcraft numerical analysis**
- **Projectile aeroelasticity**
- **Dynamic control systems for projectiles**
- **Parachute inflation aeromechanics**

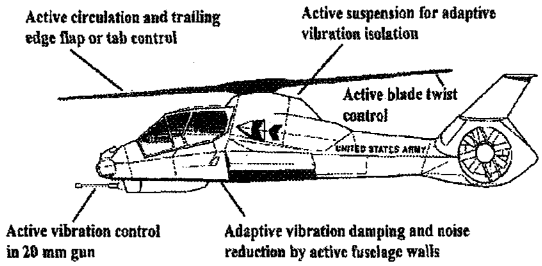


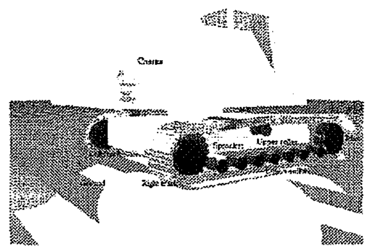
*Accurate, efficient, and economical analysis techniques to determine fuselage dynamic response, rotor blade aeromechanical stability, composite structural response*

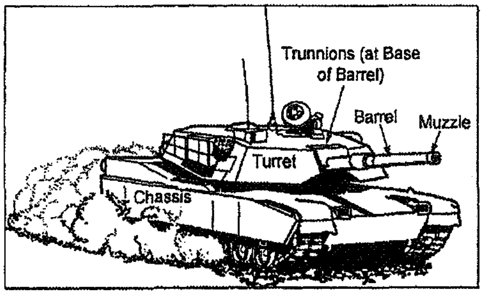
*Numerical prediction of parachute inflation dynamics involving coupled CFD and structural dynamics codes: non-linear finite element modeling, fabric material models, wrinkling analysis, fabric flutter,*

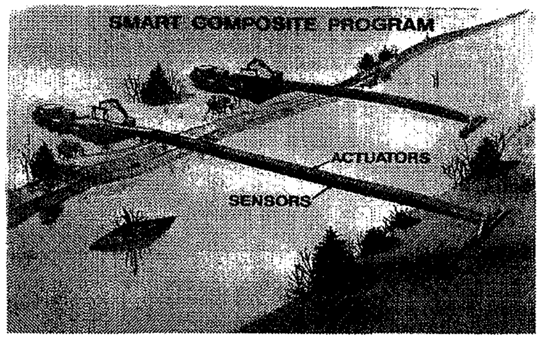
# Strategic Research Objective on Smart Structures

## *Defense Relevance*






---

*Engineering and Environmental Sciences Division*

ARO

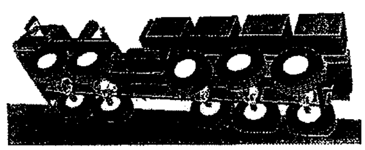
## Overview of Issues in Multibody Dynamics


*Ahmed Shabana, University of Illinois at Chicago*
*Eduardo Bayo, University of La Coruna*


*Recursive Formulation Characteristics:*

- **Multibody simulation is notoriously difficult (DAE)**
- **Specialized algorithms : roots in robotics**
- **Order N Complexity (rigid bodies only)**
- **Symbolic Processing Predominates**
- **Computer Generation Amenable**
- **Graph Theoretic Foundations**
- **Topology Induced Parallelism**
- **Real-time performance achieved 1988**

Palletized Load System



- Snapshot of Vehicle as it Rolls Over on the Hairpin Curve
- A View of Vehicle Few People Have Seen or Want to See

Technical Obstacles

- **Recursive : not Order N for flexible systems**
- **Flexible systems of growing interest to military**
  **Vibration isolation of sensor mounts, Barrel Pointing, active suspension systems (MRF)**

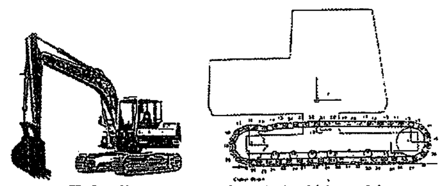
*Engineering and Environmental Sciences Division*

## Tracked Vehicle Dynamics: Formulation of Equations and Numerical Solutions

*Ahmed Shabana, University of Illinois at Chicago*

*Approach:*

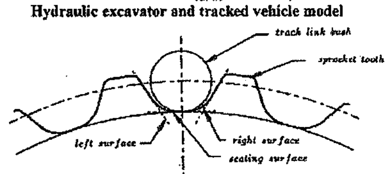
- Highly redundant Lagrange multiplier method
- Constraint enforcement through independendent coordinate reduction
- Constraint Correction via Iterative Newton-Raphson Iteration



Hydraulic excavator and tracked vehicle model

*Accomplishments:*

- Transient Simulation of contact forces
- Detailed stress analysis of individual tracks
- Accurate prediction of track trajectory
- 3D Visualization for CAD Possible




The sprocket teeth surfaces

*Engineering and Environmental Sciences Division*

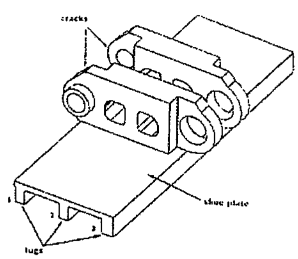
## Tracked Vehicle Dynamics: Formulation of Equations and Numerical Solutions

*Ahmed Shabana, University of Illinois at Chicago*

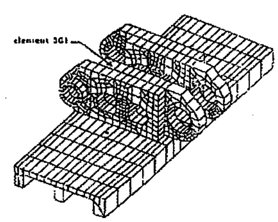
*Rationale:*

High-fidelity simulation of multibody tracked vehicles is a requirement limited to the military and a few heavy vehicle companies.

- Track links are subjected to high contact forces that produce high stress levels.
- Detailed models of sprocket track interaction
- Detailed models of roller track interaction
- Detailed models of ground track interaction



Triple lugs track link



Finite element model

*Objectives:*

- Develop a computer aided dynamic analysis to study the track-link deformation 3D
- Incorporate flexibility of track links
- Accurate calculation of contact forces

*Engineering and Environmental Sciences Division*

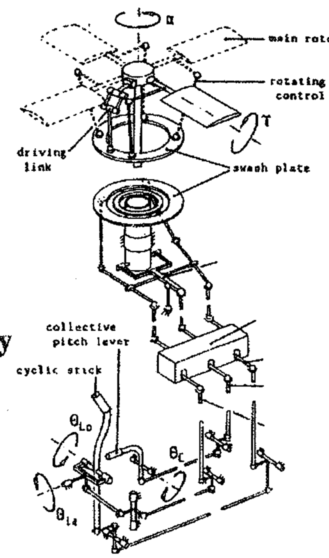
## Methods for Intelligent Real-Time Simulation of Multibody Dynamics

*Eduardo Bayo, University of La Coruna*

*Rationale:*

**Virtual prototyping : Crucial for desing of the next generation of military vehicles**

- **Multibody simulation : full DAE's ill-advised**
- **Specialized algorithms : roots in robotics**
- **Performance limited: treatment of rigid bodies**
- **Performance limited :**
  **"topology induce parallelism"**
- **Some military structures do not exhibit such topology**




**Objectives**

- **Novel, Multi-index, variable time step methods**
- **Novel variants of Augmented Lagrangian methods**
- **Real-time performance for a richer class of models**

*Engineering and Environmental Sciences Division*

## Methods for Intelligent Real-Time Simulation of Multibody Dynamics

*Eduardo Bayo, University of La Coruna*

*Advantages:*

**Index-3 Methodologies**

- **Provide a regularization (DAE)**
- **Constraint violation bounds derived [Kurdila,94]**
- **Order N performance for rigid bodies**
- **Order N performance for some flexible systems**
- **Parallelism independent of vehicle topology**
- **Based on methods from CSM, CFD**
- **Variable method/time step switching**

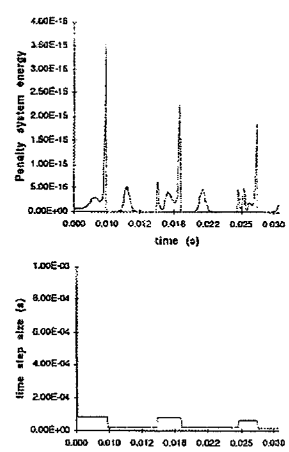



Figure 6. Andrew's squeezing mechanism integration history.

*Engineering and Environmental Sciences Division*

# Real Time Simulation of Multi-Body Dynamics

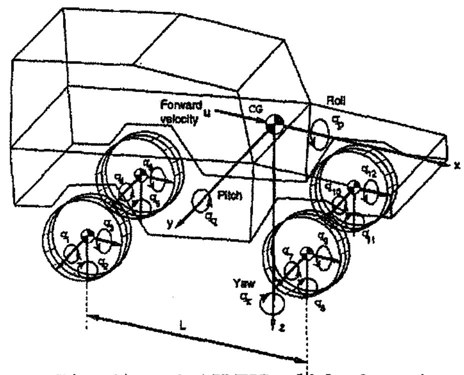
ARO

Goals: Conduct basic research to develop

- Methods for faster than real time simulation of multi-body systems
- Simulation tools fast enough to include
  - Hardware-in-the-loop and man-in-the-loop
  - Intelligent vehicle control systems

*Accomplishments:*

- Tested for simulation
  - Two augmented Lagrangian formulat
  - New state space formulation for stiff systems
  - New fully recursive formulation
- Simulated the Bombardier ILTIS at a speed 2-3 times the real time in an SGI Indy workstation




*The 1/4 ton 4x4 ILTIS vehicle: dynamic simulations based on known inertial and suspension properties.*

Eduardo Bayo
Escuela Politecnica Superior
Universidad de la Coruna

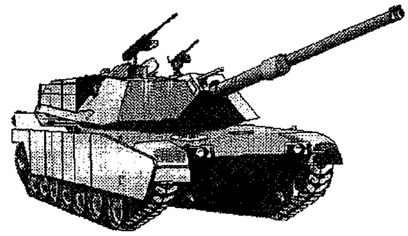
*Engineering and Environmental Sciences Division*

# Innovative Structural Damping Control Techniques

ARO

*Benefits:*

- Extended structural fatigue life
- Reduced noise (communications, crew fatigue, detectability)
- Increased maneuverability
- More economical operation

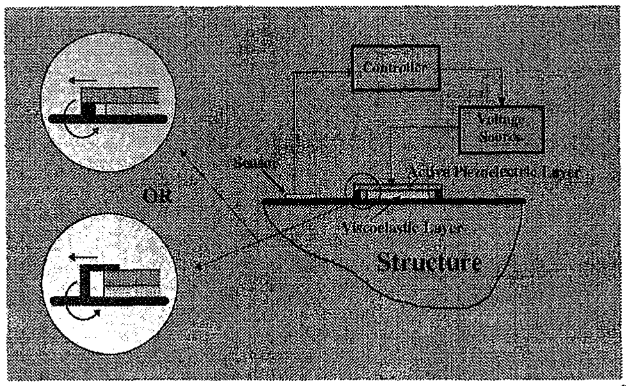


PENNSTATE

## New and Enhanced ACL (EACL) Idea

Create new configuration to increase transmissibility

- Both active and passive actions can be effectively utilized
- Outperform both active and passive structures in most cases - a more robust design




- *Edge elements* to increase transmissibility and enhance active action contribution
  => More effective than current ACL and outperform PCL
- Still maintain passive VEM damping
  => Outperform purely active systems

*Structural Dynamics and Controls Lab*

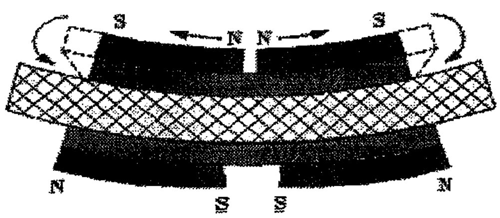
ARO

*Engineering and Environmental Sciences Division*

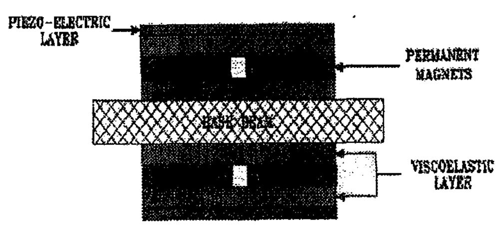
## Active/Passive Magnetic Dampers

**Concept: Include permanent magnets or electromagnets in a structure to obtain high control authority**

- **Integrate with viscoelastic damping layers**
- **Augment constraint with piezoelectric layers**
- **Determine optimal size and placement respecting weight and energy considerations**




*Viscoelastic layer with rare earth magnets*




*Two viscoelastic layers with magnets and exterior piezoelectric layers*

*Engineering and Environmental Sciences Division*

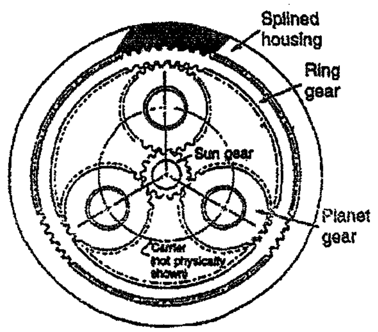
# PLANETARY GEAR DYNAMICS IN ROTORCRAFT TRANSMISSIONS

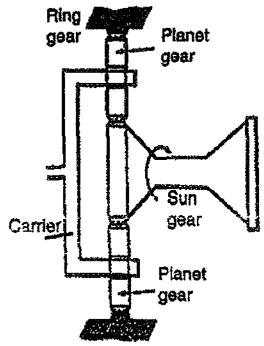
***GOAL:*** **Develop analytical and computational tools for planetary gear dynamics to address**

- **Noise**
- **Weight**
- **Dynamic load carrying capacity**
- **Reliability**

***Dynamic Analysis Complications:***

- **Multiple interconnected bodies**
- **Time varying mesh stiffness and contact loss non-linearity**
- **Complex mesh interactions at multiple tooth contacts**
- **Detailed kinematics from motion of the planets and carrier**





*Robert Parker*
*Ohio State University*

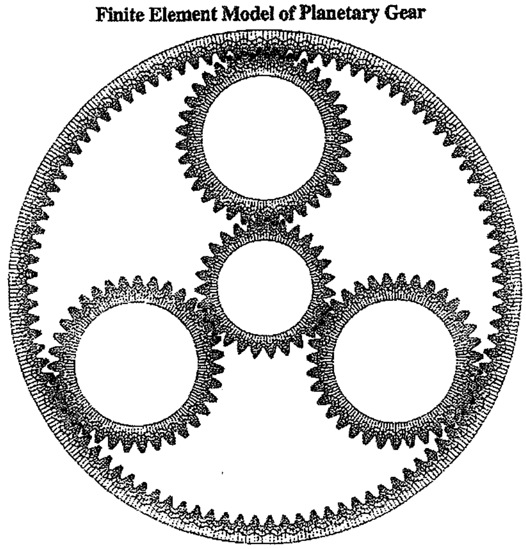

*Engineering and Environmental Sciences Division*

# PLANETARY GEAR DYNAMICS

***Approach:***

- **Analytical modeling of planetary gears**
- **Computational contact mechanics and finite element analysis**
- **Geometric imperfections**
- **Elastic ring gear vibration**
- **Vibration isolation of transmission mounting**
- **Experimental investigation of planetary gear dynamics**

**Finite Element Model of Planetary Gear**



*Bell Helicopter OH-58 Kiowa planetary gear (output carrier omitted for clarity)*

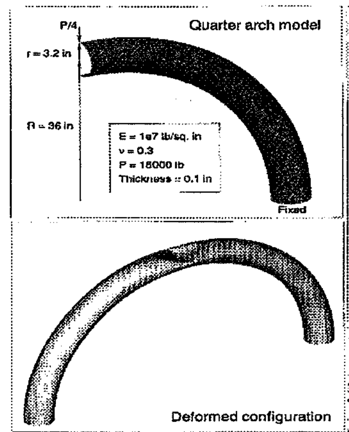
*Engineering and Environmental Sciences Division*

## Static and Dynamic Analysis of Inflatable Arches and Beams

***Motivation:*** **Examine the feasibility of constructing large, tent-like maintenance shelters that can be used for helicopters, land vehicles, and airplanes.**

***Objective:*** **Develop mathematical formulations and numerical solution techniques for toroidal tubes built from inflatable fabrics**

- **static and dynamic loads**
- **optimal designs with respect to material and geometry**
- **compute deflections, stresses, buckling loads, frequencies, and mode shapes**




**Deformation of a semi-cirucular arch-tube under apex load**

Raymond Plant
Rakesh Kapania
Virginia Polytechnic Institute

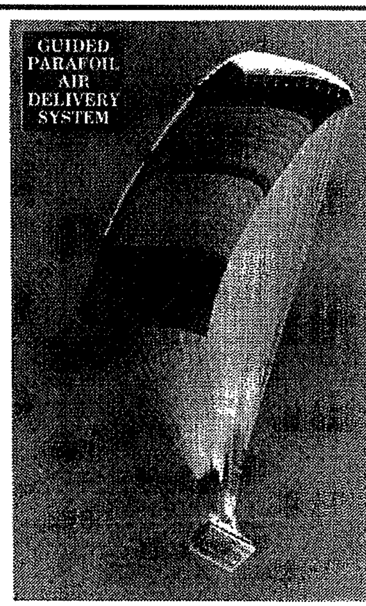
*Engineering and Environmental Sciences Division*

## A Structural Model for Parachute Inflation Simulations

***Goals:***

- **Develop a structural model of a parachute to couple to CFD codes to simulate inflation, terminal descent, and control of parachute and para-foil systems**
- **Devise a new finite element method-ology to predict combined complex aerodynamic and structural dynamic phenomena that occur during para-chute deployment.**

John W. Leonard
Michael L. Accorsi
University of Connecticut

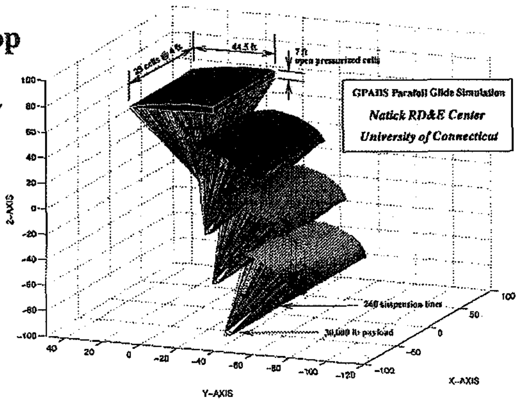


*Engineering and Environmental Sciences Division*

# A Structural Model for Parachute Inflation Simulations

__*Significance:*__

- Developing new and reliable airdrop systems
- Retrofitting extant systems for new applications
- Developing new control strategies for airdrop systems
- Testing feasibility of innovative airdrop designs
- Applications to dynamic deployment of
  - high altitude balloons
  - large span tents
  - temporary and extra-terrestrial structures



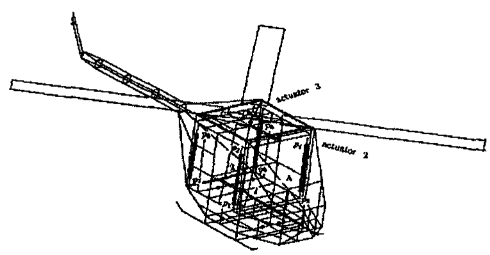

***Simulation of the gliding of a Guided Precision Aerial Delivery System parafoil. The system starts in a flat configuration, pitches forward, then reaches a steady state glide.***

*Engineering and Environmental Sciences Division*

# Active Control of Rotorcraft Structural Response

__*Goals:*__

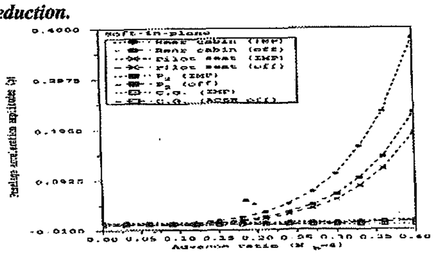
- Develop a mathematical simulation capability for the active control of helicopter fuselage response
- Use this capability to demonstrate vibration reduction and determine force and power requirements



***Mount the engine, gearbox, and rotor on a rigid platform. Locate actuators at four corners to produce vibration reduction.***

__*Accomplishments:*__

- Vertical accelerations in the fuselage are reduced below 0.05 g
- Power requirements less than 1 HP
- Actuator strokes are small (0.001")
- Actuator force requirements are in practical range at 4/rev



***Fuselage vertical accelerations versus advance ratio with the controller engaged or disengaged.***

Peretz Friedmann
UCLA

*Engineering and Environmental Sciences Division*

## Parallel Computing Methods for Helicopter Trim and Stability Calculations

***Trim Analysis:*** **Compute the control inputs and helicopter orientation for the required flight conditions (prerequisite for flight mechanics and vibration analyses)**

***Stability Analysis:*** **Compute the eigenvalues of the Floquet transition matrix to determine the damping levels or stability margins.**

***Accomplishments:***
- **Develop a reliable parallel fast Floquet analysis (Peters-McNulty method)**
- **Removed run time barrier using fast Floquet analysis (1000 states)**

Gopal Gaonkar
Florida Atlantic University

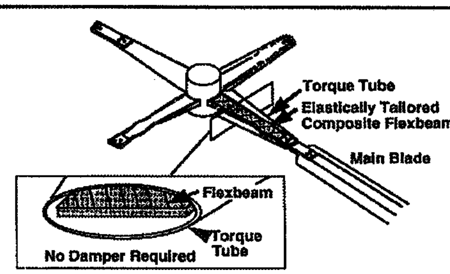
*Engineering and Environmental Sciences Division*

## Vibration and Stability of Rotorcraft with Elastically Tailored Composite Rotor Blades

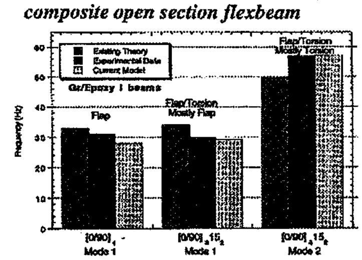
***Goals:***
- **Develop new structural design tools**
- **Incorporate non-uniform inflow and blade stall modeling**
- **Devise rotor blade design strategies for stable, low vibration rotor systems**

***Accomplishments:***
- **Developed and validated a new finite element for modeling open section composite flexbeams (improved accuracy)**
- **Included blade torsion effects dominated by warping restraint effects**
- **Exploited bending-torsion couplings to**
  - improve stability • simplify hub design
  - reduce vibrations • enhance handling qualities

*Edward Smith*
*Pennsylvania State University*




***Bearingless rotor with an elastically tailored composite open section flexbeam***




***Comparison of natural frequencies for graphite/epoxy I beams***

## *Engineering and Environmental Sciences Division*

# Energy Absorption for Crashworthy Design of Composite Structures

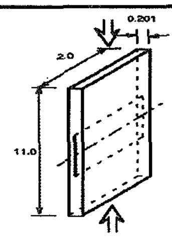
***Goals:***

- Develop accurate models for investigating pre- and post-buckling in delaminated composite structures
- Devise a non-linear sensitivity analysis to assess effects of material and geometry changes on energy absorption

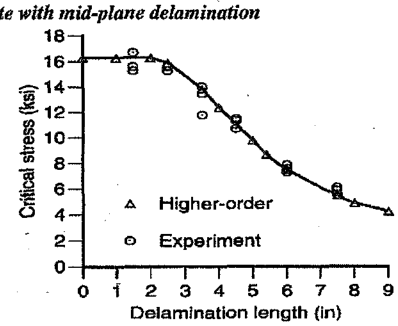
***Approach:***

- Compare results from the refined theory for delamination buckling and the 3-D theory of elasticity (simply supported orthotropic plates)
- Conduct an experimental investigation to validate the theoretical results
- Study the effects of
  - ply stacking sequence
  - location of delamination
  - length of delamination

Aditi Chattopadhyay, Arizona State University




*Test specimen: $[0°/90°/0°]_{12}$ graphite/epoxy composite plate with mid-plane delamination*



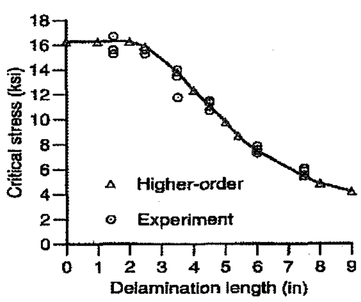

*Geometry of the delaminated composite plate*

## *Engineering and Environmental Sciences Division*

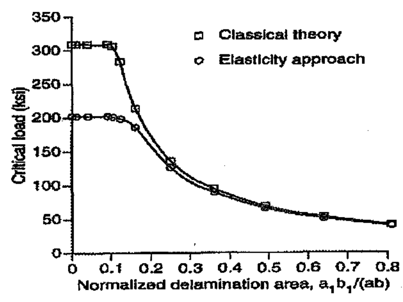
# Energy Absorption for Crashworthy Design of Composite Structures

***Accomplishments:***

- Composite laminates can retain their load bearing capacity after buckling
- In some cases, the *ultimate load* is 3 times the *corresponding critical load*
- Excellent agreement between experimental and computed values of the critical loads
- Classical theory is inadequate to predict critical buckling loads in short rectangular orthotropic plates




*Comparison of experimental and calculated values of the critical stress versus delamination length (high order transverse shear theory was used)*



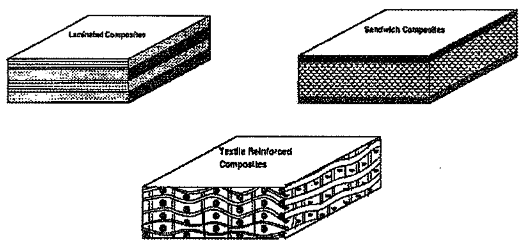

*Variation of the critical load with delamination area for a $[0°_6/90°_6/0°_6]$ boron/epoxy laminated plate*

Engineering and Environmental Sciences Division

## Impact Response of Laminated and Textile Composite Structures

*Motivation:*

- There is a need for a light weight, survivable, and rapidly deployable ground combat vehicle.
- Analytical tools and design methodologies are required for light weight laminated and 3-D reinforced textile composite structures to predict
  - deformation • failure • survivability
- No such tools are currently available for thick walled laminates and textile composite structures exposed at near ballistic impact loads




*Laminated, sandwich, textile reinforced, functionally graded, and other composites can be analyzed by the proposed methods.*

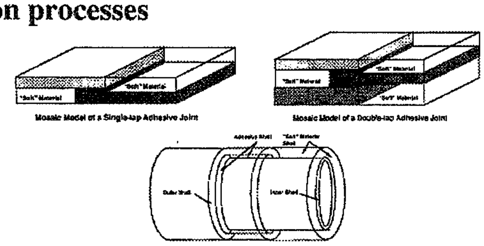
Engineering and Environmental Sciences Division

## Impact Response of Laminated and Textile Composite Structures

*Goal:* Develop computational tools for stress and failure analysis of thick-walled laminated and textile composite structures under moderate velocity (50-100 m/s) impact.

*Approach:* Devise unified computer codes through:

- a general formulation allowing any distribution of external static and/or dynamic surface loads
- Avoiding any a priori assumed hypotheses when characterizing impact contact phenomena (e.g., Hertzian contact law, etc.)
- Accounting for stress wave propagation processes



*Complex geometries (adhesively bonded plates, cylindrical elements, stiffened plates and shells) can be investigated by the proposed methods.*

# Solid Mechanics Program
# Office of Naval Research

Roshdy George S. Barsoum
Office of Naval Research
Arlington, VA

# Solid Mechanics Program

## Office of Naval Research

## Ship Structures and Systems Division

**Workshop on**
**Government Sponsored Programs in Structures**
**April 6, 1997**

**Roshdy George S. Barsoum**

## Solid Mechanics Thrust Areas

### Simulation-Based Methodology for Weapons Effects on Ship Structures

**Objectives:** *Predictive Capability for Dynamic Failure in Undex*

**Issues:**

- Scaling
- Competing and cascading failure mechanisms
- Prediction of dynamic fracture propagation, especially for welds.

**The most advanced practices use damage rather than fracture.**
**Failure strain is reduced by a 4-8 ignorance factor, to account for failure at welds.**

**Approach:**

- Integration of knowledge (failure) from macro to micro behavior.
- Computational methods and failure criteria for prediction of dynamic fracture of large structures.
- Hierarchical: constitutive models (material scale) for the welds (HAZ) and metal to the structural scale.
- Prediction of ductile and brittle fracture - high strain rate effects.
- Integration methods - structural sensitivity analysis and advanced computations.
- Address variability in properties as well as structural geometry.

**Technical Payoffs:**

- Evaluation of performance from the viewpoint of weapon protection and crew casualty.
- Battle-damage assessment and prediction of progression of damage under various operating conditions.

## Structural Reliability of Ships

**Objectives:** *Life Prediction for Ship Structures*

**Issues:**

- Probabilistic loading, response of large structures and fatigue prediction.
- Effect of variability: structure, welds (and HAZ), material, details, etc.
- Archaic HCF/S-N (Goodman, etc.) - initiation criterion (threshold).
- Methodology for hull/ship redesign for improved dynamics and acoustics performance.
- Bridging the gap between experiments and predictions using model calibration.

**Approach:**

- Understand ship structural response to sea loading - its structural modes (experimental - fluid/structural interaction).
- Probabilistic methods in ship structure - understanding the important factors influencing ship reliability.
- Fatigue initiation criterion - threshold - time to "failure" - crack initiation, unstable crack growth.
- Deterministic methods and past experience of ship reliability, advanced computations and understanding fatigue.
- Initiation on the structural level - expert system and concurrent engineering.
- Computational techniques to bridge the scales from micro to macro behavior - constitutive behavior for cyclic loading, coupled micro/macro mechanical models of fatigue.

## Reliability of Power Electronic Building Blocks

**Objectives:** *Reliability of PEBB Modules and High-Temperature Semiconductors*

**Issues:**

- Thermomechanical stresses - current/voltage characteristics in semiconductor
- Intrinsic stresses in semiconductor and defects in compliant substrate
- Thermal stresses in modules and fracture of multilayers.

**Approach:**

- Defects in advanced high-temperature semiconductors (SiC, SiN)
- Mechanics of growth of strained film compliant substrates - wafer splitting (hydrogen implantation)
- Quantitative methods for intrinsic stresses - effect on the critical thickness, and bifurcation of strained films
- Surface roughness of the films
- Fracture mechanics and test methodology - PEBB modules are also subject to high temperature and very large gradients
- Experiments to simulate thermal and mechanical loading effects on devices
- The reliability of packaging and solder.

## Active Materials and Adaptive Structures

*High-Performance Actuators for Naval Applications*

**Issues:**

- Mechanics of coupled fields
- Design of high-performance actuators
- Reliability of high-strain active materials
- Nonlinear behavior of active materials

**Approach:**

- Mechanics of high-strain, high-frequency active materials
- Reliability and life prediction methodologies for fatigue life especially for ferroelectric ceramics
- Fracture mechanics methodology in coupled fields
- Coupled electrical - thermal - mechanical response
- Nonlinear behavior in coupled fields - control fidelity/nonlinear control - new high strain actuators
- Actuator design - approach: high-strain/high-frequency actuators, new actuator concepts, hybrid actuators and embedding of actuators in composite

**Program is addressing the mechanics required for the feasibility of the following naval applications:**

*Near Term:*

- Structural acoustic and machinery vibration control, and radiated noise reduction.
- Shape control/flow control in propulsor (reduced cavitation, vibration or signature), vortex wake control (sail control surfaces), large array active surface (target strength and SA control)
- MEMS accelerometers, magnetic anomaly devices (MAD), micropumps, gyroscopes, angular velocity meters, and various applications in weapons and UUVs, NiTi variable ballast system

*Future:* Health monitoring and CBM, battle damage assessment and realtime targeting.

## Research Areas

- Reliability of complex structural systems
- Computational methods and prototype simulation
- Mechanics of structural materials
- Mechanics of electronic materials

*Common Broad Research Themes:*

- Performance and life-cycle prediction for complex structures
- Hierarchical strategies for deformation, damage and failure control

## S&T of Significant Impact

- Real-time monitoring of damage
- Design of efficient and maintainable structures
- Power electronics
- Problems of welding and joining
- Reliable design with composites
- Mechanics of megastructures
- Response of materials and structures to severe events
- Speculative technologies

## Reliability of Complex Structural Systems

Rational consistent probabilistic models to estimate the reliability of novel structures.

Basis:

- Prediction of loads
- Prediction of structural response
- Development of strength criteria

- Development of reliability procedures for complex ship structures

## Mechanics of Structural Materials

- Constitutive relations for deformation and damage
- Progressive damage and failure
- Mechanics of joining and bonding
- Composite materials

Mechanics of Electronic Materials

- Electro-thermomechanical effects
- Reliability: Effect of defects on performance (damage models..., etc.)

## Computational Methods and Prototype Simulation

- Modeling of dynamic and acoustic response
- Modeling the dynamic environment for a large range of scales
- Nonlinear simulation
- Design to optimization for function and cost

Two Major Impediments:

1) The inability to predict damage and fracture in a complex structure;

2) The inability to model the interaction between a fluid medium and the failing structure.

# Overview of FAA Structural Integrity Program for Large Transport Airport

Paul W. Tan
Federal Aviation Administration
Atlantic City, NJ

# OVERVIEW OF FAA STRUCTURAL INTEGRITY PROGRAM FOR LARGE TRANSPORT AIRPORT

Paul W. Tan
Federal Aviation Administration
Atlantic City, New Jersey

On April 28, 1988, multiple fatigue cracks caused an Aloha Airlines Boeing 737-200 aircraft to lose part of its upper fuselage. Although the aircraft was able to land safely, the accident resulted in the death of one flight attendant and injury to many passengers. The aircraft, which entered service in April 1969, had accumulated 35,496 hours and 89,690 flight cycles. Less than five weeks after the Aloha Airlines accident, the FAA convened an international conference to discuss the issue of aging aircraft in the world-wide fleet. Of particular concern was the fact that many airplanes were approaching or had exceeded the manufacturers' design operational life. The conference included operations, maintenance, manufacturing and regulatory representatives. A general consensus was reached that, with proper maintenance and structural modifications and with attention to service-related damage such as fatigue and corrosion, the design operational lives of airplanes could be safely exceeded. The resulting issues, initiatives and recommendations later became the basis for the FAA's National Aging Aircraft Research Program (NAARP).

## Structural Integrity Program Overview

Paul W. Tan
Federal Aviation Administration
Atlantic City, NJ

AIAA Structures Technical Committee Meeting
April 6, 1997
Orlando, FL

## STRUCTURAL INTEGRITY PROGRAM OVERVIEW

The NAARP is a multidisciplinary program and this overview of one sub-program covers the research in the structural integrity of large transport aircraft (SITA). There are three major elements within this sub-program: a) methodologies to predict the onset of widespread fatigue damage, b) structural integrity of repairs, and c) probabilistic methodologies for widespread fatigue damage.

# Structural Integrity Program Overview

Three major elements:

- Methodologies to Predict the Onset of Widespread Fatigue Damage
  - Crack Initiation
  - Crack Growth and Link-up
  - Residual Strength
- Structural Integrity of Repairs
- Probabilistic Methodologies for Widespread Fatigue Damage

## METHODOLOGIES TO PREDICT THE ONSET OF WIDESPREAD FATIGUE DAMAGE

Since the NAARP started in 1989, SITA has completed thirteen major milestones shown as described in the following viewgraphs. Reports are available on those projects and will not be discussed here.

| |
|---|
| **Methodologies to Predict the Onset of Widespread Fatigue Damage** |

## Methodologies to Predict the Onset of Widespread Fatigue Damage

Major Tasks:

1) Fracture and Fatigue Strength Evaluation of Multiple Site Damaged Aircraft Fuselages - Curved Panel Testing and Analysis (Foster-Miller)
   - Built full-scale curved panel test rig
   - Flat and curved panels (7) MSD test
   - Completed March 1991
   - Report: DOT/FAA/CT-94/10

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

2) Full-Scale Testing and Analysis of Curved Aircraft Fuselage Panels (Foster-Miller)
   - 8 curved panels test: 7 residual str., 1 fatigue
   - Completed March 1992
   - Report: DOT/FAA/CT-93/78

3) Aircraft Fuselage Lap Joint Fatigue and Terminating Action Repair (Foster-Miller)
   - 2 full-scale curved panels fatigue test
     - to characterize initiation and growth
   - Foster-Miller report completed Aug. 1993

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

4) Load Tests of Flat and Curved Panels with Multiple Cracks (Foster-Miller)
   - 12 flat panels, 10 curved panels
   - Foster-Miller report completed Sept. 1993
5) Fracture Testing of Large-Scale Thin-Sheet Aluminum Alloy (NIST)
   - Completed Jan. 1995
   - Report: DOT/FAA/AR-95/11

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

6) Axial Crack Propagation and Arrest in Pressurized Fuselage (Univ of Washington)
   - Completed June 1995
   - Report: FAA report in preparation
7) Investigation of Fuselage Structure Subject to Widespread Fatigue Damage (Boeing)
   - Completed Aug. 1995
   - Report: DOT/FAA/AR-95/47

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

8) Computational Modeling of Aircraft Structures (COE)
   - Completed Phase I Oct. 1995
   - Over 100 technical reports
9) Residual Strength Tests on Stiffened Panels with MSD (conducted by NLR)
   - 11 stiffened panels (80x50)
   - Completed Feb. 1996
   - Final report expected Dec. 1997

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

10) Elastic Finite-Element Alternating Method (E-FEAM) (COE)
    - Ongoing Phase II activity
    - Completed March 1997
11) Elastic-Plastic Crack Growth Criteria Based on T* with Elastic-Plastic FEAM (COE)
    - Ongoing Phase II activity
    - Completed March 1997

## Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)

12) Experimental Verification of the T* Theory (Univ. of Washington)
    - Completed work for single cracked specimen
    - One technical paper published
    - Ongoing investigation on MSD specimen
13) NASGRO (JSC)
    - PC-based NASGRO development ongoing
    - Expected completion date Jan. 1997

**METHODOLOGIES TO PREDICT THE ONSET OF WIDESPREAD FATIGUE DAMAGE**

Milestone 14 deals with the development of an engineering tool for the prediction of the residual strength of aircraft fuselage structures in the presence of widespread fatigue damage. It uses finite element bulging data to account for fuselage curvature fracture toughness. A ligament yield criterion is used to predict crack instability.

**Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)**

14) Engineering Residual Strength Model Development and Validation (Broek and Foster-Miller)
    - PC Windows based residual strength tool
    - Expected completion date Jun. 1997

## METHODOLOGIES TO PREDICT THE ONSET OF WIDESPREAD FATIGUE DAMAGE

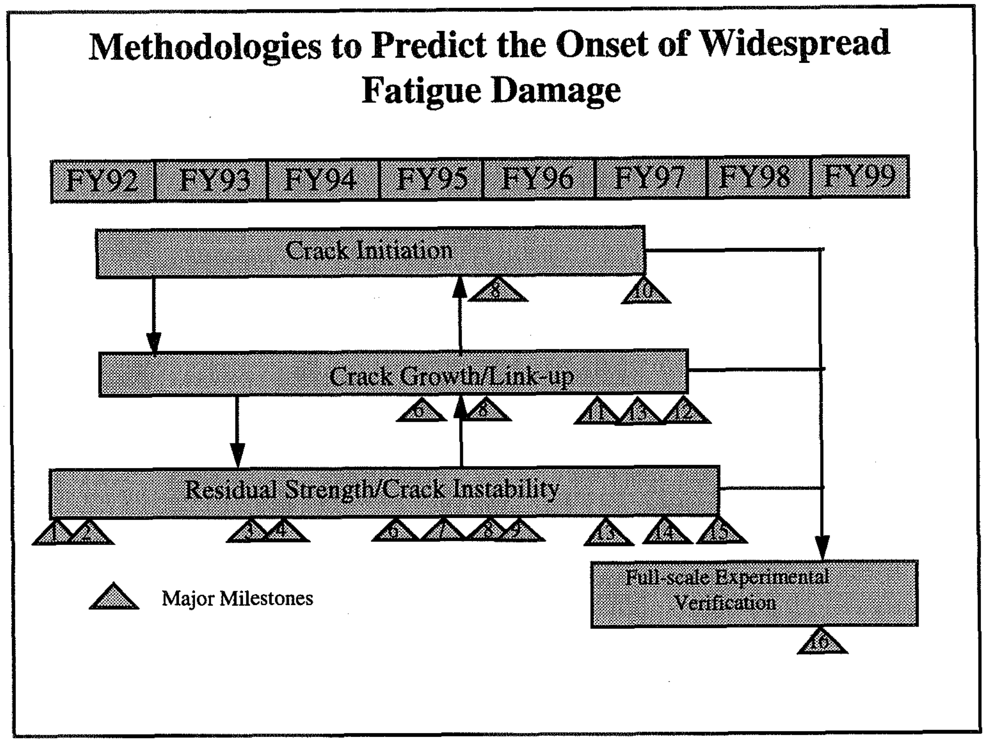
Milestone 15 is a project that is funded by the FAA and conducted at NASA Langley Research Center. The project consists of testing five stiffened and five unstiffened panels with and without multiple site damage (MSD). The objective of this test program is to measure the crack tip opening angle (CTOA), plastic zone size at the crack tip, and the elastic-plastic crack tip energy T*. This data will be used to predict residual strength of a structure in the presence of MSD.

Milestone 16 is a project that conducts an evaluation and validation of the technologies and methodologies developed by the FAA and NASA within their aging aircraft programs. McDonnell Douglas will be evaluating these technologies to predict the onset of widespread fatigue damage.

**Methodologies to Predict the Onset of Widespread Fatigue Damage (Cont'd.)**

15) Stiffened and Unstiffened Flat Panel Test (NASA Langley)
    - Start date Oct. 1996
    - Expected completion date Oct. 1997
16) Widespread Fatigue Damage Evaluation (McDonnell Douglas)
    - Awarded August 1996
    - Expected completion date Dec. 1999

## METHODOLOGIES TO PREDICT THE ONSET OF WIDESPREAD FATIGUE DAMAGE



## STRUCTURAL INTEGRITY OF REPAIRS

In the Structural Integrity of Repairs element, the FAA has developed a PC-based tool to perform a damage tolerance analysis of repairs. Four releases are planned:

- Release Version 1: for simple fuselage repairs
- Release Version 2: repairs over stringers, frames and splices
- Release Version 3: repairs at door corners
- Release Version 4: common repairs for commuters.

# Structural Integrity of Repairs

## Structural Integrity of Repairs

Three Phases:

Phase I: Repair Assessment Procedure and Integrated Design (RAPID)

- Completed simple skin repair model and GUI
- Version I, released March 1996

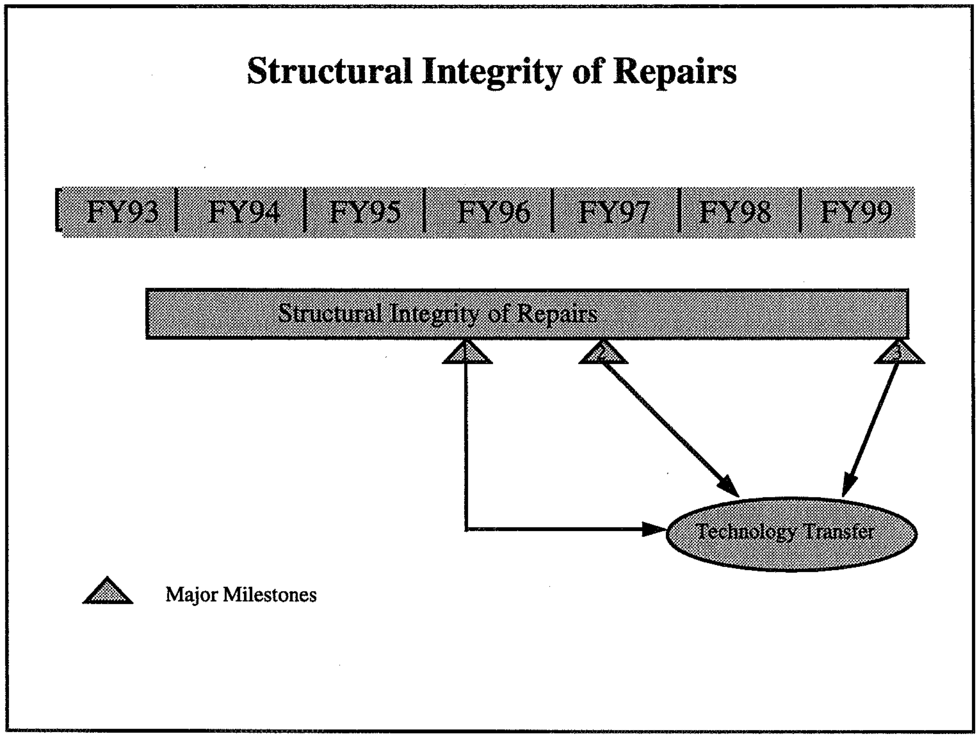
## Structural Integrity of Repairs (Cont'd.)

Phase II: Repair Assessment Procedure and Integrated Design (RAPID) - funded by USAF/NDAA

- Complex structural repairs
- Ongoing activity
- Expected version II release Aug. 1997

Phase III: Repair Assessment Procedure and Integrated Design (RAPID)

- Repairs of commuter aircraft
- Planned activity for FY98 and FY99


Structural Integrity of Repairs
FY93
FY94
FY95
FY96
FY97
FY98
FY99
Structural Integrity of Repairs
Technology Transfer
Major Milestones

# Probabilistic Methodologies for Widespread Fatigue Damage

## PROBABILISTIC METHODOLOGIES FOR WIDESPREAD FATIGUE DAMAGE

The Probabilistic Methodologies for Widespread Fatigue Damage Project involves the development of a probabilistic framework to conduct risk analyses of structural components prone to WFD. Uncertainties in crack initiation, loads, material properties, manufacturing qualities, and corrosion are modeled probabilistically.

**Probabilistic Methodologies for Widespread Fatigue Damage**

**Task:**

- An Integrated Risk Assessment Methodology for Widespread Fatigue Damage in Aircraft
  - New activity
  - Awarded Sept. 1996
  - Expected completion date June 1998

## Probabilistic Methodologies for Widespread Fatigue Damage (Cont'd.)

**Task Objective:**

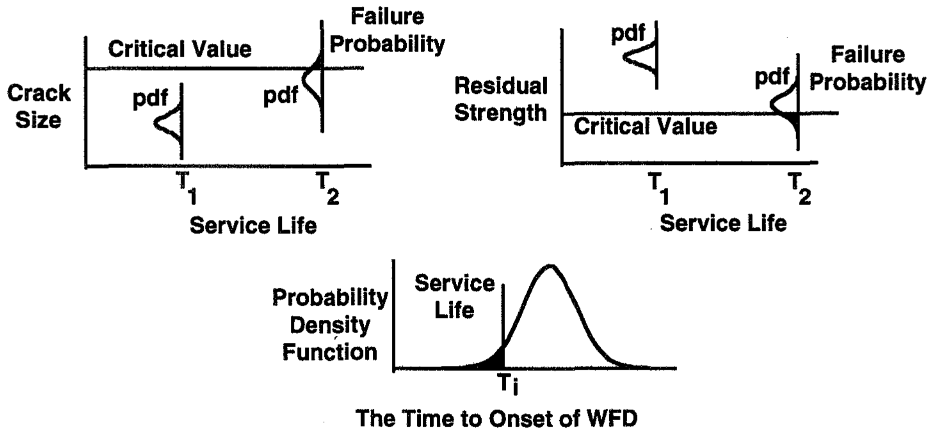
- Develop a probabilistic analytical tool to aid in understanding WFD mechanisms under various sources of uncertainties.
- Use risk-based decision tool to quantify risk associated with both MSD and ME and ensure continued airworthiness of the aging fleet.

## Probabilistic Methodologies for Widespread Fatigue Damage (Cont'd.)

**Task Approach:**

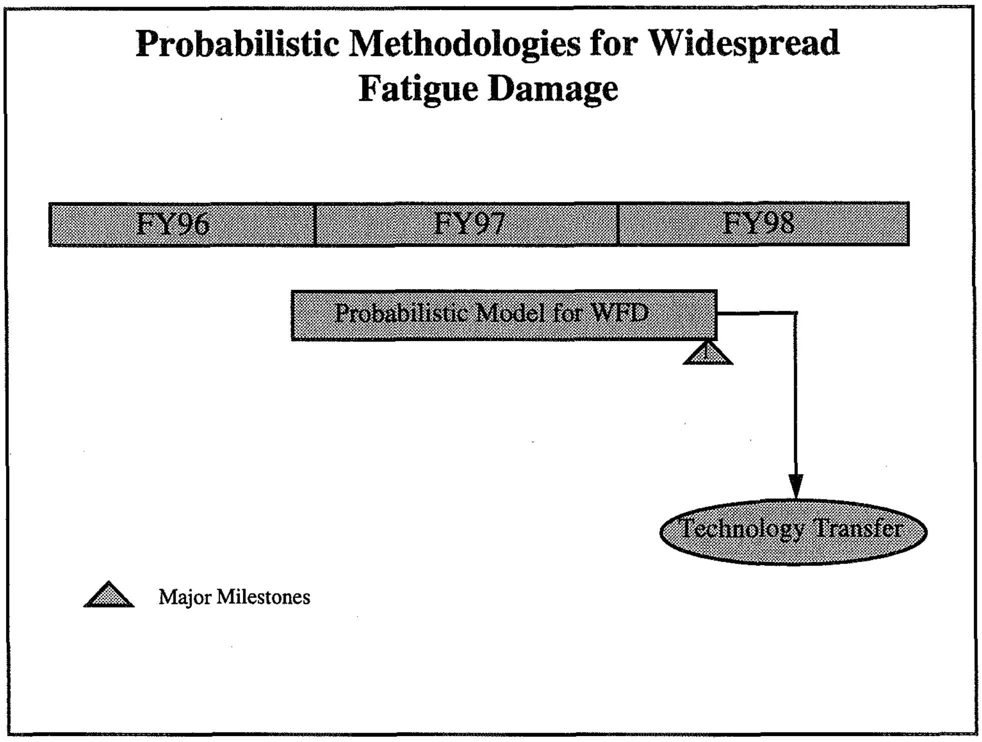
- Quantify uncertainties in WFD process
  - Crack initiation
  - Crack growth
  - Residual strength and instability.
- Propagate uncertainties using fatigue and fracture mechanics.
- Predict results using probabilistic methods.

# Probabilistic Methodologies for Widespread Fatigue Damage (Cont'd.)



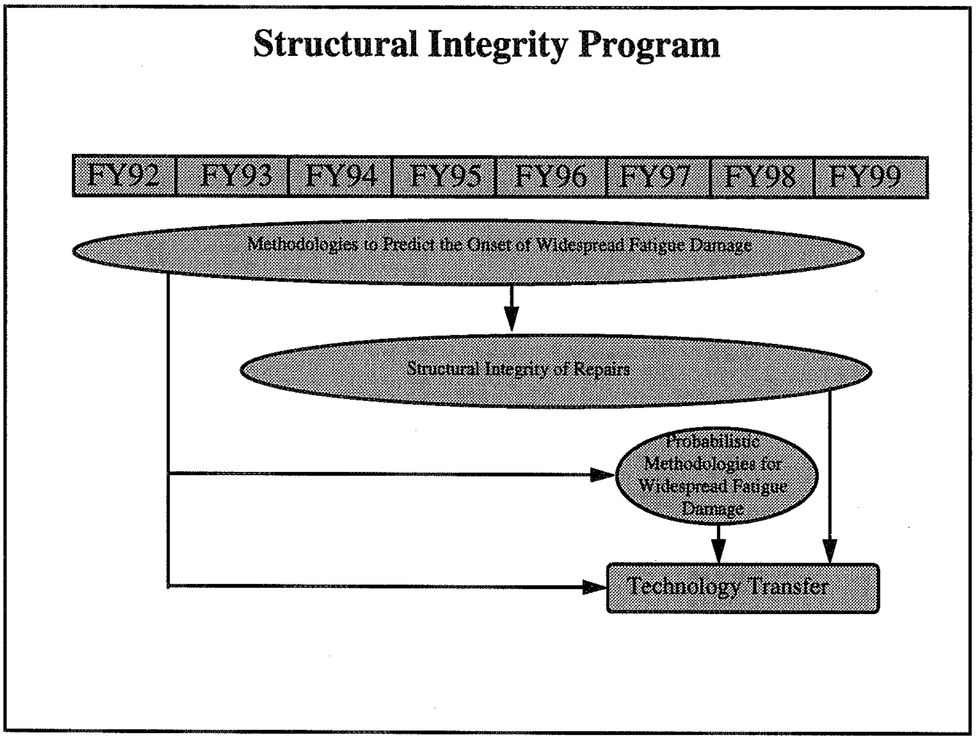

Failure Probability = Shaded Area

## PROBABILISTIC METHODOLOGIES FOR WIDESPREAD FATIGUE DAMAGE



## Summary

- Evaluation and validation of WFD methods will be completed in FY99.
- RAPID Version II to be released Aug. 1997.
- Planned FAA funding for RAPID for commuters applications in FY98 and FY99.
- An integrated risk assessment methodology for WFD will be completed in FY98.


Structural Integrity Program
FY92
FY93
FY94
FY95
FY96
FY97
FY98
FY99
Methodologies to Predict the Onset of Widespread Fatigue Damage
Structural Integrity of Repairs
Probabilistic Methodologies for Widespread Fatigue Damage
Technology Transfer

# Overview of Research, Development and Application Activities at Sandia National Laboratory

Paul J. Hommert
Sandia National Laboratories
Albuquerque, NM

# OVERVIEW OF RESEARCH, DEVELOPMENT AND APPLICATION ACTIVITIES AT SANDIA NATIONAL LABORATORY

Paul Hommert
Director, Engineering Sciences
Sandia National Laboratories
Albuquerque, New Mexico

## Overview of Research, Development and Application Activities at Sandia National Laboratories

**Presentation for Workshop on Government Sponsored Programs in Structures**
**April 6, 1997**

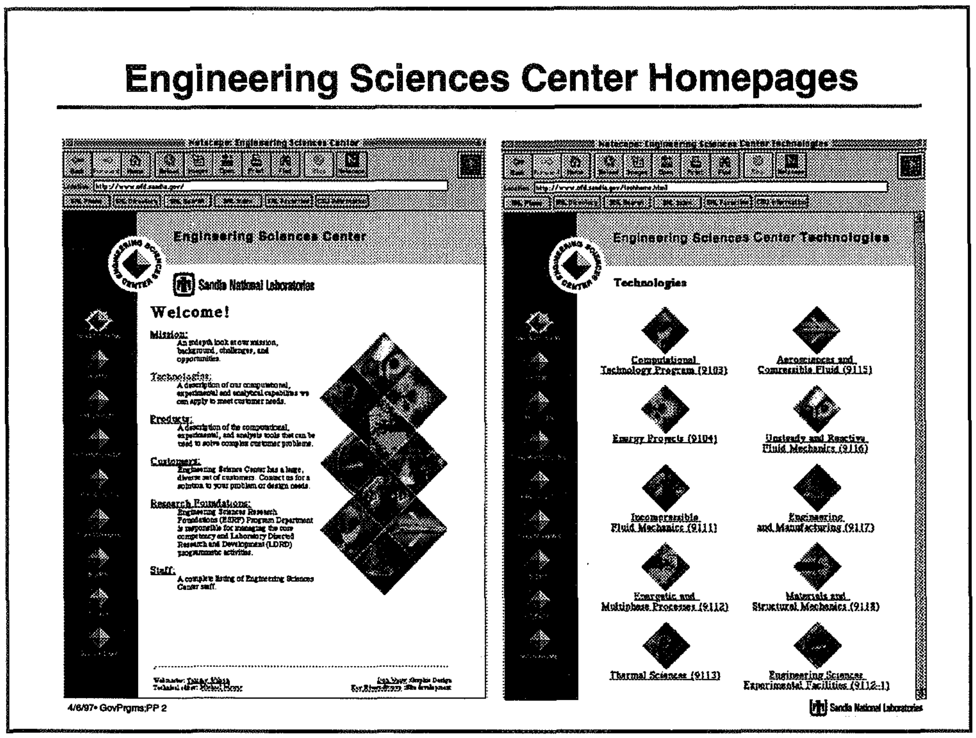
**Paul Hommert**
**Director, Engineering Sciences**
**pjhomme@sandia.gov**

4/6/97• GovPrgms;PP 1

Sandia National Laboratories

## ENGINEERING SCIENCES CENTER WEB PAGES

This viewgraph shows two web pages. The left page provides an Internet address that can be used to gather additional background information. The right page shows Engineering Sciences Center technologies as illustrated by another web page.

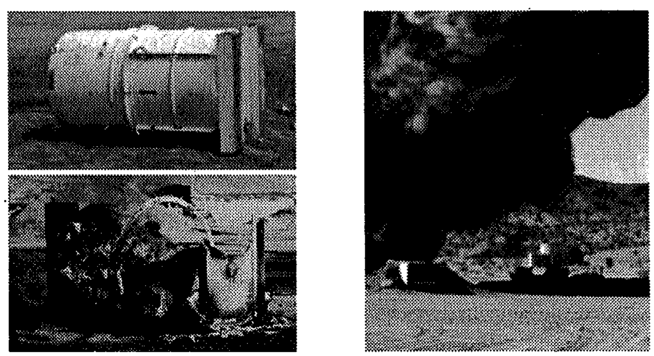


# NUCLEAR WEAPONS SAFETY IN ABNORMAL THERMAL ENVIRONMENTS IMPROVED CONFIDENCE THROUGH TOOL DEVELOPMENT

Indicates one of the prime responsibilities of the Laboratory in the weapons program; namely, weapon safety in an abnormal environment. This particular viewgraph highlights the importance of being able to simulate fire conditions.

## Nuclear Weapons Safety in Abnormal Thermal Environments Improved Confidence Through Tool Development

**Numerous weapon system safety assessments have identified fire as a dominant risk in the transportation and storage of nuclear weapons.**



"Describing the...severity of a..fire requires the use of considerable engineering approximation" (Severities of Transportation Accidents, SLA74-000-1, July 1976)

"Minor changes in the fire characteristics can severely change the thermal response of a system" (A Broad Range of Lessons Learned in Design of Weapon Systems, SAND93-1085, Feb. 1994).

4/6/97• GovPrgms;PP 3

Sandia National Laboratories

# EVENTS AND MECHANICAL PHENOMENOLOGY OF A B61 LAYDOWN

Similar to the previous viewgraph, this provides an example of another weapon related environment for which simulation capability is being developed; namely, laydowns. This environment requires predictive capabilities for large deformation mechanics and structural dynamics.

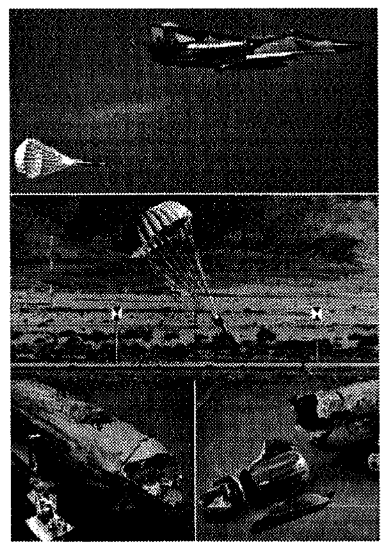
## Events & Mechanical Phenomenology of a B61 Laydown

**Events**

- Aircraft Release
- Parachute Retardation
- Nose Impact
- Tail Slapdown
- Centercase Impact

**Phenomenology**

- Large Deformations
- Material Contact & Penetration
- Material Crush-up & Fracture
- Material Damping
- Late-Time Component Response



4/6/97• GovPrgms;PP 4

Sandia National Laboratories

## MISSION DEMANDS FOR ENGINEERING SIMULATION

The following three viewgraphs are self-explanatory and provide a high level of summary of the mission responsibilities of the Laboratory and how those responsibilities generate the need for phenomenology and simulation capabilities across a range of disciplines.

### Mission Demands for Engineering Simulation

**Nuclear Weapons: Our Primary Mission**

| | | |
|---|---|---|
| **Performance:** | **Gravity/Laydown Systems** | **Transient Dynamics** |
| | **Parachutes** | **Non-Linear Large Deformation Mechanics (NLLDM), Aerodynamics** |
| | **Reentry Vehicles** | **Structural Dynamics, Aerothermal,** |
| | **Contact Fusing, NG Standoff** | **NLLDM** |
| | **Neutron Generators** | **NLLDM** |
| | **Arming, Firing & Fusing** | **Energetic Materials, Structural Dynamics** |
| | **Detonators** | **Energetic Materials** |
| | **Gas Transfer Systems** | **Quasistatics, Material Mechanics** |
| | **Hostile Environments** | **Structural Dynamics, NLLDM Thermal** |
| **Safety:** | **Abnormal Environments** | |
| | **Thermal/Mechanical** | **Thermal Sciences, Fire Physics, NLLDM, Energetic Materials** |

4/8/97• GovPrgms;PP 5

Sandia National Laboratories

MISSION DEMANDS FOR ENGINEERING SIMULATION

## Mission Demands for Engineering Simulation

**Nuclear Weapons - Our Primary Mission**

| | |
|---|---|
| **Reliability - Component Design & Aging** | **Quasistatic Analysis**<br>**Material Mechanics**<br>**Reactive Processes**<br>**Micromechanics** |
| **Manufacturing - Product & Process Design** | **Fluid Mechanics**<br>**Plasma Processes**<br>**Quasistatics**<br>**Thermal Science**<br>**Reactive Processes** |

4/6/97• GovPrgms:PP 6

Sandia National Laboratories

# MISSION DEMANDS FOR ENGINEERING SIMULATION

## Mission Demands for Engineering Simulation

### Energy and Critical Infrastructures

| | |
|---|---|
| Fossil Energy | Quasistatics<br>Geomechanics<br>Multiphase processes<br>Reactive Processes |
| Renewable Energy | Thermal Science<br>Fluid Mechanics<br>Aerodynamics |
| Nuclear Energy | Thermal<br>Fluid Mechanics<br>Quasistatics<br>Multiphase processes |
| Critical Infrastructure<br>- Energy<br>- Transportation<br>- Information<br>- As built | NLLDM<br>Energetic Materials<br>Fire<br>Aerosols |

## DRIVERS

This viewgraph summarizes key drivers related to the nuclear weapons program in the post cold war era. These drivers all result in the expectation of a greater reliance on simulation-based methods for accomplishing the weapons program in the future.

### Drivers

| | |
|---|---|
| **Performance**<br>Normal & Hostile Environments | • No new system development<br>• Loss of UGT<br>• Changing STS requirements<br>• System modifications<br>• Reduced test infrastructure |
| **Safety**<br>Abnormal Environments | Simulation provides a means for substantive improvement in nuclear safety design and assessment methodology |
| **Reliability** | • Unprecedented stockpile aging coupled with limited information on aged weapons<br>• *Anticipate* rather than *react* |
| **Manufacturing** | • Reduced design and manufacturing capacity<br>• Sunsetting of key manufacturing technologies<br>• Requirement for small lot, rapid response with low defect rate |

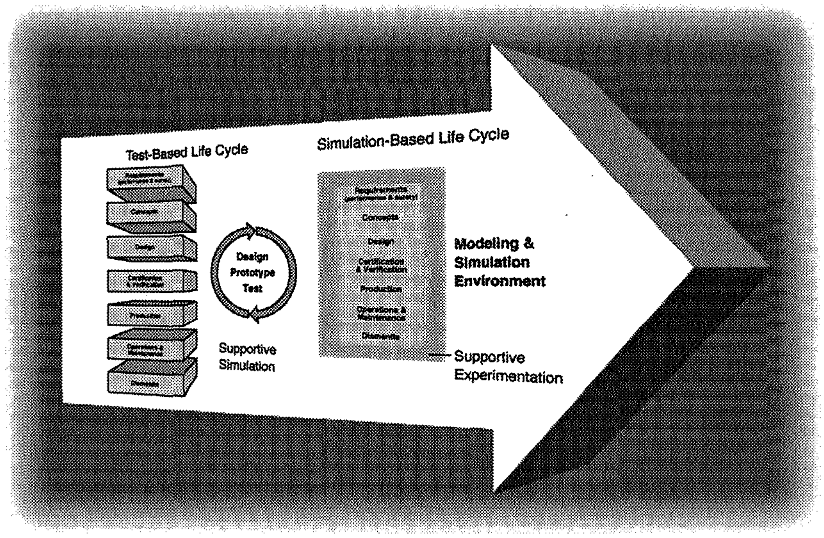
4/6/97• GovPrgms:PP 8

Sandia National Laboratories

## MODELING AND SIMULATION BASED LIFE CYCLE ENGINEERING

Overview of the shift to greater simulation-based approaches that we entitle, "modeling and simulation-based life cycle engineering." Key in the viewgraph is the vision of shifting from an engineering design cycle where simulation is supportive of a traditional test-based approach to one where experimentation for validating models is supportive of a simulation-based life cycle.

### Modeling and Simulation Based Life Cycle Engineering




4/6/97• GovPrgms:PP 9

Sandia National Laboratories

## THE EVOLVING ROLE OF MODELING AND SIMULATION DEMANDS UNPRECEDENTED CONFIDENCE AND FUNCTIONALITY

Enumerates the key elements of achieving the level of functionality and confidence necessary to achieve the vision discussed in the previous viewgraph. Achieving these elements reflect how numerous programs within the Laboratory are being coordinated to achieve the necessary simulation capability.

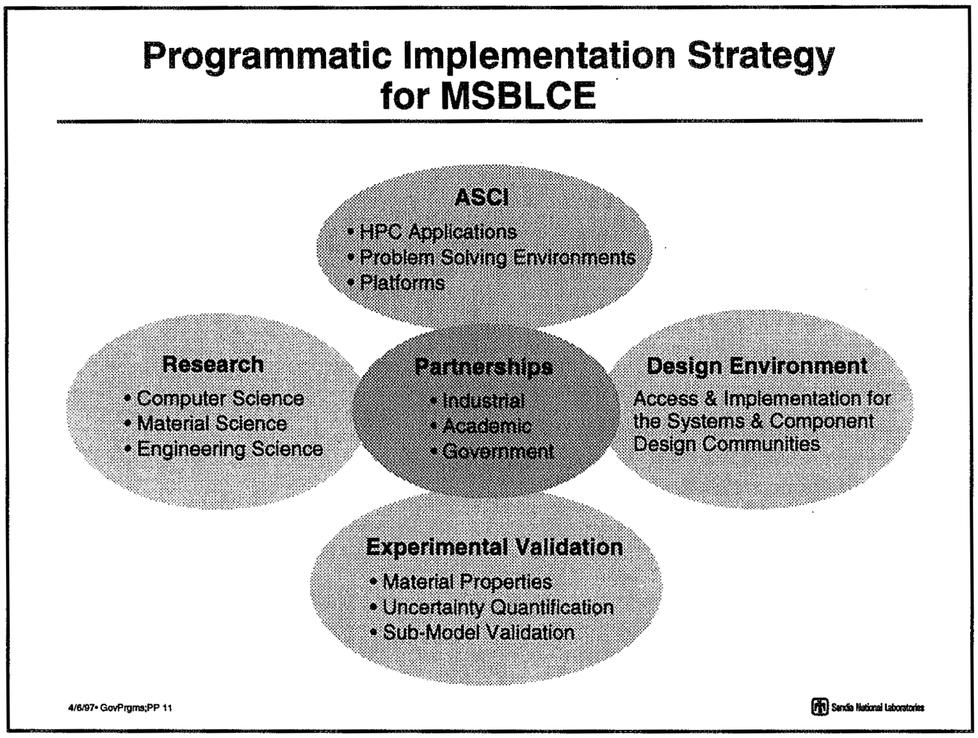
### The Evolving Role of Modeling and Simulation Demands Unprecedented Confidence and Functionality

- **Fidelity**
  - Full treatment of relevant physics
  - Full dimensionality
  - Software verification
  - Multiple length and time scales
- **High Performance Computing**
- **Experimental Validation and Discovery**
- **Explicit Treatment of Uncertainty**
- **Problem-Solving Environment**

4/8/97• GovPrgms;PP 10 Sandia National Laboratories

## PROGRAMMATIC IMPLEMENTATION STRATEGY FOR MSBLCE

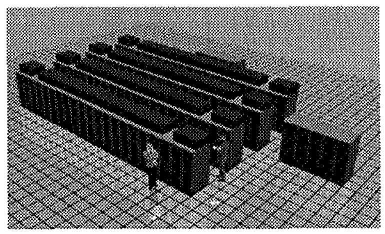
Introduces the different program elements that are currently being worked to increase the simulation capabilities to meet the demands in confidence. This viewgraph introduces the DOE's ASCI Program which is dramatically increasing the computational capabilities at the Laboratory. It also indicates the need for partnerships with other research and technology entities to achieve the necessary technology development.



## ASCI SUPERCOMPUTER EXCEEDS ONE TRILLION OPERATIONS PER SECOND

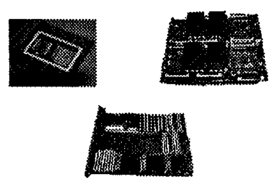
This viewgraph summarizes the computing capabilities of the first teraflop machine that is currently operational at Sandia. This is the first in a series of machines that will be placed at the DOE Weapon Laboratories over the next seven years. These machines are on track to achieve 10-100 Tflops in that time period.

### *ASCI Supercomputer Exceeds 1 Trillion Operations per Second*



- **1.81 TeraFlops peak performance using 9072 Pentium Pro processors**
  ***Equivalent to 6 billion people doing 300 calculations per second or 36,000 Cray 1's***
- **583,000 MBytes memory**
  ***Equivalent to 140 million pages of text or about 400,000 books***
- **2419 GigaBytes/second memory communication bandwidth**
  ***Internal communication equivalent to 302 million simultaneous telephone conversations***
- **Capability at Sandia through 1999**
  ***Enables important nuclear weapons simulations***

***Uses Intel's Commodity COTS Building Blocks***



4/6/97• GovPrgms;PP 12

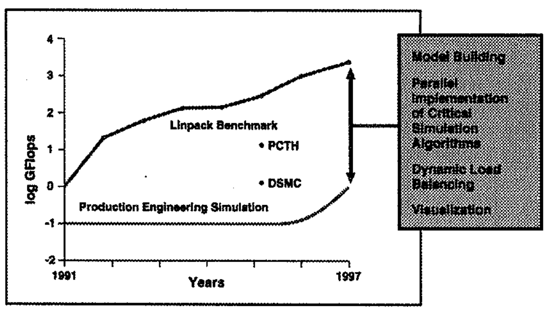
Sandia National Laboratories

## SANDIA HAS HAD A LONG TERM COMMITMENT TO HIGH-PERFORMANCE COMPUTING RESEARCH

This viewgraph points out that the magnitude of simulation capability jump that is about to occur rests upon a foundation of computational science related to the use of massively parallel architectures. This research has been underway for about ten years and has now reached the point where production engineering calculations on these machines can be accomplished.

### Sandia Has Had a Long Term Commitment to High-Performance Computing Research

- Ten years of research in MPP.
- Numerous achievements and awards.
- Success underpinned by advances in software - OS, domain decomposition, algorithm development.




ASCI provides the resources to realize the full potential of MPP for weapons mission simulation.

4/6/97• GovPrgms;PP 13 Sandia National Laboratories

## 1.0 SCOPE AND PRIMARY CHALLENGES IN MATERIAL MECHANICS

The next five viewgraphs briefly identify research areas and indicate some specific projects underway in the area of structural dynamics. Of particular note is the major software development effort, SALINAS, to develop a structural dynamics code capable of 100 million DOF simulations on a massively-parallel computer.

### 1.0 Scope and Primary Challenges in Structural Dynamics

**Technical Area Description, Scope**

***Computational and Experimental Structural Dynamics***

- Modeling and Simulation
- Finite Element Code Development (Teraflop Machine)
- Model Validation (System Identification)
- Optimization
- Probabilistic Structural Dynamics
- Health Monitoring
- Virtual Test / Optimal Test Design
- Advanced Signal Processing
- Non FE Methods (e.g., Neural nets)

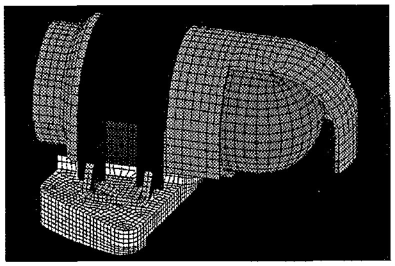
***Nonlinear Dynamics and Controls***

- Controls
- Active Vibration (Acoustic) Control
- Smart Structures and Materials
- Rotating Dynamics / Multi-Body Dynamics
- Flexible Robotics
- Damping
- MEMs

4/6/97• GovPrgms;PP 14 Sandia National Laboratories

# SALINAS - STRUCTURAL DYNAMICS FINITE ELEMENT CODE DEVELOPMENT

## Salinas - Structural Dynamics FE Code Development



***Objectives***

Provide capability for dynamic structural analysis on MP machines

DP Driver - Provide capability to simulate STS environments and propagate loads to DOE components for Normal, Hostile and Fratricide environments.

Provide FE capability on MP machines to perform optimization, estimation (model validation) and non-deterministic analysis.

***Approach***

•Develop Salinas, a structural dynamics (modal and transient) FE code for ASCI machines. Salinas will be structured to leverage efforts in SIERRA and other ASCI software.

•Incorporate emerging capabilities in iterative linear equation solvers, and eigensolutions.

•Develop iterative eigensolver for MP machines.

***Schedule, Funding, and Milestones***

Funding: FY96 0.3M; FY97 0.6M; FY98 2.0M;

| | |
|---|---|
| Prototype Code available | 7-97 |
| Improved Eigensolution Available | 8-98 |
| Initial Software Completion | 8-99 |

Partnerships: U of Colorado, Rice.

PI: Garth Reese (845-8640) gmreese@sandia.gov

Dan Segalman, djsegal@sandia.gov

4/8/97• GovPrgms:PP 15

Sandia National Laboratories

# TECHNICAL TARGETS IN STRUCTURAL DYNAMICS

## Technical Targets in Structural Dynamics

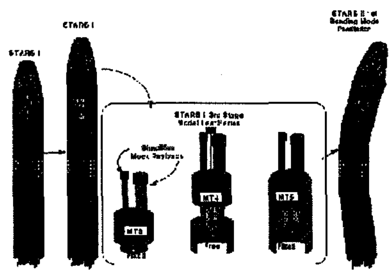
| Mission | Mission Need | Technical Capability Needed |
|---|---|---|
| •Performance<br>•Product Realization | Component Shock & Vibration Response of Weapon Systems for MSBLCE | •MP FE Code (high fidelity, 3-D Dynamic Structural Models<br>•Model Validation & Refinement,<br>•Optimization Methodology<br>•Rapid Prototyping & Virtual Test<br>•Predictive Damping Capability<br>•Modeling of Joints and Interfaces (Non-Linear)<br>•Non-Deterministic Methods<br>•Extended Experimental Ranges |
| •Product Realization | •Precision Motion Control for Advanced Manufacturing | •Active / Passive Controls<br>•Smart Structures & Materials |
| Performance | Simulation for Advanced MEM's Design and Applications | Microscience Dynamics |
| Performance | Simulation for Missile/Payload, Telescope, and Space Systems | Model Validation & Refinement,<br>Non-Contacting Sensing |
| Performance | Intelligent Structure Design for Weapon Systems/Components | Hybrid Controls, Optimization, and Health Monitoring Methods |

4/6/97• GovPrgms;PP 16

Sandia National Laboratories

# SYSTEM IDENTIFICATION FOR STRUCTURAL DYNAMICS

## System Identification for Structural Dynamics



**Problem:**

**Locate sources of error and systematically correct computational models to improve predictive accuracy of dynamics simulations**

**Technical Approach:**

**Combine statistical estimation theory, finite element numerical methods and modal analysis to develop reconciliation codes**

**Accomplishments:**

**STARS Missile, JPL Interferometer, GM Cradle and Body-in-White**

**Estimation Codes: SSID, PEGA, PESTDY**
**Error Localization: ELAPSE (Modified Hemez Algorithm)**

**Partnerships: GM, Goodyear,JPL Phillips Lab, Aerospace Corp.**

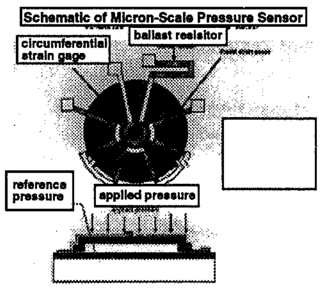
**PI: Kenneth Alvin, 844-9329, kfalvin@sandia.gov**

4/6/97• GovPrgms;PP 17

Sandia National Laboratories

# ESRF PROJECT OVERVIEW: STRUCTURAL DYNAMICS MICROSCIENCE AND MICROELECTRONICS RESEARCH

## ESRF Project Overview: Structural Dynamics Microscience and Microelectronics Research




**Problem:**

- Design optimization of micro scale silicon diaphragms used in pressure and acceleration sensors.
- Develop self-sensing solder joint using micro scale sensors and actuators.

**Technical Approach:**

- Nonlinear FE modeling with comparisons to measured data.
- Develop experimental solder joint test bed.

**Accomplishments:**

- Baseline static simulation of silicon diaphram correlated with experimental data.

**Partnerships:** MEMS research in Center 9100 investigating microsensors for defense systems applications.

**PIs:** Don Lobitz, 844-9398,
dwlobit@sandia.gov
Don Longcope, 844-2530,
dblongc@sandia.gov

## SCOPE AND PRIMARY CHALLENGES IN SOLID MECHANICS

The next six viewgraphs summarize current research efforts in solid mechanics. Included are brief summaries of current code capabilities for quasistatics, and transient dynamics (PRONTO). As an example of a key solid mechanics related algorithm that enables scalable finite element transient dynamic calculations on a massively parallel machine, the RCB contact algorithm is briefly described. The last viewgraphs in this group highlights a new research direction in transient dynamics simulation; namely, gridless approaches such as smooth hydrodynamics (SPH), in this case applied to the problem of penetration.

### Scope and Primary Challenges in Solid Mechanics

**Technical Area Description, Scope**

**The Solid Mechanics Technical Area provides computational codes which enable the simulation of material and structural response necessary to meet mission requirements. The focus is on development of high performance computer codes in the area of nonlinear, large deformation, quasistatic through high-strain rate mechanics.**

**Primary Challenge & Strategy**

**The primary challenge is to enable accurate, efficient and robust modeling and simulation which encompasses all required loadings, deformation amplitudes and rates, and length- and time-scale physics. The strategy is to develop leading edge finite element technology and solution algorithms, and implement them into the JAS and PRONTO codes.**

4/6/97• GovPrgms;PP 19

Sandia National Laboratories

# JAS: A 3D FINITE ELEMENT CODE FOR NONLINEAR, LARGE DEFORMATION QUASI-STATIC SOLID MECHANICS

## JAS: A 3D Finite Element Code for Nonlinear, Large Deformation Quasi-static Solid Mechanics

- Iterative equation solvers using CG and dynamic relaxation
- Objective material coordinate system
- Eight-node hexahedral (3D), four-node shell (3D), four-node quadrilateral (2D)
- Mean quadrature
- FB and assumed strain hourglass control
- Master/Slave contact algorithm with global detection
- Common source with PRONTO
- Vector and parallel implementation

4/6/97• GovPrgms;PP 20

Sandia National Laboratories

# PRONTO: A 3D FINITE ELEMENT CODE FOR NONLINEAR, LARGE DEFORMATION TRANSIENT DYNAMIC SOLID MECHANICS

## PRONTO: A 3D Finite Element Code for Nonlinear, Large Deformation Transient Dynamic Solid Mechanics

Explicit mid-point time integration

Objective material coordinate system

Eight-node Hexahedron (3D), four-node shell (3D), four-node quadrilateral (2D)

Mean quadrature

FB and assumed strain hourglass control

Adaptive time step

Symmetric contact algorithm with global detection

Common source with JAS

Vector and parallel implementation

4/8/97• GovPrgms;PP 21

Sandia National Laboratories

## TECHNICAL TARGETS IN SOLID MECHANICS

The next four viewgraphs discuss research in optimization methods, the results of which are being incorporated into the overall simulation environment being developed for the weapons' programs greater reliance on simulation.

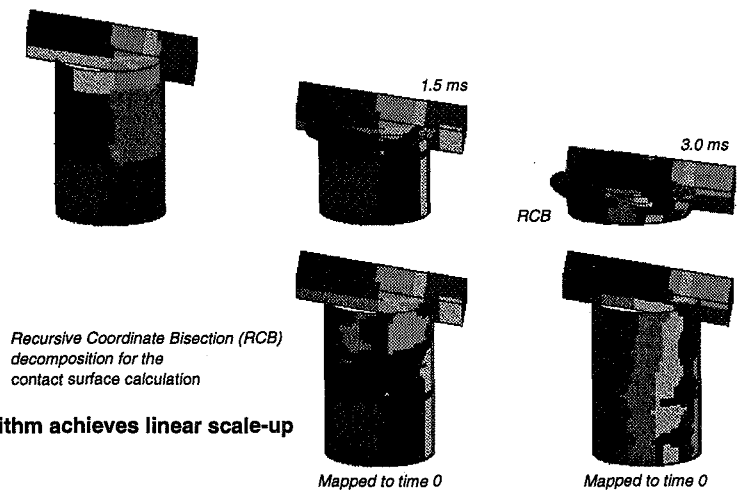
### Technical Targets in Solid Mechanics

| Mission | Mission Need | Technical Capability Needed |
|---|---|---|
| Weapon Performance | Penetration | Models for High Pressure Interfaces |
| | Laydown | Hex Shells, Nonlinear Tets, MP Codes, Solution Algorithms for Subcycling |
| | Neutron Generator Hostile Threats | Radiation Transport and Transient Dynamics Coupling |
| Weapon Safety | Crash and Burn | Hex Shells, Nonlinear Tets, Gridless Methods for Fuel Dispersal |
| | Thermal Cookoff | Thermal-Chemical-Mechanical Coupling, Robust Solution Algorithms for Quasi-statics |
| Product Realization | Encapsulation, Welding, Forging, Brazing, Soldering, and Adhesive Bonding | Thermal-Chemical-Mechanical Coupling, Robust Solution Algorithms for Quasi-statics |
| Aging and Reliability | Thermomechanical Fatigue, Fracture, Polymer Embrittlement | Multi-domain Solution Algorithms, Gridless Methods for Fracture |

4/6/97• GovPrgms;PP 22 Sandia National Laboratories

## CONTACTS ARE AN EXAMPLE OF A CRITICAL SIMULATION ALGORITHM SUCCESSFULLY IMPLEMENTATED FOR PARALLEL ARCHITECTURES

### Contacts are an Example of a Critical Simulation Algorithm Successfully Implemented for Parallel Architectures



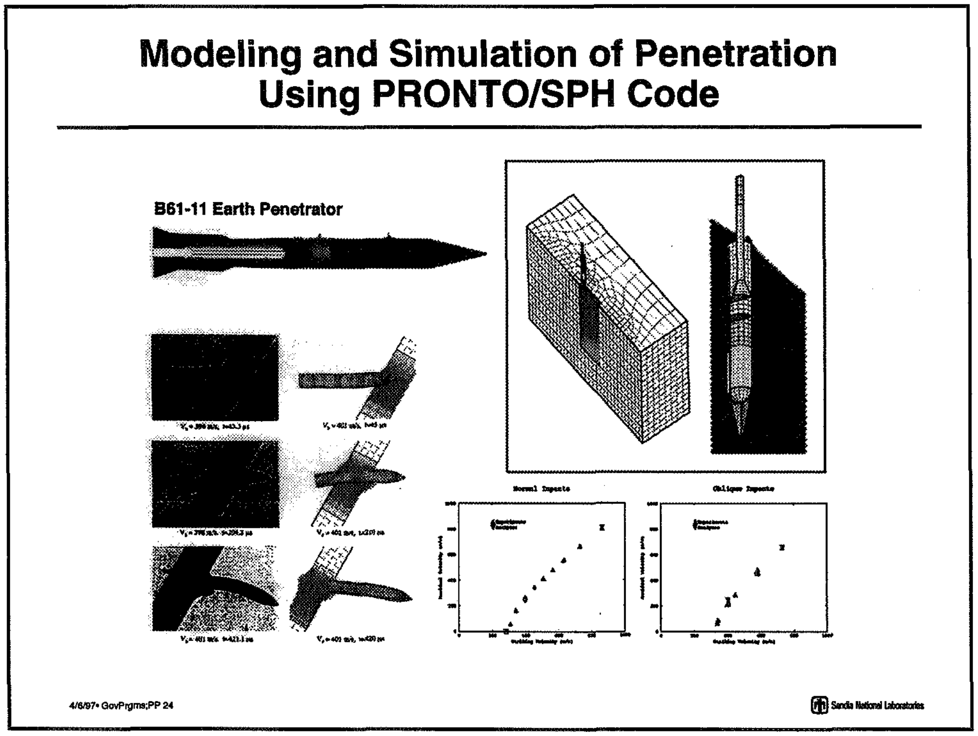

*Recursive Coordinate Bisection (RCB) decomposition for the contact surface calculation*

**Algorithm achieves linear scale-up**

4/6/97 • GovPrgms;PP 23

Sandia National Laboratories

# MODELING AND SIMULATION OF PENETRATION USING PRONTO/SPH CODE



## SCOPE AND PRIMARY CHALLENGES IN MATERIAL MECHANICS

The following seven viewgraphs highlight research directions in material mechanics. Of particular emphasis are new efforts to link the micro- and macro-scale to achieve more fundamentally based constitutive treatments for material response. This field will be particularly enabled by Teraflop scale computing.

### Scope and Primary Challenges in Material Mechanics

- **Technical Area Description, Scope**
  - Focuses on materials in the solid state
  - Develops constitutive models for solid mechanics finite element codes
  - Shares development of friction, wear and other interface models with solid mechanics technical area
  - Includes development of process models so as to:
    - understand material microstructural evolution throughout life cycle.
- **Primary Challenge and Strategy**
  - Develop predictive constitutive models for solid mechanics finite element codes governing deformation, damage/failure/fracture, and degradation in service.
  - Long-term challenge is to:
    - Build linkages between different length scales according to the application and based on sound thermodynamic and statistical frameworks
    - Understand role of defects and microstructure on properties and performance
    - Develop and apply models for defects and microstructure at all appropriate length scales
    - Retain computational efficiency in constitutive models.

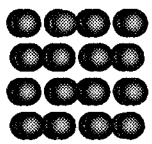
4/6/97• GovPrgms;PP 25

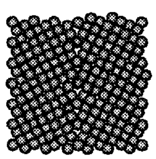
Sandia National Laboratories

# BACKGROUND: ATOMISTIC, MICROSTRUCTURE, AND CONTINUUM MATERIAL MODELING IN USE AT SANDIA

## Background: Atomistic, Microstructure, and Continuum Material Modeling in Use at Sandia

**Atomistic Methods:**





- **$A_1$ First Principle Methods:**
  - Plane-wave LDA-Pseudopotential
  - Mixed-basis-set LDA-Pseudopotential
  - KKR-CPA (Korringa-Kohn-Rostocker method & coherent potential approx.)
  - LMTO-CVM (Linear muffin-tin orbital & cluster variational method)
- **$A_2$ Approximate Methods:**
  - Tight-binding methods
- **$A_3$ Semi- Empirical Methods:**
  - EAM for noble metals
  - Cluster functional approach for transition metals
  - MEAM (Modified EAM) for covalent solids

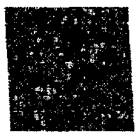
4/6/97• GovPrgms;PP 26

Sandia National Laboratories

# BACKGROUND: ATOMISTIC, MICROSTRUCTURE, AND CONTINUUM MATERIAL MODELING IN USE AT SANDIA

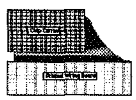
## Background: Atomistic, Microstructure, and Continuum Material Modeling in Use at Sandia

**Microstructure Models**



- $M_1$ Cellular automations and scaling theory
- $M_2$ Monte Carlo simulations
- $M_3$ Rate theories: master and Fokker-Planck equations
- $M_4$ Mean field theories

**Continuum Models**



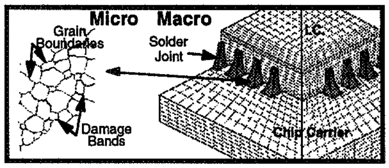
- $C_1$ Constitutive equations
- $C_2$ Internal variable approaches for plasticity and "damage" accumulation
- $C_3$ Effective medium theories for multi-phase materials

4/6/97• GovPrgms;PP 27

Sandia National Laboratories

# ESRF PROJECT OVERVIEW: TOOLS FOR BRIDGING LENGTH AND TIME SCALES

## ESRF Project Overview: Tools for Bridging Length and Time Scales




**Problem:**

Predictive numerical simulations of macroscopic material response require a means of determining macroscopic behavior from accurate microstructural process simulations. Effective material properties can be obtained from averaging over a representative volume element (RVE), but no objective criteria exist for establishing the size of the RVE. Knowing the RVE size explicitly is essential for using the results of the fine-scale simulations of heterogeneous materials to characterize the typical macroscopic behavior. Additionally, alternatives to volume averaging are needed when the RVE is larger than practical for finite element calculations.

**Technical Approach:**

- Apply the statistical physics concepts of thermodynamic limit and correlation length to develop length-scale bridging techniques. Use the thermodynamic limit to determine macroscopic property values directly from microstructural process simulation results, or use the correlation length to define the RVE size so that volume averaging is possible.

**Accomplishments:**

- "Correlation Length in Statistical Physics and RVE Size," SAND97-X, draft completed.
- "Overview of Scale-Bridging Capabilities," SAND97-X, in preparation.

**Resources:**

- $110K ESRF

**Partnerships:**

- None

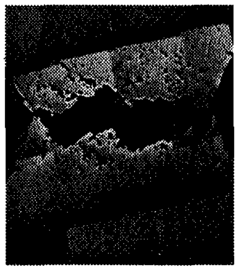
**PI:** John Aidun, (505) 844-1209
jbaidun@sandia.gov

4/8/97• GovPrgms;PP 28

Sandia National Laboratories

## ESRF Project Overview: Damage and Failure of Metals

Damage of a notched 304L tension specimen loaded at 800 C shows void growth and coalescence



**Problem:**

Large scale simulations require an accurate, yet computationally-efficient prediction of ductile failure. Our approach is based on evolution equations for void nucleation, void growth and coalescence. An accurate knowledge of the current stress state and past loading history is essential.

**Technical Approach:**

- Determine appropriate damage evolution for high temperature and high stress triaxiality combining numerical micromechanical modeling and experimental data
- Develop void nucleation and coalescence models for materials with precipitates, inclusions and other phases

**Accomplishments:**

- Nucleation model has been developed based upon micromechanical simulations

**Resources:** $130 K ESRF

**Partnerships:**

- Georgia Tech (McDowell)
- USAMP Cast Light Metals CRADA

**PI:** Mark F. Horstemeyer, (510) 294-1459
mfhorst@sandia.gov
Douglas J. Bammann, (510)-294-2585
bammann@sandia.gov

4/8/97• GovPrgms;PP 29

Sandia National Laboratories

# AN IMPORTANT USE OF STATE VARIABLE MODELS IS TO TRACK MATERIAL STATE THROUGH MANUFACTURING PROCESSES

## An important use of state variable models is to track material state through manufacturing processes.

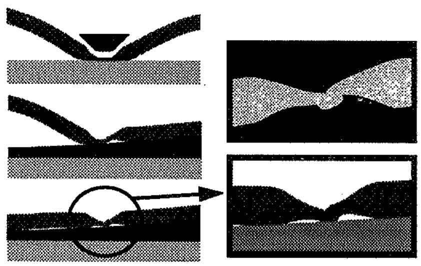
- Material parameters are determined for annealed material
- In each step, state variables are tracked and final variables from one step used as initial variables in next step
- For example, a multistage manufacturing process such as rolling is modeled and final values of state variables used to track ensuing anisotropy in hydroforming
- Final state of material after manufacturing is used as initial state in component design
- Important that state variables evolution incorporate temperature history, strain rate history and load path (include evolving anisotropy) history

4/6/97• GovPrgms;PP 30

Sandia National Laboratories

# APPLICATION OF THE BCJ STATE VARIABLE MODEL TO A GAS TRANSFER SYSTEM BURST DISK

## Application of the BCJ state variable model to a gas transfer system burst disk



Prediction of scoring, reforming and folding in the GTS Burst Disk

**Problem:**

Inconsistent burst pressures and fractures were obtained for the burst disk component of the GTS ACORN system. This led to excessive uncertainty in the performance and reliability of this critical DP component.

**Technical Approach:**

- Model the entire multi-stage manufacturing process of the burst disk from initial forming to scoring to reforming to welding to proofing to burst
- Apply the BCJ constitutive model, utilizing the strain rate and temperature dependence and ductile failure capabilities

**Impact:**

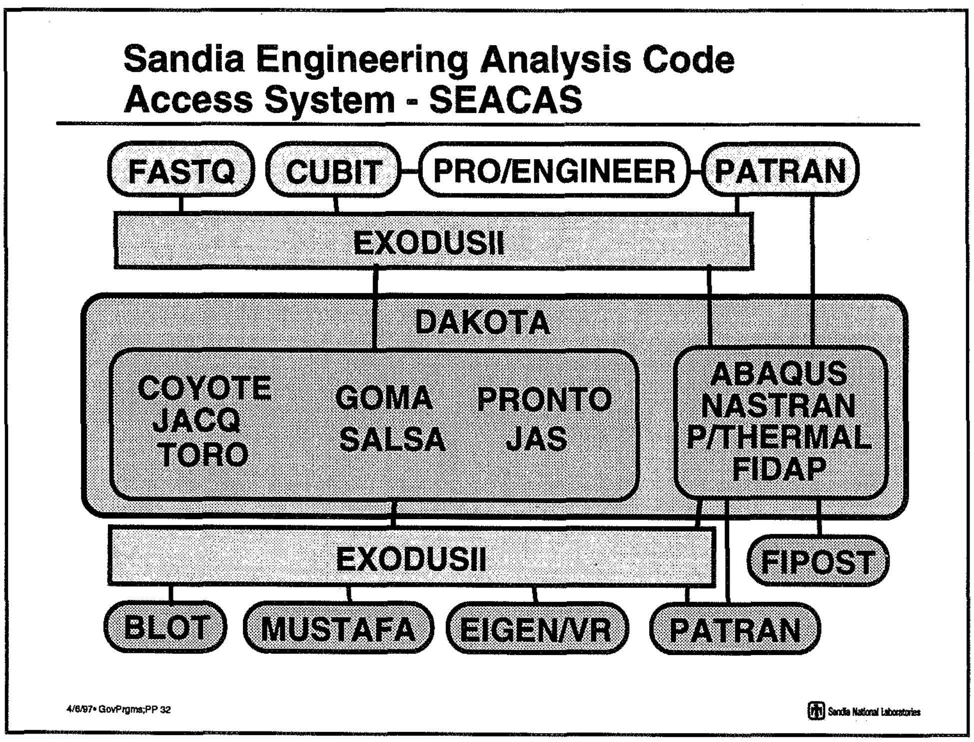
- Modeling showed that the inconsistent results were primarily a result of the manufacturing process
- Modeling helped to redefine the forming dies, scoring tools and manufacturing processes to prevent previously observed problems
- The new manufacturing process resulted in a design with predictable, reliable and consistent burst pressures

4/6/97• GovPrgms;PP 31

Sandia National Laboratories

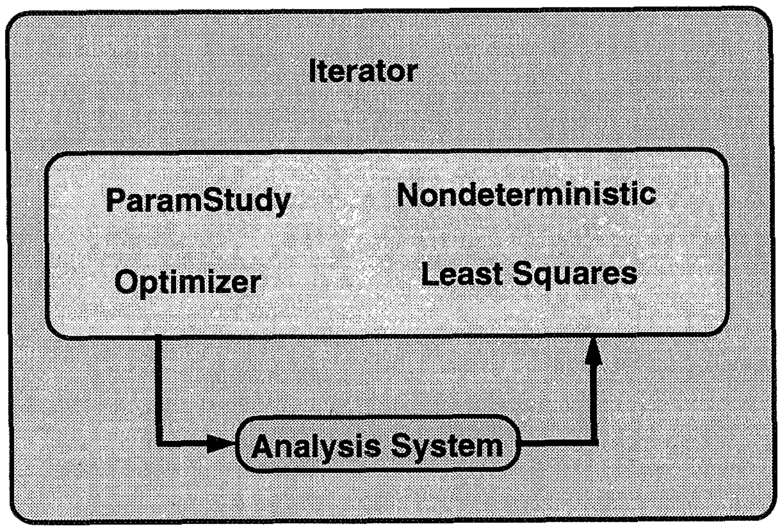
## SANDIA ENGINEERING ANALYSIS CODE ACCESS SYSTEM - SEACAS

The next four viewgraphs discuss research in optimization methods, the results of which are being incorporated into the overall simulation environment being developed for the weapons programs' greater reliance on simulation.



## DAKOTA "TOOLKIT" FOR OPTIMIZATION AND PERFORMANCE ANALYSIS

### DAKOTA "ToolKit" for Optimization and Performance Analysis

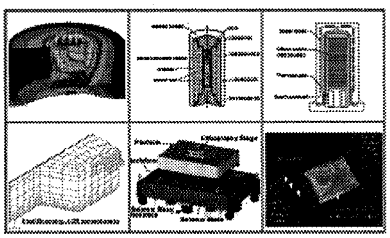



4/6/97• GovPrgms;PP 33

Sandia National Laboratories

# 5.0 ESRF PROJECT OVERVIEW: OPTIMIZATION RESEARCH AND DAKOTA DEVELOPMENT

## 5.0 ESRF Project Overview: Optimization Research and DAKOTA Development



WWW: http://endo.sandia.gov/9234/sd_optim.html

### Problem:

MSBLCE requires an accessible, useful, general-purpose "toolkit" for design optimization and performance analysis of complex engineering problems.

Answer fundamental engineering questions:
- What is the best design?
- How safe is it?
- How much confidence do I have in my answer?

### Technical Approach:

Flexible, extensible, object-oriented architecture provides broad problem-solving environment

Research in novel algorithms, hybridization, seq. approx., parallel proc., opt. under uncertainty

### Accomplishments:

Many successful application studies

Toolkit supports opt., uncertainty, parametric analysis, least squares, combination strategies

Single-level parallel approaches demonstrated

Successful GA/CPS/NLP hybrids demonstrated

### Partnerships:

Dave Zimmerman, Univ. of Houston

### PI:

Mike Eldred, 844-6479, mseldre@sandia.gov

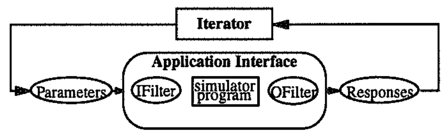
4/6/97• GovPrgms;PP 34

Sandia National Laboratories

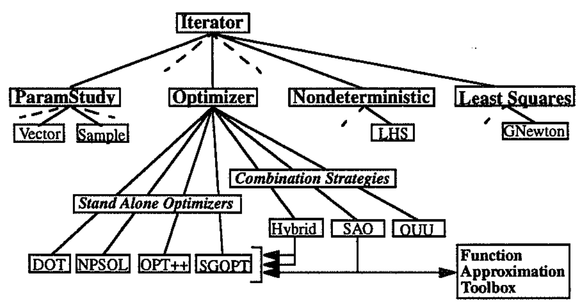
# DAKOTA OBJECT-ORIENTED SOFTWARE DESIGN

## DAKOTA Object-Oriented Software Design

- **Object-oriented design with C++: flexible, extensible, abstract.**
- **Generic "Application Interface" design isolates application specifics.**




- **Optimization is a part of a larger hierarchy of "Iterators," which leverages the utility of the interfacing software.**




4/6/97• GovPrgms;PP 35

Sandia National Laboratories

## UNCERTAINTY QUANTIFICATION

These last viewgraphs introduce an important topic that will be increasingly important as greater reliance is placed on simulation. That area is uncertainty quantification. A few brief examples of the impact that uncertainty quantification can have in reaching engineering judgments are provided. This is an area of increasing research emphasis at the Laboratory.

### Uncertainty Quantification

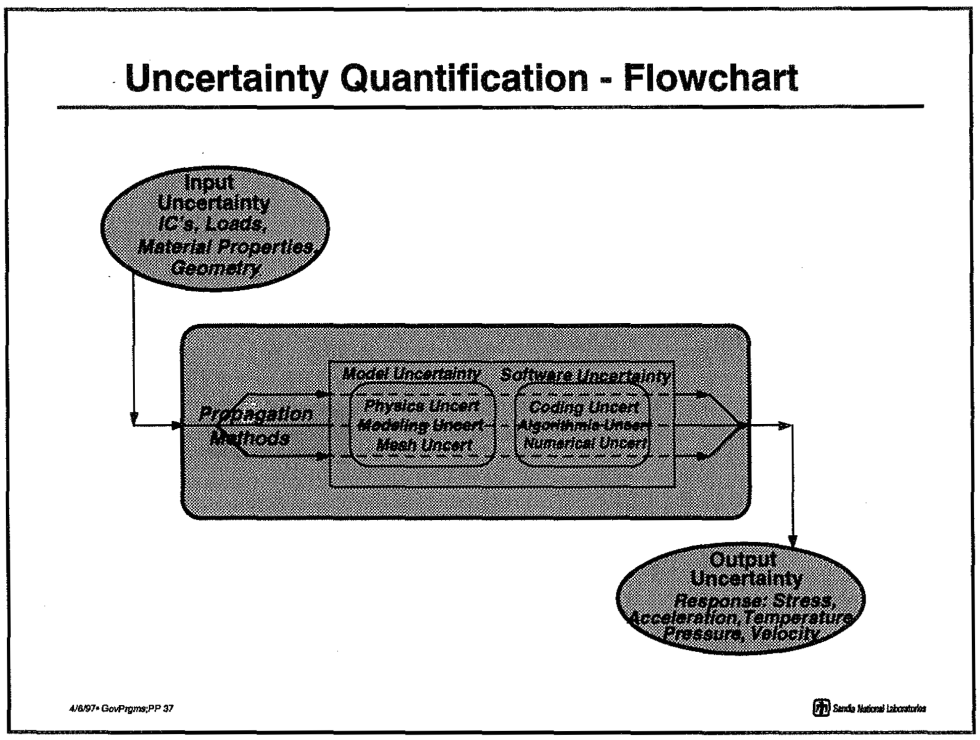
**Goal: To quantify our confidence that numerical simulation represents the physical world to answer an engineering question.**

**This deals directly with the issue of accuracy / predictability / uncertainty of our numerical simulations and is complementary to our other efforts in computational mechanics.**

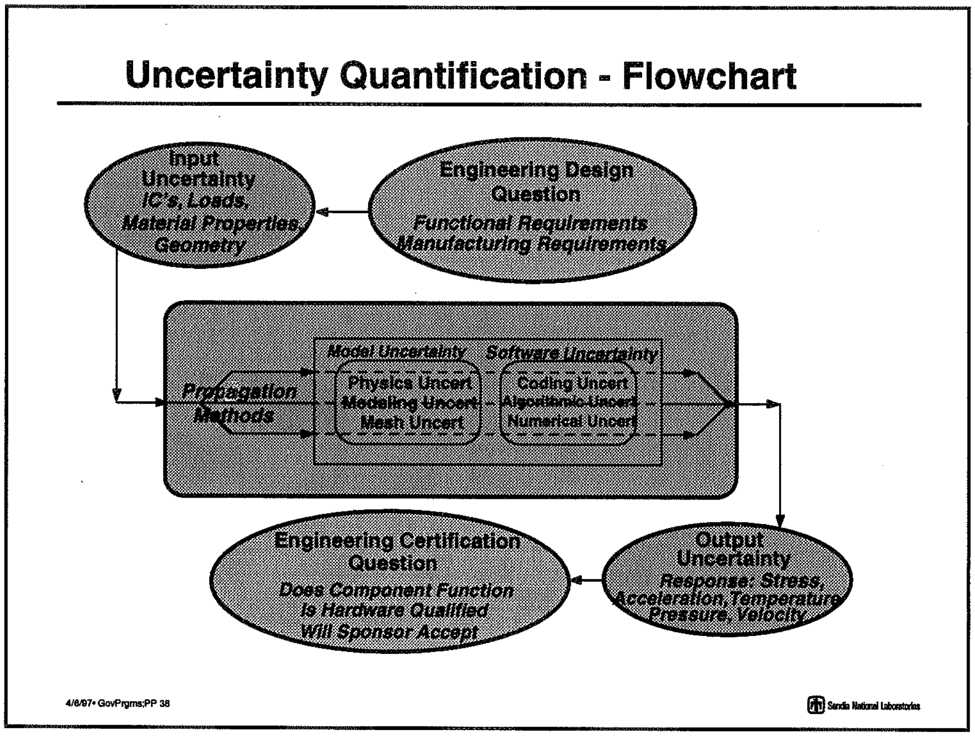
4/6/97• GovPrgms;PP 36

Sandia National Laboratories

## UNCERTAINTY QUANTIFICATION - FLOWCHART



# UNCERTAINTY QUANTIFICATION - FLOWCHART



## SCOPE AND PRIMARY CHALLENGES IN UNCERTAINTY QUANTIFICATION

### Scope and Primary Challenges in Uncertainty Quantification

Primary Challenges

- Account for All Sources of Uncertainty
- Validation and Verification Methodology
- (Codes, Models, Physics)
- Computationally Efficient Propagation/Analysis Methods
- Impact Projects to Answer "Engineering Questions"

Strategy

- Develop General Methodology Plan
- Develop Code Verification and Model Validation Plan
- Develop Fast Probability Integration Methods
- Develop Sampling Methods
- Input Uncertainty Quantification
- Incorporate Software Tools into DAKOTA
- Approximation Concepts for Analysis Codes

4/8/97• GovPrgms:PP 39

Sandia National Laboratories

# CREATING AN ENGINEERING SIMULATION ENVIRONMENT WHERE UNCERTAINTY QUANTIFICATION IS AN INTEGRAL COMPONENT

## Creating an Engineering Simulation Environment Where Uncertainty Quantification is an Integral Component

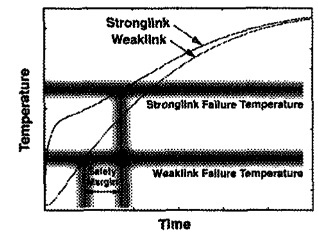
### Uncertainty is pervasive

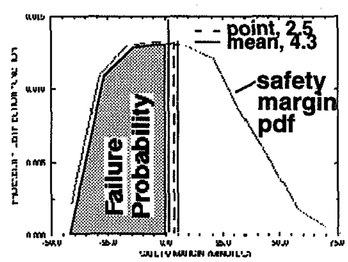
- Material properties
- Failure criteria
- Geometry
- Models

### Research Thrusts

- Monte Carlo methods
- Reliability-based methods
- Perturbation techniques

### Realistic treatment of uncertainty is critical to confidence




4/6/97• GovPrgms;PP 40

Sandia National Laboratories

# Structural Mechanics Code Development at Lawrence Livermore National Laboratory

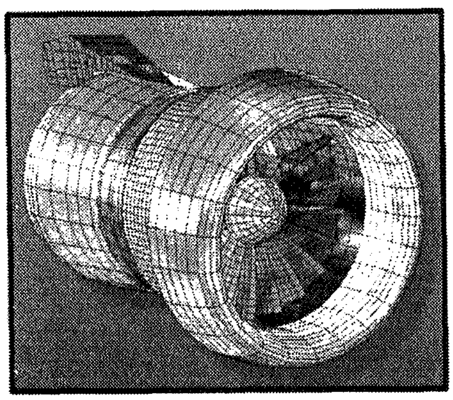
Peter J. Raboin
Lawrence Livermore National Laboratory
Livermore, CA

# STRUCTURAL MECHANICS CODE DEVELOPMENT AT LAWRENCE LIVERMORE NATIONAL LABORATORY

Peter J. Raboin
Group Leader
Methods Development Group
Defense Technologies Engineering Division
Mechanical Engineering
Lawrence Livermore National Laboratory
Livermore, CA

Structural Mechanics Code Development At Lawrence Livermore National Laboratory

Peter J. Raboin



This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48

## LLNL DEVELOPED COMPUTATIONAL MECHANICS CODES ARE ESSENTIAL TO THE DELIVERY OF UNIQUE ANALYSIS CAPABILITIES TO LAB PROGRAMS

Lawrence Livermore National Laboratory has developed a unique set of finite element codes for solving structural mechanics problems for Laboratory programs, specifically the Weapons and Lasers programs. Going back twenty years, these codes have developed into a family of explicit and implicit finite element codes called DYNA and NIKE. The TOPAZ code is our implicit heat transfer code and it is integrated with the DYNA and NIKE codes. The Methods Development Group is responsible for the development of these codes and supports the sixty or so analysts who use these codes daily. New SMP and MPP computers are coming into use at our Lab and we have reason to be very optimistic about the increased modeling capabilities that improved compute speeds provide. New code capabilities however are driven by the need to solve problems presented by our program analysts.

### LLNL Developed Computational Mechanics Codes Are Essential To The Delivery Of Unique Analysis Capabilities To Lab Programs

- The Methods Development Group is responsible for the continuous improvement and support of computational mechanics codes: DYNA – NIKE – TOPAZ
- MDG codes are used by 60 LLNL analysts, and hundreds of institutions around the world.
- Recent advances in SMP and MPP computer hardware are rejuvinating MDG codes with unprecedented possibilities.

Programmatic problems provide the strongest impetus to drive increased code capabilities.

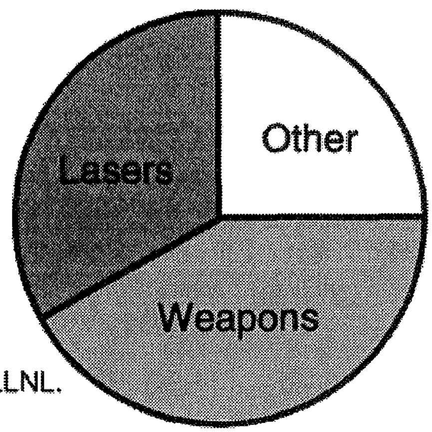
## ME CODE DEVELOPMENT CATALYZES SIXTY LLNL ANALYSTS WITH NEW CAPABILITIES AND INCREASED FLEXIBILITY

As previously mentioned, the DYNA, NIKE and TOPAZ codes are used by sixty analysts at LLNL. Just over 40% of these experts work on Weapons projects, a third for the Lasers program, and the balance on an assorted mix of energy, materials, and new technologies projects. We have a code collaboration program which allows us to share our developments with others provided they agree to return code improvements to our effort. In the last year, several code improvements, most notably a solver from NASA, have provided strong benefits to solving our Lab's problems. Fundamentally though, we direct our code developments at internal issues, the collaborators make improvements for their own benefit, and then we share the fruits. Frequently our efforts are synergistic.

### ME Code Development Catalyzes 60 LLNL Analysts With New Capabilities And Increased Flexibility

#### The Customer Base:

- 50 – 60 Analysts depend on state-of-the art numerical analysis tools. 40+ in ME alone with the complement in Physics, C&MS, Earth Sciences and Energy.
- LLNL Weapons and Lasers programs are the primary beneficients.
- 152 code collaboration partners also develop our software and return new code developments to LLNL.
  - Solvers from NASA
  - Contact algorithms from Universities.
  - Material models from US industries.
  - Bug fixes from British Aerospace.

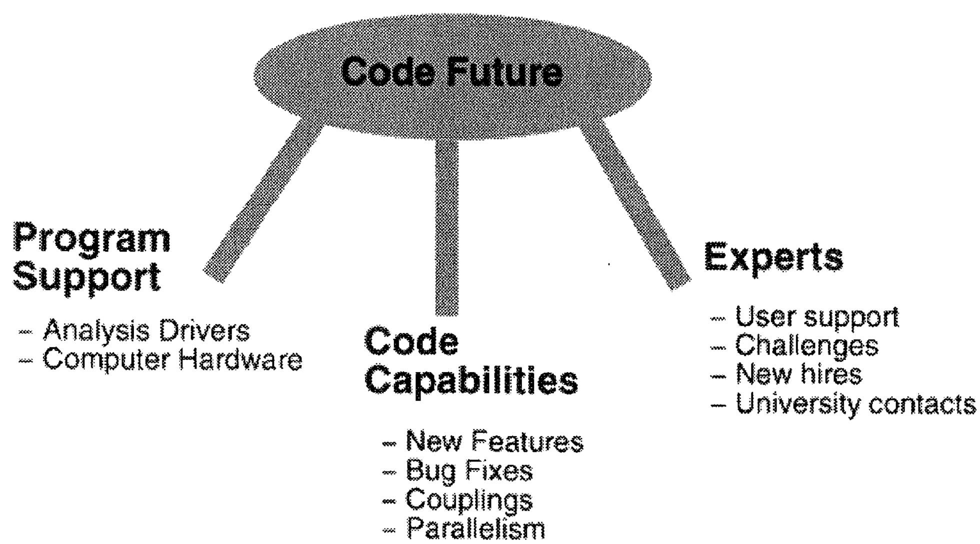



**Code Development is Wholly Driven By Customer Needs**

# THE FUTURE OF COMPUTATIONAL MECHANICS CODE DEVELOPMENT DEPENDS ON BALANCED IMPROVEMENTS

Three components are essential for a healthy, well-balanced code development effort. First and most important are the programmatic drivers that provide the Laboratory's mission. We are a support group, so we must remain lean and efficient in order to maintain our high value to the programs. The second essential component is to provide the continuous forward momentum in the development of new code capabilities. DYNA, NIKE and TOPAZ are not "static" codes but are under sustained development. This perception is important to our analysts, the funding programs, and the code developers who desire work on relevant, cutting-edge codes. Lastly, staffing our code development with experts in computational mechanics is a significant challenge given the constraints of salary and job mobility in the software industry today. We must increasingly rely on university graduates.

## The Future Of Computational Mechanics Code Development Depends On Balanced Improvements



## LARGE SYSTEM ANALYSIS IS THE FUTURE TREND FOR STRUCTURAL MECHANICS CODE DEVELOPMENT AT LLNL

The common thread in our code development activities is the trend toward large systems analysis. This trend is reflected in our projects for parallel methods, rigid body mechanics and code couplings. In the parallel methods projects called ParaDyn we will be parallelizing the DYNA, NIKE and TOPAZ codes. The work on DYNA3D is mostly complete with separate parallelization strategies for the element loop and contact algorithms. The rigid body mechanics projects aim to simplify the numerical models by allowing the analyst to represent those bodies which do not significantly deform with simpler six degree-of-freedom representations that retain their complex geometries and surfaces for contact. Likewise, the code coupling projects seek to integrate different physics into larger system responses. We have coupled the NIKE3D code to two different optic codes in the past year to support our Lasers program.

### Large system analysis is the future trend for structural mechanics code development at LLNL

| LLNL Programs | Applications |
|---|---|
| Weapons | Structural integrity,damage, manufacturing simulations |
| Lasers | Thermo-Mechanical-Optical |
| ASCI | Multi-physics, parallelisms |
| Misc. | |
| - DoD/DSWA | Explosive/structure interactions |
| - Caltrans | Civil eng. structural integrity |
| - FAA | Fan blade-off, failure and out of balance loads |
| - FHWA | Vehicle/barrier/occupant simulations |
| - PNGV | Composites and metal springback |

**Computational R&D**

Parallel methods
- Expliciti and implicit
- Contact strategies

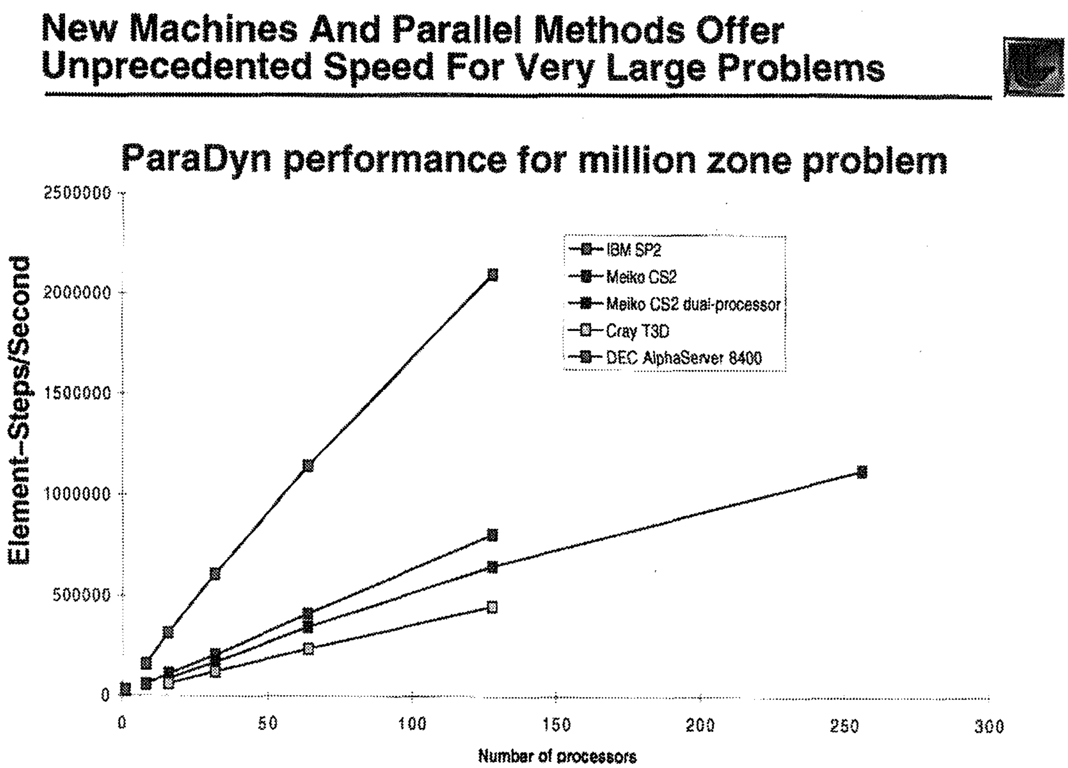
Rigid body mechanics
- Dynamic integration
- Material switching

Code couplings
- Multi-physics
- Explicit and implicit mechanics
- Unified element technologies

**Large system analysis can reveal multi-component interactions that are essential to understanding complex system behaviors.**

## NEW MACHINES AND PARALLEL METHODS OFFER UNPRECEDENTED SPEED FOR VERY LARGE PROBLEMS

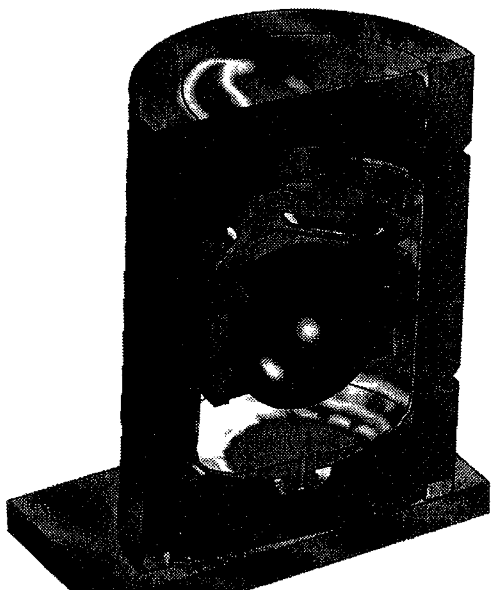
Our largest code development project is for the parallelization of DYNA, NIKE and TOPAZ codes. The ParaDyn project has parallelized DYNA3D and then performed benchmark calculations on a million-element underground shock problem. The code performance demonstrates good processor scaleability and indicates that our newest MPP supercomputer, IBM's SP2, has outstanding compute speed for DYNA3D problems.



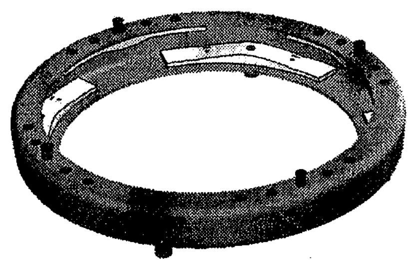
## DYNA3D SIMULATIONS ARE CRITICAL TO THE PROCESS OF DESIGN/ANALYSIS EXPERIMENT

This viewgraph provides an example of how dramatic speed-ups in DYNA3D can have a potent effect on the design process. In this shipping container which must withstand impact loadings, DYNA3D running on a CRAY-YMP, took 140 hours to complete execution. With 60K plus nodes and more than 25 slide surfaces, the compute time fell to less than 10 hours using parallel DYNA3D on IBM's SP2. Similar speed-ups were obtained on the Meiko MPP supercomputer. With these advantages our analyst was able to provide design changes backed up by simulations faster than the experiments could be performed.

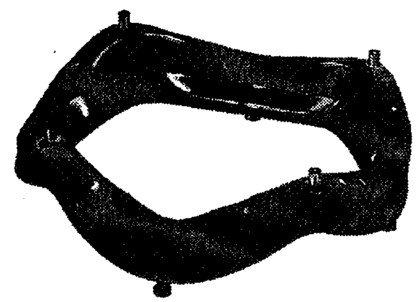
### DYNA3D simulations are critical to the process of design/analysis/experiment



AT400A
shipping container



An energy absorption
requirement demanded an
analysis-driven flange design



EAG-DR-Rabon-3/97-9

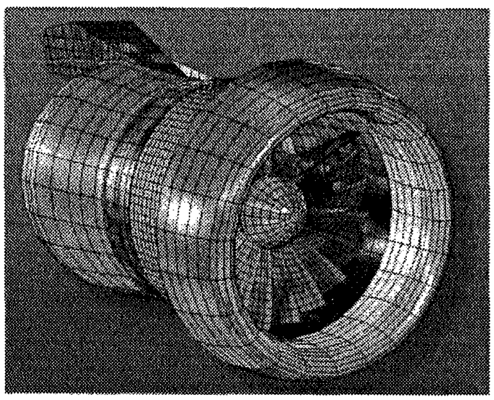
## DYNA3D IS A FINITE ELEMENT PROGRAM FOR ENGINEERING PROBLEMS

DYNA3D is our explicit finite element code and is useful for solving high rate events and predicting structural dynamic responses. In these examples, larger system responses are obtained from the failure of key components. For the jet engine, a blade failure causes out-of-balance rotor loads, rubbing of blades at their outer tips, and blade-to-blade contact during the failure. In the second case, a failure in a suspension system joint affects the tire motion.

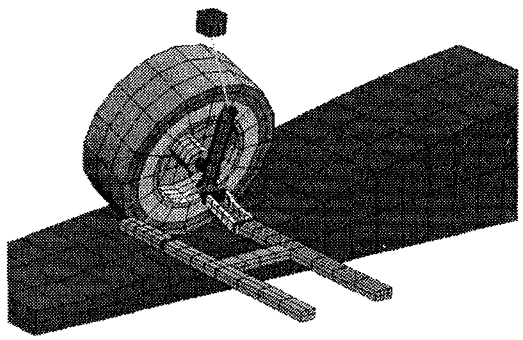
### DYNA3D is a finite element program for engineering problems

**Explicit – High Rate Dynamics**

- Computes deformations, forces, and accelerations for each element
- Wide variety of material models including metals, foams, rubbers, composites, explosives, rocks and concrete
- ParaDyn – parallel version of DYNA3D



Boeing blade-off
- Rotational Invariance
- Shell Failure



Rigid body systems
- Rigid body contact
- Joint Failure

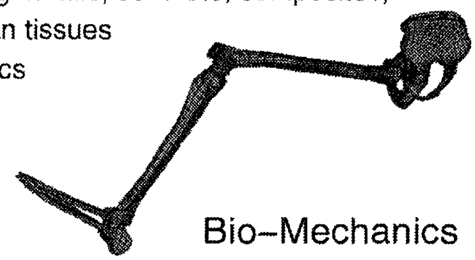
## NIKE3D FINITE ELEMENT CODE FOR ENGINEERING APPLICATIONS

NIKE3D is our structural dynamics and statics code. This code offers a more accurate solution with its increased element integration scheme but it must solve the nonlinear set of equations derived from element stiffness matrices describing the degrees of freedom at each node. NIKE3D has become more important in recent years as the capabilities of SMP computers with their prodigious memory capacity has improved.These computers with special matrix solvers are able to factorize and solve hundreds of thousands of degree-of-freedoms in reasonable time periods. In these two examples large system analyses are performed to obtain local solutions to problems which are driven by more global boundary conditions. The overpass on I-580 and I-24 in California is subjected to earthquake loadings and the lower body skeleton is subjected to vehicle impact loadings.

### NIKE3D
### Finite Element Code for Engineering Applications

Implicit – Structural Dynamics & Statics

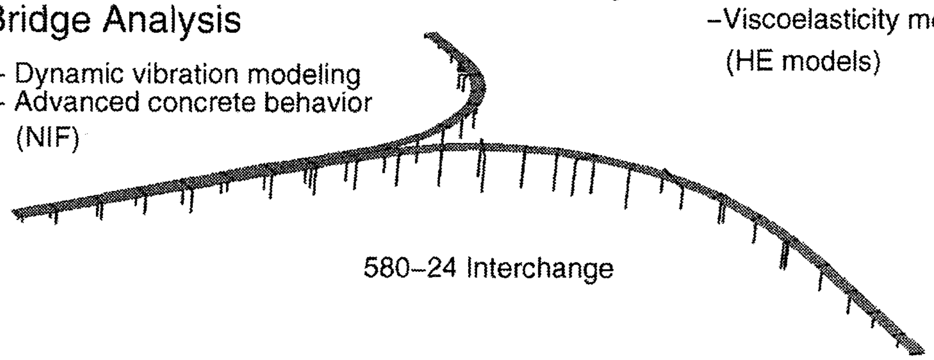
- Computes stiffnesses, deformations, accelerations and forces for each element
- Wide variety of material models including metals, concrete, composites, foams, rubbers and visco-elastic human tissues
- Coupled thermal and structural mechanics



Bio–Mechanics
-Viscoelasticity models (HE models)

CALTRANS Seismic Bridge Analysis

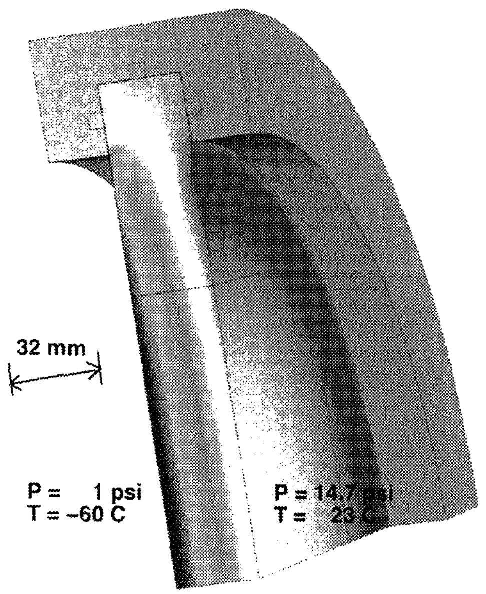
- Dynamic vibration modeling
- Advanced concrete behavior (NIF)



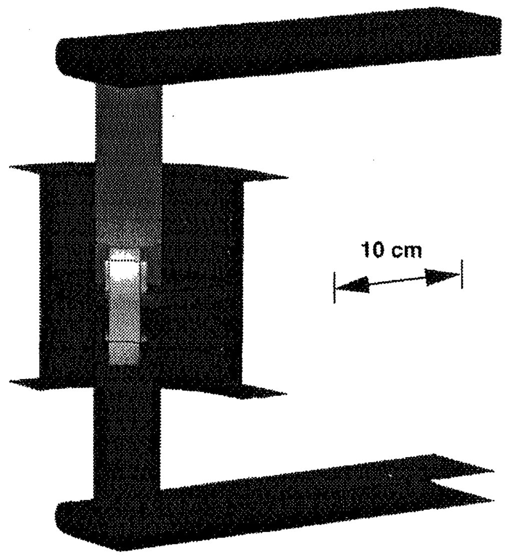
## TOPAZ3D FINITE ELEMENT CODE FOR HEAT TRANSFER

TOPAZ3D is the implicit heat transfer code which is integrated with the DYNA and NIKE codes. This workhorse code continues to solve problems important to our Laboratory. In these examples, TOPAZ calculates a thermal gradient in an optic to be used by NIKE3D for a thermal stress calculation. The second case examines temperature profiles for the Advanced Production Tritium facility that is being designed.

### TOPAZ3D
### Finite Element Code For Heat Transfer




HIRIS
Infrared Transmissive
Pressure Window




APT
Vacuum Barrier Window

## COMPUTATIONAL MECHANICS CODES ARE A CORNERSTONE CAPABILITY FOR SUPPORTING LLNL PROGRAMS

Lawrence Livermore National Laboratory has a long history of developing computational mechanics codes for its Laboratory mission. These programs remain strong today and the needs and sophistication of the mechanics analysts who use DYNA, NIKE and TOPAZ software are increasing. SMP and MP supercomputers require software advances to harness their increased capabilities. Our ParaDyn project will parallelize the DYNA, NIKE and TOPAZ codes, and secure for them the benefits of the increased compute power of our new SMP and MPP computers. We have already benefited from these gains with better designs for shipping containers and a new ability to solve large system analyses.

### Computational mechanics codes are a cornerstone capability for supporting LLNL programs

- Code development investments have paid-off for LLNL
  - DYNA, NIKE & TOPAZ codes are the mainstay of engineering analysis
  - The importance of these codes is international recognized
  - Early research in parallelization is paying off.
- Strong enabler for B-Division ALE3D development: past and present.
- The new SMP and ASCI capability investments enable us to again achieve world class results for Grand Challenge problems.

**Structural mechanics code development has increased our opportunities and expectations for solving important problems**

# Aircraft Engine Materials: Recent Trends and Future Directions

Jim C. Williams
General Electric Aircraft Engines
Cincinnati, OH

# Aircraft Engine Materials: Recent Trends and Future Directions

*Jim C. Williams*

**AIAA Structures Technical Committee**
**Hampton, VA**

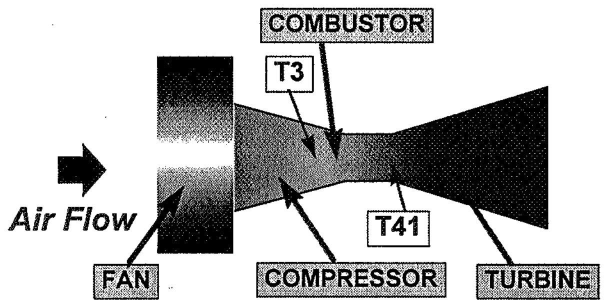
**September 4, 1997**



## Outline

- Introduction
- Engine performance discussion
- Role of materials
  - Disks
    - + Current status
    - + Barriers/Issues
      - $T_3$ and $T_{41}$
      - Life methods
      - Cost
  - Airfoils
    - + Turbine
      - Current status
    - + Compressor
      - Current status
- Summary and Take-aways

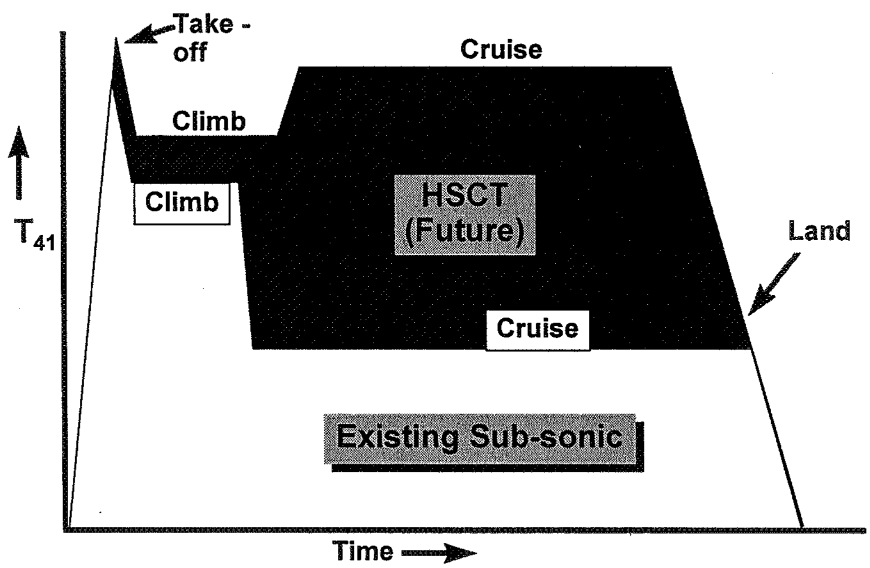
## Time Series of Engine Operating Parameters




| Year | OPR | T3 (° C) | T41 (° C) | BPR |
|---|---|---|---|---|
| 1970 (CF6) | 15:1 | 590 | 1345 | 5 - 6 |
| 1994 (GE90) | 38:1 | 695 | 1425 | 8 - 9 |
| -2010 Adv. Demo. | 75:1 | 815 | 1760 | 12-15 |
| -2006 HSCT | 25:1 | 620-705 | 1540-1650 | ~1 |

aiaa noor.ppt 3

## Conceptual Cycles and Temperatures

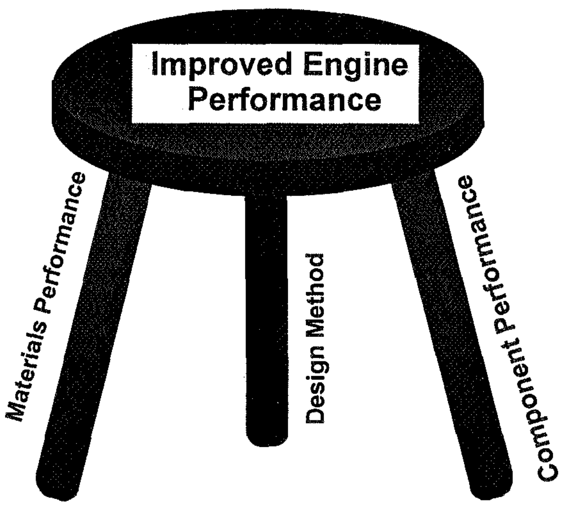



aiaa noor.ppt 4

## GE90 Cross Section

alaa noor.ppt 5

## Improved Engine Performance




Improved Engine Performance is a 3-Legged Stool

alaa noor.ppt 6

## Requirements for SFC Improvement

- Higher cycle temperatures
  - Higher T capability disks - compressor & turbine
  - Higher T capability compressor airfoils and casings
  - Higher T capability turbine airfoils
- Improved component designs
  - Improved cooling efficiency - turbine
  - Flatter combustor profiles
  - Improved aerodynamic efficiency - compressor & turbine
- Lighter weight, stiffer designs for better clearances
  - Selective use of higher specific stiffness materials, e.g. TMC's
  - Introduction of lower density materials, i.e. TiAl
  - Improved fan case and nacelle designs (using PMC's?)

**These improvements must be achieved affordably !**



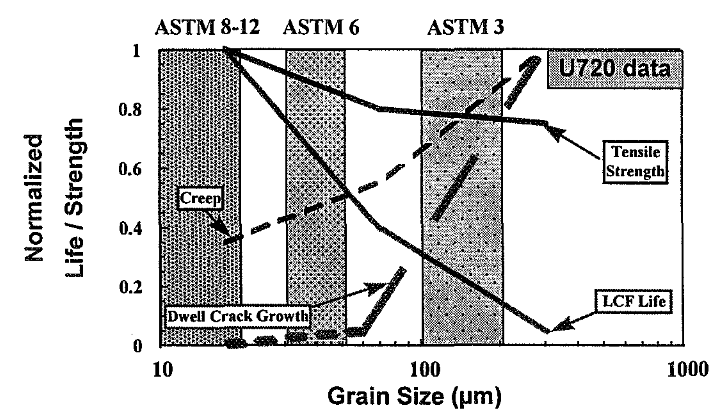
## Disk Materials

## Trends / Issues in Ni Base Disks

- Higher operating temperatures
  - Transition from fatigue to creep limited domain in wrought alloys
  - Higher solute alloys fix creep but require powder metallurgy methods
    - + Improved / different approaches for life methods
  - Hold time fatigue crack growth accelerates rapidly with temperature
  - Creep and Hold Time Crack Growth (HTCG) Rate resistant alloys
    - + New alloy compositions / dual alloys / dual microstructures
    - + Coarse grain processing methods
    - + Increased producibility issues
- Use of process modeling for forging and heat treatment
  - Allows faster, better definition of process window
- Improved inspection capabilities
  - Very useful for process window verification
- Long hot times for High Speed Civil Transport
  - No experience in the industry with these requirements

aiaa noor.ppt 9

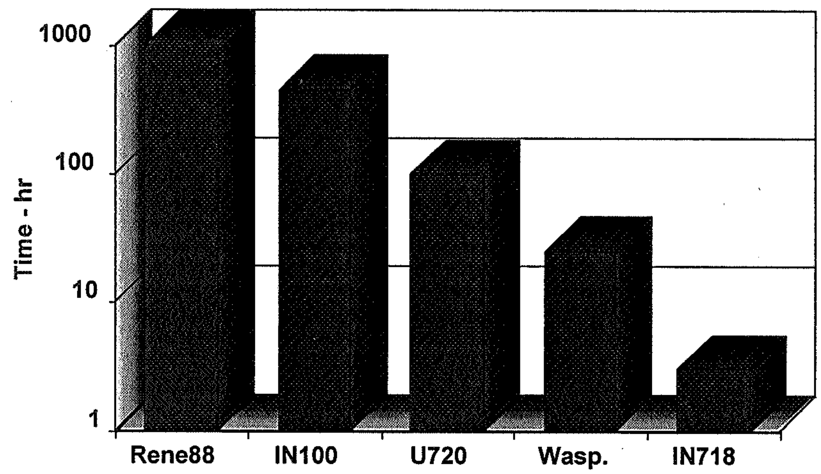
## Grain Size Impacts Are Powerful




**Significant implications for processing choices**

aiaa noor.ppt 10

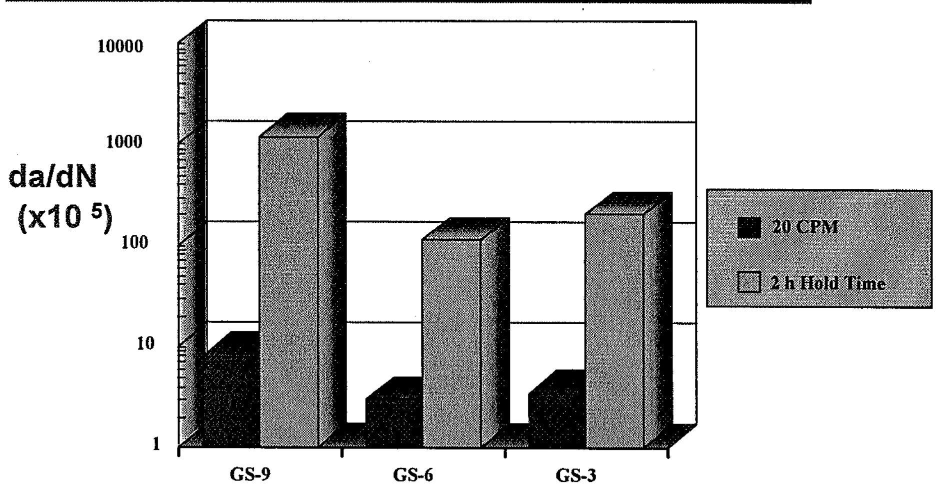
## Disk Alloy Creep Strength




650° C (1200° F) / 115 ksi / 0.2% Creep time



## Effect of Grain Size and Hold Time on Crack Growth




Increasing Grain Size Improves Crack Growth
Until Carbide Film Formation Occurs

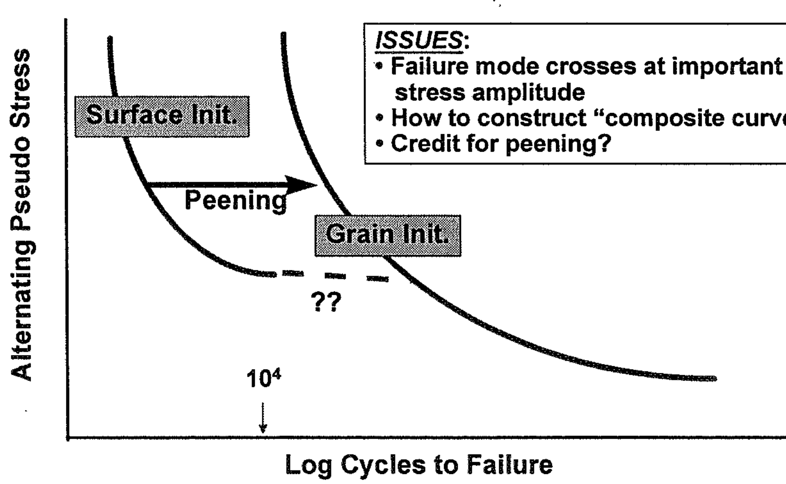
## Life Methods for Disks

- Transition from cast & wrought to PM alloys changes approach
  - Deterministic methods being replaced by probabilistic methods
  - New models and methods are more comprehensive and inclusive
    + Required to meet longer life, higher service temperature
    + New life limiting considerations
  - Additional input data required
    + Ceramic inclusion content and distribution
    + Effects of surface treatment, i.e. shot peening
- Increasingly robust products required
  - Greater precision in determination of margin
  - Recognition of process variation and incorporation in design
  - Use of process modeling to control degree of variation
    + Moving from implicit to explicit process understanding

**New methods require broader enterprise integration**

aiaa noor.ppt 13

## LCF Issues in Designing with PM Disk Alloys




*ISSUES*:
- Failure mode crosses at important stress amplitude
- How to construct "composite curve"?
- Credit for peening?

**Must balance real materials behavior with margin in life**

aiaa noor.ppt 14

## Rotor Cost Issues

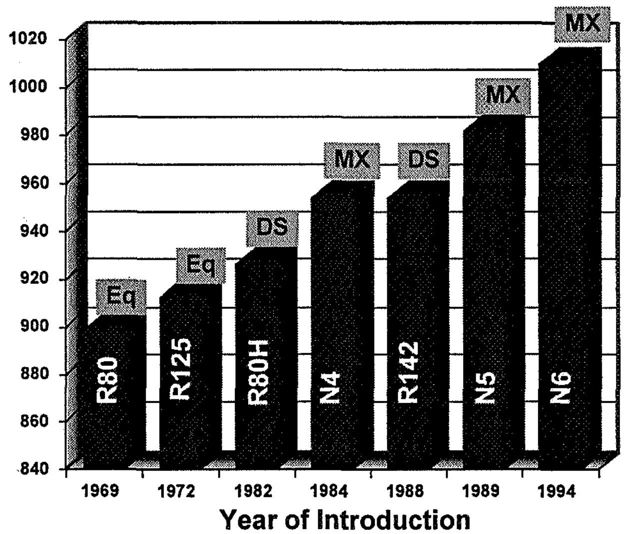
- Powder metallurgy billet and forgings very expensive
  - Extrude and iso-forge (E + I) process stable but expensive
  - Current powder yields of -270 mesh stable but not improving
  - Using coarser mesh size would create life issues
  - Coarse grain processing adds to cost
  - Machining distortion more severe with higher T capability alloys
- Alternatives to E + I not mature at present
  - HIP + forge
    - + Possible for conventional sub-solvus processing
    - + Less clear for coarse grain processing
  - Clean melt sprayforming
    - + Cleanliness demonstrated with ESR+CIG technology
      - + Processibility and yields (cost) being worked

**Alternatives to E + I at least 3 years from qualification**



## Turbine & Compressor Airfoils

## *Turbine Blade Alloy Temperature Capability*






## *Current Generation Turbine Airfoil Issues*

- **Producibility issues with current generation alloys**
  - Castibility of advanced cooling designs
    - + Non-reactive cores expensive and hard to remove
    - + Multi-piece cores can create yield losses
- **Trend to higher refractory element content alloys**
  - Hurts oxidation
    - + Tip retention issues in long life applications
    - + Alloy stability more critical for high T, long life
  - SRZ and coating induced reactions increase stability concerns
  - Cost of alloying additions and increases in density
- **Hotter service Temperatures will require internal coatings**

**Probably only one more generation of Ni- base alloy left**

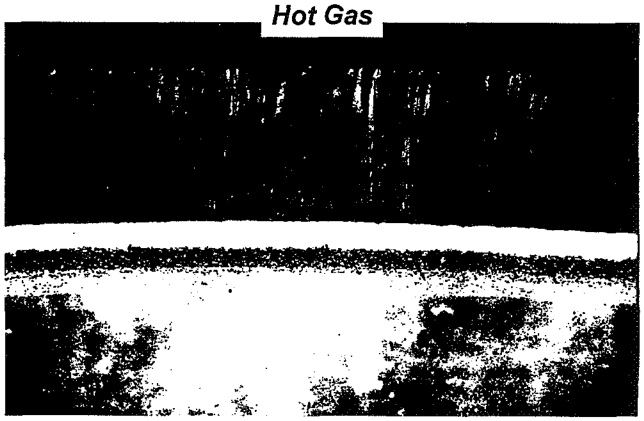
## Higher T Capability Turbine Airfoils

- **Material & coating requirements**
  - Creep strength
  - Stability
    - + Microstructural
    - + Coating growth
  - Oxidation resistance
    - + Tip oxidation / EGT retention
  - TBC's
    - + Durability improvements now
    - + Highly reliable TBC's for ΔT later
- **Component requirements**
  - Improved cooling designs
    - + Producibility vs. cooling air use
  - Initial cost
  - Repair?

**Must treat alloys and coatings as a system**

alaa noor.ppt 19

## Thermal Barrier Coatings




TBC Features:
- Columnar structure in top coat for spall resistance
- Oxidation resistant and adherent bond coat
- Bond coat compatible with alloy substrate

alaa noor.ppt 20

## Future Generation Turbine Airfoils

- More complex cooling and aero designs - Ni base
  - Fabricated blade production and inspection methods not ready
    - + Cost and Producibility?
    - + Coating / cooling hole interaction?
- New materials
  - Monocrystal NiAl
    - + Successful vane demostration
    - + Significant manufacturing issues
    - + No longer working due to FOD sensitivity
  - CMC's - many issues to be worked (to be discussed later)
    - + MI SiC may hold promise
      - Cooling needs to be worked out
      - Environmental degradation in question
  - TiAl
    - + Moving toward introduction for LP applications
    - + TiAl maximum uncoated use TŠ760° C



## Future Generation Compressor Airfoils

- Higher $T_3$ requires improved creep strength
- Complex shapes (3D aero) harder to forge
- FOD and HCF an issue for compressor airfoils
- Alloy selection and shape may require casting
  - Existing conventionally cast HP turbine airfoil alloys adequate
  - Leading edge fill challenging for thin compressor cross sections
  - HCF resistance of cast airfoils lower than current wrought blades
  - Impact resistance (FOD) not as well characterized in cast blades
  - Blisk manufacturing more difficult with cast airfoils
  - Cost of cast airfoils may be attractive

**Cast compressor airfoils at least several years from qualification**

## Summary and Take-aways

- Improved SFC demands will continue to require higher T capability materials
- Higher T disk alloys will use PM and coarse grain processing
  - Probabalisitic lifing methods
  - Cost will be major issue in future implementation
  - Processes for dual heat treatment and dual alloys not mature
- Higher T HPT airfoils will require improved alloys, coatings and cooling designs
  - Probably one more full generation of one piece airfoils
- Cast higher T compressor airfoils most promising
  - HPTB Alloys adequate
  - Casting process not mature yet

**Cost will pace the rate of technology introduction and investment !!**

| REPORT DOCUMENTATION PAGE | | | *Form Approved* *OMB No. 07704-0188* |
|---|---|---|---|



| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | November 1997 | Conference Publication |

**4. TITLE AND SUBTITLE**
Government-Sponsored Programs on Structures Technology

**5. FUNDING NUMBERS**
522-31-21-33

**6. AUTHOR(S)**
Ahmed K. Noor and John B. Malone, Compilers

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
NASA Langley Research Center
Hampton, VA 23681-2199

**8. PERFORMING ORGANIZATION REPORT NUMBER**
L-17670

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA/CP-97-206241

**11. SUPPLEMENTARY NOTES**
Ahmed K. Noor: University of Virginia Center for Advanced Computational Technology, Hampton, VA
John B. Malone: Langley Research Center, Hampton, VA
Co-sponsor: AIAA Structures Technical Committee, Reston, VA

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified–Unlimited
Subject Category 39 Distribution: Standard
Availability: NASA CASI (301) 621-0390

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** ***(Maximum 200 words)***
This document contains the presentations from the joint UVA/AIAA workshops on Government-Sponsored Programs on Structures Technology, held on April 6, 1997 in Kissimmee, Florida and on September 4, 1997 in Hampton, Virginia. Workshop attendees were the Members and Friends of the AIAA Structures Technical Committee. The objectives of the workshops were to a) provide a forum for discussion of current government-sponsored programs in the structures area; b) identify high-potential research areas for future aerospace systems; and c) initiate suitable interaction mechanisms with the managers of structures programs.

**14. SUBJECT TERMS**
Structures technology; Smart materials and structures; Multifunctional structures; Flexible, load-bearing structures; Extreme environmental structures; Computational methods

**15. NUMBER OF PAGES**
290

**16. PRICE CODE**
A13

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | |