

# **Large Composite Structures Processing Technologies for Reusable Launch Vehicles**

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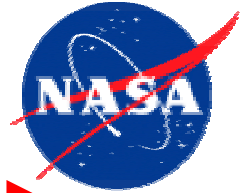
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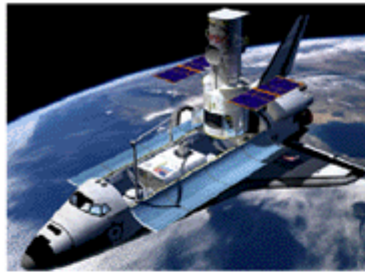
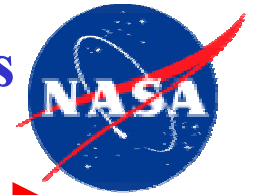
**Presented at  
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# Outline



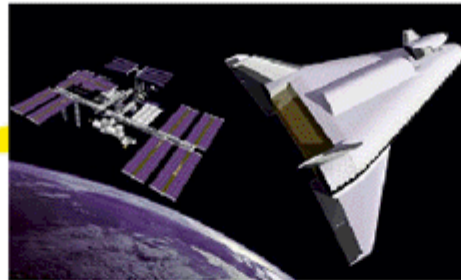
- **Second Generation RLV Goals and Technology Drivers**
- **Current Technology for Large Scale Polymer Matrix Composites**
- **Technology Scale-up Issues**
- **Emerging Out-of-Autoclave Processing Technologies**
- **NASA Development Activities**
- **Industry Experience**
- **Summary**

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



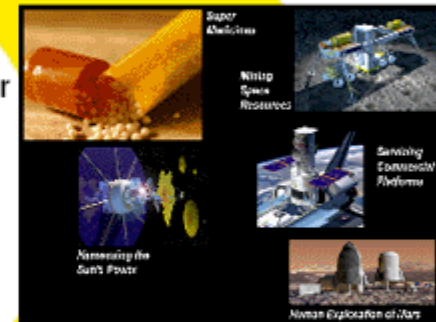
## Today: Space Shuttle 1st Generation RLV

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



## 2010: 2nd Generation RLV

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



## 2025: 3rd Generation RLV

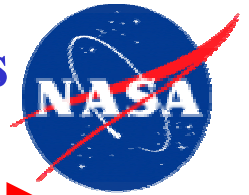
- ◆ New Markets Enabled
- ◆ Multiple Platforms / Destinations
- ◆ 100x Cheaper
- ◆ 10,000x Safer

## 2040: 4th Generation RLV

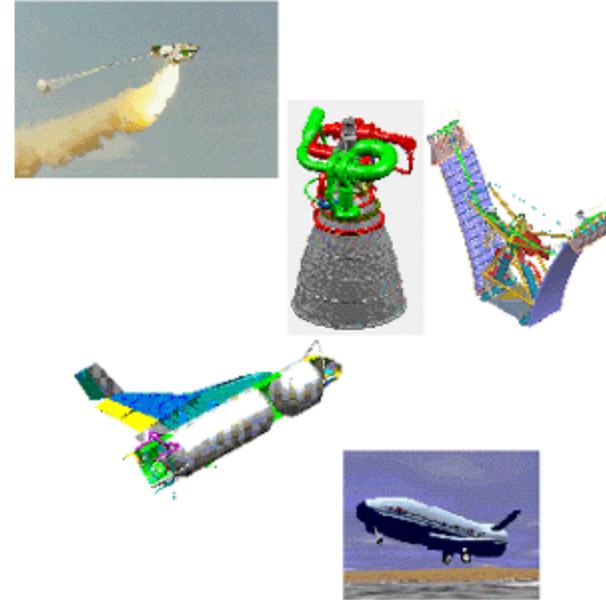
- ◆ Routine Passenger Space Travel
- ◆ 1,000x Cheaper
- ◆ 20,000x Safer



# Large Composite Structures Processing Technologies for Reusable Launch Vehicles

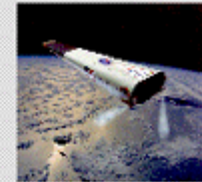
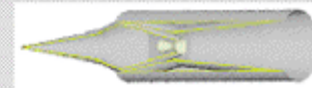


- ◆ **Crew Escape and Survival**
  - ◆ Detection, separation, ascent/descent
- ◆ **Operable, Long-life  $H_2/O_2$  and  $RP/O_2$  Engines**
  - ◆ 200 mission life, 100 missions to overhaul
- ◆ **Long life, lightweight integrated airframe**
  - ◆ Critical integrated cycle testing (500 missions)
- ◆ **Advanced TPS, IVHM, and Operations**
  - ◆ Quick turn vehicle with intelligent data analysis

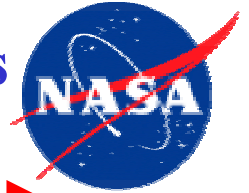


- ◆ **Ejector Ramjet**
  - ◆ Improved performance margin
- ◆ **SHARP Leading Edges**
  - ◆ Global crossrange from orbit

*Cutting Edge for 2nd Generation*



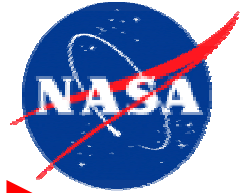
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## Current Technology

- No known proven processes, tooling, or equipment to manufacture composite cryogenic tank structures over 25 ft. in diameter in the U.S.
  - Relatively small tanks built to date have been fabricated by hand, an improbable process for RLV.
  - Fiber placement and autoclave processes have been demonstrated at small scale (LMMSS X-33 10 ft. demo tank and LMSW X-33 LH<sub>2</sub> proto-flight tank).
- NASA/LaRC has supported substantial material and process technology development through the High Speed Research (HSR) and Advanced Composites Technology (ACT) programs for large scale vehicle structures (wing, fuselage, joints).
  - Resin film infusion-autoclave cure.
  - RTM/VARTM-oven cure.
  - Hand lay-up autoclave cure.
  - PETI-5 material and out-of-oven-autoclave processing.
  - Stitched composite preform development.
- Demonstrations have hinted at feasibility of manufacturing technologies.
- Progression to RLV scale structures requires new manufacturing developments.

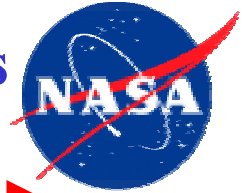
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## **Fiber Placement Machine Technology Scale-Up Issues.**

- Software upgrades.
  - Accommodate effects of large scale tooling.
  - Accommodate complex (design-specific) geometries.
  - Address simulation requirements.
- Hardware upgrades.
  - Placement head/drives must accommodate complex geometries.
  - Build material delivery system (potential).
- While not a technology issue, long lead times will be required for system design, fabrication, assembly, and operational verification which must be considered in program planning.

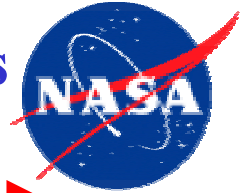
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## **Autoclave Technology Scale-Up Issues.**

- Control of thermal field (rise rates, holds, cooldown).
- Sealing issues.
  - Lock ring assembly fabrication and installation.
  - Door seal alignment.
- Special requirements for assembly and facilitization.
- While not a technology issue, long lead times will be required for system design, fabrication, assembly, and operational verification which must be considered in program planning.

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles

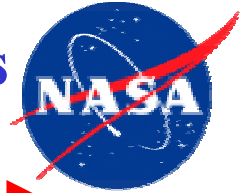


## Tooling Technology Scale-Up Issues.

- Tool design and analysis.
  - Single or multi-piece construction trades.
  - Material selection: weight; CTE issues; compatibility with part fabrication and curing requirements (deformation under load, sag, thermal mass, etc.).
  - Lay-up tolerances.
  - Integration with fiber placement and curing equipment.
  - Part removal.
- Tool handling.
  - Removal from fiber placement machine.
  - Transportation to curing equipment.
  - Disassembly (if required) and storage.



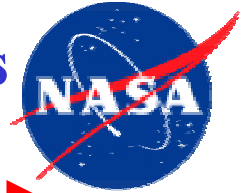
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## Emerging Out-of-Autoclave Processing/Manufacturing Technologies.

- Among the foremost challenges associated with fabrication and assembly of large polymer matrix composite structures is curing.
- Conventional aerospace PMC components typically require high temperature autoclave cures, and the associated tooling to achieve acceptable mechanical properties and dimensional tolerances.
- The economics of conventional curing techniques is acceptable on small scale components, however, as part sizes increase, scale-up of autoclave equipment and component tooling increases dramatically.
- Out-of-autoclave processing methods may enable significant cost savings in the fabrication of large scale composite articles.
- Currently several out-of-autoclave processing methods are under consideration for large component fabrication.
  - Thermoplastic in-situ consolidation.
  - “All at once” electron beam (E-Beam) curing.
  - In-situ e-beam cure.
  - Vacuum assisted resin transfer molding (VARTM).

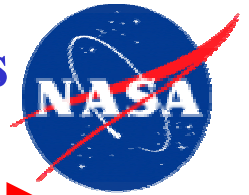
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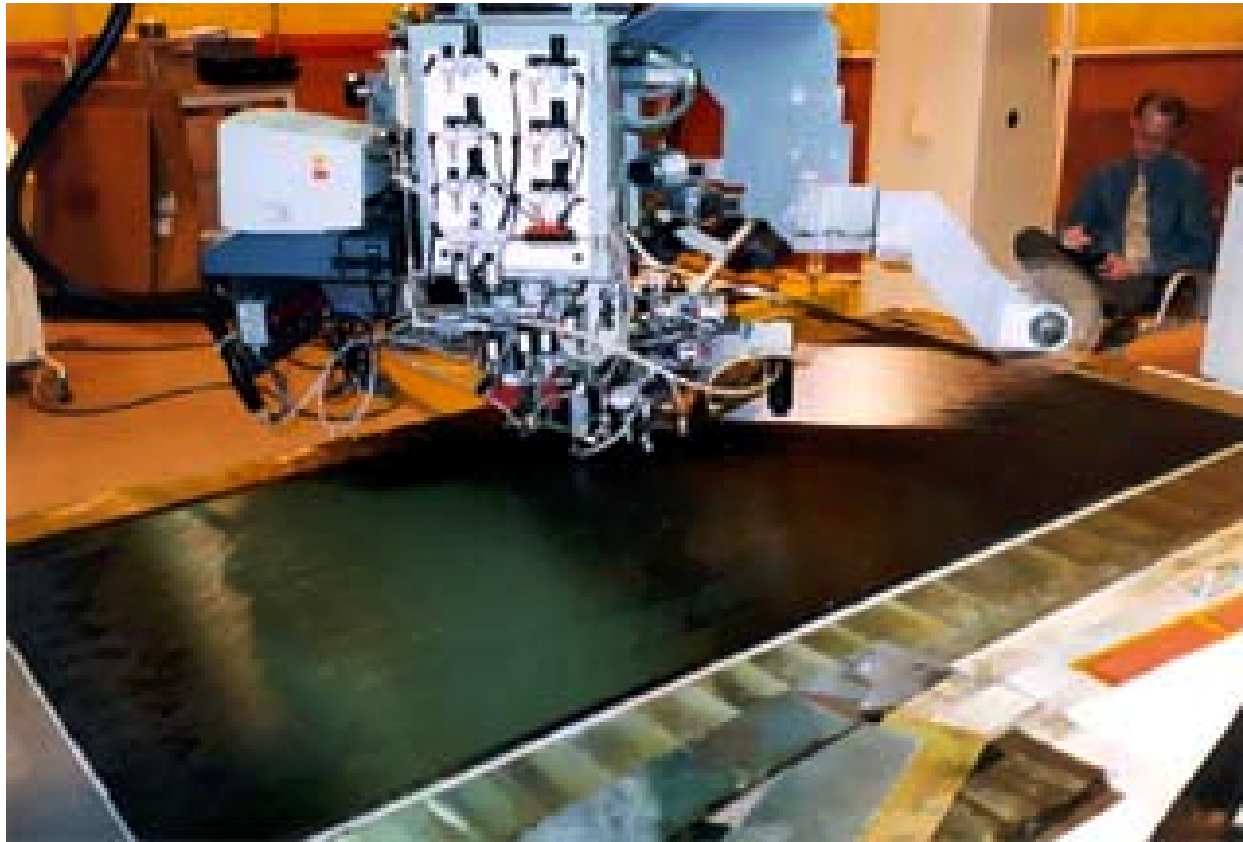
## **Thermoplastic In-situ Consolidation (Fiber Placement).**

- Fully consolidated thermoplastic prepreg which is heated to above the resin melt temperature and bonded to the composite substrate ply by a heated compaction device.
- Advantages:
  - The process allows for simultaneous ply lay-up and consolidation while achieving 85%-100% of autoclave mechanical properties.
  - Thermoplastic materials allow for virtually infinite shelf life of the material.
- Disadvantages:
  - The technology has not been completely demonstrated for complex contoured part geometries due to the need for a conformable compaction system.
  - No commercial equipment is currently available for tape and fiber placement.
  - Elevated temperature accumulation of residual stress.
  - Process will still require expensive tooling.

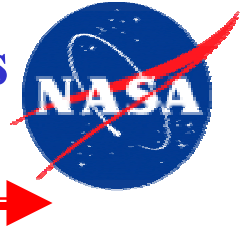
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## Thermoplastic In-situ Consolidation (Fiber Placement)



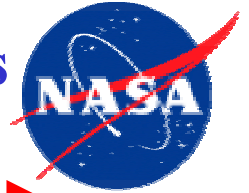
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## “All-At-Once” E-beam Cure.

- Electron-beam energy is used to cure specially formulated composite resin systems.
- The composite part is typically fabricated using hand lay-up or automated techniques.
- Part is cured at ambient temperature and pressure by irradiation with a high energy electron source.
- Advantages:
  - Low cure temperature, generally around room temperature.
  - No thermal residual stress.
  - Substantially lower tooling cost.
  - Faster cure times.
  - Resins systems have very long out life.
- Disadvantages:
  - No high performance or tough e-beam resins yet available.
  - Lack of commercially available equipment.
  - No compaction force used during consolidation.
  - Little experience in fabrication of open section skins.
  - No relevant property data.
  - Radiation levels require substantial shielding.

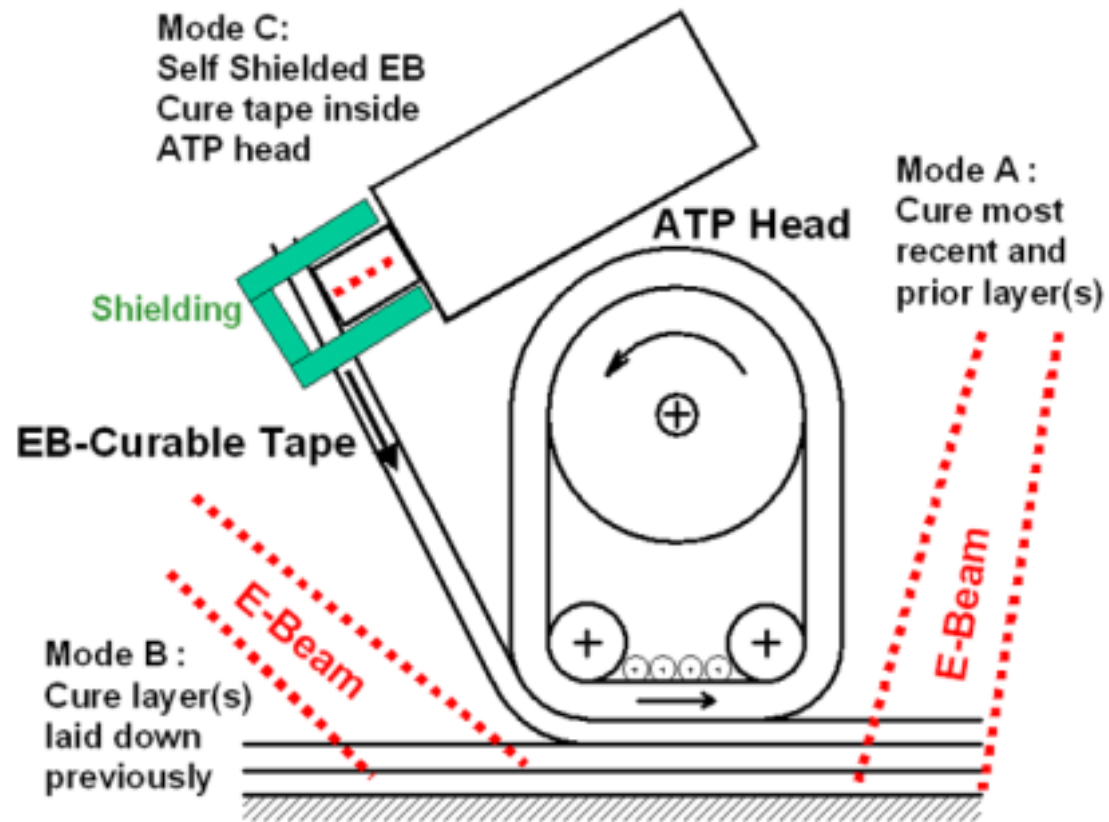
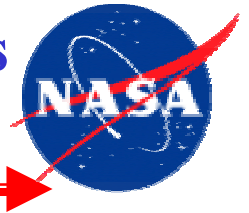
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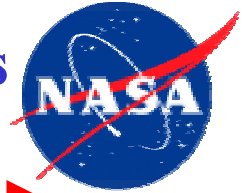
## **In-Situ E-beam Cure.**

- Offers a novel approach that combines the construction sequence and cure.
- The concept is being developed for automated tape placement (ATP) processes.
- Irradiation to partial or full e-beam cure occurs as the ATP head lays each tape layer.
- The process may utilize lower energy electrons since the beam need only penetrate through a few layers of tape rather than penetrating the full part thickness.
- Advantages:
  - Low cure temperature, generally around room temperature.
  - No thermal residual stress.
  - Substantially lower tooling cost.
  - Faster cure times.
  - Resins systems have very long out life.
  - Lower level radiation shielding is required.
  - Single step process (construction and cure simultaneously).
- Negative:
  - No high performance or tough e-beam resins yet available.
  - No commercial equipment available.
  - No compaction force used during consolidation.
  - Little experience in fabrication of open section skins.
  - No relevant property data.
  - Significant challenges synchronizing placement processing parameters and cure kinetics.

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



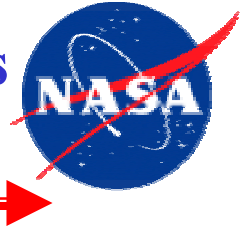
# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



## **Vacuum Assisted Resin Transfer Molding (VARTM).**

- A vacuum assisted resin injection system is used to impregnate an assembled fiber preform.
- The VARTM process has been used to make large structures, however experience with large aerospace laminate fabrication is limited.
- Typically this process is used with glass fiber to manufacture products such as railroad containers, truck containers, and boat hulls.
- Advantages:
  - Low cost tooling.
  - Low cost fabrication materials.
  - Commercial availability of resins and preforms.
  - Allows for complex, very large part fabrication.
- Disadvantages:
  - Small database with carbon/epoxy composites.
  - Typically uses low temperature, thermoset resin systems.
  - Atmospheric pressure for compaction and consolidation.
  - Complex preforms can be expensive.
  - Fabric must be used with this process.

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles

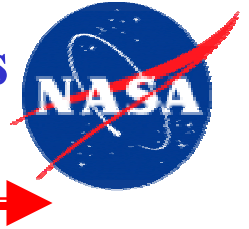


## **NASA Development Activities.**

- NASA seeks new and innovative technologies for materials, processes, and manufacturing that will provide safe, reliable, lightweight, and less expensive launch vehicle and spacecraft components.
- Conceptual designs for reusable space transportation systems require the manufacture of composite structures of unprecedented scale to achieve the necessary mass fraction.
- Current research has identified that advanced manufacturing processes, and the level of performance of engineering tools are not available today for production of these very complex structures.
- Toward this end NASA has established the National Center for Advanced Manufacturing (NCAM) to address the research and technology development needs for manufacturing the next generation of reusable space transportation systems.



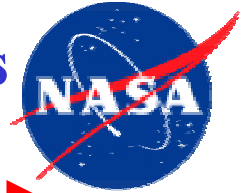
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## NASA Development Activities.

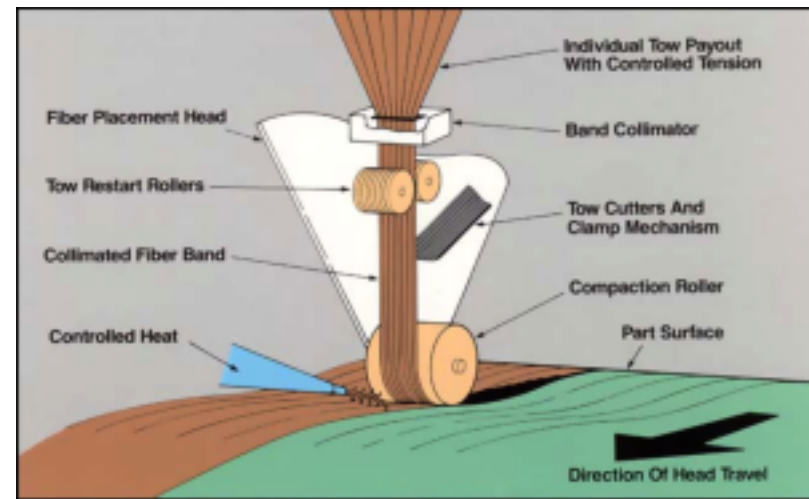
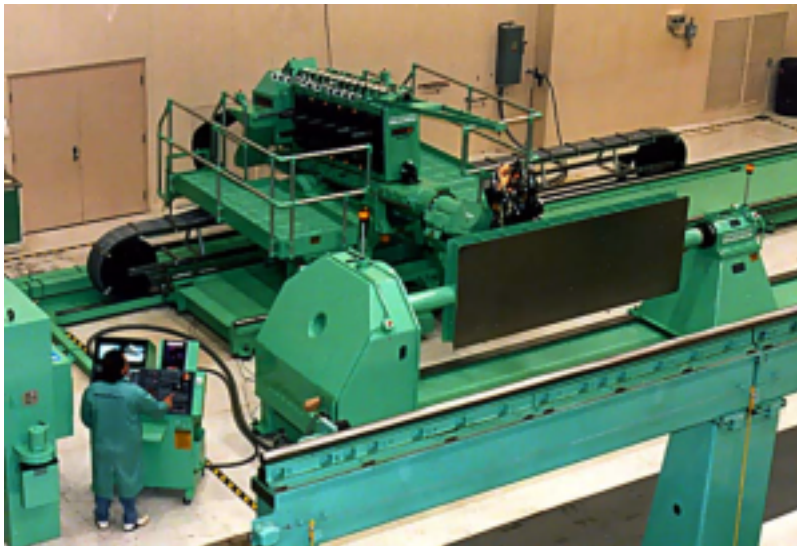
- Automated robotic placement of tow, ribbon, and tape has emerged as an important technique for fabrication of high performance fiber-reinforced composite structure.
- Production-ready equipment controlled by sophisticated computer software has been used to manufacture major portions of the Boeing 777 empennage, F18EF stabilator and inlet ducts, and V22 parts, among others.
- A fiber placement capability exists at NASA Marshall Space Flight Center's (MSFC) Productivity Enhancement Complex to provide materials and processes research and development, and to fabricate components for many of the Center's Programs.
- This equipment provides unique capabilities to build full scale and/or prototype composite parts in complex 3-D shapes with concave and other asymmetrical configurations, and localized reinforcements.
- This enabling capability assures a repeatable, controlled process that will provide government and industry a database for materials and processing development and evaluation.
- Fiber placement is projected to be next step for thermoplastic in-situ consolidation and in-situ e-beam construction as process development efforts advance.

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles

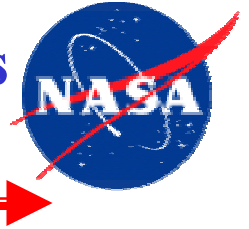


## NASA Development Activities

- Fiber Placement Machine and Operational Schematic



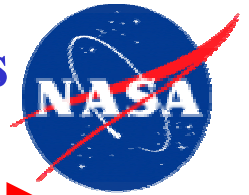
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## **NASA Development Activities.**

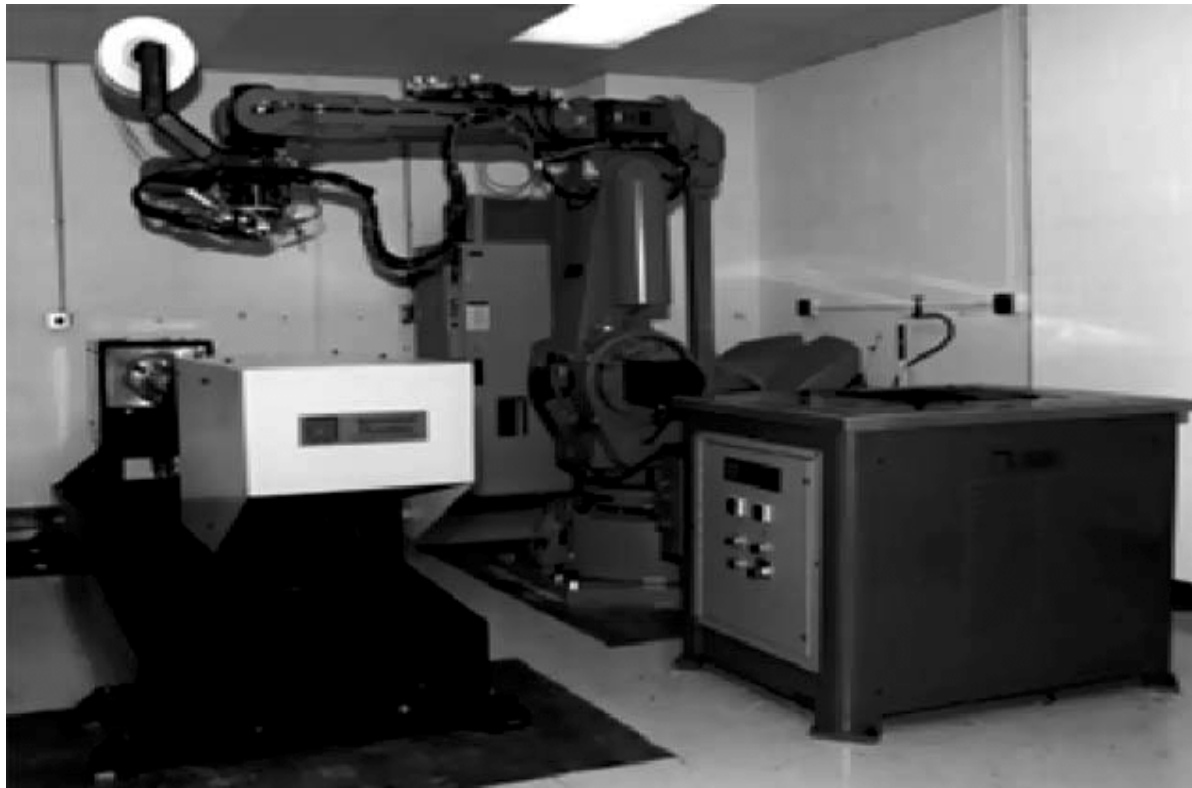
- A new NASA fiber placement facility at the Langley Research Center has proved to be a valuable asset for obtaining data, experience, and insights into the automated fabrication of high performance composites.
- The facility consists of an ABB robot armed with a modified heated head capable of hot gas and focused infrared heating.
- While uncured thermoset tow and tape, e.g., epoxy and cyanate prepreg can also be placed with this equipment; its most powerful attribute is the ability to place thermoplastic material to net shape.
- Future activities will include:
  - Development of sensors for on-line part quality information and in-situ defect repair;
  - Automated placement of metal-composite hybrids using magnetic induction heating;
  - Development of conformable compactors for ply drops, ply adds, and complex geometry;
  - Development of non-autoclave processes for epoxy thermosets including net shape placement combined with ply-by-ply, cure-on-the-fly.

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



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## NASA Langley Robotic Composite Fabrication Facility

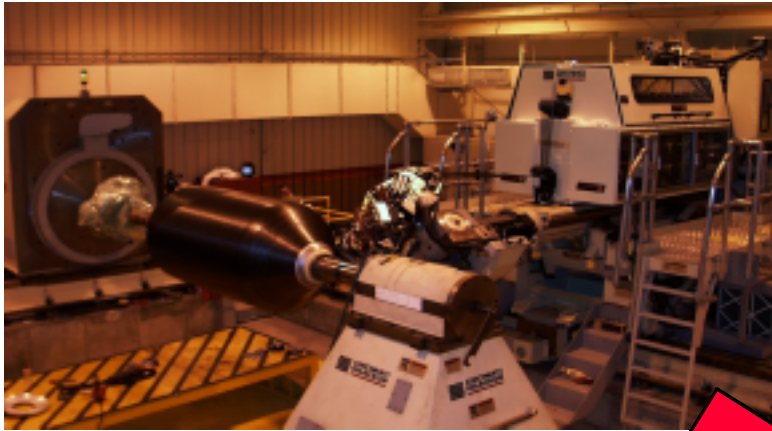




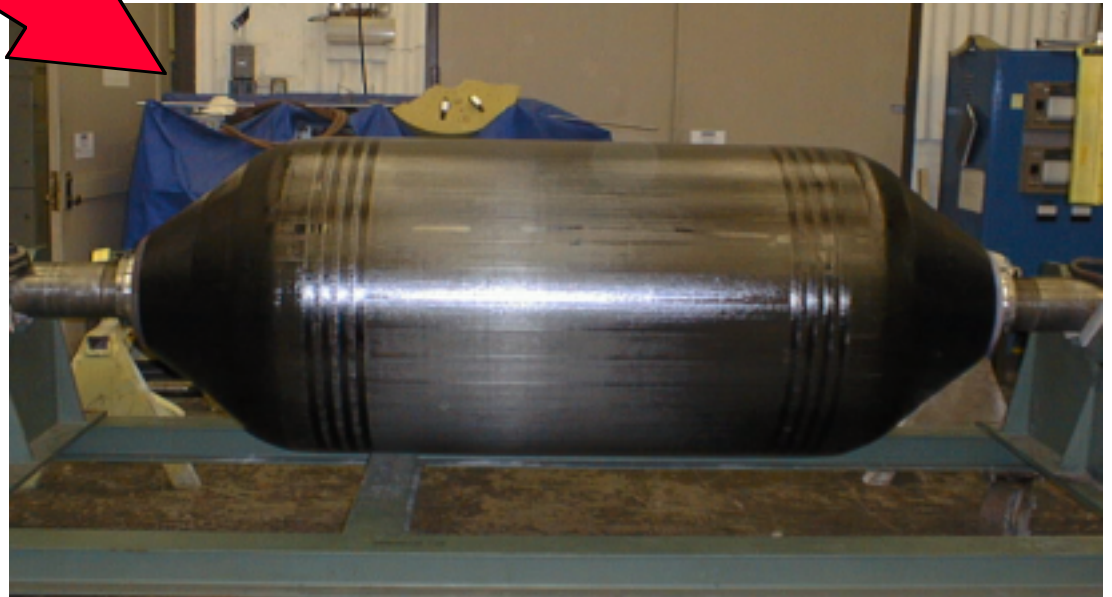
## **Industry Experience**

**Lockheed Martin - Michoud**

# Large Composite Structures Processing Technologies for Reusable Launch Vehicles



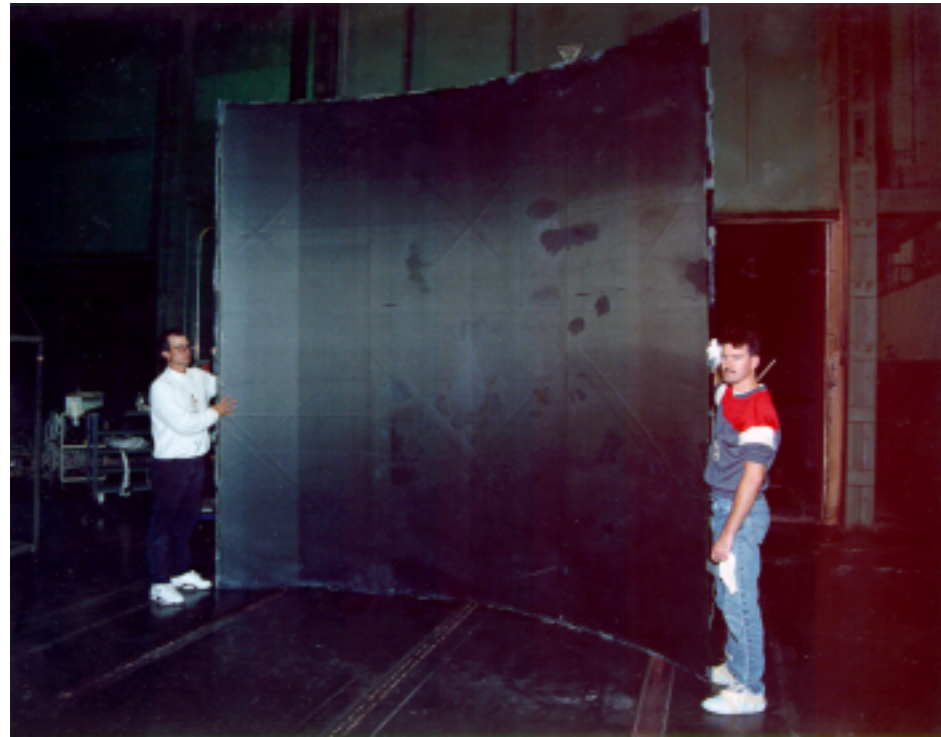
- Fiber placed toughened epoxy subscale tank demonstration.
- Autoclave grade consolidation.
- Challenges for Non-Autoclave Processes for Large Tanks.
  - Compatibility of process with toughened material systems required for cryogenic service.
  - Ability to scale up and maintain performance
  - Maintaining essentially zero defects (voids, porosity, wrinkles) for sufficient containment.
  - Maintaining adequate consolidation for optimum properties.
  - Sufficient database for implementation.



# Large Composite Structures Processing Technologies for Reusable Launch Vehicles

## Vacuum Assisted Resin Transfer Molding (VARTM)

- LM-Michould's patented Resin Infiltration process.
- Issues with VARTM.
  - Porosity > autoclave cure.
  - Uniformity of resin content.
  - Limited to fairly brittle resins.
- Good candidate for dry structure.





## **Industry Experience**

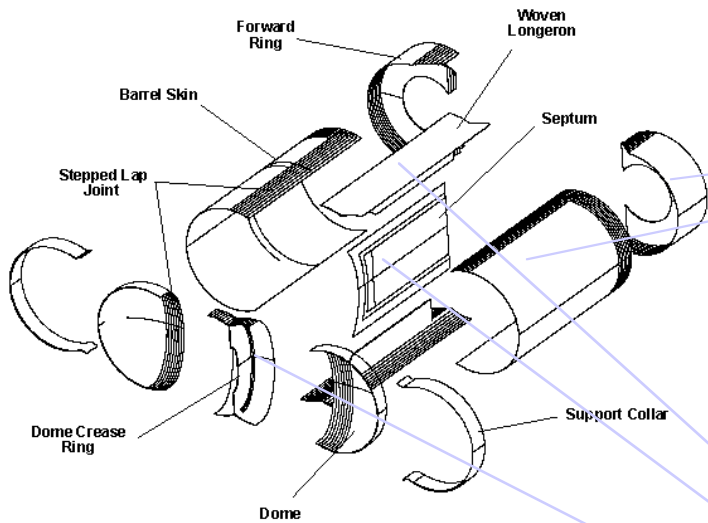
**Lockheed Martin Aeronautics - Palmdale**



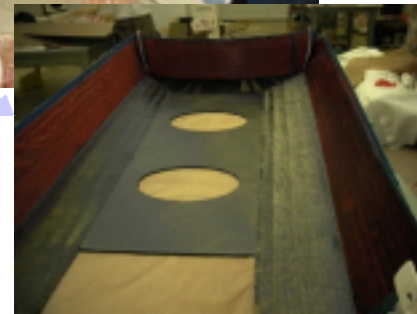


# Out-Of-Autoclave Process Development

## EB LH<sub>2</sub> Tank



EB Barrel & FWD Ring



EB Septum/Longeron/Crease Ring Assy



Tank Assembly



# Out-Of-Autoclave Process Development

## EB LH<sub>2</sub> Tank - Lessons Learned

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### *Material*

- Material out-time in storage (sealed in bags) - 1 year
- Material out-time protected from UV but not sealed - 2 months
- Lay-up must be sealed & UV light protected when stored

### *Heat debulk*

- Requires more definitive temp vs time evaluation for optimum debulk
- Multiple heat debulks may limit useful out time of material

### *Lead shielding*

- Application of proper shielding (to allow staged curing and assembly of “green” mating surfaces) is not a trivial issue. Care must be taken in shielding design to avoid EB “leakage” and unwanted cure

### *Tooling*

- Thin shell fiberglass/graphite tooling is sufficient for most applications
- High density foam tooling for large parts not manageable
- “Green” assembly technique is very demanding on support tooling design (tooling stiffness, tolerances, tooling “breakdown” features to allow part access, etc.)
- Minimal support tooling increases difficulty in positioning “green” joints

### *Design*

- Tooling design must be fully integrated with component design
- Tooling requirements more demanding as structure increases in size



# Air Canada - Aircraft Repair Program For Composites EB Processing Approach

## Wet Lay-up Disadvantages

Time Consuming  
45 Hours for Simple Repair  
Pot Life Constraints  
Cured Properties Not Optimum  
Special Storage Requirements  
Special Equipment Requirements  
Tooling Requirements  
High Maintenance Costs

## E-Beam Repair Advantages

Rapid Cure Cycle  
1 – 3 hours for simple repair  
No Pot Life Restrictions  
Cure on Aircraft  
No Special Storage Requirements  
Multiple Repairs at Same Time  
Simple Tooling  
Reduction in Repair Costs

### **Reduction in Man-hours**

One-sided; 11% (Min.), 47% (Max.)  
Two-sided; 40% (Min.), 51% (Max.)

Queue Time for Pre-preg Thaw; 8 Hrs to 0

Freezer Cost: Reduced to 0

Material Costs: Same Price

Time-out Scrap Costs: Reduced to 0

Revisit Costs: Reduced 50%

Tool Costs: Reduced by 90%

Utilities

Electricity; Reduced 98%

Nitrogen; Reduced to 0

Aircraft Downtime: Reduced by 1 Day



Airbus A319



## Industry Experience

**Boeing – Phantom Works  
Space and Communications Group**

# Advanced Composite Preform Technology Boeing/NASA Stitching Center



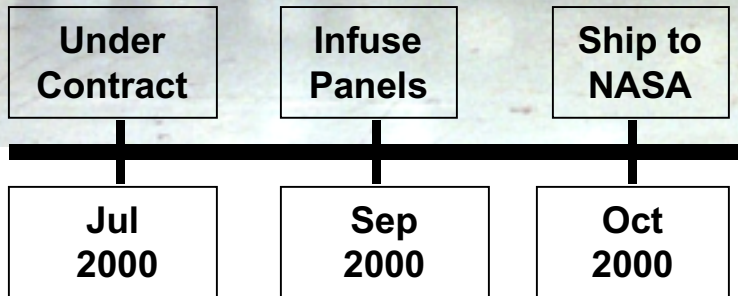
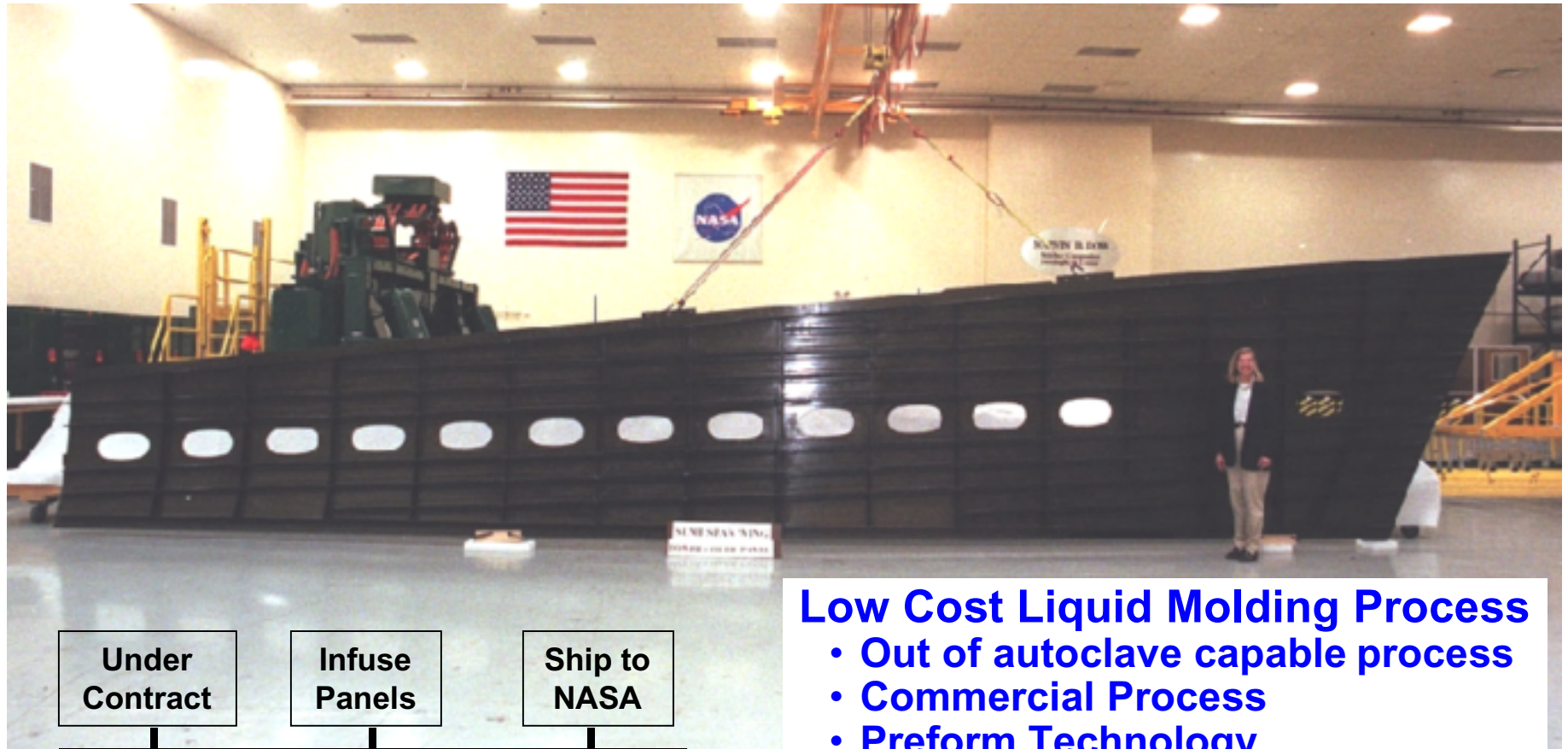
*Space and Communications Group*

*BOEING*

*PHANTOM  
WORKS*

# Boeing/NASA Activity

## Boeing/NASA ACT Wing Program



### Low Cost Liquid Molding Process

- Out of autoclave capable process
- Commercial Process
- Preform Technology
- New Aerospace Resins
- NASA Testing

# Boeing/NASA AST Composite Wing Test



## Met All Limit Load Test Requirements

- Up Bending / Down Bending
- Brake Roll
- FAA Discrete Source Damage Test

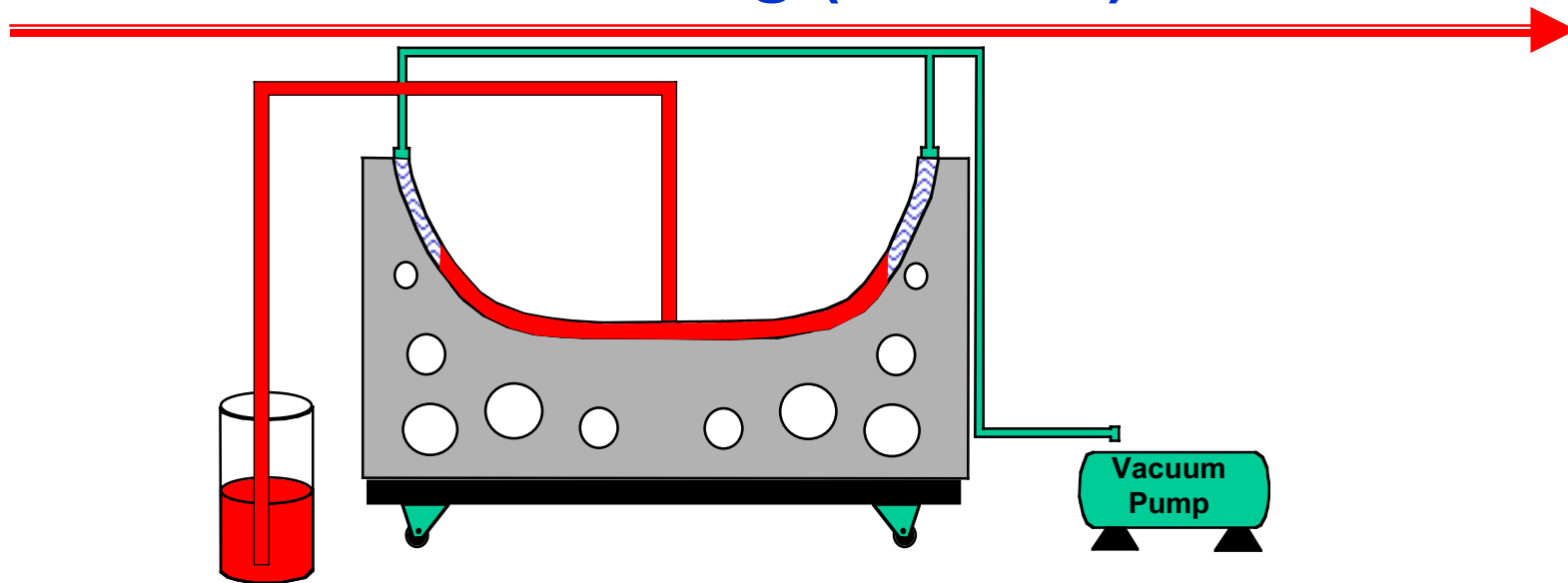
## Successfully Repaired

## Tested to Failure (145% DLL)

- Failure As Predicted
- No Failure Through Repair Area
- No Delaminations

## ... Met All Program Requirements

# Vacuum Assisted Resin Transfer Molding (VARTM) Process



## VARTM Advantages

- Low Cost/Simple Processing
- Allows Complex, Very Large Part Fabrication
- Eliminates Autoclave Requirement
- Tool One Side
- Reduced Material Storage
- Reduced Debulking





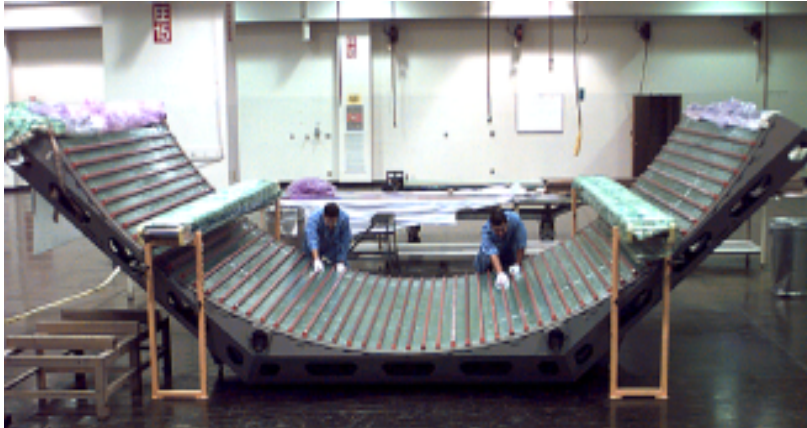


**Industry Experience**

**Northrop Grumman**

## Kistler K1 RLV Fabrication

### Hat Stiffened Epoxy and BMI Shell Structure



- NGC Developed Rapid Prototype Tooling and Assembly Jigs for Low Rate RLV Production on K1 Program
- Baselined Hand Lay-up Autoclave Cure due to Low Rate
- Automated Processes do not Justify Non-recurring Cost for Low Rate RLV

- Produced Intertanks with Cutouts and Access Details
- Applied Experience from F-18 for Local Stiffener Termination Details
- Demonstrated Fast Design and Fabrication Response to Customer



NORTHROP GRUMMAN

# SSTO Wing Box Test



## Description

- 54" x 120" x 36" Gr/BMI Wing Box
- Polyimide Core Sandwich Construction
- 4-ply 0.020" Gr/BMI Min Gauge
- Static Upward and Downward Bending Load Applied Through Metal Load Box
- 120 Channels Strain Gages
- 16 Fiberoptic/14 AE/AU Sensors for Structural Health Monitoring
- Tested at NASA LaRC 30 May 1996

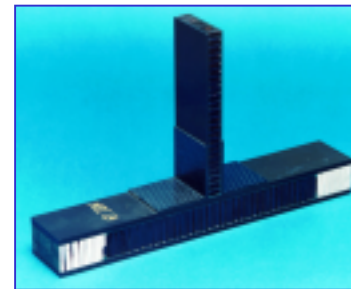
## Summary of Results

- **Validated NGC Design and Analysis Methods**
  - *Within 3% Predicted Failure*
- **Demonstrated NGC Lightweight Composites Mfg**
  - *Within 2% of Predicted Weight*
- **Demonstrated Integration of Structural Health Monitoring (i.e., Fiberoptic, Acoustic Sensors)**
  - *Performance Data Base on Large Test Article*

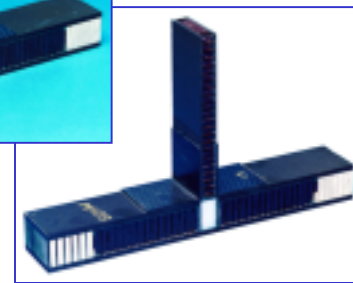
# Composite Joining and Assembly

- Scaled up Innovative Joint Concepts used on Beech Starship for HSCT Aircraft
- Performed Design, Analysis, and Fabrication Activity at NGC
- Element Validation Test Program Performed at NASA LaRC
- Applied Proven Joint Concepts in Wing Box Subcomponent. Tested at LaRC to 119% Ultimate

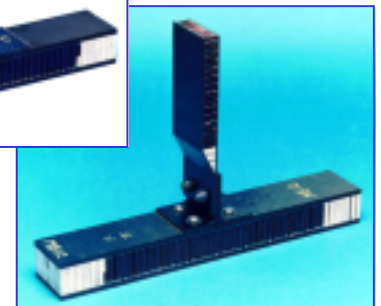
Test Element Concept #1



Concept #2



Concept #3



Original Application



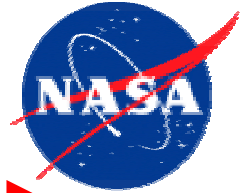
Severe Loads and Environment



Structural Subcomponent Test

NORTHROP GRUMMAN

## Summary



- Significant effort have been devoted to establishing the technology foundation to enable the progression to large scale composite structures fabrication.
- We are not capable today of fabricating many of the composite structures envisioned for 2<sup>nd</sup> Generation RLV.
- Conventional “aerospace” manufacturing and processing methodologies (fiber placement, autoclave, tooling) will require substantial investment and lead time to scale-up.
- Out-of-autoclave process techniques will require aggressive efforts to mature the selected technologies and to scale up.
- Focused composite processing technology development and demonstration programs utilizing the building block approach are required to enable envisioned 2<sup>nd</sup> Generation RLV large composite structures applications.
- Government/industry partnerships have demonstrated success in this area and represent best combination of skills and capabilities to achieve this goal.