Accelerated Insertion of Materials – Composites: a Technology Investment Agreement

Presented at
MMS-OTRC Workshop
“Qualifying New Technology for Deepwater Oil and Gas Development”
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<th>Limitation of Abstract</th>
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<td>a. REPORT</td>
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<td>48</td>
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<td>b. ABSTRACT</td>
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AIM-C Team - Boeing (St. Louis, Seattle, Canoga Park, Philadelphia), Northrop Grumman, Materials Sciences Corporation, Convergent Manufacturing Technologies, Cytec Fiberite, Inc, Massachusetts Institute of Technology, Stanford & NASA (Langley)
The Traditional Process
Why We Test

- Using an Un-augmented “Building Block Approach”, a Typical Composites Program Requires 6000 to 10,000* Specimens to:
  - Characterize the Material
  - Develop Design Allowables
  - Select/Develop the Design Concept
  - Calibrate Semi-Empirical Analysis Methods
  - Validate the Design and Analysis

* Ref. F/A -18 and 777 empennage
How Much It Costs

- The Total Cost of Building and Testing These Specimens is between $50M and $100M and takes at least several years.
- Despite several very expensive component tests, much of this money and time is spent on the numerous coupons, elements, and subcomponents.

Specimen types and numbers are averages based on various test plans:
- New composite material specimens only
- Only 1 full-scale Test Component testing includes items such as fuel box, side-of-body joint, large fittings, etc.

- Fab. And Test Hours/specimen (for each type) based on internal Boeing estimating documents
- Typical Industry Labor Rates
- Fabrication and Test Cost Only – Facilities, Equipment, Material, and Design/Analysis Costs not included
Boeing is the World’s Largest Manufacturer of Composite Aerospace Parts

- 4 Million Pounds Annually
- ~ $300M Spent on Raw Material
- We Add ~ 5 times to the value
- $2B Annually Fly Away
Accelerated Insertion of Materials Goals

**Transform** traditional materials database and qualification practice into an efficient and interactive process fully integrated into the available design tools and design community that retains/improves upon the robustness and reliability of traditional practice.

Use the **right** source (model, experiment, experience) to fill in the data
AIM Methodology: Criteria for Success

1. Architecture
   • Open/controlled (secure/open)
   • Platform independent (Intranet vs. Internet)

2. Capabilities – at least 4 capabilities/modules
   • Properties – time dependent properties
   • Durability/Lifing
   • Processing/Manufacturing/Producibility
   • Cost
AIM Methodology: Criteria for Success

3. Features/Outputs

- Demonstrate that the methodology reproduces the designer knowledge base
- Demonstrate that “a rogue” process spec will result in a flag by the system
- Demonstrate that a rogue “geometry” results in an “un-producible” flag
- Demonstrate the ability of the system to direct experiment – to direct an experiment to determine a “benchmarking” parameter, or a basic physical quantity. (validation/calibration)
The Objective of the AIM-C Program is to Provide Concepts, an Approach, and Tools That Can Accelerate the Insertion of Composite Materials Into DoD Products

AIM-C Will Accomplish This Three Ways

Methodology - We will evaluate the historical roadblocks to effective implementation of composites and offer a process or protocol to eliminate these roadblocks and a strategy to expand the use of the systems and processes developed.

Product Development - We will develop a software tool, resident and accessible through the Internet that will allow rapid evaluation of composite materials for various applications.

Demonstration/Validation - We will provide a mechanism for acceptance by primary users of the system and validation by those responsible for certification of the applications in which the new materials may be used.
DESIGN TEAM’S NEEDS
Requirements Flow-Down

Program/Product Level
- Performance
- Life Cycle Cost
- Development and Delivery Schedules
- Risk Posture

Component Level
- Weight, Smoothness, etc.
- Service Environment
- Unique Functionality
- Unit Cost Targets
- Production Concept
- O&S Concepts

Part Level
- Strength and Stiffness
- Temperature
- Geometry Assurance
- Fab and Assembly Concepts
- Damage Tolerance & Repair

Material Choice is Influenced by Higher Level Requirements (and Vice Versa)
DESIGN TEAM’S NEEDS
Requirements are Multi-Disciplined

**Structural**
- Strength and Stiffness
- Weight
- Service Environment
  - Temperature
  - Moisture
  - Acoustic
  - Chemical
- Fatigue and Corrosion Resistant
- Loads & Allowables
- Certification

**Material & Processes**
- Development Cost
- Feasible Processing Temperature and Pressure
- Process Limitations
- Safety/Environmental Impact
- Useful Product Forms
- Raw Material Cost
- Availability
- Consistency

**Manufacturing**
- Recurring Cost, Cycle Time, and Quality
- Use Common Mfg. Equipment and Tooling
- Process Control
- Inspectable
- Machinable
- Automatable
- Impact on Assembly

**Supportability**
- O&S Cost and Readiness
- Damage Tolerance
- Inspectable on Aircraft
- Repairable
- Maintainable
  - Accessibility
  - Depaint/Repaint
  - Reseal
  - Corrosion Removal
- Logistical Impact

**Miscellaneous**
- Observables
- EMI/Lightning Strike
- Supplier Base
- Applications History
- Certification Status
  - USN
  - USAF
  - ARMY
  - FAA

Risk in Each Area is Dependent Upon Application’s Criticality and Material’s Likelihood of Failure
DESIGN TEAM’S NEEDS
Data Drives Decisions

- Are Current Materials, Designs, and Methods Capable of Meeting Needs?
  - YES
  - NO

- Is Program/Customer Willing to Invest in New Materials for Performance Improvement?
  - YES
  - NO

Pursue New Material

- Are Current Materials Capable of Meeting Needs (with changes to design and/or methods)?
  - YES
  - NO

Change Design and/or Methods

Materials Development Effort

- Type and Amount of Materials Data Required
- Criticality/Complexity of Application

- Conceptual Design
- Preliminary Design
- Detail Design

Criticality/Complexity of Application
Methodology That Links an Accelerated Process to the Knowledge Requirements

Embedded In

Software That Links the Methodology to Knowledge, Analysis Tools, and Test Recommendations

Validated By

Demonstrations Focused on Recreating Existing Data, Precluding Persistent Problems, and Independent Peer Assessment

AIM-C Will Validate the Process
“Building Block” Test Program

Material/Process and Design Development

Kathryn L. Nesmith, Roland Cochran and Denise Wong
May 21-24, 2001
Naval Air Systems Command
Air Vehicle Department
National Conference
Jacksonville, FL

Material Properties
- Repair
- Physical/Chemical/Processing
- Environmental Effects
- Mechanical Properties
- Statistical Knockdown
- Fatigue Scatter
- Effects of Defects

Manufacturing Process
- Process Development
- NDT Standards

Material Selection
- Metals
- Composites

Reproduction Verification
- Design Details
- Damage Tolerance
- Repair
- Validation of Analysis Methodology
- Fatigue
- Static
- Acoustic

Elements/Subcomponents
- Configuration Details
- Damage Tolerance
- Static
- Fatigue
- Repair
- Validation of Analysis Methodology

Components
- Static
- Fatigue
- Drop
- Dynamics

Full Scale Laboratory Certification Tests
- Flight Test
- Ground Test

EMD Aircraft

Same Basic Building Block Process Used For Metals
The AIM Process Uses a Team Approach to Drive Rapid Insertion

**Conventional Building Block Approach to Certification**

- **Application Requirements**: 3 Months
- **Target Properties**: 3 Months
- **Supplier Offerings**: 3-6 Months
- **Trade Studies**: 2-6 Months
- **Fabrication Studies**: 2-6 Months
- **Allowables Development**: 6-18 Months
- **Full Scale Fab & Test**: 12-24 Months

**Time Reduction**

- **Critical Details Fab & Test**: 2-6 Months
- **Subcomponent Fab & Test**: 2-6 Months
- **Component Fab & Test**: 2-6 Months

**Cost Reduction**

**Risk Reduction**

**The AIM Focused Approach to Certification**

- **Application Requirements**: 3 Months
- **Trade Studies**: 3 Months
- **Design Features**: 2-6 Months
- **Allowables Development**: 4-9 Months
- **Full Scale Fab & Test**: 12-24 Months
- **Supplier Offerings**: 3-6 Months
- **Manufact. Features**: 3-6 Months
- **Risk Reduction Fab & Test**: 4-9 Months
- **Target Properties**: 2-6 Months
- **Key Features Fab & Test**: 2-6 Months

**35% Reduction in Total Time to Certification**

**45% Reduction in Time to Risk Reduction**
Material Insertion Methodology

**Methodology Covers:**
- **What** Needs to be Done?
- **When** is it Done?
- **How** is it Done?
- **Why** is it Done?

**Tool Sets:**
- Technology Readiness Level (TRL) Definitions/Chart/Worksheet
- \( (x) \) Readiness Level (xRL) Definitions/Chart/Worksheet
- Technical Requirements Definitions
- Definitions/Worksheets/Templates
- Physics/Science Based Models
- Math/Statistics Models & Functions
- Heuristic Models
- Relational Data Bases for Information Storage/Retrieval
- Usage Scenarios
- Other

**Methodology Has to Accommodate:**
- Designer Perspective + Others
- Product Certification Requirements
- Material Qualification Requirements
- Multiple Tool Sets
- Testing
- Traceability
- Integration

**What, When, Why**
Methodology – What & When

Technology Readiness Level

10. Disposal
9. Production
8. Flight Test
7. Ground Test
6. Component Test
5. Design Maturation (Subcomponents)
4. Preliminary Design (Stable Mat’l & Process + Elements)
3. Proof of Concept Prototype
2. Concept Definition
1. Concept Exploration

Activity Steps Moving to Certification

(x) Readiness Level

9. Industry Std
8. Production
7. Qualified Mat’l/Process
6. Pre-Production
5. Pilot Production
4. Lab/Prototype Production
3. Beaker/Bench Product
2. Theoretical/Beaker Product
1. Concept Exploration

Activity Steps Moving to Qualification

Technologist Activity Description

Final Capabilities
Expanded Capabilities
Preliminary Capabilities
Preliminary Investigations, Research, Development
## Technology Readiness Levels

<table>
<thead>
<tr>
<th>TRL</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td><strong>Application Risk</strong></td>
<td>Very High</td>
<td>High</td>
<td>High - Med</td>
<td>Med - High</td>
<td>Medium</td>
<td>Med - Low</td>
<td>Low</td>
<td>Low - Very Low</td>
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<tr>
<td><strong>Application Maturity</strong></td>
<td>Concept Exploration</td>
<td>Concept Definition</td>
<td>Proof of Concept</td>
<td>Preliminary Design</td>
<td>Design Maturation</td>
<td>Component Testing</td>
<td>Ground Test</td>
<td>Flight Test</td>
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<tr>
<td><strong>Certification</strong></td>
<td>Certification Requirements Documented</td>
<td>Certification Plan Documented</td>
<td>Certification Plan Approved</td>
<td>Preliminary Design</td>
<td>Subcomponent Testing</td>
<td>Full Scale Component Testing</td>
<td>Full Scale Airframe Tests</td>
<td>Flight Test</td>
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<tr>
<td><strong>Design</strong></td>
<td>Concept Exploration/ Potential Benefits Predicted</td>
<td>Concept Definition/ Applications Revised by Lamina Data (Coupons)</td>
<td>Applications Revised by Laminates Data (Elements)/ Design Closure</td>
<td>Applications Revised by Assy Detail Test Data (Elements)/ Preliminary Design</td>
<td>Applications Revised by Subcomponent Test Data/ Design Maturation</td>
<td>Applications Revised by Component Test Data/ Ground Test Plan</td>
<td>Applications Revised by Airframe Ground Tests/ Flight Test Plan</td>
<td>Production Plan</td>
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<tr>
<td><strong>Assembly</strong></td>
<td>Assembly Concept</td>
<td>Assembly Plan Definition</td>
<td>Key Assembly Detail Definitions</td>
<td>Key Assembly Details Tested</td>
<td>Subcomponents Assembled</td>
<td>Components Assembled</td>
<td>Airframe Assembled</td>
<td>Flight Vehicles Assembled</td>
</tr>
<tr>
<td><strong>Structures Maturity</strong></td>
<td>Preliminary Properties- Characteristics</td>
<td>Initial Properties Verified by Test</td>
<td>Design Properties Developed</td>
<td>Preliminary Design Allowables</td>
<td>B-Basis Design Allowables</td>
<td>A-Basis Design Allowables</td>
<td>EMD Material Supplied</td>
<td>LRIP Material Supplied</td>
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<tr>
<td><strong>Materials Maturity</strong></td>
<td>Lab Prototype Materials</td>
<td>Pilot Production Materials</td>
<td>Pre-Production Materials</td>
<td>Production Materials/ Material Specs</td>
<td>Production Materials/ Material Specs</td>
<td>Production Materials/ Material Specs</td>
<td>EMD Material Supplied</td>
<td>LRIP Material Supplied</td>
</tr>
<tr>
<td><strong>Fabrication Maturity</strong></td>
<td>Unfeatured-Panel Fabrication</td>
<td>Feature Based Generic Small/Subscale Parts Fabricated</td>
<td>Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts</td>
<td>Process Specs/ Effects of Fab Variations Tested/ Elements Fab’d/ Production Representative Parts Fab’d</td>
<td>Subcomponents Fab’d</td>
<td>Full Scale Components Fabricated</td>
<td>EMD Fabrication</td>
<td>Low Rate Initial Production (LRIP)</td>
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<tr>
<td><strong>Cost Benefits Maturity</strong></td>
<td>Cost Benefit Elements ID’d &amp; Projected</td>
<td>ROM Cost Benefit Analysis</td>
<td>Cost Benefit Analysis Reflect Size Lessons Learned</td>
<td>Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned</td>
<td>Cost Benefit Analysis Reflect Subcomponent Fab &amp; Assembly Lessons Learned</td>
<td>Cost Benefit Analysis Reflect Component Fab &amp; Assembly Lessons Learned</td>
<td>Cost Benefit Analysis Reflect EMD Lessons Learned</td>
<td>Cost Benefit Analysis Reflect LRIP Lessons Learned</td>
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<tr>
<td><strong>Supportability</strong></td>
<td>Repair Items/Areas Identified</td>
<td>Repair Materials &amp; Processes Identified</td>
<td>Repair Materials &amp; Processes Documented</td>
<td>Fab Repairs Identified</td>
<td>Fab Repair Trials/ Subcomponent Repairs</td>
<td>Component Repairs</td>
<td>Production Repairs Identified</td>
<td>Flight Qualified Repairs Documented</td>
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<td><strong>Intellectual Rights</strong></td>
<td>Concept Documentation</td>
<td>Patent Disclosure Filed</td>
<td>Proprietary Rights Agreements</td>
<td>Data Sharing Rights</td>
<td>Vendor Agreements</td>
<td>Material and Fabrication Contracts</td>
<td>Production Rate Contracts</td>
<td>Vendor Requal Agreements</td>
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Methodology – Tool Sets

**Tool Sets:**
- **Technology Readiness Level (TRL)** Definitions/Chart/Worksheet
- **(x) Readiness Level (xRL)** Definitions/Charts/Worksheets
- **Technical Requirements Definitions**
- **Physics/Science Based Models**
- **Math/Statistics Models & Functions**
- **Heuristic Models**
- **Relational Data Bases for Information Storage/Retrieval**
- **Usage Scenarios**
- **Other**

**Technology Readiness Levels**

- **For Aerospace Applications**
  - Fiber
  - Resin
  - Prepreg
  - Fabrication
  - Assembly
  - Quality
  - Other

**(x) Readiness Levels**

- **Detailed Technical Properties/Characteristics**
- **Primary Test/Analysis Methods**
- **Secondary Test/Analysis Methods**
- **Sequencing Requirements**
- **Data Requirements**
- **Quality Requirements**
AIM-C System Vision
The Oculus Integration System

**CO™: A Plug & Play Modeling Environment**

- Integrates Data and Software Applications on-the-fly
  - Drag & Drop, Plug & Play
  - Simple to create, modify, manage, maintain

- Enables Real-time data sharing between applications
  - Secure
  - Controlled
  - Intra/Internet

- Platform Independent
  - Distributed
  - Neutral to Platforms and Applications

- Increases Value of Previous Investments
  - Software
  - Hardware
  - Networks
The User Is Able to Run the Module At *Three* Different Levels

1. Through the System Software
2. Through the Integration Software
3. For trouble-shooting, and validation, the individual modules can be ran directly from a driver program.
AIM-C Transition Plan

Customer Team – To ensure that the product meets the needs of the funding agents
Design Team – To ensure acceptance among users in industry
Certification Team – To ensure acceptance among the certification agents for structures
Implementation Team – To ensure acceptance among the user community
Commercialization Team – To ensure commercial support of users
AIM-C Certification Team

<table>
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<tr>
<th>Agency</th>
<th>Integration</th>
<th>Structures</th>
<th>Materials</th>
<th>Producibility</th>
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<td>Charley Saff</td>
<td>Eric Cregger</td>
<td>Pete George</td>
<td>John Griffith</td>
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<td>Navy</td>
<td>Don Polakovics</td>
<td>Dave Barrett</td>
<td>Kathy Nesmith</td>
<td>Steve Claus</td>
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<td>Air Force</td>
<td>(Joe Gallagher)</td>
<td>Dick Holzwarth</td>
<td>Katie Thorp</td>
<td>Bob Reifenberg</td>
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<td>FAA</td>
<td>Curt Davies</td>
<td>Larry Ilcewicz</td>
<td>David Swartz</td>
<td>Dave Ostrodka</td>
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<td>Army</td>
<td>Mark Smith</td>
<td>Jon Schuck</td>
<td>Marc Portanova</td>
<td>N/A</td>
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<tr>
<td>NASA</td>
<td>N/A</td>
<td>Jim Starnes</td>
<td>Tom Gates</td>
<td>Tom Freeman</td>
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To Insure That the Methodology, Verification, and System Validation We Do Satisfies Certifying Agencies
Comments and Summary

• Accelerated Insertion of Materials Can be Achieved by
  – Definition of requirements
  – Focus based on insertion needs (design knowledge base)
  – Approach for use of existing Knowledge
  – Validated Analysis tools
  – Focused Testing
  – Feature Based Demonstration
  – Rework Avoidance
  – Knowledge management
Accelerated Insertion of Materials – Composites: Impact of Manufacturing on Performance

Presented at
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29 October 2002
Polymer & Composite Material Properties

• Effects of Defects
  – Mechanical effect of common defects
  – Voids, delamination, FOD, wrinkles, impact

• Repair
  – Develop repair materials and processes
  – Demonstrate utility

Product:
Engineering data to support part disposition
Repair specifications and procedures
Polymer & Composite Process Development

• Define process limits
  – Develop mechanical properties at limit
• Demonstrate reproducibility within the limits
• Define critical steps/tools/equipment
• Develop inspection and QC process

Product: Process specifications
Part Fabrication

• **Elements And Subcomponents**
  - Fabrication of design details
  - Validation of analysis
  - Further definition of inspection and repair requirements
  - Risk reduction for manufacturing and assembly

• **Components**
  - Fabricate actual components
    - Manufacturing demonstration
    - Destructive evaluation
  - Demonstrate repairs
  - Demonstrate component level mechanical performance
  - Validate analysis
  - Demonstrate systems interfaces
  - Demonstrate damage tolerance
Common Manufacturing Insertion Issues

Process Specification
Calls out ±6-7% Thickness Tolerance

Thickness Zoning
Thick Parts Having Large Thickness Variability (Within Parts and Part-to-Part)

1.0 in. Excess Trim
Out of Spec Condition

Edge Thickness Thinning for >1 in.

Complex Tooling Mismatches Giving Steps and Puckers
Common Manufacturing Insertion Issues

- Multiple Material Processing Compatibility (i.e. Structural Resin and Adhesives)
- Microcracking in Large, Cocured Structure (Interactions of Different Material Cure Requirements and Tooling Concepts)
- Insufficient Out Times

Process Specification/Tooling Incompatibilities for Heat-up (Invar/Steel)
Other Encountered Shop Issues

• Exotherm of Thick Parts
• Thick/Rigid Part Distortion
• Incorrectly Compensated Spring-in Angles
• Prepreg Tack
• Secondary Processing Requirements (Drying, Peel Ply, Sanding, Bonding, Painting, etc.)
Other Encountered Issues

• Resin Solvent Resistance

• Microcracking with Cure, Thermal Cycles, and/or Moisture

• Incompatibility of Resin Characteristics and the Manufacturing Process

• Final Part Accuracy/Repeatability Relative to Tooling Concepts
**Background**

**Surface Fidelity Variations**
- Rework
  - Shimming
  - Moldline Splining
- Multiple Grip Length Fasteners

**Assembly Variations**
- Hard Shim Required for Gaps in Excess of .03 in.
- Engineering Disposition
- Multiple Grip Length Fasteners

**Major Variation Types**

**Part Mismatch**
- Skin-to-Substructure
- Substructure-to-Substructures

**Moldline Fidelity**
- Skin-to-Door
- Skin-to-Access Panel
- Skin-to-Skin
## Variability Flow Chart

**Unitized Structure**
- Assembly Variability
  - Part Variability
    - Assembly Tooling
    - Assembly Design
  - Residual Stresses
- Processing Variability
  - Part Design & Fabrication Tooling
- Material Variability
  - Part Design

### Level | Factor | Item/Cause
--- | --- | ---
Assembly | Assembly Design | Concepts (Piece Parts, Subassembly/Assembly), Length, Width, Thickness
Part Variability | Materials, Processing, Fabrication Design, Fabrication Tooling, Warpage
Assembly Tooling | Primary Tool, Details, Accuracy, Repeatability, Tool/Part Coordination
Assembly Method | Assembly Sequence, Fastener Types, Hole Drilling/Countersinking, Fastener Installation Method
Fabrication | Material Variability | Prepreg, Reinforcement, Resin
| Processing Variability | Cure Pressure, Bagging, Debunking, Out Time, Resin Content
| Residual Stress | Materials, Processing, Tooling, Designs
| Part Design | Length, Width, Thickness, Configuration, Ply Orientations
| Fabrication Tooling | Primary Tool, Caul Sheet, Accuracy, Repeatability, Tool/Part Coordination

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**Subtask 1 - Root Cause Analysis**

**Precision Assembly for Composite Structures**
Precision Assembly of Composite Structures

Assembly Variability

Variability Flow Chart

Unitized Structure

Assembly Variability

Part Variability

Assembly Tooling

Material Variability

Assembly Design

Part Design

Processing Variability

Residual Stress

Part Design & Fabrication Tooling

Assembly Method

Material and Processing Part Tolerance Accumulations

Fiber Yield

Fiber Areal Weight

Fiber Density

Resin Film Thickness

Resin Content

Thickness

Configuration

Size

Debulking

Layup

Out-Time

Bagging

Curing

Dam Gap

Caul Plate

Pressure

Heat-up Rate

Hold Temp

Hold Time
### Part Variability Factors

<table>
<thead>
<tr>
<th>Design</th>
<th>Materials</th>
<th>Processing</th>
<th>Cure</th>
<th>Tooling</th>
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<tbody>
<tr>
<td>• Orientation</td>
<td>• Unidirectional</td>
<td>• Material Out Time</td>
<td>• Pressure</td>
<td>• Caul Plate</td>
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<tr>
<td>• Thickness</td>
<td>• Cloth</td>
<td>• Bleeder</td>
<td>• Vacuum</td>
<td></td>
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<tr>
<td>• Size</td>
<td>• Net Resin</td>
<td>• Inner Bag Perforations</td>
<td>• Heating Rate</td>
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<tr>
<td></td>
<td>• Excess Resin</td>
<td>• Dam Gaps</td>
<td>• Hold Temp</td>
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<tr>
<td></td>
<td>• FAW</td>
<td>• Dam Type</td>
<td>• Hold Times</td>
<td></td>
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<tr>
<td></td>
<td>• Resin Content</td>
<td>• Debulking</td>
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<td></td>
<td>• Prepreg</td>
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<td></td>
<td>Manufacturing</td>
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Material Variability

Fiber Variability (210 Batches)

Prepreg Variability (21 Batches)

- Fiber Yield Variation Translates to Fiber Areal Weight Variation (Cloth)
- Prepreg Variation is Driven By Fiber Areal Weight Variation
Material Variability

Theoretical Prepreg Variability

Prepreg Variability Contributing Factors
IM7/977-3 Unidirectional, Net Resin
(per Material Specification Limits)

<table>
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<tr>
<th>Component</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Resin Areal Weight</td>
<td>290 ± 10g/m²</td>
<td>300 ± 10g/m²</td>
<td>5.68%</td>
</tr>
<tr>
<td>Fiber Areal Weight</td>
<td>300 ± 10g/m²</td>
<td>310 ± 10g/m²</td>
<td>3.45%</td>
</tr>
<tr>
<td>Fiber Density</td>
<td>1.78 ± 3 g/cc</td>
<td>1.80 ± 3 g/cc</td>
<td>1.04%</td>
</tr>
<tr>
<td>Resin Density</td>
<td>1.29 ± 1 g/cc</td>
<td>1.30 ± 1 g/cc</td>
<td>0.31%</td>
</tr>
</tbody>
</table>

Total Variations: 10.95%

---

Fiber Density: 1.78 ± 3 g/cc
Resin Density: 1.29 ± 1 g/cc
Resin Areal Weight: 290 ± 10g/m²
Fiber Areal Weight: 300 ± 10g/m²
Resin Content: 32 ± 3%
Material Variability - Process Capability

±1 and ±3 Sigma Process Capability for Thickness

The Probability of Consistently Achieving ±7% Desired Part Thickness is Very Low!
Primary Model Usage

- Material Options
- Processing Options
- Part Configurations
- Tooling Options

Conceptual Design

- Material Specs
- Processing Specs
- Part Configurations
- Tooling Options

Detailed Design

- On-Line Control
- Quality Dispositions

Part Fabrication
Understanding Uncertainty – The Benefit of Linked Simulation Tools and Methodology

**Producibility Uncertainty**

- **Prepreg Module Uncertainty Considerations**
- **Resin Module Uncertainty Considerations**

**Modeling of the Process**

<table>
<thead>
<tr>
<th><strong>Temperature Boundary Conditions</strong></th>
<th><strong>Variation in temperature throughout an autoclave; variation in bagging thickness across part</strong></th>
<th><strong>Modeling of heat transfer coefficient of autoclave includes pressure effect but not shielding of part. Assumptions made about tool-part resistance.</strong></th>
<th><strong>Convergence of mesh must be checked. Time-steps and temperature steps must be small enough.</strong></th>
<th><strong>Errors in setup files, and other initialization procedures. Errors in code.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tool Part Interaction</strong></td>
<td><strong>Part to part and point to point variations in tool limit and application of release agent</strong></td>
<td><strong>Tool-part interaction is very complex, and very local effects may at times be significant.</strong></td>
<td><strong>Current model of tool-part interaction is too simple for large parts on high CTE tools.</strong></td>
<td><strong>Errors in calibrating the tool-part interaction.</strong></td>
</tr>
<tr>
<td><strong>Layup</strong></td>
<td><strong>Variation in lay-up during hand or machine lay-up.</strong></td>
<td><strong>The layers are smeared within an element and it is assumed that the smeared response is representative.</strong></td>
<td><strong>Error in defining layup, or alternatively errors in the manufactured part compared to model.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Residual Stresses</strong></td>
<td><strong>Many parameters can affect residual stress: local fiber volume fraction, ...</strong></td>
<td><strong>Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.</strong></td>
<td><strong>The formulation is believed to be most accurate when the cure cycle temperature is higher than the Tg. Otherwise the residual stress calculated can be an overestimate.</strong></td>
<td><strong>Errors in material property definition, errors in code, errors in integrating process and structural models.</strong></td>
</tr>
</tbody>
</table>
# AIM-C Methodology Impact on Traditional Qualification

<table>
<thead>
<tr>
<th>Structures Maturity</th>
<th>Non Structural Applications</th>
<th>Secondary Structural Applications</th>
<th>Primary Structural Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM-C Application</td>
<td>AIM-C System Run to Identify Critical Factors for Analysis, Test, Demonstration To Fill Screening Database Requirements</td>
<td>AIM-C System Run to Define Preliminary Design Database Requirements</td>
<td>AIM-C System Run to Define Remaining Design Database Requirements</td>
</tr>
<tr>
<td></td>
<td>Screening Database Exists</td>
<td>Preliminary Design Database Exists</td>
<td>Allowables Database Exists</td>
</tr>
<tr>
<td></td>
<td>Broad Range of Data Limited Replications</td>
<td>Full Distribution on Few Key Properties</td>
<td>Full Distribution on Key Properties</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRL Confidence Lvl</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>50%</td>
<td>60%</td>
<td>70%</td>
<td>80%+</td>
</tr>
</tbody>
</table>

- **Criteria-Based Assessment**: Rework Cycles & Failure Modes
  - Uncertainty

- **Quantitative Assessment via Distance From Experience**
  - Distance
  - Design Point
  - Experience Data Point
  - Axes are the “drivers” for this application

- **Distance from experience**
  - (“similar” hardware, building block tests, and/or anchor points for models)
  - Measured using “anchored” models
AIM-C Reduces Time and Cost of Insertion through Orchestration of Knowledge, Analysis, and Test

Reduction in rework cycles driven by reduced uncertainty (increased confidence)

Slope gives average cost of rework cycle

Uncertainty reduction from risk mitigation activity

Cost Of Rework Cycles $B

Number Of Corrective Actions

Uncertainty

Known-Unknowns

Unknown-Unknowns

Close to Experience

YEARSCOST OF REWORK CYCLES

0 0.5 1.0 1.5

0 50 100 150 200 250 300

Uncertainty reduction from risk mitigation activity
Conclusions

- It is vital to work as a team - customers, suppliers, integrator, certifier. *Any constituent can be holding the critical link to insertion.*
- An approach or methodology serves as an alignment tool to the team.
- Look at the full picture to devise focused plan. Ask *all* questions and fill in as appropriate from knowledge, analysis, and test.
- Don’t forget that it is not an “ideal” world. Plan for robustness.
- Demonstrate and validate success.