



Accelerated Insertion of Materials - Composites



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DARPA Workshop, Annapolis, August 27-28, 2001



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- Program Overview - Gail Hahn
 - Accelerated Insertion of Materials – Composites
 - Composite Materials Insertion Process and Issues
 - Issues for this audience

- Uncertainty - Issues and Challenges - Raj Rajagopal
 - Definition
 - Composite Materials Domain
 - Technologies Under Consideration
 - Challenges

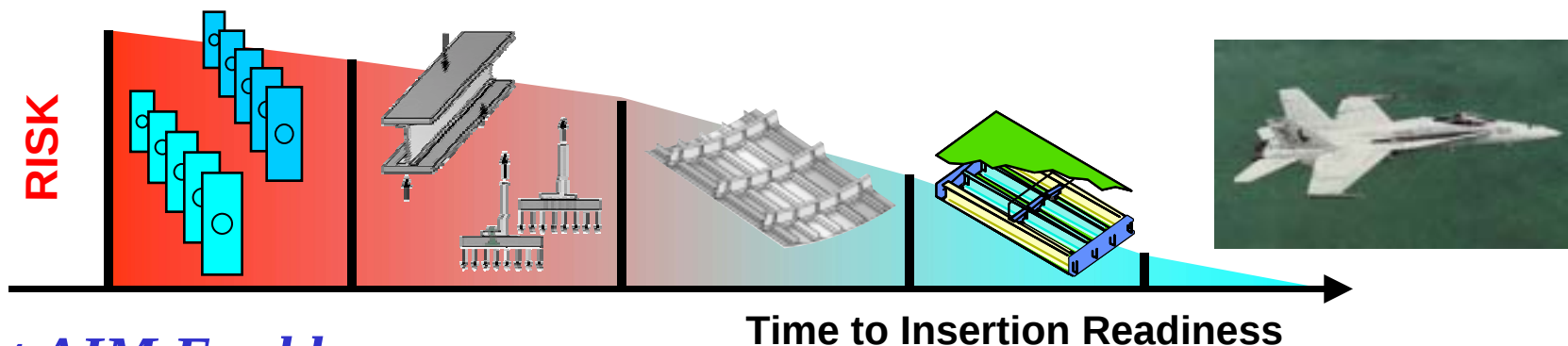




Accelerated Insertion of Materials



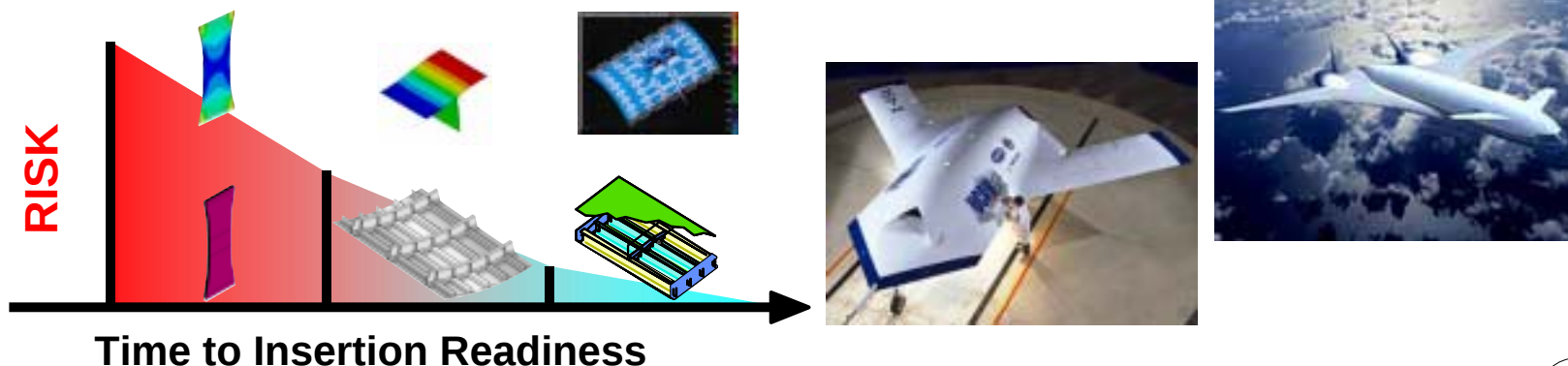
Traditional Building Block Approach Improves Confidence
by Extensive Testing Supported by Analysis:
Too Often Misses Material Insertion Windows



What AIM Enables

AIM Methodology Improves Confidence More Rapidly & Effectively by
Analysis Supported By Test / Demonstration -

Focusing on the Designer Knowledge Base Needs





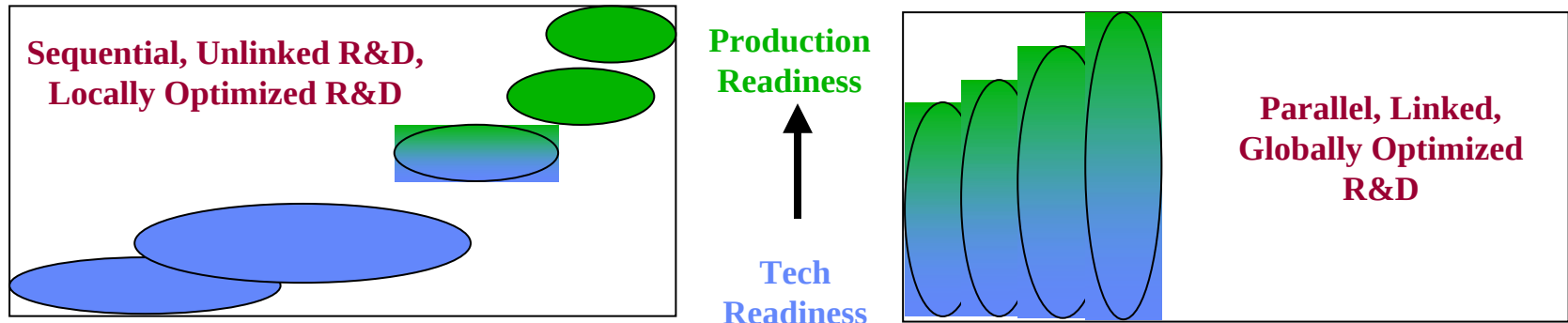
Accelerated Insertion of Materials



Dr. Steven G. Wax, November 16, 1999

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Defense Sciences Office



- **Development of Properties, Processing Done Without Quantifiable Link to Designer Needs**

- Processing Reality Requires Rework of Properties, Still No Link to Designer
- Production Readiness Steps Reworks Technology Readiness
 - » Designer Knowledge Base NOT Ready Until Final Stages

- **Development of Properties, Processing Explicitly (Through Models/Experiments) Linked to Designer**

- Development of Designer Knowledge Base Begins at Outset of R&D Based on Designer Needs
- Time/Effort Refines Knowledge Base
 - » Driven by Properties, Performance, Accuracy Really Needed

A New Paradigm in Materials Development is Required to Significantly Reduce the Timeframe of Insertion

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

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

Material & Processes

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

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



Dr. Steven G. Wax, November 16, 1999

Some Critical Issues



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Defense Sciences Office

- **Knowledge Base Construction**
 - Content and Structure
 - Proper Mix of Experiments and Models
 - Knowledge of Uncertainty and Source
- **Linking of Scales**
 - Hierarchical Averaging Principles for Scaling (Without Losing Extremes)
- **New, Efficient Experimental Approaches (Including Legacy)**
 - Linked to Models
 - Compatible with Legacy Data
- **Propagation of Errors and Variations**
 - In Models and Experiments
- **Representation of Materials and Materials Properties**
 - Full Composition/Microstructure/ Defects
 - Model Independent, Measurement Independent
 - Amenable to Both Model and Experimental Determination

File

Edit

View

Go

Communicator

Help

Yahoo!

Back

Forward

Reload

Home

Search

Netscape

Print

Security

Stop

Bookmarks

Netsite: http: darpa.org/aim.navy.mil

Home

Application

Certification

Assembly

Design

Supportability

Cost

Schedule

Strength

Fabrication

Quality

Mat'l & Proc

Legal/Rights

Output

structure 1 m

laminate 10⁻² m

lamina 10⁻³ m

fiber and interface 10⁻⁶ m

resin 10⁻⁹ m

assembly 10⁺² m

Methodology

Process

New Features

Chemistry to Component in the Shortest Time at Acceptable Risk

Edit Existing File

Compute Results

Save & Close

DARPA

NAVY

TEAM

AIM-C

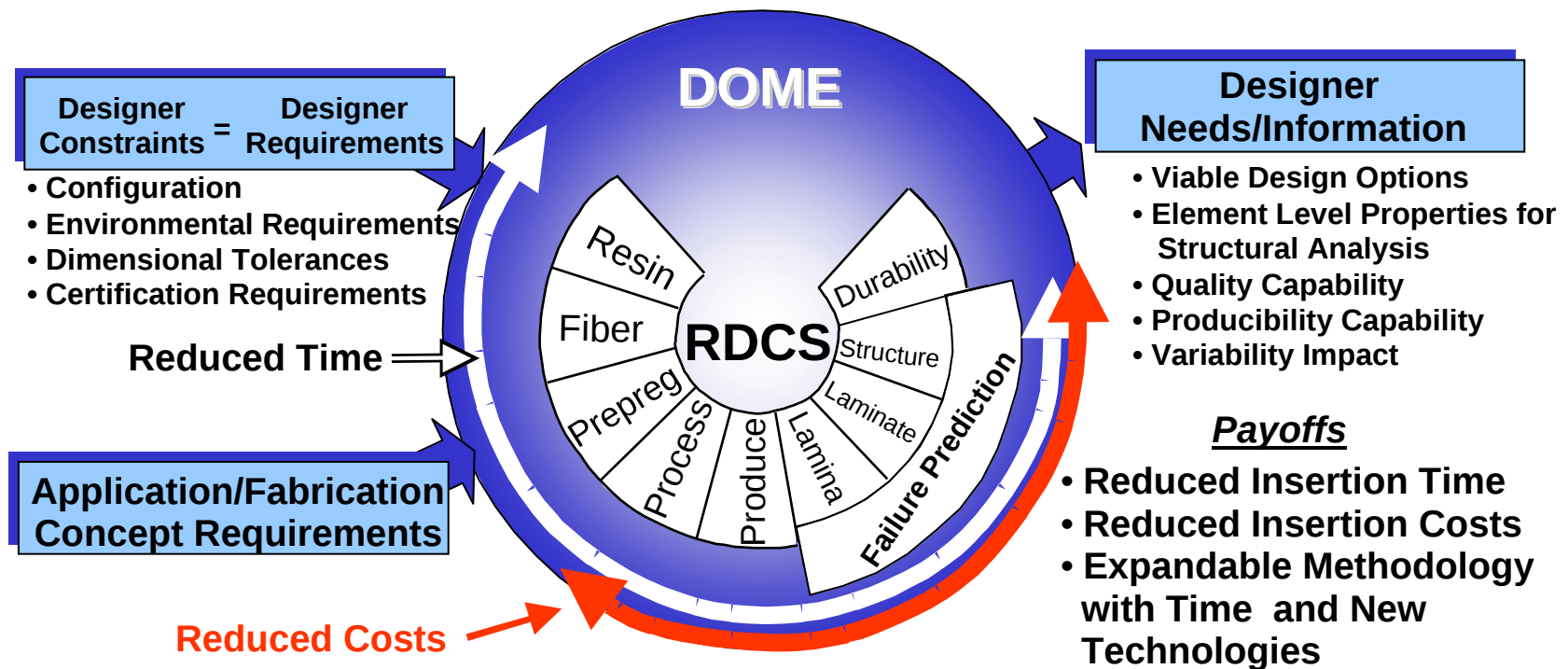
BOEING



Boeing AIM - C Goals

AIM-Composites Will Take Us From Test Supported
by Analysis to Analysis Supported by Test

Designer Knowledge Base Driven

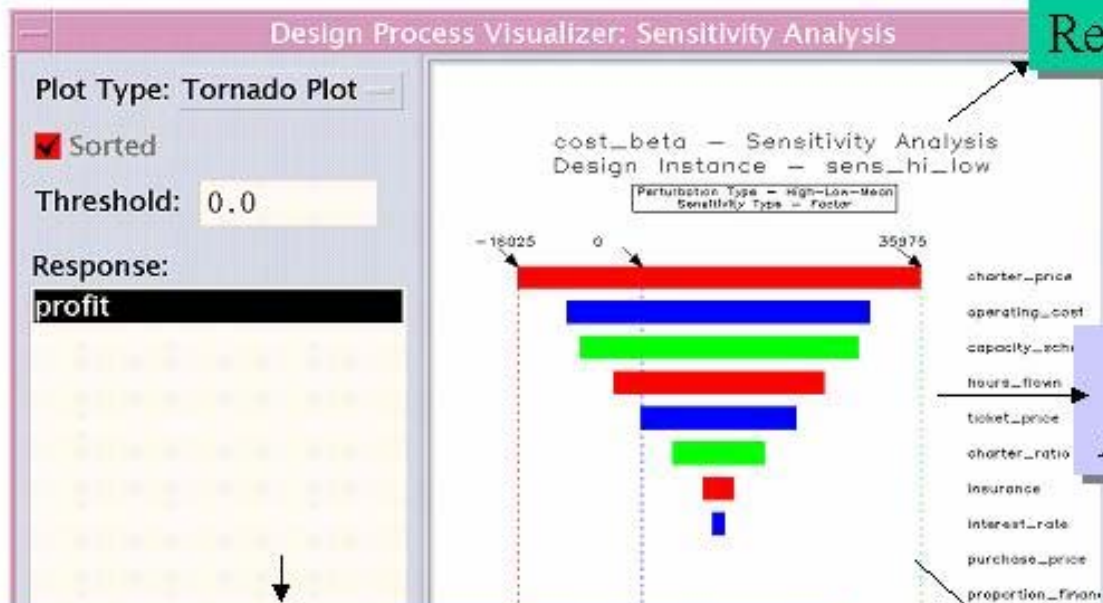


RDCS- Robust Design Computational Systems (Rocketdyne)
DOME- Distributed Object Oriented Modeling Environment (MIT)



Example Output of AIM-C Comprehensive Analysis Tool

Drivers of Cost, Schedule, Technical Outcomes



Related Tests

Recommended
Analysis Methods

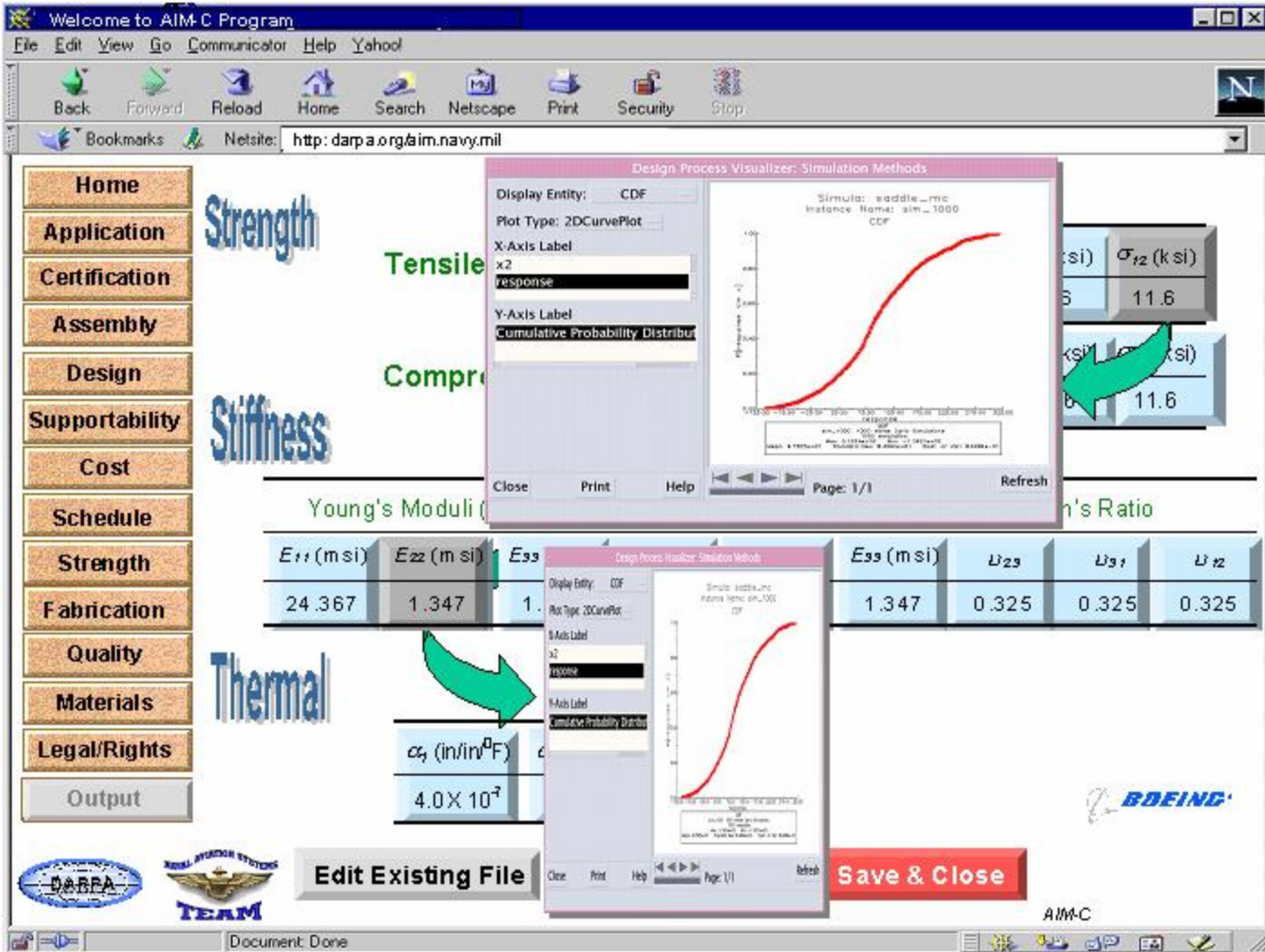
Further considerations

- More interrogations
- Links to related lessons learned
- Links to more information

Recommended
Demonstration
Features



Example Output of AIM-C Comprehensive Analysis Tool





AIM-C Comprehensive Analysis Tool Ties the Output to the Methodology

RDCS/DOME Framework

**Structure
Models**

(Science Based)

**Material & Process
Models**

(Science Based)

**Producibility
Models**

(Science Based)

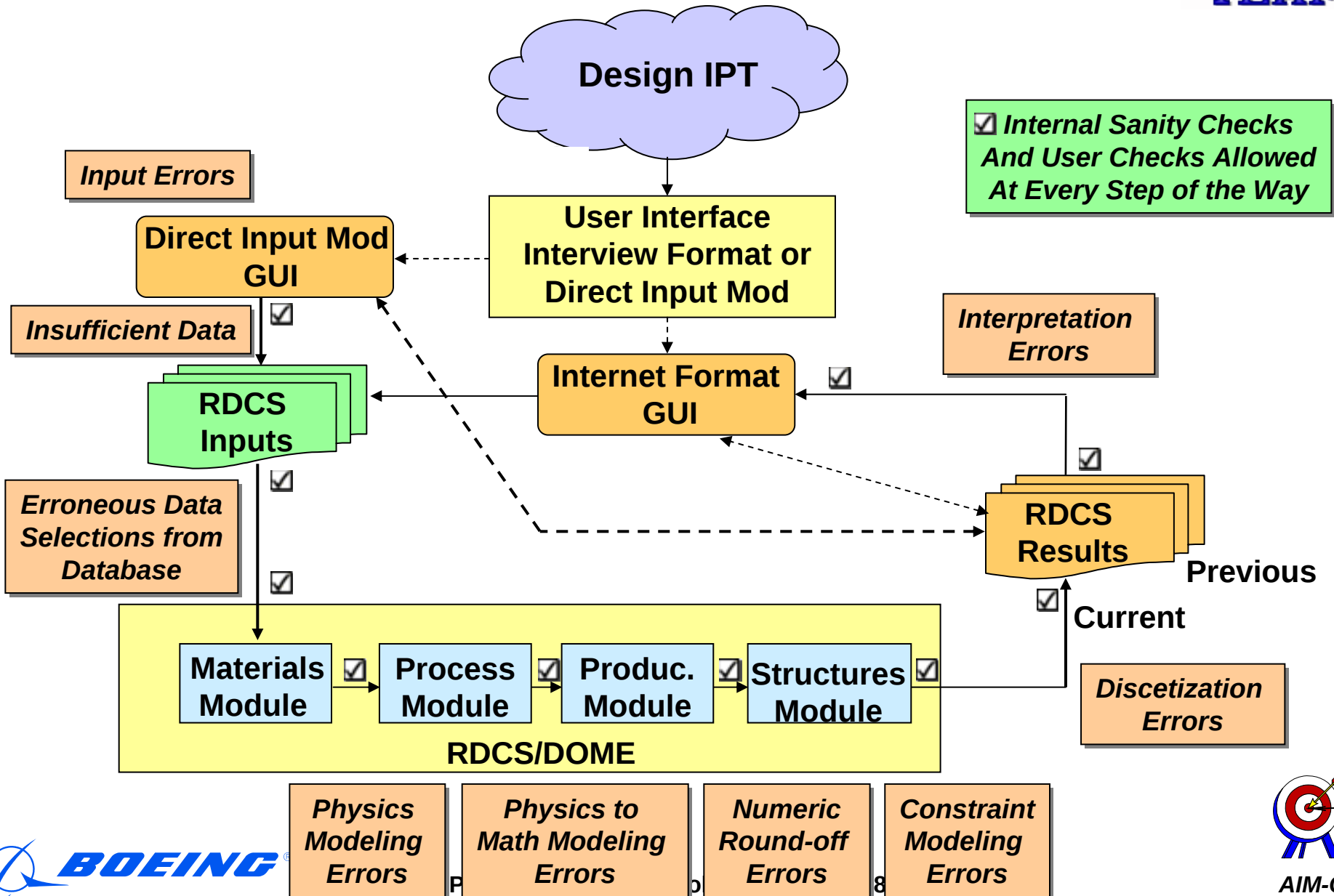
**Heuristic
Models**

Data Bases

Methodology



Error Sources and Mitigation in The AIM-C Product





AIM-C CAT Development Levels



Basic Product

**Architecture Backbone in Place
Limited Heuristic Link to Methodology
Modules Very Limited Utility
No AIM User Interface / Use existing DOME
and RDCS interfaces**

Optional Product

**Architecture with Moderate Robustness
Firm Heuristic Link to Methodology
Modules with Validated Functionality
Internet User Interface for Input**

Phase II Product

**Architecture Robust
Firm Heuristic Link to Methodology
Modules with Complete Functionality
Internet User Interface for Real Time Input /
Output Manipulation Capability**





Industry Benefits from AIM

- Cost, schedule, performance with confidence factor
- Focus based on needs
- Knowledge management – orchestrated models, simulations, experiments to maximize useful information
- Built on building block methodology while facilitating discipline integration
- Internet access
- Path from criteria based to probabilistic based approaches
- Platform support for changes – bill of materials, pedigree, re-certification
- Design process application
- The best of emergent modeling and explicit modeling
- Applications to other problem sets

Improve productivity, facilitate radically new approaches to material insertion





“Building Block” Test Program

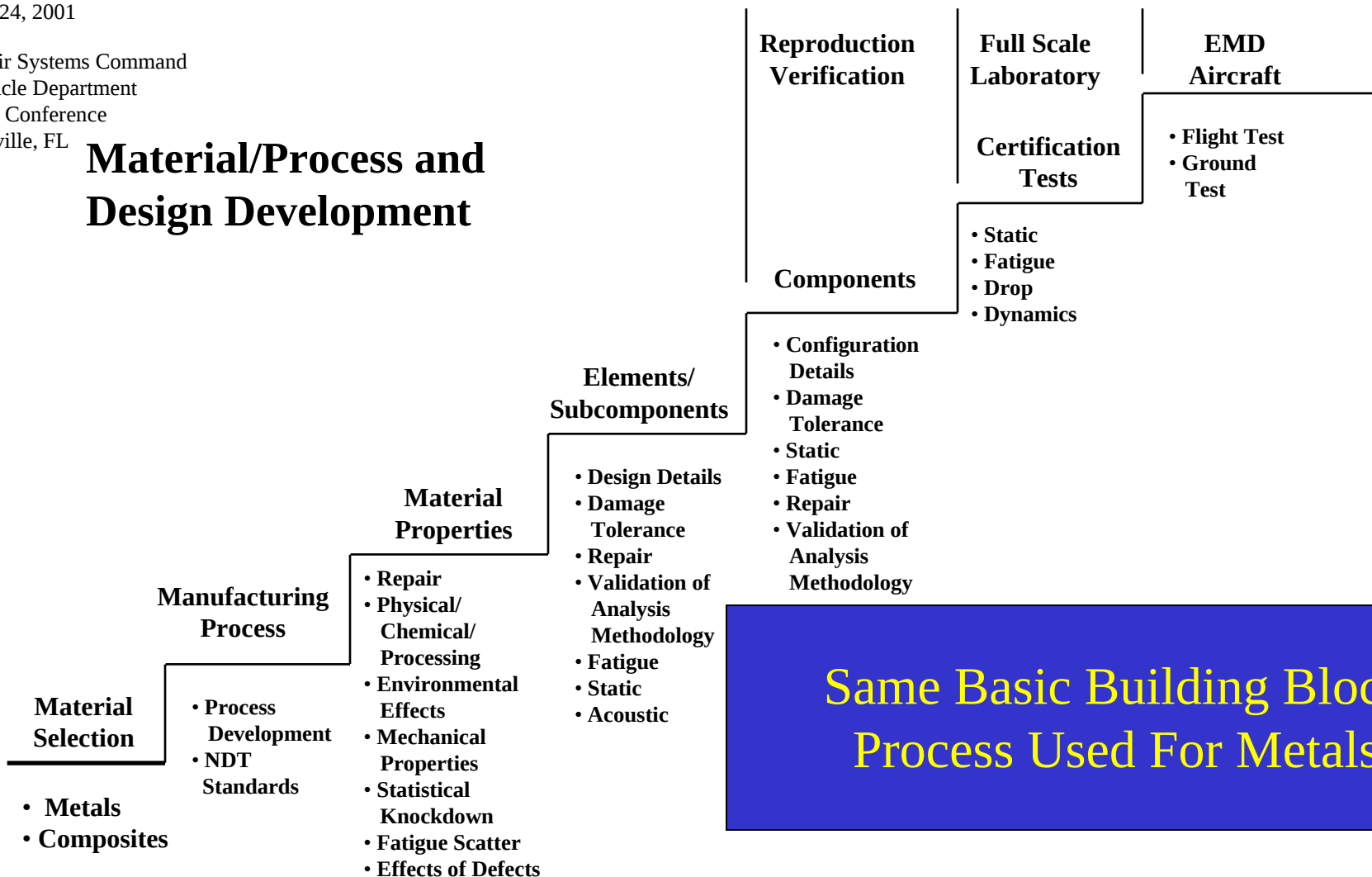


Kathryn L. Nesmith,
Roland Cochran and Denise Wong

May 21-24, 2001

Naval Air Systems Command
Air Vehicle Department
National Conference
Jacksonville, FL

Material/Process and Design Development



Same Basic Building Block
Process Used For Metals



DARPA Workshop, Annapolis, August 27-28, 2001



AIM-C

Specifics for Polymer & Composite Material Certification

- Essential to look at materials and related process together
- “B”-Basis design allowables are used
 - Dependent on material form
- Experience from other programs can be used; however, ability to achieve properties must be demonstrated
 - Many test methods used are company proprietary



Polymer & Composite Material Properties

- Physical and Chemical
 - Tg
 - Density
 - Viscosity
 - Cure Kinetics
 - Out Time
 - Tack
- Environmental Effects
 - Fluid Resistance
 - Upper/Lower Use Temps
 - Thermal Cycling and Shock
 - Moisture Absorption
 - Vibration & Acoustic
- Mechanical Properties
 - Strength / Modulus
 - Notch Sensitivity
 - Fatigue
 - Adhesion
 - Damage Tolerance
 - All critical modes and environments

Products:
Material Specifications, B-Basis Design Allowables





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





Requalification of Polymer / Composite Parts



Graphite Composites

	<u>Constituents</u>	<u>Equipment</u>
• Fiber	Precursor Sizing	Precursor Fiber Lines Carbonization Fiber Lines
• Resin	Multiple Monomers & Polymers Solvents	Mixers
• Prepreg • Slit Tape	Impregnation Level	Prepreg Lines Slitter
• Fabric/Preforms		Weavers / Braiders



Requalification of Polymer / Composite Parts



- Part Fabrication Process Changes
 - New Process, Baseline Material
 - Example: Change to Selective Laser Sintering process of nylon reduced elongation by 90% compared to baseline process
 - Modification / Replacement / Relocation of Process Equipment
 - Change to Process Parameters Outside Qualified Process Window



Small Portion of ONR Protocol

Key

- - Must evaluate amount of testing requested to address this issue. No testing required may be an acceptable answer. Testing amount dependent upon contractual requirement, application, complexity and level of acceptable risk
- Q - Typically required for quality control testing of each batch of material fabricated
- ☐ - Test not required. Identified change is not anticipated to affect this property or a related property will identify this material as not being equivalent.

	New Fiber, New Resin, New Airframe	New Fiber, New Resin	New Resin, Baseline Fiber	New Fiber, Baseline Resin	New Process, Baseline Fiber & Resin	New Prepreg Supplier, Baseline F & R (mixes)	New Prepreg Supplier, Baseline F & R (buys)	New Fiber line, Baseline Fiber	New PAN line, Baseline Fiber	Mod to Qual. Fiber Line, Baseline Fiber
Fiber Characterization	•	•	Q	•	Q	Q	Q	•	•	•
Resin Characterization	•	•	•	Q	Q	•	Q	Q	Q	Q
Interface Characterization	•	•	Q	•	Q	Q	Q	•	•	•
Chemical	•	•	•	Q	•	•	Q	Q	Q	Q
Physical	•	•	•	•	•	•	•	•	•	•
Nominal Cure Process	•	•	•		•					
Nominal NDE Process	•	•	•							
Mechanical (Lamina)	•	•	•	•	•	•	•	•	•	•
Structural Properties (Static)										
Unnotched Tension	•	•	•	•	•	•	•	•	•	
Unnotched Compression	•	•	•	•	•	•	•	•	•	•
Pin Bearing	•	•	•	•	•	•	•			
Flexure (w/ & w/o holes)	•	•	•							
Others	•	•	•	•	•	•	•	•	•	•



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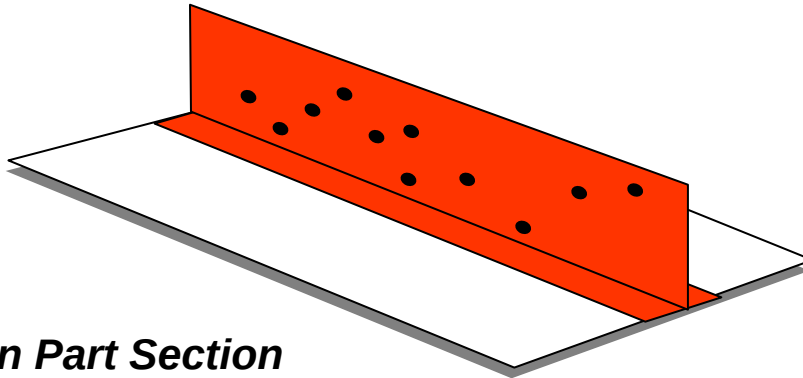


Summary

- Polymer & composite part certification differs in some ways from metallic structure
 - Very dependent on both material and processing from raw material to part fab
 - Allowables based on “B”-basis
 - 1st article destruct testing is needed for primary structure and significant secondary structure
- Requalification testing is required for changes in:
 - Raw material constituents (source, quality)
 - Equipment (new, modifications, relocation)
 - Processing parameters
 - Additional design certification may be required if material properties, component geometry or reaction to manufacturing processes are different than baseline component



Common Manufacturing Insertion Issues

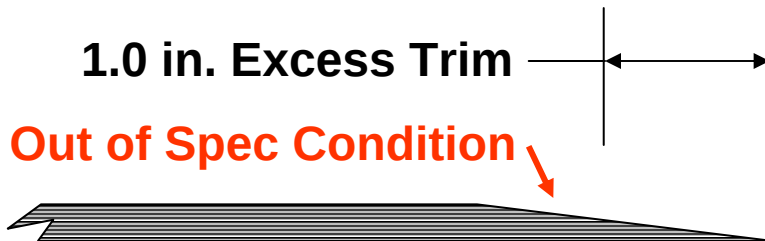


*Thin Part Section
with Cocure Having Voids and Porosity*

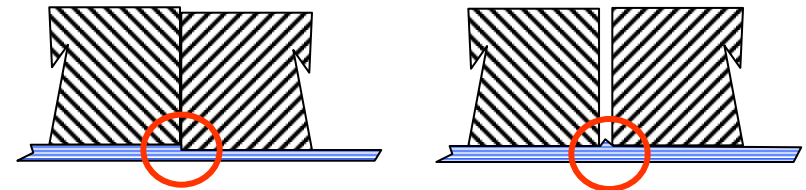
**Process Specification
Calls out $\pm 6-7\%$
Thickness Tolerance**

Thickness Zoning

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



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)***



***Process
Specification/
Tooling Incompatibilities for Heat-up
(Invar/Steel)***

***Insufficient Out Times
(Never Enough)***



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**
- **Moisture/Solvent Absorption with Plastization and/or Reduced Tg**
- **Incompatibility of Resin Characteristics and the Manufacturing Process**
- **Final Part Accuracy/Repeatability Relative to Tooling Concepts**

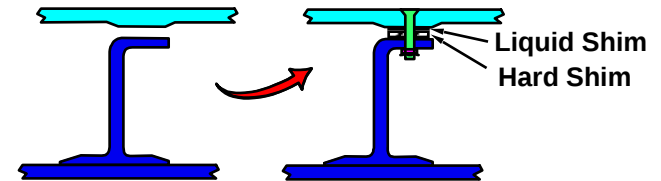




Background

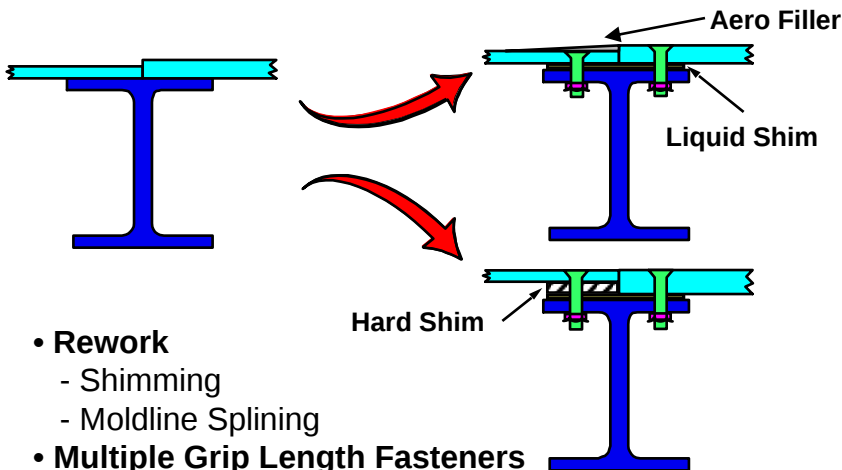


Assembly Variations



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

Surface Fidelity Variations



- Rework
 - Shimming
 - Moldline Splining
- Multiple Grip Length Fasteners

Major Variation Types

Part Mismatch

- Skin-to-Substructure
- Substructure-to-Substructures

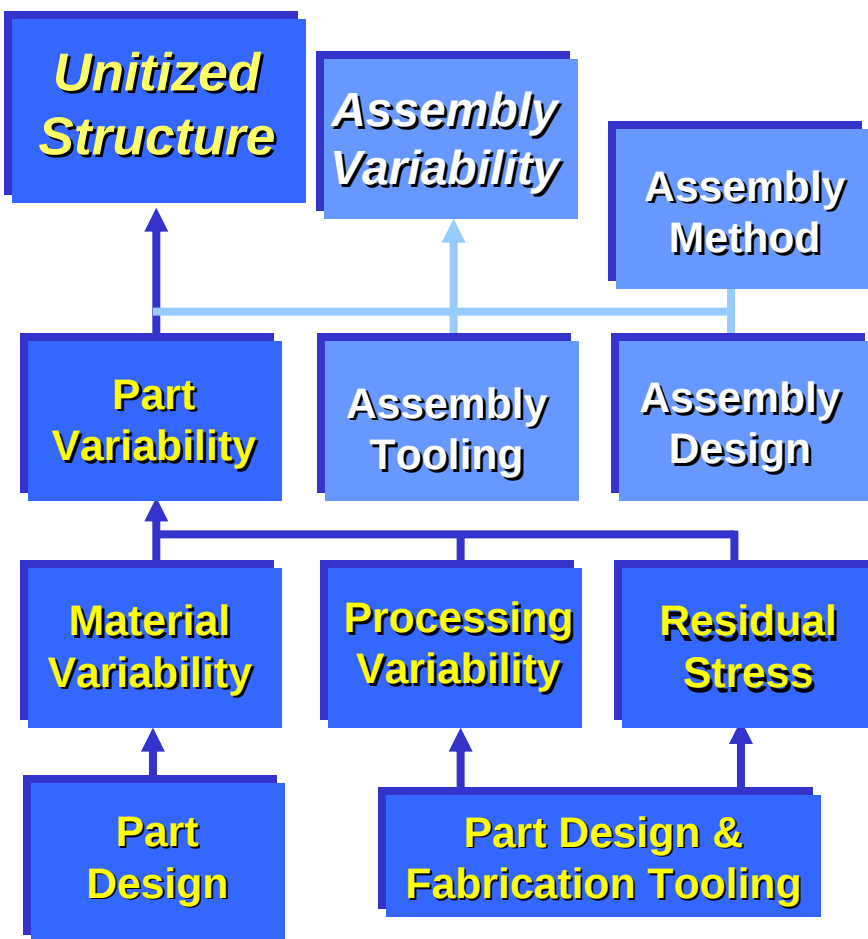
Moldline Fidelity

- Skin-to-Door
- Skin-to-Access Panel
- Skin-to-Skin

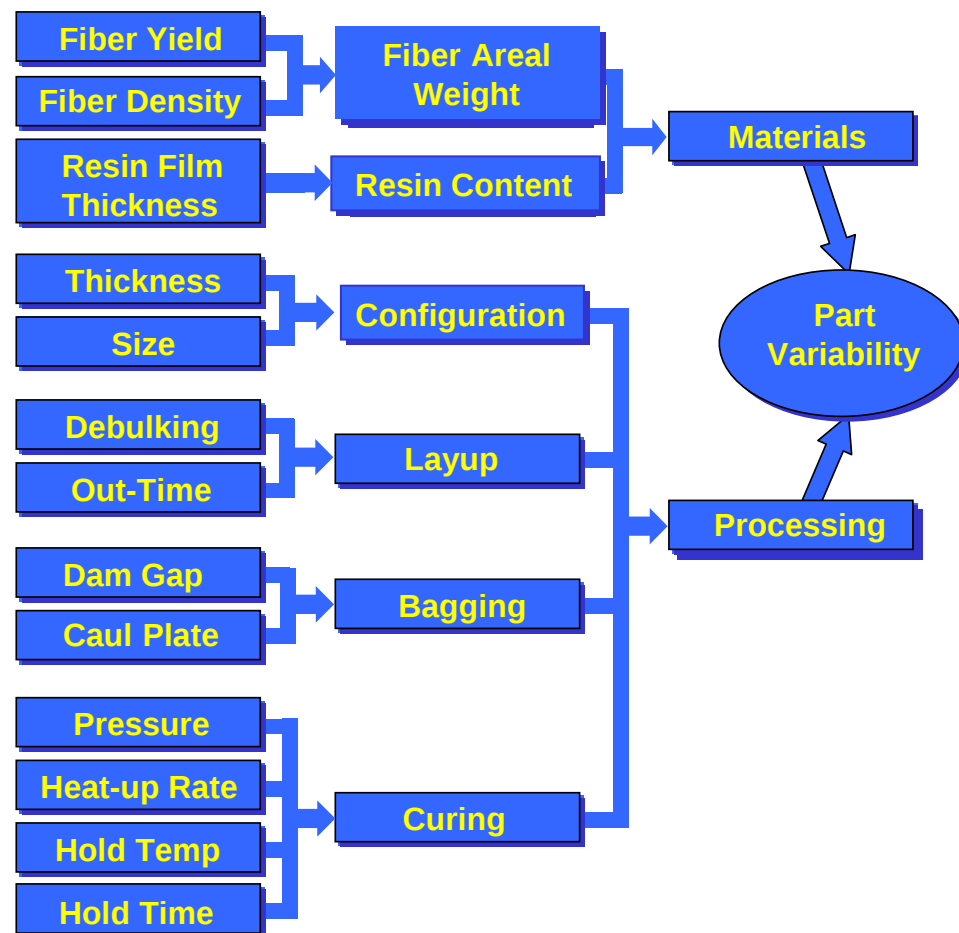


Assembly Variability

Variability Flow Chart



Material and Processing Part Tolerance Accumulations





Part Variability Factors

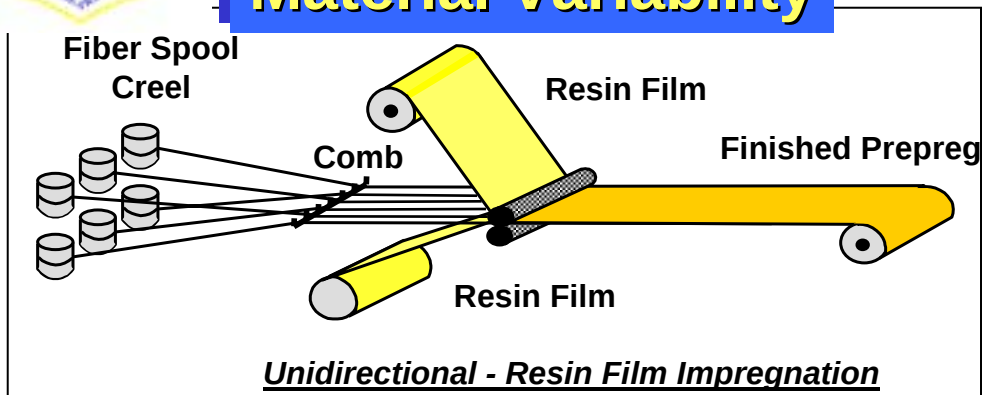
<u><i>Design</i></u>	<u><i>Materials</i></u>	<u><i>Processing</i></u>	<u><i>Cure</i></u>	<u><i>Tooling</i></u>
• Orientation • Thickness • Size	• Unidirectional • Cloth • Net Resin • Excess Resin • FAW • Resin Content • Prepreg Manufacturing	• Material Out Time • Bleeder • Inner Bag Perforations • Dam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



Precision Assembly of Composite Structures

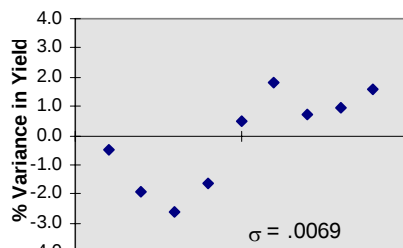


Material Variability



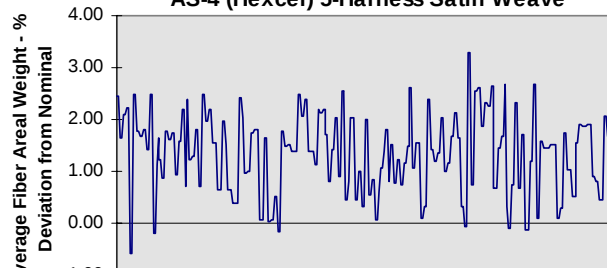
Fiber Variability (210 Batches)

Hexcel AS4 6K



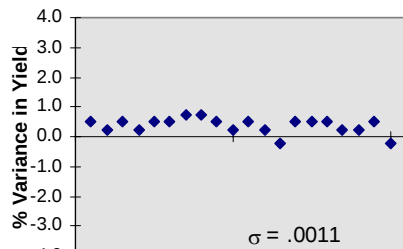
Fiber Lot

AS-4 (Hexcel) 5-Harness Satin Weave



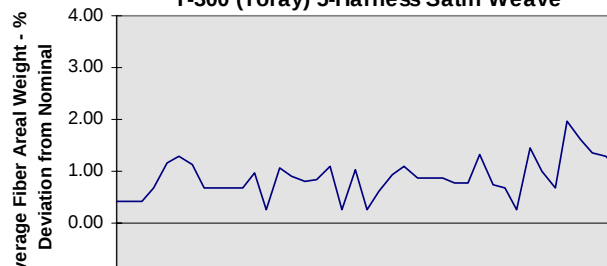
Fabric Lot

Toray T-300 6K



Fiber Lot

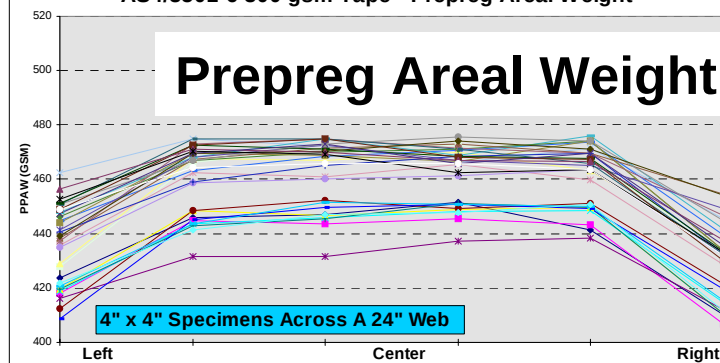
T-300 (Toray) 5-Harness Satin Weave



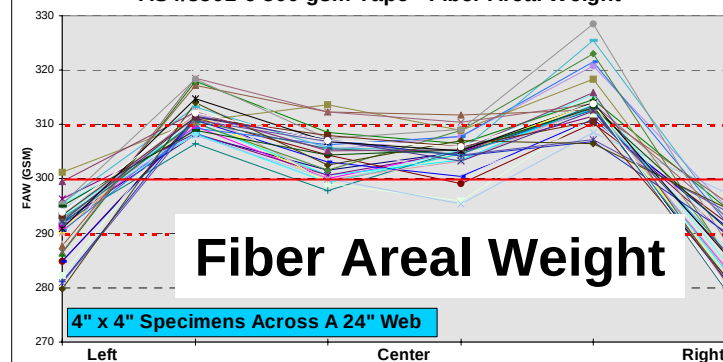
Fabric Lot

Prepreg Variability (21 Batches)

AS4/3501-6 300 gsm Tape - Prepreg Areal Weight



AS4/3501-6 300 gsm Tape - Fiber Areal Weight

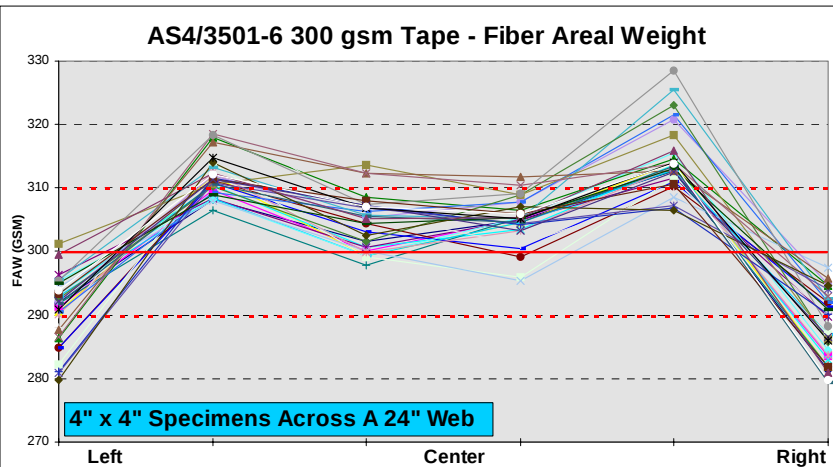


- Fiber Yield Variation Translates to Fiber Areal Weight Variation (Cloth)
- Prepreg Variation is Driven By Fiber Areal Weight Variation

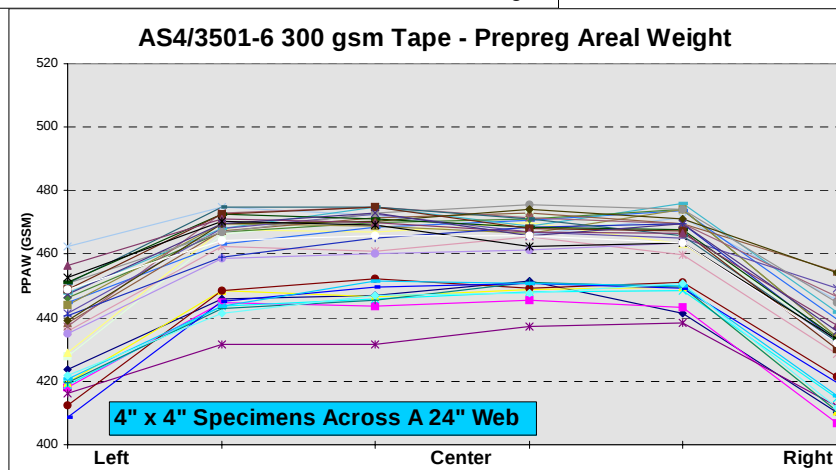


Subtask 1 - Material Variations Material Variability Assessment

...Prepreg Areal Weight Versus Fiber Areal Weight



- 4"x4" Specimens Taken Across A 24" Web
- 46 Rolls of Material Tested - 36 Excess Resin, 10 Net Resin



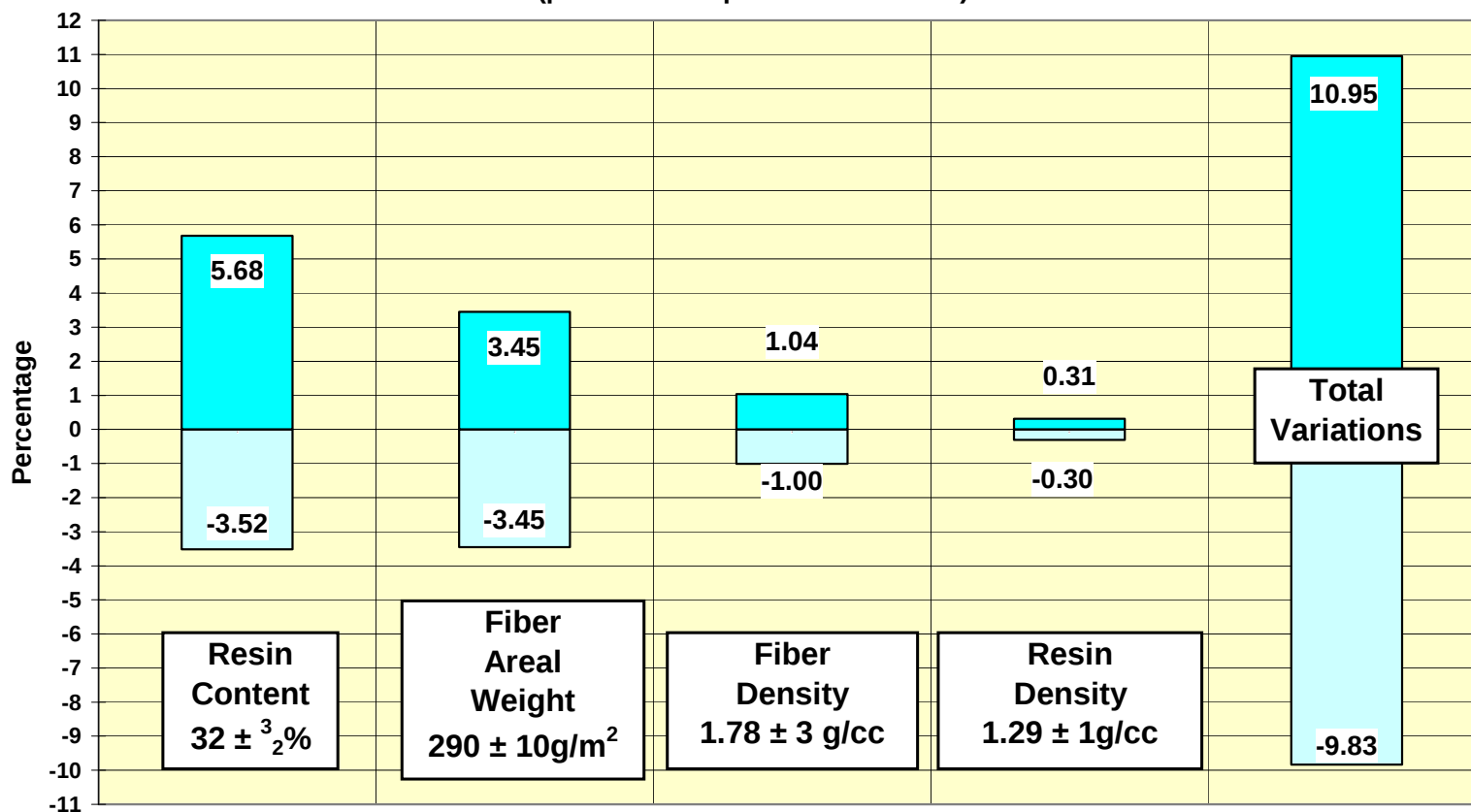
**Significant Edge
Effect on Prepreg
Areal Weight Due
Mainly to Edge
Drop-Off Of Fiber
Areal Weight**



Material Variability

Theoretical Prepreg Variability

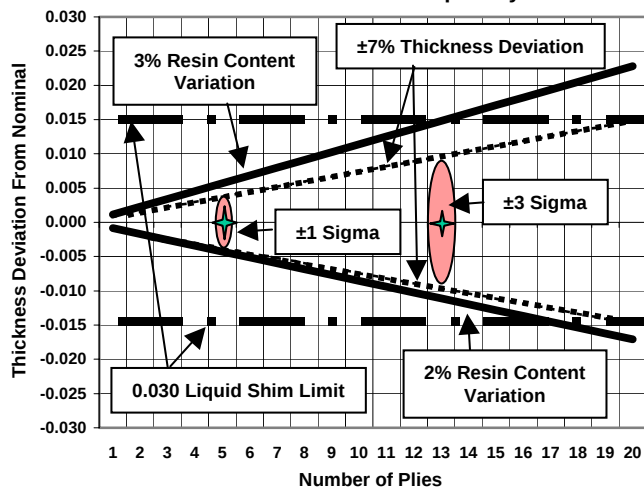
Prepreg Variability Contributing Factors
IM7/977-3 Unidirectional, Net Resin
(per Material Specification Limits)



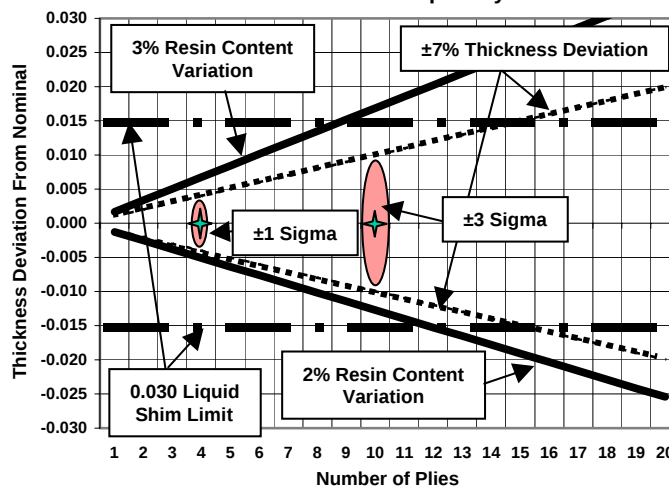


Material Variability - Process Capability

Unidirectional Part Thickness Capability

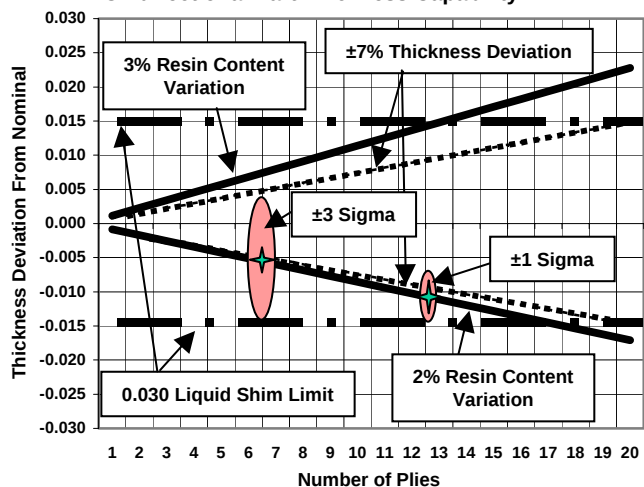


Cloth Part Thickness Capability

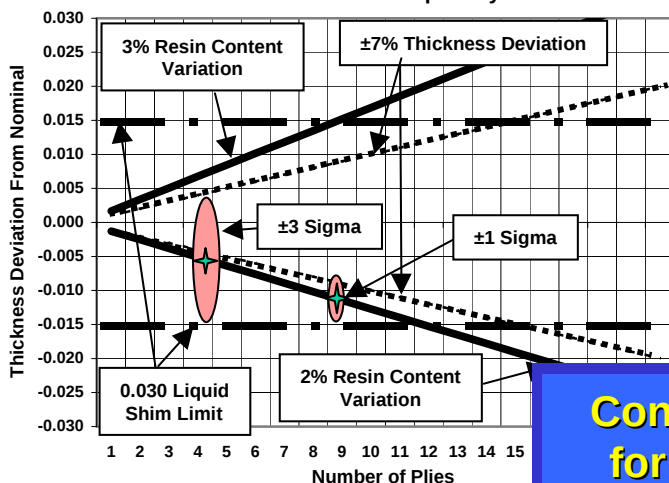


± 1 and ± 3 Sigma
Process Capability
for Thickness

Unidirectional Part Thickness Capability



Cloth Part Thickness Capability



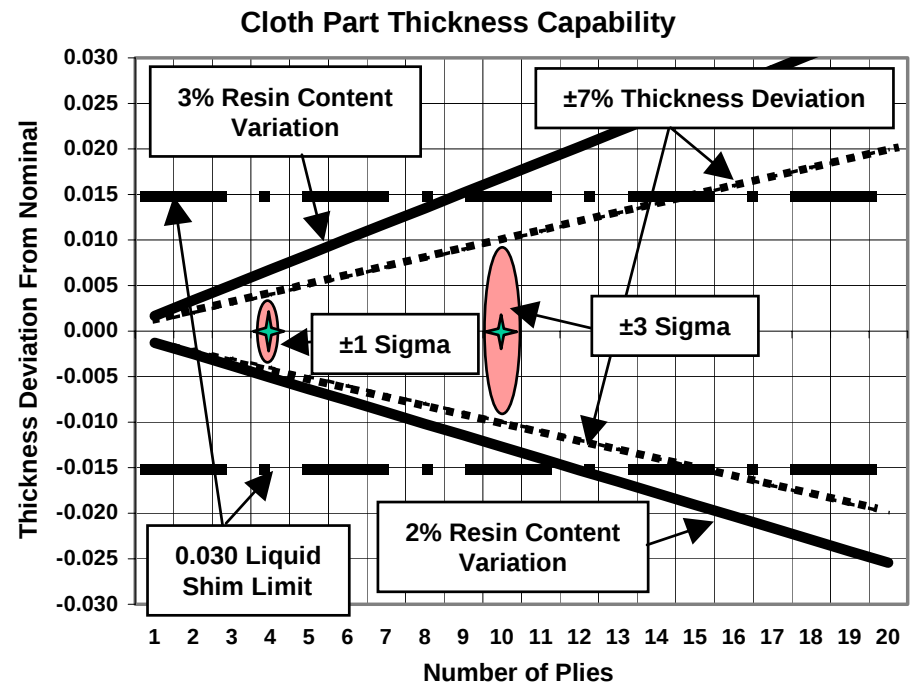
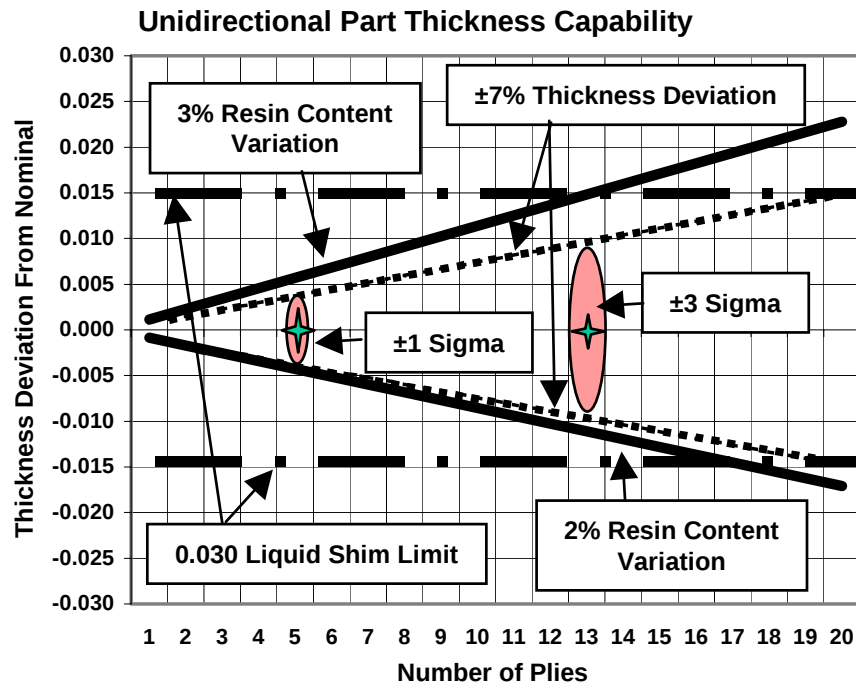
± 0.015 in. for Liquid
Shim Maximum
Tolerances

**Contradictory Requirements
for Process Capability and
Assembly Tolerances**



Material Variability - Process Capability

± 1 and ± 3 Sigma Process Capability for Thickness

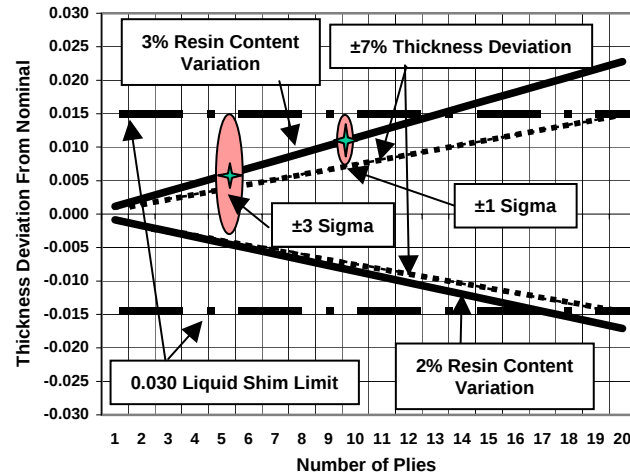


..... **The Probability of Consistently Achieving $\pm 7\%$ Desired Part Thickness is Very Low!**

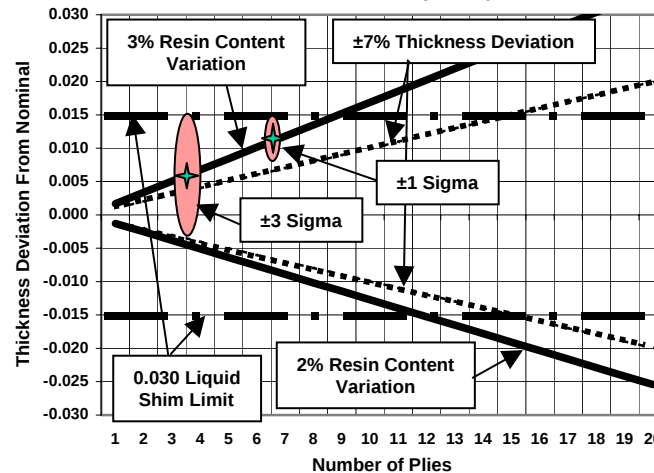


Material Variability - Process Capability

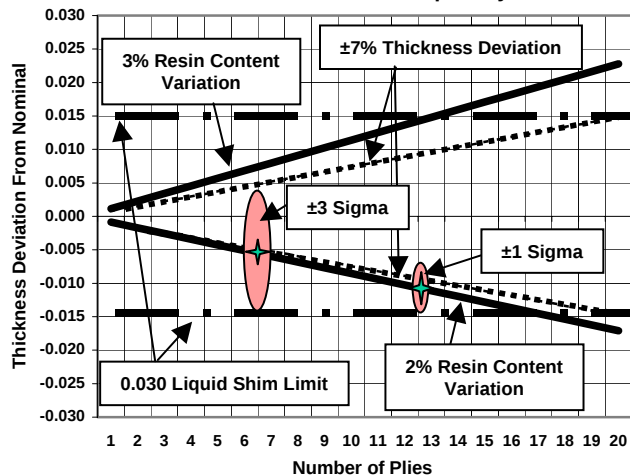
Unidirectional Part Thickness Capability



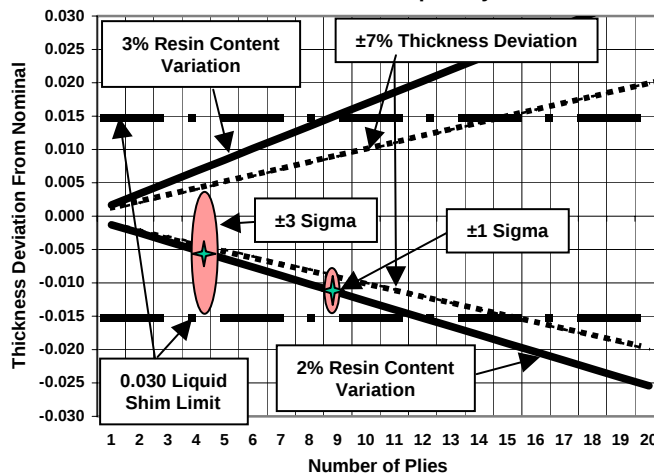
Cloth Part Thickness Capability



Unidirectional Part Thickness Capability



Cloth Part Thickness Capability

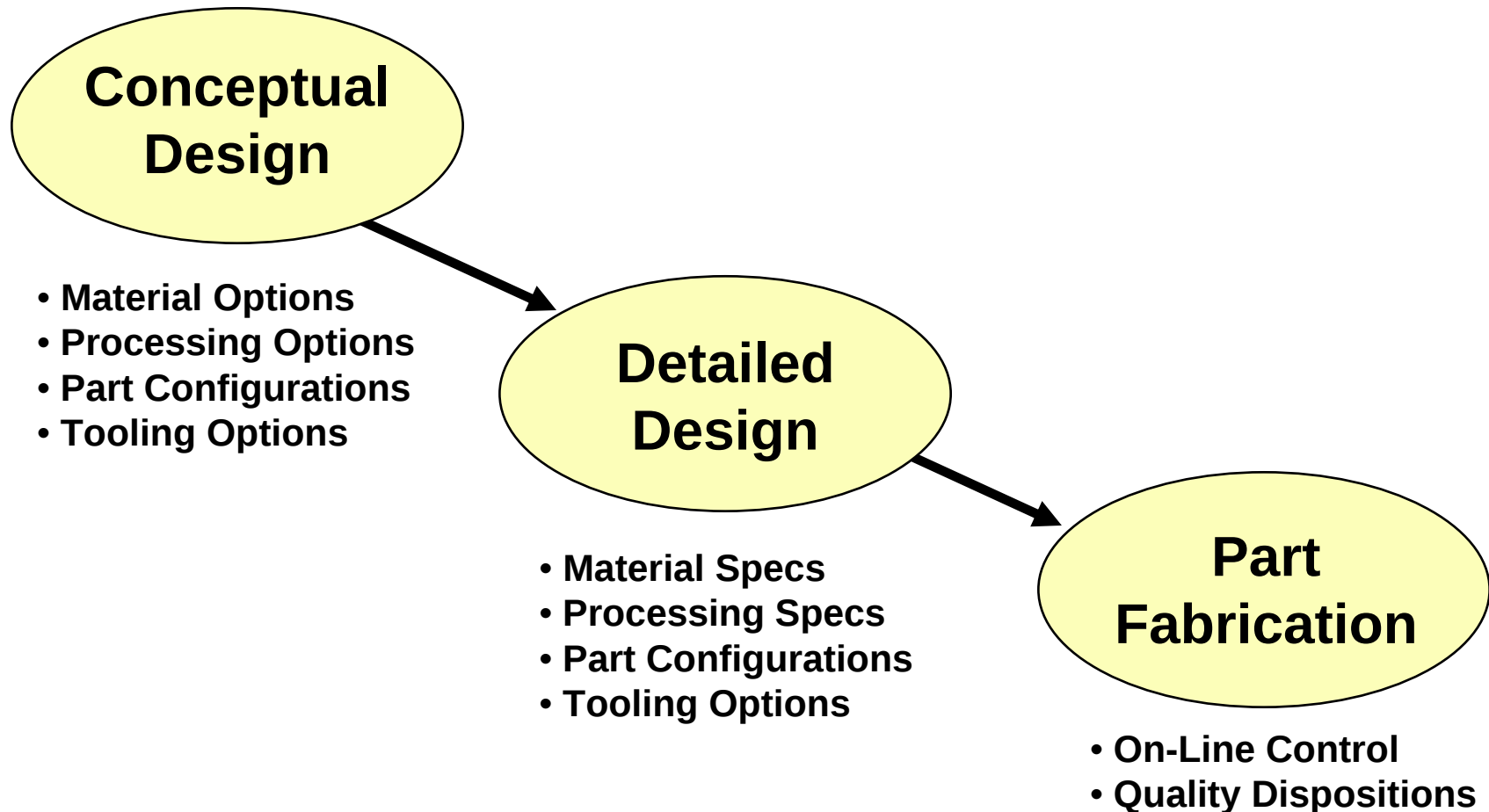


- With Existing Tolerances on Prepreg Materials, It is Difficult to Maintain ± 0.015 Inch Liquid Shim Assembly Requirements

.....**Process Spec and Assembly Requirements are Mutually Exclusive With ± 3 Sigma Process Capability !**

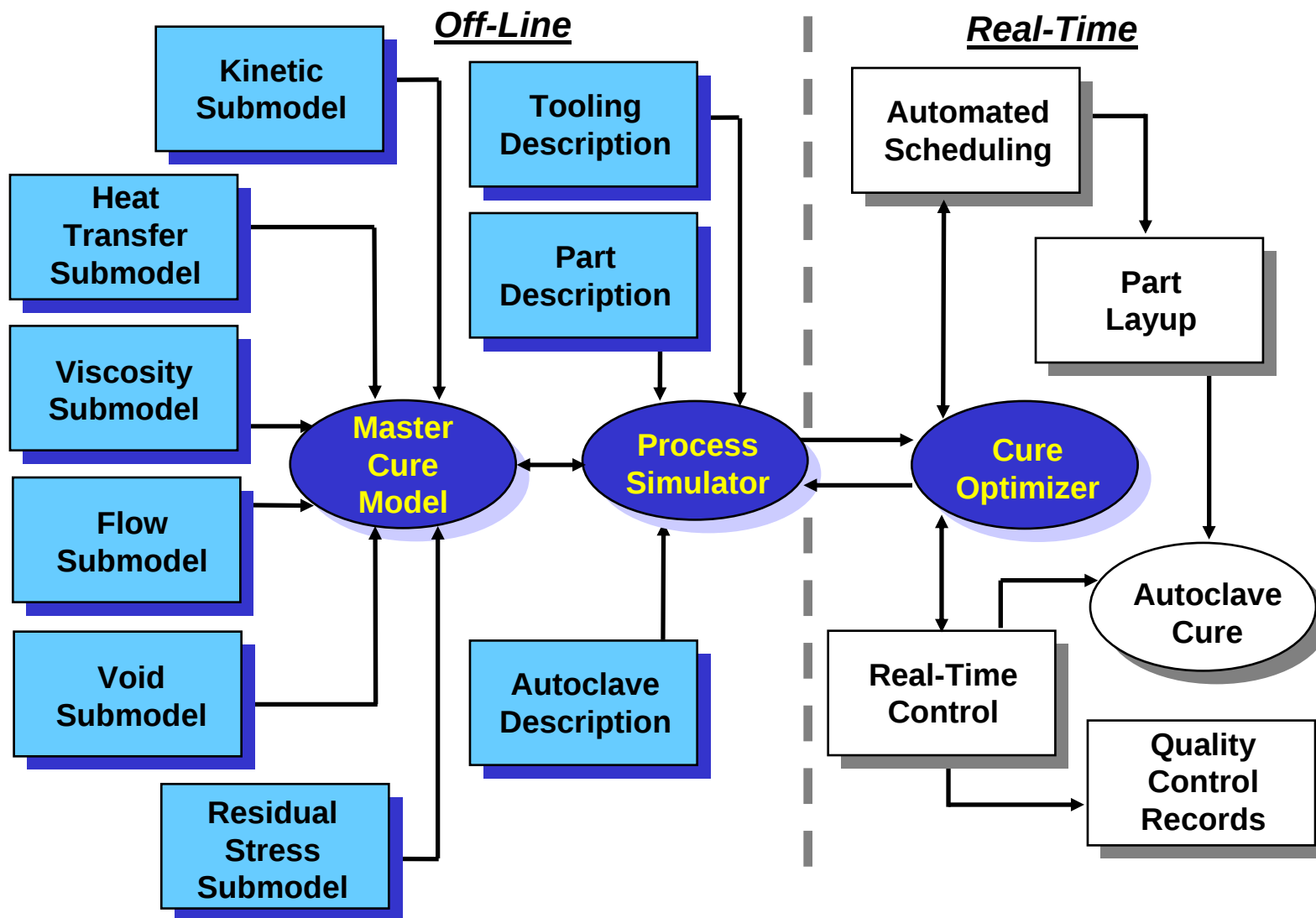


Primary Model Usage Times





CACC Cure Process Modeling





Understanding and managing uncertainty is an integral part of the AIM Materials and Processes approach

- Present clear traceability to data input pedigree
- Identify when models are out of their predictive bounds, validated bounds
- Collect uncertainty information as calculation progresses

Practical Aspects of Managing Uncertainty

- Indirect property measurement often required
- Testing expense and/or history can limit data populations
- Assumptions necessary to develop efficient models
- Focus on significant inputs (can vary from case to case)





- Input Material Properties
 - Test methods – accuracy, repeatability
 - Distribution – data correlation, population
- Modeling
 - Accuracy of physics
 - Assumptions
 - Interpolation, extrapolation of input datasets
- Output values
 - Interpolation, extrapolation of output datasets
 - Post processing of data



•Input Material Properties

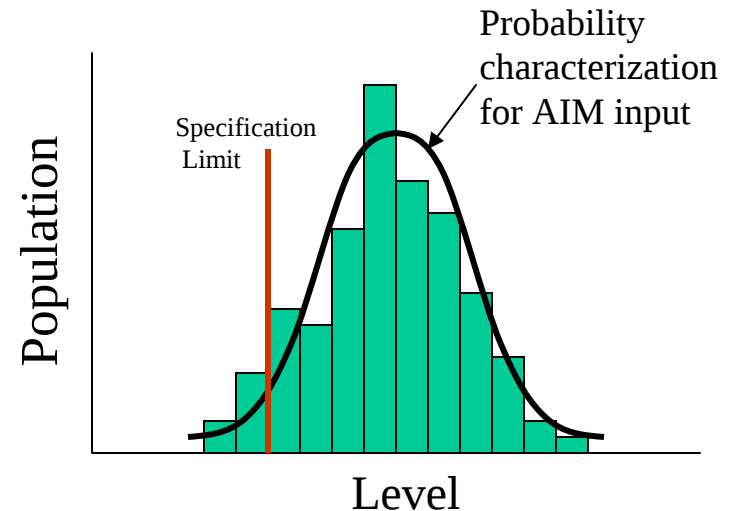
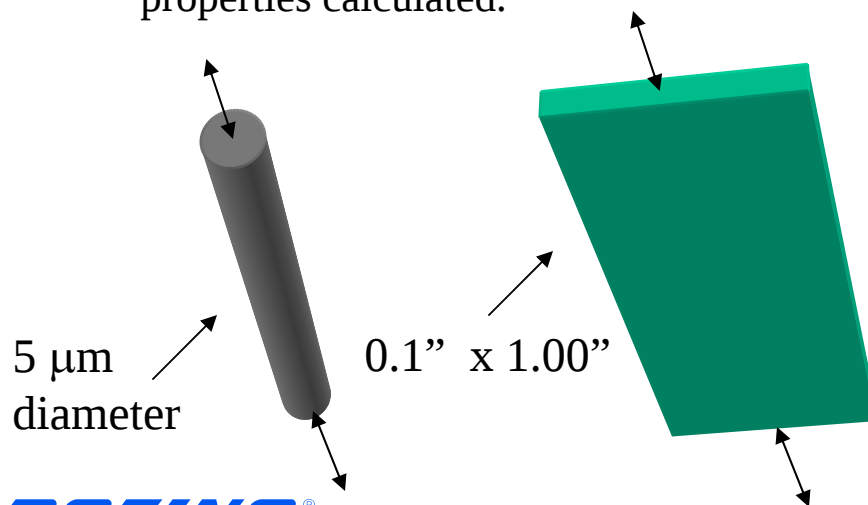
- Test methods – accuracy, repeatability
- Distribution – data correlation, population

Example:

Fiber properties

single fiber tests not practical

Laminate tests performed, fiber properties calculated.



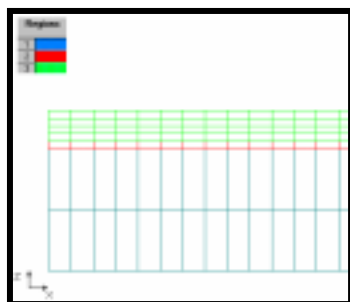
Example:

Actual data may not be ideal distribution shape, Distribution of material actually used may be truncated by specification acceptance criteria

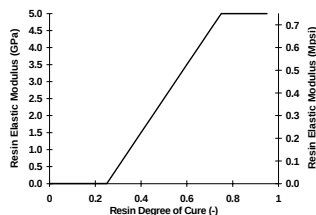
•Modeling

- Accuracy of physics
- Use of models outside of known limits
- Code Bug

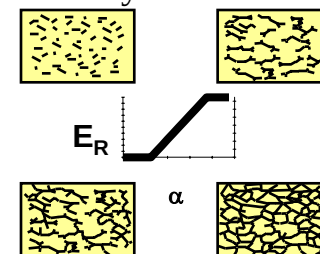
Example: The tool surface finish is not uniform for a tool or between tools.



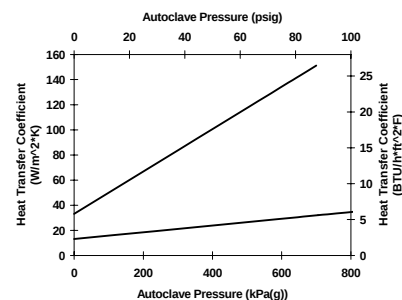
Example: Physics of cure-hardening linear elastic versus fully viscoelastic



Example: Unknown mistake in calibrating DSC leads to wrong heat of reaction and incorrect temperature history



Example: Autoclave heat transfer equation is used outside of known limits





Modeling of the Resin



TEAM

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Degree of Cure	batch to batch variation in rate of reaction.	Validity of the form of the equation; including physical basis: empirical, semi-empirical ...	Use of model outside of bounds (eg temperature range, rates). In general modules should be self-checking. Are all input parameters within predefined bounds?	DSC not calibrated; base-line choice (Need to track history of usage – at all levels. Over time this will reduce uncertainty due to this)
Modulus	Specimen to specimen variation; batch to batch variation.	For partially cured materials, the assumption of cure hardening, linear elastic response. For cured materials, the response under mixed mode loading.	Use of model outside of bounds (eg strain range). Approximation of straight line fit to curve.	Testing machine not calibrated. Poor specimen preparation; poor strain measurement techniques.
Strength (to failure)	Specimen to specimen variation; batch to batch variation.	Definition of failure; particularly for some loading cases. Initiation versus propagation of a crack.	Use of model outside of bounds (eg temperature range).	Testing machine not calibrated. Poor specimen finish, poor alignment in grips.
Strain (to failure – linked to strength)	Specimen to specimen variation; batch to batch variation. This value is correlated with strength and somewhat to modulus	Definition of failure; particularly for some loading cases. Initiation versus propagation of a crack.	Use of model outside of bounds (eg temperature range).	Testing machine not calibrated. Poor specimen finish, poor alignment in grips.





Modeling of the Prepreg



	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Prepreg Degree of Cure	Carried forward from resin module	Assumption that the fiber does not affect the resin reaction behavior.		Coding errors (bugs)
Prepreg Volume Fraction of Fiber	Point to point variation along width and along length of prepreg. Effect of combination of many layers to form the structure thickness.	Assumption that there are no visible voids	Use of a pre-defined value for compaction of layers due to pressure application	Poor measurements in acid digestion tests, optical techniques, etc.,.
Aerial weight	Correlated value with prepreg volume fraction of fiber, ply thickness, and resin and fiber densities			
Prepreg ply thickness	Correlated value with aerial weight and volume fraction of fiber			Difficulty in measurement of a small value that varies across the width and along length





Modeling of the Process

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Temperature Boundary Conditions	Variation in temperature throughout an autoclave; variation in bagging thickness across part	Modeling of heat transfer coefficient of autoclave includes pressure effect but not shielding of part. Assumptions made about tool-part resistance.	Convergence of mesh must be checked. Time-steps and temperature steps must be small enough.	Errors in setup files, and other initialization procedures. Errors/bugs in code.
Tool Part Interaction	Part to part and point to point variations in tool finish and application of release agent	Tool-part interaction is very complex, and very local effects may at times be significant	Current model of tool-part interaction is too simple for large parts on high CTE tools.	Errors in calibrating the tool-part interaction
Layup	Variation in lay-up during hand or machine lay-up.	The layers are smeared within an element and it is assumed that the smeared response is representative		Error in defining layup, or alternatively errors in the manufactured part compared to model
Residual Stresses	Many parameters can affect residual stress: local fiber volume fraction, ...	Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.	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.	Errors in material property definition, errors in coding, errors in integrating process and structural models.



Modeling of the Fiber

	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Coefficient of thermal expansion, α_1, α_2	Batch to batch variation in material, arising from variations in PAN precursor, and carbonization process	Models almost always assume no temperature or moisture effect.	Lack of direct measurement techniques; property is measured on a lamina/laminate basis.	Back-calculation values based on micromechanics. Complex experimental methods.
Modulus (E11, E22)				
Strength (to failure)				
Strain (to failure – linked to strength)				





Stochastic Variables

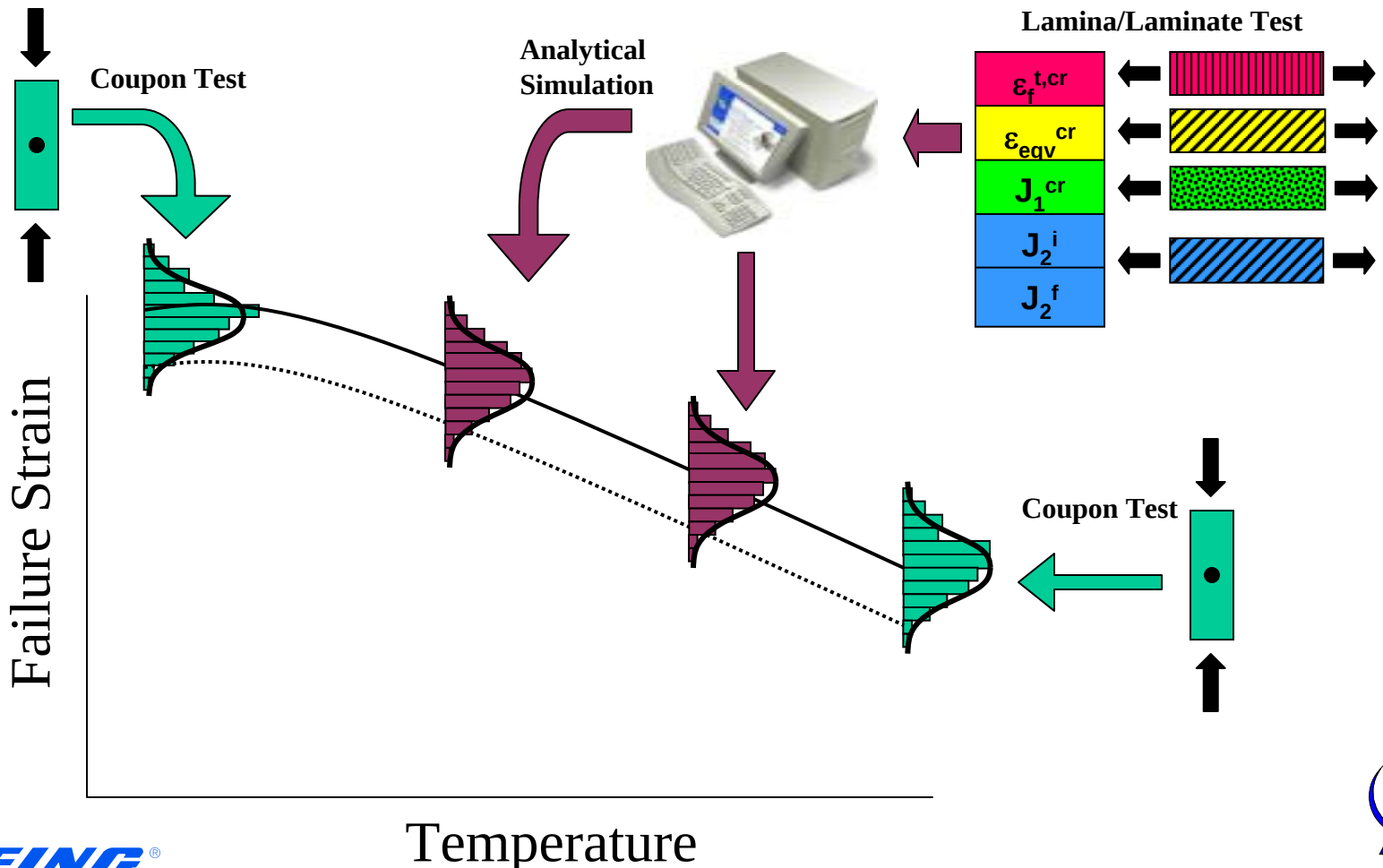
Fiber Module

Modulus E1	(Fi_E1_analog)
Strength S1	(Fi_strth_1_analog)
Strain St1	(Fi_strn_1_analog)
Thermal Expansion Alpha	(Fi_rho_analog)
Yield Yd	(Fi_tw_yld_analog)



Short Term Issues

- Prediction of Coupon Stiffness, Damage Initiation, and Failure Loads
 - Typical Properties
 - B-Basis Allowables
- Obtaining Design Values from Mixed Test and Analysis Data





Long Term Issues

- Prediction of Stiffness, Damage Initiation, and Failure Loads for Complex Structure
 - Increased Test Cost and Complexity
 - Little Statistical Information
 - More Uncertainty in Loading, Boundary Conditions
- Reliability-Based Design
 - Characterization of Environment
 - Loads, Temperature, Moisture, Damage
 - Very High Reliability Required (interested in extremes/tails)





Understanding and managing uncertainty is an integral part of the AIM Structural Property Prediction approach.

The Structural Property Prediction tools must:

- Present clear traceability to data input pedigree
 - Redundant methods for data checking
- Identify when models are out of their predictive bounds, validated bounds
- Have stochastic definition of important Input and Output properties
- Possess a simple automated user interface to minimize I/O errors
- Undergo extensive validation to identify errors

Practical Aspects of Managing Uncertainty

- Indirect property measurement often required
- Testing expense and/or history can limit data populations
- Assumptions necessary to develop efficient models
- Focus on significant inputs (can vary from case to case)
 - Use sensitivity studies to identify criticality of factors





- Input Material Properties
 - Test methods – accuracy, repeatability, errors
 - Distribution – data correlation, population, inferred properties
- Modeling
 - Accuracy of physical models
 - Idealization assumptions
 - Interpolation, extrapolation of input datasets
- Output values
 - Interpolation, extrapolation of output datasets
 - Post processing of data





Coupon Failure Modeling Errors and Uncertainties



	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Lamina Stiffness/ Thermal Properties (CCA and/or Empirical)	Variation in all fiber and resin moduli, Poisson's ratio, and CTE properties. Test uncertainties such as specimen misalignment, load/displacement measurement	Unmeasurable Constituent Properties (transverse fiber modulus, etc.) Interphase effects	CCA: Use of model outside of bounds.(e.g., woven 3D preform) Empirical: Extrapolation beyond test data (fiber volumes, temperatures, etc.)	CCA: I/O errors, code bugs Empirical: Testing machine not calibrated. Poor specimen preparation; poor strain measurement techniques.
Laminate Stiffness Calculation (CLPT)	Variations in ply-thickness, ply angles, etc.	Assumes thin plate with no shear deformation, material or geometric nonlinearity, or significant transverse strains.	Use of model outside bounds for items listed under Epistemic uncertainty)	I/O errors (ply thickness, material, layup definition), code bugs
Stress-Free Temps/ Residual Curing Strain Input (COMPRO)	Many parameters can affect residual stress: local fiber volume fraction, ...	Micro-stresses are considered to be independent of meso-stresses; there are few independent measurements of residual stress.	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.	Errors in material property definition, errors in coding, errors in integrating process and structural models.
Coupon Geometry and Load/BC Input (COMPRO, User-defined, Empirical)	Cured ply thickness variations, specimen dimensional tolerances, specimen curvatures due to residual stress/strain			Errors in Coupon Geometry Definition or Improper Idealization of Loading or Boundary Conditions

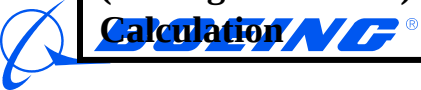




Coupon Failure Modeling Errors and Uncertainties



	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also known as variability, stochastic uncertainty E.G. manufacturing variations, loading environments	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models information from expert opinions.	Known Errors (acknowledged) e.g. round-off errors from machine arithmetic, mesh size errors, convergence errors, error propagation algorithm	Mistakes (unacknowledged errors) human errors e.g error in input/output, blunder in manufacturing
Laminate/Lamina Stress/Strain Field (ANSYS or ABAQUS)	All material and geometry variables listed previously.	Unknown or highly-variable geometry (of fillets, etc.) near geometric free edge singularities.	Mesh convergence - generally converged to within 5%, tends to favor slight overprediction	I/O errors, bugs in UMAT or APDL coding for mesh convergence, thermal and mechanical strain superposition, and failure value extraction.
Constituent Stress/Strain Calculation (UC-FEA or PASS)	Variation in fiber volume, packing arrangements, fiber and matrix moduli, Poisson's ratios, CTEs..	Unknown local variations of items listed under Aleatory uncertainty. No direct measurement of certain fiber properties. Unknown effect of interphase.	UC-FEA: Use of model outside of bounds (eg different product form). Mesh convergence. PASS – Assumes averaging of constituent stresses/strain.	I/O errors, code bugs Testing and measurement errors in input constituent properties (listed under aleatory uncertainties)
Critical Constituent Failure Property Input (Empirical or Empirical+Analysis)	Specimen variation; Test uncertainties such as specimen misalignment, load/displacement measurement		Often measured indirectly from lamina/laminate testing. Conversion to constituent values by analysis is subject to all analytical errors previously listed. Errors minimized due to simple coupon geometries.	Testing machine not calibrated. Poor specimen finish, poor alignment in grips. Poor strain measurement techniques. I/O and coding errors in analytical procedures.
Constituent Failure (Damage Initiation) Calculation	Variations in critical failure parameters and constituent stress strain field (from items above)		Use of criteria outside of theoretical or validated bounds.	Inappropriate choice of failure criteria (by user or tool). Code bugs.





Workshop Topics of Interest

- Methodology for identifying uncertainties, characterizing them, and documenting them productively.
- Case studies which demonstrate success in handling uncertainty and pitfalls to avoid.
- Recommended methodologies for handling a mix of experimental and analytical data.





Workshop Topics of Interest

- Issues in developing probabilistic models from sparse data (such as 5 tests each at 3 to 5 temperatures or 5 tests on each of 3 to 5 batches).

Issues in use of these models in design of systems that demand high reliability.

Ideal and acceptable approaches to this issue

Compute intensive and non-compute intensive situation of numerical simulations





Workshop Topics of Interest

- Model validation approaches for deterministic and stochastic models in the context of limited experiments to verify/augment model results.
- Technologies used in other domains that have been most successful in the treatment of uncertainties comparable to AIM uncertainty treatment objectives.





Uncertainty Definition

- “Uncertainty” is used to encompass a multiplicity of concepts
 - Used to describe incomplete information
 - Used to describe to variability
 - Uncertainty may arise because of simplification or approximations introduced to analyze the information cognitively or computationally more tractable
 - Uncertainty may refer to uncertainty in our decisions



Uncertainty Definition and Use



- It is necessary to distinguish between different types and sources of uncertainty so that they can be treated differently
- Probability is considered as an appropriate way to express some of the above uncertainties
- Uncertainty analysis could be the framework of arriving at design allowable

Propagation Interpretation

- All the following refer to the same process
 - Propagation of Uncertainty
 - Error Propagation
 - Variance Propagation
- $y = F(X)$
 - Given the uncertainty in X , compute the uncertainty in y



Propagation Interpretation

- $F(x)$ Representation
 - Surrogate Models
 - Taylor Series for low order statistics
 - Response Surface
 - Actual Models
 - Single or multiple models connected in the form of a network



Functional Models

- Some closed form but mostly finite element based codes - commercial and in-house proprietary
- linear and nonlinear analysis
- special purpose material model libraries
- compute intensive nature
 - solution time problem dependent





Composite Materials Domain



- Uncertainties are introduced at all levels
 - Fiber, Resin and the interface
 - Prepreg
 - Lamina
 - Laminate
 - Sub-component/Component
 - Structure
 - Manufacture and use conditions
- Modeling of material processing is critical



Probability Computation Technologies



- Simulation Based
 - Monte Carlo simulation and variations
- Global Response Surface
 - Full and Fractional factorial designs based on DOE technology
- Structural Reliability Methods
 - First order Reliability Methods and its many variants





Challenges

Mathematical Foundations

- Quantifying the Error bands and/or confidence interval
 - Database with data of different pedigree
 - data from analytical models, test results, and from past experience database of same or similar material
 - Computationally tractable approaches
 - Simulation within a simulation can be expensive for compute intensive models





Challenges

Mathematical Foundations

- Extrapolation (tail sensitivity- impact on the design of highly reliable systems)
 - Distribution approximations from small sample sizes
 - sample sizes are typically 5 to 10 for each treatment
 - Due to large treatment combinations, large number of samples are involved and pooling is resorted to





Challenges Mathematical Foundations

- Deterministic and stochastic model validation and/or updating
 - development of technologies for focused testing with model update/validation as a goal
 - consideration of experimental errors
 - limited but high value added tests





Technology Basis

- Probabilistic Analysis civil engineering books
 - Benjamin and Cornell
 - Ang and Tang
 - Ditlevsen and Madsen
- Statistics, DOE, Response Surface books
 - Box and Hunter
- Reliability Engineering books
 - Kapur
- Robust Engineering books
 - Taguchi, Padke





Technology Basis



- Research reports
 - PRA from Nuclear Industry
 - DOE National Laboratory
 - EPA Risk Analysis
- Technologies from other disciplines would be helpful
 - control systems, operations Research, artificial intelligence, network Theories, investment banking

