



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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Gail Hahn (PM), Charley Saff (DPM), & Karl Nelson (DPM) - Boeing Corp.

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

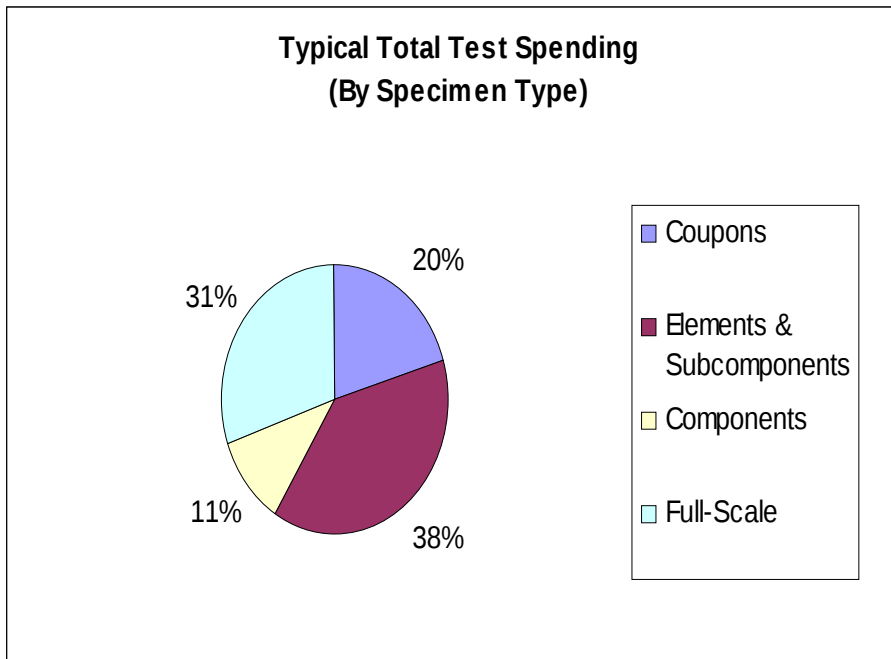
- Using an Un-augmented “Building Block Approach”, a Typical Composites Program Requires 6000 to 10,000* Specimens to:
 - Characterize the Material
 - Develop Design Allowables
 - Select/Develop the Design Concept
 - Calibrate Semi-Empirical Analysis Methods
 - Validate the Design and Analysis

* 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

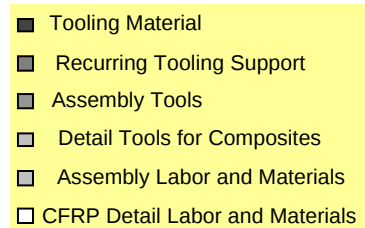
- New composite material specimens only
- Only 1 full-scale Test Component testing includes items such as fuel box, side-of-body joint, large fittings, etc.

• Fab. And Test Hours/specimen (for each type) based on internal Boeing estimating documents

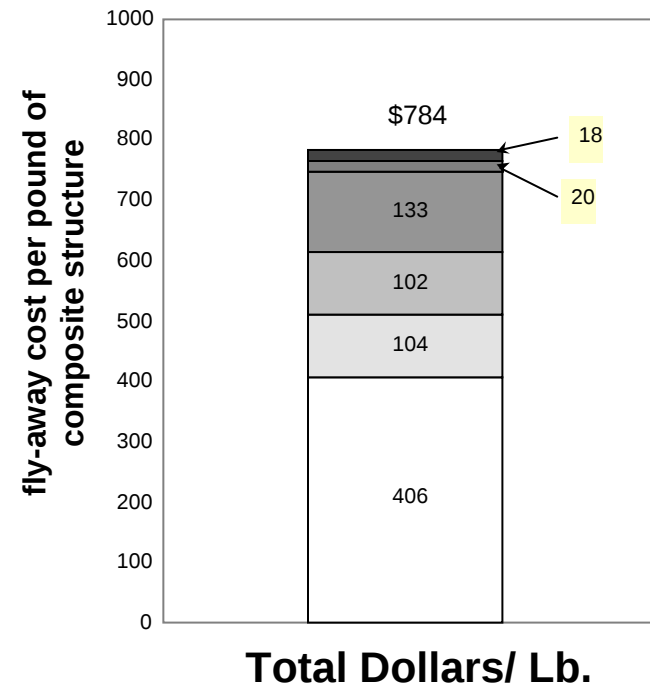
• Typical Industry Labor Rates

• Fabrication and Test Cost Only –Facilities, Equipment, Material, and Design/Analysis Costs not included

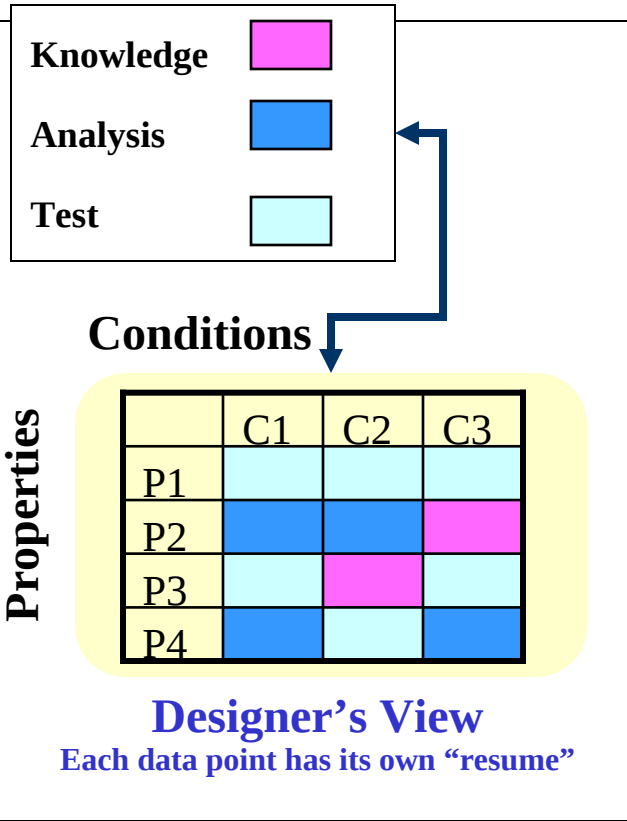
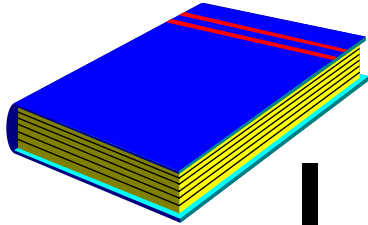
Boeing is the World's Largest Manufacturer of Composite Aerospace Parts



- 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)



AIM-C Alignment Tool

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.*

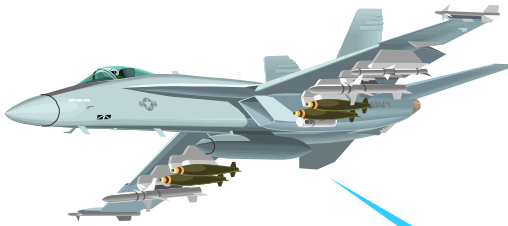
Product Development - *We will develop a software tool, resident and accessible through the Internet that will allow rapid evaluation of composite materials for various applications.*

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

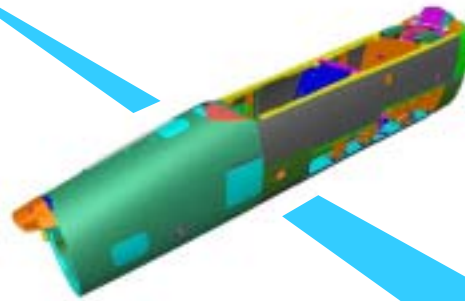
Requirements Flow-Down

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

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

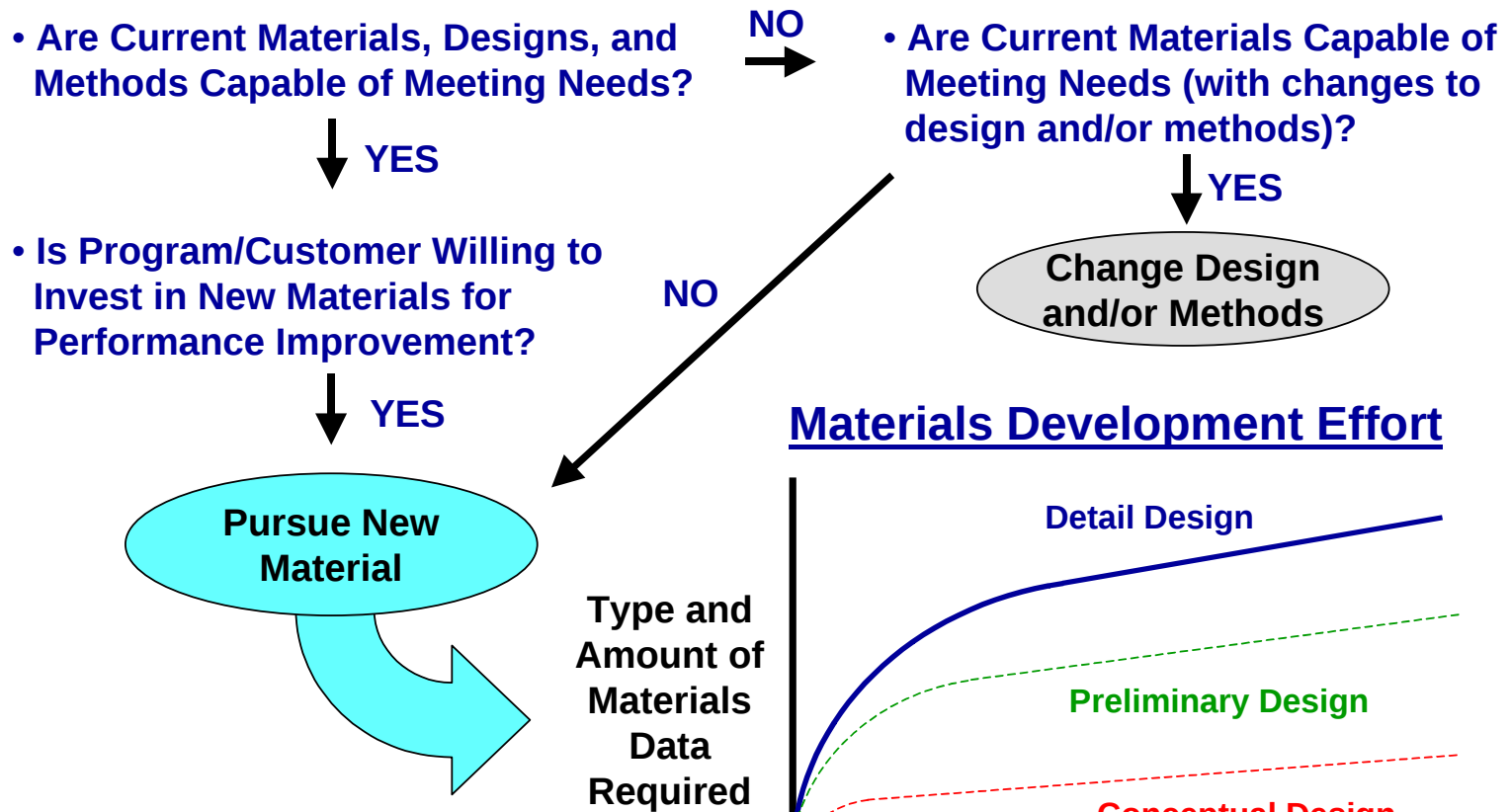
Miscellaneous

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

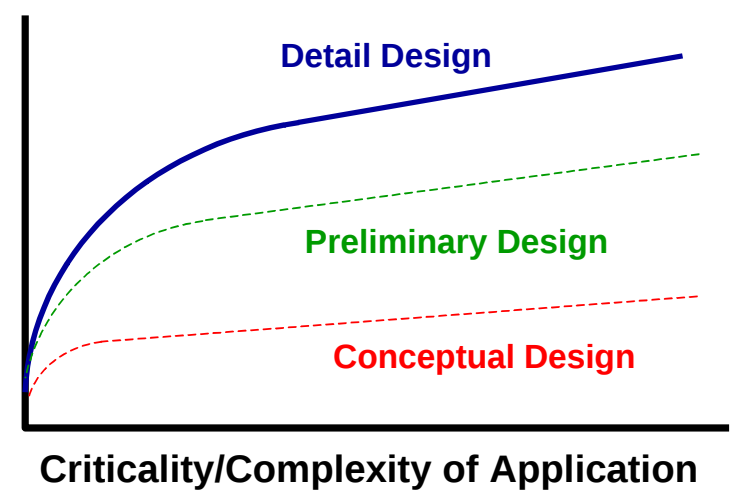
Risk in Each Area is Dependent Upon Application's Criticality and Material's Likelihood of Failure

DESIGN TEAM'S NEEDS

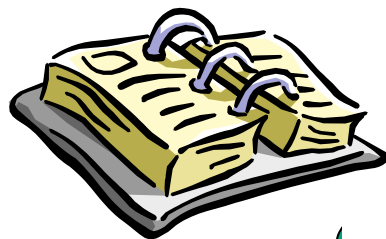
Data Drives Decisions



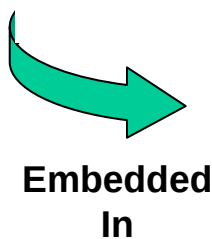
Materials Development Effort



AIM-C Will Validate the Process



**Methodology
That Links an
Accelerated
Process to the
Knowledge
Requirements**



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



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



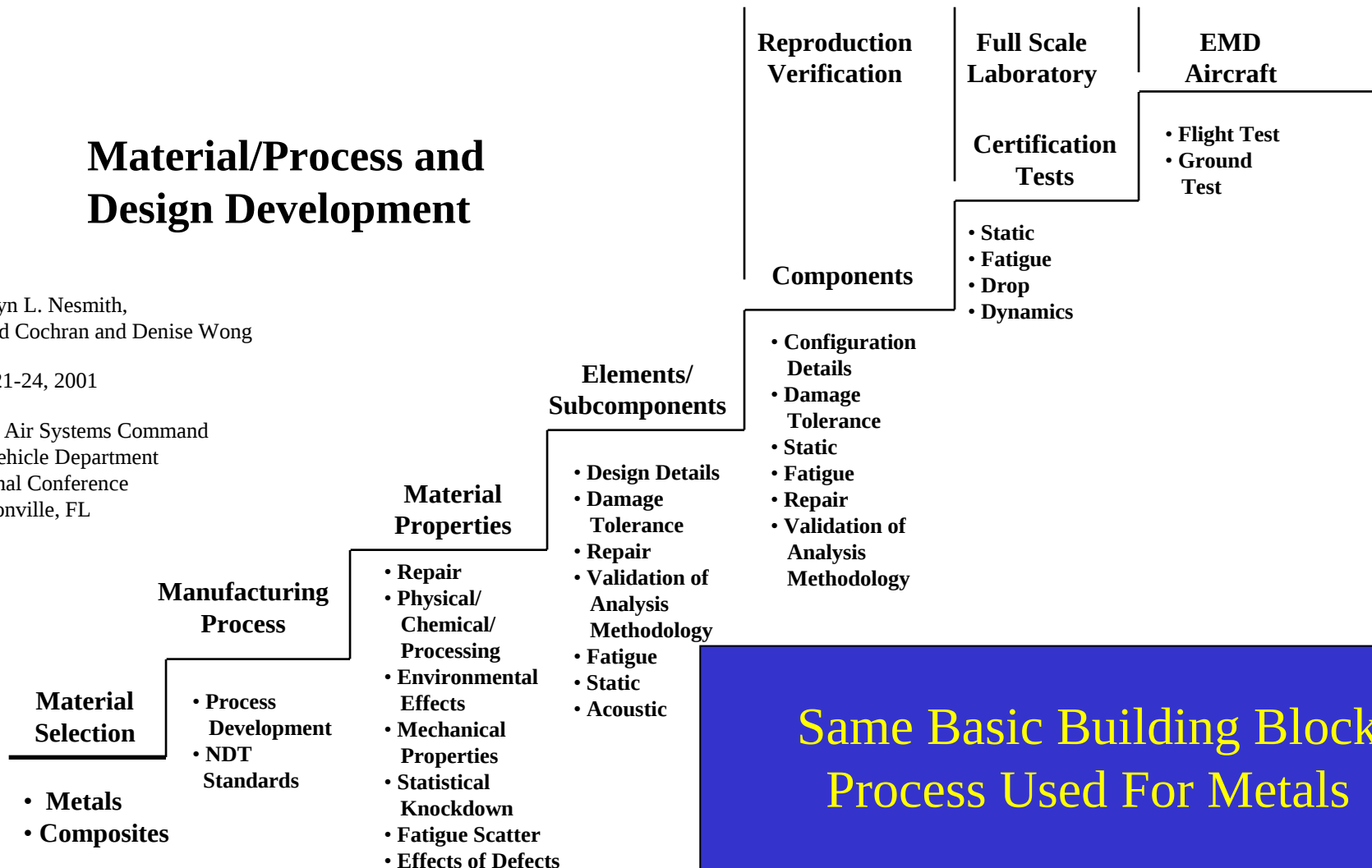
“Building Block” Test Program

Material/Process and Design Development

Kathryn L. Nesmith,
Roland Cochran and Denise Wong

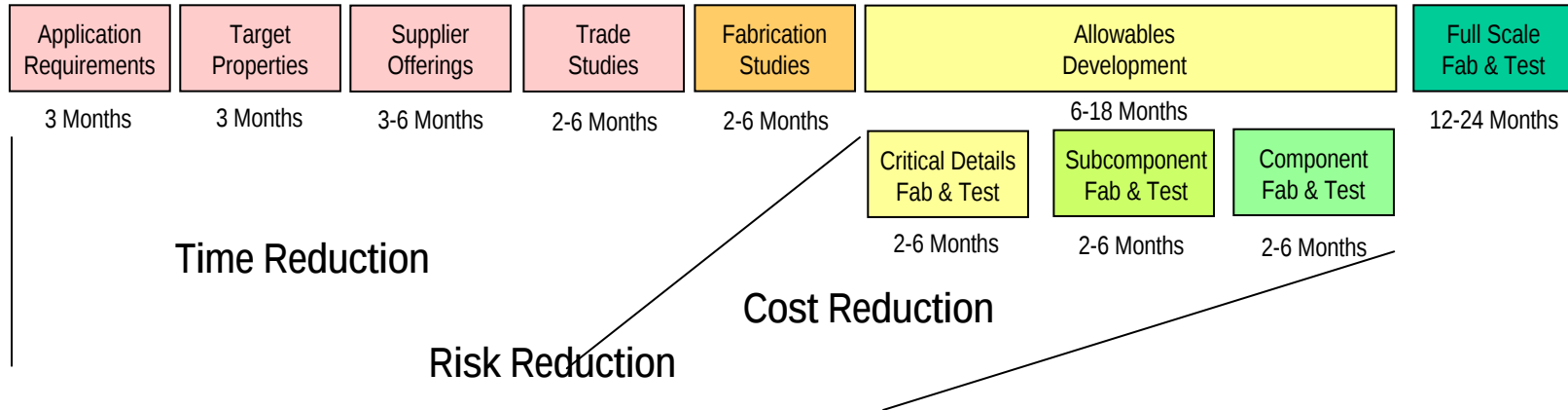
May 21-24, 2001

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

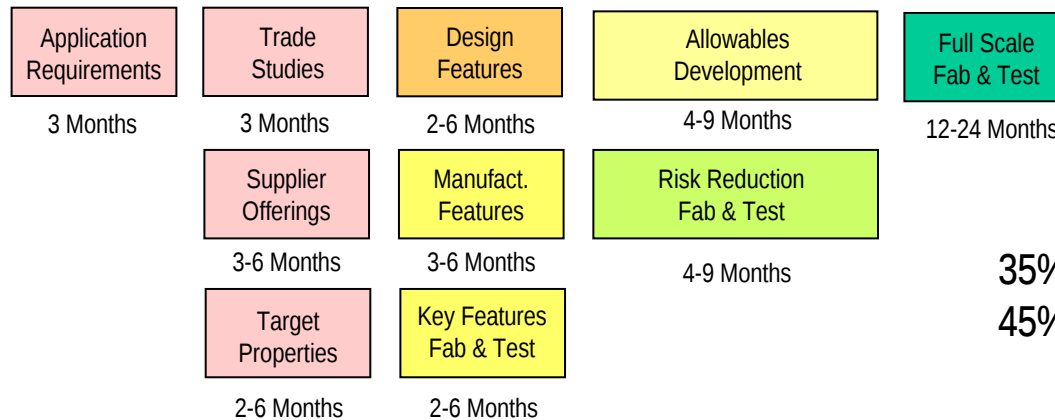


The AIM Process Uses a Team Approach to Drive Rapid Insertion

Conventional Building Block Approach to Certification



The AIM Focused Approach to Certification



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?

Methodology Has to Accommodate:

- Designer Perspective + Others
- Product Certification Requirements
- Material Qualification Requirements
- Multiple Tool Sets
- Testing
- Traceability
- Integration

How

What, When, Why

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 – 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

System

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

Technologist Activity Description

Final Capabilities

Expanded Capabilities

Preliminary Capabilities

Preliminary Investigations, Research, Development

Activity Steps Moving to Qualification



Technology Readiness Levels



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





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

Certification	Certification Requirements Documented	Certification Plan Documented	Certification Plan Approved	Preliminary Design Approval	Subcomponent Testing	Full Scale Component Testing	Full Scale Airframe Tests	Flight Test
Des	Concept	Definition	Applications	Revised by	Applications	Revised by	Applications	Revised by
Des								
Asses								
Struct								
Matu								
Fabric								
Cost								
Support								
Intelle								

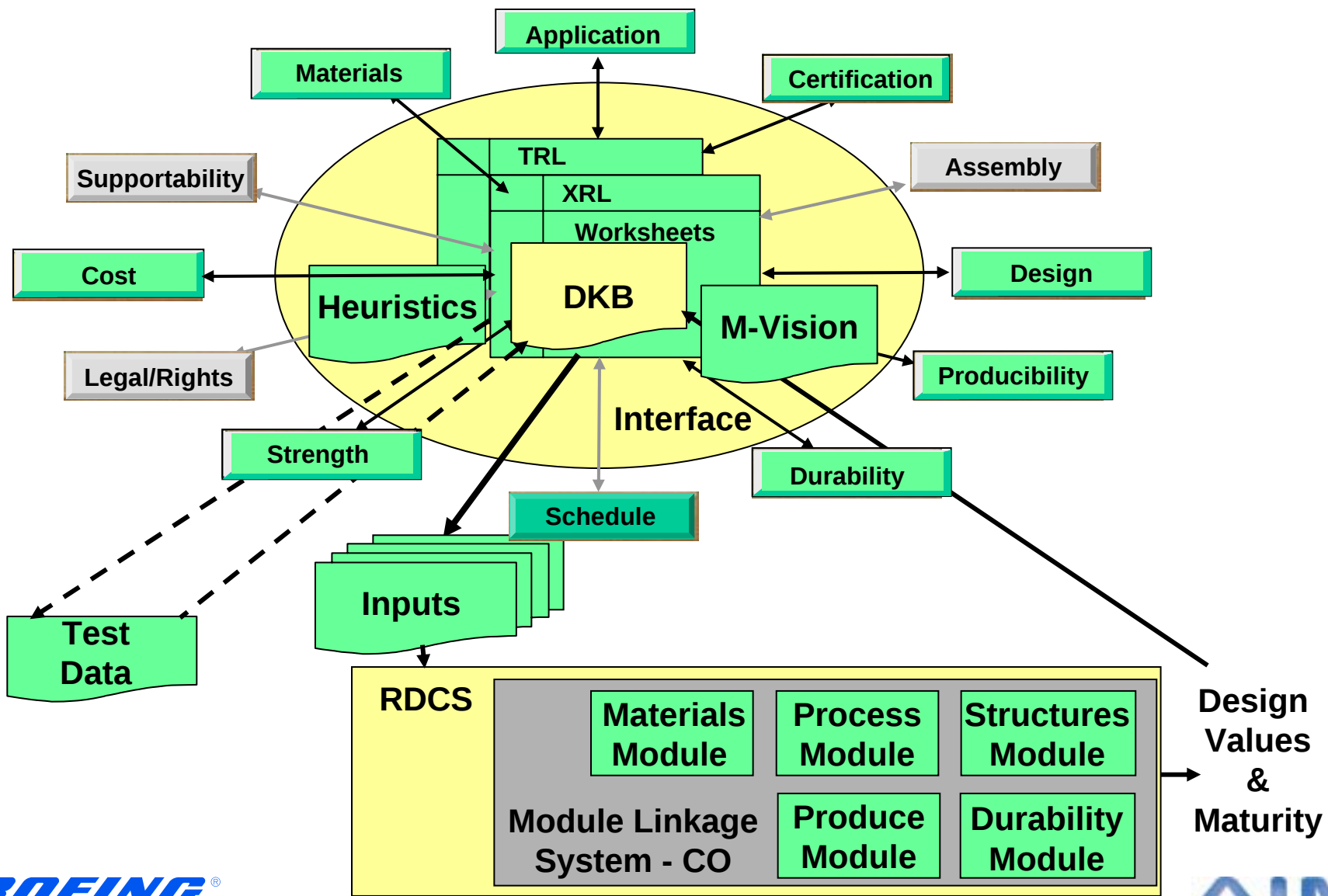
(x) Readiness Levels

Fiber
Resin
Prepreg
Fabrication
Assembly
Quality
Other

Fiber
Resin
Prepreg
Processing
Producibility
Lamina
Laminate
Durability
Elements

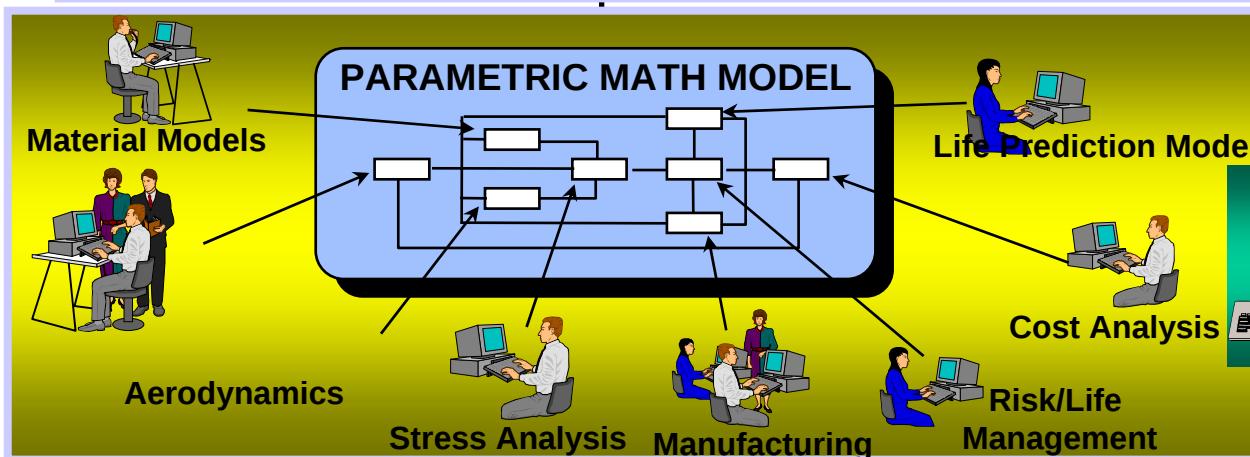
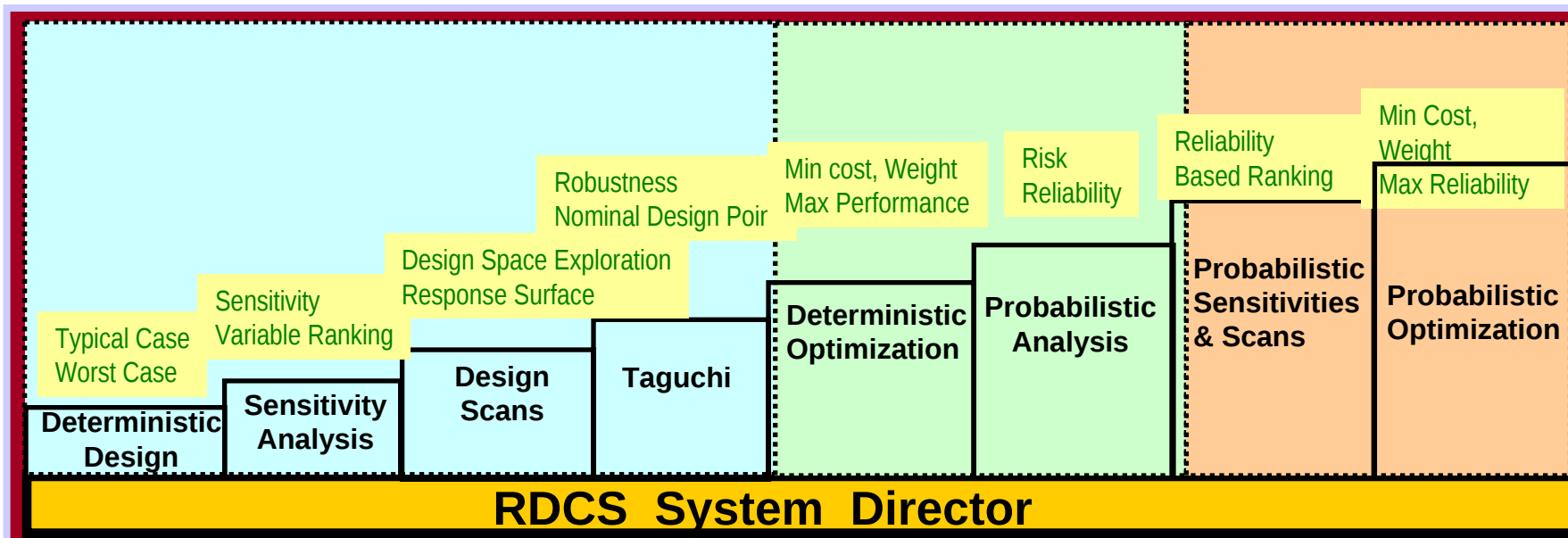
- Detailed Technical Properties/Characteristics
- Primary Test/Analysis Methods
- Secondary Test/Analysis Methods
- Sequencing Requirements
- Data Requirements
- Quality Requirements

AIM-C System Vision



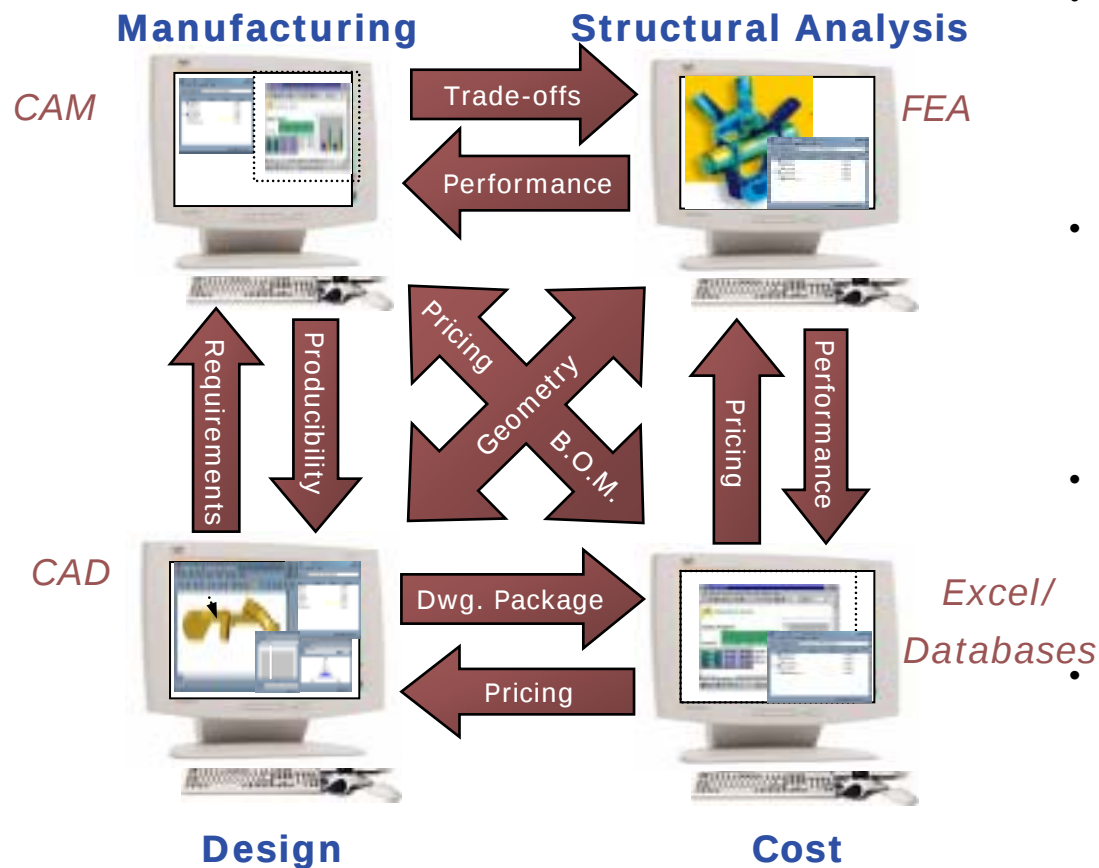


Robust Design Computational System



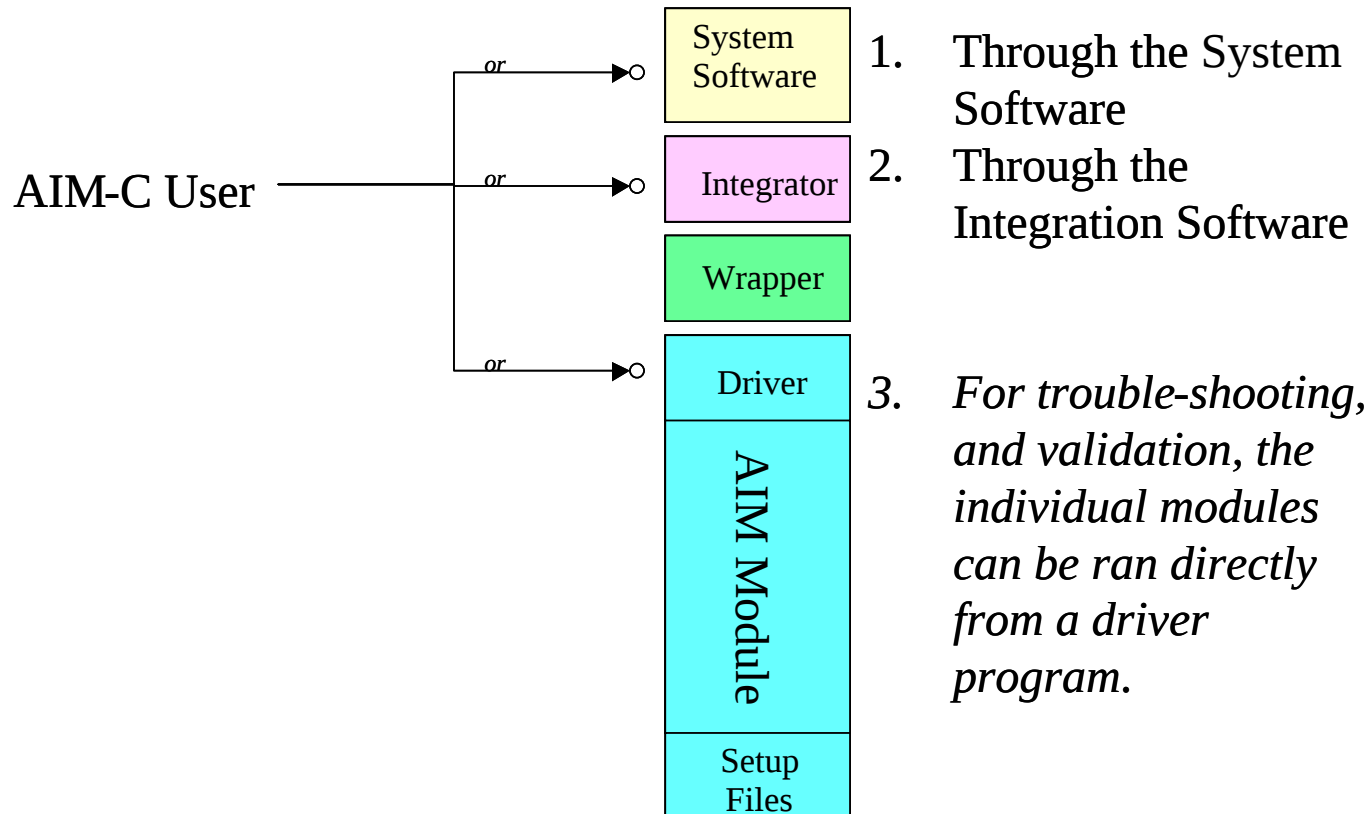
The Oculus Integration System

COTM: A Plug & Play Modeling Environment

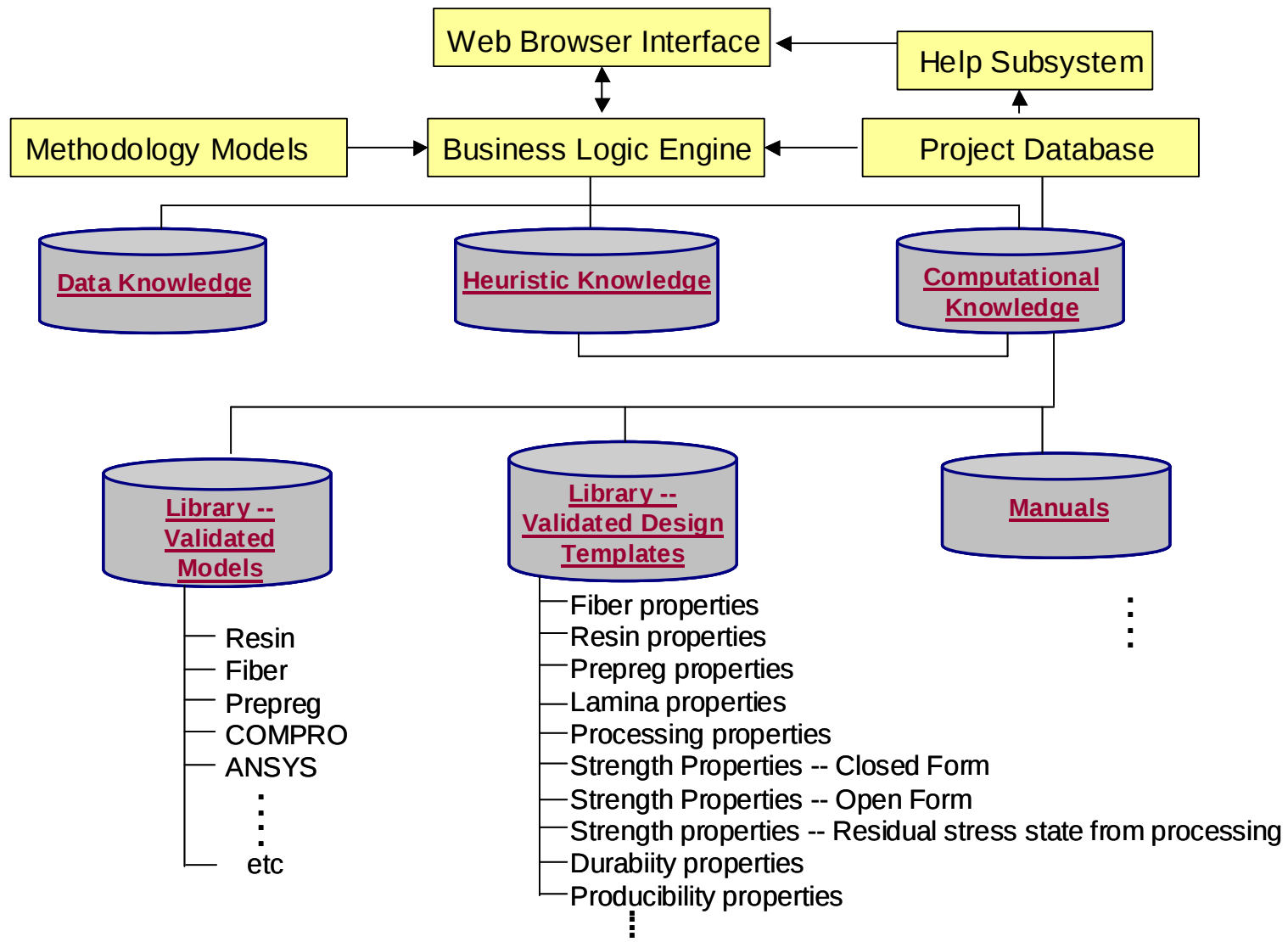


- **Integrates Data and Software Applications on-the-fly**
 - Drag & Drop, Plug & Play
 - Simple to create, modify, manage, maintain
- **Enables Real-time data sharing between applications**
 - Secure
 - Controlled
 - Intra/Internet
- **Platform Independent**
 - Distributed
 - Neutral to Platforms and Applications
- **Increases Value of Previous Investments**
 - Software
 - Hardware
 - Networks

The User Is Able to Run the Module At Three Different Levels



AIM-C Software Architecture



AIM-C Transition Plan

February 2001

February 2002

February 2004

AIM Product
Development

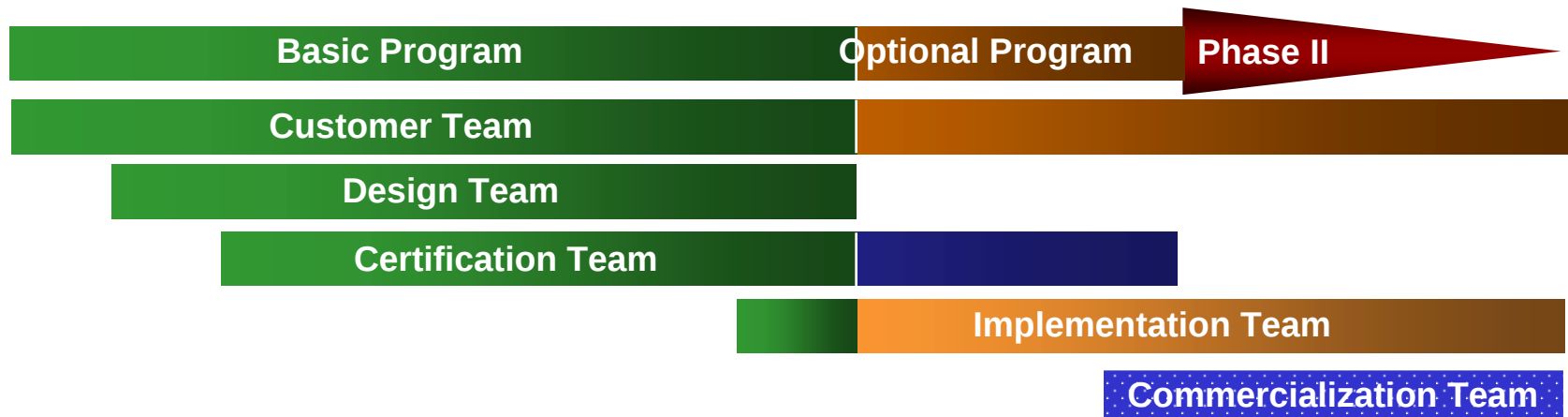
AIM Product
Verification

AIM Product
Demonstration

AIM Product
Refinement

AIM Product
Validation

AIM Product
Implementation



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



Agency	Integration	Structures	Materials	Producibility
Boeing	Charley Saff	Eric Cregger	Pete George	John Griffith
Navy	Don Polakovics	Dave Barrett	Kathy Nesmith	Steve Claus
Air Force	(Joe Gallagher)	Dick Holzwarth	Katie Thorp	Bob Reifenberg
FAA	Curt Davies	Larry Ilcewicz	David Swartz	Dave Ostrodka
Army	Mark Smith	Jon Schuck	Marc Portanova	N/A
NASA	N/A	Jim Starnes	Tom Gates	Tom Freeman

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
MMS-OTRC Workshop
“Qualifying New Technology for
Deepwater Oil and Gas Development”

by Gail Hahn
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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

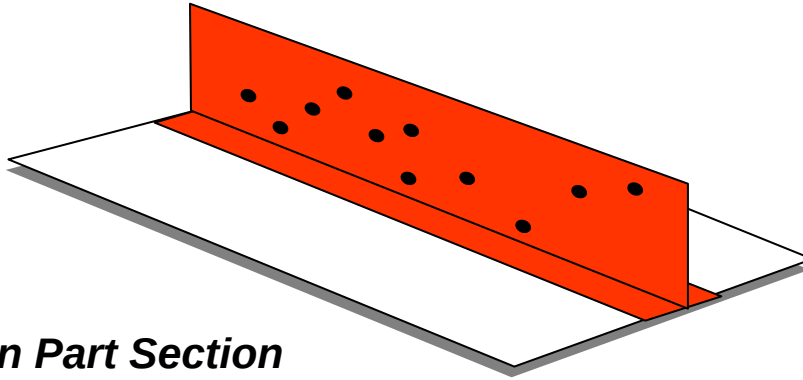
- **Elements And Subcomponents**

- 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

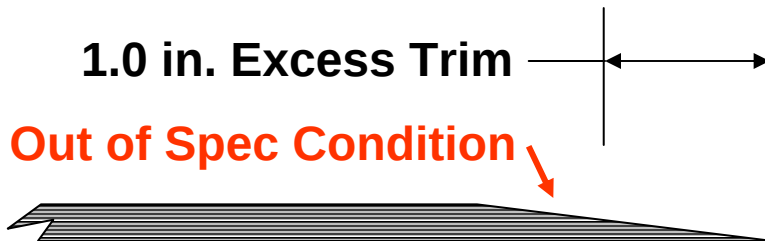


*Thin Part Section
with Cocure Having Voids and Porosity*

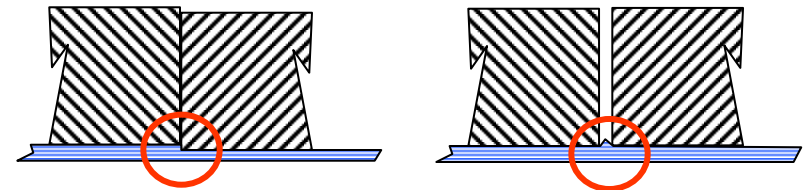
**Process Specification
Calls out $\pm 6-7\%$
Thickness Tolerance**

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



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

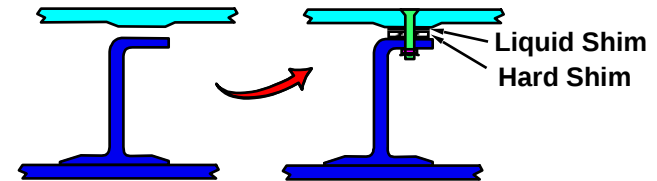
- **Resin Solvent Resistance**
- **Microcracking with Cure, Thermal Cycles, and/or Moisture**
- **Incompatibility of Resin Characteristics and the Manufacturing Process**
- **Final Part Accuracy/Repeatability Relative to Tooling Concepts**



Background

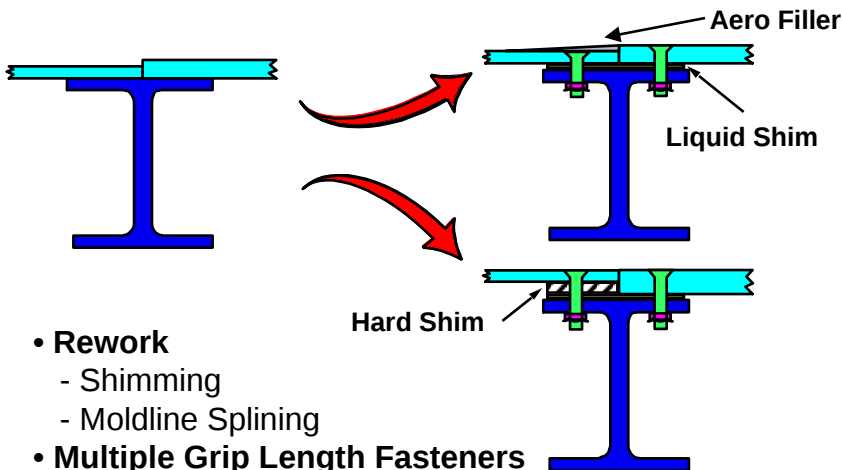


Assembly Variations



- 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

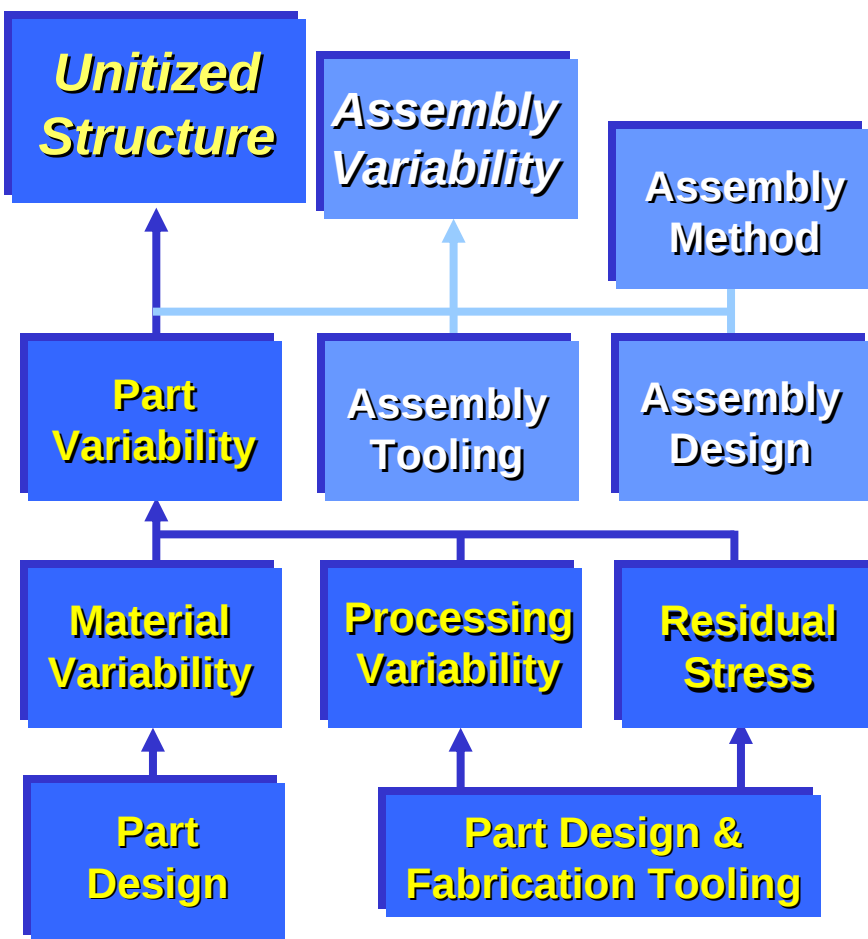
Moldline Fidelity

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

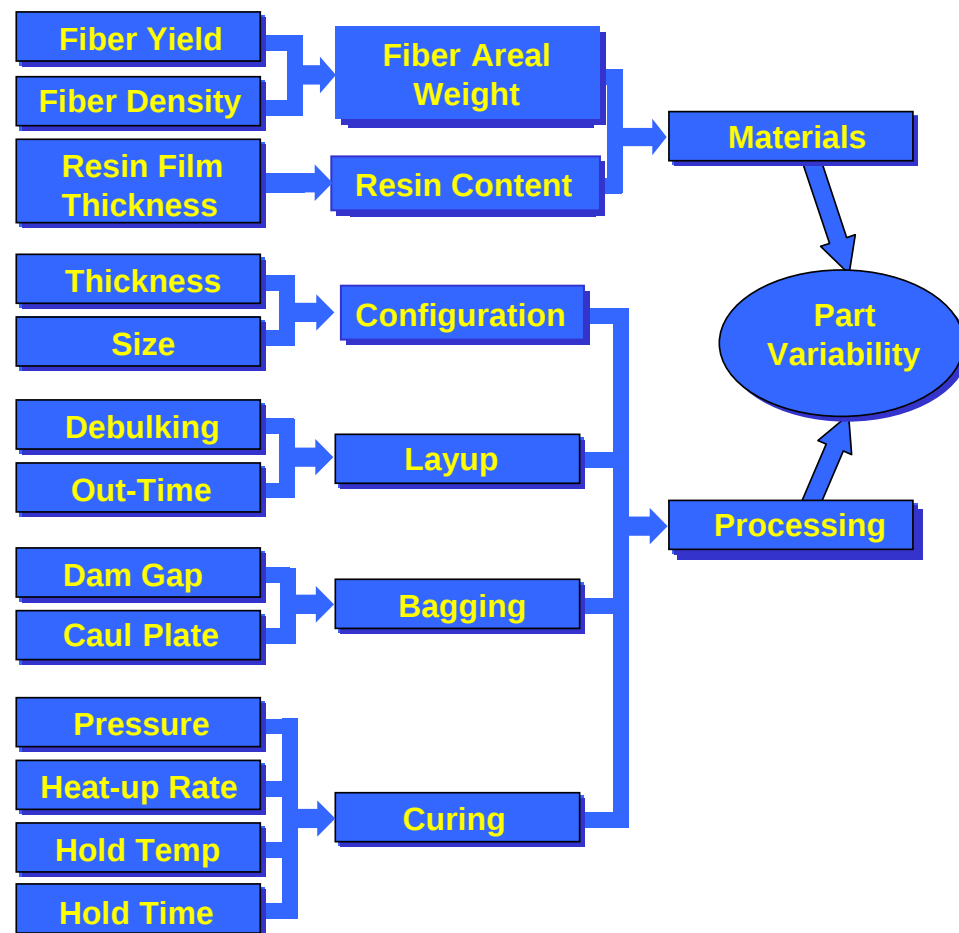


Assembly Variability

Variability Flow Chart



Material and Processing Part Tolerance Accumulations





Part Variability Factors

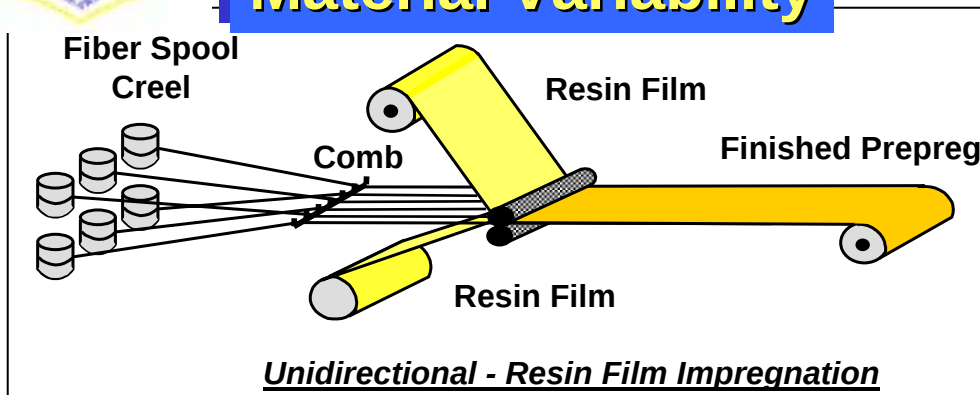
<u><i>Design</i></u>	<u><i>Materials</i></u>	<u><i>Processing</i></u>	<u><i>Cure</i></u>	<u><i>Tooling</i></u>
• Orientation • Thickness • Size	• Unidirectional • Cloth • Net Resin • Excess Resin • FAW • Resin Content • Prepreg Manufacturing	• Material Out Time • Bleeder • Inner Bag Perforations • Dam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



Precision Assembly of Composite Structures

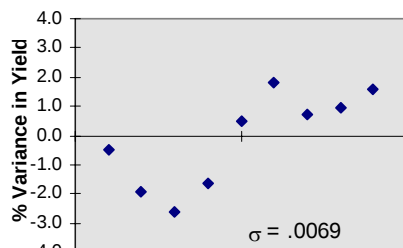


Material Variability



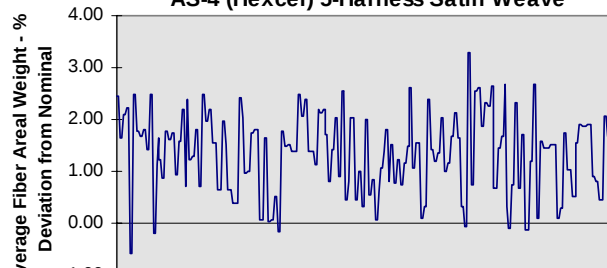
Fiber Variability (210 Batches)

Hexcel AS4 6K



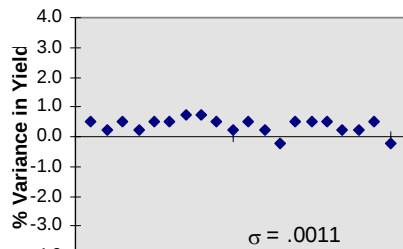
Fiber Lot

AS-4 (Hexcel) 5-Harness Satin Weave



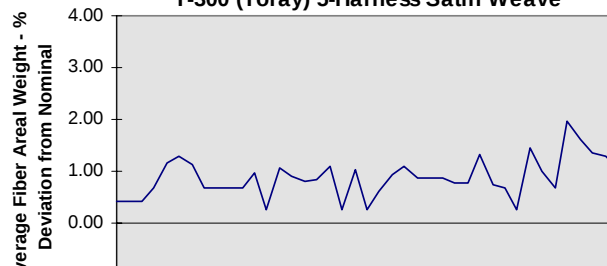
Fabric Lot

Toray T-300 6K



Fiber Lot

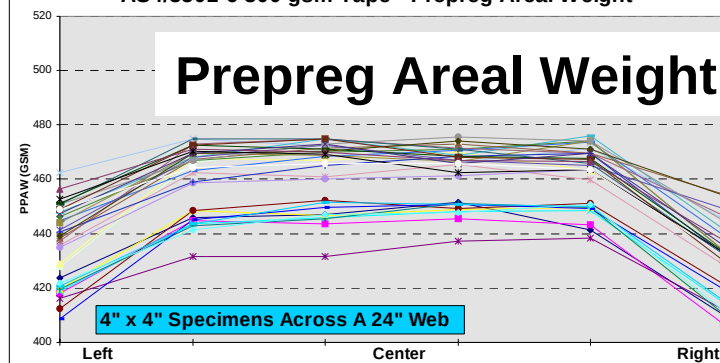
T-300 (Toray) 5-Harness Satin Weave



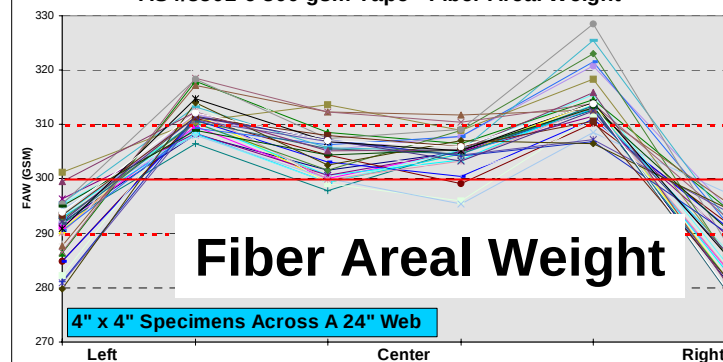
Fabric Lot

Prepreg Variability (21 Batches)

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



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



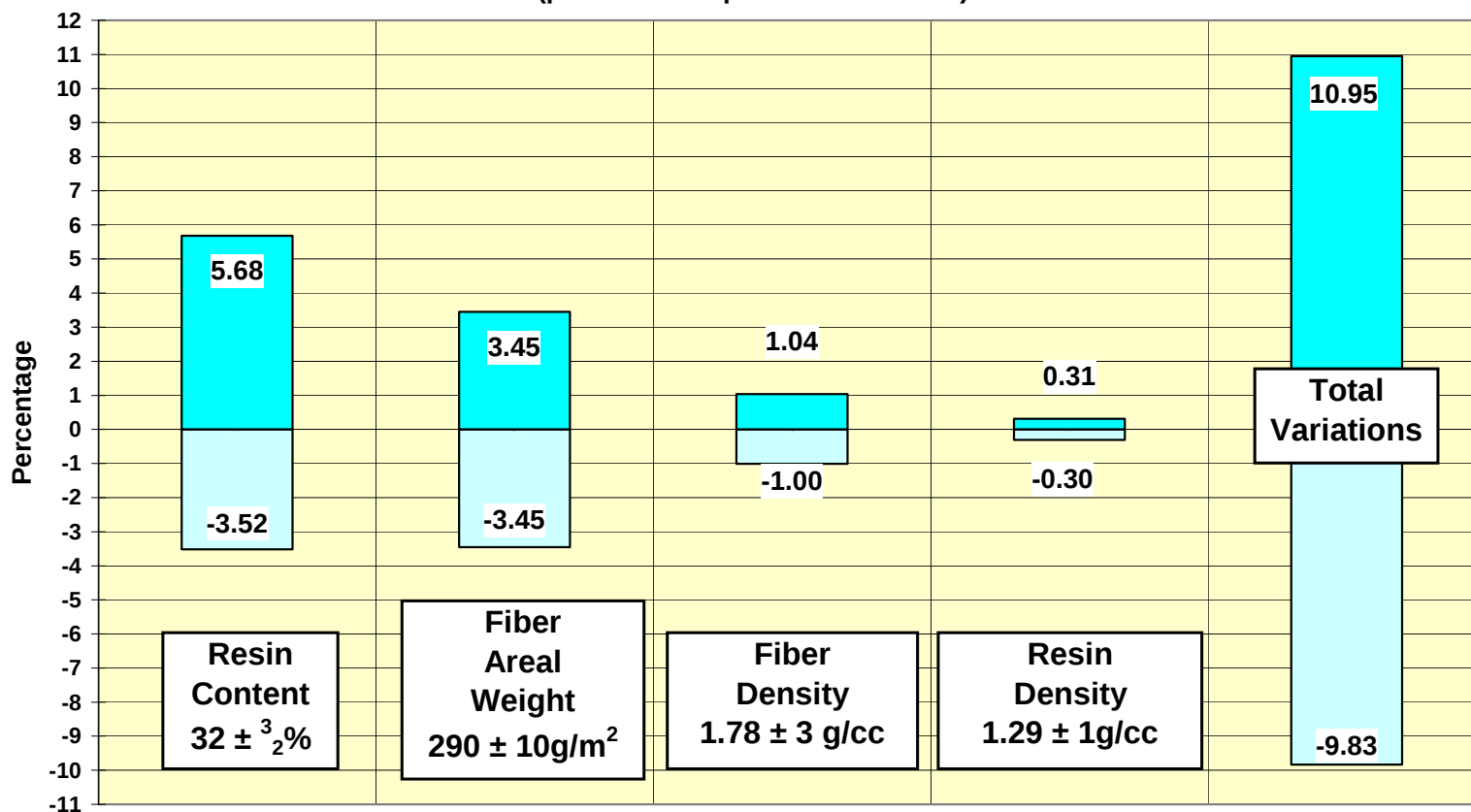
- Fiber Yield Variation Translates to Fiber Areal Weight Variation (Cloth)
- Prepreg Variation is Driven By Fiber Areal Weight Variation



Material Variability

Theoretical Prepreg Variability

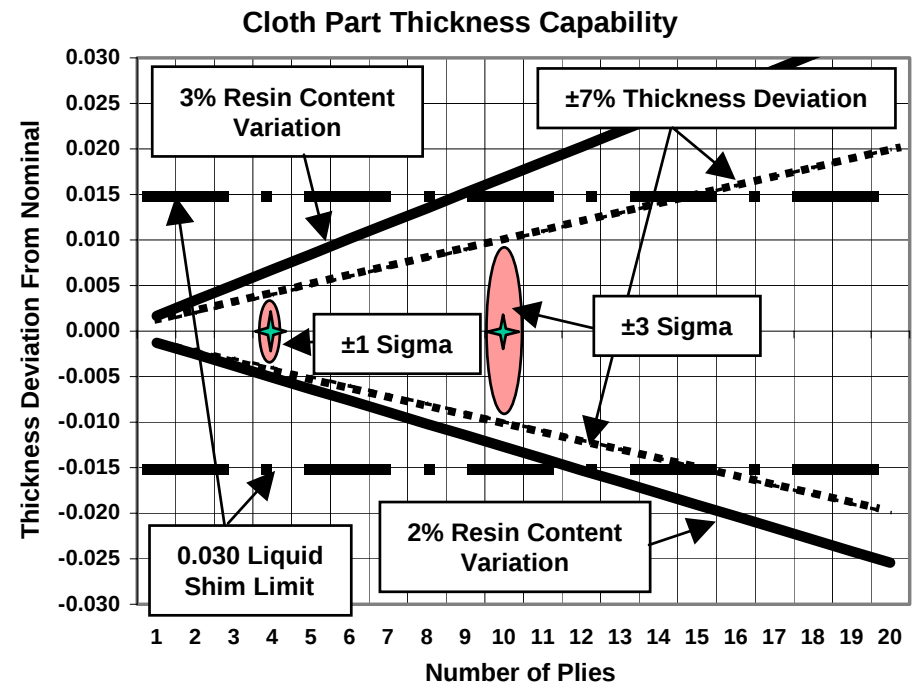
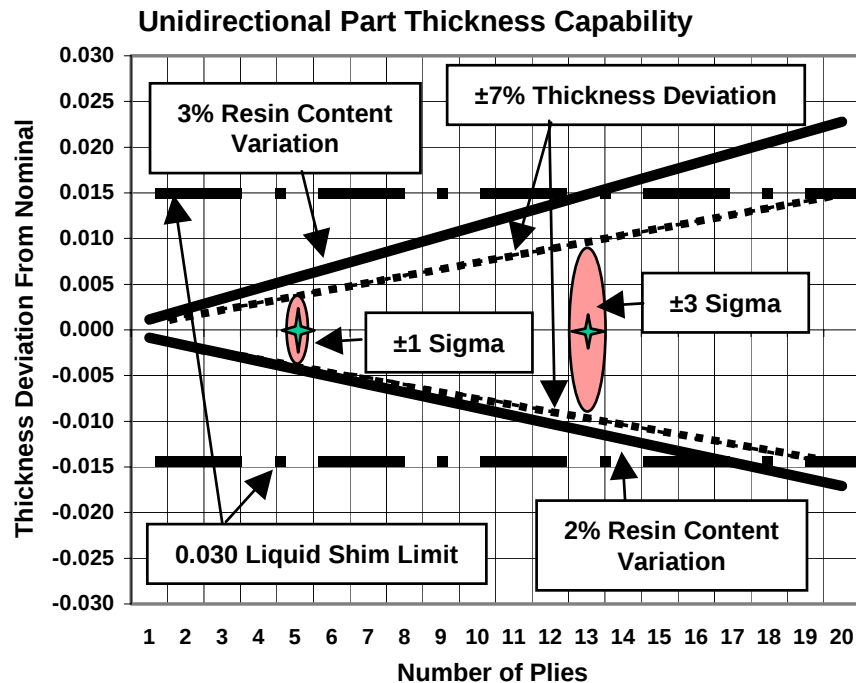
Prepreg Variability Contributing Factors
IM7/977-3 Unidirectional, Net Resin
(per Material Specification Limits)





Material Variability - Process Capability

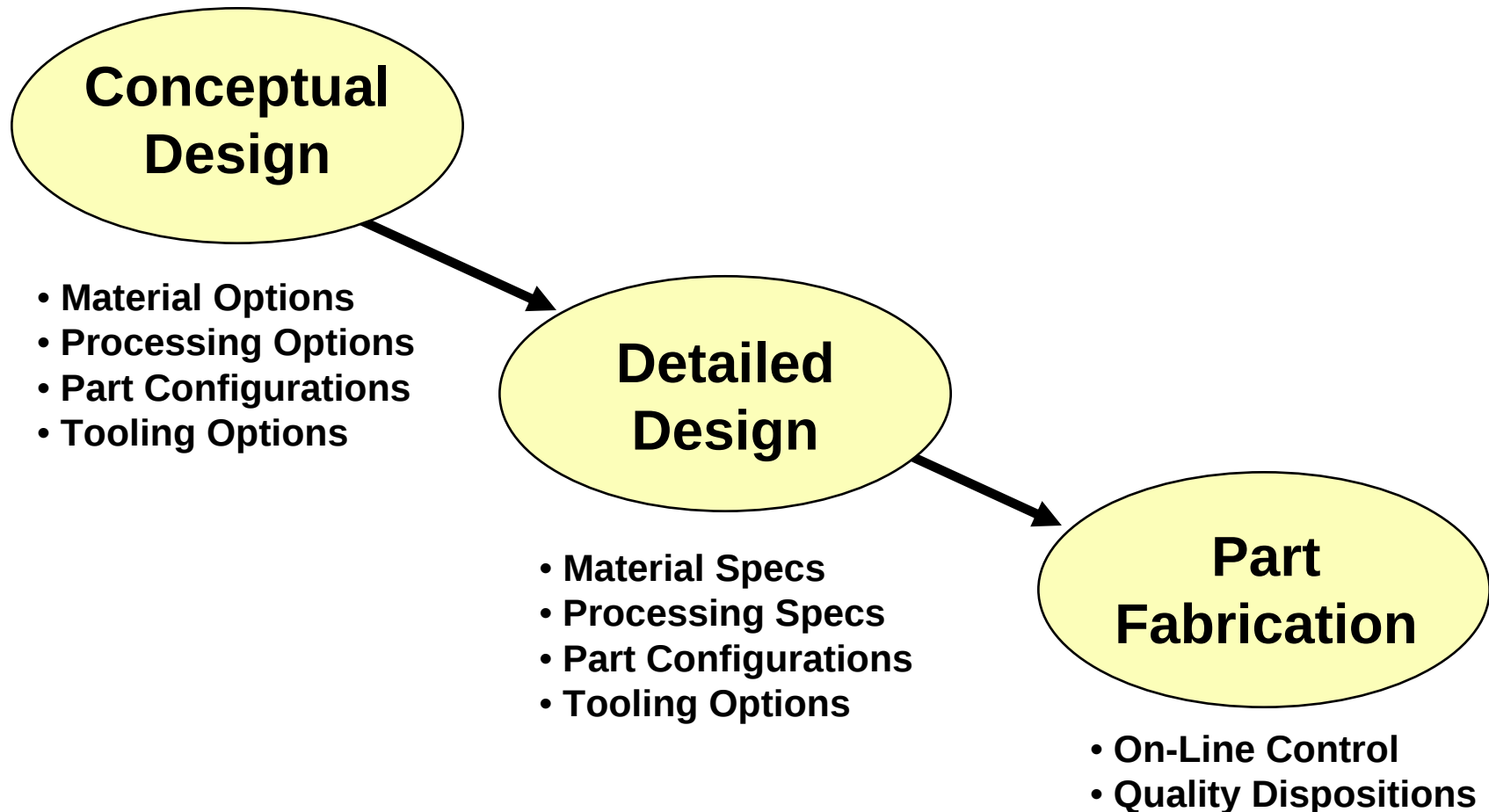
± 1 and ± 3 Sigma Process Capability for Thickness



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

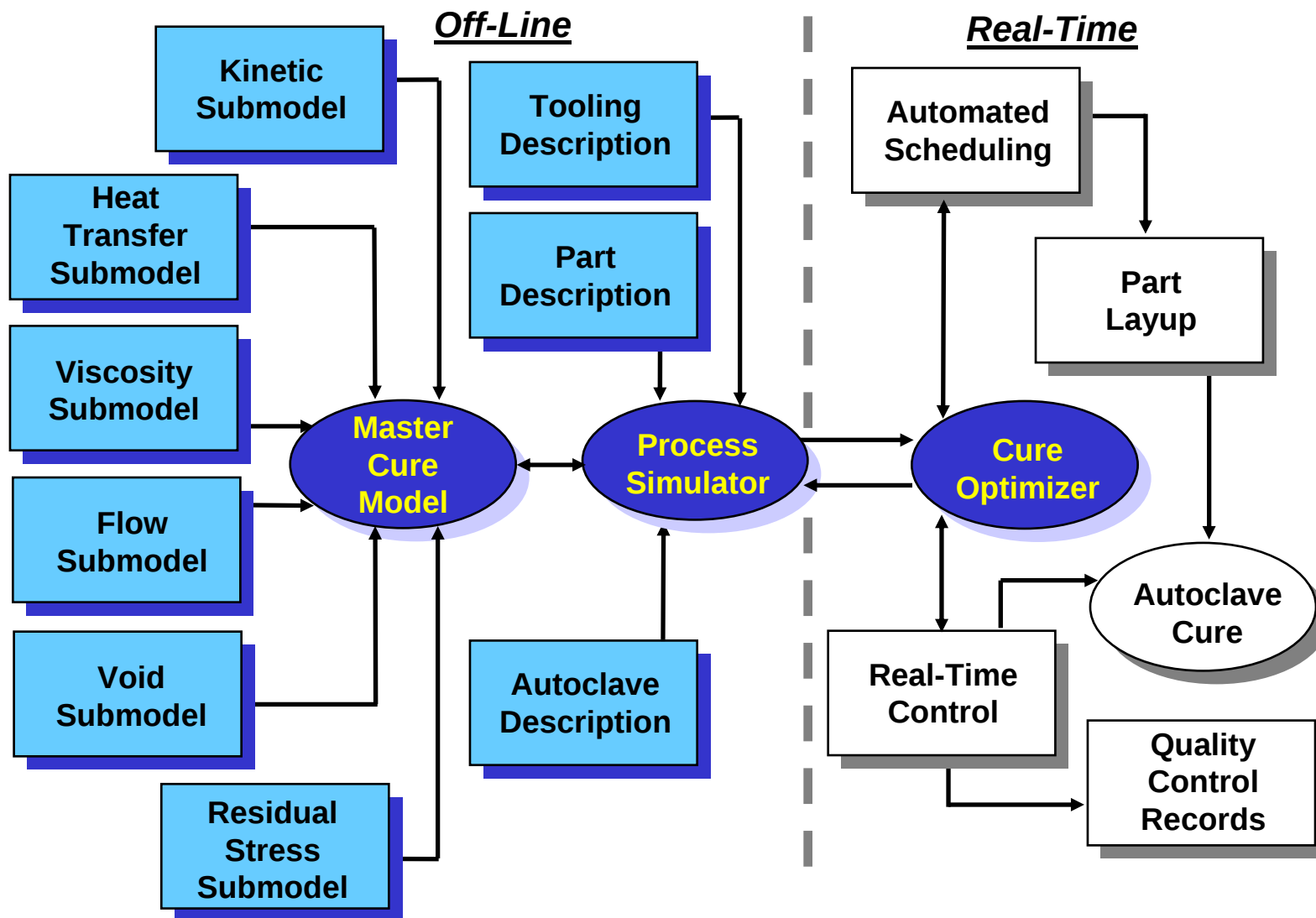


Primary Model Usage

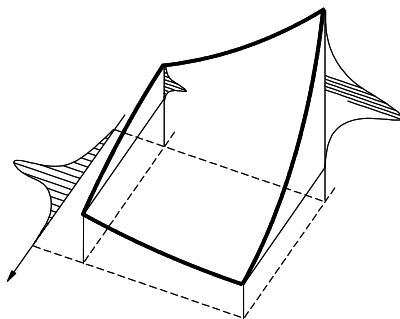
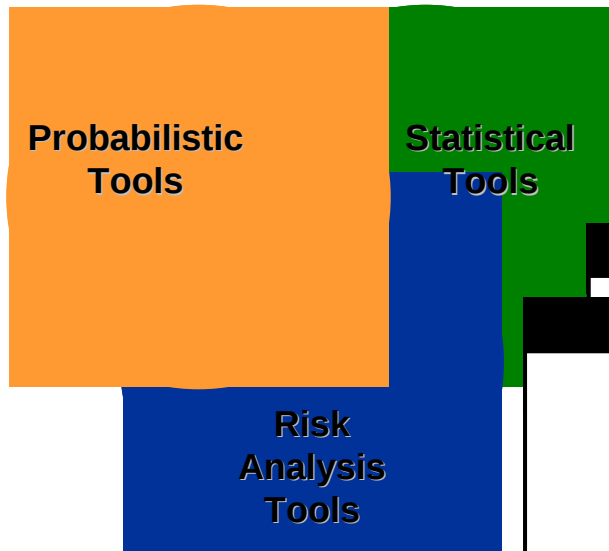




CACC Cure Process Modeling



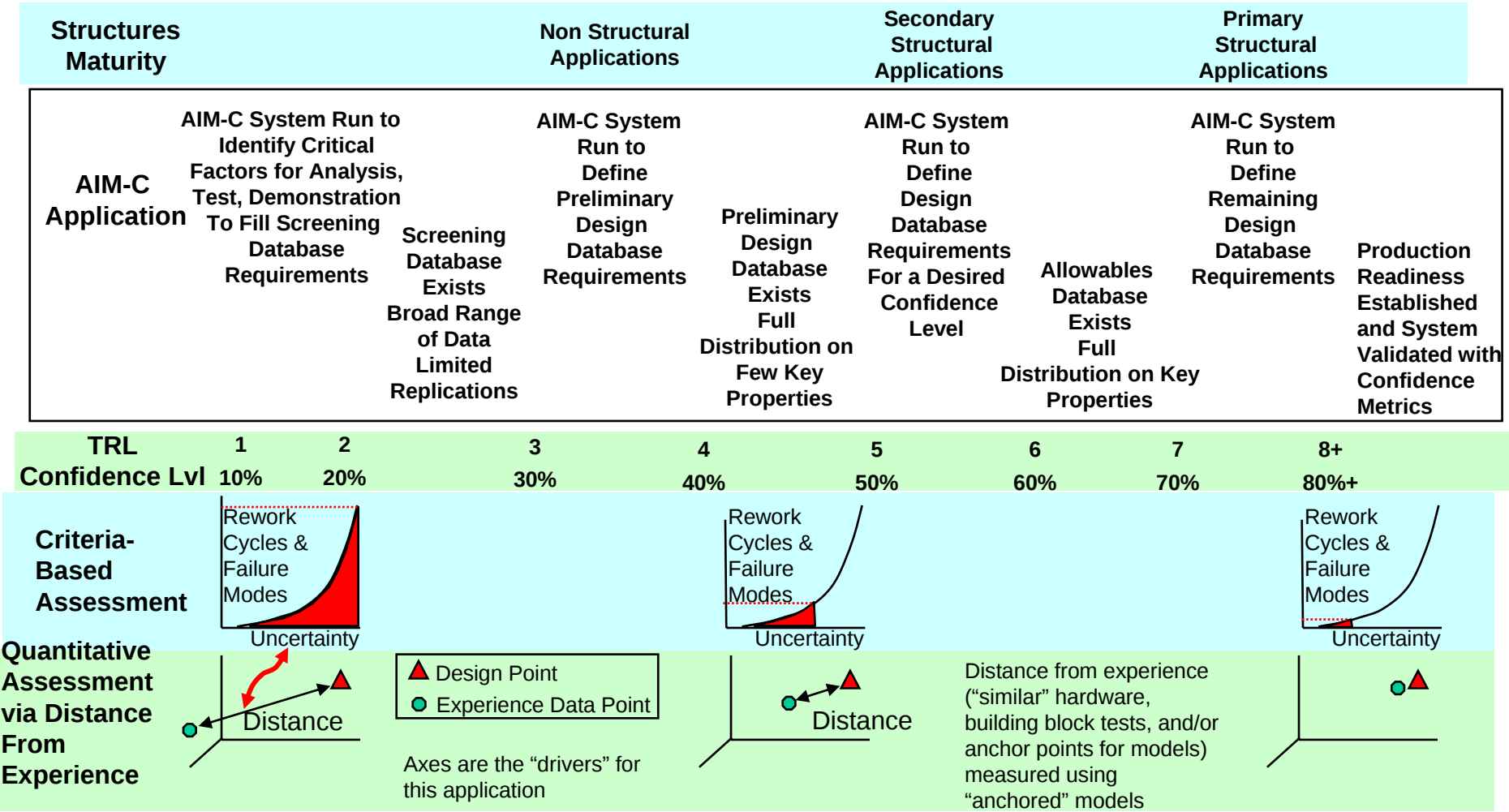
Understanding Uncertainty – The Benefit of Linked Simulation Tools and Methodology



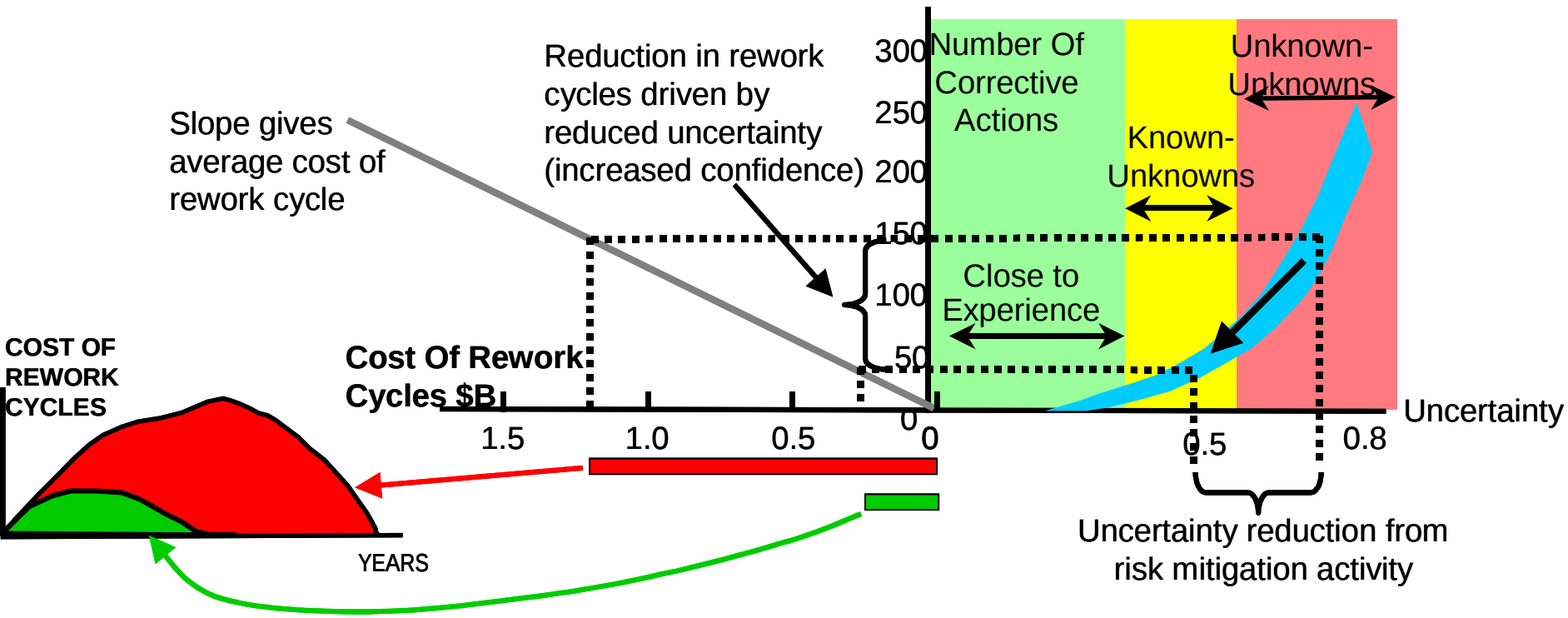
Coupon Failure Modeling Errors and Uncertainties				
Producibility Uncertainty				
Prepreg Module Uncertainty Considerations				
Resin Module Uncertainty Considerations				
Modeling of the Process				
	Inherent variations associated with physical system or the environment (Aleatory uncertainty) Also 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 T _g . Otherwise the residual stress calculated can be an overestimate.	Errors in material property definition, errors in coding, errors in integrating process and structural models.



AIM-C Methodology Impact on Traditional Qualification



AIM-C Reduces Time and Cost of Insertion through Orchestration of Knowledge, Analysis, and Test



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.