Accelerated Insertion of Materials - Composites

Presented to the Engineering Foundation

by

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Jointly accomplished by BOEING and the U.S Government under the guidance of NAST

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Report Documentation Page

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Overview

Accelerated Insertion of Materials (AIM)

AIM Objective:

Develop and validate new approaches for materials development that will accelerate the insertion of materials into production hardware

Phase 1 Basic Program -- 15 months (ends May 1992)

Proof of concept demonstration using existing material

Phase 1 Option Program -- 27 months

Complete development for existing material

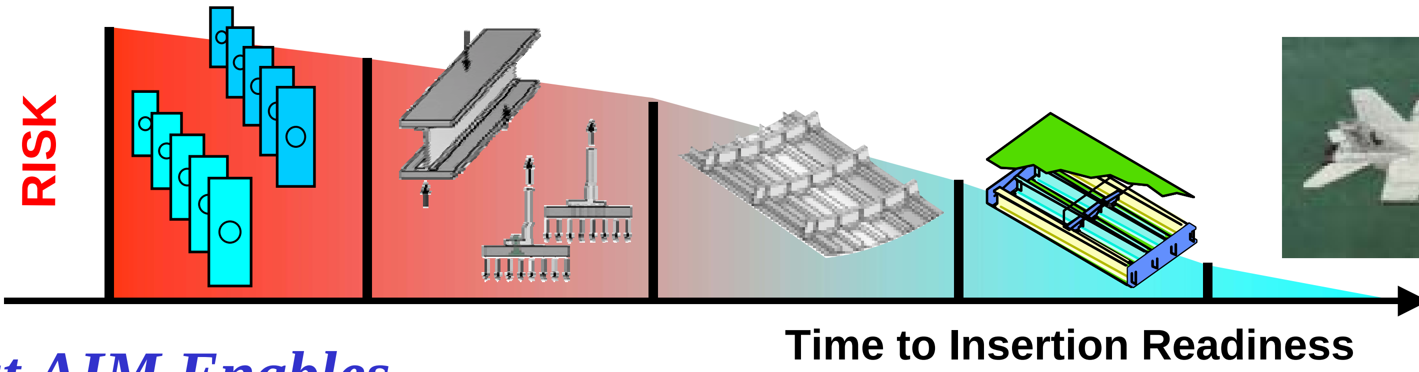
“Blind” validation by independent team

Phase 2

Make Phase 1 system generic

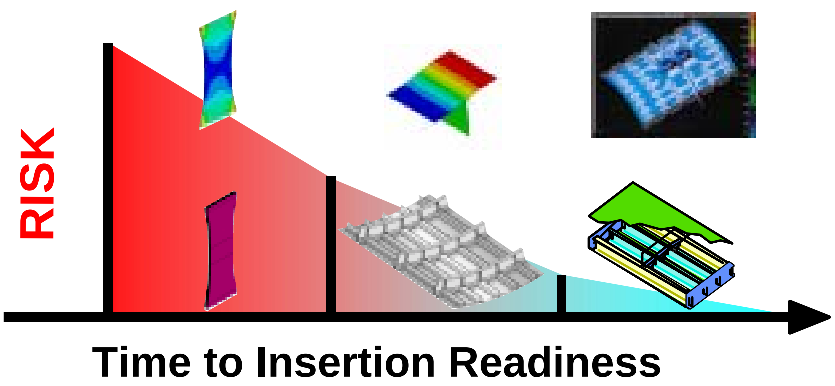
Accelerated Insertion of Materials

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**

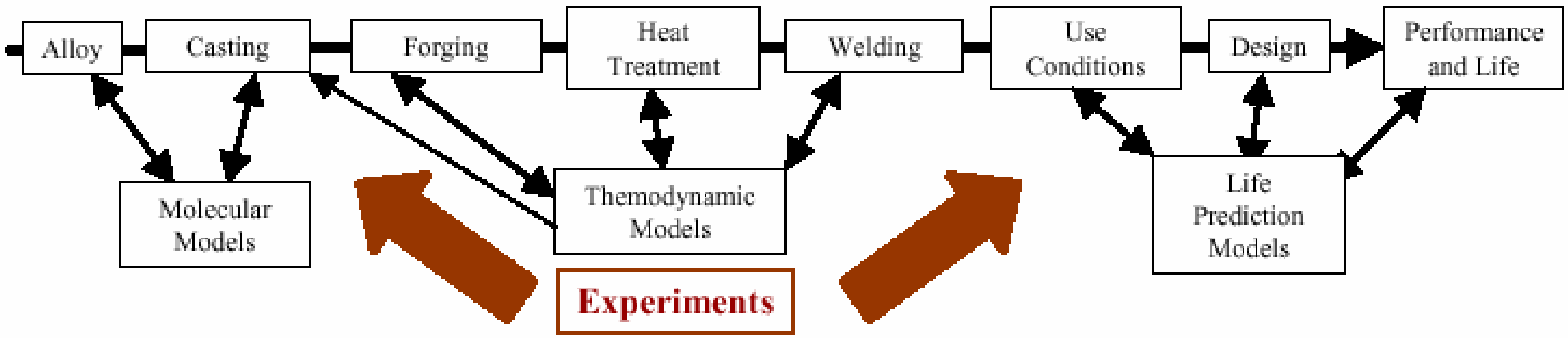


Barriers to Accelerated Introduction of Materials

- Performance
- Cost
- Confidence in materials database (especially variance)
  - Measured properties
  - Predicted properties
  - Producibility

Confidence in the material is intimately tied to the reliability of knowledge of the state of the material throughout production and use.

Complex Interactions in Materials Processing



- **Independent Models Uncoupled to Developing Performance, Life (Designer Knowledge Base) Information**
  - **Resulting Microstructures Not Useful for Input to Other Models**
  - **Precision/Accuracy Unknown, Not Useable in Other Models**
  - **Assumptions Internally Contained Not Transferable**
  - **Doesn't Consider Non-Linear, Non-Continuous Behavior Of Dependent Process Steps**
- **Experiments Have Same Limitations!**

Kathryn L. Nesmith,
Roland Cochran and Denise Wong

May 21-24, 2001

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

"Building Block" Test Program

Material/Process and Design Development

Material Selection
- Metals
- Composites

Manufacturing Process
- Process Development
- NDT Standards

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

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

Reproduction Verification

Components
- Configuration Details
- Damage Tolerance
- Static
- Fatigue
- Repair
- Validation of Analysis Methodology

Full Scale Laboratory

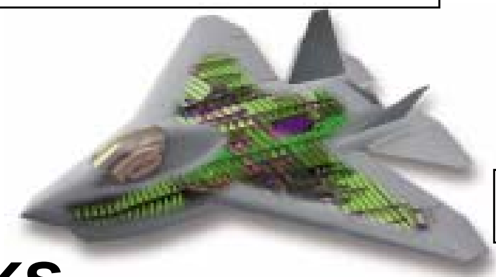
Certification Tests
- Static
- Fatigue
- Drop
- Dynamics

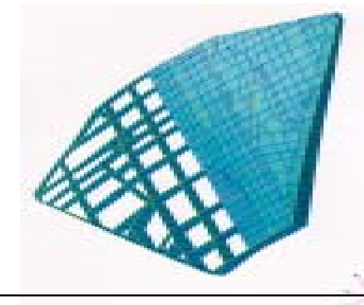
EMD Aircraft
- Flight Test
- Ground Test

Same Basic Building Block Process Used For Metals

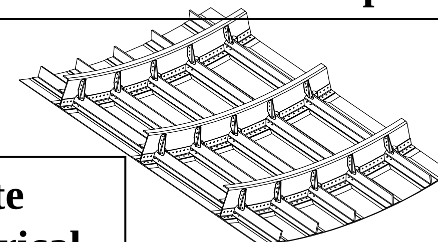
Focus Testing and Reduce Reliance on Empirical Point Design

Validate the Design and Analysis





Concept Selection and Development



Building Blocks

Supporting Technologies

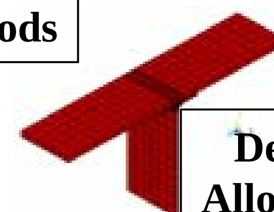
Analysis

Full-Scale Tests (1 to 3)

Component Tests (3 to 10)

Calibrate Semi-Empirical Analysis Methods

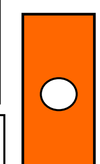
Subcomponent Tests (~250)



Design Allowables

Element Tests (~2000)

Coupon Tests (~8000)



Characterize the Material

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

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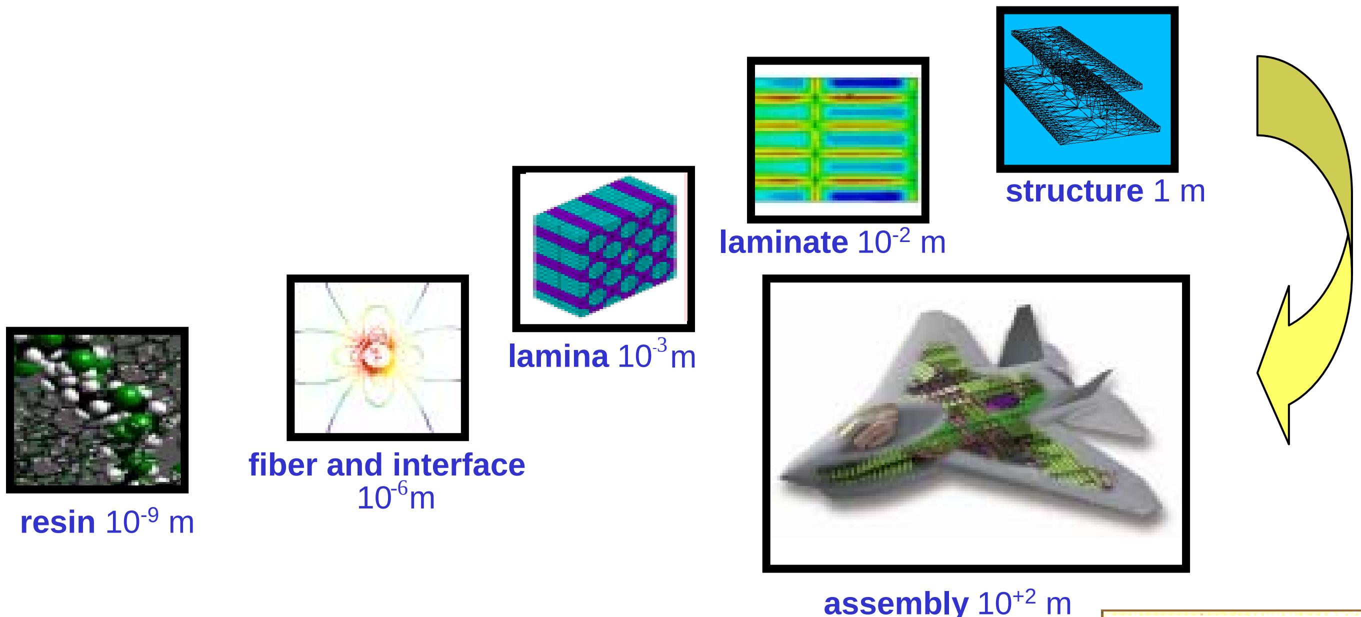
- Strength
- Fabrication
- Quality
- Mat'l & Proc
- Legal/Rights
- Output

Accelerated Insertion of Materials



- Methodology
- Process
- New Features

Chemistry to Component in the Shortest Time at Acceptable Risk

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Application	Structural Criticality	Usage Environment
Space Vehicle	Non-Structural	Flight Loads Usage
Missile	Secondary Structure	Design Service Life
Launch Vehicle	Primary Structure	Temperature
Commercial Transport	Flight Critical Structure	Chemical Environments
Military Transport		
Tactical Aircraft		
Bomber		
Rotary Wing		
Tanker		
Uninhabited Vehicle		
Ground Vehicle		

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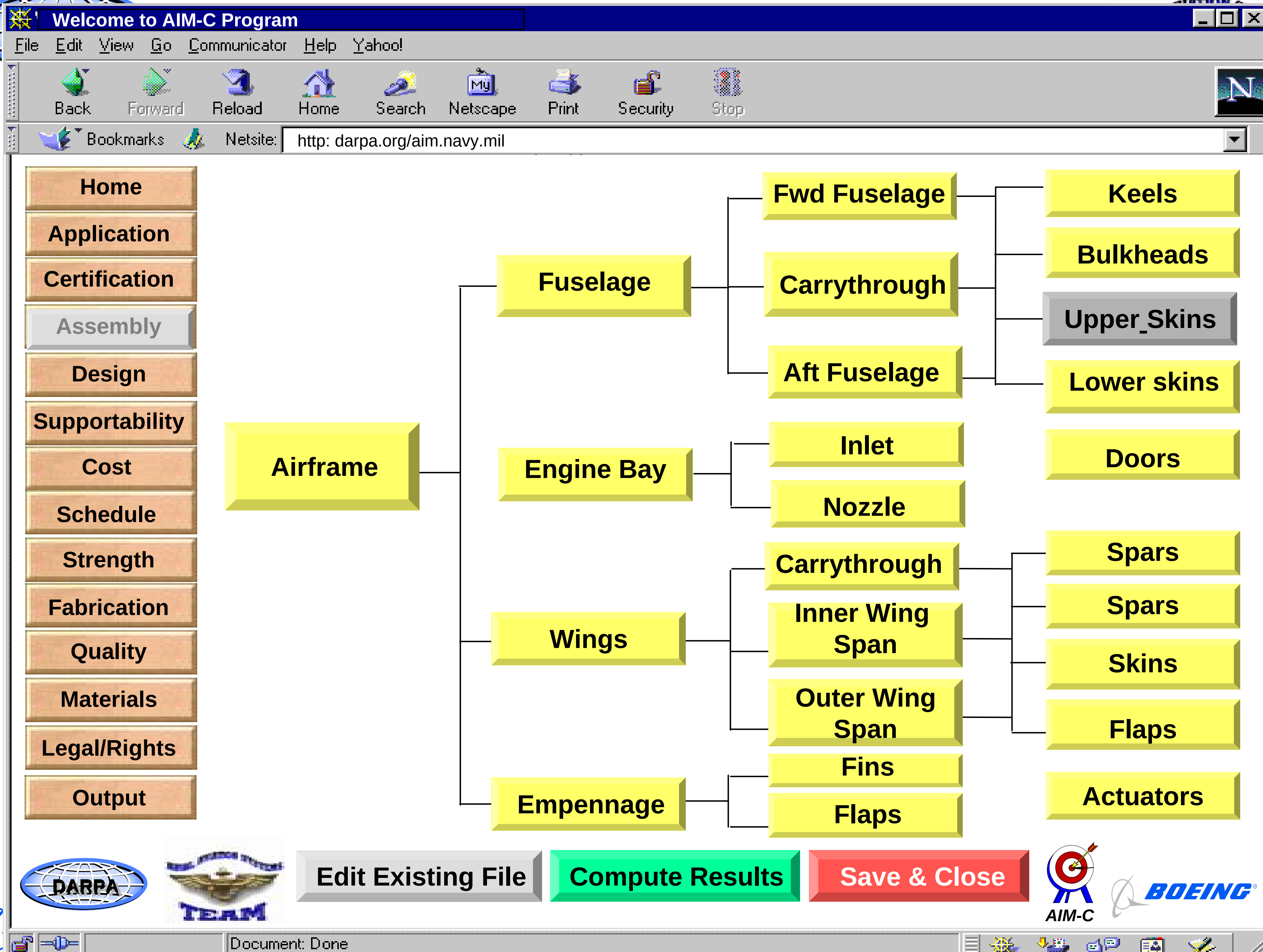
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Airframe
Fuselage
Engine Bay
Wings
Empennage
Fwd Fuselage
Carrythrough
Aft Fuselage
Inlet
Nozzle
Carrythrough
Inner Wing Span
Outer Wing Span
Fins
Flaps
Keels
Bulkheads
Upper_Skins
Lower skins
Doors
Spars
Spars
Skins
Flaps
Actuators
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Part Complexity

- Flat
- Single Curvature: Large Radii
- Single Curvature: Small Radii
- Double Curvature : Large Radii
- Double Curvature : Small Radii
- Multi-Plane
- Stiffened
- Sandwich

Assembly Concept

- Mechanically Fastened
- Co-Cured
- Bonded
- Welded

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TRL	1	2	3	4	5	6	7	8	9	10
Application Maturity	Concept Exploration	Concept Definition	Proof of Concept	Preliminary Design	Design Maturation	Component Testing	Ground Test	Flight Test	Production	Recycle or Dispose
Application Risk	Very High	High	High - Med	Med - High	Medium	Med - Low	Low	Low - Very Low	Very Low	Negligible - Recycle or Disposal
Certification		Certification Plan Documented	Certification Plan Approved	Preliminary Design Allowables	Design Allowables / Subcomponents	Full Scale Component Testing	Full Scale Airframe Tests	Flight Test	Production Approval	Disposal Plan Approval
Assembly	Assembly Concept	Assembly Plan Definition	Assembly Definition	Assembly Details Tested	Subcomponents Assembled	Components Assembled	Airframe Assembled	Flight Vehicles Assembled	Production	Disassembly for Disposal
Design	Concept Exploration	Concept Definition	Design Closure	Preliminary Design	Design Maturation	Ground Test Plan	Flight Test Plan	Production Plan	Production Support	Disposal Support
Supportability		Repair Processes Identified	Repair Processes Documented	Fabrication Process Repairs Identified	Fabrication Repair Process Trials Subcomponent Repairs	Repair of Component Test Articles	Production Repairs Identified	Flight Qualified Repairs Documented	Repair / Replace Decisions	Support for Recycle or Disposal Decisions
Cost/Benefit Maturity	Cost Benefits Projected	ROM Cost Benefit Analysis	Cost / Benefit Analyses Reflect Lessons Learned	Cost / Benefit Analyses Reflect Sizing Lessons Learned	Cost / Benefit Analyses Reflect Component Assembly Lessons Learned	Cost / Benefit Analyses Reflect Vehicle Assembly Lessons Learned	Cost / Benefit Analyses Reflect Low Rate Production Lessons Learned	Production Support	Cost / Benefit Analyses Reflect Production Lessons Learned	Cost / Benefit Analyses Reflect Disposal Lessons Learned
Structures Maturity	Potential Benefits Predicted	Applications Revised by Lamina Data	Applications Revised by Laminate Data	Testing of Critical Details / Elements	Sub-Component Tests of Applications	Component Tests of Applications	Full Scale Aircraft Level Ground Tests	'Flight Qualified' via Test and Analysis	Flight Tracking / Production Support / Fleet Support	Retirement for Cause
Fabrication Maturity	Target Applications Identified	Target Application Processes Tested	Target Application Full Scale Trials / Assembly Methods Defined	Sized Sub-components Fabricated / Assembly Methods Tested	Sized Components Fabricated / Assembly Methods Refined	Fabrication & Assembly Methods Documented / Production Methods Defined	Low Rate Production for Flight Test Vehicles Begins	Low Rate Production	Production Support / Recycle or Disposal Methods Defined	Recycle or Dispose
Quality		Initial Inspection and Repair Processes Identified	Inspection Trials	Inspection and Repair Processes Identified	Inspection of Components	Inspection and Repair of Component Test Articles	Vehicle Inspection Plan Documented / Production Repairs Identified	Flight Qualified Repairs Documented	Repair / Replace Decisions	Support for Recycle of Disposal Decisions
Materials Maturity	Key Target Properties Defined from Chemistries	Key Target Properties Obtained in Test	Initial Property Reproduc-ibility Tests	Design Properties Developed	Preliminary Allowables Available / Support Materials Identified	Design Allowables Available / Support Materials Tested	Ground Test Certification / Support Materials Qualified	Low Rate Production Support	Production Support / Recycle or Disposal Methods Defined	Support for Recycle of Disposal Decisions
Intellectual Rights										

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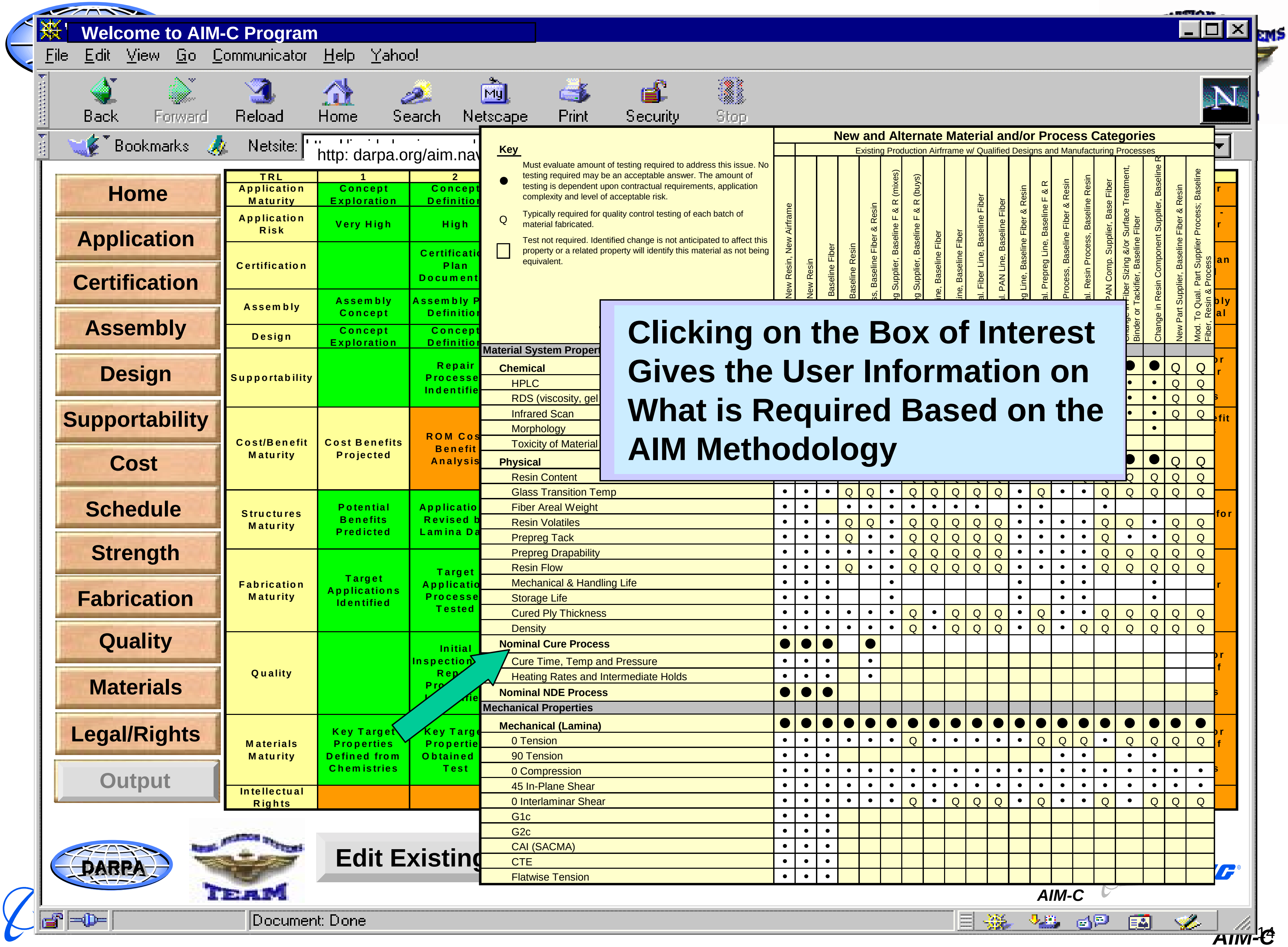

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TRL Application Maturity
Application Risk
Certification
Assembly
Design
Supportability
Cost/Benefit Maturity
Structures Maturity
Fabrication Maturity
Quality
Materials Maturity
Intellectual Rights
Concept Exploration
Very High
Assembly Concept
Cost Benefits Projected
Potential Benefits Predicted
Target Applications Identified
Key Target Properties Defined from Chemistries
Key
Must evaluate amount of testing required to address this issue. No testing required may be an acceptable answer. The amount of testing is dependent upon contractual requirements, 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 and Alternate Material and/or Process Categories
Existing Production Airfrrame w/ Qualified Designs and Manufacturing Processes
Material System Proper
Chemical
HPLC
RDS (viscosity, gel
Infrared Scan
Morphology
Toxicity of Material
Physical
Resin Content
Glass Transition Temp
Fiber Areal Weight
Resin Volatiles
Prepreg Tack
Prepreg Drapability
Resin Flow
Mechanical & Handling Life
Storage Life
Cured Ply Thickness
Density
Nominal Cure Process
Cure Time, Temp and Pressure
Heating Rates and Intermediate Holds
Nominal NDE Process
Mechanical Properties
Mechanical (Lamina)
0 Tension
90 Tension
0 Compression
45 In-Plane Shear
0 Interlaminar Shear
G1c
G2c
CAI (SACMA)
CTE
Flatwise Tension
Clicking on the Box of Interest Gives the User Information on What is Required Based on the AIM Methodology
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Strength

Tensile

σ_{11} (ksi)	σ_{22} (ksi)	σ_{33} (ksi)	σ_{23} (ksi)	σ_{13} (ksi)	σ_{12} (ksi)
370.6	7.32	7.32	11.6	11.6	11.6

Compressive

σ_{11} (ksi)	σ_{22} (ksi)	σ_{33} (ksi)	σ_{23} (ksi)	σ_{13} (ksi)	σ_{12} (ksi)
235.1	7.32	7.32	11.6	11.6	11.6

Stiffness

Young's Moduli (tensile)			Young's Moduli (compressive)			Poisson's Ratio		
E_{11} (msi)	E_{22} (msi)	E_{33} (msi)	E_{11} (msi)	E_{22} (msi)	E_{33} (msi)	υ_{23}	υ_{31}	υ_{12}
24.367	1.347	1.347	22.946	1.347	1.347	0.325	0.325	0.325

Thermal

α_1 (in/in/^{0}F)	α_2 (in/in/^{0}F)	α_3 (in/in/^{0}F)
4.0×10^{-7}	2.0×10^{-5}	2.0×10^{-5}

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Recommended Tests for Your Requirements

Test Type	Number of Specimens CTD	RTA	ETW	Total	Emphasis	Specimen
Lamina						
0^{O} Tension	4	5	2	11	Fiber	Recommended
0^{O} Compression	…	…	…	…	Fiber/Matrix	Recommended
45^{O} Compression	…	…	…	…	Fiber/Matrix	Recommended
0^{O} Interlaminar Shear	…	…	…	…	Fiber/Matrix	Recommended
…… ……	…… ……					
Laminate						
Unnotched Tension	3	5	4	12	Stress Riser	Recommended
Open/Fill Hole Compression	…	…	…	…	Stress Riser	Recommended
Tension Bearing Interaction	…	…	…	…	Bearing Strength	Recommended
Compression Bearing Interaction	…	…	…	…	Bearing Strength	Recommended
…… ……	…… ……					

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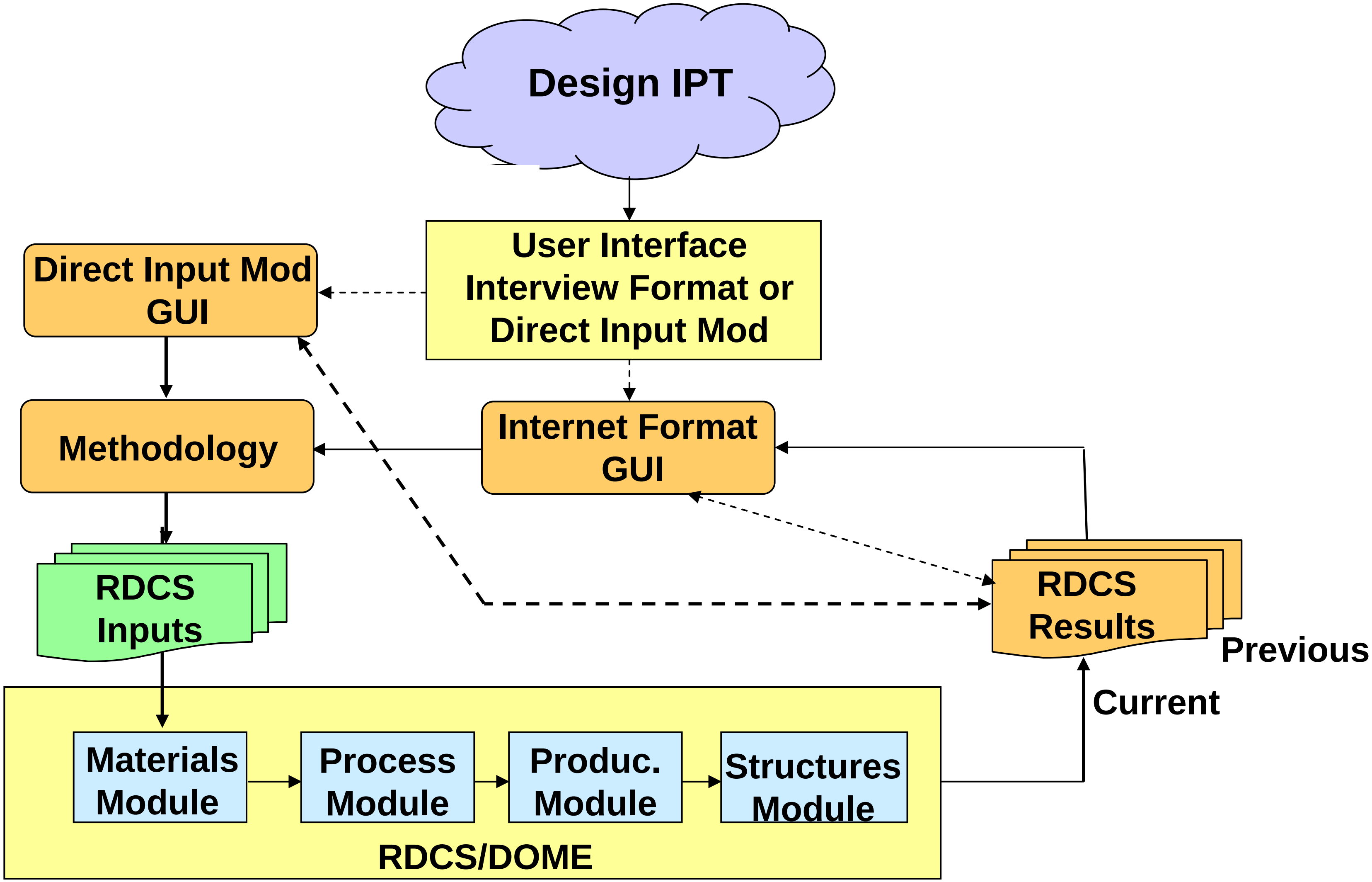
Our Current Vision of the AIM Product



Methodology is the Foundation of the AIM-C Comprehensive Analysis Tool

RDCS/DOME Framework

Structure Models
(Science Based)

Material & Process Models
(Science Based)

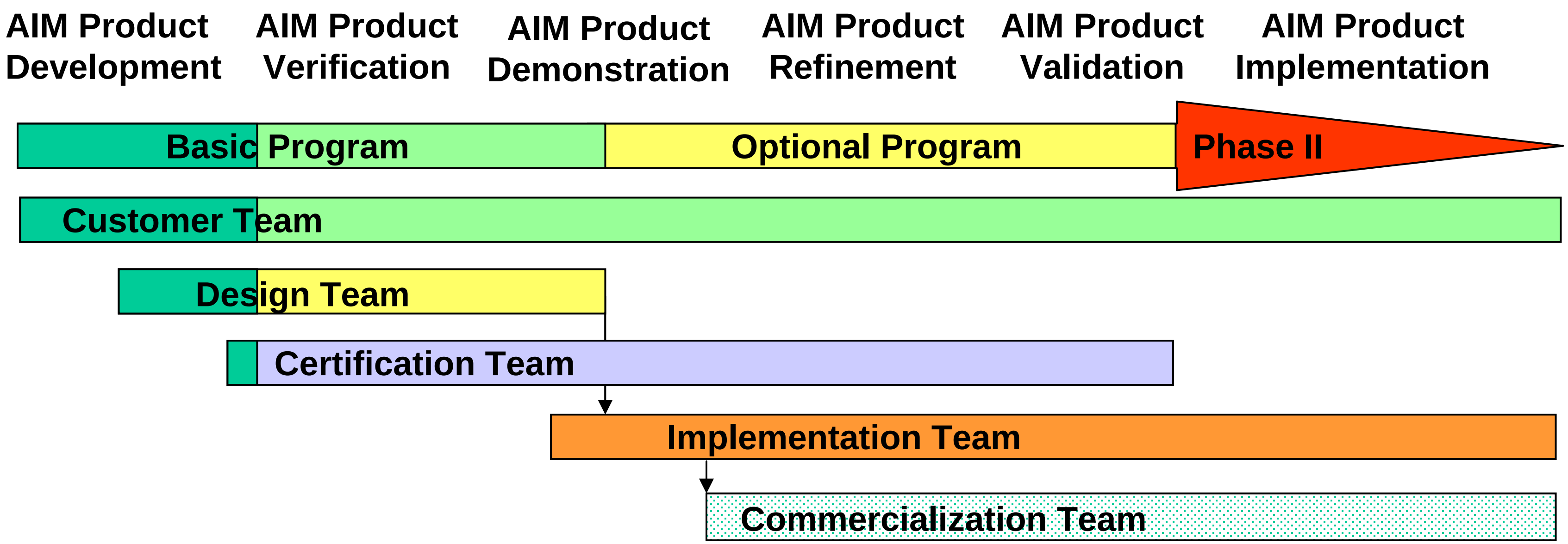
Producibility Models
(Science Based)

Heuristic Models

Data Bases

Methodology

Technology Transition Plan



Customer Team – To Insure that the Product Meets the Needs of the Funding Agents

Design Team – To Insure Acceptance Among User IPTs in Industry

Certification Team – To Insure Acceptance Among the Certification Agents for Structures

Implementation Team – To Insure Acceptance Among the User Community

Commercialization Team – To Insure Commercial Support of Users

The Certification Team Will Validate Our Methodology and Our Verification Approach

Step 1

Individual Module Validation

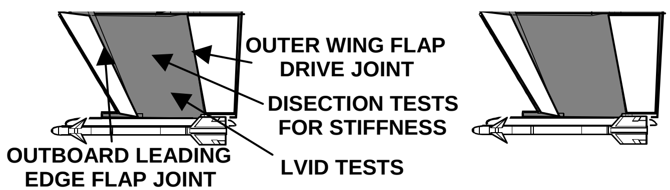
Existing Data

Step 2

Process Validation

Existing Subcomponent Test Results

Existing Component Test Results

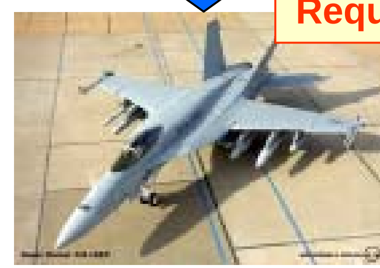


& Tests of Wing Skin Validate Projected Means and Scatter

Step 3

System Validation

Known Design Requirements



"Blind" Subcomponent Test Results

"Blind" Component Test Results

Validates Technical Results, Time Reductions, Cost Reductions

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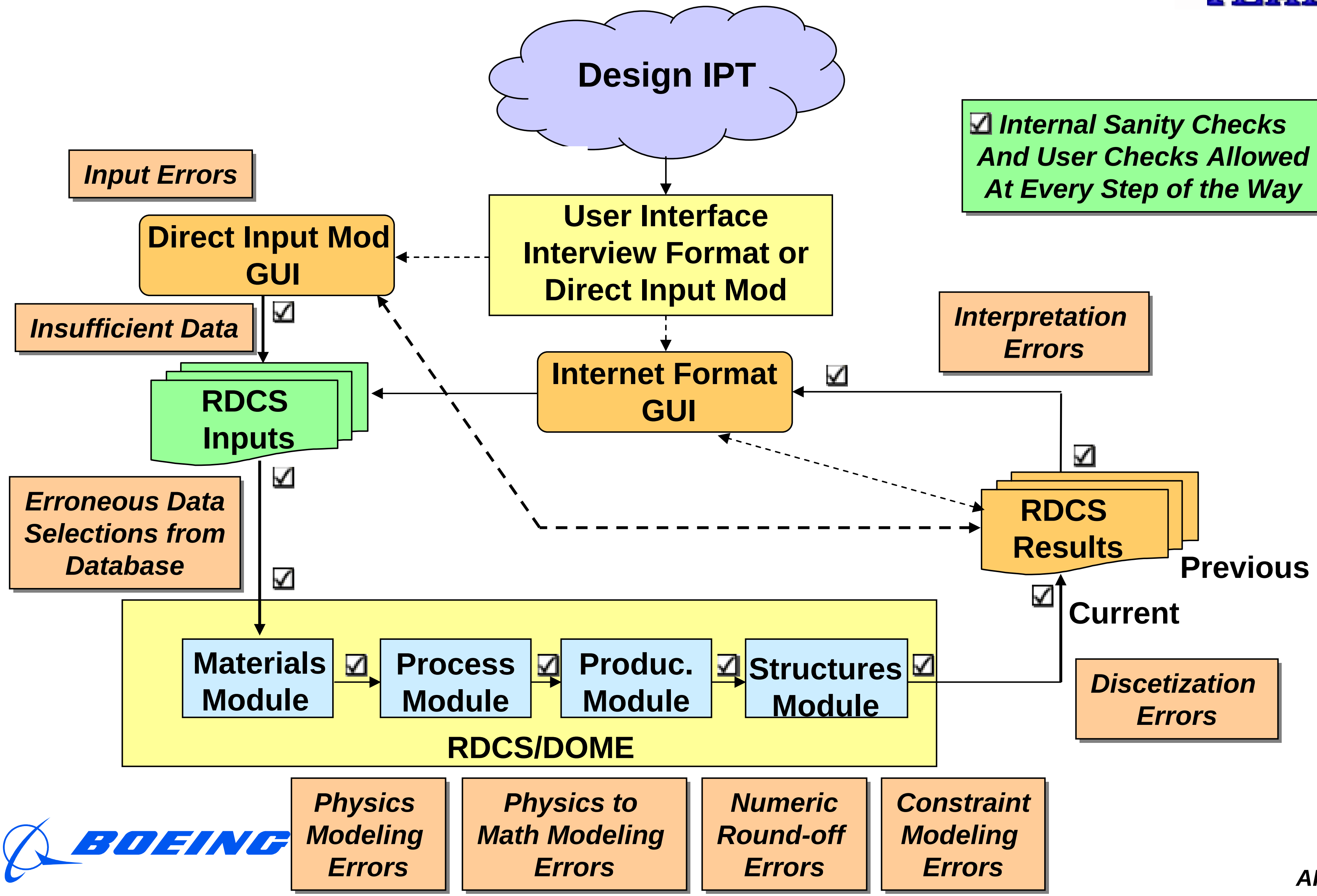
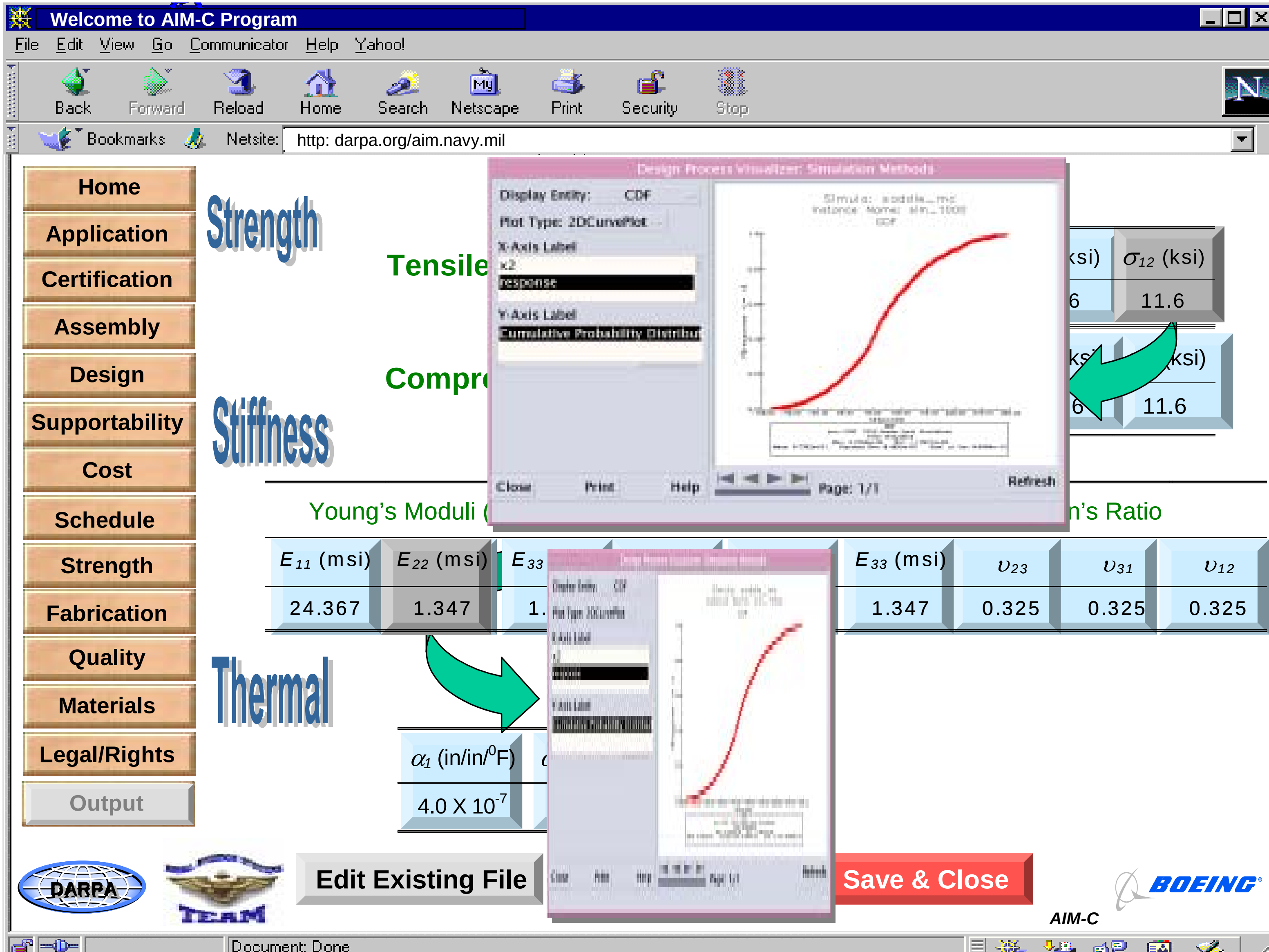
Certification Team Feedback
Roadblocks to Success

Limitations of the Process	Prediction Accuracy	Validation	Intellectual Property Rights	Technology Transition	Commercialization
This is a moving target depending on the modules being used and the data input. I think this goes beyond just knowing the 'errors'. We've seen before instances in which engineers who did not understand the limits of the software came out with answers tha	How does one insure that the company that actually builds the part can achieve the required properties? Additional testing?	There is going to have to be a lot of 'proof testing' (validation of AIM-C results) to convince the overall M&P/Structures community	Intellectual property rights to protect databases, test methodologies, and process specifications	Getting past 'Not Invented Here" or industry familiarization.	Developers leave and the certifiers of the next generation process are the next generation
Missing an important behavioral characteristic (ex., crystallinity in thermoplastics, free edge effects in laminates)	Unavailability of useful accurate models for specific technical areas will limit the scope of AIM.	Populating models with 'actual' values and distributions of variations	Protecting company proprietary information; magnitude of variations, costs, etc.	Getting past the "It will never work" crowd	Commercialization buy-in. What is the product?
Complexity of designing aircraft. There are thousands of issues to be considered. How is AIM going to capture them and deal with them in a logical fashion.	Will the producibility module really be able to identify fabrication show stoppers? As this point it is more a lessons learned from the past collection area.	Diversity and the extent of the validation activities (more contour, highly loaded, higher fatigue requirements)	Proprietary limitations: Commercial marketing may limit access to non-Boeing data sources.	Certification of materials and structures has different rules depending on who is doing it, the ultimate use of the structure, history of certifying organization… Not sure the 'one size fits all" approach will work.	Training to make it work: expert vs casual users
Input data validation: To be universally accepted, data from a large array of sources will be required (I.e., a world standard, ala, MIL-HDBK-5). Who sets this up?	Ability to address long term exposure and fatigue data in a manner different from today. May have to rely on testing for this.	Validation data: gathering sufficient data to certify the multitude of constituent software tools resident in AIM. For instance data to certify strain invariant (if that will be the failure theory used).		Broad adoption by the user community when faced with the "not invented here" syndrome.	Selection of the appropriate time to commercialize. Too early (before the tool is really ready) could be fatal.
Overselling the program to user community on what CAT can and cannot predict, I.e., showstoppers.	Failure of multi-axially loaded composites still difficult to predict.	Can you really provide compelling evidence that you've validated the tool? Criticism could be that since you knew the answers, you developed a system that can regurgitate the answers.		Perception that this is just another big program with no practical value.	Commercialization plan. At the end of AIM, what? Where are the $ for maintenance, improvements, advertising, and sales, training
Limited funding limits the scope of the program to results in specific technologies. It eliminates those not fully developed (I.e., RTM, fiber placement) resulting in loss of interest by user community, I.e., will not be able to please everybody.		Providing enough confidence to the user community for computational analysis to replace experimental testing for specific applications.		Unfamiliarity of the certification community with computational approaches will result in fall back to building block approach to materials certification.	Where are the $ to support adoption by other industries, sites? Software, hardware, training, new personnel, revision practices, codes, standards
How far will AIM assist in better understanding composite / metal structure interactions?		Partial validation. Demo leaves loose ends in fatigue, environmental testing, and structural details.		"Not invented here" roadblock. Aim will be perceived as a Boeing only, or a Boeing subcompany process.	How do you partition AIM so that portions can be used before having to use the whole thing?
Can you include a prediction of risk versus benefit for different levels of materials development maturity?					Can AIM be structures so that portions can be spun off and used prior to validation of the whole system?

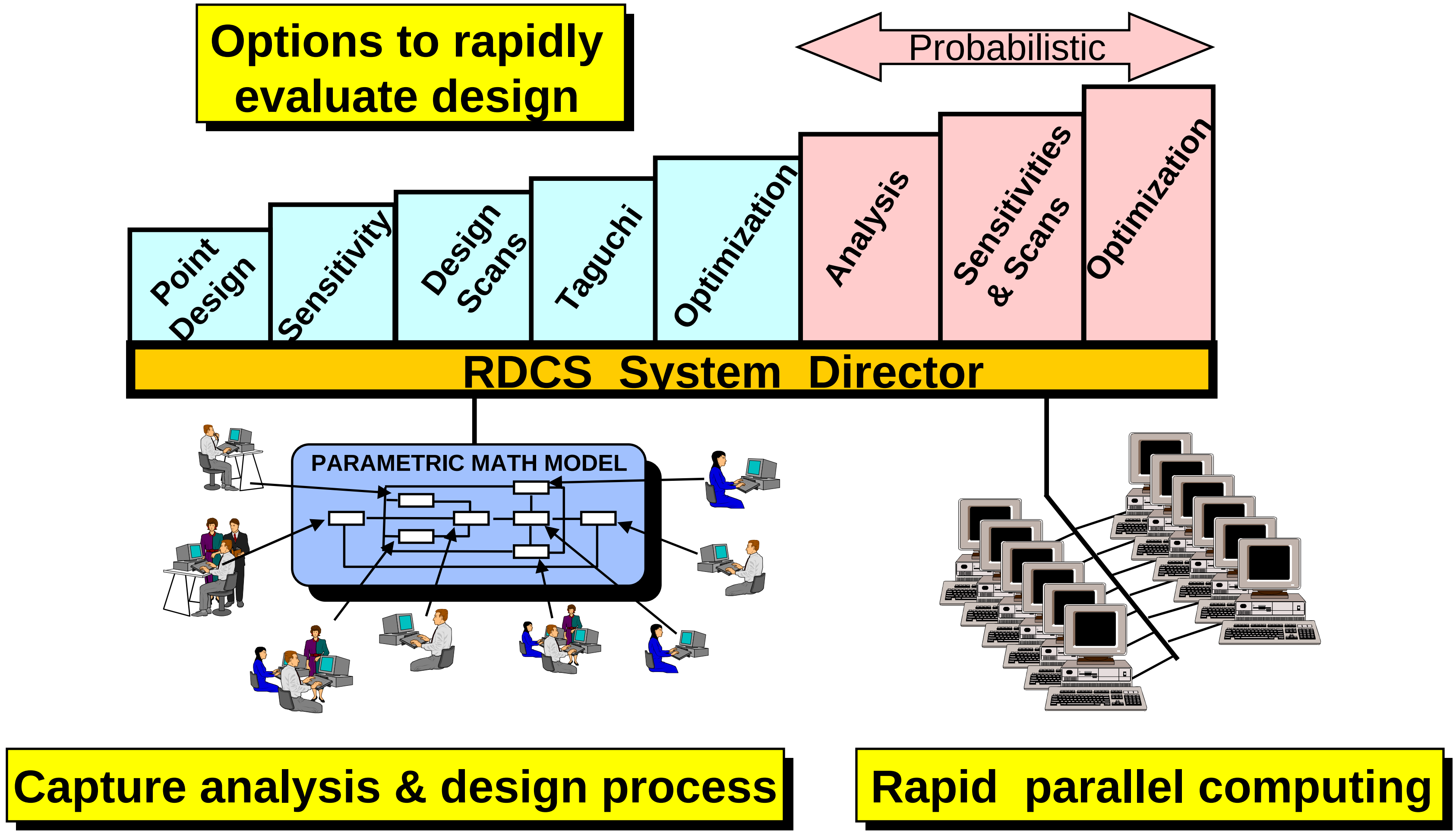
Error Sources and Mitigation in The AIM-C Product



Example of an Output Screen for the AIM-C CAT

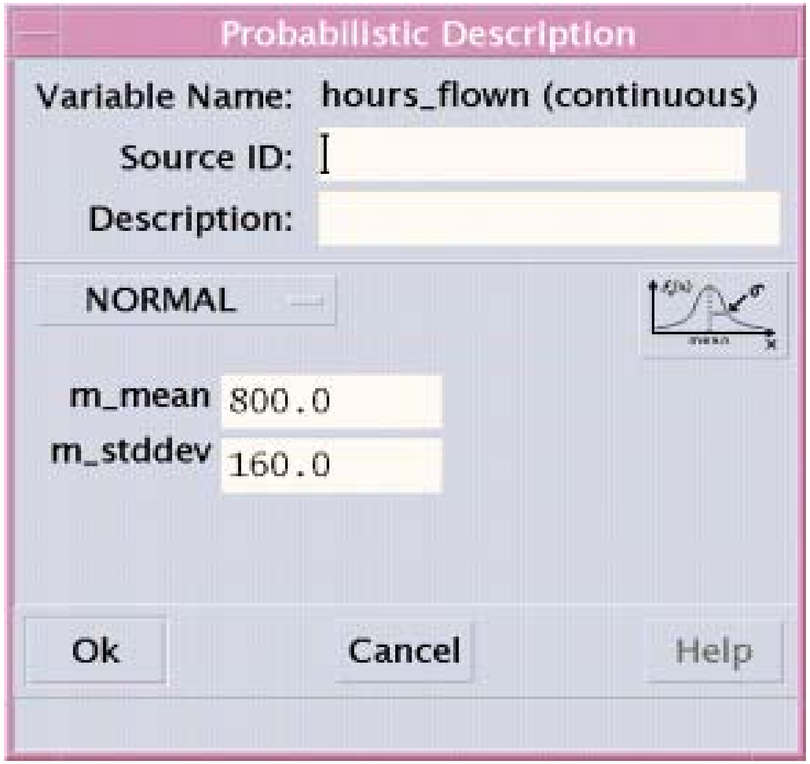


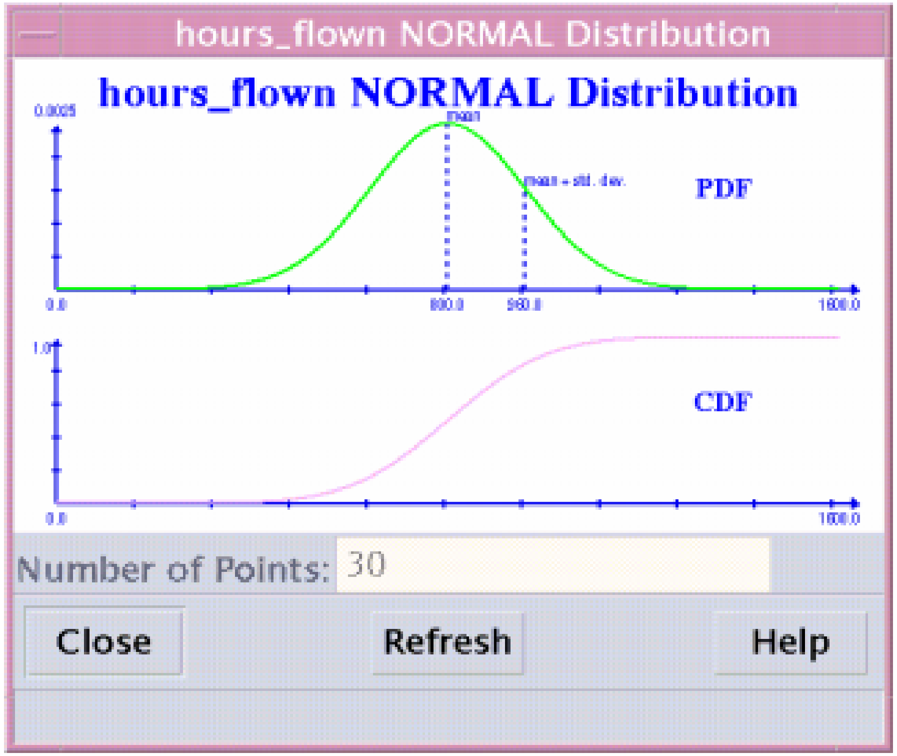
Robust Design Computational System
(Commercially available from MSC Software)



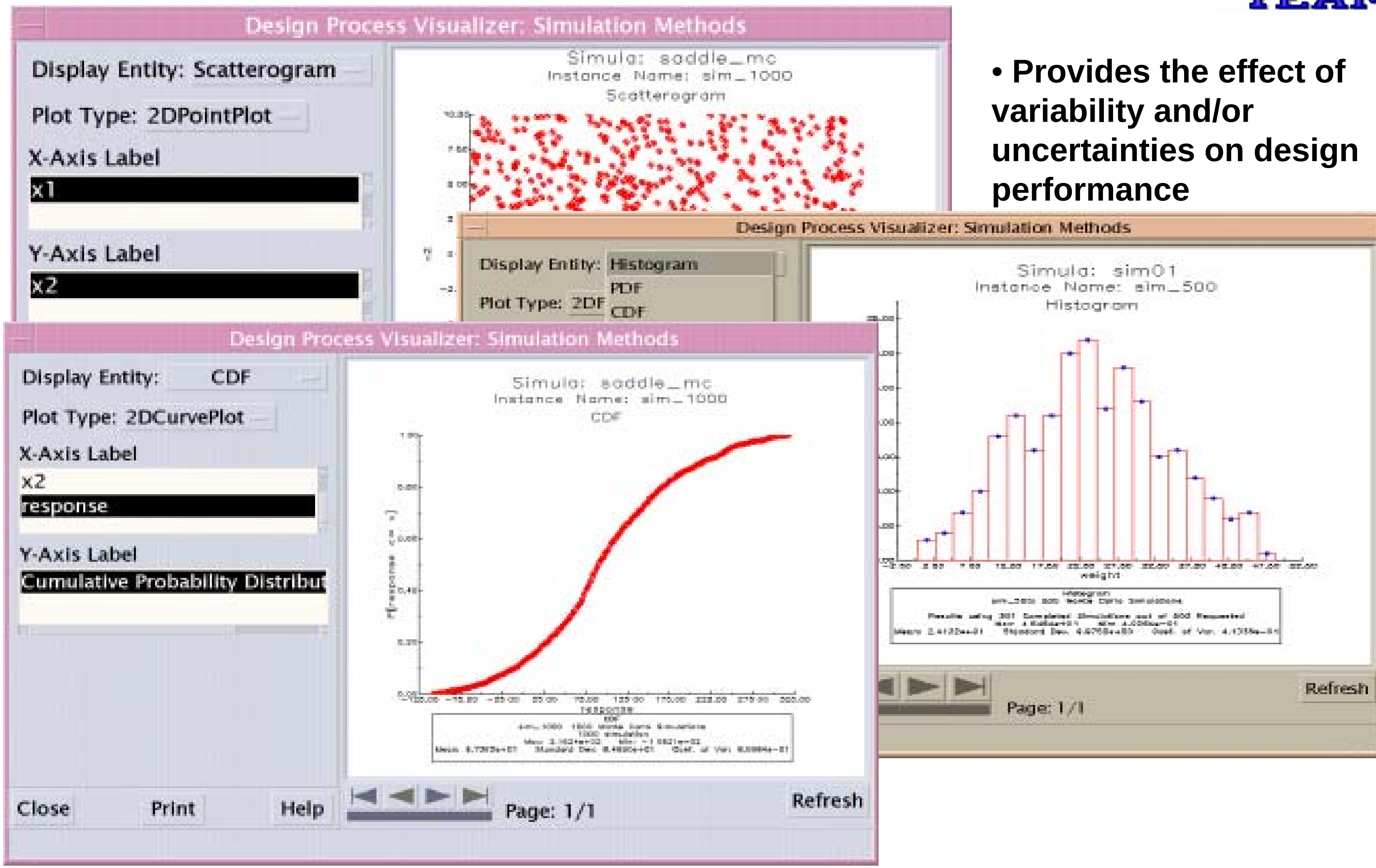
Definition of Global Variables
Probabilistic Description

- **Numerous Probabilistic Distribution Models Such As Normal, LogNormal, Weibull etc. are available for Characterizing The Variations**



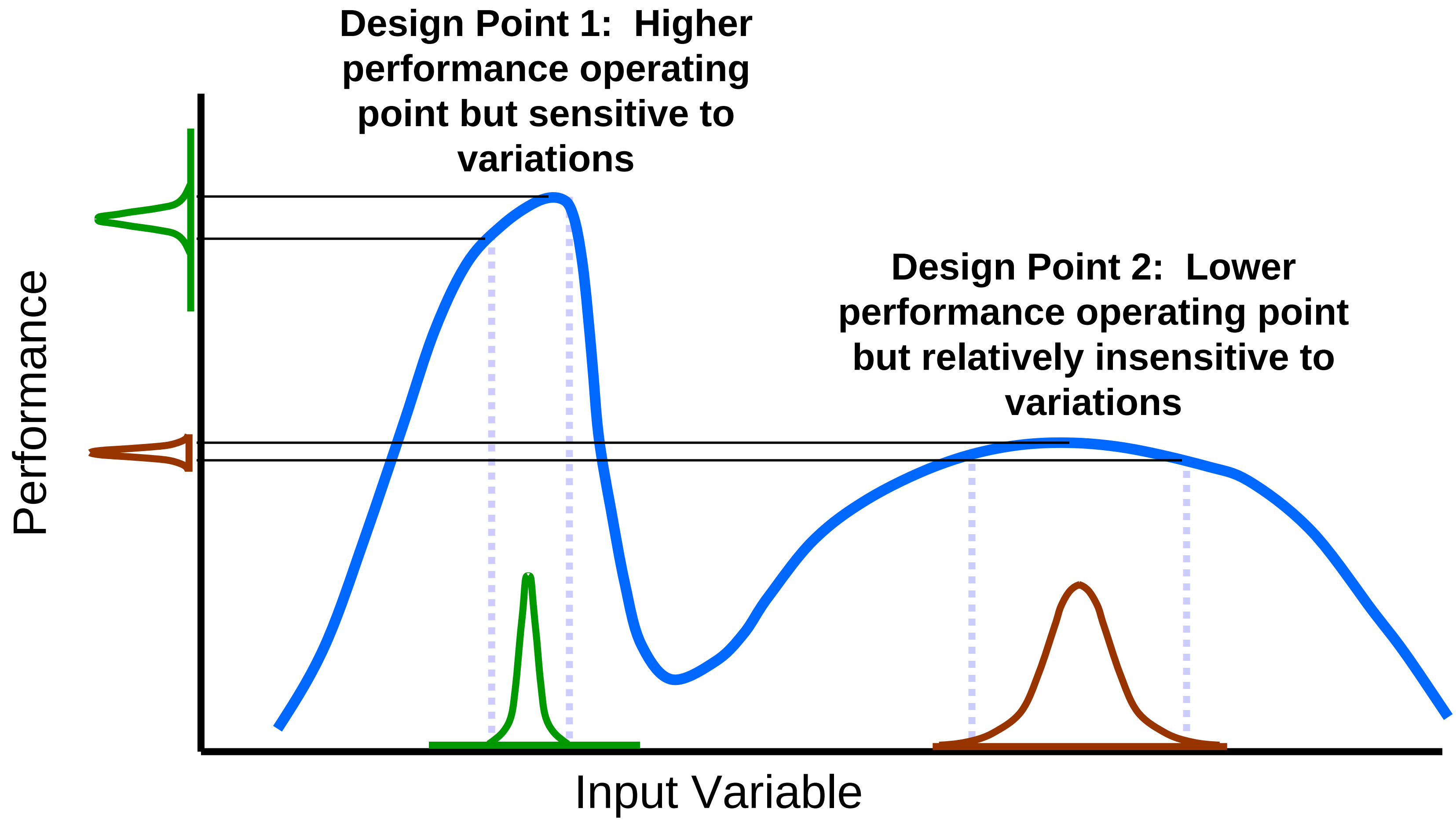


Uncertainty Analysis Results in Phase - 1



- **Provides the effect of variability and/or uncertainties on design performance**

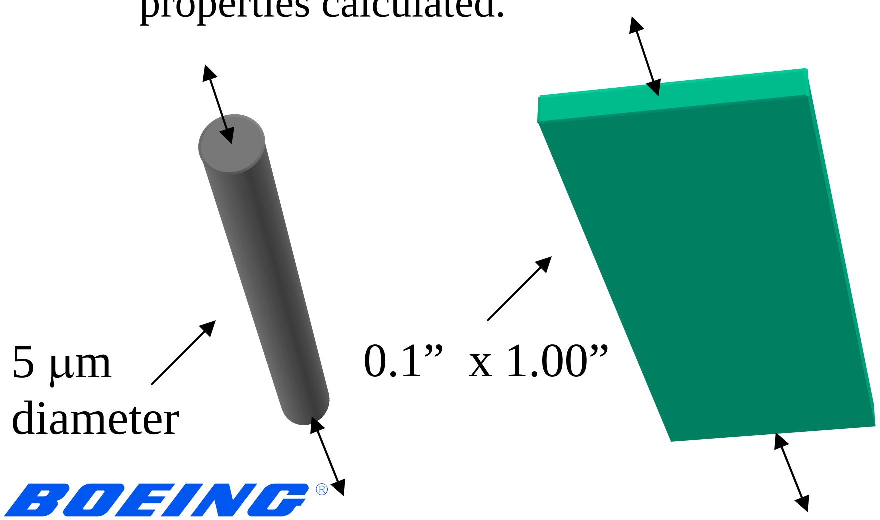
Robust Design Illustrated Using Single Variable

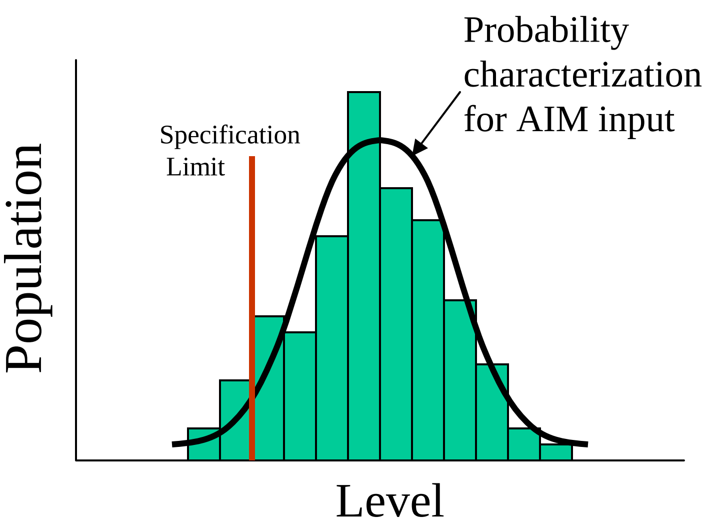


•Input Material Properties

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

Example:
Fiber properties
single fiber tests not practical
Laminate tests performed, fiber properties calculated.



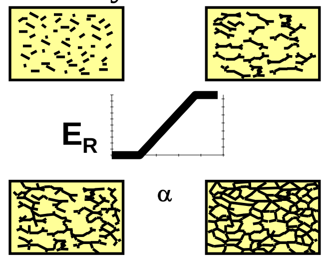


Example:
Actual data may not be ideal distribution shape, Distribution of material actually used may be truncated by specification acceptance criteria

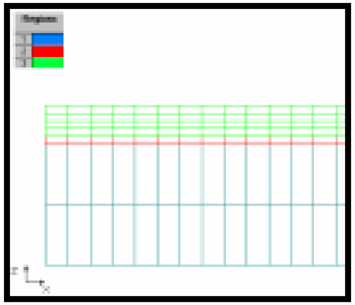
•Modeling

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

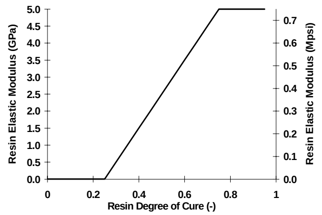
Example: Unknown mistake in calibrating DSC leads to wrong heat of reaction and incorrect temperature history



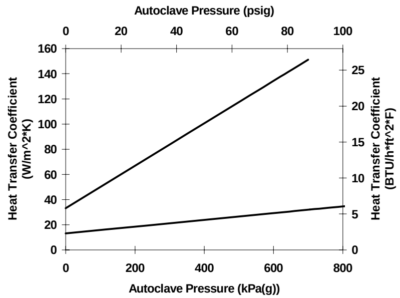
Example: The tool surface finish is not uniform for a tool or between tools.



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

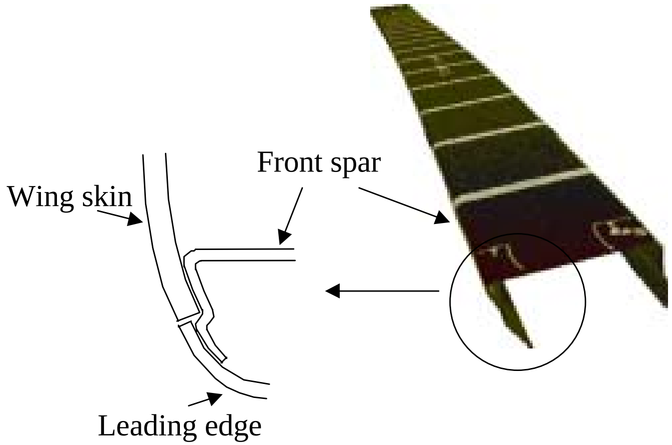


Example: Autoclave heat transfer equation is used outside of known limits

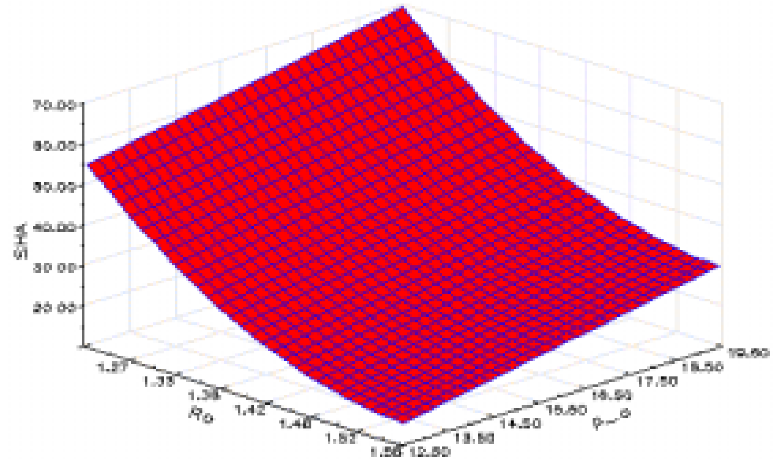


AIM-C CAT Benefits: COMPRO Integration with Robust Design Computational System (RDCS)

767-400 Raked Wingtip Front Spar DOE Sensitivity Analysis



RDCS Sensitivity Analysis Plus Design Scan



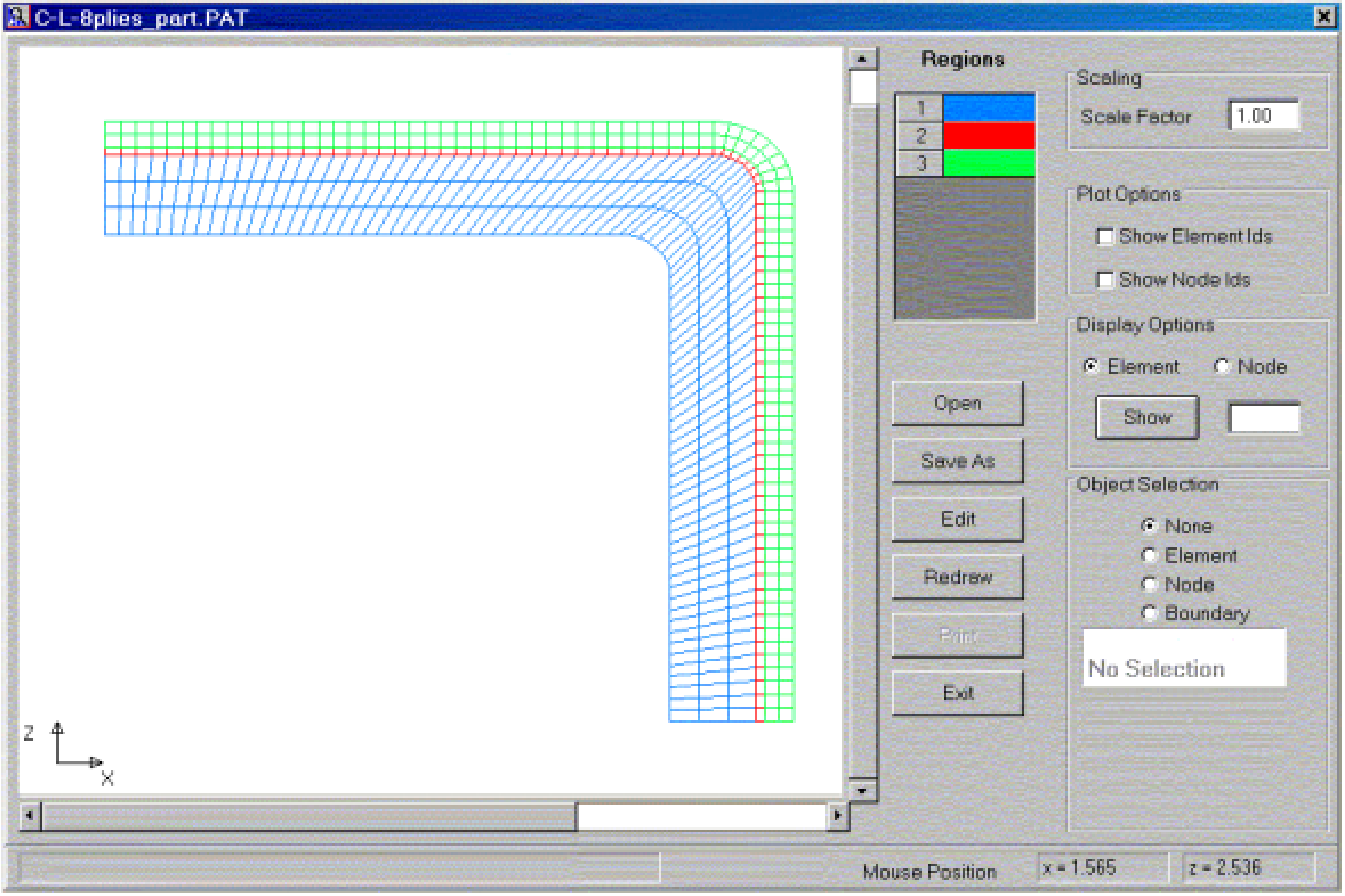
Conventional Approach

- 32-Runs for Simple DOE
- 4-Months Calendar Time to Set-Up and Solve
- Computer (time) intense
- 216-Hrs Actual Labor to Complete
- Labor-Intense Data Reduction

Integrated with RDCS

- 127-runs for Sensitivity Analysis and Design Scan
- 1-2 Weeks Calendar Time to Set-Up and Solve
- User Isolated from Intense Interaction with Multiple Codes
- 28-Hrs. Actual Labor to Complete
- Automated Data Reduction and Graphics

Initial Application of Processing Module: L-Bracket Example Problem



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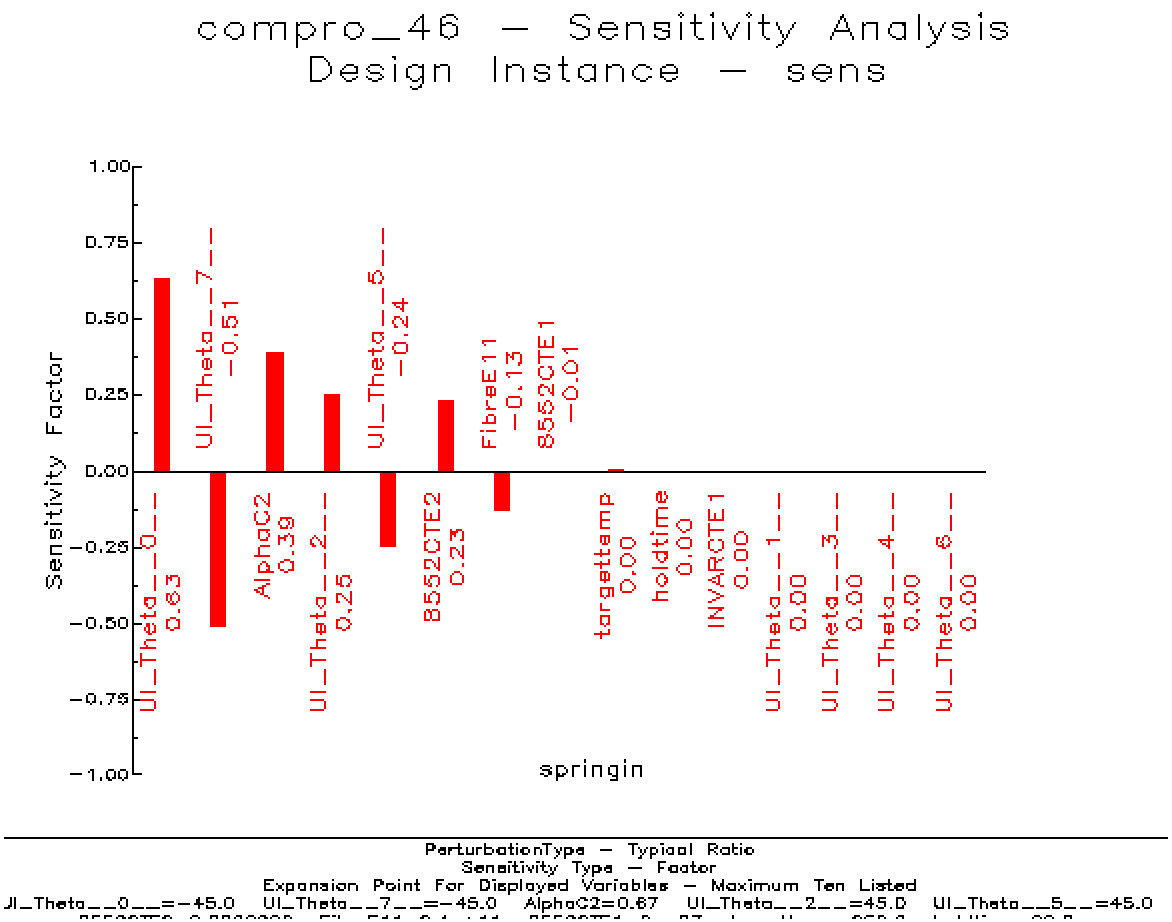
Input Parameters for L-Bracket Example Problem Involve Variability

Variable	Nominal	Lower	Upper	Std. Dev.
Target Temp	250	240	260	3.3
Hold Time	60	50	120	**
Alpha C2	0.67	0.5	0.8	0.05
8552 CTE 1	6.0E-07	5.4E-07	6.6E-07	0.2E-07
Fiber E11	2.73E+11			6.80E+09
Invar CTE	6.0E-07	5.4E-07	6.6E-07	0.2E-07
Theta_0	-45.0	-43.0	-47.0	0.667
Theta_7	-45.0	-43.0	-47.0	0.667

Hold Time was modeled using a 3-parameter Weibull Distribution
X_0 = 50, Char. = 60.0 Alpha = 0.78

Identification of Parameters to Which Spring In is Sensitive

L-Bracket Example Problem



Summary of Responses

L-Bracket Example Problem

Variable	Mean Response	Std. Dev. Response
Theta 7	1.057	0.106
Alpha C2	1.068	0.1175
Hold Time	1.06	0.1065
Target Temp	1.06	0.1055
All	1.012	0.115

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

Accelerated Insertion of Materials -- Composites (AIM-C)

Wrap Up

- AIM attempting to provide methodology and tools to enable integrated product teams to accelerate insertion of materials into products

- Barrier -- Confidence in material "which is intimately tied to the reliability of knowledge of the state of material throughout production and use"

- AIM tool under development includes

  - A quantitative tool set
    - Combination of analysis and test
    - Requires management of uncertainty and error
      - Challenge to materials community -- Understand and manage uncertainty and error in models and tests

  - A qualitative tool set
    - Capture lessons learned, experience
    - Anchor AIM to established practices