



Accelerated Insertion of Materials – Composites



Presented at
SAMPE ISSE 2002
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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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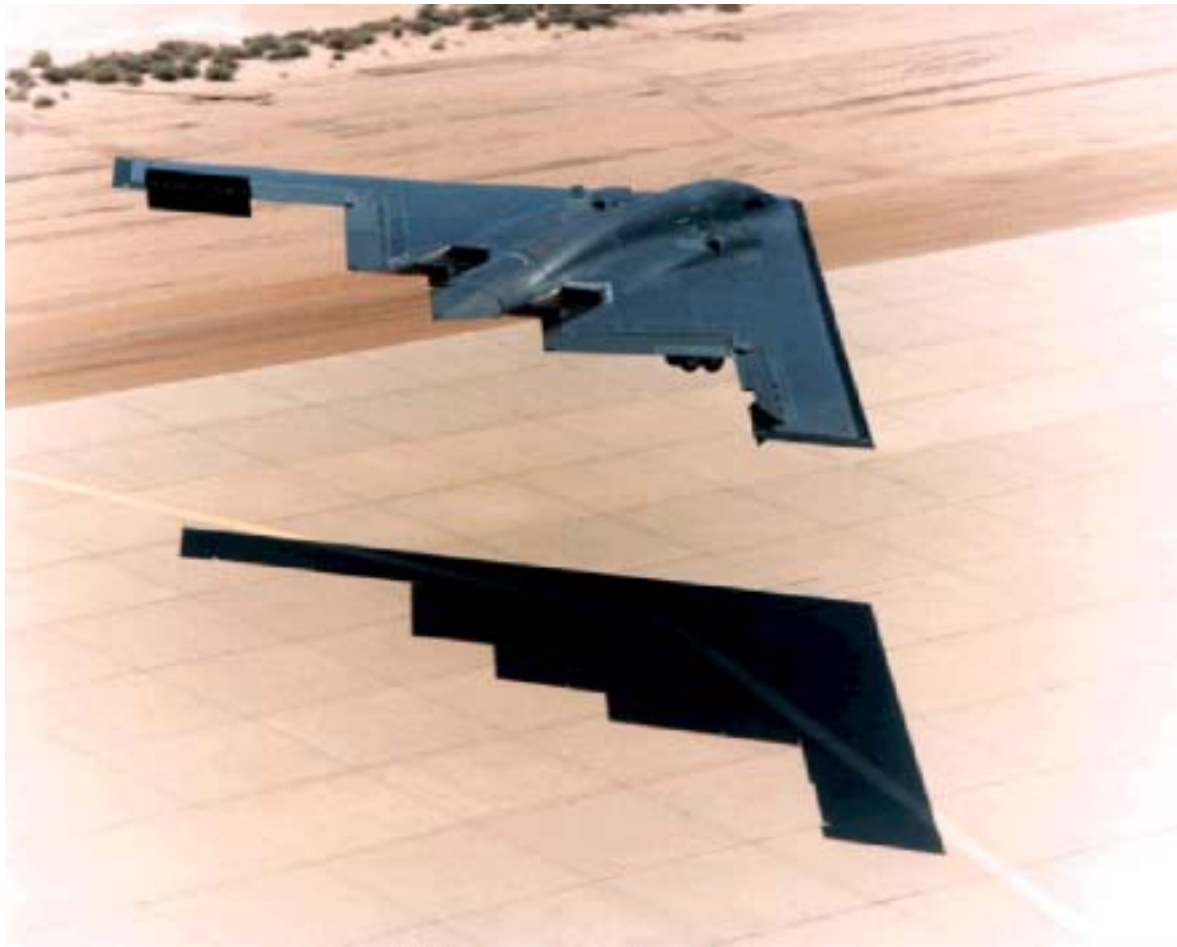
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It is Costly to Test, Qualify, Re-Qualify,
and Generally Manage Materials



B-2 Program Experience



Between 1981 and 1986

- \$100M Spent by Boeing Alone
- 12,000 Specimens Broken, Range from Small Adhesion Test to 8' Wing Box
- Combinations of all Layups Were Tested

Engineering Estimated That

- \$20M Could be Saved with AIM Methodology
 - 2-Years Could be Shaved Off
-
- Cytec Fiberite 934/T300 Wing BMS 8-297
 - Hexcel F584/T300 Center BMS 8-256

What About AIM-C Accelerates Insertion?

- Definition of requirements
- Focus based on insertion needs (DKB)
 - Focused Testing
- Earlier risk reduction
- Validated analysis tools
- Approach for use of existing knowledge
- Reduced rework
- Knowledge management

The AIM-C Team

- Boeing – Seattle and St. Louis – AIM-C CAT, Program Management
- Boeing – Canoga Park – Integration, Propagation of Errors
- Boeing – Philadelphia – Effects of Defects

CMT

- Convergent Manufacturing Technologies - Processing
- Cytec Engineered Materials – Constituent Materials, Supplier



- Materials Sciences Corporation – Structural Analysis Tools
- MIT – Dr. Mark Spearing – Lamina and Durability
- MIT – Dr. David Wallace – DOME, Architecture
- Northrop Grumman – Bethpage – Blind Validation
- Northrop Grumman – El Segundo – Producibility Module
- Stanford University – Durability – Test Innovation



NORTHROP GRUMMAN





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

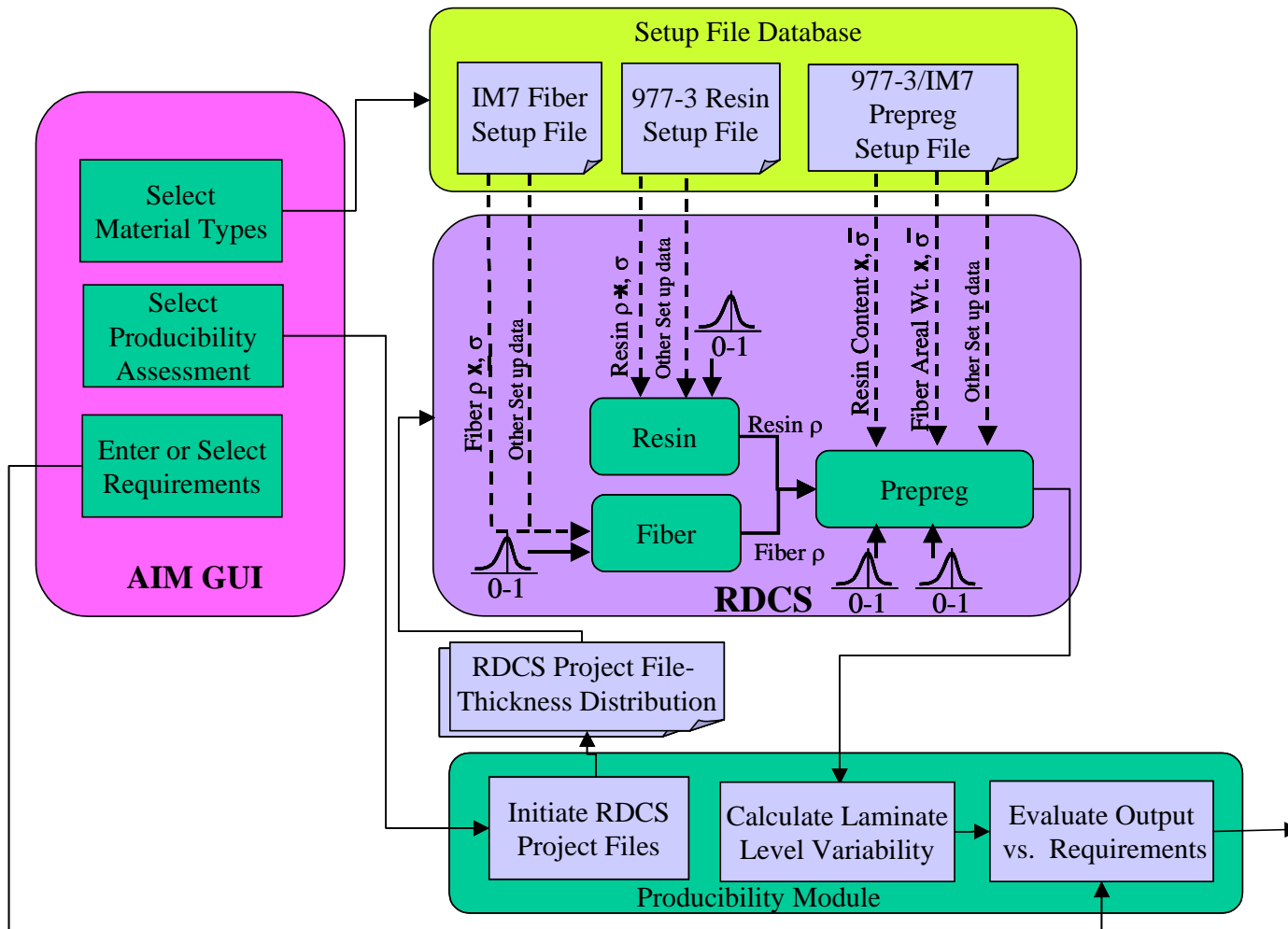
AIM-C Will Accomplish This Three Ways

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.*

Architecture Example





Technical Components of AIM-C



Materials Insertion Methodology

Baseline Material and Structure

Modular Approach to Modeling

Prediction of Structural Response

Composite Mechanical Properties, including
Progressive Damage Failure, and
Durability

Distributed Object-based Modeling Environment (DOME)

An *emergent* network of models (information services)

Robust Design Computational System (RDCS)

Distributed computing capability
Uncertainty and Error Propagation
Probabilistic Analysis

Materials, Processing, Producibility and Manufacturing (M&P)²

Raw material physical and mechanical properties
Residual stress state as dependent on processing
Producibility aspects of new materials and structure

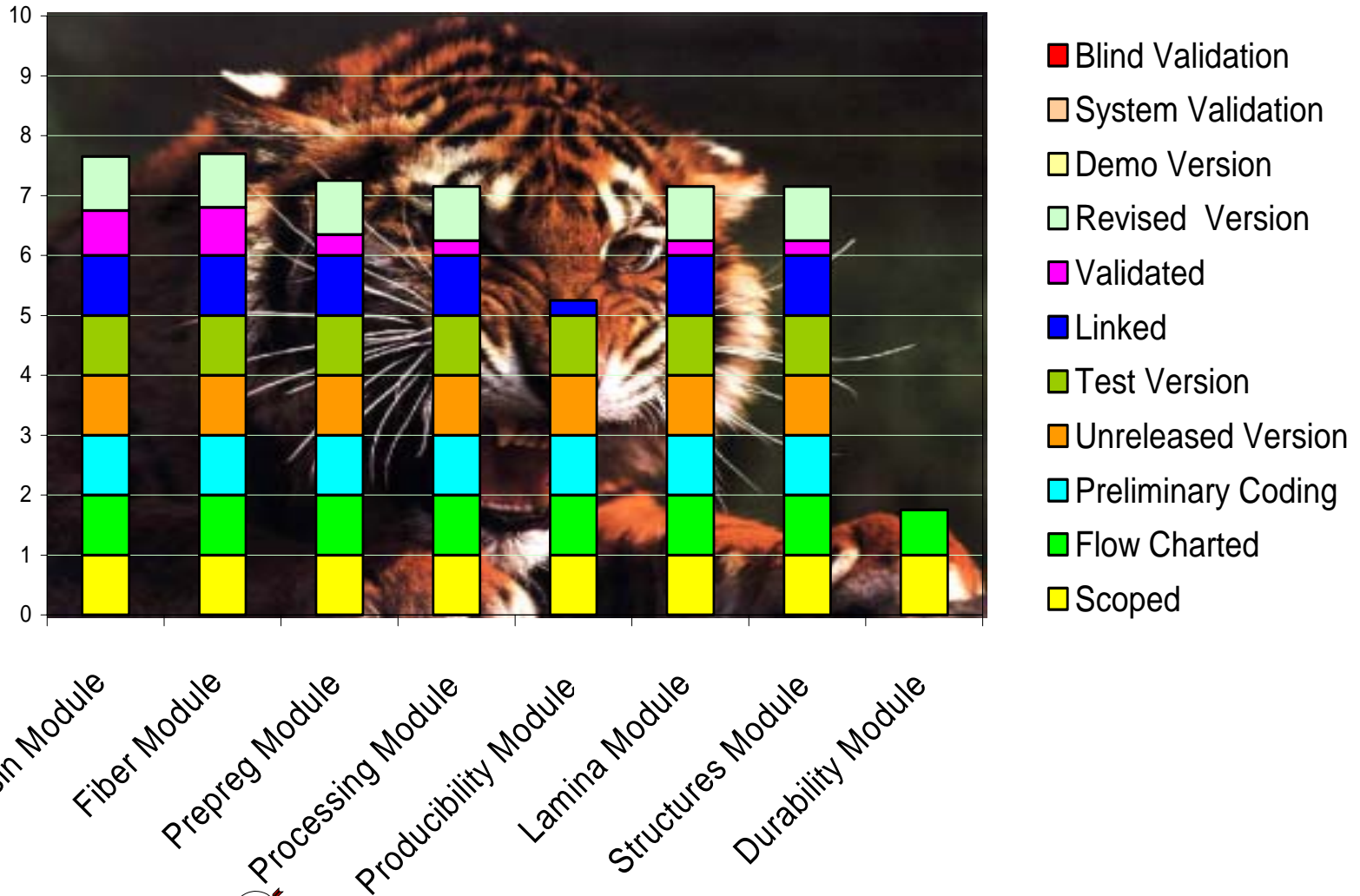
Validation

Design, Certification, Implementation Considerations





Module Development *of the CAT*





Near Term or Current Capabilities

1. Processing Module

- Processing Window Studies
- Spring-In and Deformation Calculations
- Evaluation of Novel Processes (i.e. staging, VaRTM)
- Thick Laminate Structure

2. Structures Module

- Stiffener termination/pull off problem
- OHC, OHT, Un-notched Coupon Prediction
- Large Notch Type Damage Problem

3. Robust Design Computational System (RDCS)

- Already in use by Sonic Cruiser
- Combined Structure/Processing Effects -- Microcracking
- Sensitivity Analysis/Design Space Scans, Optimization, etc.

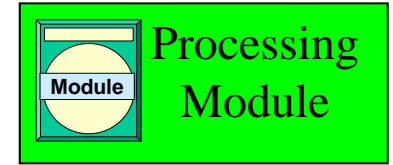
• Qualification/Re-qualification of Materials



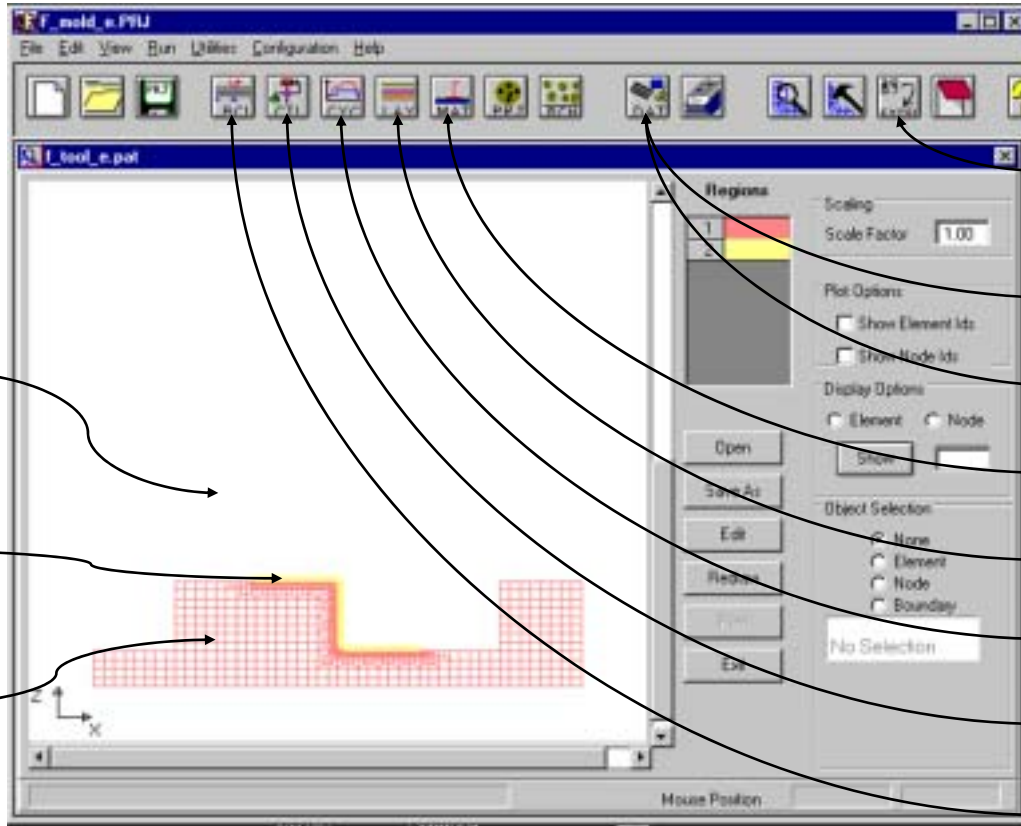


Processing Module

CMT's COMPRO



2D FEM



Autoclave Model

Part Model

Tool Model

Output formatted for text, Excel or Tecplot

Resin Models

Fiber Properties

Choice of Material

Layup Definition

Cure Cycle

Program Controls

Boundary Conditions





AIM-C Structural Property Prediction

Basic Effort Goals

Capture the Effect of Changes in Material, Design, Manufacturing/Processing, and Testing Variables On Typical Failure Values

**Two Methods for Structural Property Prediction
The Strain Invariant Failure Theory (SIFT)**

The Boeing Company

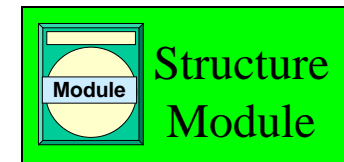
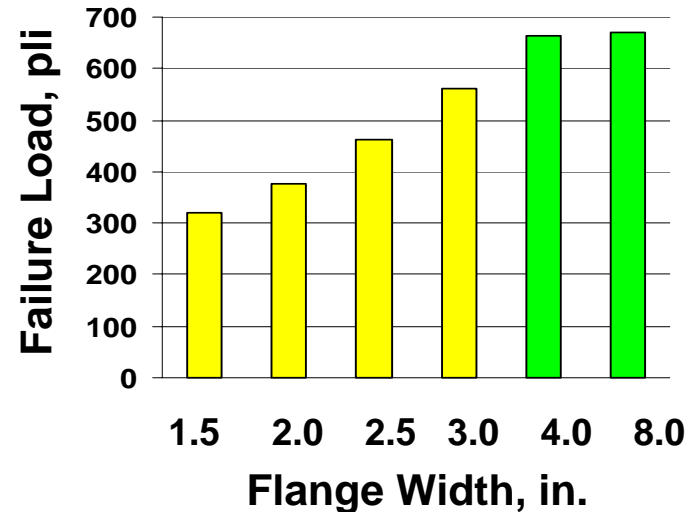
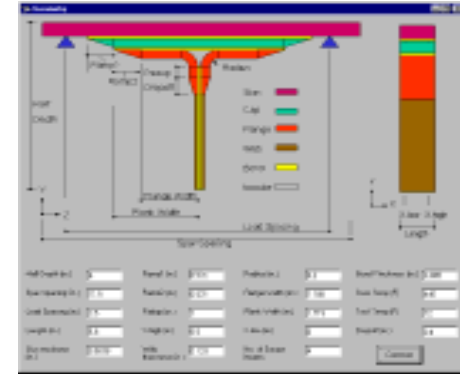
Mechanistic Approaches

Materials Sciences Corporation

Examples:

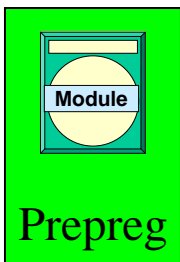
- Effect of Fiber Modulus on OHC
- Effect of Specimen Width on OHC
- Effect of Mfg Tolerances on OHC
- Effect of Tooling Material CTE on OHC
- Effect of Fiber/Matrix Interface on OHT

- Direct your efforts to the areas that matter the most
- Analytically “weed out” non-viable design concepts





Lower Lying Modules



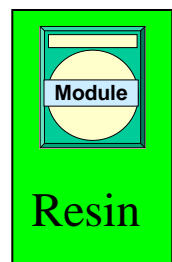
Prepreg Module

Combines constituents with controlled changes to resin properties

Basic Effort - properties, variability through historical data

Option Effort - Model resin staging

Phase II - Predict tack and drape



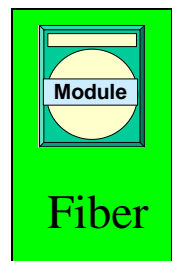
Resin Module

Resin does change during processing

Basic Effort - Properties, Models

Option Effort - Expand Models, Add Resins

Phase II - Out time, Add resin/fiber interface capability, aging?



Fiber Module

Fiber does not change during processing (excluding interface)

**Basic Effort - properties, variability through historical data,
Include placeholders for interface**

Option Effort - Expand selection of Fibers, explore interface issues

Phase II - Add interface capability



Resin Module Simple Demonstration

Ran in Isolation

Output to Text File to Excel

```

CureCycle.DAT - Notepad
File Edit Format Help
:Cure Cycle Set Up File For Testing the Resin Module
:English units version
:
: Note: the semicolon ";" in the first column identifies
:       the beginning of a comment. All other lines are data.
:
:Version
:"01/30/02kmn"
:
:The number of ramp - hold segments
:3
:
: starting degree of cure and temperature (c)
:0.010, 22.0
:
:Segment No. 1
:Ramp Rate (C/min), Target Temp (C), and Hold time (min)
:1.0, 122.0, 1.0
:
:Segment No. 2
:Ramp Rate (C/min), Target Temp (C), and Hold time (min)
:1.0, 179.5, 360.0
:
:Segment No. 3
:-2.0, 22.0, 1.0
:
:End of File
  
```

```

Resin_977_Ver-25Nov-2001.dat - Notepad
File Edit Format Help
//Defining the unique ID for the file but need to find a way to verify its
uniqueness
//For now it is omitted until we can find a way.
//ResinMatConstFileID = -maybe a path to a local file?
//file name or full path on MS windows (UNIX can use relative path)
CreatedBy = Karl Nelson, Boeing Phantom Works
ModifiedBy = Pete George, Boeing
Date = Feb 25, 2002
Version = Beta 1.1
//The above info is not used by the resin module, and will be added in the future.
// the userInputFile may be omitted by default the Request units are SI and the
DistributionLocation is 0.5 of Type Default
userInputFile = Resin_977_Ver_25Nov-2001_User_Input.txt
-----
// Density
StartProperty = ResinDensity
ModelID = Constant
ModelID = 1
DefaultValue = 1.290E+03 //mean
//The units line may be omitted by default no units are used
DefaultUnits = kg/m^3 //SI=kg/m^3 or Imperial = lb/ft^3
//The Default distribution model is the distribution to be used when a user wants
to use the distribution of the actual
// property. The other way (Local Distribution Model) is for the user to use a
distribution for each of the material constants that
// make up the material property. If no Distribution Model is given (Default
and/or Local), a Normal distribution will be used with
// a std dev of 0.0
Default Distribution Model = normal
//Std dev
Default Distribution Model Const = 0.005 // g/cm^3 same units as the
DefaultUnits if not defined
Default Distribution Model Const units = g/cm^3
//Note! you can have more than one line of validation comments
ValidationComments = values from Pete e-mail Oct 12 2001
//data section
ConstID = 1.290E+03 //NomResinDensity at DOC=1.0
//The units line may be omitted by default none units are used
  
```

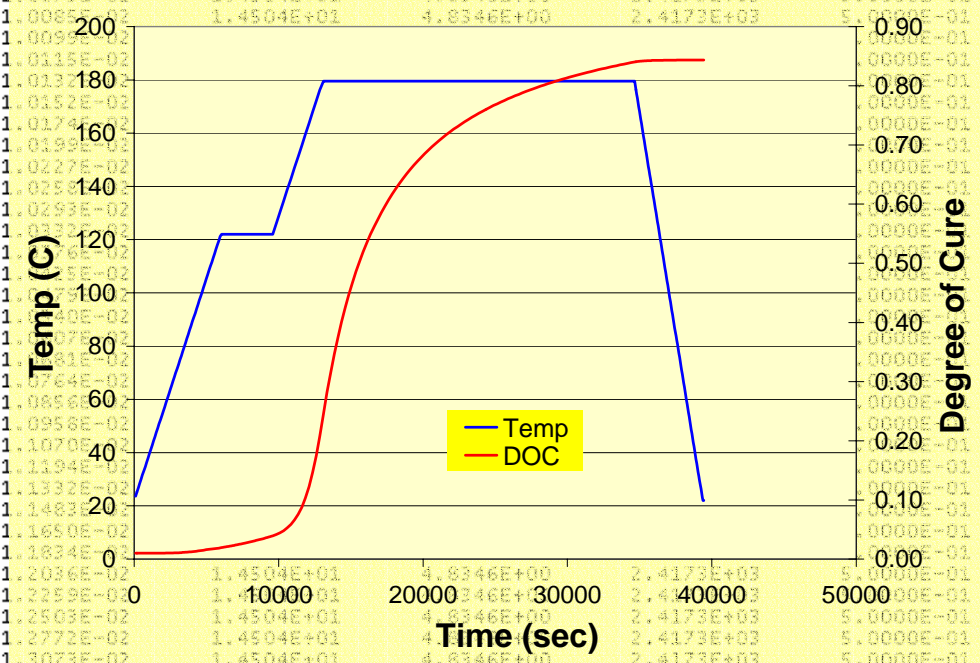
Execute Resin Module



977-3 Property Values
ResinMainVKMN by Karl M. Nelson Jan. 30, 2002
Boeing Accelerated Insertion of Materials - Composites

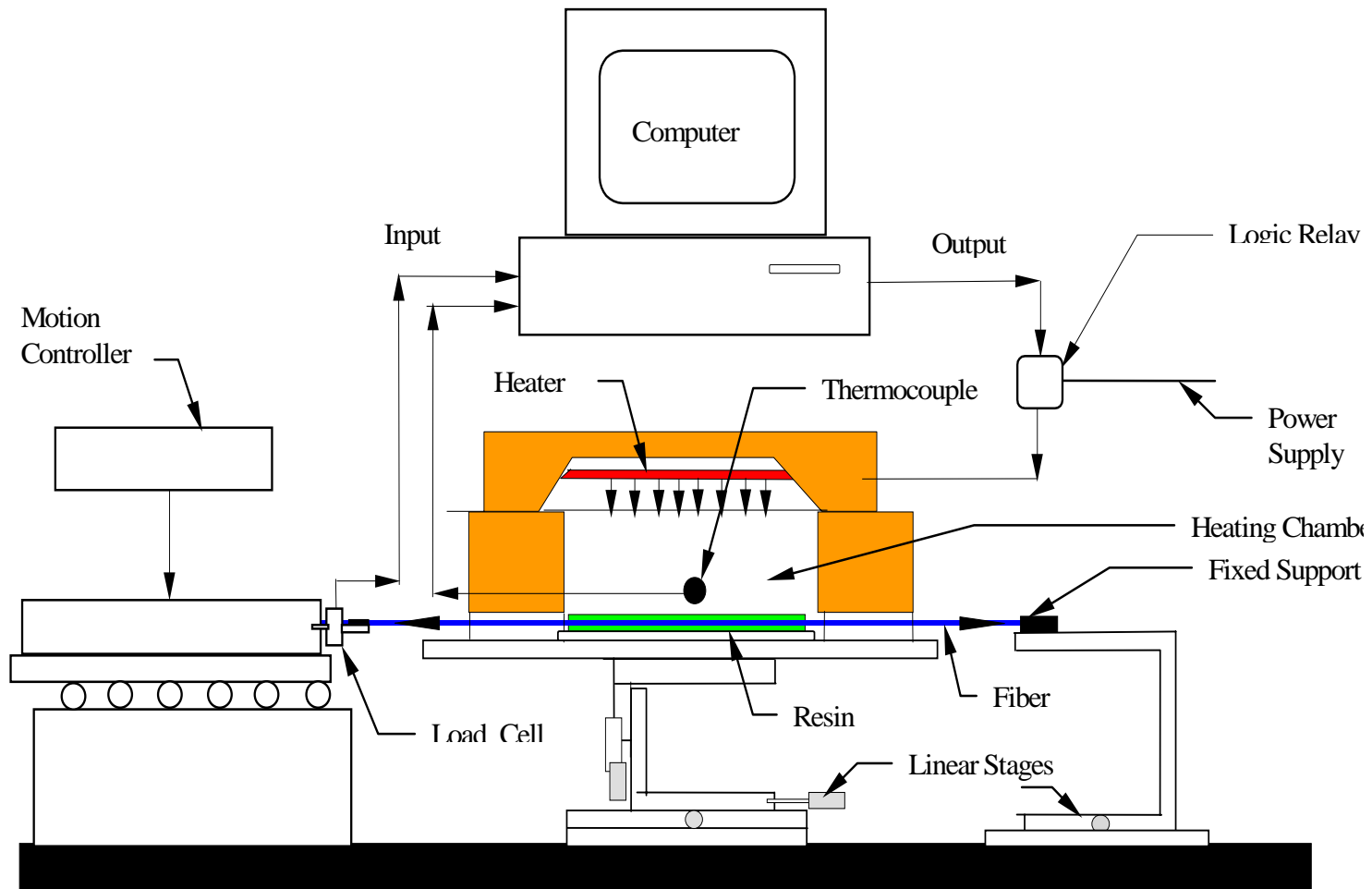
Time	Temp	DOC	E	G	BulkK	Nu	StrainToFailT	StrainToFail
9.6000E+01	2.3600E+01	1.0002E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.9200E+02	2.5200E+01	1.0005E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.8800E+02	2.6800E+01	1.0008E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
3.8400E+02	2.8400E+01	1.0011E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
4.8000E+02	3.0000E+01	1.0015E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
5.7600E+02	3.1600E+01	1.0019E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
6.7200E+02	3.3200E+01	1.0024E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
7.6800E+02	3.4800E+01	1.0030E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
8.6400E+02	3.6400E+01	1.0037E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
9.6000E+02	3.8000E+01	1.0044E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.0560E+03	3.9600E+01	1.0053E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.1520E+03	4.1200E+01	1.0062E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.2480E+03	4.2800E+01	1.0073E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.3440E+03	4.4400E+01	1.0085E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.4400E+03	4.6000E+01	1.0099E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.5360E+03	4.7600E+01	1.0115E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.6320E+03	4.9200E+01	1.0132E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.7280E+03	5.0800E+01	1.0152E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.8240E+03	5.2400E+01	1.0174E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
1.9200E+03	5.4000E+01	1.0199E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.0160E+03	5.5600E+01	1.0227E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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2.3040E+03	6.0400E+01	1.0332E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.4000E+03	6.2000E+01	1.0375E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.4960E+03	6.3600E+01	1.0422E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.5920E+03	6.5200E+01	1.0473E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.6880E+03	6.6800E+01	1.0528E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.7840E+03	6.8400E+01	1.0587E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.8800E+03	7.0000E+01	1.0650E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
2.9760E+03	7.1600E+01	1.0717E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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3.1680E+03	7.4800E+01	1.0863E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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3.3600E+03	7.8000E+01	1.1194E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
3.4560E+03	7.9600E+01	1.1332E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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3.6480E+03	8.2800E+01	1.1650E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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3.8400E+03	8.6000E+01	1.2036E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
3.9360E+03	8.7600E+01	1.2259E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
4.0320E+03	8.9200E+01	1.2503E-02	1.4504E+01	4.8346E+00	2.4173E+03	5.0000E-01	2.6600E-02	2.6600E-02
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Resin Module Output

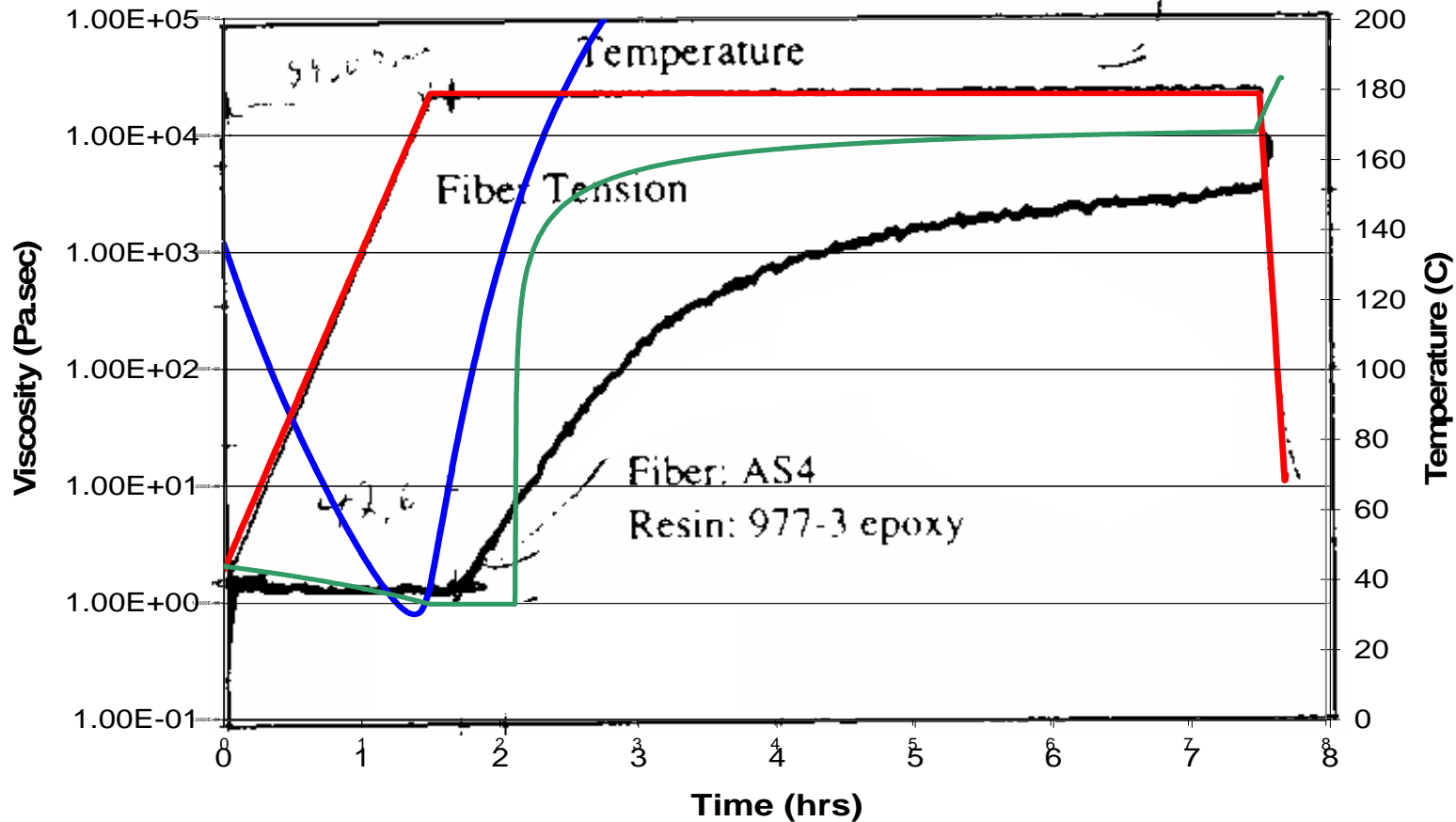


Schematic of CIST Apparatus

cure-induced stress test



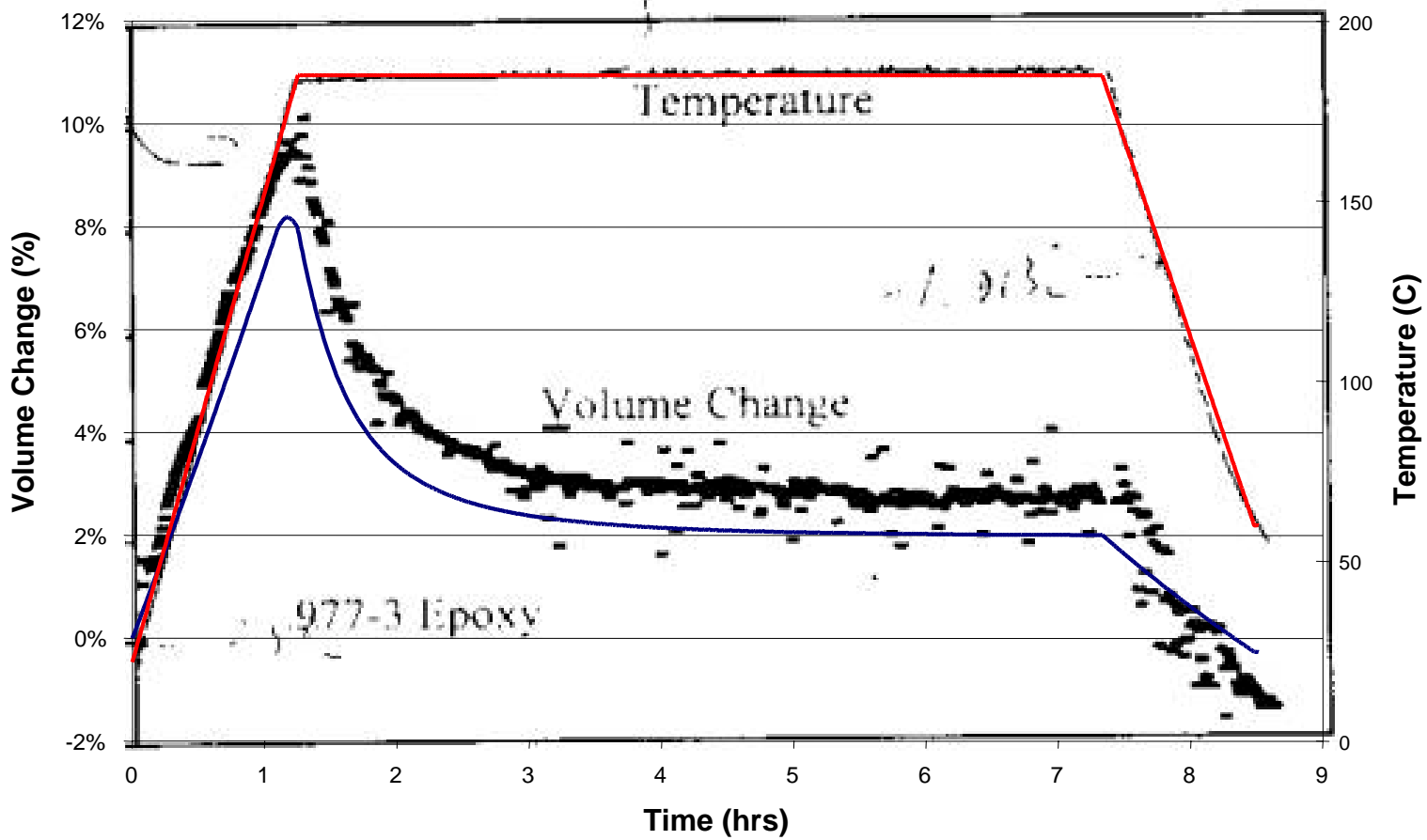
Gel Point is Consistent Although Magnitude Needs Study



Data From Genidy, Madhukar, and Russell, Journal of Composite Materials, Vol. 34, No. 22/2000



Cure Shrinkage Effect is Consistent with Published Work



Data From Genidy, Madhukar, and Russell, Journal of Composite Materials, Vol. 34, No. 22/2000





AIM-C

Linking Processing to Structures

Effects of Processing Variables
on Laminate Performance

Demonstration of Problem Solving

- Approach
 - Experimental Design
 - Input Variable Description
 - Output Variable Description
- CAT Architecture and Interface
- Results
 - Processing Module
 - Stress Free Temperature
 - Structures Module





Approach – Output or Response Variables

- Processing
 - Maximum Temperature in Laminate
 - Maximum Air to Part Delta (Exotherm)
 - Maximum Internal Part Gradient
- Structures (Laminate)
 - Stress-Free Temperature
- Structures (SIFT)
 - Load to First Crack

Experimental Design

Materials: IM7/977-3 and IM7/8552

Input/Design Variables:

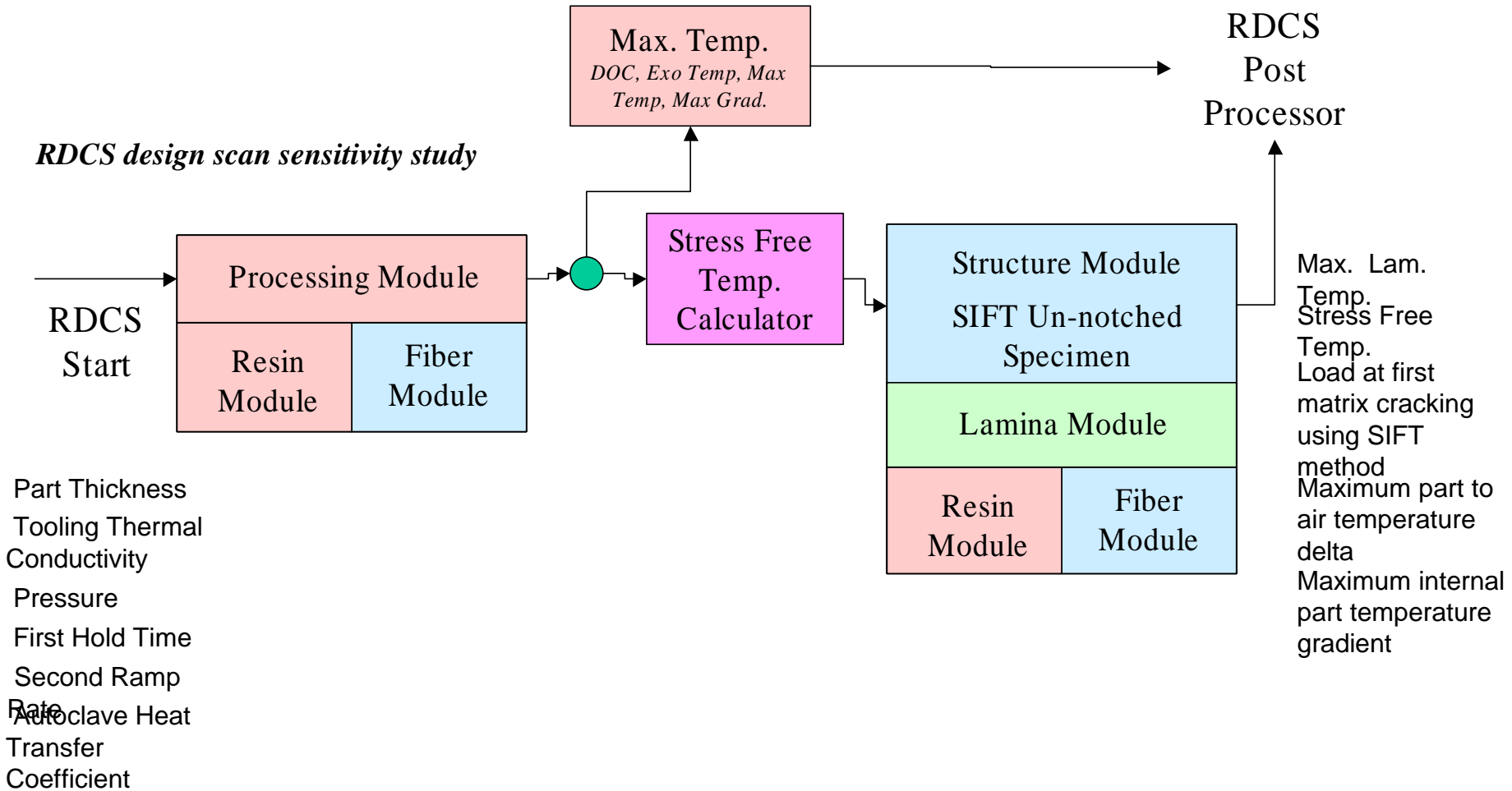
	Input Variable Description/Name	Level 1 (Min)	Level 2 (Nom.)	Level 3 (Max.)
A	Part Thickness	0.08	0.39	0.7
B	Tooling Material	Composite	Invar 42	Alum.
C	Pressure	15	82.5	150
D	First Hold Time	1	60	120
E	Second Ramp Rate	1	5.5	10
F	Autoclave Heat Transfer Coefficient	5	12.5	20

	Variable Name
1	Maximum Laminate Temperature during Cure
2	Maximum Air to Part Delta during Cure
3	Maximum Laminate Gradient during Cure
4	Approx. Stress Free Temperature resulting from Cure
5	Load at first matrix cracking using SIFT method

Output/Response Variables:

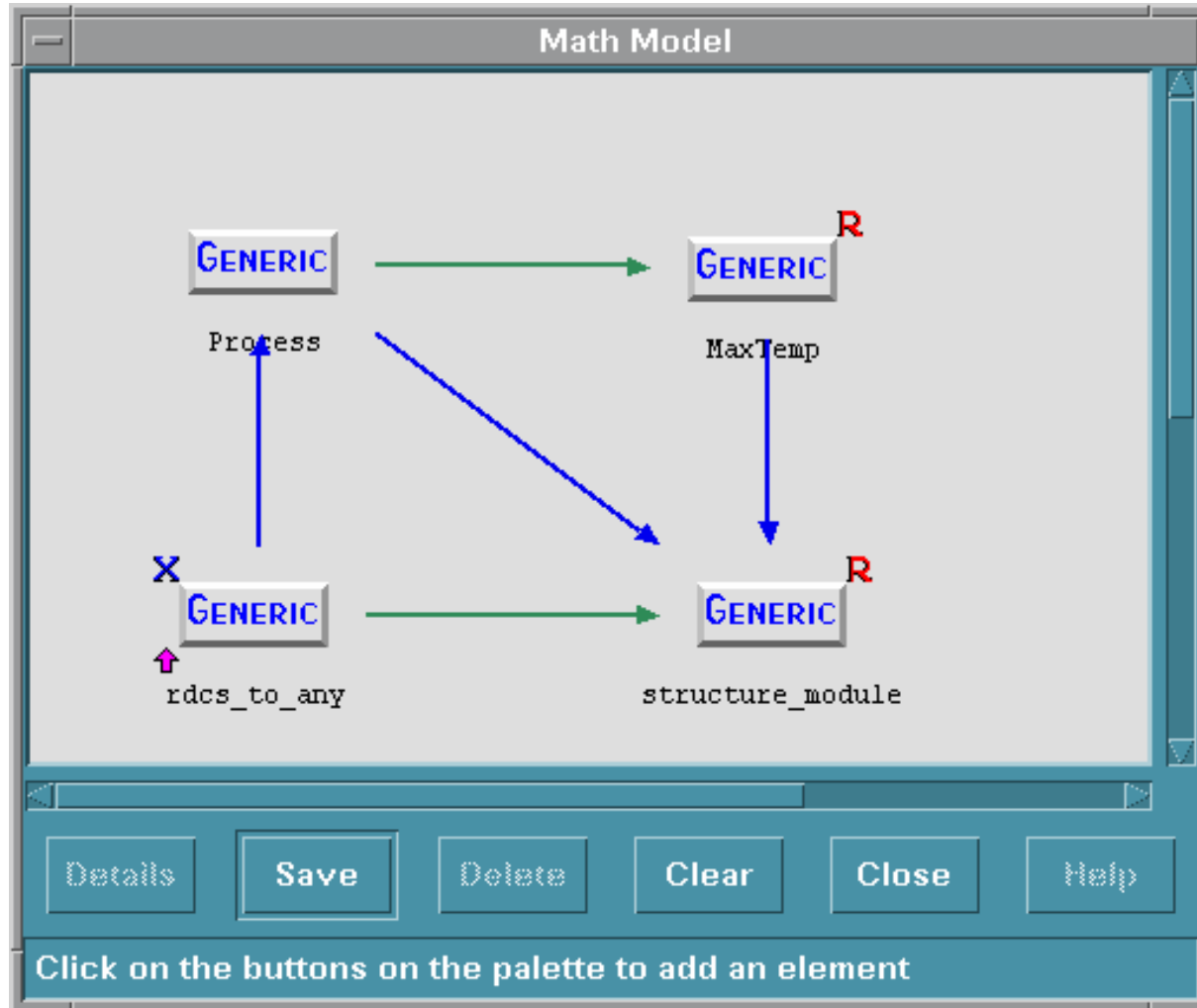
The “design scan” (one-factor at a time) with six input parameters, required only $2*6+1 = 13$ runs per material. It is performed at 3 levels – a maximum, a minimum and a center point) so that non-linearities can be assessed.

System Architecture





RDCS Math Model

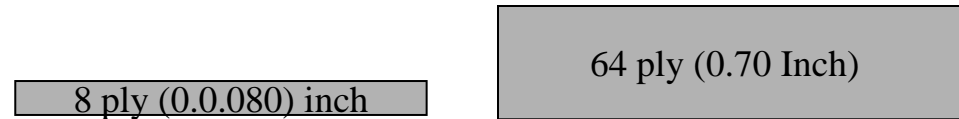


Approach – Input/Design Variables

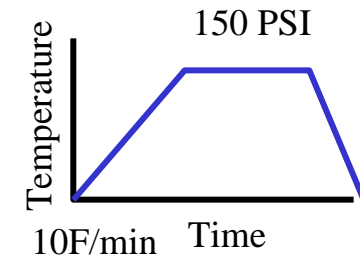
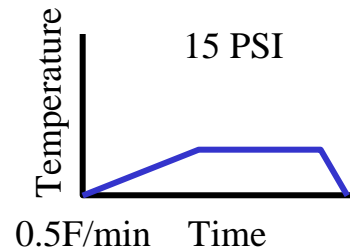
•Tooling Thermal Conductivity



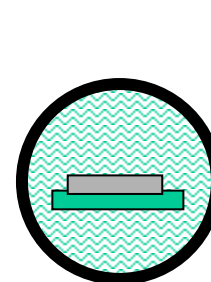
•Part Configuration – Thickness



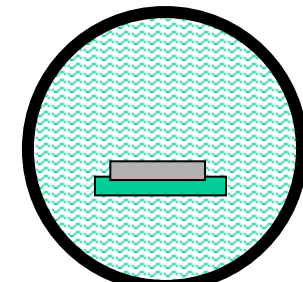
•Processing – Pressure, Temperature



•Autoclave - Heat Transfer Coefficient



5 W/sq. m-K



20 W/sq. m-K

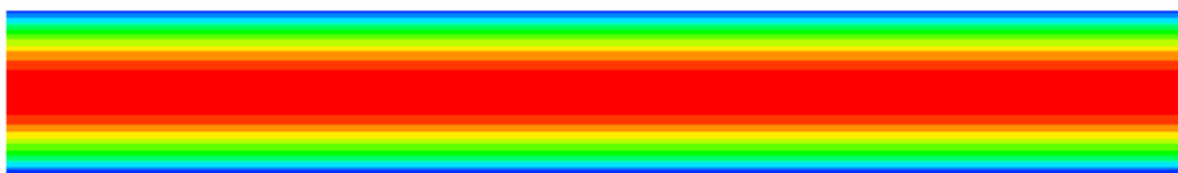
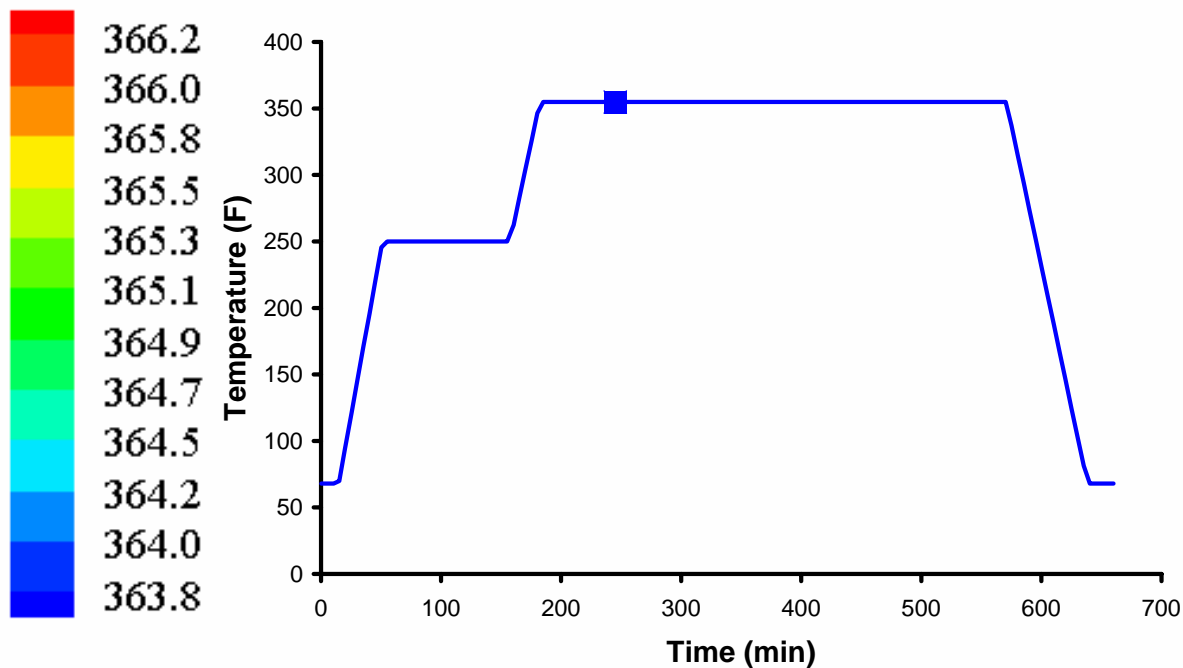


Processing Module

Part Temperature at Max. Exotherm (977-3)

In Depth Analysis Using Processing Module

All Variables Nominal except Part thickness – High (0.7")



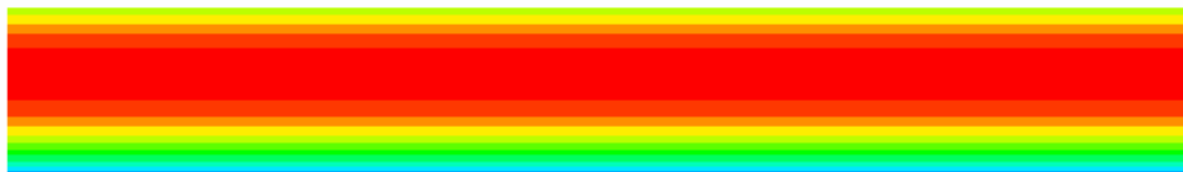
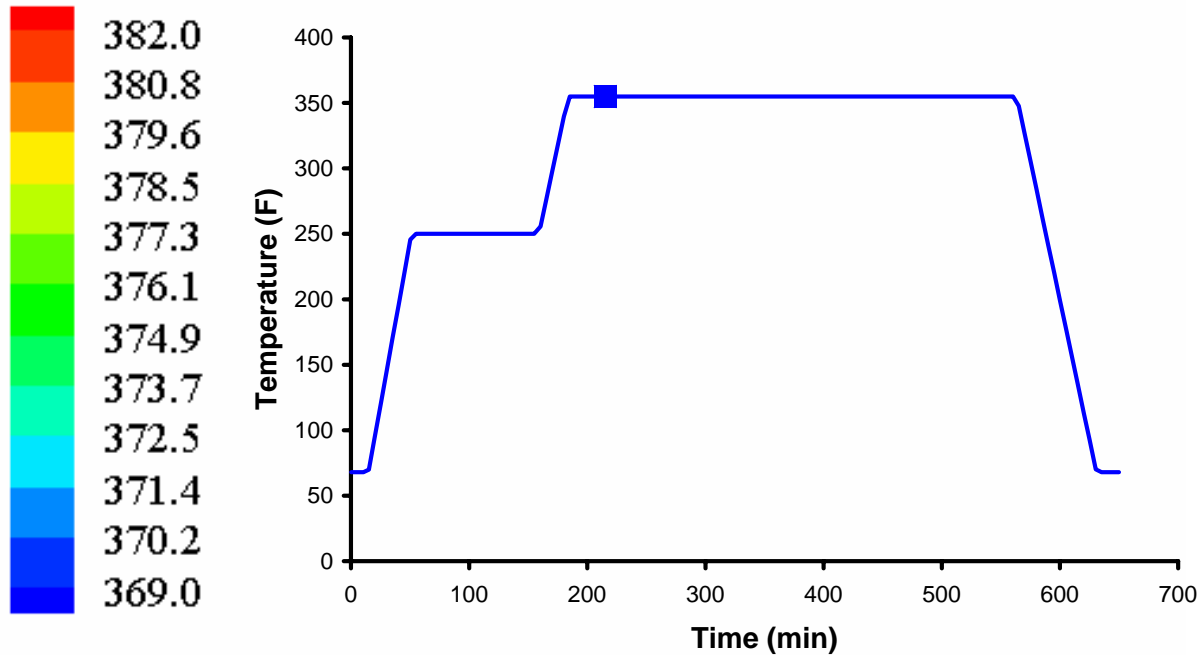


Processing Module

Part Temperature at Max. Exotherm (8552)

In Depth Analysis Using Processing Module

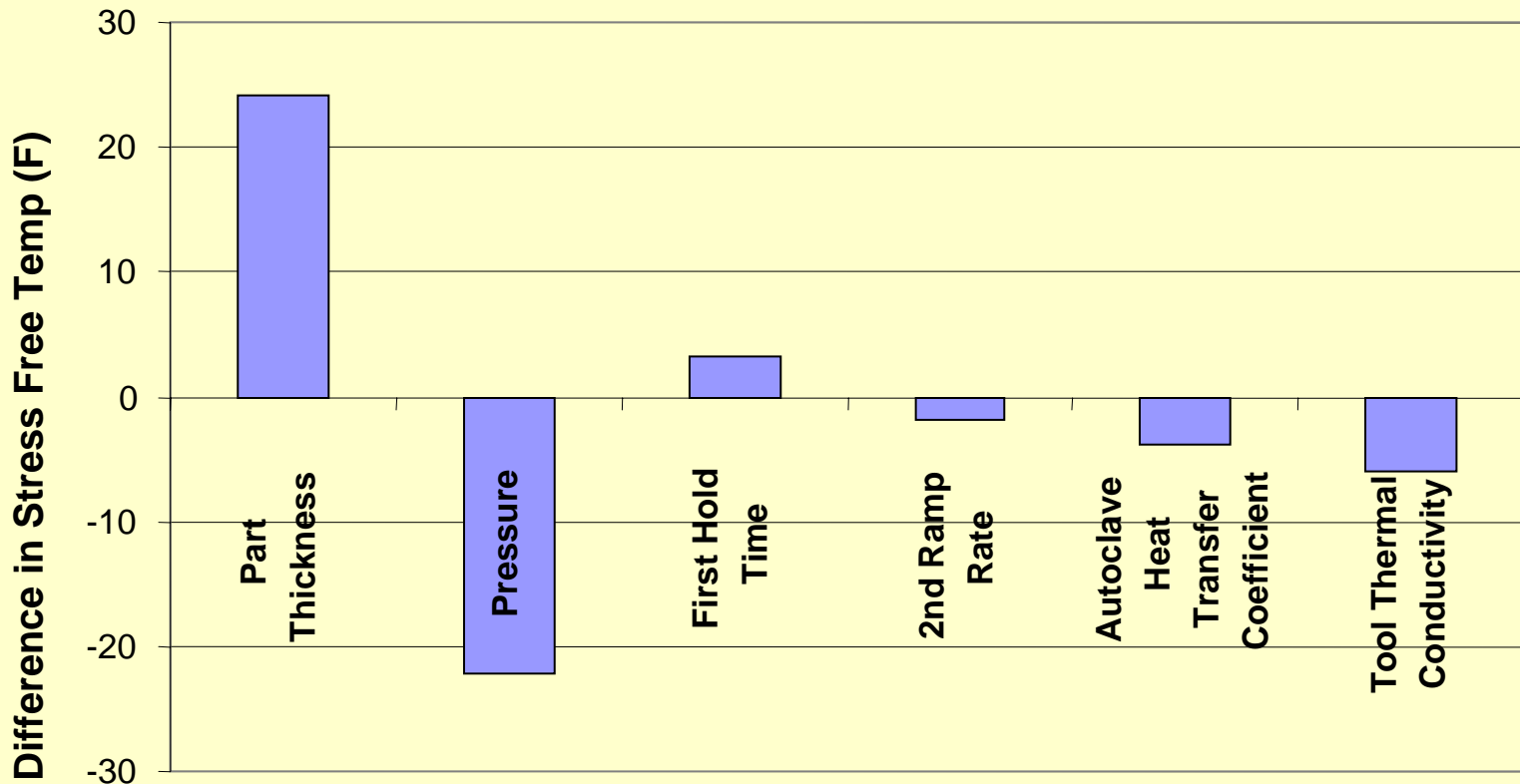
All Variables Nominal except Part thickness – High (0.7")





Results – Importance of Main Variables

Stress Free Temperature Sensitivity Results



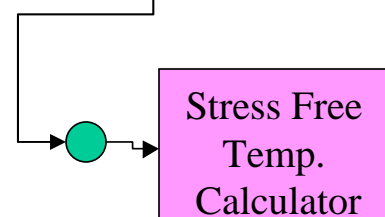
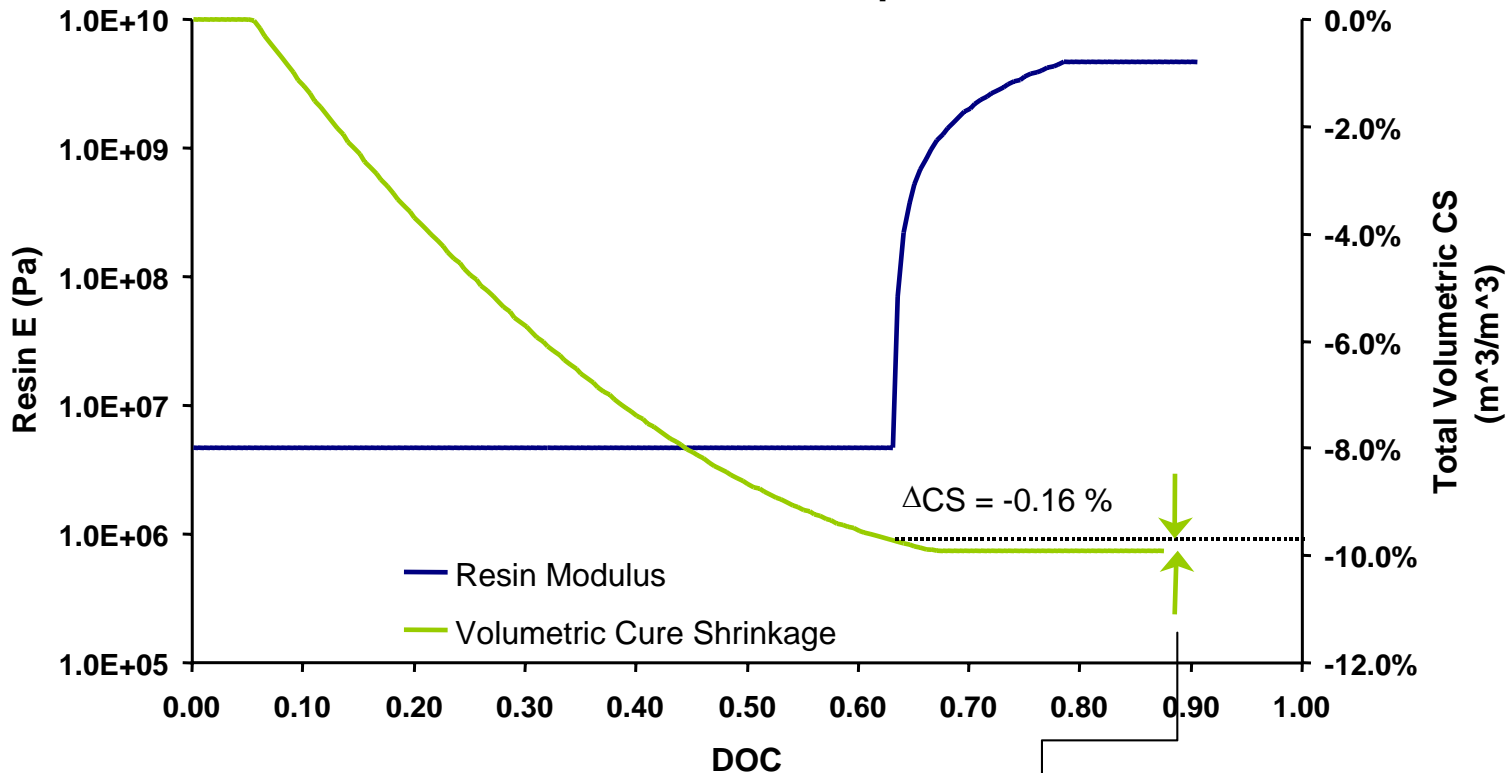
- **Part Thickness and Pressure are the most important drivers**
 - High Pressure and thin parts are better
- **Tool Material and Autoclave Heat Transfer Coefficient have a moderate effect**
 - Higher is better for both parameters
- **Hold Time and Ramp Rate have little effect**



AIM Analysis Results

Stress Free Temperature

Resin Modulus and & Cure Shrinkage for 8552 (1995)
180 C Cure Temperature

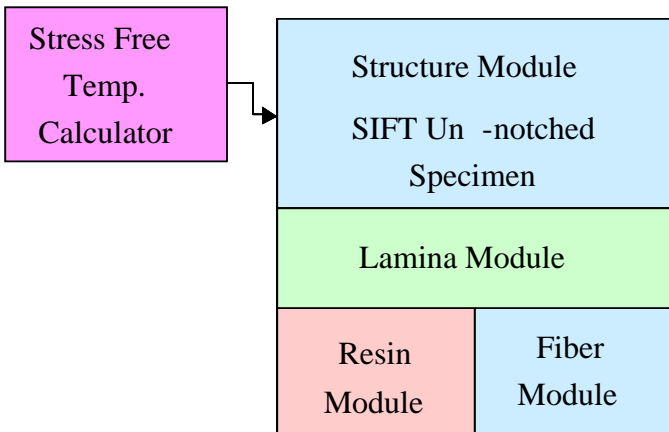
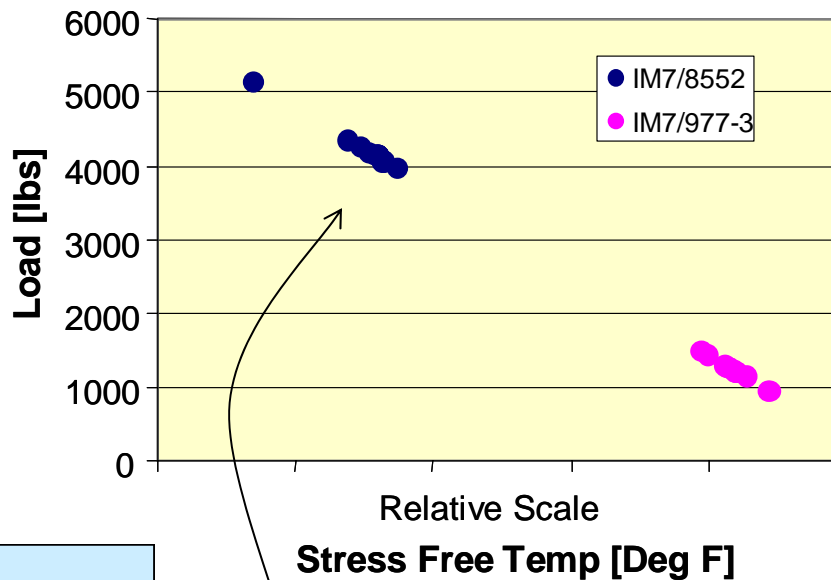




Critical Load Versus Stress Free Temp.



Critical Load Vs. Stress Free Temp.

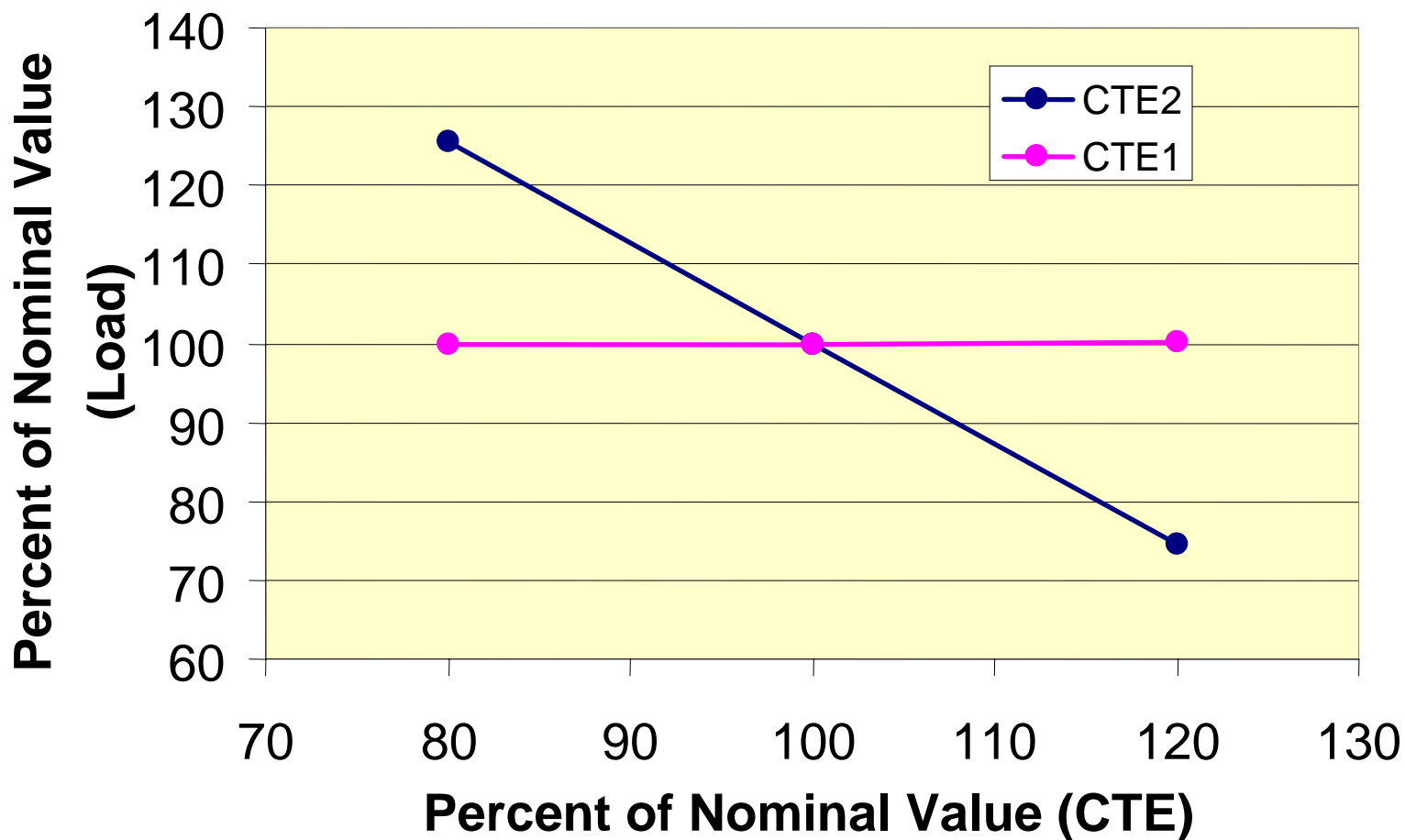


We Have to Get This Right!!!



Thermal Expansion Effect

Side Study on Sensitivity due to CTE



We Have to Get This Right!!!

Summary

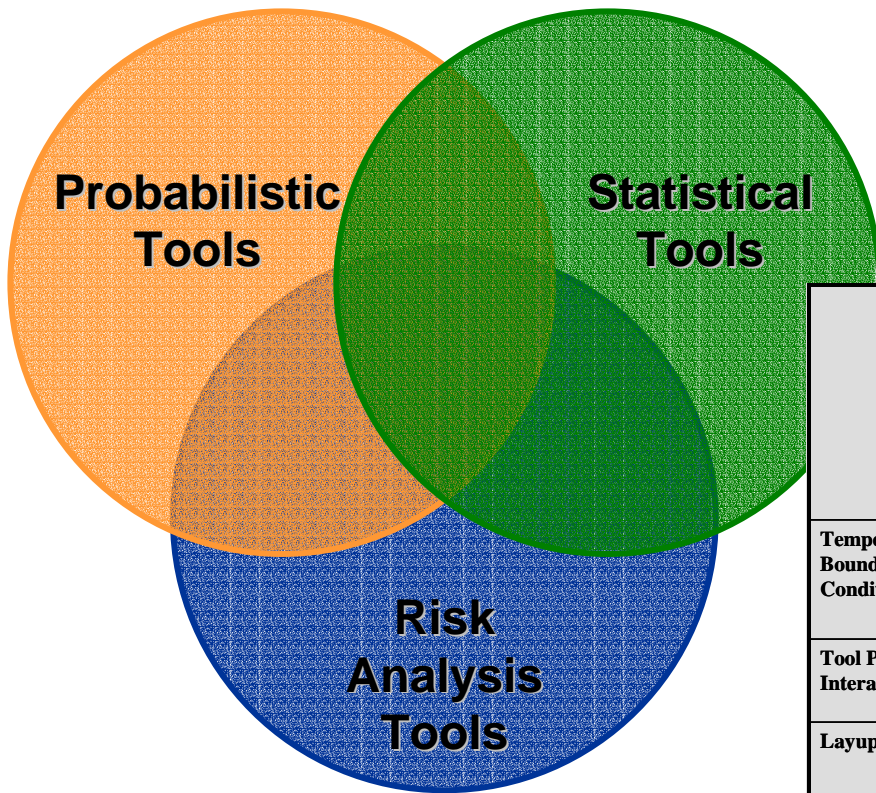
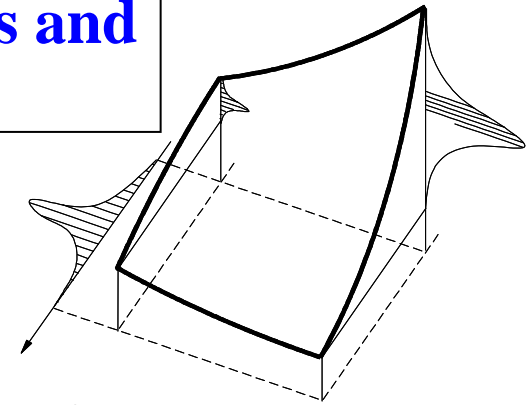
- Processing Module is Ready to be Used
 - Rich History of Commercial and Military Studies
 - Strong at Solving 2D Heat Transfer Problem
 - Good at Solving Residual Deformation Problem
- Structures Module -- *Useful Functionality*
 - Predict Simple Coupon-Level Properties
 - Solve Sub-Component Problem?
- Combined Effects of Processing and Structure
 - Residual Stresses from Process Passed Directly to Structures Analysis.
 - Understand the relationship between processing and structural performance.



Backup Charts



Understanding Uncertainty – The Benefit of Linked Simulation Tools and Methodology



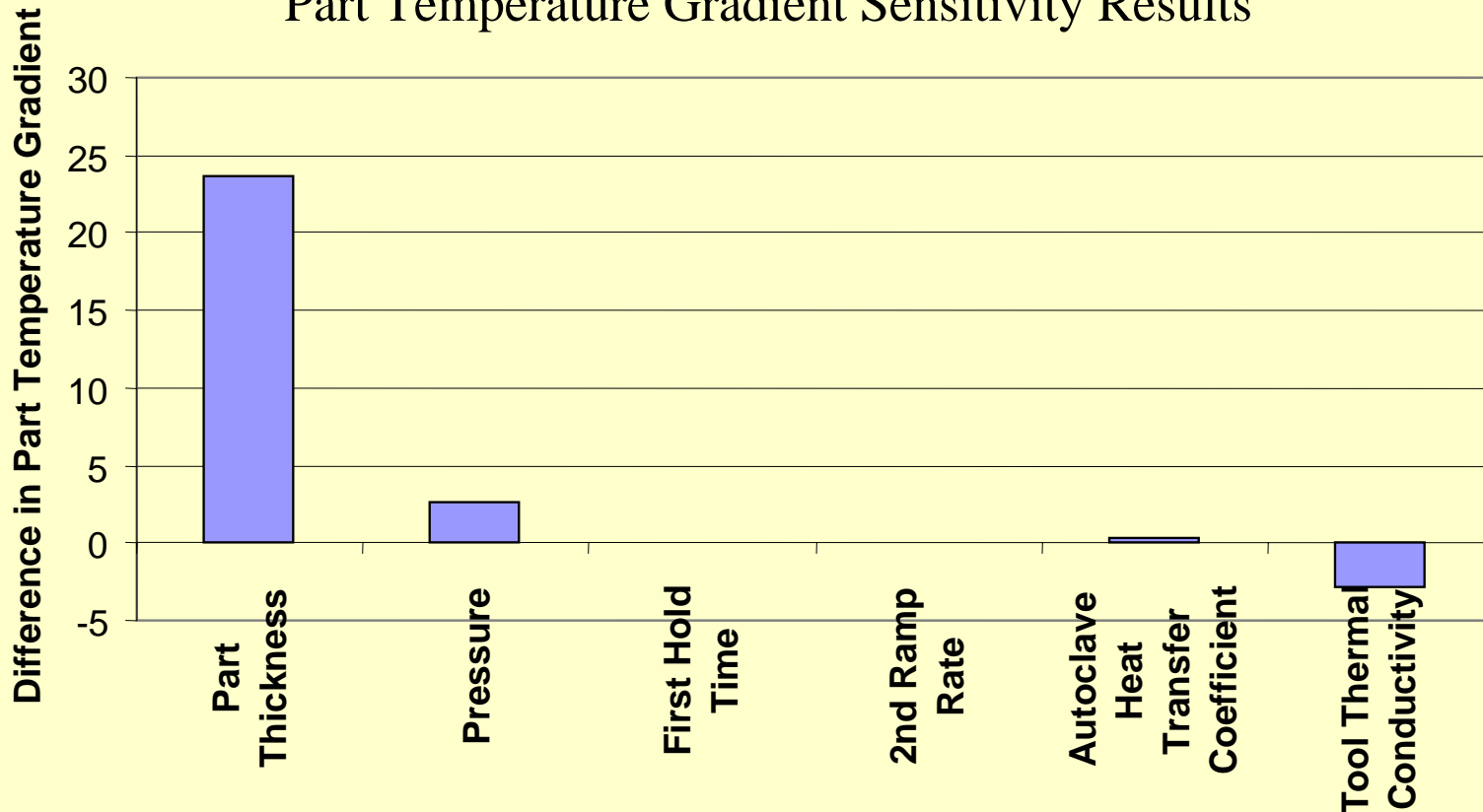
Modeling of the Process

	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.



Results – Importance of Main Variables

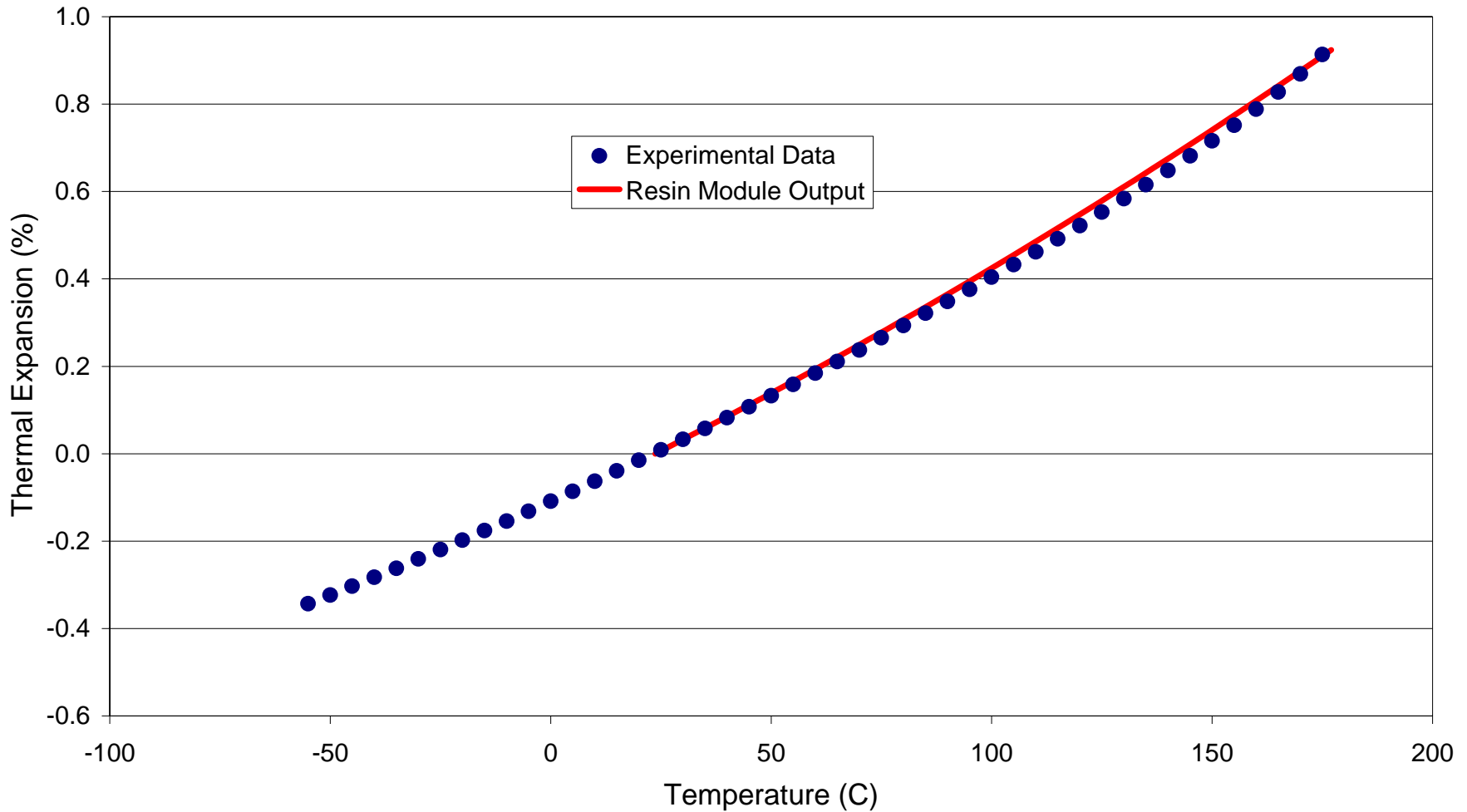
Part Temperature Gradient Sensitivity Results

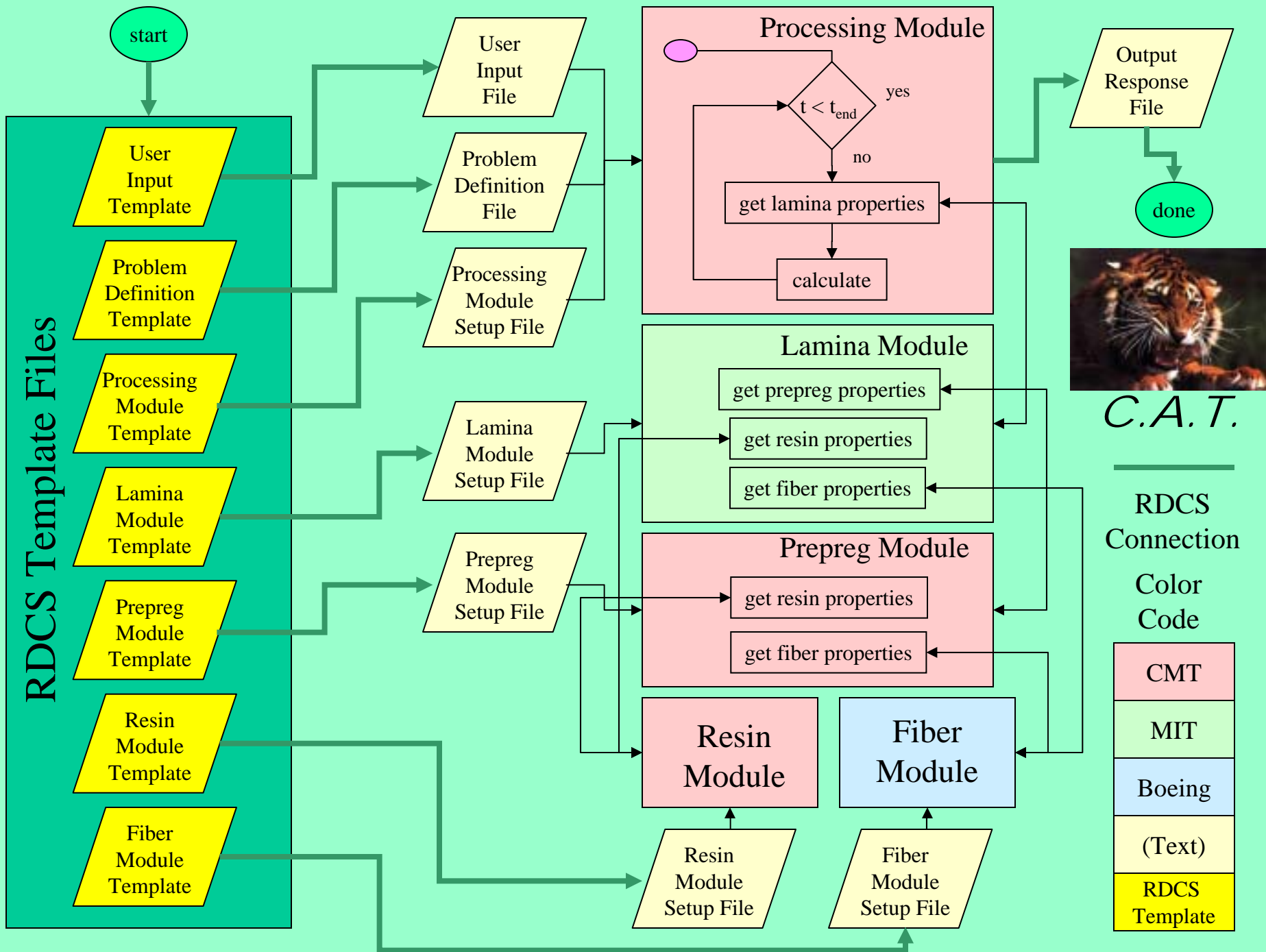


- Part Thickness, Pressure, and Tool Conductivity are the most important drivers
 - Thin parts, High tool conductivity, and lower Pressure are better
- Other variables have little effect



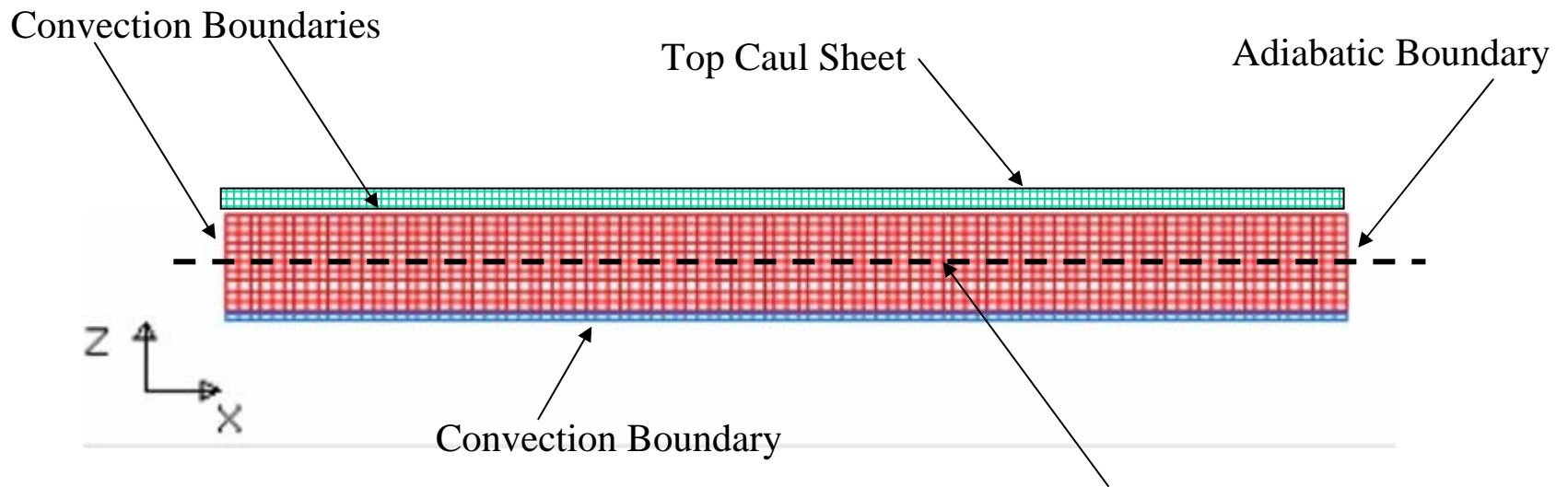
Resin Module Captures Resin CTE Behavior Dependant on Temperature and Degree of Cure





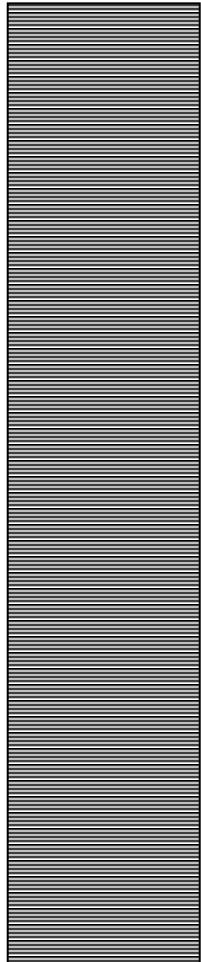
AIM Processing Module (COMPRO)

5" thick part on 0.5" thick Invar tool



- Look at part temperature with respect to time and position along center line

977-3 5" thick



5.0 inch

