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

This program was developed under the guidance of Dr. Steve Wax and Dr. Leo Christodoulou of DARPA. It is under the technical direction of Dr. Ray Meilunas of NAVAIR.

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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

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

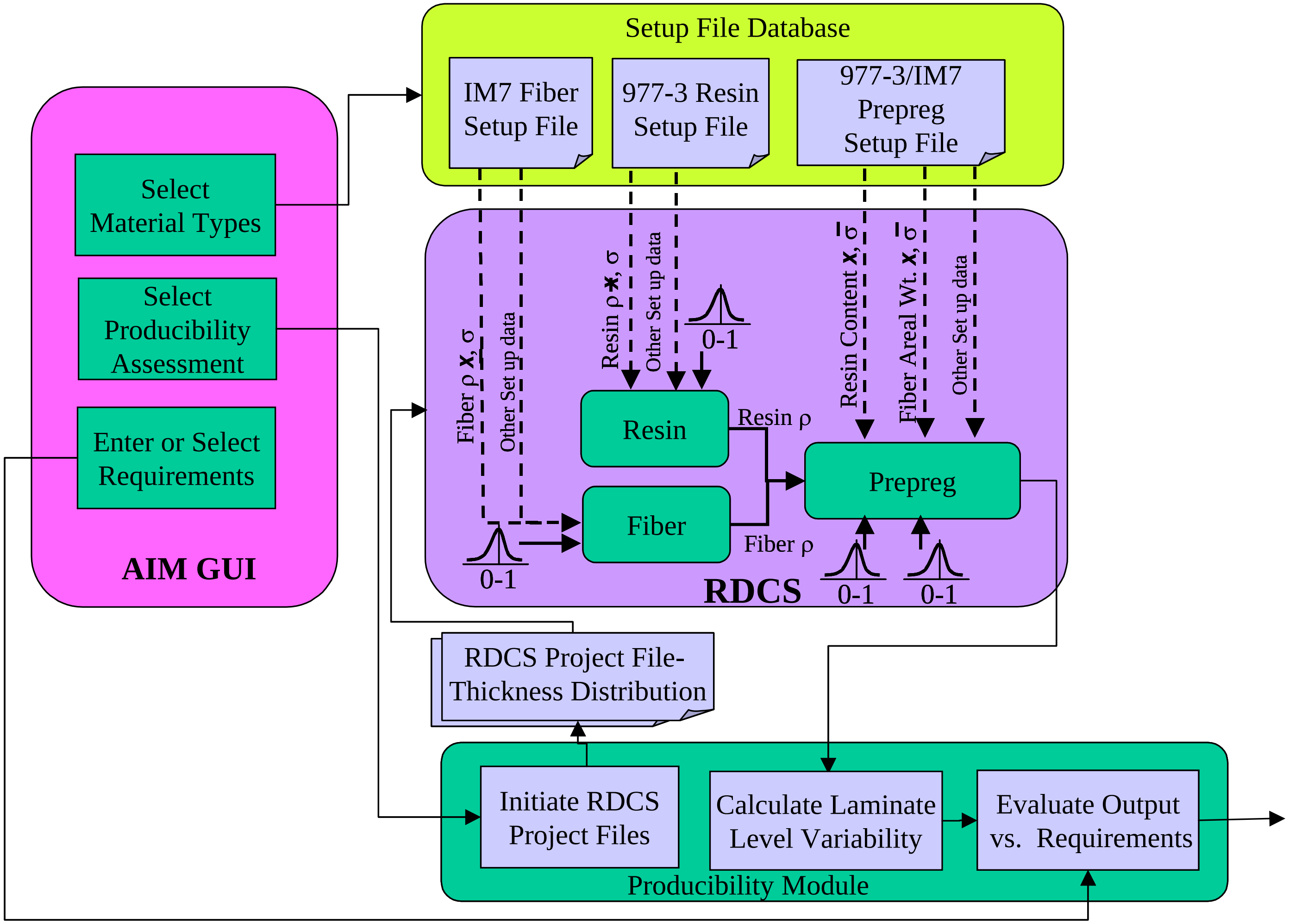
AIM-C Will Accomplish This Three Ways

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



Setup File Database

IM7 Fiber Setup File

977-3 Resin Setup File

977-3/IM7 Prepreg Setup File

AIM GUI

Select Material Types

Select Producibility Assessment

Enter or Select Requirements

RDCS

Fiber ρ $\bar{x}$, σ

Other Set up data

Resin ρ $\bar{x}$, σ

Other Set up data

Resin Content $\bar{x}$, σ

Fiber Areal Wt. $\bar{x}$, σ

Other Set up data

0-1

Resin

Fiber

Resin ρ

Fiber ρ

Prepreg

0-1

0-1

0-1

RDCS Project File-Thickness Distribution

Producibility Module

Initiate RDCS Project Files

Calculate Laminate Level Variability

Evaluate Output vs. Requirements

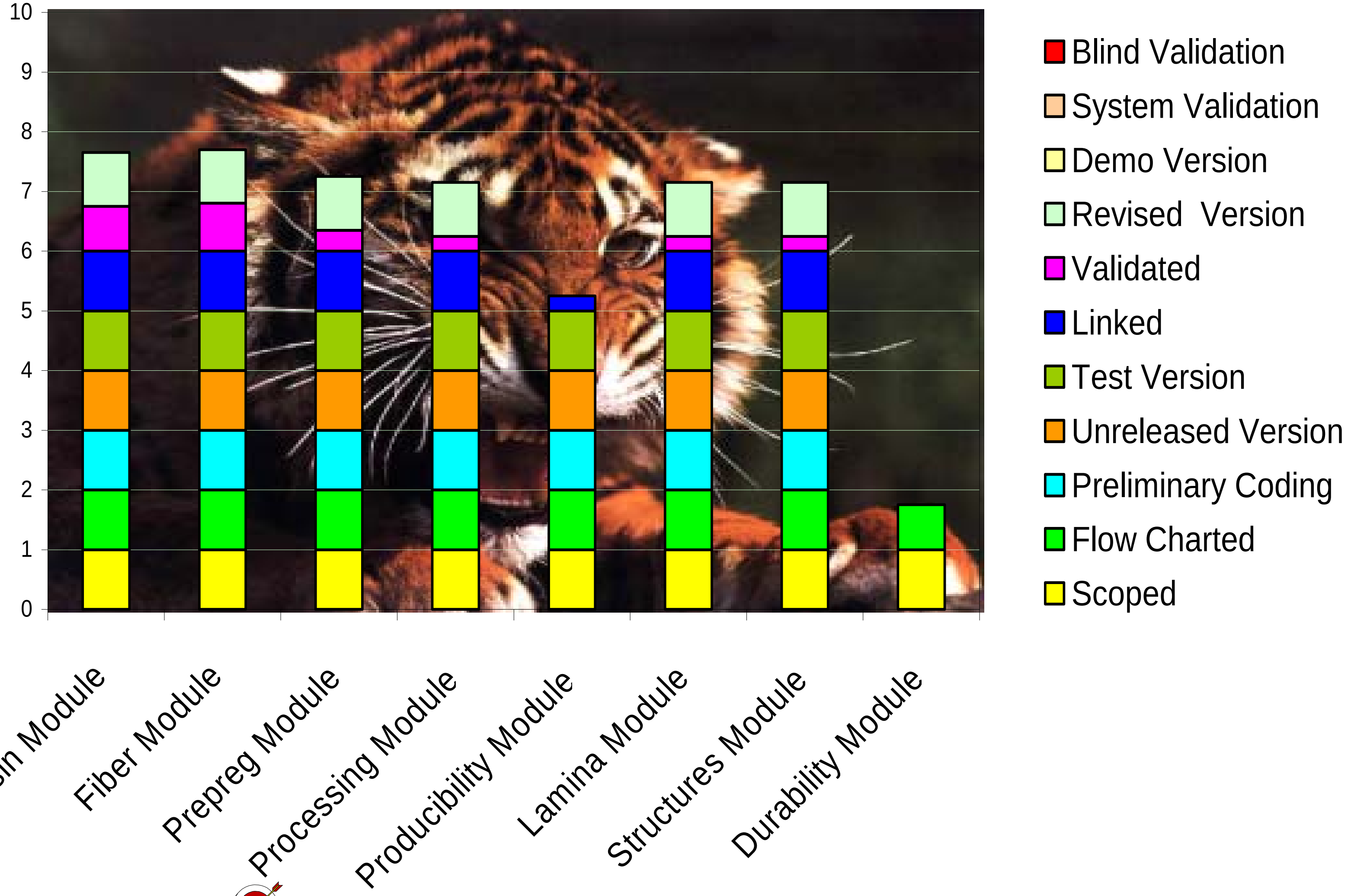
Technical Components

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.

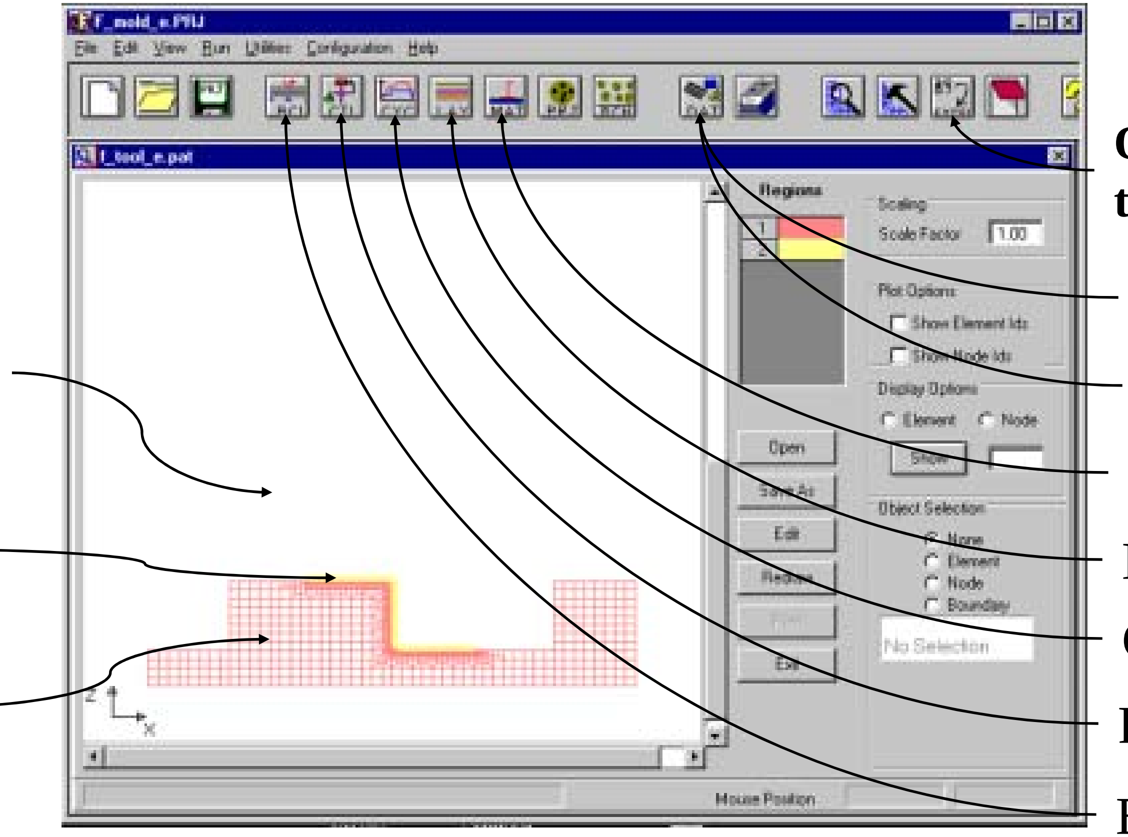
- Qualification/Re-qualification of Materials

Processing Module

CMT's COMPRO

Processing Module

2D FEM



Autoclave Model

Part Model

Tool Model

Output formatted for text, Excel or Tecplot

Resin Models

Fiber Properties

Choice of Material

Layup Definition

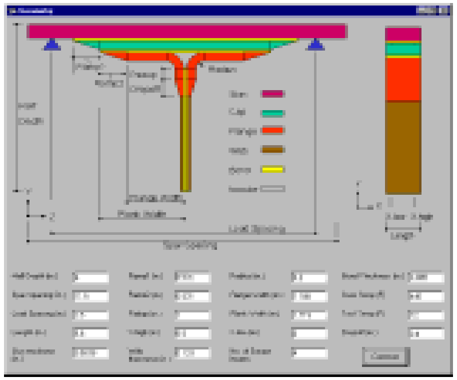
Cure Cycle

Program Controls

Boundary Conditions

AIM-C Structural Property Prediction
Basic Effort Goals

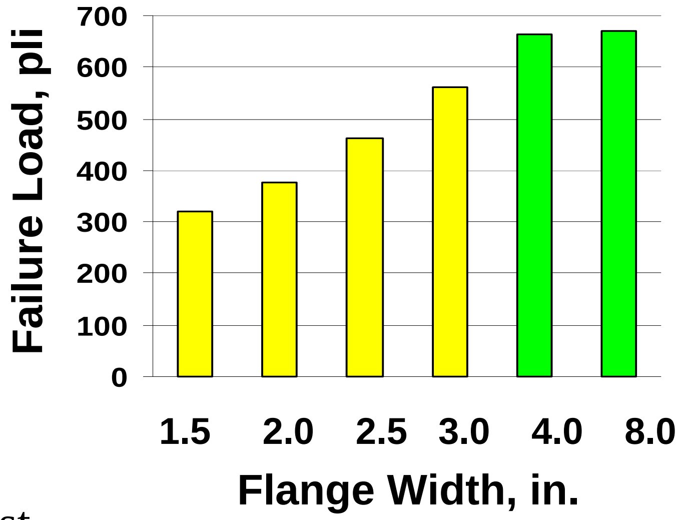
Capture the Effect of Changes in Material, Design, Manufacturing/Processing, and Testing Variables On Typical Failure Values



Two Methods for Structural Property Prediciton
The Strain Invariant Failure Theory (SIFT)
The Boeing Company

Mechanistic Approaches
Materials Sciences Corporation

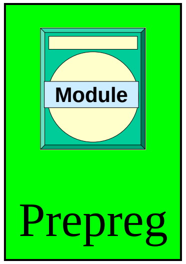
Examples:
Effect of Fiber Modulus on OHC
Effect of Specimen Width on OHC
Effect of Mfg Tolerances on OHC
Effect of Tooling Material CTE on OHC
Effect of Fiber/Matrix Interface on OHT



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

Module
Structure Module

Lower Lying Modules



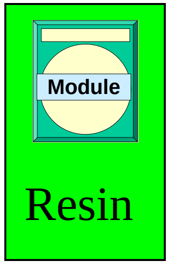
<u>Prepreg Module</u>

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



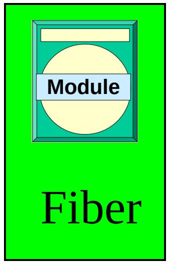
<u>Resin Module</u>

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?



<u>Fiber Module</u>

Fiber does not change during processing (excluding interface)

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

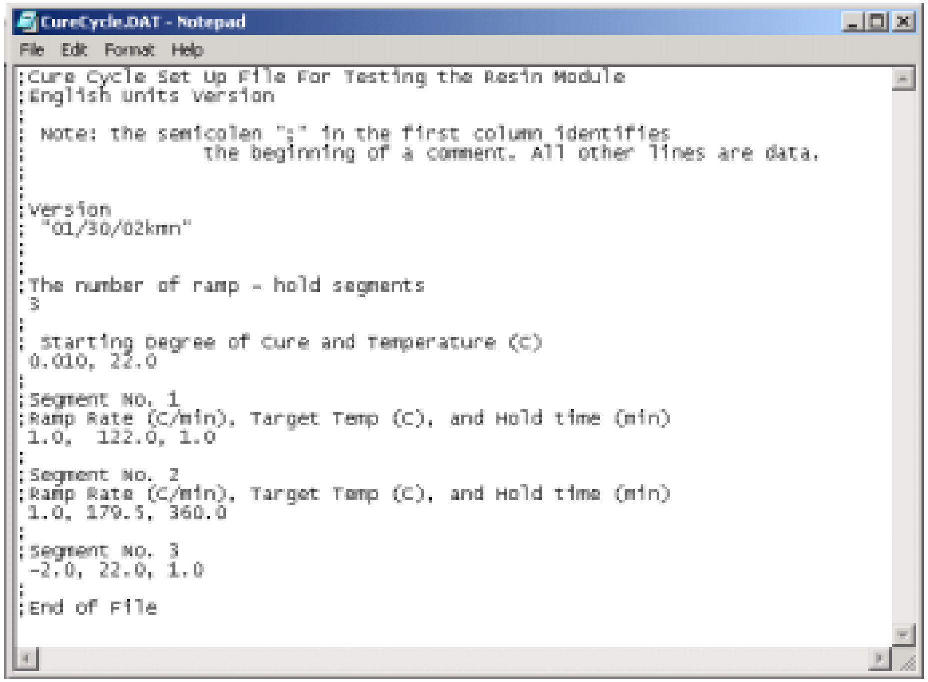
Option Effort - Expand selection of Fibers, explore interface issues

Phase II - Add interface capability

Resin Module Simple Demonstration

Ran in Isolation

Output to Text File to Excel

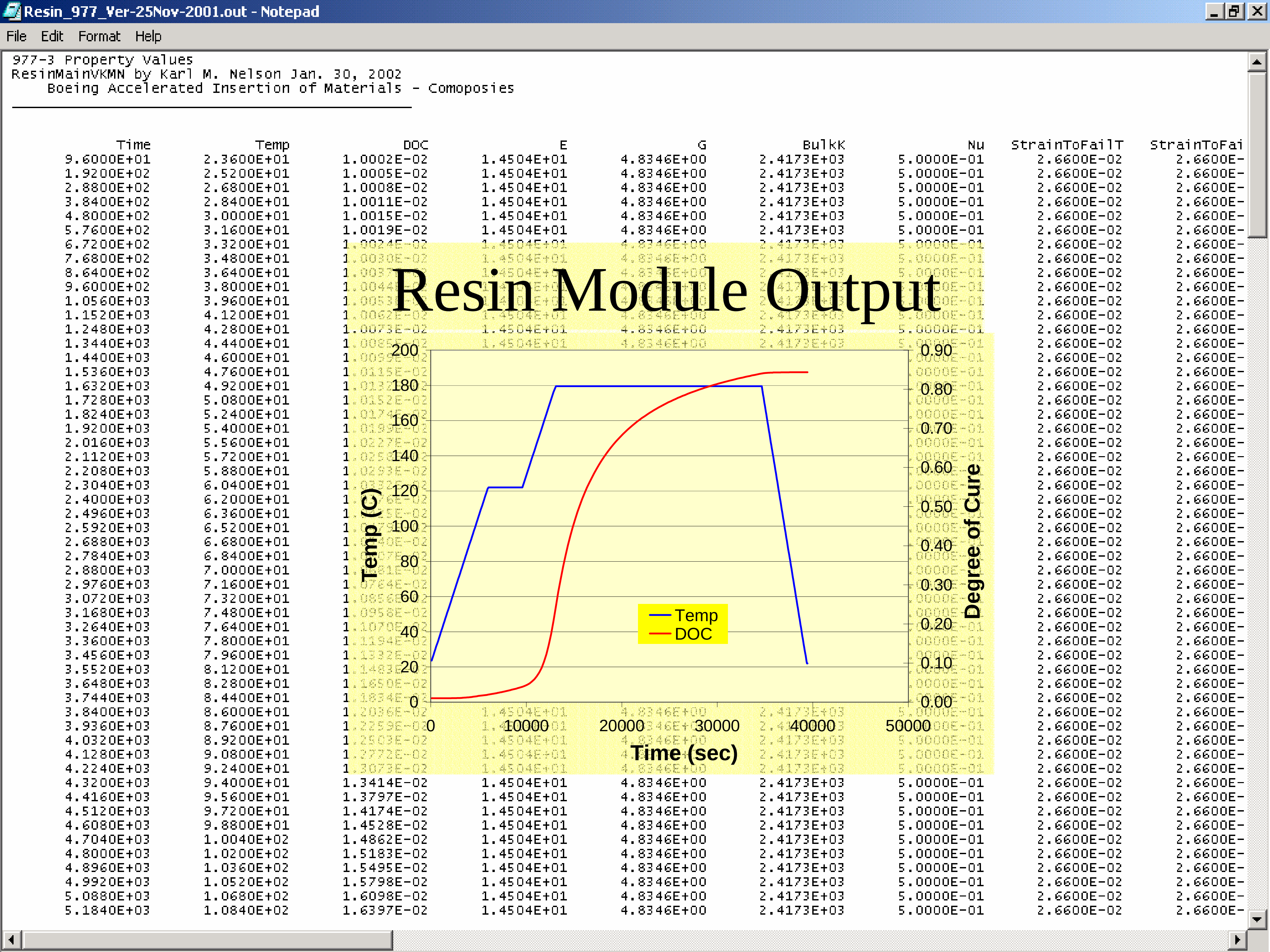


```
;Cure Cycle Set Up File For Testing the Resin Module
;English units Version
;
; Note: the semicolen ";" in the first column identifies
;              the beginning of a comment. All other lines are data.
;
;
;Version
; "01/30/02kmn"
;
;
;The number of ramp - hold segments
 3
;
; Starting Degree of 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
```

```
//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 1.5
//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
ModelDim = 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 Noraml 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 then one line of validation comments
ValidationComments = Values from Pete e-mail Oct 12 2001


//Data section
Const1D = 1.290E+03     //NomResinDensity at DOC=1.0
//The units line may be omitted by default none units are used
```

Execute Resin Module

Resin Module Output



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


              Time              Temp               DOC                 E                 G             BulkK                Nu     StrainToFailT       StrainToFai
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
        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-
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        2.1120E+03        5.7200E+01        1.0258E-02        1.4504E+01        4.8346E+00        2.4173E+03        5.0000E-01        2.6600E-02        2.6600E-
        2.2080E+03        5.8800E+01        1.0293E-02        1.4504E+01        4.8346E+00        2.4173E+03        5.0000E-01        2.6600E-02        2.6600E-
        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-
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        2.6880E+03        6.6800E+01        1.0540E-02        1.4504E+01        4.8346E+00        2.4173E+03        5.0000E-01        2.6600E-02        2.6600E-
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        4.8000E+03        1.0200E+02        1.5183E-02        1.4504E+01        4.8346E+00        2.4173E+03        5.0000E-01        2.6600E-02        2.6600E-
        4.8960E+03        1.0360E+02        1.5495E-02        1.4504E+01        4.8346E+00        2.4173E+03        5.0000E-01        2.6600E-02        2.6600E-
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```
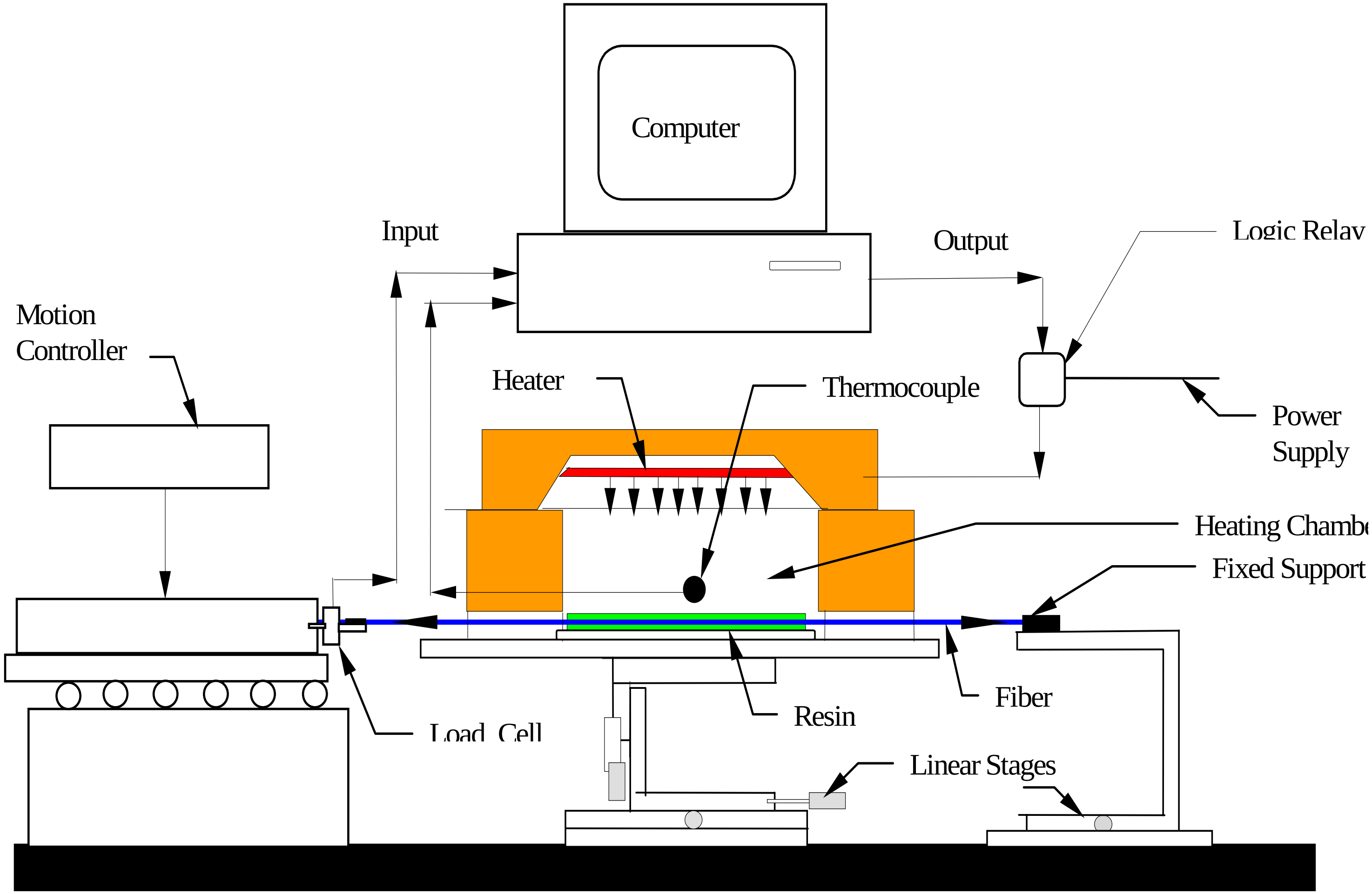
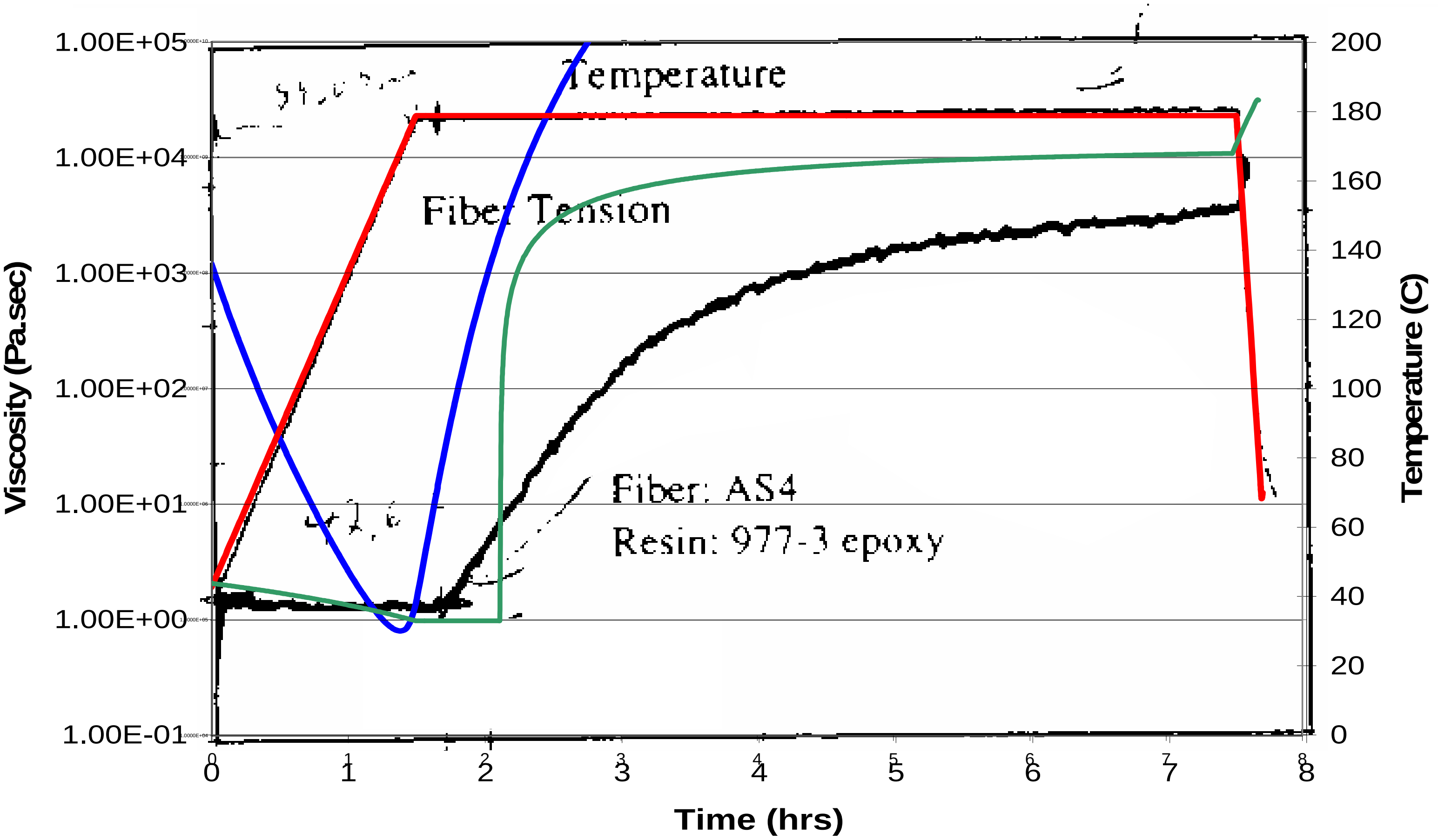

Schematic of CIST Apparatus

cure-induced stress test

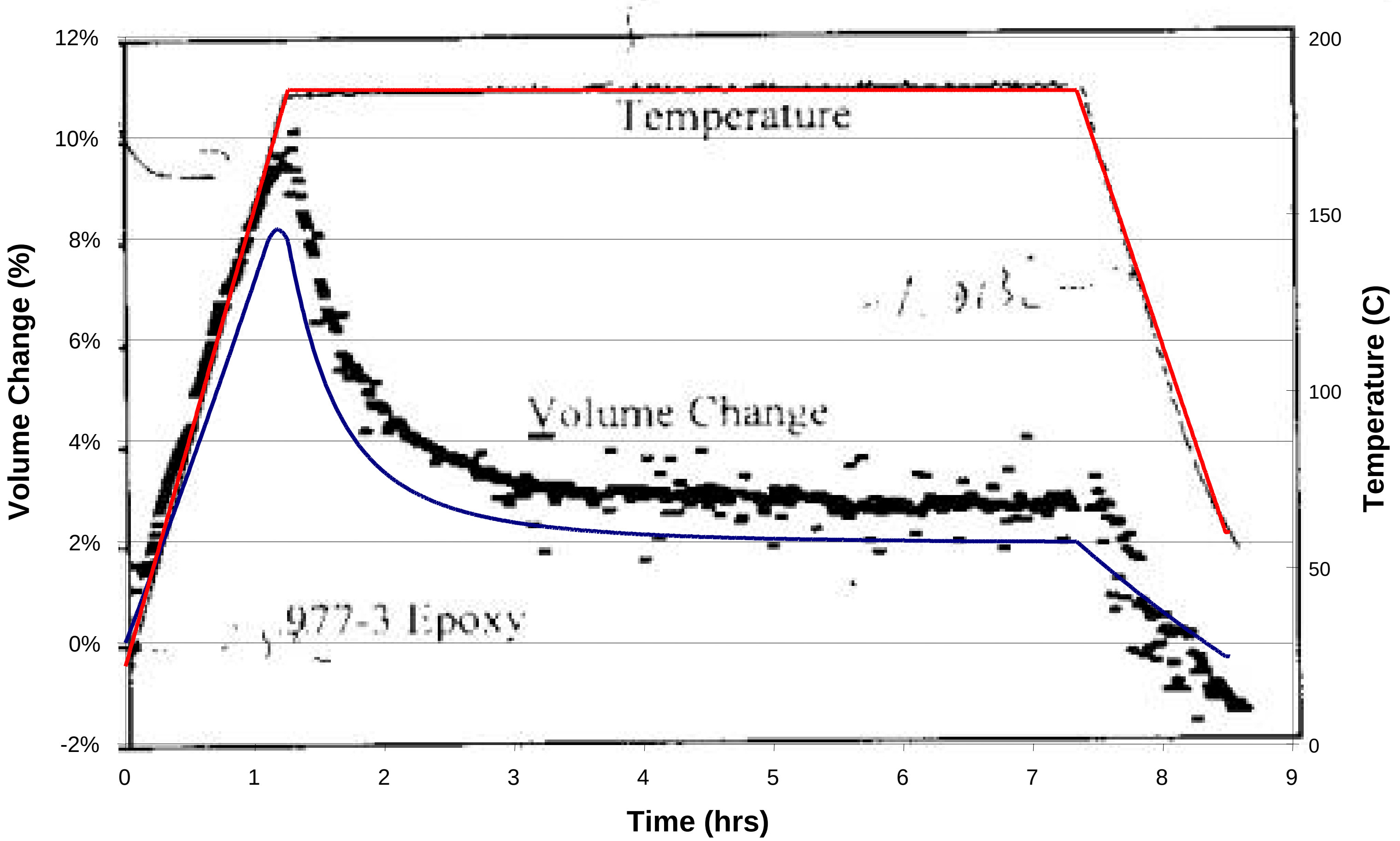


Gel Point is Consistent Although Magnitude Needs Study



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

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

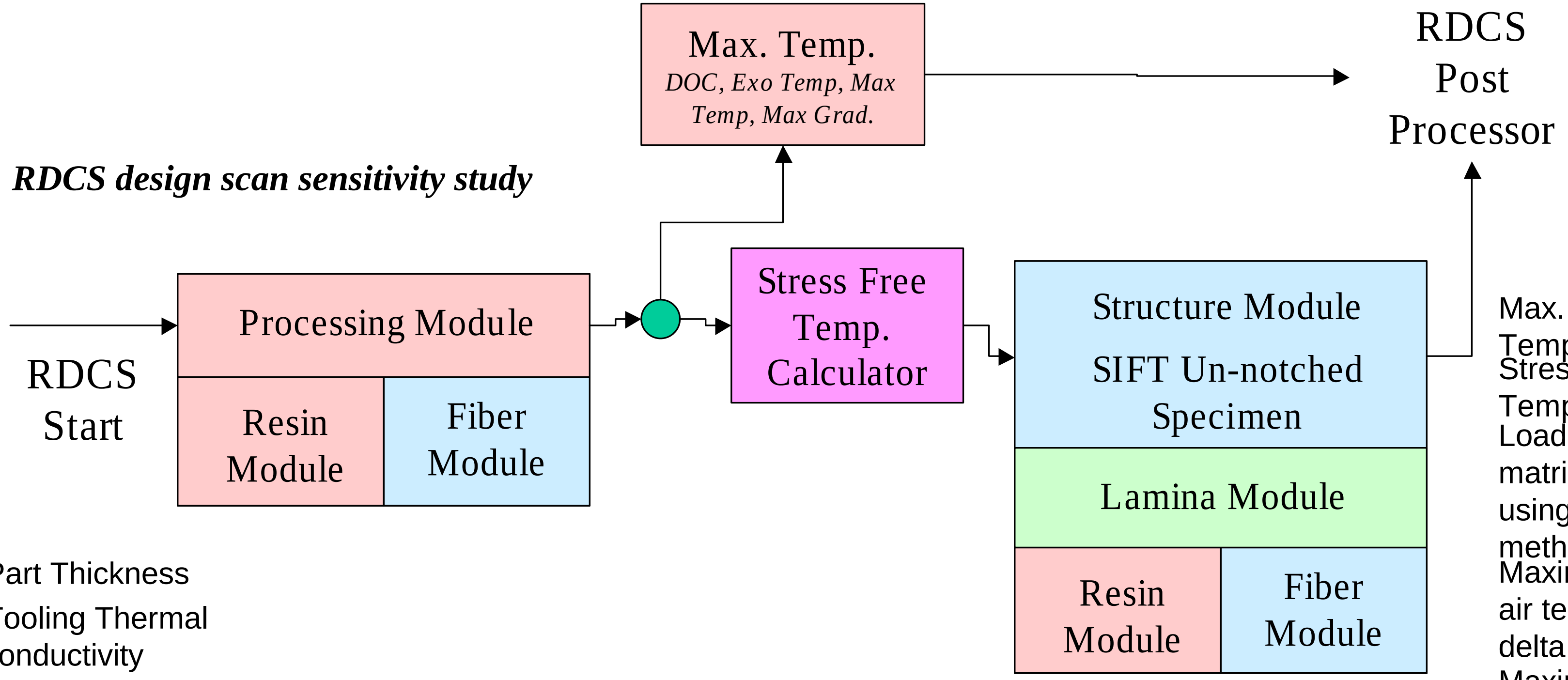
Output/Response Variables:

	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

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 design scan sensitivity study



RDCS Start

Processing Module

Resin Module

Fiber Module

Max. Temp.

DOC, Exo Temp, Max Temp, Max Grad.

Stress Free Temp. Calculator

Structure Module

SIFT Un-notched Specimen

Lamina Module

Resin Module

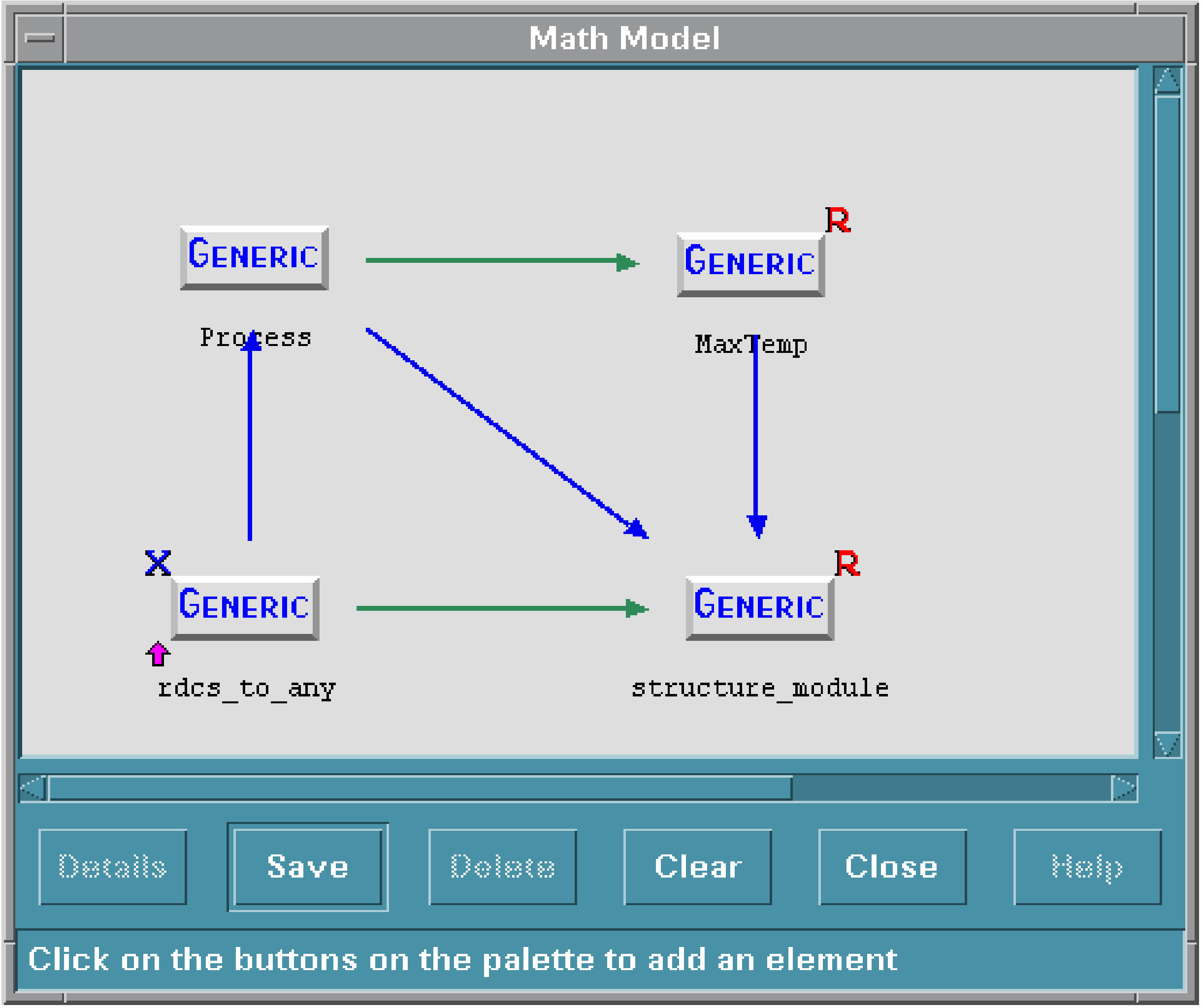
Fiber Module

RDCS Post Processor

- Part Thickness
- Tooling Thermal Conductivity
- Pressure
- First Hold Time
- Second Ramp Rate
- Autoclave Heat Transfer Coefficient

- Max. Lam. Temp.
- Stress Free Temp.
- Load at first matrix cracking using SIFT method
- Maximum part to air temperature delta
- Maximum internal part temperature gradient

RDCS Math Model



Click on the buttons on the palette to add an element

Approach – Input/Design Variables

- **Tooling Thermal Conductivity**

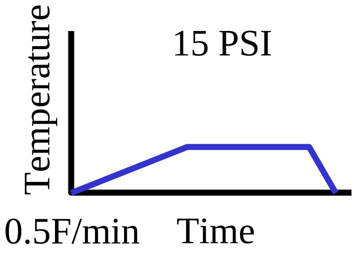
Composite | INVAR | Aluminum

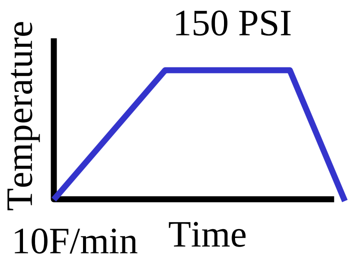
- **Part Configuration – Thickness**

8 ply (0.0.080) inch

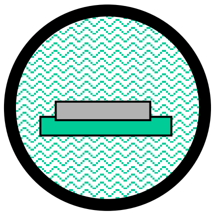
64 ply (0.70 Inch)

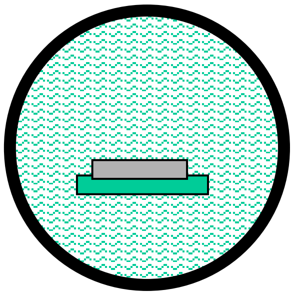
- **Processing – Pressure, Temperature**





- **Autoclave - Heat Transfer Coefficient**

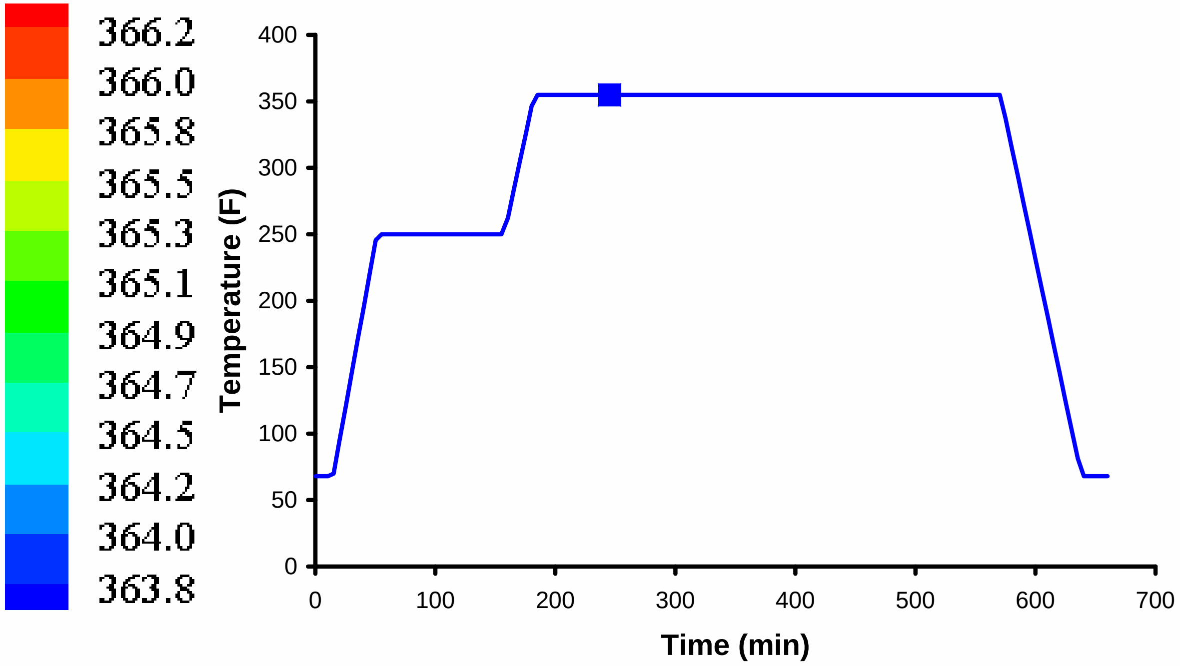

5 W/sq. m-K

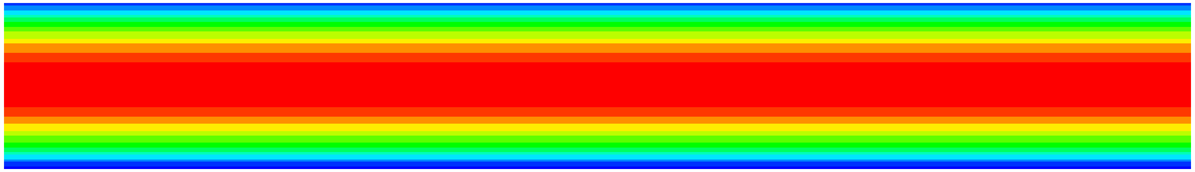

20 W/sq. m-K

Processing Module
Part Temperature at Max. Exotherm (977-3)

In Depth Analysis Using Processing Module

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

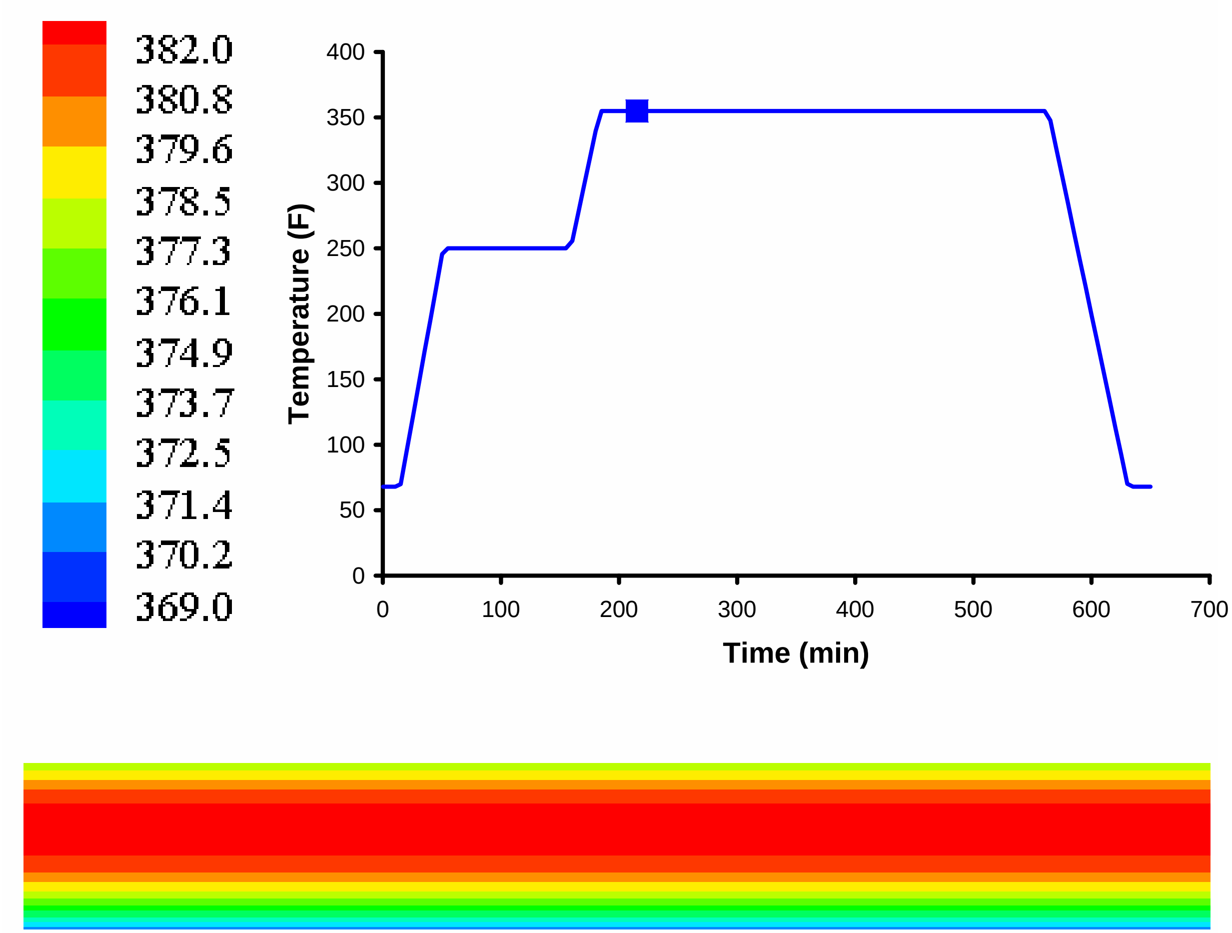




Processing Module
Part Temperature at Max. Exotherm (8552)

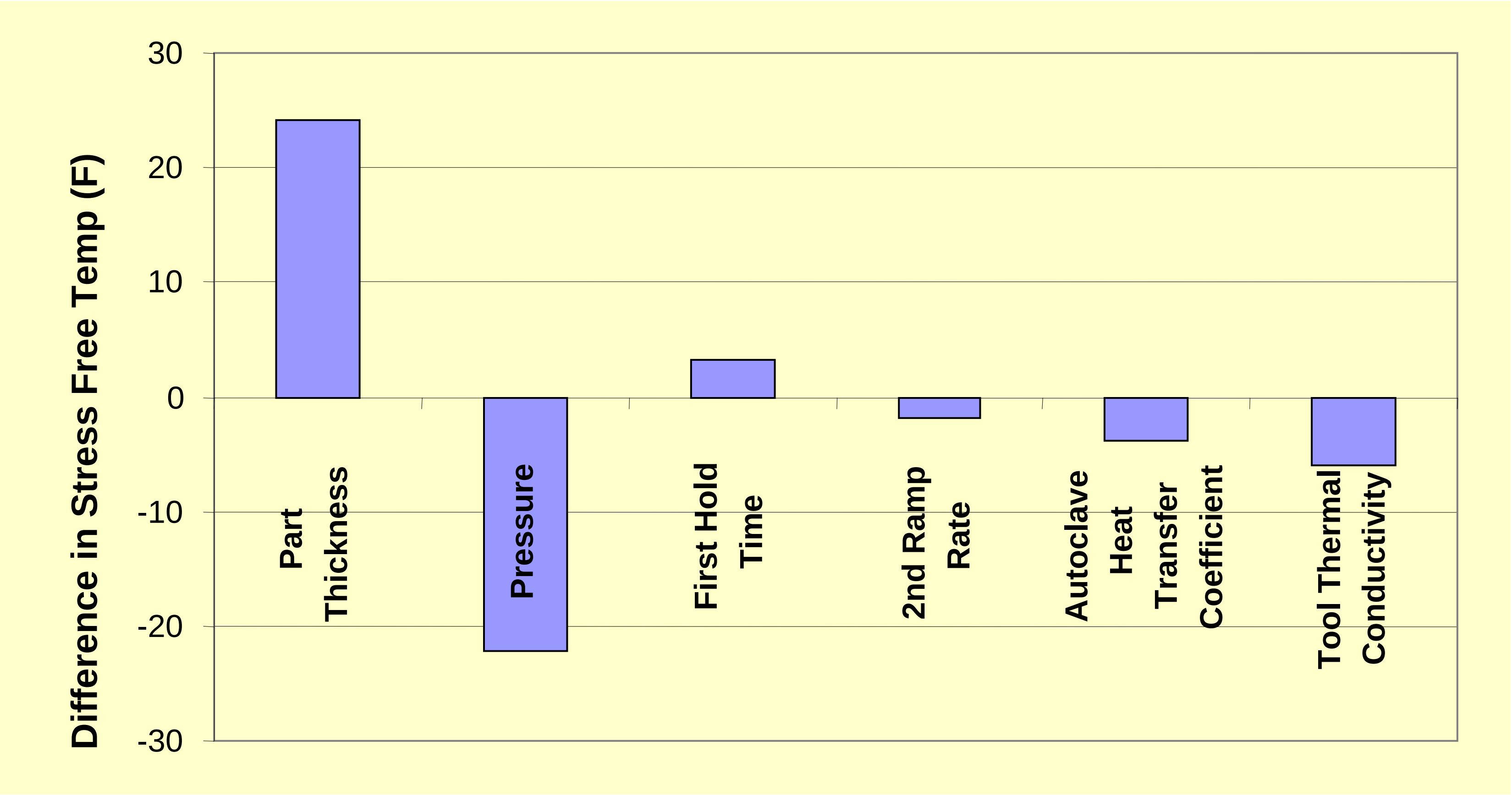
In Depth Analysis Using Processing Module

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



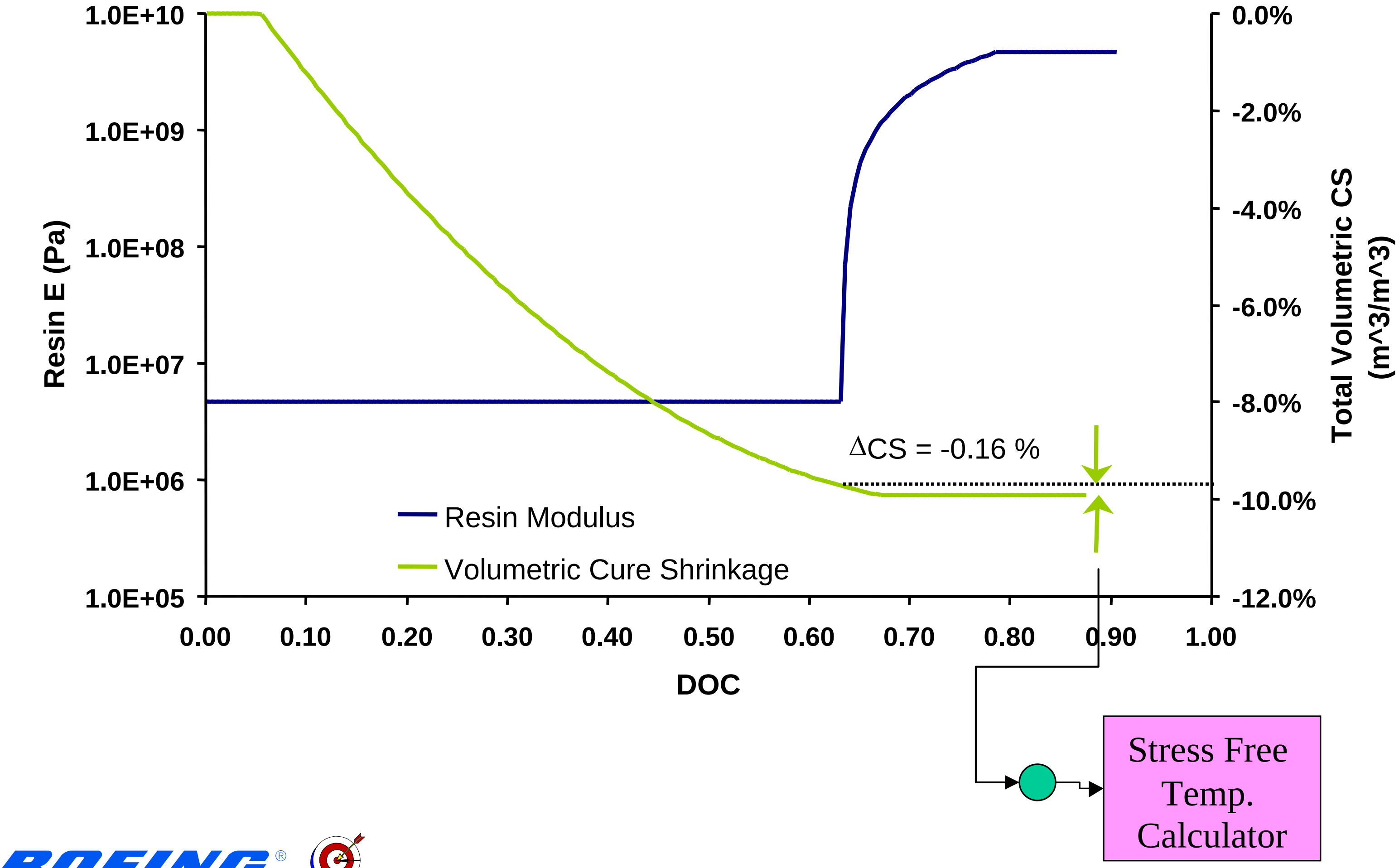
Results – Importance of Main Variables

Stress Free Temperature Sensitivity Results



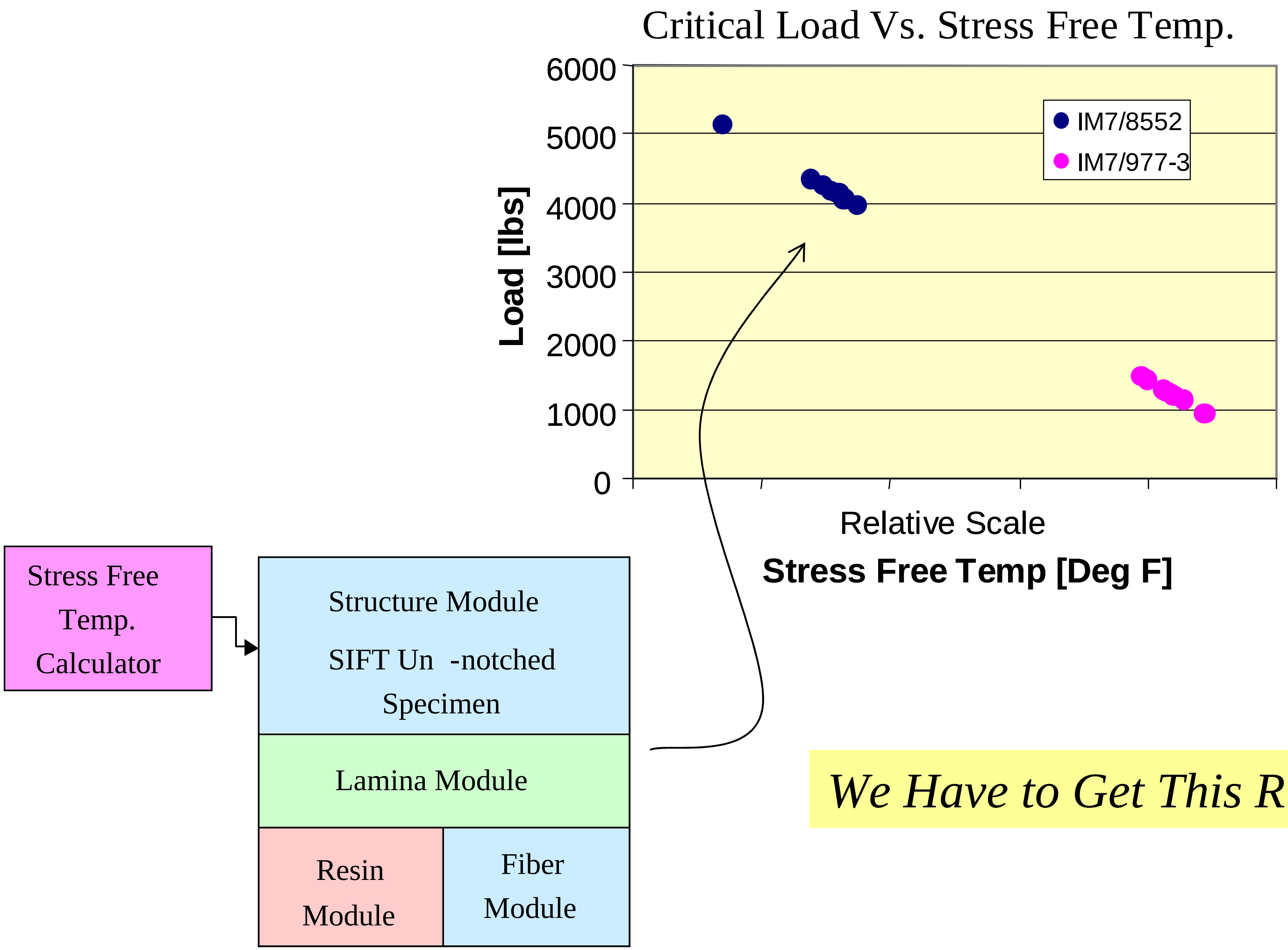
- Part Thickness and Pressure are the most important drivers
  - High Pressure and thin parts are better
- Tool Material and Autoclave Heat Transfer Coefficient have a moderate effect
  - Higher is better for both parameters
- Hold Time and Ramp Rate have little effect

AIM Analysis Results
Stress Free Temperature


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

Stress Free
Temp.
Calculator

Critical Load Versus Stress Free Temp.



Critical Load Vs. Stress Free Temp.

Stress Free Temp. Calculator

Structure Module

SIFT Un -notched Specimen

Lamina Module

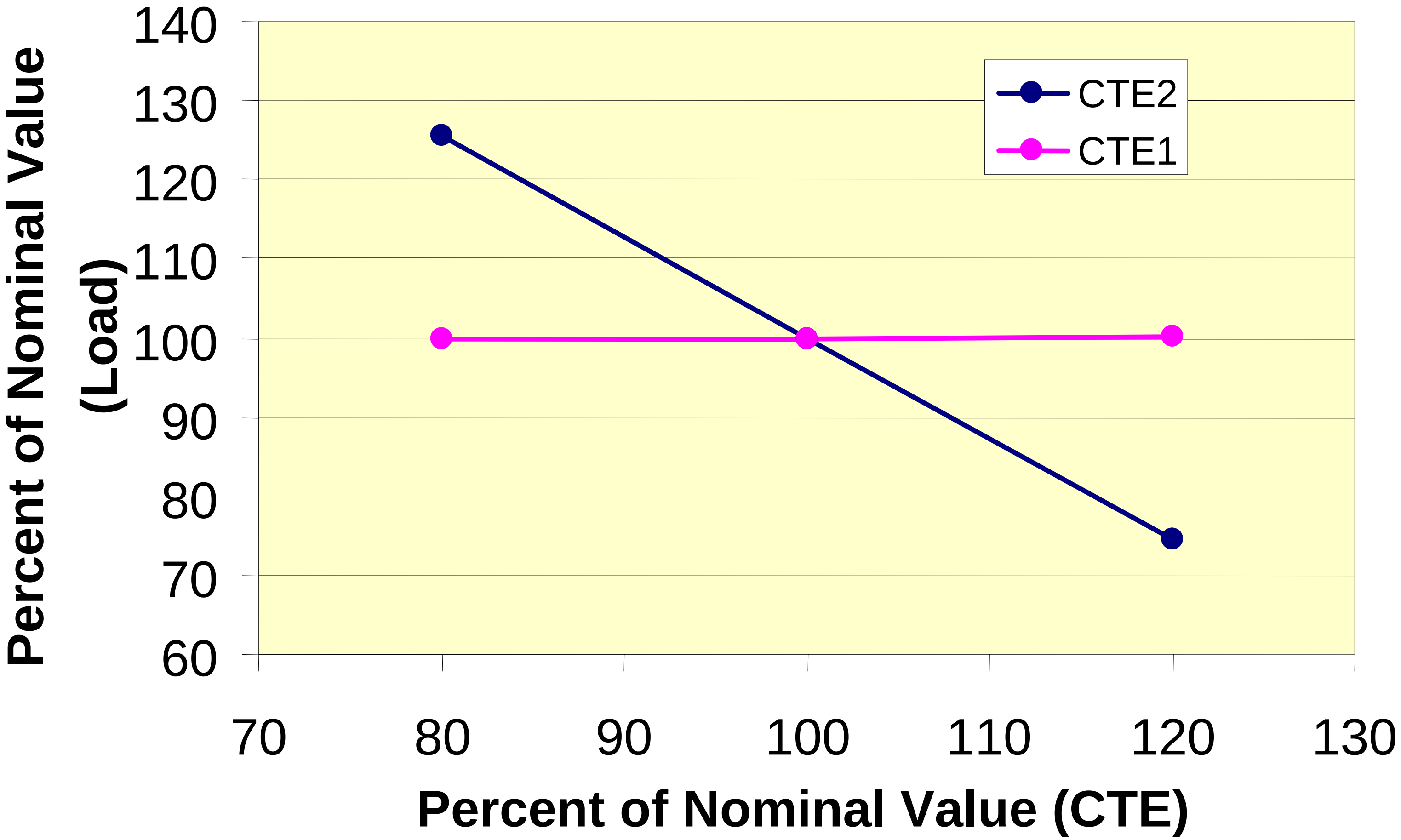
Resin Module

Fiber Module

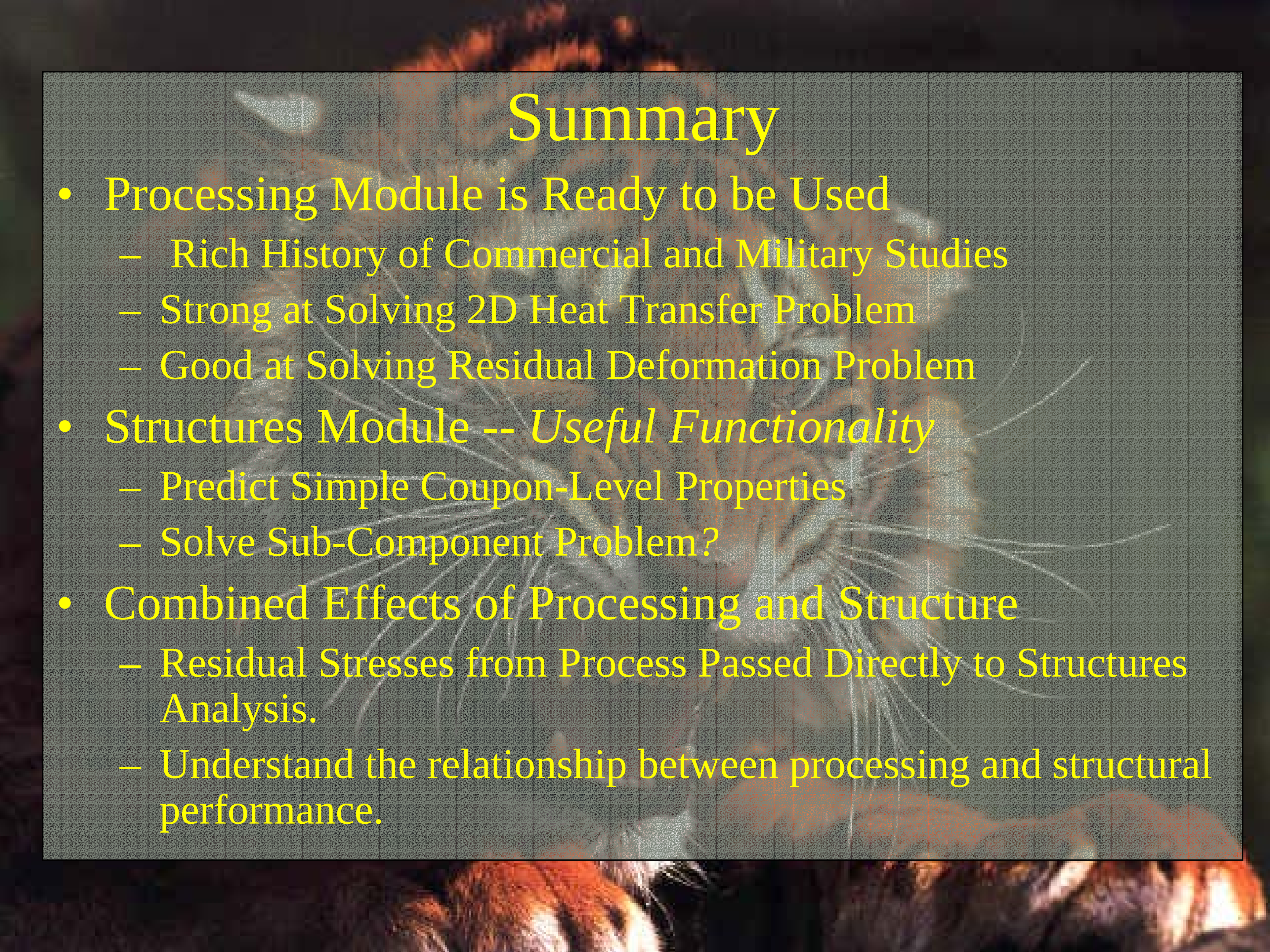
We Have to Get This Right!!!

Thermal Expansion Effect

Side Study on Sensitivity due to CTE



We Have to Get This Right!!!

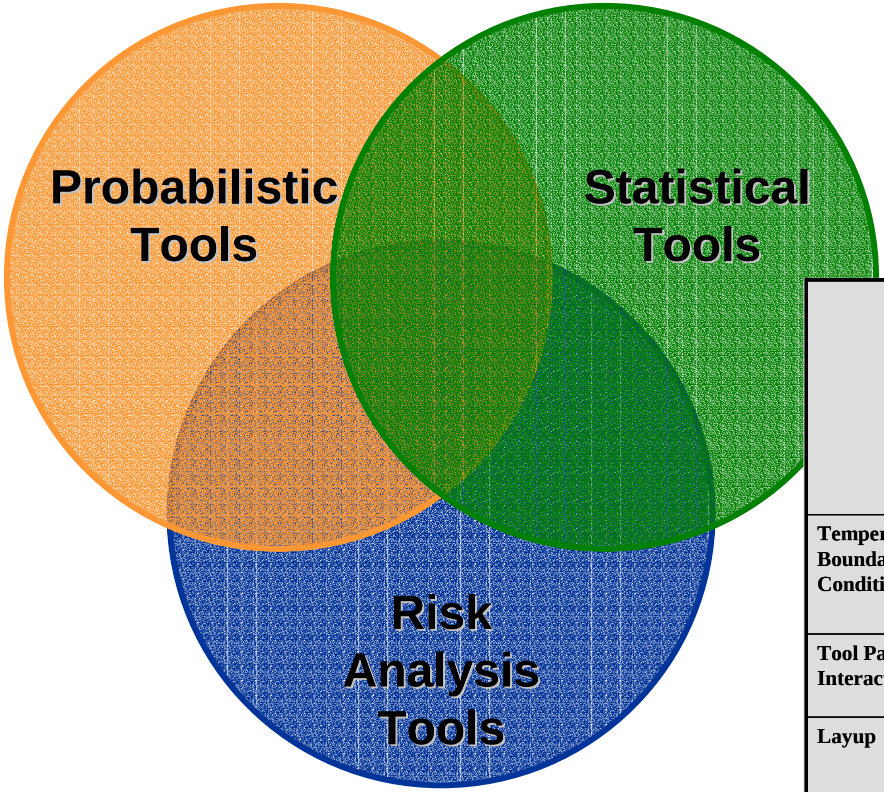


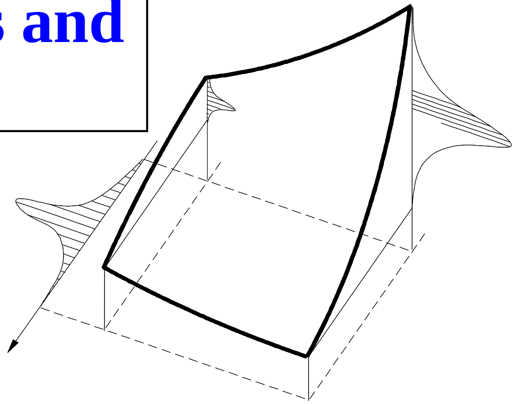
Summary

- 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

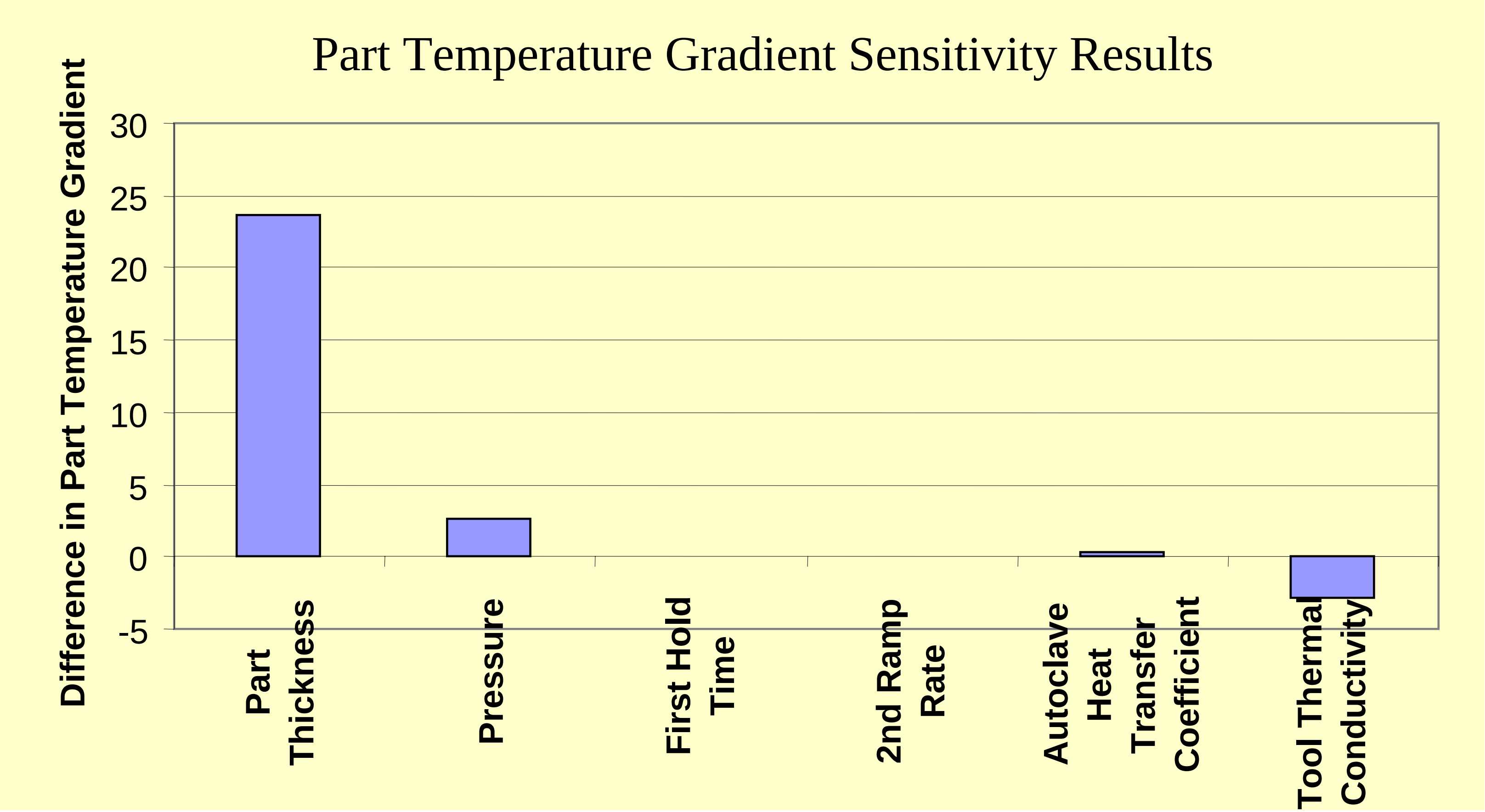




Modeling of the Process

	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 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.

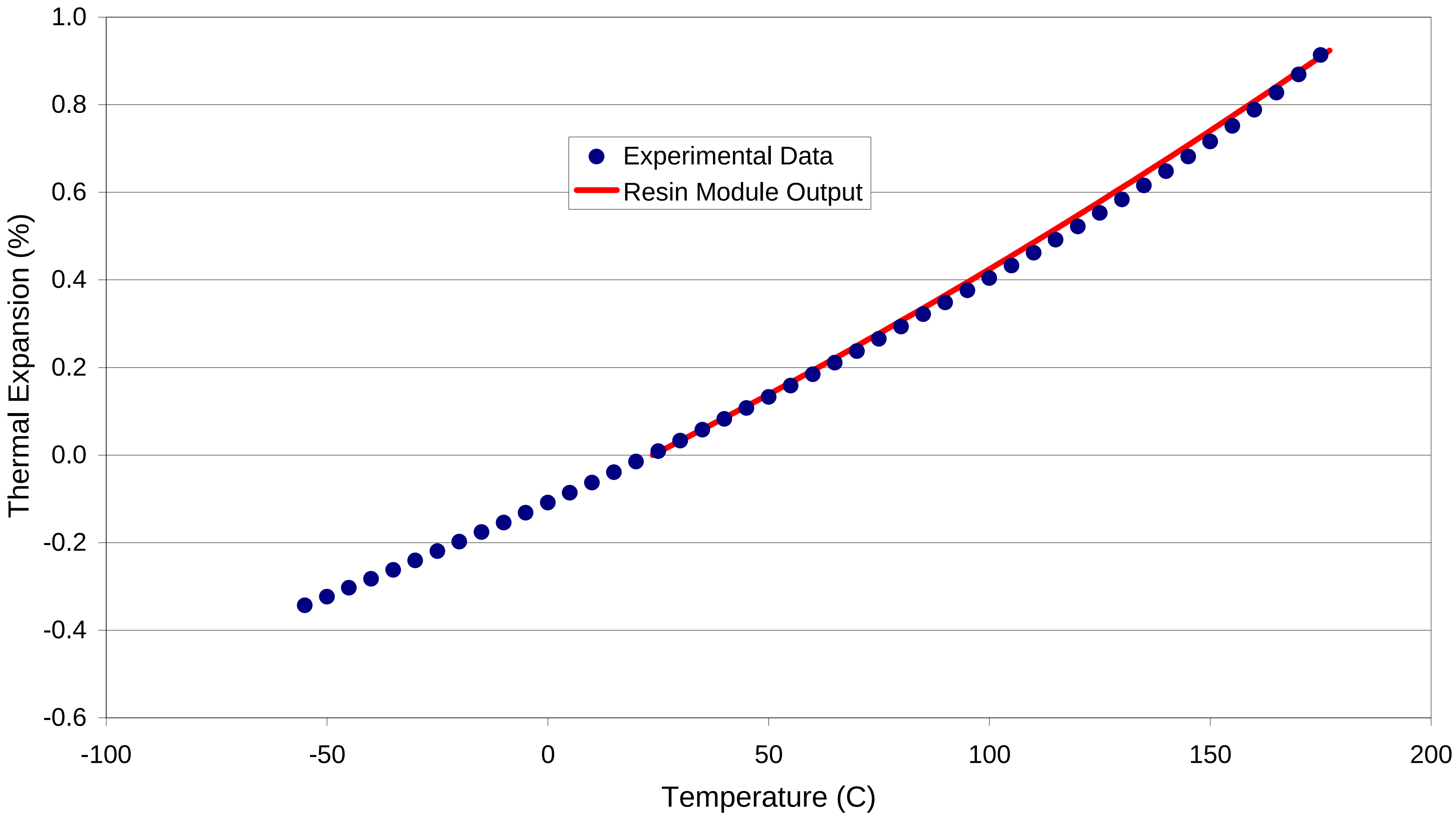
Results – Importance of Main Variables

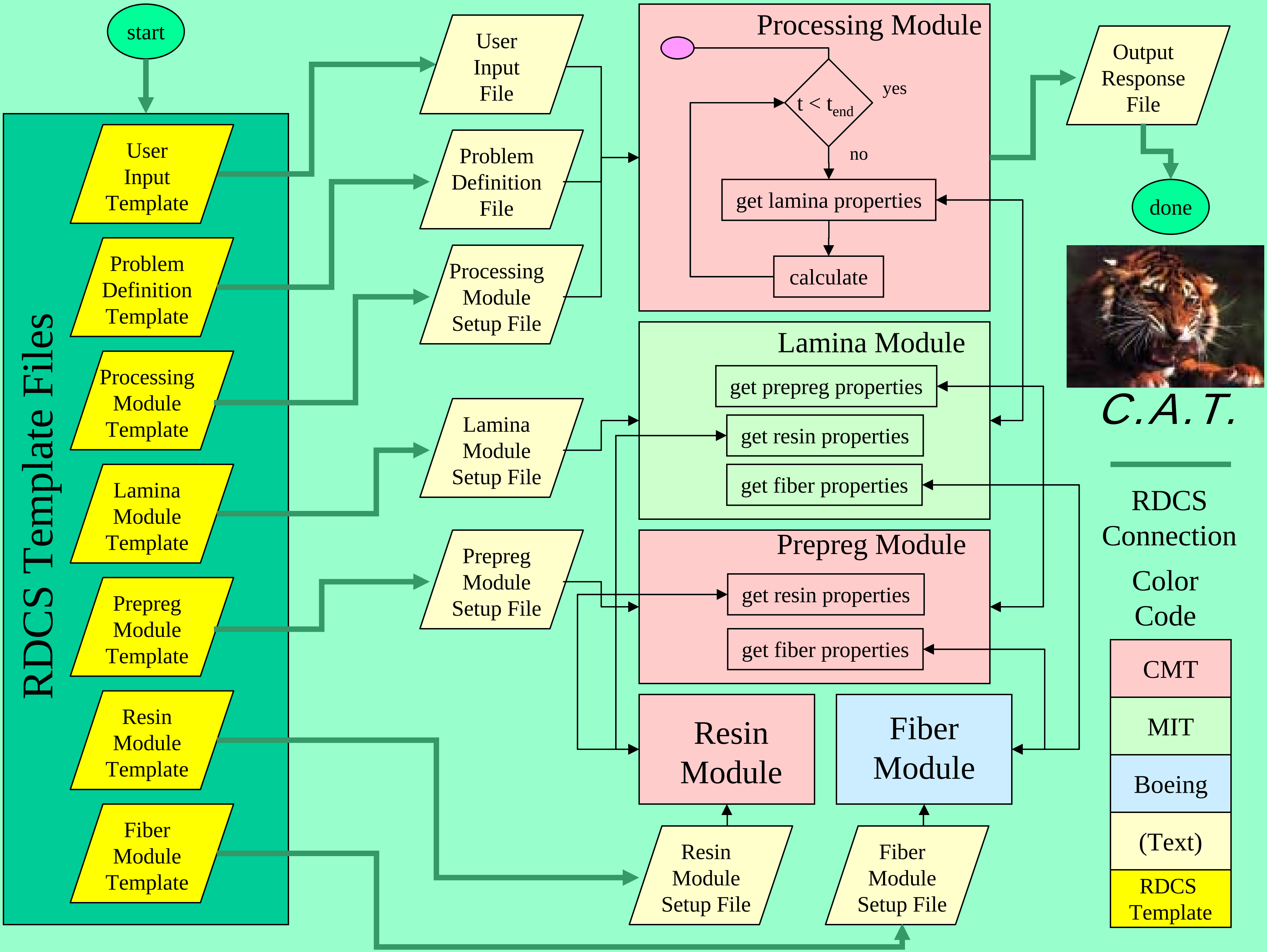


- **Part Thickness, Pressure, and Tool Conductivity are the most important drivers**
  - **Thin parts, High tool conductivity, and lower Pressure are better**
- **Other variables have little effect**

Resin Module Captures Resin CTE

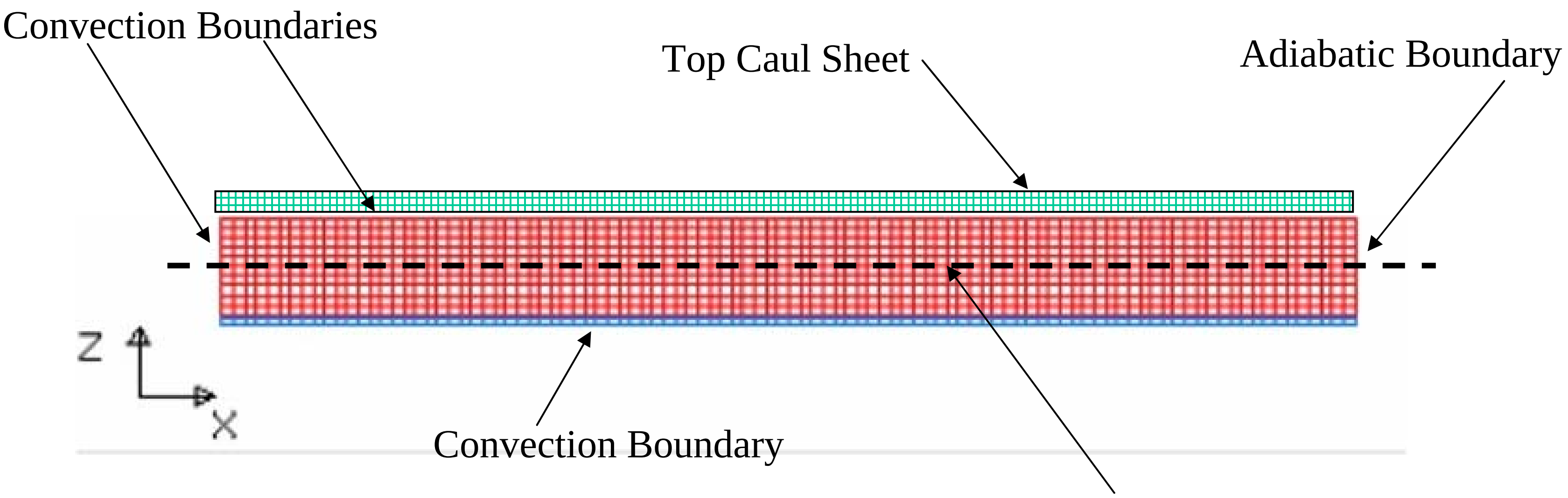
Behavior Dependant on Temperature and Degree of Cure




start
RDCS Template Files
User Input Template
Problem Definition Template
Processing Module Template
Lamina Module Template
Prepreg Module Template
Resin Module Template
Fiber Module Template
User Input File
Problem Definition File
Processing Module Setup File
Lamina Module Setup File
Prepreg Module Setup File
Resin Module Setup File
Fiber Module Setup File
Processing Module
$t < t_{end}$
yes
no
get lamina properties
calculate
Lamina Module
get prepreg properties
get resin properties
get fiber properties
Prepreg Module
get resin properties
get fiber properties
Resin Module
Fiber Module
Output Response File
done
C.A.T.
RDCS Connection Color Code
CMT
MIT
Boeing
(Text)
RDCS Template

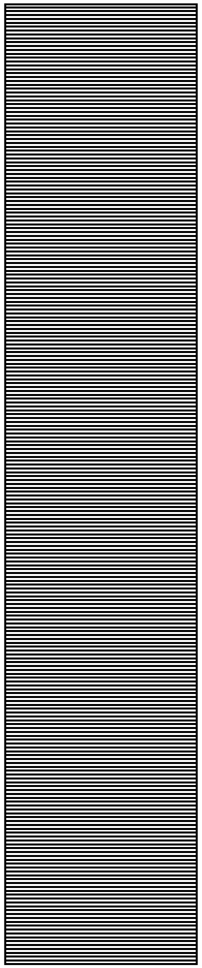
AIM Processing Module (COMPRO)

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