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Identification and analysis of manufacturing process data relationships: Investigation and demonstration

Evans, Patricia Ann, Ph.D.
The Ohio State University, 1994

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IDENTIFICATION AND ANALYSIS OF
MANUFACTURING PROCESS DATA RELATIONSHIPS:
INVESTIGATION AND DEMONSTRATION

DISSertation

Presented in Partial Fulfilment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

By

Patricia Ann Evans, B.M., M.S.

*****

The Ohio State University
1994

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ACKNOWLEDGEMENTS

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To my family, thanks for your interest in my work and my education, and for your belief in me.

John Evans, you’re the best.
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CHAPTER I
INTRODUCTION

Introduction

This chapter discusses the research issue in general, gives the purpose and scope of the research, presents definitions and background for the reader, and discusses general results and their significance. A user scenario is presented. Finally, the contents of this dissertation are presented.

The Research Issue

Learning to process new materials to make quality products often entails a rather long learning curve. The length of this curve is affected by many things, for example, the experience of the learner, fortunate accidents, and how similar the new material is to other materials. Possibilities are complex and far-reaching, facts may be uncertain, different people use different approaches and work on variations of the problem—the list goes on. The problem is compounded when materials and their processing are expensive and lot sizes are often just one part. Analyzing data from the manufacturing process and interpreting the results are useful for arousing or confirming suspicions about part quality or process variables, or to suggest other possible ways to carry out the process.

This research addressed the interpretation of the analysis of manufacturing process data captured using sensors or human input. The emphasis was on identification and analysis of semantic relationships among different kinds of data for
some given manufacturing process. The demonstration process for this research was the autoclave curing of composite materials.

In a nutshell, this research was about determining what data to use and how to use it to give the user insight about composite materials and their processing.

**Purpose**

The purpose of this research was to assist materials or manufacturing specialists in analyzing and learning about new materials and processes by exploiting the meaning behind manufacturing process data relationships in further exploration of the material or process. In attempting to fulfill this purpose, a tool providing automated assistance in analyzing data was researched and a prototype was constructed. Ultimately, the goal is to increase the possibility of making acceptable products more quickly and more cheaply.

**Approach to the Research**

Philosophically, this research was completely exploratory and experimental. Each step was open-ended. All of the results were data-driven, that is, they were directed solely by what turned up along the way. The only exception to this approach was that as each step was performed, the purpose of the research was recalled—to find ways to assist materials or manufacturing specialists in analyzing and learning about new materials and processes by exploiting the meaning behind manufacturing process data relationships in further exploration of the material or process.

Mechanically, the approach used in this research included finding relevant kinds of data to analyze for the manufacturing process being used, finding semantic relationships among the data, exploring and selecting appropriate analysis techniques, exploring ways to synthesize the data and analysis techniques, developing a system construction procedure, and prototyping an automated and customized analysis tool.
Scope of the Research

Although the ideas generated during the course of this research may be usable for various manufacturing processes, identification of semantic relationships and implementation of a demonstration data analysis tool were carried out for only the autoclave curing of certain composite materials.

The importance of the user interface is recognized and current technology was used to advantage during this research. However, user interface research was not a part of this work.

Among the tasks in the course of this research was a prototype implementation of analyses, including construction of a sample database. The database represents as comprehensive a set of different kinds of data we might like to analyze for the demonstration process as could be found. Within the database, there are entries containing various kinds of information about the data. While the information important to this research was completely researched, some of the other information about each kind of data is incomplete.

During the analyses the demonstration program was written to perform, various kinds of conclusions are made which have been pre-programmed or are hypothesized by the program. Every effort was made, in consultation with experts, by examining literature, and by testing, to consider all possible eventualities that fit within the scope of the analyses and to write a program which would include them. However, it is likely that not every possible conclusion, even within the scope of the analyses, will have been programmed or will be hypothesized by the system.
Background and Definitions

**Curing.** To cure is to prepare a substance for some purpose using physical or chemical processing. An autoclave is a large pressure cooker in that it heats and compacts materials, thereby curing materials by physically and chemically altering them.

**Composite Materials.** Composite materials are, as the name implies, a combination of different materials. For this research project, the composites of interest were a type of matrix material with fibers embedded in the matrix. The fibers give the matrix anisotropic properties much like metal reinforcing rods used in concrete structures. Certain composite materials are becoming useful in structural applications such as aircraft wings, sporting equipment, appliances, and even artificial limbs. Besides allowing anisotropy, composite materials tend to be lighter than metals of the same strength, have generally greater corrosion resistance and damage tolerance, and have an extremely reduced radar reflectivity.

Examples of composite materials are graphite epoxy, bismaleimides with graphite fibers, and the most familiar of composite materials, those which contain glass fibers—fiberglass. Bismaleimides with graphite were the type of material for which processing data was used in this study. Bismaleimides are a relatively new type of material. Therefore users suffer from a lack of knowledge about bismaleimide processing. This lack of knowledge, along with other factors such as specialized machinery and supply/demand, translates into high costs. This research was an exploration of how data from the processing of new materials such as these might be analyzed to speed the acquisition of processing knowledge by identifying unknown relationships or confirming or clarifying known relationships among different kinds of data.
Commonly, manufacturers purchase materials in a form called a prepreg. Prepregs are flat pieces of material composed of woven or unidirectional graphite fibers embedded into a bismaleimide matrix material.

**Autoclave Curing.** To cure composite materials in an autoclave, a layup is prepared and placed inside the autoclave. The layup consists of prepregs, absorbent materials, tools for shaping the final part and various adhesives, dams, and other materials as necessary to make a shaped part. The entire layup is covered with a vacuum bag and a vacuum is drawn. The part is loaded into an autoclave and the autoclave door is closed. Heat and pressure inside the autoclave are manipulated to heat and compact the part the right amount to attain desired part shape and properties. Heat and pressure are directly controllable variables, and heat, pressure, and dielectric properties are variables which may be measured during the process. The word "dielectric" refers to the ability of a material to resist the flow of electrical current. Dielectric properties for which data was provided in this research are identified as MPhase, Mgain, Dissipation, and Filtered Dissipation.

The heat applied during the curing process softens the matrix material, making it possible to blend the matrix material from each ply with other plies, and making it possible to mold the materials on a tool which is the shape of the desired product. Pressure compacts the materials, shaping the part and removing air pockets and volatiles. At some point during the cure, the matrix material begins to undergo a chemical change and hardens. Heating and pressurization continues until the part is thought to be fully cured, meaning it should now have the desired properties.

After the cure, other kinds of data can be collected, such as part strength, glass transition temperature, and void content (air or volatiles that remain in the cured part). Still other kinds of data are known before the layup is constructed, such as material
composition, fiber content, and the amount of time the material has spent out at room
temperature. Certain relationships among these different variables are known, others
may be discovered later. The point of this research was to look for unknown
relationships or confirm or clarify known relationships.

**Semantics.** The word semantic refers to meaning. Where syntax refers to a set
of rules specifying how to put symbols together to make sentences or lines of code,
semantics are the mapping from those syntactic structures to real objects in a domain. In
other words, semantics are the meaning behind the syntax. For example, when writing
a computer program, the programmer knows that certain words, numbers, spaces, etc.
are used in a certain order. This is syntax. Semantics are what the computer program
means, what it is trying to do, and what its context is.

To people, semantics combines words with tone of voice, the experience of both
the speaker and the listener, body language, and possibly a myriad of other nuances.
For example, the symbol 1040 means different things to different people. In early April
each year, most U.S. citizens would believe that 1040 refers to a tax form. To people
of other countries, 1040 would rarely mean a tax form. 1040 can refer to a time, a year,
the number of seashells in a shell collection, or any number of other possible things.
Semantics help us understand what 1040 stands for in a particular case. Unless the
context or associations among this number and other symbols are known, 1040 is
really meaningless. It has syntax but not semantics.

As an example of semantics in terms of data analysis, consider the two graphs in
Figure 1.
These two graphs look like they might plot the same process or an identical one. It looks like these graphs are related to one another. But without semantics, the relationship between the graphs is unknown. If they are time and temperature graphs, and axes and scales are the same in both, the graphs might be showing a correlation between two parts begin processed in the same autoclave. Both parts cool down at the same time, but one part cooling down doesn't cause the other to cool down. On the other hand, one graph might be autoclave temperature and the second graph part temperature. In this case, what is shown in the first graph causes what is shown in the second graph. These are two kinds of relationships which might look the same in the graphs. Without knowing context, no conclusions can be made.

Semantic data relationships take into account what the relationships among the different kinds of data are, including under what circumstances the relationships exist (context) and what the implications of the existence of these relationships might be.

Results and Their Significance

Results from this research can be measured according to a six level scale. Each level can be called a level of success. Figure 2 shows the possible levels of success.
System notices something new

User notices something new

Synthesis of data and analyses

Customized for manufacturing processes

Customized for user

Automated analysis tool

Figure 2. Levels of Success
The level of success of this research can be measured by finding the highest successful level in the hierarchy. At the bottom level of the hierarchy is what is available off the shelf today—tools which can be used for analysis. This level is not an acceptable research result.

The next two levels are customization for a specific user and for a manufacturing process. The user is a materials or manufacturing specialist. Success at these levels contributes the identification and structuring of semantic data relationships for certain composite materials, selection of analysis methods for the process, and a data analysis tool customization method.

The highest three levels give additional levels of success for the research. The first of these levels adds synthesis of data and analyses. If successful, the user would be able to achieve synergy, that is, the user would get more information from combinations of analyses than with any analysis alone. This level adds synthesis to the contribution.

The next level presents data to the user in such a way that the user notices something interesting (unexpected or coincidental) which leads to new insight about the process. This level adds the contribution of a first step toward automating insight, plus the added insight.

At the top level of success, the automated system would actually point out something new to the user. This level would add to previous contributions the automatic recognition of something interesting.

The top two levels were not reached during the course of this research. The next level, which provides the user with a synthesis of data and analyses, along with manufacturing process and user customization, and the identification and structuring of data and relationships, was reached. In addition, one of the analyses performed during the research pointed out a relationship that was known to the user but was unknown to
this researcher. Had this relationship been unknown to the user, the top level of success
would have been reached.

It is understood that not all of the semantics embodied in any situation, including
the analysis of manufacturing data, can be programmed into a computer. Certainly more
will be possible in time, however the state of the art of computer usage is many years
from being able to represent concepts such as tone of voice and body language. This
research is presented as a small step toward including semantics in an automated data
analysis program.

**User Scenario**

During the course of this research, an automated and customized tool for
assisting manufacturing or materials specialists was demonstrated. Though there are
many ways such a tool might be used, a simple scenario in which a user (manufacturing
or materials specialist) might use such a tool to learn something about a material or
manufacturing process is presented here. This example shows one possible set of data
which might be analyzed and some possible results of programming a customized
analysis tool for the user. Later in this dissertation, other sets of data and different
kinds of analyses are presented in depth, including the mechanics of both programming
and using such a tool.

Assume the tool has been programmed to deal with certain kinds of data and
analyses, and the user has taken measurements of the data of interest. The data being
collected and analyzed in this scenario include minute by minute temperatures of two
different composite parts as they are cured, and each part's thickness. The
measurements are shown in Table 1.
TABLE 1. Example Part Temperature and Thickness Comparison

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<th>Part 1</th>
<th>Part 2</th>
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<tr>
<td>Minute 1 Temp</td>
<td>200</td>
<td>175</td>
</tr>
<tr>
<td>Minute 2 Temp</td>
<td>250</td>
<td>230</td>
</tr>
<tr>
<td>Minute 3 Temp</td>
<td>300</td>
<td>340</td>
</tr>
<tr>
<td>Minute 4 Temp</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td>Part Thickness</td>
<td>1 inch</td>
<td>2 1/2 inches</td>
</tr>
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</table>

The program might look at the temperatures of each part and make note that part 1 starts at a higher temperature and ends at a lower temperature than part 2. Noting that Part 2 is thicker than Part 1, the program could hypothesize that the part thickness affects the part's temperature during processing. In the above example, the thicker part heats more slowly than the thinner part at first. After some time, the thicker part seems to heat more quickly and its temperature passes that of the thinner part. This faster heating in the thicker part is a phenomenon known as exotherm, in which material generates heat and therefore is being heated by more than the heat externally applied.

A program written to look for semantic relationships between the different kinds of data must have some knowledge already programmed within it. Since exotherm is a known phenomenon, the program developer will have made the possibility of the existence of, possible causes of, and possible effects of exotherm known to the program. Since it is known that exotherm may happen in thicker parts, the program can then confirm that this happened as expected (using text) and present the results to the user (perhaps in tabular form as shown in Table 1). This is an example of confirming a suspicion that something might happen, and in this case, that exotherm does appear to happen in a 2 1/2 inch part. This example would result in reaching the third level of
success shown in Figure 2. Though the top level of success would not be reached, this confirmation of exotherm may still be valuable information.

As a second example, carried on from the first, the user may wish to know at which thickness exotherm can be expected and therefore dealt with. More parts would need to be made in order to see at what thickness this happens. Table 2 shows a somewhat expanded list of parts and some hypothetical measured variables.

<table>
<thead>
<tr>
<th>TABLE 2. Second Example Part Temperature and Thickness Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Minute 1 Temp</td>
</tr>
<tr>
<td>Minute 2 Temp</td>
</tr>
<tr>
<td>Minute 3 Temp</td>
</tr>
<tr>
<td>Minute 4 Temp</td>
</tr>
<tr>
<td>Part Thickness</td>
</tr>
</tbody>
</table>

In this case, the program would note that all of the parts follow a pattern of increasing temperature, but that parts 3 and 4 start at lower temperatures and end up at higher temperature than parts 1 and 2. It could hypothesize that the thickness of a part which undergoes exotherm, all other things being equal, is between 1 1/2 and 2 inches. It could further hypothesize, after examining the data, that exotherm occurs halfway through a processing run of 4 minutes. This is the point at which, in this simple example, the temperatures of parts 3 and 4 surpass those of parts 1 and 2. Assume that these two hypotheses are unknowns and are not knowledge the program has been given. Therefore, if the user was not already aware of these relationships and possibilities, and is sure that they are factual, the program has pointed out something new and has reached the top level of success shown in Figure 2.
Dissertation Contents

In Chapter II, the state of the art in data analysis and other technologies related to this work is summarized.

Chapter III contains detailed information about how the research was approached and how the demonstration automated system was designed. It gives general results and conclusions about ways to perform analyses and how some of the analyses can be used in an automated system such as that proposed here. It defines a procedure for designing and constructing an automated data analysis tool.

Chapter IV contains the results of applying the procedure for constructing an automated data analysis system. It gives descriptions of the data which was collected and how it was structured, and what analyses were selected and the results of performing these analyses. It includes demonstration system implementation details and presents the results of the research.

Chapter V discusses lessons learned during this research. This chapter contains topics such as assumptions made to scope each part of the research, problems encountered, and how certain parts of the research might be approached differently in order to give better results.

Finally, Chapter VI gives a summary of the research and the significance of its results. Further work, based partially on lessons learned during the current work and partially on possible ways to extend the work, is suggested.
CHAPTER II
LITERATURE REVIEW

Introduction

In this chapter, the state of the art in data analysis and other topics related to this research are reviewed. Several methods were used to collect information for this chapter. Indexes and abstracts, in book form, on compact disc, and via on-line information services were used to find literature related to manufacturing data analysis and interpretation. Popular literature, corporate advertising, and demonstration software packages were surveyed for information on commercial data analysis techniques. Several contacts were made to companies which use the autoclave curing of bismaleimide matrix composites in making their products. These companies were asked about data they collect and the types of analyses they currently perform.

This review of the state of the art is segmented by topic and covers semantic data relationships, data analysis in general, automated analysis, automated analysis for specific applications (non-manufacturing and manufacturing systems), composite materials, analyzing data from the autoclave curing of composite materials, efforts parallel to the research reported here, and informal company interview results.

Semantic Data Relationships

With the exception of discovery systems research, literature discussing semantic data relationships is primarily concerned with how these relationships
are represented rather than finding the relationships in the first place. Identifying these
relationships is largely a manual task, requiring product and process development
expertise.

There are several general data structures popular for representing data
relationships. They provide a framework for keeping together the name of a concept of
central interest and all of its important properties and relationships. For example, the
semantic network shown in Figure 3 is a simple graphical representation of a concept
and some possible properties and relationships.

Figure 3. A Semantic Network

In computer code, these concepts, properties, and relationships can be
represented in any number of ways, including within commercial relational databases or
hypertext programming environments.
Data Analysis

The state of the art in data analysis fills volumes on library shelves. To most technical people, data analysis means statistical analysis of some sort. Certainly statistical analysis is useful in studying the autoclave curing of composite materials and in almost every other domain. Outside statistics, literature about data analysis is slim. However there is one other significant kind of analysis that has become quite popular. Exploratory data analysis (EDA), made known by John Tukey, is an approach to analyzing data by its appearance rather than attempting to confirm a hypothesis of some type.

EDA’s advocates do not suggest that confirmatory analysis is unnecessary, just that there are other ways to help a data analyst draw insight from data. Methods for depicting sets of data are presented in books and papers about EDA (e.g., Cleveland; Jones; Tukey). Each method follows the philosophy of appearance-based, exploratory analysis. For example, star diagrams compare sets of variables. In Figure 4, star diagrams have been constructed for doing a simplistic comparison of three diamonds. Points on the stars represent variables related to the diamond being represented. For this comparison, the longer the distance to the point from the center of the star, the higher the quality (or cost) of each of the variables.
Exploratory data analysis has become popular enough that there are several rather sophisticated software packages which assist users in performing this type of analysis.

Opening the data analysis solution space shows that there are other ways to analyze data. Pattern recognition might be finding a closest match between objects with similar shapes, sizes, or other features. Other useful kinds of analysis might be noting unexpected occurrences, finding contradictions to accepted theories, finding coincidences in timing among events, or finding regularities among events. All of these kinds of data analysis can be performed without statistics.

**Automated Analysis**

The state of the art in computerized data analysis consists primarily of numerous commercial statistical analysis software used in universities, industry,
and even on personal computers. Like all software, these statistical software
packages range from very cryptic to relatively easy to use.

Besides statistical analysis, there are commercial software packages
providing assistance with experimental design, plotting capabilities (often in
conjunction with statistical analysis), linear programming, signal processing,
spreadsheet capabilities, and mathematical computations. Like the others, these
software packages range from cryptic to easy to use. None of them performs
interpretation of results—they provide conclusions based on the type of processing
they do. Statistical packages generally provide numerical results in statistical
nomenclature, graphical packages show plots and other pictorial representations,
spreadsheets show numerical results, and so on, including combinations of these.
A few of them have facilities which allow a programmer to customize a user
interface. This makes it possible for a customized data analysis package to be
prepared.

In terms of context based automated analysis, there has been some
research into providing assistance to users beyond presenting them with a list of
possible analyses to choose from. A review of several such systems is given
here.

Gale (1) reports on work in translating research questions into statistical
terms, choosing techniques, carrying out the analysis, and testing assumptions for
data sets before using certain techniques. These areas were shown to be feasible.

The SITO system was developed in the USSR and reported on by
Alexandrov. SITO is a research tool for assisting people without a computer
education in doing data analysis. It is claimed to be a working, user-friendly
system. SITO uses statistical tools and several non-statistical tools developed
especially for this integrated tool. The non-statistical tools include methods for variable transformation and similarity measures of different variable types based on their structures. The system is said to choose analysis techniques automatically by consulting with the user about the problem. SITO's demonstration application was analysis of text.

Aside from general statistical analysis software, it appears to be easier to prepare software for specific kinds of analyses in specific domains than to develop generalized analysis software. This is in agreement with a conclusion that was reached years ago by Hahn, who said when referring to the difficulties involved in the development of systems for automated statistical consultation and data analysis "The best opportunities for technical progress seem to be in the development of specialized, rather than general, applications packages."1 Evidence of this continuing limitation is shown by a paucity of general automated analysis tools which claim to allow context based or intelligent data analysis. These tools still do not include interpretation of results without customized programming, which then makes them a specialized tool.

There is however, an abundance of tools available or under development which are specialized. Among other things, they diagnose machine failures, analyze molecular structures, and provide real-time display of manufacturing process variables. Some of these tools integrate various techniques for data analysis. Most are in a research stage, but several are in use. A number of these tools, which are representative of those in current literature, are described in the next sections.

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Non-Manufacturing Analysis Systems

Smith and Baker report on the Dipmeter Advisor system. This system interprets well log data including data giving tilts of rock layers, local geology, and rock properties. The system combines several rule-based expert systems along with other tools to emulate human expert performance in dipmeter interpretation. The tools each have a specific purpose and are used in a certain order. They are not integrated. Each tool picks up results from the last analysis from a common data repository. At any point the user may manipulate the work the system has done or repeat any of the steps.

DENDRAL, reported on by Buchanan, is one of the oldest expert systems. It uses a "plan-generate-test" strategy to interpret spectral data in order to find the molecular structure of organic molecules. The "plan" part of the strategy defines constraints which narrow down the space of possible molecules based on data gathered from a spectrometer. "Generation" simulates candidate molecules as hypotheses to be tested. "Test" finds the best fit of spectral data to candidate molecules.

Hillman reports on INQUEST, a tool whose intent is to assist intelligence analysts to analyze data. INQUEST correlates pertinent data for intelligence situations, provides rationale to evaluate retrieved data, and generates database queries corresponding to the analysis problem and the rationale provided. Data are correlated to a frame of reference (world knowledge such as locations, military operations, politics, etc.), in order to determine what data are pertinent. Evaluation rationale is provided based on doctrine related to certain types of intelligence work and on the heuristics of an expert analyst. In this system,
semantic data relationships in terms of context are maintained and analysis techniques are selected according to the situation.

RX, a system by Blum, performs data analysis on a database of patient data. By correlating all data points with all other data points, only the most significant possible relationships are considered for further study. Confounding variables are dealt with according to a separate knowledge base of known data relationships. Next, multiple regression is used to look for relationships among the data. The one surprising relationship RX found was that a certain drug has a certain effect on people. Although this was not an unknown relationship, it was truly a discovery for RX, since the developers did not know this fact themselves. Thus RX could not have been programmed to learn specifically this relationship. Following discovery and testing of new relationships, the relationships are added to the knowledge base for future use.

Manufacturing Data Analysis Systems

The most well developed data analysis tool for manufacturing is called "statistical process control." Statistical process control is alive and well in many industrial plants. According to Grant, this technology monitors critical processing variables and products and alerts machine operators or supervisors to "out-of-control" situations. Various charts are generated showing averages, medians, standard deviations, moving averages, fractions of parts rejected, nonconforming parts, and other statistical measurements. The charts may indicate an acceptable range. Many of these charts show product or process variables over time, but for the most part, they are used to immediately notify process personnel that something is wrong, so they may correct the problem before more goes wrong.
The production of defective parts or a continued suspicious process reading can be clearly seen on charts showing, for example, trends or out-of-range variables.  

The Intelligent Analysis System (IAS) reported on by Yousry and Parry at AT&T in Princeton, NY, uses a combination of knowledge-based and probabilistic methods to locate causes for process problems in manufacturing environments. Statistics are used to estimate yield distributions and defect levels. When a problem is found, a rule-based expert system based on process experts' knowledge is used to diagnose a cause for the problem.  

Posco and Brown propose a hypothesis-driven diagnostic expert system which, put simply, provides heuristics to limit possible diagnoses based on a data set. The possible diagnoses become hypotheses. The system uses these hypotheses plus heuristics to determine appropriate statistical data reduction and analysis techniques. The process repeats and when the data are in an appropriate form, the expert system reaches diagnostic conclusions.  

The Parametric Interpretation Expert System (PIES), reported on by Pan and Tenenbaum, is a diagnostic tool for finding problems in semiconductor fabrication processes by analyzing parametric test data. A hierarchical causal structure with levels leading from parametric measurements to physical structure to fabrication process to root cause has been built. The system compares expected results in terms of means and standard deviations with observed results after removing what are considered bad data points. Next, the system hypothesizes about the cause at the next level of the hierarchy. It moves up the hierarchy until it reaches a conclusion about the cause of the problem.  

Another system which combines statistical methods and artificial intelligence methods has the goal of learning about laser cutting of materials.
According to Aberkane, experiments are performed to discover relationships among process variables. Statistical tests (linear regression, variance analysis to test sensitivities, and factorial correspondence analysis) are performed on the data recorded during laser cutting (material, cutting quality, and laser settings). For data sets showing significant positive results, expert system rules are generated. These rules can then be used in setting up a laser cutting process in the future.

Bharwani discusses the Process Development Advisor (PDA). PDA emphasizes assistance in acquiring process knowledge in order to understand variable relationships and to design control systems for new materials quickly. Its scope includes experimental design. The focus of the PDA system is on similarity-based reasoning, i.e., seeking similarities between current processes of interest and those learned about in the past. The types of similarities PDA seeks are geometric, mechanical, thermal, and chemical properties.

Composite Materials

The ASM Engineered Materials Handbook, Volume 1: COMPOSITES is a comprehensive manual on designing and processing many different types of composite materials. Within its many chapters, it discusses numerous relationships among different kinds of data regarding composite products and processes, and lists numerous potential variables.

Analyzing Data from the Autoclave Curing of Composite Materials

Three pieces of literature were found which address methodical data analyses for the autoclave curing of composite materials. The first, by Reid, describes LTV Aircraft Products Group's experiences using statistical process control in composites manufacturing. This company has developed a well defined, step by step process for implementing statistical process control into their
work. They have experienced success in controlling processes from raw materials to part preparation, tool preparation, autoclave curing, machining and special processes, and inspection.

The second article, by Metter, Lakin, and Houser, reports on several trend analyses of parts made from an epoxy matrix with glass fibers. The authors considered 13 variables including raw material variables, part preparation variables, and cure cycle variables. They analyzed 33 cured parts. Analyses were done to find trends related to material lot numbers, part preparation personnel, and curing personnel. Based on the results of these analyses, recommendations were made for future curing.

The third article is discussed in the next section, since it describes a study which in nature is similar to the research reported on here.

Efforts Parallel to the Research Reported Here

The third article, by Joseph et al, describing the analysis of data from the autoclave curing of composite materials, describes a comparison of statistical analysis methods (specifically regression) with neural networks, a branch of artificial intelligence which, put very simply, combines processing units in a network in which active nodes activate other nodes, eventually resulting in identification of some pattern or performing some other programmed task. The authors found that for linear data generated from a simulator for the autoclave curing of composite materials, both methods worked well and neither worked well for severely nonlinear data. The authors suggest a need for preprocessing the data using induction techniques before feeding the data to either of the other methods. The aim of the preprocessing would be to divide the data into segments which may be more linear than the original data. Although no automated
interpretation of results was attempted, this research studied the combining of a number of techniques for synthesizing the analysis of data.

The EXPLORA system, reported on by Hoschka and Klosgen, is an integrated system for analyzing and searching for interesting relationships within the data. By comparing data to types of predetermined patterns of possibly interesting statements, the system uses search algorithms to find "true" statements in the data. Statements which are generalizations or specializations of other statements are hierarchically linked. When more than one statement in one of these hierarchies is found true, only the most specific is given to the user. This is done to avoid redundancy. In the other direction, the system can also try to generalize a statement and perform a kind of discovery function, i.e., it performs induction. The system also tests for significance of results. Finally, it displays summary reports in the form of text. Because much experience was available for the authors to tap, EXPLORA was developed to perform routine interpretations in the domain of market research.

The INLEN system is an integrated set of tools for analyzing data. According to Kaufman, et al, the system searches for interesting relationships, regularities, and patterns. The system does these things using three concepts: learning of general rules, classifying facts, and discovering equations to characterize data. For each of these concepts, the development team has written modules to perform the analysis in different ways. Each module was developed as a stand alone module which could be integrated with the others.

Han and Wee have developed a system called KIPSE (Knowledge-based Interactive Problem-Solving System). KIPSE combines a number of pattern recognition and neural network tools to perform data analysis. The system allows
the user to select the type of analysis to perform. Results are in the form of a decision tree.

Anand and Kahn have developed SPOTLIGHT, a system whose purpose it is to help users to understand what is significant in point-of-sale scanner data databases. The system recognizes significant shifts among product segments and changes in distribution and prices leading to shifts and market share. It looks for patterns of common behavior across competing products. It uses heuristic methods to determine possible causes for changes in sales. It tracks product sales and movement, assesses the effectiveness of promotional strategies, and compares the performance of competing products. SPOTLIGHT is an integrated package which, along with performing these functions, has a customized graphical and textual user interface, and data retrieval capabilities.

PROSAIC (Process Signal Interpreters Assistant) is a proprietary system developed by Love et al at the ALCOA Co. in Pittsburgh, PA. The system provides its users with various analysis techniques for the analysis of data from the process of rolling mills for aluminum sheet metal. A discovery module which looks for coincidental events is also proposed. Developers based their tool construction on exploratory data analysis methods.

**Company Interviews**

Because extensive literature review throughout this research turned up very little in terms of analyzing data for manufacturing processes, eight brief, informal interviews were conducted with representatives from companies ranging from military research installations to commercial composite fabrication facilities. Two questions were asked. The first was: “What kind of data do you collect for analysis?” The second question was: “How do you analyze the data?”
There were a variety of answers to the first question, but answers to the second question were more telling. With one exception, the question about what kinds of analysis were done were answered with variations on a theme: someone with experience looks at the data to see if it looks as expected. The data these experienced people look at are generally results or quality data, such as strength measurements, void content, or glass transition temperature. When data don't look as expected, then perhaps the person will look at any available processing data and vary some processing parameter in an experiment or in future processing. Again, this is generally done based on the opinion of an experienced person. No detailed data analysis is done.

The one exception to the answers discussed above was from a commercial company who is testing a design of experiment and statistical analysis computer program for analyzing data to use for the autoclave curing of composite materials. The company declined to give details on this work, but the fact remains that they are doing significant and formal data analysis.

Conclusions

Data analysis in the curing of composite materials in an autoclave is something that is rarely done in any formal way. Data analysis, when performed at all, usually takes the form of an experienced person perusing available data and making decisions based on their own experience. Results from any kind of analysis done to measure properties such as strength of a composite object could actually be input to other data analysis systems, including the demonstration of the work reported on in this document.

Prior to this research, semantic data relationships structured for use in data analysis systems did not appear to exist for the curing of composite materials.
Like analyzing data from the process, these relationships were a matter of expert knowledge. Many relationships have been identified but had not been structured in any way in which they could be accessed and used in analysis or even in study.

It is clear that automated data analysis, aside from the very mature statistical packages, is in its infancy. Generally, it is still at a research level. Still, there are some analysis tools being developed.

Some systems offer exploratory capabilities and have been impressive with their rediscoveries of concepts. However, we have failed to learn anything new from them, and aside from RX, it is difficult to tell whether these systems were programmed (unintentionally) to discover what they discovered.

In the next chapter, the general approach taken in this research is discussed and a method for prototype system design is given.
CHAPTER III
STEPS IN THE RESEARCH AND PROTOTYPE SYSTEM DESIGN

Introduction

This research was about finding out what kinds of data are useful for analysis, identifying semantic relationships among the data, finding or developing analysis methods, and finding ways to synthesize the data and analyses to help the user make conclusions about what the data and its analysis might mean.

In this chapter, the approach to performing these tasks is detailed and a prototype system design is presented.

Approach

The first step required for this research was to find and structure kinds of data that might be useful in analysis, and finding semantic relationships among these different kinds of data.

The second step in the research was selection of analysis techniques for interpreting specific process data. This was done by surveying different techniques for performing data analysis, classifying them into six categories, and by comparing the techniques to a set of functional requirements, which are shown in Table 3. In addition, since the prototype system was to be customized for specific users, those users were asked to specify the most important kinds of analyses to them.

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TABLE 3. Functional Requirements for Analysis Techniques

FUNCTION A: Find more relationships or refine those you think you already know.

FUNCTION B: Use the identified relationships in analyzing future processes.

Abilities necessary to perform these functions:

1. Be a watchdog (follow sequences) in order to:
   - point out unexpected occurrences (exceptions)
   - note reactions (e.g., to find a causal chain or to check to make sure what is supposed to happen happens)
   - recognize unreasonable data sets (e.g., something is wrong with a sensor...here's why it seems so)

2. Compare data sets in order to:
   - evaluate part goodness
   - compare old results to current run

3. Critically look at single data sets in order to:
   - note correlations and look for causal relationships
   - recognize patterns (old or new)
   - diagnose a problem
The third step in the research was to develop a method for constructing a user tool which would use domain knowledge, data, and analyses in analyzing data during and after processing future runs. The intent is to provide a set of instructions outlining how a customized data analysis system such as this can be built. Actual tool construction is then a knowledge engineering exercise (a capturing of knowledge from literature and knowledgeable people), where experience, education, and understanding about the specific domain of interest can be brought into the system. The user of this set of instructions must be a scientist or engineer who is knowledgeable about the domain (or has access to someone else who is knowledgeable about the domain), and wishes to build a customized tool to help analyze data. The user of the constructed analysis tool is the "end user" and may be somewhat less knowledgeable about the domain but has a desire to learn more about it.

Prior to beginning this research, a method for tool construction was outlined. During the course of the research, the method was refined based on lessons learned. A recommended method for construction of an analysis tool follows. The list is generally in order of performance, but there is always some iteration of steps in any kind of construction--computer program or otherwise. The list is given at a fairly high level, but includes all of the necessary steps in construction of a tool such as the one proposed. Details of the specific implementation using this method for this research are given later in this chapter and in the next chapter. Steps in the construction method are:

1. Specify the process.

2. Specify available and desired data, including the amount of data to be provided and its format. Do this step by surveying
knowledgeable people (eventual users of the system) and literature.

3. Find the semantic relationships among the data. Do this step by surveying knowledgeable people and literature.

4. Determine what analysis techniques might be useful and desirable for the user, for this data, and for this process. Do this step by first creating a list of required functionality for a particular user and process. The list would look something like the one shown in Table 3. Next, survey available or programmable techniques and tools.

5. Determine whether combinations of data and analyses can be used effectively. Compare the kinds of data and analyses being considered to see what might be used together. Survey analysis techniques or tools which make it possible to use these combinations.

6. Survey ways to meaningfully display information to a user so that the "big picture" is quickly seen. Do this step by finding or creating user interfaces which give the user concluding information, allow for graphical components, and allow the user the option of getting more information.

7. Determine what analysis tasks will be performed by the user and what tasks will be automated. Do this step by developing a list of analysis functions and dividing the tasks according to some criteria. These criteria may be obtained from literature or from a
customized task list devised by the developer and user(s) of the system.

8. Determine the method of data input to the system. Consider whether there will be questions the user must answer. Consider whether the data will be input by hand or read in automatically from some other computer program.

9. Determine how to structure the data for system use. The structure must maintain all known relationships among the different kinds of data.

10. Make technique and tool selections based on types of analyses desired and required according to functional requirements as those shown in Table 3, the desired structure of the data, and according to the previously completed surveys, available hardware and software tools, allowable expenses, and ease of tool customization for the user.

11. Encode the kinds of data and relationships for access and use during the later analyses. (This may be as simple as setting up a database system.)

12. Write a program which accesses necessary data (either by prompting the user or by reading data from some other input source) and performs the required analyses. If possible, write the program in reusable modules for ease of maintenance and reuse. Reuse is important for transferability of the program to other kinds of data and to other users.

13. Write an introduction to the tool and encode it into an introductory user screen.
Test each module of code before combining the different modules. Use either simulated or real data for testing purposes. Show the user what they can expect at each step.

The fourth step in this research was prototype implementation using the method described above. A discussion of the prototype system design is given next. Implementation and results are discussed in the next chapter.

**Prototype System Design**

Figure 5 is a very high level picture of the proposed analysis tool. Inputs to the tool are data, semantic relationships among the different kinds of data, and selected analysis tools or methods. Outputs from the tool are newly found or confirmed semantic data relationships and other data analysis as deemed useful by the system developer and user(s).

![Figure 5. The Analysis Tool](image)

Each step of the procedure outlined above will be given here along with general results of performing that step. Specific results from the procedure and system implementation are given in the next chapter.

1. Specify the process.

   The process is the autoclave curing of bismaleimide matrix composite materials.
2. Specify available and desired data, including the amount of data to be provided and its format. Do this by surveying knowledgeable people (eventual users of the system) and literature.

Seventy-six different kinds of data which might be useful were identified by examining literature and by interviewing potential users of the system. Numerous sources were consulted.\(^1\) The different kinds of data are delineated in the next chapter.

Potential users of the system provided specific kinds of data for analysis. The kinds of data provided were measurements of time, autoclave temperature, autoclave set point temperature, temperature at the top of the part, temperature at mid-part, desired glass transition temperature, actual glass transition temperature, autoclave pressure, and several dielectric measurements.

The user who provided real data for evaluating the prototype system resulting from this research requested only an analysis of glass transition temperature, time the part spent above a certain temperature, and the maximum part temperature during processing. As will be discussed in detail later, this analysis was done; then a second analysis was programmed for autoclave pressure and the dielectric measurements.

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\(^1\)Complete citations are listed within the bibliography of this dissertation. Specifically, the sources for this step are Abrams, Adams, ASM International, Bascom, Budinski, Cumming, Diefendorf, Dominguez (1,2, and 3), Donaldson, Everest, Fiber Materials, Inc., Gilkey, Gosnell, Hansen, Harvey, Hauwiler, Hinrichs, Horton, Humphreys, Hopper, Kim, Konarski, Lang, Leissa, Levine, March (1 and 2), May, Mccarvill (1 and 2), McGann, Newman, Noton, Parker, Payne, Reinhart, Roberts, Rosen, Sanders, Schiermeier, Scola, Servais, Brian Smith, Stark, Thower, Vennard, Wang, Warnock, Watson, and Wilson.
3. Find the semantic relationships among the data. Do this step by surveying knowledgeable people and literature.

   The semantic relationships among the different kinds of data were identified as the data themselves were identified. The sources used in this step were the same as those used in step 2 above. Relationships are discussed in the next chapter.

4. Determine what analysis techniques might be useful and desirable for the user, for this data, and for this process. Do this step by first creating a list of required functionality for a particular user and process. The list would look something like the one shown in Table 3. Next, survey available or programmable techniques and tools.

   The original list of required functionality is shown in Table 3. This list was simplified to better express functionality in terms of analyzing data. A list of seven techniques, shown in Table 4 along with their relationships to the entries in Table 3, resulted.
TABLE 4. Revised Analysis Technique Functionality List

1. Find or refine relationships.
   May include:
   "Find more relationships or refine those you think you already know"
   "Point out unexpected occurrences"
   "Note reactions"
   "Note correlations and look for causal relationships"
   "Recognize patterns"

2. Use the identified relationships in analyzing future processes.
   May include:
   "Use the identified relationships in analyzing future processes"
   "Recognize unreasonable data sets"
   "Evaluate part goodness"
   "Diagnose a problem"

3. Point out exceptions.
   May include:
   "Point out unexpected occurrences"

4. Note reactions.
   May include:
   "Point out unexpected occurrences"
   "Note reactions"
   "Note correlations and look for causal relationships"
   "Recognize patterns"

5. Recognize unreasonable data sets.
   May include:
   "Recognize unreasonable data sets"

6. Evaluate part goodness.
   May include:
   "Evaluate part goodness"

7. Compare data sets.
   May include:
   "Compare old results to current run"
   "Note correlations and look for causal relationships"
   "Recognize patterns"
At the same time as these new definitions of functionality were developed, a survey of programming techniques and tools was performed. As the different techniques and tools were encountered, each was classified according to functionality similar to other tools and techniques. This resulted in yet another set of classifications for data analysis. The five categories into which the techniques and tools fell are "identify patterns", "identify trends", "identify causal relationships", "identify irregularities/inconsistencies", and "predict outcome of processing". A mapping was performed between the seven functionality categories and the five data analysis categories. The results of this mapping are shown in Table 5.
TABLE 5. Mapping Between Two Kinds of Analysis Categorization

1. Identify patterns
   Supports:
   "Find or refine relationships"
   "Note reactions"
   "Compare data sets"

2. Identify trends
   Supports:
   "Find or refine relationships"
   "Note reactions"
   "Compare data sets"

3. Identify causal relationships
   Supports:
   "Find or refine relationships"
   "Note reactions"
   "Compare data sets"

4. Identify irregularities/inconsistencies
   Supports:
   "Find or refine relationships"
   "Use the identified relationships in analyzing future processes"
   "Point out exceptions"
   "Note reactions"
   "Recognize unreasonable data sets"
   "Evaluate part goodness"
   "Compare data sets"

5. Predict outcome of processing
   Supports:
   "Use the identified relationships in analyzing future processes"
   "Evaluate part goodness"
   "Compare data sets"
Finally, a sixth category of techniques and tools was added, called "show big picture". These are techniques which would give the user an overall view of what happened during processing. Table 6 contains a listing of the six kinds of analysis and some possible associated techniques.
### TABLE 6. Analysis Techniques

<table>
<thead>
<tr>
<th>Type of Analysis</th>
<th>Some Techniques for Performing the Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify patterns</td>
<td>Matching.</td>
</tr>
<tr>
<td></td>
<td>Exploratory data analysis.</td>
</tr>
<tr>
<td></td>
<td>Statistical analysis.</td>
</tr>
<tr>
<td></td>
<td>Neural networks.</td>
</tr>
<tr>
<td></td>
<td>Categorization/classification/clustering, in order to apply rules to groups or to see if different things ought to be treated alike.</td>
</tr>
<tr>
<td></td>
<td>Look for coincidental relationships (things that happen at the same time or with the same pattern).</td>
</tr>
<tr>
<td>Identify trends</td>
<td>Make note of changes over time, particularly those that tend to stay constant or have regular patterns once changed.</td>
</tr>
<tr>
<td></td>
<td>Time series analysis.</td>
</tr>
<tr>
<td>Identify causal</td>
<td>Note things that always happen after something else happens (note similarity to “identify patterns” above).</td>
</tr>
<tr>
<td>relationships</td>
<td>Compare data to a model of known relationships, hypothesizing a relationship if data cannot be explained by the existing model.</td>
</tr>
<tr>
<td>Identify irregularities/ inconsistencies</td>
<td>Compare data to a model of expectation and find things in the current data set that should match the model, but don’t. This includes finding things that don’t happen when they should and finding things that happened that were not expected.</td>
</tr>
<tr>
<td></td>
<td>Hypothesize whether the problem is sensor-based (e.g., does the data make sense?) or there is a problem with the part.</td>
</tr>
<tr>
<td></td>
<td>Analysis of variance.</td>
</tr>
<tr>
<td></td>
<td>Significance testing.</td>
</tr>
<tr>
<td>Predict outcome of</td>
<td>Regression analysis.</td>
</tr>
<tr>
<td>processing</td>
<td>Forecasting techniques.</td>
</tr>
<tr>
<td></td>
<td>Use decision trees to determine if the process matches any known relationships.</td>
</tr>
<tr>
<td></td>
<td>Categorization/classification/clustering to match current situation to one whose consequences are known.</td>
</tr>
<tr>
<td>Show big picture</td>
<td>Show results of more than one analysis.</td>
</tr>
<tr>
<td></td>
<td>Show known and hypothesized relationships.</td>
</tr>
<tr>
<td></td>
<td>Show plots.</td>
</tr>
</tbody>
</table>
5. Determine whether combinations of data and analyses can be used effectively. Compare the kinds of data and analyses being considered to see what might be used together. Survey analysis techniques or tools which make it possible to use these combinations.

This step was performed after deciding upon which kinds of data, analyses and techniques would be used. At that point, each of the analyses of interest were considered together to see what could be used as combined evidence for some conclusion.

6. Survey ways to meaningfully display information to a user so that the "big picture" is quickly seen. Do this step by finding or creating user interfaces which give the user concluding information, allow for graphical components, and allow the user the option of getting more information.

Table 7 contains a listing of the six kinds of analysis and some possible display techniques.
### TABLE 7. Display Possibilities

<table>
<thead>
<tr>
<th>Type of Analysis</th>
<th>Display Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify patterns</td>
<td>Color or patterns showing matching or showing distance of data from other data. Plotting of different processing runs or parts together to show similarities. Exploratory data analysis. Text.</td>
</tr>
<tr>
<td>Identify trends</td>
<td>XY plots Contour plots with color or pattern changes according to value changes. Point out variables seeming to cause the change according to known relationships or otherwise where possible. Text.</td>
</tr>
<tr>
<td>Identify causal relationships</td>
<td>Causal diagram noting where current data departs from expectation. Text.</td>
</tr>
<tr>
<td>Identify irregularities/inconsistencies</td>
<td>Display distance from expectation or norm with XY plots or text. Note whether the distance is acceptable or not and why, and if a sensor problem or bad part is suspected. Use color to point out discrepancies. Use contour plots to show lack of smoothness. Plot expectation vs. result. Scatter plots to show deviation points. Text.</td>
</tr>
<tr>
<td>Predict outcome of processing</td>
<td>Equations. XY plots. Text.</td>
</tr>
<tr>
<td>Show big picture</td>
<td>Show results of more than one analysis. Show known and hypothesized relationships. Show plots.</td>
</tr>
</tbody>
</table>
Determine what analysis tasks will be performed by the user and what tasks will be automated. Do this step by developing a list of analysis functions and dividing the tasks according to some criteria. These criteria may be obtained from literature or from a customized task list devised by the developer and user(s) of the system.

A list of major tasks to be performed during the analysis was prepared. Given that the analysis tool to be researched and prototyped was to provide automation for the user, the decisions as to whether or not certain tasks should be automated were biased. However, any number of the tasks could be allocated to the user should that be desirable. Criteria aside from this type of bias included practicality and possible psychological and safety factors (concern about alienating the user by not giving choices, and about allowing, in fact insisting upon, the user having the final say in everything). Though no other criteria were used during this research, other occasions may demand criteria such as skill availability and cost. Table 8 shows the list of tasks and how they were allocated for this prototype (under the "Automated Bias" heading).

Table 8 also shows a possible distribution of tasks for making the system rely more on the user. Note that only the most mundane and the most computationally complex tasks were allocated to the computer in the "manual bias" column. All other tasks, which typically require some amount of knowledge or reasoning about the domain, would be allocated to the user. Most programs today are written in this vein, without domain knowledge and reasoning capability. This research is
intended to stretch current work and include some of that domain knowledge and reasoning. Therefore, the only tasks selected for the user are deciding whether or not the conclusions seem reasonable (after the system has done all it was programmed to do), and making final decisions.

TABLE 8. Task Distribution

<table>
<thead>
<tr>
<th>Task</th>
<th>Automated Bias</th>
<th>Manual Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read data</td>
<td>Computer</td>
<td>Computer</td>
</tr>
<tr>
<td>Select analyses to perform</td>
<td>Computer</td>
<td>User</td>
</tr>
<tr>
<td>Perform calculations</td>
<td>Computer</td>
<td>Computer</td>
</tr>
<tr>
<td>Prepare displays</td>
<td>Computer</td>
<td>User</td>
</tr>
<tr>
<td>Review database for known relationships</td>
<td>Computer</td>
<td>User</td>
</tr>
<tr>
<td>Reach conclusions (e.g., suggest hypotheses or recommend changes to a process)</td>
<td>Computer</td>
<td>User</td>
</tr>
<tr>
<td>Check for &quot;common sense&quot; of conclusions</td>
<td>User</td>
<td>User</td>
</tr>
<tr>
<td>Make decisions about future processing</td>
<td>User</td>
<td>User</td>
</tr>
</tbody>
</table>

8. Determine the method of data input to the system. Consider whether there will be questions the user must answer. Consider whether the data will be input by hand or read in automatically from some other computer program.

Data will be provided in spreadsheet format.

9. Determine how to structure the data for system use. The structure must maintain all known relationships among the different kinds of data.

The data will be structured in a hypertext format allowing relationships among the different kinds of data to be maintained.
10. Make technique and tool selections based on types of analyses desired and required according to functional requirements and related techniques and tools as shown in Tables 3-7, the desired structure of the data, and according to the previously completed surveys, available hardware and software tools, allowable expenses, and ease of tool customization for the user.

The six data analysis categories were presented to the potential users of the prototype system. They were asked to specify their preferences as to which types of analysis should be done for their customized system. The potential users selected “identify causal relationships” as their top priority. In addition, “show big picture” was developed to provide the user with an overall picture as discussed earlier.

For implementation purposes, another survey was performed which resulted in a list of commercial data analysis tools which might be used in the prototype data analysis system. Using as criteria the capabilities of the various packages, their cost, and the hardware to be used (a Macintosh® computer), two commercial software packages were chosen for the prototype. They were Claris® HyperCard® hypertext software and Informix® WingZ™ spreadsheet software.²

11. Encode the kinds of data and relationships for access and use during the later analyses. (This may be as simple as setting up a database system.)

²Macintosh and HyperCard are registered trademarks of Apple Computer, Inc. Claris is a registered trademark of Claris Corporation. Informix is a registered trademark of Informix Software, Inc. WingZ is a trademark of Informix Software, Inc.
As stated in step 10 above, HyperCard software was one of the software packages chosen for prototype implementation. HyperCard provides a means for maintaining and showing the user relationships among different kinds of data in at least two ways. One way is to list all possible relationships along with the name and other information about the data. Another way is to connect the different types of data by using HyperCard's hypertext feature. This feature allows the user to make a selection from the computer screen. Once the selection has been made, an underlying command is activated, causing the system to jump to another location to show the user the relationships of interest.

A screen (called a "card" in HyperCard) was prepared for each kind of data, showing the data name, at what point during the process the data are collected, where information about the data was obtained, why the data are important, whether or not the data are collectible, whether or not the data are manipulable, range of the data if known, and known relationships among this kind of data and other kinds of data. A section for comments was also provided.

A second set of cards was prepared which contained all of the same information with the exception of the known relationships. In place of this, "buttons" were provided for the user to select what relationships were of most interest. Upon clicking on the button using the hand-held mouse attached to the computer, the user is shown another card on which relationships of potential interest are listed. Samples of these cards are shown in the next chapter. These "stacks" of cards containing data are called DataStax.
12. Write a program which accesses necessary data (either by prompting the user or by reading data from some other input source) and performs the required analyses. If possible, write the program in reusable modules for ease of maintenance and reuse. Reuse is important for transferability of the program to other kinds of data and to other users.

Programs were experimented with and written to access data, perform the analyses of most interest to the users of the prototype system, and present the results. The resulting programs are detailed and results of the analyses are given in the next chapter.

13. Write an introduction to the tool and encode it into an introductory user screen.

An introduction to the tool was written and placed on a set of HyperCard cards. Besides an introduction to the tool, the user is given choices about analyses to be done. Samples of the cards are shown in the next chapter.

The prototype system flows as shown in Figure 6.
Introduction to the System

Explore the Data and Relationships

Start Analysis

Get Instructions

Select Analysis Desired

Analyze Glass Transition Temp and Other Temps

Analyze Autoclave Pressure and Dielectric Measurements

Let System Perform Analysis

Perform Analysis Yourself

Let System Perform Analysis

(Undeveloped)

Data are Read into System

Known Relationships are Read into System

Analysis is Performed and Plots are Drawn

Conclusions are Made

User May View Data or Other Information

Exit from System

Figure 6. Prototype Program Flow
Test each module of code before combining the different modules. Use either simulated or real data for testing purposes. Show the user what they can expect at each step.

Modules of code were tested using simulated or real data at each step of the programming process. They were tested independently and in combination with the rest of the program.

In the next chapter, the results of performing the steps presented in this chapter will be detailed. The prototype program and results from performing analyses using the prototype will be described.
CHAPTER IV
DATA AND ANALYSIS

Introduction

As data were collected and analyses were evaluated during the course of this research, an automated prototype system was slowly constructed. The system consists of two major parts. The first is a tool for studying or accessing information about the seventy-six kinds of data about the autoclave curing of bismaleimide composite materials which were identified during the first stages of the research. This tool is essentially a representation of the different kinds of data, information about the data, and relationships among the different kinds of data. This part of the system was implemented in HyperCard and is called DataStax. The second part of the system accesses the first and performs these analyses, prepares the presentations, and presents results to the user. This part of the system was implemented in WingZ.

In this chapter, the results of performing development steps, the implementation of the prototype data analysis system, and the results of using the system for analyzing real data will be described.

Kinds of Data Considered in the Research

The first step in the research was to identify the different kinds of data which might be of use when performing analysis for the process of autoclave curing of bismaleimide matrix composites. Seventy-six kinds of data were identified. They are shown in Figure 7, split out according to higher level categories. (Note that some of the
kinds of data appear in more than one place since they can apply to different categories. For example, "strength" can apply to fibers, resins, or to the part as a whole.)
Representing the Data and Relationships

As the different kinds of data were being identified, so were their various relationships with other kinds of data. Using tools available in the HyperCard application software, standard formats for presenting the data and associated information were prepared. The formats consist of text fields and buttons. Users select buttons to go elsewhere in the stack of cards as is described below and as is shown on the example cards pictured in this section.

Each kind of data and its associated information were represented in two similar ways. First, each of the different kinds of data and its associated information were shown on a single card. An example of this first kind of card is shown in Figure 8. Besides information about the different kinds of data, these cards contain buttons allowing the user to choose to see a definition of the kind of data being represented, go to the bibliography to see what references were used in preparing the cards, or move to other cards in the stack.
Figure 8. A Sample Card Showing Information About One Kind of Data

Each card shows the data name, at what point during the process the data are collected ("B,D, A" stands for "Before, During, After"), where information about the data was obtained, why the data are important, whether or not the data are collectible, whether or not the data are manipulable, range of the data if known, and known relationships among this kind of data and other kinds of data. A section for comments was also provided. A listing of the different kinds of data and all of their associated information, including all known relationships was generated directly from HyperCard and is contained in Appendix A.

For each of these cards, a second card was prepared, showing a definition of the data being described. A sample definition card is shown in Figure 9. A listing of the information contained on these cards, also generated directly from HyperCard, is contained in Appendix B.
The second way the data were represented was identical to the first, except instead of relationships with other kinds of data being listed on the card, "buttons" were placed on the card for the user to select what relationships were of most interest. Upon clicking on one of the buttons, the user is shown another card on which relationships of potential interest are listed. A sample of this kind of card is shown in Figure 10.
**Figure 10. A Second Way of Representing the Data**

A definition card also exists for each of these cards. For this second kind of representation, cards showing relationships were prepared. These are the cards which the user sees according to the relationship button selected on a card like that shown in Figure 10. Figure 11 is a sample of this kind of card.
Figure 11. A Relationship Card

The stacks of cards containing the data cards, the definition cards, and in the case of the second stack, the relationship cards, are fronted by a set of introductory cards. These are provided so that the user may choose what to look at at any given time. These introductory cards have a series of buttons on which the user may click to move to another card to get information of interest. The introductory cards are divided according to the higher level categories as shown in Figure 7. For example, the first card, after giving a short introduction to the stack of cards, gives the user the choice of looking at material data, part data, or environment/process data. This is the first breakout of different kinds of data in Figure 7. After making a choice from the three selections, the user is taken to a card which gives more choices about what data to look at next. The tree shown in Figure 7 is traversed until the user arrives at choices of actual kinds of data, then is taken to data cards. All of the introductory cards are pictured in Appendix C.
Potential users of the system provided specific kinds of data for analysis and provided input as to the types of analysis they desired. The kinds of data provided were minute by minute measurements of time, autoclave temperature, autoclave set point temperature, temperature at the top of the part, temperature at mid-part, desired glass transition temperature, actual glass transition temperature, autoclave pressure, and several dielectric measurements.

**Analyses Used in the Program**

The final user of this prototype system requested only an analysis of glass transition temperature, time the part spent above a certain temperature, and the maximum part temperature during processing. An analysis for these data was written, then a second, different kind of analysis was programmed for autoclave pressure and the various dielectric measurements. Each of these analyses are described generally below. Detailed implementation information is given in the next section.

Both sets of kinds of data were to be analyzed for the purpose of identifying causal relationships. When choosing methods for analysis for the first set, the bias of the user was toward looking for reasons the glass transition temperature (a final product measurement) was not in the desired range, if that was the case. Therefore, the first program looks at all of the different temperature measurements and combines them to reach conclusions about how temperature during processing might affect the glass transition temperature. A difference chart was also prepared for considering how quickly temperatures changed during the process. Finally, methods for going back to the HyperCard stack to present the user with more information about implications of the results of the analysis were explored.

After testing this first program, a second kind of analysis was performed on the second set of data, the autoclave pressure and dielectric measurements.
Because this second set of data did not include a final product measurement (e.g., a quality measurement), the analysis selected was quite different. It still has the bias of looking for things that might cause other things. This analysis looks at all of the data, trying to find things that seem to happen at the same time or immediately following something else, fairly consistently.

For both of the sets of kinds of data, a "big picture" was given at the end of the analysis, consisting of conclusions, plots, and listings of known relationships.

Implementation of the Analyses

An introduction to the analysis tool was written and placed on a set of HyperCard cards. Besides the introduction, this stack gives the user choices about analyses to be done. These cards are shown in Figures 12-17. Each is explained below.

Figure 12 is a card containing an introduction to the analysis tool. From this card the user may choose to get further instructions, to explore the HyperCard stack of data and relationships (DataStax), or to go directly into the analysis. Choosing to get instructions takes the user to the card shown in Figure 13. Choosing to explore data and relationships take the user to DataStax. Choosing to start the analysis takes the user to the card shown in Figure 14, which gives the user options for data analysis.

Selecting option A on the card shown in Figure 14 takes the user to the card shown in Figure 15, which presents choices about an analysis for glass transition temperature, time the part spent above a certain temperature, and maximum part temperature during processing. Choosing option B on the card shown in Figure 14 takes the user to the card shown in Figure 16, which presents choices about an analysis for autoclave pressure and dielectric measurements. Figures 15 and 16 are cards which offer the user the choice of continuing the analysis alone or letting the system perform
the programmed analysis. Choosing the button for continuing the analysis alone takes
the user to the card shown in Figure 17.

Figure 17 shows a dummy card, since this option was not developed. It is shown as an option here to imply that a fully developed user-oriented analysis system would allow the user to make choices each step of the way, including the choice of manual analysis. This option was not developed for this system, since the intent of the research was to provide an automated system for the user. Some considerations for developing this option are discussed in the next chapter.

Selecting the button for instructing the system to perform the programmed analysis begins a multi-step analysis. Details are given below.
This program will assist you in analyzing data from the autoclave curing of certain composite materials. It has been customized for certain users and contains analysis techniques of most interest to these users.

The analyses in this program look for causal relationships between variables, attempt to identify processing trends, and give an overall view of what happened to a part before, during, and after processing.

You may also choose to explore an included database modeling relationships between the different kinds of data involved in this process.

Choose one of the options below and click on the button to continue.

- Explore DataStax, a model of data and relationships for this process.
- Start analysis.
- Get specific instructions on installing and using this program.

Figure 12. An Introductory Card for the Analysis Program

This program is written partially with WingsTM software and partially with HyperCard® software. You will need both of these installed on your hard disk in order to use the program. All of the files associated with this program should be placed within a single folder on your Macintosh® computer.

The first time you use this program, the computer will ask you where certain files are. You must then find the files and double-click on them in the usual Macintosh® computer's way. After you have done this once, the program will know where to look the next time it needs these files (unless you have moved the files).

To use this program, you must be familiar enough with the Macintosh computer to be able to open files and use buttons, menus, and scroll bars. If you do not know how to use these Macintosh tools, please refer to your Macintosh User's Manual.

This program is System 7 compatible.

To conclude.

Figure 13. A Card With Instructions on System Use
**MANUFACTURING DATA ANALYSIS**

You have two options. Make your choice by clicking on A or B below.

- **A** Analyze this data: glass transition temperature vs. time above 440°F and maximum part temperature during processing.
- **B** Analyze this data: absolute pressure and various dielectric readings.

(Figure 14. A Card Showing Choices of Data for Analysis)

---

Analysis desired: Glass transition temperature, time above 440°F, maximum part temperature.

Do you want the program to direct the analysis or do you wish to direct the analysis yourself?

Click on one of the choices below

- **Do It Yourself**
- **Let The Program Do It**

(Figure 15. User Automation Options for The First Type of Analysis)
Figure 16. User Automation Options for The Second Type of Analysis

This incomplete option has been provided to demonstrate the possibility of the user being able to perform an analysis on their own. If this were a fully developed option, there would be recommended analyses for this type of data. The user would then click on a button which would open a spreadsheet, read in the data of interest and provide options for the user to perform an analysis.

Figure 17. A Dummy Card for Choosing Manual Analysis
The First Analysis Implementation Details and Presentation to the User

Before writing a program to perform calculations and present conclusions to user, a user interface was developed using tools available in the WingZ application package. The interface consists of a series of screens containing number fields, text fields, chart fields, and buttons from which users can make choices about what to look at next. The number, text, and chart fields can be filled in based on the different kinds of data for which the analysis was written. Figures showing the different user screens prepared for the user interface, filled in during the analysis of real data, are shown throughout this section as the steps used in converting the raw data to pictures and conclusions are given.

The first type of analysis looks at glass transition temperature, the amount of time the part spent above a certain temperature during processing, and the maximum part temperature during processing. The program performs the following steps.

1. Reads known relationships among glass transition temperature (the single final product variable being analyzed) and other kinds of data from the HyperCard program and pastes them into a window onto a conclusions screen on a specially prepared spreadsheet. This conclusions screen is shown in Figure 18. There are other entries on this screen, and these will be described as the steps of the program that created them are described.
2. Reads raw data from a provided spreadsheet of data and pastes it onto the new spreadsheet. An example of how this data looks is shown in Figure 19. Choices on this screen are to return to the screen from which the user came or to quit the analysis.
Figure 19. Data Read into a Prepared Spreadsheet for the First Type of Analysis
3. Plots all of the time and temperature data and places the plot on the conclusions screen, which is shown in Figure 18. Prepares a second plot identical to the first but larger in order for the user to see the plot more clearly if desired. These plots are implemented in color but for the purposes of this dissertation, clear differentiation between the variables are unnecessary.

4. Places the desired and actual glass transition temperatures on a window the user can access from the conclusions screen. The screen these temperatures are placed on is shown in Figure 20. Other entries on this screen will be discussed as the program steps that prepared them are described.
The part's Glass Transition Temperature (Tg) was significantly lower than desired.

<table>
<thead>
<tr>
<th></th>
<th>Actual Tg</th>
<th>Desired Tg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>453.00</td>
<td>495.00</td>
</tr>
</tbody>
</table>

The part spent 53.00 minutes above 440 degrees during a cure cycle of 107.0 minutes. The part reached a maximum temperature of 459.00 degrees during the cure. It spent a total of 10.00 minutes at this temperature.

The three most obvious ways to increase the glass transition temperature are to:
1) Increase the set point temperatures during the cure, or
2) Increase the cure time, or
3) Some combination of these two.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables may affect or be affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStar.

Click Here To Go Back  Click Here for More Analysis  Quit the Analysis

Figure 20. A Results Screen for the First Type of Analysis

5. Counts the number of minutes in the cure cycle by finding the last row of data on the spreadsheet and identifying the number representing minutes in that row. This information is used later in determining how much time was spent at certain temperatures in proportion to total processing time.

6. Counts the number of minutes in which the part is above a given temperature. Since two measurements are given for part temperature for each minute (top of part and mid-part), the program counts the minutes for each and uses the lower of the two results in the next step.
7. Places the total number of minutes above the given temperature and
the total number of minutes in the cure cycle on the screen shown in
Figure 20.

8. Creates a pie chart showing the proportion of minutes the part spent
above the given temperature to the minutes the part spent at or below the
given temperature. This chart is placed near the numbers which were
placed during step 7, and is part of the screen shown in Figure 20.

9. Searches for the highest top of part temperature and the highest mid-part
temperature reached during the cure cycle. It selects the lower of the two
to present as the highest part temperature reached, since that would the
highest temperature which the whole part reached.

10. Counts the total number of minutes the part spent at its maximum
temperature during processing and places this number along with the
maximum part temperature on the screen shown in Figure 20.

11. Creates a pie chart showing the proportion of minutes the part spent
at its maximum temperature to the minutes spent below the maximum
temperature. This chart is placed near the numbers which were
placed during step 10, and is part of the screen shown in Figure 20.

12. Compares the actual glass transition temperature to the desired glass
transition temperature to determine whether the actual number is in the
range of the desired number. The acceptable range was calculated to be
the expected number plus or minus 10 degrees Fahrenheit. (The
acceptable range is determined in consultation with experts and can easily
be changed in the program if the user of the system requires more or less
accuracy.)
13. Depending on the result of step 13, the program makes general statements about how the glass transition temperature may be raised or lowered in future processing, or if the glass transition temperature was in the desired range, how this same result might be attained in other ways. These general statements are programmed in consultation with experts and literature and used when appropriate. Appropriate statements are placed in the conclusion window on screen shown in Figure 18, at the top of the screen shown in Figure 20, and in a window giving more details as shown toward the bottom of the screen shown in Figure 20. The possible statements which may be placed in this last window are shown in Figure 21.
The three most obvious ways to increase the glass transition temperature are to:

1) increase the set point temperatures during the cure, or
2) increase the cure time, or
3) some combination of these two.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables then affect or are affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStax.

If the higher glass transition temperature is undesired and you want to try to lower it, the two most obvious ways to decrease the glass transition temperature are to:

1) decrease the set point temperatures during the cure, or
2) decrease the cure time, or
3) some combination of these two.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables then affect or are affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStax.

If you want to experiment with different ways to get the same glass transition temperature, the two most obvious possibilities are:

1) increase the set point temperatures and cure for a longer period of time, or
2) increase the set point temperatures and cure for a shorter period of time.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables then affect or are affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStax.

Figure 21. Potential General Statements about Glass Transition Temperature
14. Brings together the various values calculated (time the part spent above a certain temperature, time the part spent at its maximum temperature, and whether the glass transition temperature was below, within, or above its desired range). If the glass transition temperature is too high and one or both of the other values is also high (what constitutes "high" or "low" is also programmed in consultation with experts), a statement is made about how the high values might be related. If the glass transition temperature was too low and the time the part spent above the given temperature or the time the part spent at the maximum part temperature during processing was low, a statement is made about how these values might be related. These possible conclusions are shown in Figure 22 and are placed on the screen shown in Figure 20.

![Figure 22. Potential Conclusions about Glass Transition Temperature and Other Calculated Temperatures]

15. Creates a new table of the original data on the new spreadsheet for showing temperature differences between from minute to minute.
16. Goes through the new table of data minute by minute counting and highlighting significant differences in autoclave or part temperature, either increasing or decreasing. (A number representing a significant difference is also determined in consultation with experts.)

17. Makes a new table of data which consists of numbers representing the differences in temperature from minute to minute. An example of this table is shown in Figure 23.
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Figure 23. A Table Showing Minute by Minute Temperature Differences
18. Plots the temperature differences. An example of this plot is shown in Figure 24. This plot is also implemented in color, but for this dissertation, variables need not be clearly differentiated.

Figure 24. A Plot Showing Minute by Minute Temperature Differences

19. Looks for potential relationships between the various temperature measurements (glass transition temperature, time the part spent above a given temperature, and time the part spent at maximum temperature) and large numbers of significantly increasing or decreasing differences in autoclave or part temperature from minute to minute. (Again, what constitutes a large number of significant differences in temperature from minute to minute is determined in consultation with experts.) Potential
conclusions are shown in Figure 25. Appropriate conclusions are placed on the screen shown in Figure 20.
There were many large increases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in blue represent the times at which these large increases occurred.

Since the glass transition temperature is higher than desired, it is possible that this jumping to much higher temperatures quickly contributed to the problem. Heat sets the curing process in faster motion. A slower heatup rate or a smaller increase in set point each minute may help.

There were many large decreases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in blue represent the times at which these large decreases occurred.

Since the glass transition temperature is lower than desired, it is possible that jumping around between temperatures made it impossible for the part to stay at a high enough temperature long enough. A slower heatup rate or a longer period of time may help, both in terms of stability and in terms of getting the high temperatures needed for your desired glass transition temperature.

It is possible that the number of large decreases in temperature over a short time will lead to thermal stresses in your part. This can lead to cracking. Please look at DataStat under "cracking" to see how critical this might be for you. If it seems critical, slowing down the cooling rate by decreasing the temperature set point at a lower rate might be wise.

Figure 25. Potential Conclusions about Glass Transition Temperature and Significant Minute by Minute Changes in Temperature During Processing
20. Reads potential relationships from HyperCard's relevant relationship cards and pastes them into a window for the user's perusal. The screen on which these appear is shown in Figure 26.

![Figure 26. A Screen Showing Potential Relationships Between Glass Transition Temperature and Other Variables, and Possible Implications of These Relationships](image)

After all of the analysis is done and results are placed on appropriate screens, the user looks through the results like this:

- The screen shown in Figure 18 is presented to the user. The user may read what is contained on this screen, quit the analysis, or ask for more information. After this screen, each screen which the user may choose
to see offers the choices of quitting the analysis or returning to the screen from which the user came.

If from the screen shown in Figure 18, the user asks for more information, the screen shown in Figure 27 is presented. This screen presents the user’s next choices. The three options on this screen are to get more analysis information, see a larger plot identical to the one on the conclusions screen shown in Figure 18, or see a list of potential implications for the situation. An example of the list of potential implications was shown in Figure 26. If the user chooses to get more analysis information, the screen shown in Figure 20 is presented. The screen in Figure 20 shows the results of steps 4, 7, 8, 10, 11, and 14 above.
If from the screen shown in Figure 20, the user chooses to see more analysis information, a screen like the one shown in Figure 28 is presented.
There were many large increases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in blue represent the times at which these large increases occurred.

Since the glass transition temperature is lower than desired, it is possible that jumping around between temperatures made it impossible for the part to stay at a high enough temperature long enough. A slower heatup rate over a longer period of time may help, both in terms of stability and in terms of getting the high temperatures needed for your desired glass transition temperature.

**Figure 28. A Screen Showing More Analysis Information From the First Type of Analysis**

This screen has room for results obtained from step 19. It also offers the user the opportunity of looking at the data which underlies all of the results. An example of that data was shown in Figure 19. A final choice on the screen shown in Figure 28 is to get still more analysis information. If this is chosen, the screen shown in Figure 29 is presented.
Figure 29. A Final Screen Showing More Analysis Information From the First Type of Analysis

This screen has room for more results from step 19 and offers to show the user the graph of differences generated in step 18 and shown in Figure 24.

The Second Analysis Implementation Details and Presentation to the User

Before writing a program to perform the second analysis, a user interface similar to the first was developed. Again, figures showing the different user screens are shown throughout this section as the steps used in converting the raw data to pictures and conclusions are given.
The second type of analysis looks at autoclave pressure and several dielectric measurements (symbolized here as MPhase, Mgain, Diss, and F Diss). The program performs the following steps.

1. Reads raw data from a provided spreadsheet and pastes it onto the new prepared spreadsheet. An example of how this data looks is shown in Figure 30. Choices on this screen are to return to the screen from which the user came or to quit the analysis.
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>24</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
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<td></td>
</tr>
<tr>
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</tr>
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<td>24.90</td>
<td>24.90</td>
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<td>-0.19</td>
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<td>24.90</td>
<td>-0.19</td>
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</tr>
<tr>
<td>48</td>
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<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>-0.19</td>
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<td></td>
</tr>
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<td>-0.19</td>
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<td></td>
</tr>
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<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
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<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
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<td>54</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
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<tr>
<td>55</td>
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<td>0.00</td>
<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>56</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>57</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>2.00</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>59</td>
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<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>60</td>
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<td>0.00</td>
<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>0.00</td>
<td>0.00</td>
<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>2.00</td>
<td>0.00</td>
<td>24.90</td>
<td>24.90</td>
<td>-0.19</td>
<td>0.28</td>
<td></td>
</tr>
</tbody>
</table>

Figure 30. Data Read into a Prepared Spreadsheet for the Second Type of Analysis
2. Plots all of the autoclave pressure and dielectric data and places the plot on the conclusions screen, which is shown in Figure 31. Prepares a second plot identical to the first but larger in order for the user to see the plot more clearly if desired. Again, these plots are implemented in color but for this purposes of this dissertation, clear differentiation between the variables is unnecessary.

![Figure 31. A Conclusions Screen for the Second Type of Analysis](image)

3. Averages each ten rows of each column of original data and makes a new table of these averages. An example of this new table is shown in Figure 32.
4. Looks at the averaged data and determines where there are significant increases or decreases. Significant changes occur when a change of some number of units has taken place over the periods. The number of units used to determine significant changes is determined in consultation with experts and may be easily changed in the program when necessary. The program then creates a new chart where significant increases are entered in columns as "1", significant decreases are entered in columns as "-1", and where no significant changes have taken place, "0" is entered. An example of this type of table is shown in Figure 33.

<table>
<thead>
<tr>
<th>A/C Pressure</th>
<th>Date</th>
<th>Dose</th>
<th>1/2Phase</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>-22.06</td>
<td>-24.47</td>
<td>-0.21</td>
<td>-23.50</td>
</tr>
<tr>
<td>0.80</td>
<td>-22.20</td>
<td>-21.00</td>
<td>-0.82</td>
<td>-23.44</td>
</tr>
<tr>
<td>0.60</td>
<td>-23.67</td>
<td>-22.91</td>
<td>-0.21</td>
<td>-0.23</td>
</tr>
<tr>
<td>2.40</td>
<td>5.68</td>
<td>0.77</td>
<td>4.16</td>
<td>4.64</td>
</tr>
<tr>
<td>88.60</td>
<td>-3.03</td>
<td>-3.26</td>
<td>-23.49</td>
<td>-1.24</td>
</tr>
<tr>
<td>100.20</td>
<td>-0.59</td>
<td>0.11</td>
<td>-4.66</td>
<td>-9.19</td>
</tr>
<tr>
<td>100.20</td>
<td>-5.28</td>
<td>-5.76</td>
<td>-15.95</td>
<td>-21.01</td>
</tr>
<tr>
<td>100.20</td>
<td>-7.85</td>
<td>-8.31</td>
<td>-23.77</td>
<td>-21.77</td>
</tr>
<tr>
<td>100.40</td>
<td>-8.13</td>
<td>-8.11</td>
<td>-8.78</td>
<td>-21.83</td>
</tr>
</tbody>
</table>

Figure 33. An Example of a New Table Showing the Significant Increases and Decreases in the Data for the Second Type of Analysis
5. Compares all of the columns of increase/decrease data shown in Figure 33 looking for patterns. For this research, patterns are defined as consistencies in behavior, meaning that for each set of variables being investigated, similar things happen—for example two variables increase together over time. Consistent patterns noted as potential relationships are those in which two variables have at least two occasions on which they seem to do the same thing, and no more than one occasion on which they seem to do different things (or vice versa—doing different things consistently may also show a relationship). The kinds of patterns investigated in the program are:

- Two different kinds of data increase significantly at the same time.
- Two different kinds of data decrease significantly at the same time.
- One kind of data increases significantly while another kind of data decreases significantly.
- One kind of data increases significantly immediately before another kind of data increases significantly.
- One kind of data decreases significantly immediately before another kind of data decreases significantly.
- One kind of data increases significantly immediately before another kind of data decreases significantly.
- One kind of data decreases significantly immediately before another kind of data decreases significantly.
As patterns indicating potential relationships are found, counters keep track of what and how many times any of these things happen, and the relationships themselves are listed in temporary text fields on the spreadsheet which look like those shown in Figure 34.
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Dia and MPRes</td>
<td>The first of these variables increases significantly immediately before the second one increases significantly during this time period: 30.00 to 50.00 minutes The increase in the first variable may be causing the increase in the second.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mgen and F Dia</td>
<td>The first of these variables increases significantly immediately before the second one increases significantly during this time period: 20.00 to 40.00 minutes The increase in the first variable may be causing the increase in the second.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F Res and MPRes</td>
<td>The first of these variables increases significantly immediately before the second one increases significantly during this time period: 30.00 to 50.00 minutes The increase in the first variable may be causing the increase in the second.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mgen and F Dia</td>
<td>Both of these variables decrease significantly during this time period: 60.00 to 70.00 minutes There may be something causing both of these variables to react significantly during this time.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 34.** Temporary Text Fields Which Hold Potential Relationships for the Second Type of Analysis
6. Looks at the tallied numbers of potential relationships and selects the consistent patterns. For the variables which have these consistent relationships, the program copies the temporary text field holding the relationships and transfers them to a window which the user can access from the conclusions screen shown in Figure 31. This new window is shown on the screen pictured in Figure 35.

![Figure 35. Hypothesized Relationships Which Can Result from the Second Type of Analysis](image)

7. Makes a general conclusion about whether or not potential relationships exist. This conclusion is placed on the original conclusions screen which is shown in Figure 31.
After all of the analysis steps for this second kind of analysis are done and results are placed on appropriate screens, the user looks through the results like this:

- The screen shown in Figure 31 is presented to the user. The user may read what is contained on this screen, quit the analysis, or ask for more information.

- If from the screen shown in Figure 31, the user asks for more information, the screen shown in Figure 36 is presented. This screen presents the user's next choices. The options on this screen are to see a list of potential relationships, see a larger plot identical to the one on the conclusions screen shown in Figure 31, see the underlying data, return to the conclusions screen, or quit the analysis. An example of the list of potential relationships was shown in Figure 35. If the user chooses to see the underlying data, data like that shown in figure 30 is presented. The other options are self-explanatory.
Results Obtained From Analyzing Real Data - The First Type of Analysis

Two complete sets of data were analyzed. First, the results of the glass transition temperature, time the part spent above a given temperature, and maximum part temperature during processing are given for both sets of data.

The actual glass transition temperature of the first composite part made was 538 degrees Fahrenheit. The desired glass transition temperature was 495 degrees Fahrenheit. After performing the analysis as described earlier, the program presented results to the user.
In the format shown in Figure 18, known relationships were presented to the user. A plot was made of time and all of the temperatures, including the single glass transition temperature. A general conclusion was shown. It was:

"The part's glass transition temperature was higher than desired. There are a number of possible ways to change this. Click on the red button [the button which directs the user to “click here for more information”] below to get more information."

In the format shown in Figure 20, the actual and desired glass transition temperatures (538 and 495 degrees Fahrenheit, respectively) were presented textually. The part spent 199 minutes out of 259 minutes above 440 degrees during the cure. The part reached a maximum temperature of 487 degrees Fahrenheit and spent 11 minutes at that temperature. These last two results were given textually and in pie chart form.

Finally, on the screen shown in Figure 20, the following statement was made:

"If the higher glass transition temperature is undesired and you want to try to lower it, the three most obvious ways to decrease the glass transition temperature are to:

1) decrease the set point temperatures during the cure, or
2) decrease the cure time, or
3) some combination of these two.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables then affect or are affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStax."

A conclusion about the amount of time spent at high temperatures and the high glass transition temperature was also given on the screen shown in Figure 20. This conclusion was:

"Since the glass transition temperature is higher than desired, it is possible that the excessive amount of time the part spent above 440 degrees and
the excessive amount of time the part spent at its maximum temperature during cure may be the problem."

On a screen like that shown in Figure 28, this statement was made:

"There were many large increases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in blue represent the times at which these large increases occurred. Since the glass transition temperature is higher than desired, it is possible that this jumping to much higher temperatures quickly contributed to the problem. Heat sets the curing process in faster motion. A slower heatup rate or a smaller increase in set point each minute may help."

During this cure cycle, there was also many large decreases in the part temperature. This statement was made on a screen like that shown in Figure 29:

"There were many large decreases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in green represent the times at which these large decreases occurred. It is possible that the number of large decreases in temperature over a short time will lead to thermal stresses in your part. This can lead to cracking. Please look at DataStax under "cracking" to see how critical this might be for you. If it seems critical, slowing down the cooling rate by decreasing the temperature set point at a lower rate might be wise."

Finally, on a screen like that shown in Figure 26, these relationships to glass transition temperature which show possible implications in this situation were given:

"Following are the close relationships to glass transition temperature for these kinds of data:

Brittleness
Polymerization, degree of
Glass transition temperature (Tg)
Strength
Stiffness
Delaminations/debonds

1. A high degree of polymerization generally means a high degree of strength and stiffness since molecules are not free to move about. This in turn leads to a higher degree of brittleness and a higher glass transition temperature (Tg). (Watson pg 103)

2. As stiffness increases, brittleness increases. (Parker)"
3. The brittleness of composites makes impact resistance low. Although damage may not always be apparent from the impact surface, internal crazing and debonding may be present. (Rosen and Dow pg 180, Horton and McCarty pg 261)

4. Material loses stiffness above the glass transition temperature (Tg). (McCarvill (1) pg 135)

Following are the close relationships to glass transition temperature for these kinds of data:

- Buckling
- Stiffness
- Strength
- Stress
- Use environment
- Yarns
- Yarns/weave
- Cracks
- Delaminations

1. Heavy loading (stress) or severe impact can cause buckling. (Higher compressive strength results in heavier load tolerance, thus buckling occurs at higher stress.)

2. A smaller diameter fiber (yarn) has greater tensile strength, but may buckle faster under compressive stress. (Diefendorf pg 51)

3. Fatigue causes buckling, delaminations, and cracks, which in turn cause more damage, including strength and stiffness reduction. (Wang pg 246, Kim pg 436)

4. Cracks may form from thermal stresses in the part. This can happen when thermal stresses exceed matrix strength. These cracks usually stay within the resin. (ASM pg 15)

5. A longer float (in the fabric's weave) yields higher composite strength.

6. Higher temperatures generally decrease material strength. (ASM pp 362-415)

7. Material loses stiffness above the glass transition temperature. (McCarvill (1) pg 135)

8. A loose weave results in decreased strength. (Dominguez (3) pg 149)

Following are the close relationships to glass transition temperature for these kinds of data:
Moisture
Chemical structure & additives
Exothermic reaction
Gel point
Glass transition temperature (Tg)
Layup environment
Out time
Stiffness
Stress
Tack
Use environment
Viscosity
voids

Resin absorbs moisture (or humidity), which changes its properties. (Lang pg 740) Possible changes (which increase with lengthy out time) before and during cure include:

1. increased tack, making materials difficult to handle
2. lower viscosity throughout the cure (Warnock)
3. changed gel point (Warnock, Hauwiller)
4. because of the possible chemical structure change, deactivate the catalyst in the resin (Warnock)
5. slow exothermic reaction, possibly causing increased void content (Roberts pg 748)

After cure, moisture can:

1. reduce stiffness and service temperature capability (higher moisture absorption and heat increase these property reductions) (Marsh (1) pg 16)
2. decrease the glass transition temperature (Tg) of resins (called "Wet Tg"); drying increases the Tg again. (Warnock, Humphreys and Rosen pg 226)
3. cause swelling which causes stresses in the material (Humphreys and Rosen pg 228)

High void content makes a part susceptible to moisture absorption (ASM pg 662)

Following are the close relationships to glass transition temperature for these kinds of data:

Degree of cure
Degree of cross-linking
Glass transition temperature (Tg)
Time
Temperature, mid-part
Temperature, top-part
Temperature, set point
Viscosity

1. Resin viscosity (given indirectly by dielectric loss factor) decreases as degree of cure advances.
2. The sought degree of cure includes a certain degree of resin cross-linking and a certain glass transition temperature (Warnock), with no measurable viscosity. Thus, when viscosity is no longer measurable (that is, when the gel point has been reached), temperatures must be kept up in order to encourage crosslinking and raise the glass transition temperature of the material. (Roberts pg 754) A longer cure results in an increased glass transition temperature. (ASM pg 663)

3. A higher cure temperature results in a higher glass transition temperature. (ASM pg 811)

Following are the close relationships to glass transition temperature for these kinds of data:

Drape
Glass transition temperature (Tg)
Tack

"For a resin to exhibit good tack, drape, and handleability, it needs to have an uncured Tg less than ambient temperature". (Marsh (1) pg 16)

Following are the close relationships to glass transition temperature for these kinds of data:

Glass transition temperature (Tg)
Use environment

1. A material with a higher glass transition temperature can operate in higher service temperatures. (Hauwiller)

2. Moisture decreases the Tg of resins. This Tg is called the "Wet Tg". As the resin dries, the Tg increases again. (Warnock, Humphreys and Rosen pg 226)

3. Material loses stiffness above Tg. (McCarvill (1) pg 135)"

The actual glass transition temperature of the second composite part made was 453 degrees Fahrenheit. The desired glass transition temperature was 495 degrees Fahrenheit. After performing the same type of analysis as just described, the program presented results to the user.
In the format shown in Figure 18, known relationships were presented to the user. A plot was made of time and all of the temperatures, including the single glass transition temperature. A general conclusion was shown. It was:

"The part's glass transition temperature was lower than desired. There are a number of possible ways to change this. Click on the red button below to get more information."

In the format shown in Figure 20, the actual and desired glass transition temperatures (453 and 495 degrees Fahrenheit, respectively) were presented textually. The part spent 53 minutes out of 107 minutes above 440 degrees during the cure. The part reached a maximum temperature of 459 degrees Fahrenheit and spent 10 minutes at that temperature. These last two results were given textually and in pie chart form. Finally, on the screen shown in Figure 20, the following statement was made:

"The three most obvious ways to increase the glass transition temperature are to:

1) increase the set point temperatures during the cure, or
2) increase the cure time, or
3) some combination of these two.

Remember that other part or cure variables may affect or be affected by glass transition temperature and set point temperatures as well. Look at the list of known relationships shown with the conclusions to make sure that you are aware of the other variables related to glass transition temperature. These variables then affect or are affected by other variables. If you want to explore this or the set point temperature data relationships further, quit the analysis and go back to look directly through DataStax."

On a screen like that shown in Figure 28, this statement was made:

"There were many large increases in part temperature during the cure. You can see this by clicking on the button below to see the underlying data. The numbers in blue represent the times at which these large increases occurred. Since the glass transition temperature is lower than desired, it is possible that jumping around between temperatures made it impossible for the part to stay at a high enough temperature long enough. A slower heatup rate over a longer period of time may help, both in terms of stability and in terms of getting the high temperatures needed for your desired glass transition temperature."
Finally, on a screen like that shown in Figure 26, the relationships to glass
transition temperature which show possible implications in this situation were given.
Since this analysis was for the same kind of data as before, the same list of relationships
and potential implications was given.

Usefulness of the Results

The final user of this prototype system was given the above results and asked
about whether or not they were useful. Her response was that nothing new was
learned, but it had given her ideas for further experimentation with the curing process.

Results Obtained From Analyzing Real Data - The Second Type of Analysis

The results of the analysis of autoclave pressure and dielectric measurements are
given here for both sets of data. After performing the analysis for this data as described
earlier, the program presented results to the user.

In the format shown in Figure 31, a plot was made of time and all of the data for
the first composite part. A general conclusion was shown. It was:

"There are potential causal relationships among these kinds of data.
Click on the red button below to read about the potential relationships."

When the user chooses to see the potential relationships identified by this
analysis, a screen like the one in Figure 35 is shown. For this particular analysis, the
following results were given:

"F Diss and Diss
Both of these variables increase significantly during this time period:
20.00 to 30.00 minutes
There may be something causing both of these variables to react significantly
during this time.

Diss and F Diss
The first of these variables increases significantly immediately before the second
one increases significantly during this time period:
10.00 to 30.00 minutes
The increase in the first variable may be causing the increase in the second."
This is the last potential relationship found for F Diss and Diss.

--------------------------------------------------------------------------------------------------

F Diss and MPhase
The first of these variables increases significantly immediately before the second one increases significantly during this time period:
20.00 to 40.00 minutes
The increase in the first variable may be causing the increase in the second.

--------------------------------------------------------------------------------------------------

F Diss and MPhase
The first of these variables increases significantly while the other decreases significantly during this time period:
20.00 to 30.00 minutes
There may be something causing these variables to react in opposite directions during this time.

--------------------------------------------------------------------------------------------------

MPhase and F Diss
The first of these variables decreases significantly immediately before the second one increases significantly during this time period:
10.00 to 30.00 minutes
The decrease in the first variable may be causing the increase in the second.

--------------------------------------------------------------------------------------------------

This is the last potential relationship found for F Diss and MPhase.

--------------------------------------------------------------------------------------------------

Diss and MPhase
The first of these variables increases significantly immediately before the second one increases significantly during this time period:
20.00 to 40.00 minutes
The increase in the first variable may be causing the increase in the second.

--------------------------------------------------------------------------------------------------

Diss and MPhase
The first of these variables increases significantly while the other decreases significantly during this time period:
10.00 to 20.00 minutes
There may be something causing these variables to react in opposite directions during this time.

--------------------------------------------------------------------------------------------------

Diss and MPhase
The first of these variables increases significantly while the other decreases significantly during this time period:
20.00 to 30.00 minutes
There may be something causing these variables to react in opposite directions during this time.

--------------------------------------------------------------------------------------------------

This is the last potential relationship found for Diss and MPhase.

--------------------------------------------------------------------------------------------------

Diss and Mgain
Both of these variables increase significantly during this time period:
20.00 to 30.00 minutes
There may be something causing both of these variables to react significantly during this time.
Diss and Mgain
The first of these variables increases significantly immediately before the second one increases significantly during this time period:
10.00 to 30.00 minutes
The increase in the first variable may be causing the increase in the second.
This is the last potential relationship found for Diss and Mgain.

After analyzing the data from the second composite part, a plot was made of time and all of the data in the format shown in Figure 31. A general conclusion was shown. It was:

"There are potential causal relationships among these kinds of data. Click on the red button below to read about the potential relationships."

When the user chooses to see the potential relationships identified by this analysis, a screen like the one in Figure 35 is shown. For this particular analysis, the following results were given:

"A/C Pressure and Mgain
The first of these variables increases significantly while the other decreases significantly during this time period:
50.00 to 60.00 minutes
There may be something causing these variables to react in opposite directions during this time.

A/C Pressure and Mgain
The first of these variables increases significantly immediately before the second one decreases significantly during this time period:
40.00 to 60.00 minutes
The increase in the first variable may be causing the decrease in the second.
This is the last potential relationship found for A/C Pressure and Mgain.

F Diss and MPhase
The first of these variables increases significantly immediately before the second one increases significantly during this time period:
30.00 to 50.00 minutes
The increase in the first variable may be causing the increase in the second.
F Diss and MPhase
The first of these variables increases significantly while the other decreases significantly during this time period:
30.00 to 40.00 minutes
There may be something causing these variables to react in opposite directions during this time.

MPHase and F Diss
The first of these variables decreases significantly immediately before the second one increases significantly during this time period:
20.00 to 40.00 minutes
The decrease in the first variable may be causing the increase in the second.

This is the last potential relationship found for F Diss and MPHase.

Diss and Mgain
Both of these variables decrease significantly during this time period:
60.00 to 70.00 minutes
There may be something causing both of these variables to react significantly during this time.

Mgain and Diss
The first of these variables increases significantly immediately before the second one increases significantly during this time period:
20.00 to 40.00 minutes
The increase in the first variable may be causing the increase in the second.

Mgain and Diss
The first of these variables decreases significantly immediately before the second one decreases significantly during this time period:
50.00 to 70.00 minutes
The decrease in the first variable may be causing the decrease in the second.

This is the last potential relationship found for Diss and Mgain.

MPHase and Mgain
Both of these variables decrease significantly during this time period:
50.00 to 60.00 minutes
There may be something causing both of these variables to react significantly during this time.

MPHase and Mgain
The first of these variables increases significantly while the other decreases significantly during this time period:
60.00 to 70.00 minutes
There may be something causing these variables to react in opposite directions during this time.
Mgain and MPhase
The first of these variables increases significantly while the other decreases significantly during this time period:
20.00 to 30.00 minutes
There may be something causing these variables to react in opposite directions during this time.

MPhase and Mgain
The first of these variables increases significantly immediately before the second one decreases significantly during this time period:
40.00 to 60.00 minutes
The increase in the first variable may be causing the decrease in the second.

Mgain and MPhase
The first of these variables decreases significantly immediately before the second one increases significantly during this time period:
50.00 to 70.00 minutes
The decrease in the first variable may be causing the increase in the second.

This is the last potential relationship found for MPhase and Mgain.

Usefulness of the Results

The final user of this prototype system was given the results of these analyses and asked about whether or not they were useful. Her response was again that nothing new was learned. However, she did note that the Mgain/MPhase relationship was one that she had not pointed out prior to the analysis and therefore the analysis did find a relationship that was unknown to this researcher. She also suggested that the methods used in this analysis might give her more information if done for a different composition of material.

In the next chapter, lessons learned during this research are presented.
CHAPTER V
LESSONS LEARNED

Introduction

This chapter discusses lessons learned during this research. The topics include assumptions made to scope certain parts of the research, problems encountered, and how certain parts of the research might be approached differently in order to give better results.

Most of the lessons learned during the course of this research revolved around several themes. One theme is that it is difficult to determine the completeness of a data set, completeness of the relationships among the data, and completeness of the set of analyses from which those to be programmed may be chosen. Other themes that stand out include the difficulty of programming semantics into a computer program, the importance of planning ahead during the programming, and the importance of language when interpretation of analysis is to be attempted.

The general steps used in this research included finding relevant kinds of data to analyze for the manufacturing process being used, finding semantic relationships among the data, exploring and selecting appropriate analysis techniques, exploring ways to synthesize the data and analysis techniques, developing a system construction procedure, and prototyping an automated and customized analysis tool. Each of these general steps and lessons learned during that step are discussed in detail here.
Identifying the Data

In identifying the different kinds of important data, there were two prominent considerations—where to look to identify the data, and what kinds of data to accept as relevant. The paragraphs below detail these two considerations.

In this research, seventy-six kinds of potentially collectible data that might be of interest in analysis for a demonstration process were identified. The kinds of data were identified through literature about the domain and by discussion with and review by a number of knowledgeable people. Smith and Baker made note of the limitations of using a single knowledgeable person from whom to obtain knowledge.1 In the case of the research reported in this dissertation, knowledge to collect from this person or these persons includes important data, relationships among the data, and analyses of possible interest. One might encounter several problems when using a single person in this type of research. Problems would include a limiting the selection of identified data, limiting the number of choices of analyses, and limiting certain kinds of conclusions and interpretation results to the perspectives of this person. This person is likely to be unaware of at least some important facts, will have biases toward what is important and what is not, and may not even be aware of some of the thought processes he or she uses to come to conclusions.

The scope of the word “data” is so large that nearly anything can be classified as data. For example, the words on this page might be considered data when discussing the English language. Even for research in data analysis, the number of different kinds of data can be overwhelming. Therefore, identifying only those data which are part of

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the domain of interest and which will contribute to the kinds of analysis of interest is important.

Although there are many things that can be stated about materials and parts, no piece of literature or person consulted suggested, for example, that the property “scent” would be important in analysis. Should any kind of data be found useful at a later time, that kind of data could fairly easily be added to the database and to the analyses.

The data identified during this research do not include underlying mechanisms (e.g., physical principles) which define from where the data might come. All seventy-six kinds of data represent things that can be measured in some way, reported, and used in further analysis.

Blum emphasizes that “...any methodology that draws causal inferences based on nonrandomized data is subject to an important limitation: unknown covariates cannot be controlled. The strength of a particular knowledge base lies in its comprehensiveness, but even so, it cannot guarantee nonspuriousness.”2 A related conclusion was reached during this research: that there will probably be other things that won’t be measured or won’t be measured accurately, for example things that are assumed, things that are designed into a material, or defective materials that are received from a manufacturer and not tested upon arrival. Arriving at a truly complete set of data and performing a truly complete analysis is probably impossible. Experience of both the developer and the user of an automated analysis system must be used in order to find a reasonable set of kinds of data and a set of reasonable analysis techniques to use.

Even without including more kinds of data, there are still many different kinds identified already for this material and process. Chances that all of these data will be

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considered in any single analysis (or multiple analyses) are slim for a variety of reasons. Perhaps it is too expensive to collect all of the different kinds of data. Or perhaps the user is not interested in some kind of data and therefore will not collect it. Because of this inability to consider every possible kind of data, work in determining which variables most impact certain quality measurements would be of great benefit. Then work on what kinds of analysis are most useful for those particular kinds of data could be done.

Finding Semantic Relationships Among the Data

Semantic data relationships, as discussed in Chapter I, take into account what the relationships among the different kinds of data are, including under what circumstances the relationships exist (context) and what the implications of the existence of these relationships might be. There is a certain amount of difficulty in distinguishing a semantic data relationship from another relationship. Although this kind of research is intended to concentrate on semantic relationships, it is true that other relationships may also be important and therefore must be accounted for.

Semantic relationships were collected during the identification of possibly important kinds of data. Of course, one would define relationships only for those kinds of data being used. However, it is also true that relationships may be identified before realization that a certain kind of data is important. In other words, either the identification of a kind of data or a relationship may be uncovered first, suggesting then that the other is an important thing to consider in the analysis system.

Possible problems resulting from the use of a single knowledgeable person as stated in the above section would also be a concern in identifying relationships among the different kinds of data.
Exploring and Selecting Appropriate Analysis Techniques

Prominent analysis considerations are all related to factors influencing selection of appropriate analysis techniques. They are detailed here.

Creating a list of required functionality like that in Table 3 for assisting in the selection of analysis is subjective. Similar problems as those described earlier in using a single source, are also applicable for compiling this list. However, putting together information like that contained in Tables 3 and 4 is probably not necessary in future work. During this research, it was necessary to go through all of these steps to find the result in Table 5. Since these mappings are completed, it should be possible to use only the analysis categorizations shown in Table 5 (identify patterns, identify trends, identify causal relationships, identify irregularities/inconsistencies, predict outcome of processing, and show big picture). Given this final list of analysis categories, the subjectivity inherent in a list like that in Table 3 disappears.

There is one remaining bit of subjectivity—that of deciding which analyses are most important in an automated analysis program. These selections are made in conjunction with possible users. It is probably possible to write programs which cover all of the six categories, however this may not be useful for any specific user. Even within the different types of analysis, there will be numerous choices of possible techniques to use to accomplish the analysis. Table 6 lists some possibilities, but is by no means complete. Deciding when to quit looking for techniques to use in performing analysis and make a choice can be difficult, particularly if none of the techniques identified seems to “fit” the data.

For each analysis technique chosen, many will be rejected and it may be impossible to tell if the best technique was chosen. Though it may frequently be easy to choose between two possible techniques, in some cases it is only possible to decide if
the one chosen is useful and therefore worth using. Related decisions include choices among proven formal techniques (e.g., statistical analyses) or original analyses of varying kinds, quantitative or qualitative techniques, and descriptive or inferential techniques.

Fortunately, the above dilemma can be eased somewhat since there are always a number of factors which limit the choice of analyses (aside from required functionality and user/developer preference). Also included in the decision of whether to use a certain kind of analysis or analysis technique are such factors as available hardware and software tools, allowable expenses, the amount and kind of data that will be analyzed, and the number of data sets that will be provided for analysis. Though some of these factors may be considered restrictive, they can be useful in paring down the list of possible analyses to be considered.

In this research, many kinds of analysis were immediately rejected because the intent was to concentrate on exploratory analyses. Therefore, techniques such as most operations research analyses were inappropriate. According to Hillier and Lieberman, operations research analyses are generally models describing consequences (possible benefits and costs) of selecting from among alternative actions taken in the real world.\(^3\) Forecasting was the one type of operations research method that might have been useful in an exploratory analysis, since techniques used in forecasting might be able to give estimates of processing results.

As was stated in the section above entitled “Identifying the Data”, work in determining which variables most impact certain quality measurements would be of

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benefit, since then work on what kinds of analysis are most useful for those particular kinds of data could be done.

Also from the “Identify the Data” section, the fact that some things may not be measured or may not be measured accurately leads to a high probability of not performing a truly complete analysis. Joseph et al also reached a similar conclusion, stating that “Because of the limitations of operational data (not totally random, limited range of variables, missing pieces of data etc.), it [certain kinds of analyses] can only be used in an exploratory sense and not in a confirmatory sense.” Experience of both the developer and the user can assist in finding a set of reasonable analysis techniques to use.

Exploring Ways to Synthesize the Data and Analysis Techniques

Trying to find ways to synthesize analysis techniques was one of the more difficult steps in the research, simply because it is difficult to anticipate what kinds of combined analyses will provide synergistic results. In this research, the closest result to synthesis of techniques to achieve synergy of results was in combining different kinds of analyses to come up with possible reasons for certain part quality results. (This was done during the first type of analysis described in Chapter IV.)

This step of exploring ways to synthesize the data and analysis techniques was performed after deciding which kinds of data, analyses and techniques would be used. At that point, each of the analyses of interest were considered together to see what could be used as combined evidence for some conclusion. This was done quite informally and with no deliberate method. Trying to accomplish this step appears to require significantly more thought in order to find a more methodical approach.

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Developing a System Construction Procedure:

It is worth writing down a preliminary step by step procedure one would follow in constructing a system such as that suggested in this dissertation. Though it is true that this preliminary listing may be revised more than slightly and may even be completely discounted later, the initial procedure gives the developer a place to start. From this point, the developer can add, change, or delete steps as necessary.

This dissertation describes each step at a high level. Each of these high level steps may be detailed to any extent, however leaving the steps at a high level allows the user and developer more flexibility in program design and implementation.

One step left out of the prescribed procedure is that of stating assumptions about the incoming data (other than what the data is, how much of it there is, and in what format it will be given). Assumptions such as "the incoming data is accurate", "material properties arrive as specified from the manufacturer", and "the part design is good" would seem to be reasonable assumptions to make, but it may or may not be valuable to state assumptions such as these. This depends at least in part on the kinds of analysis that will be performed. For example, there may be no need to assume that data is complete when if an analysis is to be programmed whose intent is to report to the user that some data is missing and make a determination as to whether that incompleteness is critical. Another possible analysis using incomplete data might be an analysis looking for a "closest match". As a final example, assuming that data is accurate may be unnecessary if the analysis is intended to find outlying data points and report them to the user as possible noise, as many filtering types of analyses do.

Prototyping an Automated and Customized Analysis Tool

Step number 9 given in the tool construction procedure is "Determine how to structure the data for system use." The results of performing this step during this
research may have had the most impact on the kinds of conclusions (beyond traditional analysis) that were able to be obtained by the program.

Although the different kinds of data and their many known relationships were relatively easy to program in HyperCard using simple written language, very little thought was given as to how these would be used in analysis later. The problem became obvious when analyses were written, then interpretations of those analyses were being incorporated. These interpretations were to rely upon known relationships between different kinds of data in order to provide a better understanding to the user of current analysis results. However with no consistent language used even for similar kinds of data relationships, it was difficult to write programs to access specific sets of relationships.

As an example, looking for data and relationships for glass transition temperature is easy—one could search the database looking for “glass transition temperature” or “Tg” which is the symbol for glass transition temperature. However, looking for relationships between glass transition temperature and increasing heat is more difficult unless consistent language has been used. Again, glass transition temperature is easy, but “increasing heat” can be written in plain English a number of different ways (e.g., some possible synonyms for “increasing” include rising and ascending plus variations on these—rise or ascend). Attempting to access these kinds of relationships without having made consistent use of language is very difficult, especially if the database of data and relationships is large. It is very likely that the developer would not think of all synonyms that might have been used without examining the entire database closely. This is true even if the analysis developer is the same person that developed the database.
To summarize the above paragraphs, the language used to represent data and relationships in this research appears to represent known relationships among the different kinds of data well, if all one wants to do is browse the relationships. However using the relationships during analysis appears to require a much more formalized representation of the relationships in order to facilitate manipulation. Even with more formal representations, this may be difficult. In his 1986 article, Gale made note that "...interpretation of results...have not been shown to be supportable by current knowledge representation techniques." Though there has been some progress in knowledge representation since Gale's article was published, his statement may still be true. It is also true that there would surely be other problems in manipulating relationships during data analysis, even if the representation was better. For example, it may be discovered that some important kinds of data are missing and therefore could not be used. Another example would be not finding good analysis results (anything from incorrect conclusions to just not finding anything interesting at all) and having to begin the analysis process over again.

Although providing the user with meaningful results which incorporate semantics is a difficult task, the prototype actually built shows that there are strategies that can be used successfully, although the results achieved are limited. The first kind of analysis described in Chapter IV used built-in conclusions which gave some degree of context and implications of the results of the search through the data. The second kind of analysis used in this research provided sentences about possible relationships among the different kinds of data being analyzed. Although this result may be sufficient

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for a user who is somewhat educated in his or her domain, there is certainly much more
one could do even with the limitations language placed on the program.

For example, the program does not exclude known relationships from the report
given to the user. The two variables called “Diss” and “FDiss” refer to dissipation and
filtered dissipation. Even a barely educated user would expected these two variables to
be related. This kind of relationship could easily be excluded from the report, however
it again depends on the kind of analysis being done. One kind of analysis in which not
excluding results such as these would be valuable would be one in which the user
wishes to confirm that certain relationships exist. This type of program could compare
the result to expected relationships and report to the user that a relationship appears to
exist as expected, no relationship appears to exist as expected, no relationship appears to
exist even though one was expected, or a relationship appears to exist where one was
not expected.

Summary

Most of the lessons learned during the course of this research revolved around
several themes. One theme is that it is difficult to determine the completeness of a data
set, completeness of the relationships among the data, and completeness of the set of
analyses from which those to be programmed may be chosen. Other themes that run
through the above sections include the difficulty of programming semantics into a
computer program, the importance of planning ahead during the programming, and the
importance of language when interpretation of analysis is to be attempted.

In the next chapter, a summary of the research is given, conclusions are made,
and ideas for further work are described.
CHAPTER VI
SUMMARY AND RECOMMENDATIONS

Summary

This research addressed the analysis and interpretation of manufacturing process data. The emphasis was on identification and analysis of semantic relationships among different kinds of data for some given manufacturing process. The demonstration process for this research was the autoclave curing of bismaleimide matrix composite materials.

In a nutshell, this research was about determining what data to use and how to use it to give the user insight about composite materials and their processing.

The purpose of this research was to assist materials or manufacturing specialists in analyzing and learning about new materials and processes by exploiting the meaning behind manufacturing process data relationships in further exploration of the material or process. Finding relevant kinds of data to analyze for the manufacturing process being used, finding semantic relationships among the data, exploring and selecting appropriate analysis techniques, exploring ways to synthesize the analysis techniques, developing a system construction procedure, and prototyping an automated and customized analysis tool were all important steps in the research.

Seventy-six different kinds of data which may be useful in analysis were identified and structured in a hypertext database along with all of their known relationships with the other kinds of data. Analysis techniques and tools were investigated and cataloged. Causal analysis techniques were chosen to use in a
prototype analysis system. The prototype was constructed and tested. Real data from
the process of autoclave curing of bismaleimide matrix composite materials was
analyzed using the prototype system.

The first analysis was prepared for looking at glass transition temperature, time
the part spent over a given temperature, and maximum part temperature during
processing. Known relationships are retrieved from the database, data are read into a
specially prepared spreadsheet, a plot is created, and the program begins to look at the
data. It determines whether the glass transition temperature was below, above, or at the
expected value. Conclusions are made about the significance of the various
temperatures being explored and the resulting glass transition temperature. Knowledge
engineering was used to gather the possible conclusions which could be used.

The second analysis was prepared for analyzing autoclave pressure and various
dielectric measurements. The program examines the data searching for patterns such as
two variables consistently increasing or decreasing together or one immediately after the
other, or one variable consistently increasing immediately before, during or immediately
after another decreases. Any relationships discovered are presented to the user on final
presentation screens.

Although the user who provided the data found the results interesting, she did
not learn anything new from the system itself. Looking at the results of the first type of
analysis gave her ideas for further experimentation. The second type of analysis
provided no new information for the composition of material for which data was
provided, however the user suggested that it might be useful for a different
composition. In addition, this second type of analysis pointed out a relationship that
was known to the user but was unknown to this researcher.
Contributions

The contributions this research makes to the field of analyzing data for manufacturing processes include identification and structuring of semantic data relationships demonstrated with the autoclave curing of bismaleimide matrix composites, categorization of analysis techniques, some degree of synthesis of analyses, a data analysis tool customization method, and the demonstration of feasibility for writing an analysis tool in a specific domain. Therefore contributions exist in both the analysis tool design area and in the domain area.

The identification of important kinds of data to be analyzed resulted in a hierarchy of different kinds of data which provides ease of browsing through the different kinds of data whether manually or on a computer. The method of collecting and confirming the important kinds of data contributes to the analysis tool design area and the actual identification of data for a specific process and material contributes to the domain area. Similar statements can be made with respect to the identification and structuring of relationships among the different kinds of data. The HyperCard database containing information about all of these data and relationships is a useful reference tool and provides some capability in data analysis and interpretation. With further development, the database could provide more and better assistance with data analysis and interpretation.

Six categories of analysis were defined. These categories can be used for classifying both analysis techniques and analysis tools, both commercial and otherwise. This can be helpful for matching techniques and tools. For example, once a matching is done, it is possible to select a technique then find a tool that will perform that technique. This is something that is commonly done for various analysis techniques with which
people are familiar, but the ability to categorize the techniques and tools is useful for more obscure or original techniques.

Some degree of synthesis of analyses was achieved during this research. Combinations of analyses were used in the first type of analysis, resulting in more evidence of possible reasons for certain part quality results.

The data analysis tool customization method constructed during the course of this research was a result of planning and experience in implementation. Therefore it has a small but real empirical basis. The results of using the method resulted in a demonstration of feasibility for writing an analysis tool in a content area.

Aside from these sought after contributions, one interesting conclusion is that there is some potential for some generality of this research across hardware, software, processes, products, and users.

The transferability of this work to new users and products was accidentally shown when the user originally intended for this system could not provide data. Toward the end of the research, a different user provided data for bismaleimide materials. Originally, epoxy matrix composites were to be used for demonstration.

The software tools used to prepare the prototype to demonstrate this work are similar to tools on various hardware platforms or are available on various platforms. After some degree of completion was reached, the HyperCard and WingZ programs, which had been prepared on the Macintosh computer, were translated to similar software packages on another type of personal computer. WingZ was available on this other computer and the translation was smooth. The HyperCard program was translated into a similar software package for the other computer. This also went smoothly. This is of course the easiest of translations of this work to other platforms. However, the ideas, tools, and techniques used are quite general—hypertext, spreadsheet, and simple
exploratory analyses—and if a skilled programmer were enlisted, could be transferred to a variety of hardware and software platforms without much effort.

Transferring the results of this research to other processes is somewhat more complicated. The analyses could be used almost completely intact. However, preparing a database for a new process would likely be a significant effort since the researcher would be required to start with nothing, and through the use of literature and experts, build a database of different kinds of data and their relationships. This would also be true if the material being used was significantly different from that for which the database was prepared.

**Recommendations for Further Research**

This research touched only the tip of a large amount of work which could be done in automated data analysis. Besides demonstrating the work for only one material and one process of one domain, the research approached the difficult problem of using and maintaining semantics in an automated system. Among the many things that could be done to extend this work are the few listed here.

1. This work did not result in an automated data analysis system which helped the user discover something new about her product or process. Some thought was given to why the system was unable to do this. One possible reason is that the language or knowledge representation used may not have been rigorous enough to be manipulated into acquiring new knowledge. Further work structuring the different kinds of data more formally might make it possible to make more meaningful conclusions.

2. Since there are so many different kinds of data that chances they will all be considered in analysis are slim, work in determining which variables
most impact certain quality measurements would be of great benefit. Then work on what kinds of analysis are most useful for those particular kinds of data could be done.

3. The database of different kinds of data could be filled out in its entirety. This would make it more useful for people who would like to learn about the material and process used as a demonstration in this research.

4. The prototype system presents a completely automated data analysis system. An option for allowing the user to perform the analysis alone could be programmed. A scenario such as this could be used: the user chooses to do an independent analysis; the program opens a spreadsheet and reads data in; the system prompts the user to select the data to be analyzed and click on a button for a certain kind of analysis. An even more sophisticated system would assist the user in making analysis selections based on the kind of data being analyzed and on the category of analysis desired.

5. Similar programs could be prepared for different users, materials, processes, etc.

6. The different kinds of analysis that could be done are endless.

7. The analysis program could be made part of a larger architecture for learning about processing materials. Other modules might include a design of experiment program, a self-improving process control system (using results from rigorous data analysis), and a program which assists the user in negotiating all of the other included modules.

8. As noted in Chapter II, aside from general statistical analysis software, it appears to be easier to prepare software for specific kinds of analyses in
specific domains than to develop generalized analysis software. However it does appear that there is potential for making a generalized tool or shell for specialized analysis software development. It would probably be possible to present a computer literate user with this database structure to be filled in. The user could show relationships in graph form, which the program could convert into relationship buttons on the cards. Modules of analysis code are certainly reusable in many domains, and as noted above, many different kinds of analysis could be provided as choices for the specialized domain.


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APPENDIX A

DATA AND KNOWN RELATIONSHIPS
Data: Age of material
Reference: McCarvill (2), Wamock
Importance: These materials dry out with age and become difficult to handle. They cure slowly at room temperature.
B.D.A: Before
Collectible: Collectible - recorded in logs
Manipulable: No, other than to keep track of the materials.
Range: Data is numerical, from 0 days old to 3 years old. (Wamock)
Relationships: 1. Over time, as the materials age, they dry out and lose tack. This means that plies will not adhere to each other well and the layup will be difficult to perform. (McCarvill (2) pg 139)
Comments:

Data: Autoclave specifications
Reference:
Importance: Different autoclaves heat and pressurize differently.
B.D.A: B
Collectible: Per autoclave manufacturer’s specification.
Manipulable: Manipulable only by using a different autoclave.
Range: Various types of data—size, shape, uniformity of heating and cooling, etc.
Relationships:
Comments: 1. Interested in manufacturer, size, shape, and uniformity of heating, cooling, and pressurization.

Data: Brittleness
Reference: Thrower, Watson, Marsh (1), Parker, Wamock, Rosen and Dow, McCarvill (2), Honon and McCarty
Importance: Brittle materials are low in elasticity. They cannot be used where a great amount of elasticity is required.
B.D.A: After
Collectible: Collectible in after-cure quality checks.
Manipulable: Manipulable during part design and to a much lesser extent, during the cure.
Range: Can be numerical or qualitative.
Relationships: 1. Resin chemical structure (degree of polymerization and cross-linking) and additives (curing agents, reactants) may reduce brittleness. (McCarvill (2) pg 139)
2. As stiffness increases, brittleness increases. (Parker)
3. The brittleness of composites makes impact resistance low. Although damage may not always be apparent from the impact surface, internal crazing and debonding may be present.
4. Low service temperatures make composites more brittle. (Watson pg 99)
   (Sub-zero—Warnock) Also, the higher service temperature capability, the more brittle.
   (Warnock)

5. Since extreme brittleness is a sign of low elasticity, matrix elongation (strain) will be low.

6. A high degree of polymerization generally means a high degree of strength and stiffness,
   since molecules are not free to move about. This in turn leads to a higher degree of brittleness
   and a higher glass transition temperature (Tg). (Watson pg 103)

7. A higher degree of cross-linking in resin generally leads to higher strength (Budinski pg 46).
   It also leads to a more brittle material. (Warnock)

Comments: 1. Composite materials are generally quite brittle. (Horton and McCarty pg 259)

Data: Buckling

Reference: ASM, Leissa, Kim, Diefendorf, Wang

Importance: A buckled laminate will not perform as it was designed to perform. It is damaged.

B,D,A: After

Collectible: Collectable. Visible. If buckling occurs during tests, compressive stress causing
the buckling can be measured. Whether buckling was due to use or occurred during testing.
During testing, compressive stress

Manipulable: Manipulable only in design.

Range: Qualitative from visual inspection. Numerical during compressive testing.

Relationships: 1. A unsymmetric laminate with few plies (few layers) buckles quickly. (Leissa
   pg 447)

2. Fatigue causes damage such as buckling. (Kim pg 437)

3. Severe impact can cause buckling.

4. Heavy loading (stress) can cause buckling. (Higher compressive strength results in heavier
   load tolerance, thus buckling occurs at higher stress.)

5. A smaller diameter fiber has greater tensile strength, but may buckle faster under compressive
   stress. (Diefendorf pg 51)

6. Fatigue causes buckling, delaminations, and cracks, when in turn cause more damage,
   including strength and stiffness reduction. (Wang pg 246, Kim pg 436)
Comments:

Data: Chemical structure and additives, resin
Reference: ASM, Hauwiller, Warnock, Budinski, McCarvill (2), Dominguez (1), May, Lang, Noton
Importance: These affect final material properties.
B.D.A: Before
Collectible: Collectible; by design.
Manipulable: Manipulable; by design.
Range: Chemical names/descriptors
Relationships: 1. Resin chemical structure (degree of polymerization and cross-linking) and additives (curing agents, reactants) may reduce brittleness. (McCarvill (2) pg 139)
2. The type of resin and its additives can influence tack. (Dominguez (1) pg 144)
3. Additives may change uncured resin viscosity or reduce brittleness. (McCarvill (2) pg 139)
4. Resistance to corrosion may be affected by resin's chemical structure, curing agents, or reactants. (May pg 66)
5. Creep may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)
6. Hardness may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)
7. The fiber-resin interface may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66) Coupling agents may be added to fiber or resin to increase the strength of the fiber/resin interface. (ASM pg 8)
8. Resistance to fatigue may be influenced by resin chemical structure, curing agents, and reactants. (May pg 66)
9. Toughness may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)
10. Resin additives and fiber coatings can affect resistance to UV light. (Hauwiller, Warnock)
11. Resin absorbs moisture, which changes its properties. (Lang pg 740) Possible changes include lower viscosity throughout cure, gel time, and, because of the possible chemical structure change, deactivated catalyst in the resin (an additive). (Warnock)
12. Strength may be affected by resin chemical structure, curing agents, and reactants. (May pg 66)

13. Resin (chemical structure and additives) provides interlaminar shear strength.

14. Resin determines possible service temperature. (Noton pg 37)

15. The hardener in the resin causes cross-linking. (Budinski pg 59)

Comments: 1. Includes resin type (e.g., BMI).

Data: Coatings and surface treatments, fiber
Reference: Hauwiller, Warnock, ASM, Adams, Bascom
Importance: Can affect composite properties.
Collectible: Per design specification.
Manipulable: Per design specification.
Range: Descriptions and amounts.

Relationships: 1. Fiber coatings can affect resistance to UV light. (Hauwiller, Warnock)

2. Fiber coatings (coupling agents) contribute to the strength of the fiber/resin interface. (ASM pg 8)

3. Damping capacity is influenced by properties and proportions of resin and fiber, size of inclusions, orientation of fibers to loading axis, and surface treatment of fibers. (Adams pg 206)

4. Fibers may have finishing agents on them to aid drape. (Bascom pg 122)

5. Fibers may have fire retardant finishing agents.

6. Fibers may have finishing agents to improve certain properties, but these often compromise resistance to moisture. (Bascom pg 122)

Comments:

Data: Conductivity, Electrical
Reference: ASM, Budinski
Importance: A designer may wish to design electrical properties into a part.
Collectible: Measurable by test.
Manipulable: Manipulable only by part design.
Range: Numerical.
1. Conductivity goes up with increasing service temperatures. (ASM pg 370)

2. Resistivity is the inverse of conductivity.

Comments: 1. Consists of resin and fiber electrical properties, and is altered by the percentages of resin and fiber in the final material.

Data: Conductivity, Thermal
Reference: ASM, Warnock, Hauwiller, Diefendorf
Importance: Higher thermal conductivity means faster heat transfer.
B.D.A: B, A
Collectible: By design before cure, testable after cure.
Manipulable: Manipulable in part design
Range:
Relationships: 1. Higher thermal conductivity in tooling and layup materials leads to better heat transfer to the part. It is desirable to have similar degrees of heat reaching the part from all sides. (Warnock)

2. Tooling/mold materials affect evenness of cure. (Hauwiller) (Evenness of tool heating and tool/material thermal conductivity.)
Comments: 1. Consists of thermal conductivity of resin, of fiber, and the proportions in the final material.

Data: Consolidation
Reference: ASM, Warnock, Hinrichs
Importance: Consolidation during processing is used to eliminate voids, increase density, and control part thickness.
B.D.A: During
Collectible: Measurable after processing by measuring fiber/resin volume, density, and part thickness, and by testing to find voids.
Manipulable: Manipulable by controlling autoclave temperature and pressure during processing.
Range: Measures of fiber/resin volume, density, and part thickness and void volume are all numerical.
Relationships: 1. Fiber volume, resin content, autoclave pressure and vacuum on the part - compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

2. "If the resin viscosity is too high (temperature too low or the material advanced), flow does not occur easily and compaction does not occur." May result in air pockets (voids).

3. Consolidation during processing can eliminate voids, increase density, and control part
4. Consolidation starts with layup—the mechanic presses the plies together.

5. Too large a difference between mid-part and top-part temperatures during gelation may cause stresses, non-uniform consolidation, or trapped volatiles. (Hinrichs pg 651).

6. Ply thickness measured after cure gives a good indication of the success of the consolidation. (Wamock)

7. The time or temperature at which the vacuum bag is vented is critical to void reduction. A vacuum is needed to help hold plies together at the beginning of the cure cycle and to remove voids as much as possible. But the vacuum must be vented in order to allow full pressurization of the part, thus remaining internal voids are pressurized. (Wamock)

Comments:

Data: Corrosion, resistance to
Reference: May, Budinski, Wamock
Importance: Depending on use environment, resistance to certain substances may be necessary to prevent part damage.
B.D.A: After
Collectible: Quality check on coupon.
Manipulatable: Manipulatable by part design.
Range: Variable, depending on testing.
Relationships: 1. Resistance to corrosion may be affected by resin's chemical structure, curing agents, or reactants. (May pg 66)

2. Corrosion can reduce material strength. (Budinski pg 230)

3. Corrosion can hasten crack development. (Budinski pg 230)

Comments: 1. Interested in dry as well as hot/wet performance. (Wamock)

Data: Cracks
Reference: Marsh (1), Budinski, Hauwiller, Rosen and Hashin, Kim, Smith
Importance: Quality data. Cracks cause all sorts of mechanical problems in parts.
B.D.A: After
Collectible: Collectible during post-cure quality check.
Manipulatable: No
Range: Location, size, type (e.g., through matrix, across fibers) of cracks.
Relationships: 1. Cracks may form from thermal stresses in the part. This can happen when thermal stresses exceed matrix strength. These cracks usually stay within the resin. (ASM pg 15)
2. Cracks stress the surrounding material, causing further damage. (Rosen and Hashin pg 195)

3. Corrosion can hasten crack development. (Budinski pg 230)

4. Delamination can be caused by cracks. (Kim pg 437)

5. Fatigue can cause cracks which then causes strength reduction. (Kim pg 436)

6. Crack propagation is higher in unidirectional layers. (Hauwiller)

Comments: 1. Intra- and inter-laminar cracks stay within the resin (they don't break fibers). Trans-laminar cracks break the fibers as well. (Smith pg 786)

Data: Creep
Reference: May, Thrower, Gilkey
Importance: Creep can change dimension and properties of materials.
B,D,A: After
Collectible: Collectible by measurement over time.
Manipulable: Manipulable only by part design
Range: Variable, depending on testing.
Relationships: 1. Creep may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)

2. Higher service temperature generally causes more creep. (Thrower pg 142)

3. Stress over time causes creep. (Thrower pg 142)

4. Ductility manifests creep. (Gilkey pg 35)

5. Fatigue loading affects mechanical properties (strength, stiffness, creep).
Comments:

Data: Cross-linking, degree of (in resin)
Reference: Budinski, ASM, Warnock, McCarvill (2)
Importance: The degree of cross-linking affects material properties.
B,D,A: After
Collectible: No.
Manipulable: Manipulable indirectly by part design and process design, both of which are difficult to guarantee.
Range:
Relationships: 1. Higher cross-linking leads to higher material strength and stiffness. (Budinski
It also leads to a more brittle material. (Warnock)

2. Resin chemical structure (degree of polymerization and cross-linking) and additives (curing agents, reactants) may reduce brittleness. (McCarvill (2) pg 139)

3. The sought degree of cure includes a certain degree of resin cross-linking and a certain glass transition temperature (Warnock), with no measurable viscosity.

4. A higher degree of cross-linking leads to a stiffer material. (Budinski pg 46)

5. The hardener in the resin causes cross-linking. (Budinski pg 59)

Comments:

Data: Cure Process steps
Reference: Hauwiller
Importance: Processing the part is equal in importance to using the right design and materials in making a quality part.

B,D,A: During
Collectible: Collectible, either from a plan or from in-process sensors and control.
Manipulable: Manipulable, mostly indirectly, either from a recipe or from controls which are set in reaction to dynamic process variables.
Range: Some qualitative, some quantitative, depending on the step.
Relationships: 1. All process steps take time. Layup time, cure time, cure variables recorded at certain times.

2. Set point, mid-part, top-part, and autoclave temperatures are included in process steps.

3. Set point and autoclave pressure are part of process steps.

4. Viscosity level is a dynamic variable, changes are recorded as process steps.

5. Position in autoclave may affect evenness of cure, part temperatures and pressures. (Process steps) (Hauwiller)

6. Cooldown is included in process steps.

Comments:

Data: Cure, degree of
Reference: Roberts, Warnock
Importance: Must be in range for good part (e.g., not solid, good, burned)
Collectible: Indirectly measurable by dielectric loss factor.
Manipulable: Indirectly manipulable by changing autoclave temperature and pressure during the cure cycle.
Range: 0-100%
Relationships: 1. Heat and pressure cause resin to melt, flow, densify, and cure.

2. Resin viscosity (given indirectly by Dielectric Loss Factor) decreases as degree of cure advances.

3. The sought degree of cure includes a certain degree of resin cross-linking and a certain glass transition temperature (Warnock), with no measurable viscosity.

4. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

Comments:

Data: Cure, evenness of
Reference: Hauwiller, Warnock
Importance: An uneven cure may result in a part with uneven and undesirable properties.

Collectible: May be collectible curing post-cure quality check.
Manipulable: Indirectly manipulable during processing by altering temp and pressure to minimize through-part temperature differences.
Range: Variable. May be a "Map", a statement of unevenness, etc.
Relationships: 1. Heat and pressure cause resin to melt, flow, densify, and cure.

2. Tooling/mold materials affect evenness of cure. (Hauwiller) (Evenness of tool heating and tool/material thermal conductivity.)

3. Position in autoclave may affect evenness of cure, part temperatures and pressures. (Process steps) (Hauwiller)

4. Part geometry (e.g., thin, thick parts) affect evenness of cure. (Hauwiller)

5. An uneven cure may be due to uneven resin flow. This may be due to temperature differences within the part, or to pressure differences on the part due to tooling or placement in the autoclave (Viscosity will not be constant throughout the part. (Warnock))

Comments:
Data: Damage tolerance
Reference: ASM, Horton and McCarty
Importance: It is important to make every effort to assure that the part will perform properly throughout its life.
B,D,A: After
Collectible: Collectible either with post-cure quality checks or observation as the part serves its purpose.
Manipulable: Manipulable only by design and proper cure, which is difficult to insure.
Range: Qualitative (e.g., visible cracks) or quantitative (e.g., measurable properties, such as strength).
Relationships: 1. If fibers are parallel to load, structures fail at lower strains. (Horton and McCarty pg 260)
2. Materials with greater toughness have greater damage tolerance. (Horton and McCarty pg 262)
3. Good fatigue strength after damage is an indication of good damage tolerance.
Comments:

Data: Damping Capacity
Reference: ASM, Adams, Noton
Importance: A balanced damping capacity is needed to allow energy diffusion yet reduce vibration and noise.
B,D,A: After
Collectible: Testable after cure.
Manipulable: Manipulable only by design and proper cure, which is difficult to insure.
Range: Numerical
Relationships: 1. Damping capacity is influenced by properties and proportions of resin and fiber, size of inclusions, orientation of fibers to loading axis, and surface treatment of fibers. (Adams pg 206)
2. Damping takes time. Composites are faster than conventional metals by about 10%. (Noton pg 36)
Comments: 1. Composites damping is less noisy than that of conventional metals. (Noton pg 35)

Data: Delaminations, bridges, und/eb/disbonds
Reference: ASM, Donaldson, Warnock, Kim, Gosnell, Rosen and Dow, Horton and McCarty
Importance: Part quality.
B,D,A: After
Collectible: Collectible - post-cure quality analysis.
Manipulate: Not directly manipulable. Good design, layup, cure, and use environment are the determining factors.
Range: Visible and testable for interior flaws.
Relationships: 1. Damaged bonds decrease stiffness. (Donaldson)

2. Delaminations can be caused by stress on parts or incompatible fiber/resin mixes. (ASM pg 8)

3. Can be caused by cracks. (Kim pg 437)

4. Need reasonable resin toughness and good fiber/resin interface to guard against delaminations and disbands. (Gosnell pg 99)

5. Bridges can result in voids and dimension (size and shape) problems. (ASM pg 5)

6. Good drape is needed to guard against bridge formation.

7. Can be caused by fatigue. Then these defects cause more defects. (Kim pg 437)

8. The brittleness of composites makes impact resistance low. Although damage may not always be apparent from the impact surface, internal crazing and debonding may be present. (Rosen and Dow pg 180, Horton and McCarty pg 261)

9. Correct and careful layup procedures (e.g., pressing, debulking with vacuum) are necessary to prevent bridges in the part. (Warnock)
Comments: 1. Includes splintering

Data: Density
Reference: Vennard, Warnock, Diefendorf, McCarvill (2)
Importance: A certain density is required to achieve certain properties in materials.
B,D,A: B, A
Collectible: Measurable before and after cure. Fiber and resin densities are a matter of record from the manufacturers.
Manipulate: Per design specification for before cure. Manipulate during cure only indirectly by controlling temperature and pressure.
Range:
Relationships: 1. Density increases with stiffness. (Diefendorf pg 51)

2. Molecular activity increases with temperature (up to the glass transition temperature—Warnock), so density decreases with increasing temperature. (Vennard pg 6)

3. Pressure increases density. The molecules are forced into a smaller volume. (Vennard pg
4. A more dense material may have forced out more voids during cure.

5. Laminate consolidation during processing can eliminate voids, increase density, and control part thickness.

6. Specific gravity is the ratio of material or part density to water density at a given temperature and pressure. (Vennard pg 7)

7. The density of carbon fibers increases with increasing modulus. (Diefendorf pg 51)

Comments: 1. A constant.

2. Carbon has low density. (McCarvill (2) pg 139)

3. Graphite is a low density allotrope of carbon. (Diefendorf pg 49)

4. Composites have low density.

Data: Drape
Reference: ASM, Marsh (1), Hauwiller, Warnock, Bascom, Dominguez (3)
Importance: Good drape eases layup and helps prevent bridges.
B,D,A: Before
Collectible: Collectible when ready to use material.
Manipulable: Manipulable by design specification and by selection of correct drape when beginning layup.
Range: Qualitative—good or not good.
Relationships: 1. "For a resin to exhibit good tack, drape and handleability, it needs to have an uncured Tg [glass transition temperature] less than ambient temperature". (Marsh (1))

2. Fibers may have finishing agents on them to aid drape. (Bascom pg 122)

3. An extended material out time can dry out materials and cause some loss of tack and drape.

4. Difficult layup due to inadequate drape or care can lead to voids or bridges in the part, particularly if the part has a complex contour (geometry). (Warnock)

5. A tight weave in a ply reduces drape. (Dominguez (3) pg 149)

6. Stiffness reduces drape. (Hauwiller)

Comments:
Data: Ductility
Reference: Thrower, Gilkey
Importance: Ductile materials last but may not keep their shape for their use environments.
B.D.A: After
Collectible: Collectible via after-cure quality check.
Manipulable: Manipulable only by proper part design and cure, which is difficult to guarantee.
Range: Numerical
Relationships: 1. Ductility and strength result in toughness, giving resistance to failure under impact. (Gilkey pg 35)
2. Ductility manifests creep. (Gilkey pg 35).
Comments:

Data: Elongation
Reference: Budinski, ASM, Diefendorf, Gosnell, Reinhart and Clements
Importance: Materials which need flexibility need higher elongation.
B.D.A: After
Collectible: Collectible via after-cure quality test.
Manipulable: Manipulable only by proper part design and cure, which is difficult to guarantee.
Range:
Relationships: 1. When there is extreme brittleness (a sign of low elasticity), matrix elongation (strain) will be low.
2. Need high elongation, high resin shear strength, and moderate toughness to get good impact strength. (Gosnell pg 99)
3. Low elongation and high strength results in high stiffness. (ASM pg 15)
Comments:

Data: Environmental conditions in layup room
Reference: ASM, Lang, Warnock
Importance: Improper conditions causes problems in layups.
B.D.A: Before
Collectible: Collectible by measurement and inspection.
Manipulable: Manipulable, indirectly (usually) by setting controls, and by cleaning.
Range: Visible for some cleanliness and numerical by measurement for all conditions of interest.
Relationships: 1. A small amount of heat increases tack, but will later cure thermosets. Room temperature cures thermosets too, slowly. (Lang pg 740)
2. Humidity increases tack and makes materials difficult to handle. (Lang pg 740)
3. Resin absorbs moisture, which changes its properties. (Lang pg 740) Possible changes include lower viscosity throughout cure, gel time, and, because of the possible chemical structure change, deactivated catalyst in the resin (an additive). (Warnock)

4. Voids can be reduced by proper cleanliness and pressure within the layup room. (Lang pg 740)

5. Material left out of the freezer and out of a sealed bag may absorb moisture, especially if out time is lengthy and/or the room is not humidity controlled.

Comments:

Data: Exothermic Reaction
Reference: ASM, Hinrichs, Roberts
Importance: The reaction generates, thus the part contributes to its own heating.
B,D,A: During
Collectible: Collectible somewhat - part thermocouples gives us indication of added heat.
Manipulable: Manipulable indirectly by controlling autoclave heater.
Range: Numerical from thermocouples.
Relationships: 1. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).
2. Mid- and top-part temperatures give an indication of the time exotherm begins and the rate at which it progresses. Generally, "reaction rates double for every 10 degrees C (18 degrees F)." (Hinrichs pg 651)
3. Increased moisture content slows exothermic reaction, (slows the formation of a polymer network), resulting in increased void content. (Roberts pg 748)

Comments: 1. Interested in whether exotherm exists and its start point.

Data: Fiber/Resin Volume
Reference: Warnock, Rosen and Hashin, Adams, Konarski
Importance: Mechanical properties are affected by the fiber/resin volume.
B,D,A: B, A
Collectible: Collectible from design specification for uncured materials, measurable for cured materials.
Manipulable: Design specifies before-cure volumes. Can be altered indirectly with layup
materials and during cure by controlling variables, controlling pressure and temperature.

Range: 0-100% of each, totaling 100%.

Relationships: 1. Fiber volume, resin content, autoclave pressure and vacuum on the part-compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

2. Composite material strength is a function of fiber volume fraction and thickness per ply.

3. Higher fiber volume in cured laminae generally means a lower coefficient of thermal expansion (CTE). (Rosen and Hashin pg 190)

4. Damping capacity is influenced by properties and proportions of resin and fiber, size of inclusions, orientation of fibers to loading axis, and surface treatment of fibers. (Adams pg 206)

5. Fiber/resin volume are affected by dams and bleeder plies, which allow or disallow the flow of resin out of the part during cure.

6. Excessive pre-cure resin volume makes plies too tacky and difficult to work with.

7. Voids can be caused by resin-starved plies or excessive bleeding during cure. This can be taken care of with proper layup materials (such as bleeder plies and dams). (Konarski pg 661)

Comments:

Data: Flame, resistance to
Reference: ASM
Importance: Flammable materials are not as durable as those which are not.
B,D,A: After
Collectible: Collectible with after-cure testing.
Manipulable: Manipulable only by part design.
Range: Numerical, resistant to a temperature.
Relationships: 1. Fibers may have fire retardant finishing agents.
Comments:

Data: Gel point
Reference: ASM, Hauwiller, Warnock, Roberts, Lang
Importance: After the beginning of gelation, it becomes difficult to remove voids from the fluid or to reduce resin volume.
B,D,A: During
Collectible: Indirectly collectible by using dielectrometer.
Manipulable: Manipulable with material design and careful control of autoclave temperature.
Range: A time at a temperature.

Relationships: 1. After some time in the cure cycle where parts temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

2. Prolonged out time may make gel time (at temperature) earlier. (Hauwiller, Warnock)

3. Resin absorbs moisture, which changes its properties. (Lang pg 740) Possible changes include lower viscosity throughout cure, gel time, and, because of the possible chemical structure change, deactivated catalyst in the resin (an additive). (Warnock)

Comments:

Data: Glass Transition Temperature (Tg)

Reference: Marsh (1), Warnock, Watson, Hauwiller, Vennard, May, McCavill (1), Humphreys and Rosen, Roberts

Importance: Above the Tg, material properties change significantly.

B,D,A: D, A

Collectible: Collectible using differential scanning calorimetry (a thermal measurement) or rheometry (a mechanical measurement).

Manipulable: Indirectly manipulable by controlling autoclave temperature for certain periods of time.

Range:

Relationships: 1. "For a resin to exhibit good tack, drape and handleability, it needs to have an uncured Tg [glass transition temperature] less than ambient temperature". (Marsh (1))

2. Material loses stiffness above Tg. (McCavill (1) pg 135)

3. A high Tg causes internal stresses at room temperature, thus room temperature performance of the material suffers. (May pg 73)

4. Moisture decreases Tg of resins. This Tg is called "wet Tg". As the resin dries, the Tg increases again. (Warnock, Humphreys and Rosen pg 226)

5. A higher degree of polymerization leads to higher strength and stiffness in materials (molecules are not free to move around), but the material will then be more brittle and have a higher Tg. (Watson pg 103)

6. After some time in the cure cycle where parts temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer
network is formed. Temperatures must be kept up (controlled by set point) in order to encourage
crosslinking and raise the Tg of the material. (Roberts pg 754)

7. A material with a higher Tg can operate in higher service temperatures. (Hauwiller)

8. The sought degree of cure includes a certain degree of resin cross-linking and a certain glass
transition temperature (Warnock), with no measurable viscosity.

9. Molecular activity increases with temperature (up to the glass transition
temperature—Warnock), so density decreases with increasing temperature. (Vennard pg 6)

10. A longer cure results in an increased glass transition temperature. (ASM pg 663)

11. A higher cure temperature results in a higher glass transition temperature. (ASM pg 811)

Comments:

Data: Hardness
Reference: Thrower, Oilkey, ASM, May
Importance: Hardness is part of durability.
B,D,A: After
Collectible: Testable following cure.
Manipulable: Manipulable only by part design.
Range: Numerical
Relationships: 1. Hardness may be affected by chemical structure of resin, curing agent, and
modifying reactants. (May pg 66)
Comments:

Data: Heat, Specific
Reference: Budinski, Warnock, ASM
Importance:
B,D,A: B, A
Collectible: Yes, with a differential scanning calorimeter.
Manipulable: Indirectly manipulable by product and process design.
Range: Numerical.
Relationships: 1. Specific heat generally rises with temperature. (ASM 403, 409)
Comments: 1. A property of fiber and resin and their proportions in the final material.

2. Also known as heat capacity. (Warnock)

Data: Interface, fiber-resin
Reference: ASM, May, Gosnell
Importance: A strong interface leads to a stronger material.
B,D,A: B, A
Collectible: No
Manipulable: Structure, additives, and coatings of both resin and fiber contribute to the strength of their interface.
Range: Variable—for example may test strength of bond, evenness of bond, etc.
Relationships: 1. Stress may exist at fiber-resin interface.
2. A strong fiber-resin interface (bond strength) makes for a strong laminate. (May pg 74)
3. The fiber-resin interface may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)
4. Need reasonable resin toughness and good fiber/resin interface to guard against delaminations and disbonds. (Gosnell pg 99)
5. Coupling agents may be added to fiber or resin to increase the strength of the fiber/resin interface. (ASM pg 8)
Comments:

Data: Layup Materials
Reference: ASM, Warnock, Hauwiller, Konarski
Importance: Proper layup is as important to part quality as proper processing.
B,D,A: Before
Collectible: Collectible - record as performed.
Manipulable: Manipulable - change components.
Range: Types and amounts of materials.
Relationships: 1. Fiber/resin volume are affected by dams and bleeder plies, which allow or disallow the flow of resin out of the part during cure.
2. Voids can be caused by resin-starved plies or excessive resin bleeding during cure. This may be controlled by using dams or bleeders. (Konarski pg 661)
3. Higher thermal conductivity in tooling and layup materials leads to better heat transfer to the part. It is desirable to have similar degrees of heat reaching the part from all sides. (Warnock)
4. Tooling/mold materials affect evenness of cure. (Hauwiller) (Evenness of tool heating and tool/material thermal conductivity.)
Comments: 

Data: Layup steps
Reference: Warnock
Importance: Layup is just as important as cure when making a good part.
B.A.A: Before
Collectible: Collectible - record as done or follow recipe.
Manipulable: Manipulable - can change steps.
Range: Series of steps taken, including qualitative and quantitative information.
Relationships: 1. All process steps take time. Layup time, cure time, cure variables recorded at certain times.

2. Difficult layup due to inadequate drape or care can lead to voids or bridges in the part, particularly if the part has a complex contour (geometry). (Warnock)

3. Consolidation starts with layup—the mechanic presses the plies together.

4. Correct and careful layup procedures (e.g., pressing, debulking with vacuum) are necessary to prevent bridges in the part. (Warnock)

5. Possible causes of vacuum bag rupture include sharp edges or protrusions (wrinkles) on the laid up part, or a vacuum bag which has been stretched too thin. (Warnock)

6. Wrinkles in the part can be caused by careless layup.

Comments:

Data: Layup Team (people, experience)
Reference:
Importance: Proper layup is as important to part quality as proper processing.
B.D.A: Before
Collectible: Collectible - may be recorded.
Manipulable: Manipulable - could change teams.
Range: Number, length and type of experience.
Relationships: 1. Experienced team more likely leads to quality part and a shorter total processing time.
Comments:

Data: Moisture Absorption
Reference: ASM, Marsh (1), Warnock, Bascom, Lang, Roberts, Humphreys and Rosen, Rosen and Hashin
Importance: Moisture absorption can degrade part properties.
B.D.A: B, A
Collectible: Collectible before and after cure.
Manipulable: Manipulable by using caution in both the layup and use environments.
Range: Moisture content is expressed in percentage.
Relationships: 1. High moisture absorption "reduces stiffness and service temperature. Degradation is in proportion to moisture intake and is exacerbated by heat." (Marsh (1))

2. Fibers may have finishing agents to improve certain properties, but these often compromise resistance to moisture. (Bascom pg 122)

3. Moisture decreases Tg of resins. This Tg is called "wet Tg". As the resin dries, the Tg increases again. (Warnock, Humphreys and Rosen pg 226)

4. Material left out of the freezer and out of a sealed bag may absorb moisture, especially if out time is lengthy and/or the room is not humidity controlled.

5. Moisture increases tack. If there is too much tack, the material becomes difficult to handle.

6. Moisture swells composite materials, causing stresses. (Humphreys and Rosen pg 228)

7. Increased moisture content slows exothermic reaction, (slows the formation of a polymer network), resulting in increased void content. (Roberts pg 748)

8. Resin absorbs moisture, which changes its properties. (Lang pg 740) Possible changes include lower viscosity throughout cure, gel time, and, because of the possible chemical structure change, deactivated catalyst in the resin (an additive).

(Warnock)

9. Humidity in the use environment contributes to moisture absorption.

10. A high void content makes a part susceptible to moisture absorption. (ASM pg 662)

Comments:

Data: Number, autoclave run
Reference:
Importance: Keeps track of which parts were cured in a batch.
B,D,A: Before
Collectible: Collectible - recorded.
Manipulable: Not applicable.
Range: Numerical.
Relationships: 1. It may be possible to discover cure cycle problems by looking at data from all of the parts cured together in one autoclave run.
Comments:
Data: Number, item
Reference:
Importance: Identification number of a single item.
B,D,A: Before
Collectible: Collectible - number is assigned.
Manipulable: Not applicable.
Range: Numerical
Relationships:
Comments:

Data: Number, part
Reference:
Importance: Identification number of a part type.
B,D,A: Before
Collectible: Collectible - recorded.
Manipulable: Not applicable.
Range: Numerical.
Relationships:
Comments:

Data: Orientation of plies/fibers
Reference: Adams, Dominguez (2), Humphreys and Rosen, Horton and McCarty
Importance: Design for function-unidirectional, woven plies laid up in different directions.
B,D,A: Before
Collectible: Collectible - specified in design of composite
Manipulable: Manipulable - any orientation, can change only before cure (during design or layup)
Range: Piles can be oriented in any direction and are notated using degrees (-89 through +90)
Relationships: 1. Damping capacity is influenced by properties and proportions of resin and fiber, size of inclusions, orientation of fibers to loading axis, and surface treatment of fibers. (Adams pg 206)
2. Tensile modulus is generally reduced with more varied ply orientations. (Dominguez (2) pg 147)
3. If fibers are parallel to load, structures fail at lower strains. (Horton and McCarty pg 260)
4. If fibers are oriented in direction of load, they provide maximum strength and stiffness. (Humphreys and Rosen pg 218)
5. Poisson's ratio varies widely with orientation of plies, and this can cause stress between the
laminate's layers. (Horton and McCarty pg 260)

Comments:

Data: Out time, material
Reference: Hauwiller, Warnock
Importance: Thermosets cure slowly at room temp, so they must be refrigerated.
B,D,A: Before
Collectible: Collectible - recorded in logs.
Manipulable: Manipulable to some degree - refrigerate (or freeze) whenever possible.
Range: Numerical times, up to 10 days.
Relationships: 1. Autoclave cure time is shorter with more out time.

2. An extended material out time can dry out materials and cause some loss of tack and drape.

3. Material left out of the freezer and out of a sealed bag may absorb moisture, especially if out
time is lengthy and/or the room is not humidity controlled.

4. Prolonged out time may make gel time (at temperature) earlier. (Hauwiller, Warnock)

5. Less out time leads to lower viscosity throughout cure cycle. (Warnock)

Comments:

Data: Part geometry (part type/shape/size)
Reference: ASM, Hauwiller, Warnock, Leissa
Importance: Part is made-to-order for a certain job.
B,D,A: B, A
Collectible: Collectible - per design specification.
Manipulable: Not applicable.
Range: Observation, names of parts, measurements.
Relationships: 1. A unsymmetric laminate with few plies (few layers) buckles quickly. (Leissa
pg 447)

2. Bridges can result in voids and dimension (size and shape) problems. (ASM pg 5)

3. Tooling of the correct shape and size is necessary.

4. Part geometry (e.g., thin, thick parts) affect evenness of cure. (Hauwiller)

5. Shrinkage can change part geometry. (Hauwiller)
6. Difficult layup due to inadequate drape or care can lead to voids or bridges in the part, particularly if the part has a complex contour (geometry). (Warnock)

7. An incorrect coefficient of thermal expansion can lead to "spring-in" during cure. That is, if the part was not designed with a correct CTE, temperature changes during the cure may affect the part geometry as it hardens. (Warnock)

Comments:

Data: Pies, number of
Reference: Leissa
Importance: Part size and thickness, and material properties are partly determined by the number of plies in the part.
B,D,A: Before
Collectible: Collectible - count or get from design specification.
Manipulable: Manipulable before cure only - during layup.
Range: Number of plies (of different types and in different layers).
Relationships: 1. Thicker parts generally have more plies.

2. A unsymmetric laminate with few plies (few layers) buckles quickly. (Leissa pg 447)

3. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).

Comments:

Data: Ply manufacturer
Reference:
Importance: Different manufacturer’s materials are not always the same, even if their specifications say the same thing.
B,D,A: B
Collectible: Known in advance.
Manipulable: Manipulable by purchasing from different manufacturers.
Range: A company name.
Relationships:
Comments:

Data: Poisson’s Ratio
Reference: ASM, Horton and McCarty, Thrower
Importance:
B,D,A: After
Collectible: Per specification.
Manipulable: Per specification.
Range: Numerical.
Relationships: 1. Poisson's ratio varies widely with orientation of plies, and this can cause stress between the laminate's layers. (Horton and McCarty pg 260)
Comments:

Data: Polymerization, degree of
Reference: Budinski, ASM, Watson, McCarvill (2), Roberts
Importance: Polymerization strengthens chemical bonding, and strengthens parts.
B,D,A: During
Collectible: Per design specification.
Manipulable: Manipulable somewhat by controlling autoclave pressure and temperature.
Range: 0-100%
Relationships: 1. Resin chemical structure (degree of polymerization and cross-linking) and additives (curing agents, reactants) may change brittleness. (McCarvill (2) pg 139)
2. A high degree of polymerization generally means a high degree of strength and stiffness, since molecules are not free to move about. This in turn leads to a higher degree of brittleness and a higher glass transition temperature (Tg). (Watson pg 103)
3. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)
4. Increased moisture content slows exothermic reaction, (slows the formation of a polymer network), resulting in increased void content. (Roberts pg 748)
Comments:

Data: Precursor
Reference: ASM, Hansen
Importance: This is the basic material from which fibers are made.
B,D,A: Before
Collectible: Collectible from design specification.
Manipulable: Manipulable from per design specification.
Range: Probably a single word.
Relationships: 1. Fibers made from PAN usually have a higher tensile strength than any other fiber, due to a lack of surface defects which act as stress concentrators. (Hansen pg 112)
Comments: 1. Graphite fibers are made from polyacrylonitrile (PAN) or from pitch. (ASM pg 19)

Data: Pressure, autoclave
Reference: Vennard, Hauwiller, Warnock
Importance: Consolidates the curing part.
B,D,A: During
Collectible: Collectible from autoclave pressure sensors.
Manipulable: Manipulable indirectly by changing pressure set point.
Range: Pressure, probably in psi.
Relationships: 1. Raise or lower the autoclave pressure set point to raise or lower autoclave pressure.

2. Heat and pressure cause resin to melt, flow, densify, and cure.

3. Apply the pressure before the gel point is reached in order to consolidate the part and to rid it of voids and volatiles.

4. Pressure increases density. The molecules are forced into a smaller volume. (Vennard pg 6)

5. Autoclave pressure is included in process steps.

6. Fiber volume, resin content, autoclave pressure and vacuum on the part - compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

7. Consolidation during processing can eliminate voids, increase density, and control part thickness.

8. Vacuum adds pressure to total autoclave pressure on part.

9. Position in autoclave may affect evenness of cure, part temperatures and pressures. (Process steps) (Hauwiller)

10. Increasing autoclave temperature also increases autoclave pressure. Increased pressure facilitates a faster heat up rate and a smaller difference in temperature between the part and the autoclave. (Warnock)

11. An uneven cure may be due to uneven resin flow. This may be due to temperature
differences within the part, or to pressure differences on the part due to tooling or placement in
the autoclave. (Viscosity will not be constant throughout the part. (Warnock))

Comments:

Data: Pressure, set point
Reference:
Importance: Regulates autoclave pressure, therefore pressure on curing part.
B,D,A: During
Collectible: Collectible, always available via sensor.
Manipulable: Manipulable by control program or manually.
Range: Probably in psi.
Relationships: 1. Autoclave pressure rises or lowers with change in pressure set point.
2. Set point pressure is included in process steps.
Comments:

Data: Resistivity, Electrical
Reference: ASM, Budinski, Hauwiller, Diefendorf
Importance: A designer may wish to design electrical properties into a part.
B,D,A: After
Collectible: Measurable by test.
Manipulable: Manipulable only by part design.
Range:
Relationships: 1. Resistivity goes down with increasing service temperatures. (ASM pg 370)
2. Resistivity is the inverse of conductivity.
Comments: 1. Composed of fiber and resin resistivities and their percentages in the final part.
   (Hauwiller)

Data: Rupture, vacuum bag
Reference: Warnock, Sanders and Taha
Importance: Bag rupture could mean the loss of the part being cured. (Sanders and Taha pg 703)
B,D,A: During
Collectible: After the cure cycle is finished and the autoclave door is opened, this will be visible.
Manipulable: No.
Range: Ruptured or not ruptured.
Relationships: 1. Possible causes of vacuum bag rupture include sharp edges or protrusions on
the laid up part, or a vacuum bag which has been stretched too thin. (Warnock)
Comments:
Data: Shrinkage
Reference: May, Marsh (1), Hauwiller
Importance: Parts are designed for a specific purpose. A change in dimension or shape could change necessary properties.
B,D,A: After
Collectible: Visible and measurable.
Manipulable: Manipulable only by part design.
Range: Visible and measurable, also weight may indicate shrinkage.
Relationships: 1. Shrinkage can change part geometry. (Hauwiller)
Comments: 1. Composite materials shrink very little. (May pg 67)

Data: Specific gravity
Reference: Vennard, Warnock
Importance: A certain density, thus specific gravity, is required to achieve certain properties in materials.
B,D,A: B, A
Collectible: Measurable before and after cure. Fiber, resin, and water densities are a matter of record from the manufacturers.
Manipulable: Per design specification for before cure. Manipulate during cure only indirectly by controlling temperature and pressure.
Range: Numerical.
Relationships: 1. Specific gravity is the ratio of material or part density to water density at a given temperature and pressure. (Vennard pg 7)
Comments:

Data: Stiffness
Reference: Warnock, ASM, Parker, Watson, Budinski, Donaldson, Hauwiller, Marsh (1), (continued in comments below)
Importance: After reaching maximum stress, stiff materials break rather than bend.
B,D,A: B, A
Collectible:
Manipulable: Manipulable by part and process design, both of which are difficult to guarantee.
Range: Numerical.
Relationships: 1. Generally, strength decreases as modulus increases. (Warnock)
2. Tensile modulus is generally reduced with more varied ply orientations. (Dominguez (2) pg 147)
3. As stiffness increases, brittleness increases. (Parker)
4. A high degree of polymerization generally means a high degree of strength and stiffness, since molecules are not free to move about. This in turn leads to a higher degree of brittleness and a higher glass transition temperature (Tg). (Watson pg 103)

5. Higher cross-linking leads to higher material strength and stiffness. (Budinski pg 46). It also leads to a more brittle material. (Warnock)

6. Damaged bonds decrease stiffness. (Donaldson)

7. Density increases with stiffness. (Diefendorf pg 51)

8. Stiffness reduces drape. (Hauwiller)

9. Low elongation and high strength results in high stiffness. (ASM pg 15)

10. Material loses stiffness above Tg. (McCarvill (1) pg 135)

11. A higher degree of polymerization leads to higher strength and stiffness in materials (molecules are not free to move around), but the material will then be more brittle and have a higher Tg. (Watson pg 103)

12. High moisture absorption "reduces stiffness and service temperature. Degradation is in proportion to moisture intake and is exacerbated by heat." (Marsh (1))

13. If fibers are oriented in direction of load, they provide maximum strength and stiffness. (Humphreys and Rosen pg 218)

14. Fatigue causes buckling, delaminations, and cracks, when in turn cause more damage, including strength and stiffness reduction. (Wang pg 246, Kim pg 436)

15. Composite compressive strength goes up with resin shear modulus. (Horton and McCarty pg 262)

16. For fibers, CTE decreases with increasing modulus. (Diefendorf pg 52)

17. Unidirectional plies are higher in tensile modulus than woven plies. (Dominguez (1) pg 144)

18. Fatigue loading affects mechanical properties (strength, stiffness, creep). Comments: 1. References continued: McCarvill (1), Humphreys and Rosen, Horton and McCarty, Kim, Wang, Diefendorf, Dominguez (1,2)
Data: Strength
Reference: Budinski, Thrower, Gilkey, ASM, Wamock, Watson, May, Kim, Wang, Noton (continued in comments below)
Importance: Strength is one of the basic properties we look for in all materials.

Collectible: Some strengths are collectible by measurement before and after processing.
Manipulable: Manipulable by part design and processing, both of which are difficult to guarantee.
Range: Numerical
Relationships: 1. Heavy loading (stress) can cause buckling. (Higher compressive strength results in heavier load tolerance, thus buckling occurs at higher stress.)

2. Composite compressive strength goes up with resin shear modulus. (Horton and McCarty pg 262)

3. Fatigue may be caused by chemical changes or by stress. (Thrower pg 141).

4. Fatigue causes buckling, delaminations, and cracks, when in turn cause more damage, including strength and stiffness reduction. (Wang pg 246, Kim pg 436)

5. Resistance to fatigue may be influenced by resin chemical structure, curing agents, and reactants. (May pg 66)

6. Good fatigue strength after damage is an indication of good damage tolerance.

7. Low service temperature decreases impact resistance. (Thrower pg 144)

8. Ductility and strength result in toughness, giving resistance to failure under impact. (Gilkey pg 35, Rosen and Dow pg 180)

9. The brittleness of composites makes impact resistance low. Although damage may not always be apparent from the impact surface, internal crazing and debonding may be present. (Rosen and Dow pg 180, Horton and McCarty pg 261)

10. Need high elongation, high resin shear strength, and moderate toughness to get good impact strength. (Gosnell pg 99)

11. A high degree of polymerization generally means a high degree of strength and stiffness, since molecules are not free to move about. This in turn leads to a higher degree of brittleness and a higher glass transition temperature (Tg). (Watson pg 103)

12. A higher degree of cross-linking in resin generally leads to higher strength. (Budinski pg 46). It also leads to a more brittle material. (Warnock)
13. Strength may be affected by resin chemical structure, curing agents, and reactants. (May pg 66)

14. Corrosion can reduce material strength. (Budinski pg 230)

15. Cracks may form from thermal stresses in the part. This can happen when thermal stresses exceed matrix strength. These cracks usually stay within the resin. (ASM pg 15)

16. Low elongation and high strength results in high stiffness. (ASM pg 15)

17. Composite material strength is a function of fiber volume fraction and thickness per ply.

18. Strong fiber-resin interface (bond strength) makes for a strong laminate. (May pg 74)

19. If fibers are oriented in the direction of load, they provide maximum strength and stiffness. (Humphreys and Rosen pg 218)

20. Longer float yields higher composite strength.

21. Higher temperatures generally decrease material strength. (ASM pp 362-415)

22. Strength is the amount of stress a material can tolerate before bending or fracture.

23. Generally, strength decreases as modulus increases. (Warnock)

24. Fatigue loading affects mechanical properties (strength, stiffness, creep).

25. Resin (chemical structure and additives) provides interlaminar shear strength.

26. A smaller diameter fiber has greater tensile strength, but may buckle faster under compressive stress. (Diefendorf pg 51)

Comments: 1. Composites in general have good fatigue properties if they are loaded in the fiber direction. (Budinski pg 74, Rosen and Hashin pg 203)

2. Tensile strength is much greater for composite materials than for conventional metals. (ASM pg 3, Noton pg 35)

3. References continued: McCarvill (2), Rosen and Hashin, Gosnell, Rosen and Dow, Diefendorf, Horton and McCarty, Humphreys and Rosen, Hansen

Data: Stress
Reference: ASM, Thrower, Schiermeier, Hauwiller, Hinrichs, May, Hansen, Diefendorf,
(continued in comments below)
Importance: Stress on a part is always present in one form or another. Stress tolerance is necessary for parts.

Collectible: Parts are designed to withstand certain amounts of stress. Collectible per specification and test.

Manipulable: Stress during testing is manipulable—apply certain amounts of stress to the material.

Range: Numerical

Relationships:
1. Heavy loading (stress) can cause buckling. (Higher compressive strength results in heavier load tolerance, thus buckling occurs at higher stress.)

2. Too large a difference between mid-part and top-part temperatures during gelation may cause stresses, non-uniform consolidation, or trapped volatiles. (Hinrichs pg 651).

3. Cracks may form from thermal stresses in the part. This can happen when thermal stresses exceed matrix strength. These cracks usually stay within the resin. (ASM pg 15)

4. Cracks stress the surrounding material, causing further damage. (Rosen and Hashin pg 195)

5. Stress over time causes creep. (Thrower pg 142)

6. Delaminations can be caused by stress on parts or incompatible fiber/resin mixes. (ASM pg 8)

7. A high Tg causes internal stresses at room temperature, thus room temperature performance of the material suffers. (May pg 73)

8. Stress may exist at fiber-resin interface.

9. Moisture swells composite materials, causing stresses. (Humphreys and Rosen pg 228)

10. Poisson's ratio varies widely with orientation of plies, and this can cause stress between the laminate's layers. (Horton and McCarty pg 260)

11. Fibers made from PAN usually have a higher tensile strength than any other fiber, due to a lack of surface defects which act as stress concentrators. (Hansen pg 112)

12. Fatigue may be caused by chemical changes or by stress. (Thrower pg 141).

13. Strength is the amount of stress a material can tolerate before bending or fracture.

14. Stresses may be due to mechanical load, temperature and moisture. (Humphreys and Rosen pp 227-229)

15. "Differences in thermal expansion coefficients cause stresses along the material interfaces,"
which creates singularities at the points at the ends of the interfaces. (Schiermeier)

16. Tool material affects heat rate (both warming up and cooling down), thus stresses (Hauwiller).

17. A smaller diameter fiber has greater tensile strength, but may buckle faster under compressive stress. (Diefendorf pg 51)

Comments: 1. References continued: Rosen and Hashin, Horton and McCurry, Humphreys and Rosen.

Data: Tack
Reference: ASM, Marsh (1), McCarvill (2), Dominguez (1), Lang
Importance: Tack allows plies to adhere to each other until they can be permanently bonded during curing.
B,D,A: Before
Collectible: Collectible.
Manipulable: Manipulable by keeping plies refrigerated and using them before they get too old.
Range: Qualitative—low to high. (Or boardy to tacky)
Relationships: 1. "For a resin to exhibit good tack, drape and handleability, it needs to have an uncured $T_g$ [glass transition temperature] less than ambient temperature". (Marsh (1))

2. The type of resin and its additives can influence tack. (Dominguez (1) pg 144)

3. Excessive pre-cure resin volume makes plies too tacky and difficult to handle.

4. Moisture (or humidity) in the layup room increases tack. If there is too much tack, the material becomes difficult to handle. (Lang pg 740)

5. A small amount of heat increases tack, but will later cure thermosets. Room temperature cures thermosets too, slowly. (Lang pg 740)

6. Long out times reduce tack (the material cures). (McCarvill (2) pg 139)

7. Over time, as the materials age, they dry out and lose tack. This means that plies will not adhere to each other well and the layup will be difficult to perform. (McCarvill (2) pg 139)

Comments:

Data: Temperature, autoclave
Reference: Warnock
Importance: Used to heat and cure parts.
B,D,A: During
Collectible: Collectible - thermocouples various places in autoclave.
Manipulable: Manipulable - indirectly by controlling autoclave heater.
Range: Numerical
Relationships: 1. If autoclave temperatures rise, part temperatures should rise.

2. Autoclave temperature is included in process steps.

3. When autoclave temperature set point is increased, autoclave temperature should increase.

4. Increasing autoclave temperature also increases autoclave pressure. Increased pressure facilitates a faster heat up rate and a smaller difference in temperature between the part and the autoclave. (Warnock)

Comments:

Data: Temperature, mid-part
Reference: Vennard, Hauwiller, Warnock, Hinrichs, Konarski, Roberts
Importance: Must heat to cure thermosets.

B,D,A: During
Collectible: Collectible - thermocouples throughout part or coupon.
Manipulable: Manipulable - indirectly by autoclave temperature setting and exotherm.
Range: Numerical.
Relationships: 1. As autoclave temperature and exothermic reactions rise, so does part temperature.

2. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

3. "If the resin viscosity is too high (temperature too low or the material advanced), flow does not occur easily and compaction does not occur." May result in air pockets (voids).

4. Heat and pressure cause resin to melt, flow, densify, and cure.

5. Molecular activity increases with temperature (up to the glass transition temperature—Warnock), so density decreases with increasing temperature. (Vennard pg 6)

6. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).
7. Mid- and top-part temperatures give an indication of the time exotherm begins and the rate at which it progresses. Generally, "reaction rates double for every 10 degrees C (18 degrees F)". (Hinrichs pg 651)

8. Part temperatures are included in process steps.

9. Slow part heating and low viscosity with pressure can help rid a curing part of voids. (Konarski pg 661)

10. Position in autoclave may affect evenness of cure, part temperatures and pressures. (Process steps) (Hauwiller)

11. Too large a difference between mid-part and top-part temperatures during gelation may cause stresses, non-uniform consolidation, or trapped volatiles. (Hinrichs pg 651).

12. Increasing autoclave temperature also increases autoclave pressure. Increased pressure facilitates a faster heat up rate and a smaller difference in temperature between the part and the autoclave. (Warnock)

13. An uneven cure may be due to uneven resin flow. This may be due to temperature differences within the part, or to pressure differences on the part due to tooling or placement in the autoclave (Viscosity will not be constant throughout the part. (Warnock))

14. A higher cure temperature results in a higher glass transition temperature. (ASM pg 811)

Comments:

Data: Temperature, set point
Reference: Roberts
Importance: Autoclave temperature control is based on this.
B.D.A: During
Collectible: Collectible, always available.
Manipulate: Manipulable by control program or manually.
Range: Numerical
Relationships: 1. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

2. Autoclave temperature, part temperature - these rise or lower with temperature set point.

3. Set point temperature is included in process steps.
4. A higher cure temperature results in a higher glass transition temperature. (ASM pg 811)

Comments:

Data: Temperature, top-part
Reference: Vennard, Hauwiller, Warnock, Hinrichs, Roberts, Konarski
Importance: Must heat to cure thermosets.
B,D,A: During
Collectible: Collectible - thermocouples throughout part or coupon.
Manipulable: Manipulable - indirectly by autoclave temperature setting and exotherm.
Range: Numerical.
Relationships: 1. As autoclave temperature and exothermic reactions rise, so does part temperature.

2. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn’t rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

3. “If the resin viscosity is too high (temperature too low or the material advanced), flow does not occur easily and compaction does not occur.” May result in air pockets (voids).

4. Heat and pressure cause resin to melt, flow, densify, and cure.

5. Molecular activity increases with temperature (up to the glass transition temperature—Warnock), so density decreases with increasing temperature. (Vennard pg 6)

6. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).

7. Mid- and top-part temperatures give an indication of the time exotherm begins and the rate at which it progresses. Generally, "reaction rates double for every 10 degrees C (18 degrees F)." (Hinrichs pg 651)

8. Part temperatures are included in process steps.

9. Slow part heating and low viscosity with pressure can help rid a curing part of voids. (Konarski pg 661)

10. Position in autoclave may affect evenness of cure, part temperatures and pressures. (Process steps) (Hauwiller)
11. Too large a difference between mid-part and top-part temperatures during gelation may cause stresses, non-uniform consolidation, or trapped volatiles. (Hinrichs pg 651).

12. Increasing autoclave temperature also increases autoclave pressure. Increased pressure facilitates a faster heat up rate and a smaller difference in temperature between the part and the autoclave. (Warnock)

13. An uneven cure may be due to uneven resin flow. This may be due to temperature differences within the part, or to pressure differences on the part due to tooling or placement in the autoclave. (Viscosity will not be constant throughout the part. (Warnock))

14. A higher cure temperature results in a higher glass transition temperature. (ASM pg 811)

Comments:

Data: Thermal expansion, coefficient of (CTE)
Reference: ASM, Budinski, Schieimier, Warnock, Diefendorf, Wilson, Rosen and Hashin
Importance: An incorrect CTE can lead to stresses and ill-fitting parts due to temp changes; or spring-in during cure.
B,D,A: A
Collectible: Measurable by test.
Manipulable: Indirectly manipulable by product and process design.
Range: See "Comments" below.
Relationships: 1. Choose tooling compatible with the part or the process. (Wilson pg 428) (E.g., you probably want net 0 CTE between tooling and part.

2. Higher fiber volume in cured laminate generally means a lower coefficient of thermal expansion (CTE). (Rosen and Hashin pg 190)

3. For fibers, CTE decreases with increasing modulus. (Diefendorf pg 52)

4. "Differences in thermal expansion coefficients cause stresses along the material interfaces, which creates singularities at the points at the ends of the interfaces". (Schieimbier)

5. An incorrect coefficient of thermal expansion can lead to "spring-in" during cure. That is, if the part was not designed with a correct CTE, temperature changes during the cure may affect the part geometry as it hardens. (Warnock)

Comments: 1. Measured in longitudinal and transverse.

Data: Thickness of part/laminate
Reference: Hauwiller  
Importance: Insure that the part fits where it is supposed to fit.  
B,D,A: B, A  
Collectible: Collectible - measurable.  
Manipulable: Indirectly manipulable through part design (e.g., number of plies) and process (e.g., consolidation).  
Range: Numerical  
Relationships: 1. Number of plies - more plies usually leads to thicker parts.  
2. Consolidation during processing can eliminate voids, increase density, and control part thickness.  
3. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).  
4. Fewer thicker plies may make the same thickness of part as more thinner plies.  
5. Thicker parts are more likely to retain voids than thinner parts. (Hauwiller)  

Comments:  

Data: Thickness, ply  
Reference: Warnock  
Importance: Ply thickness may partially determine cure cycle and part properties.  
B,D,A: B, A  
Collectible: Collectible - per design specification.  
Manipulable: Manipulable - per design specification.  
Range: Numerical  
Relationships: 1. Fewer thicker plies may make the same thickness of part as more thinner plies.  
2. Ply thickness measured after cure gives a good indication of the success of the consolidation. (Warnock)  

Comments:  

Data: Time  
Reference: Thrower, Warnock, Noton, Roberts, Hinrichs  
Importance: Entire process occurs over time. Some variables require critical timing to make a good part.  
B,D,A: B,D,A
Collectible: Collectible - recordable.
Manipulable: No
Range: Hours, minutes, seconds.
Relationships: 1. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

2. All process steps take time. Layup time (which may be related to the experience of the layup team), cure time, cure variables recorded at certain times.

3. Stress over time causes creep. (Thrower pg 142)

4. Higher actual autoclave temperatures over a period of time leads to exotherm in thicker parts (with more plies).

5. Mid- and top-part temperatures give an indication of the time exotherm begins and the rate at which it progresses. Generally, "reaction rates double for every 10 degrees C (18 degrees F)". (Hinrichs pg 651)

6. Damping takes time. Composites are foster than conventional metals by about 10%. (Noton pg 36)

7. Fiber volume, resin content, autoclave pressure and vacuum on the part - compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

8. A long cure results in an increased glass transition temperature. (ASM pg 663)

Comments: Of interest aside from relationships:

1. Total cure time.

Data: Tooling/molds (shape, material, etc.)
Reference: ASM, Hauwiller, Warnock, Wilson, May
Importance: Tooling partially controls dimensions and sometimes cure cycles.
B,D,A: Before
Collectible: Collectible - known.
Manipulable: Manipulable - tools are selected for part.
Range: Various - shape, size, material, mechanical properties, etc.
Relationships: 1. Choose tooling compatible with the part or the process. (Wilson pg 428) (E.g., you probably want net 0 CTE between tooling and part.)

2. Tooling/mold materials affect evenness of cure. (Hauwiller) (Evenness of tool heating and tool/material thermal conductivity.)

3. Higher thermal conductivity in tooling and layup materials leads to better heat transfer to the part. It is desirable to have similar degrees of heat reaching the part from all sides. (Warnock)

4. An uneven cure may be due to uneven resin flow. This may be due to temperature differences within the part, or to pressure differences on the part due to tooling or placement in the autoclave (Viscosity will not be constant throughout the part. (Warnock))

5. Tool material affects heat rate (both warming up and cooling down), thus stresses (Hauwiller).

Comments: 1. Composite is probably anisotropic, tool may be isotropic.

2. Includes shape, material, mass, CTE, other properties, just as the part does.

3. Choose tooling that does not react with the material being processed. (May pg 77)

Data: Toughness
Reference: Gilkey, May, Gosnell, Horton and McCarty
Importance: Good toughness contributes to keeping a part in good shape through various stresses.
B,D,A: After Collectible: Testable, after cure.
Manipulable: Manipulable only through proper part design and cure, which are hard to guarantee.
Range: Numerical Relationships: 1. Toughness may be affected by chemical structure of resin, curing agent, and modifying reactants. (May pg 66)

2. Need reasonable resin toughness and good fiber/resin interface to guard against delaminations and disbonds. (Gosnell pg 99)

3. Ductility and strength result in toughness, giving resistance to failure under impact. (Gilkey pg 35)

4. Toughness assists in resistance to failure under impact. (Gilkey pg 36)

5. Materials with greater toughness have greater damage tolerance. (Horton and McCarty pg 262)
Comments:

Data: Ultraviolet light, resistance to
Reference: ASM, Hauwiller, Warnock
Importance: UV light can be harmful to some materials.
B,D,A: After
Collectible: Testable
Manipulable: Manipulable only by proper part design and proper cure, which are difficult to
provide.
Range: Resistant to some degree, numerical or not.
Relationships: 1. Resin additives and fiber coatings can affect resistance to UV light.
(Hauwiller, Warnock)
Comments: 1. UV light can initiate chemical reactions due to short wavelengths. (ASM pg 24)

Data: Use conditions of end product
Reference: ASM, Watson, Thrower, Marsh (1), Hauwiller, Warnock, Humphreys and Rosen,
(continued in comments below)
Importance: A part must be designed and cured with its end use in mind.
B,D,A: Before
Collectible: This is known before part design.
Manipulable: No.
Range: Probably numerical.
Relationships: 1. Stresses may be due to mechanical load, temperature and moisture.
(Humphreys and Rosen pg 227-229)
2. Low service temperatures make composites more brittle. (Watson pg 99)
(Sub-zero—Warnock) Also, the higher service temperature capability, the more brittle.
(Warnock)
3. Higher service temperature generally causes more creep. (Thrower pg 142)
4. A high Tg causes internal stresses at room temperature, thus room temperature performance
of the material suffers. (May pg 73)
5. High moisture absorption "reduces stiffness and service temperature. Degradation is in
proportion to moisture intake and is exacerbated by heat." (Marsh (1))
6. Low service temperature decreases impact resistance. (Thrower pg 144)
7. Higher temperatures generally decrease material strength. (ASM pp 362-415)
8. Specific heat generally rises with temperature. (ASM pp 403, 409)
9. Resin component of composite generally determines allowable service temperature. (Noton pg 37)

10. Material loses stiffness above Tg. (McCarvill (1) pg 135)

11. Higher service temperatures can be used with a higher Tg. (Hauwiller)

12. Humidity in the use environment contributes to moisture absorption.

13. Fatigue loading affects mechanical properties (strength, stiffness, creep).

14. Resin determines possible service temperature. (Noton pg 37)

Comments: 1. Interested in intended service temperature, humidity, salt air, other corrosives/chemicals, fatigue loading.

2. References continued: McCarvill (1), May, Noton

Data: Vacuum level
Reference: Warnock, May, Harvey, McGann and Crilly
Importance: Holds plies together and adds pressure to part during cure.
B,D,A: B,D,A
Collectible: Collectible - metered.
Manipulable: Manipulable by control program or manually.
Range:
Relationships: 1. Vacuum adds pressure to total autoclave pressure on part.

2. Fiber volume, resin content, autoclave pressure and vacuum on the part - compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

Comments: 1. Vacuum and its bag protect the part from outside air and gasses while curing. (McGann and Crilly pg 644).

Data: Vent time (vacuum bag)
Reference: Warnock
Importance: Vent timing is critical to void reduction.
B,D,A: During
Collectible: Collectible - record how much time was used to vent bag.
Manipulable: Manipulable - can change amount of time to be vented.
Range: A time at a temperature.
Relationships: 1. The time or temperature at which the vacuum bag is vented is critical to void reduction. A vacuum is needed to help hold plies together at the beginning of the cure cycle and to remove voids as much as possible. But the vacuum must be vented in order to allow full pressurization of the part, thus remaining internal voids are pressurized. (Warnock)

Comments:

Data: Viscosity
Reference: Payne, Levine, Warnock, Sanders and Taha, Lang, May, Roberts, McCarvili (2),
Importance: Indirectly gives degree of cure.
B,D,A: B,D,A
Collectible: Indirectly collectible using dielectric loss factor (E2) or ultrasound measurement relationships.
Manipulable: Indirectly manipulable using temperature, time, and pressure.
Range: Numerical.
Relationships: 1. Part temperature, autoclave pressure, time - holding part temperature and autoclave pressure at certain levels (not necessarily known) over a certain amount of time (not necessarily known) leads to viscosity changes.

2. Additives may change uncured resin viscosity or reduce brittleness. (McCarvili (2) pg 139)

3. Resin viscosity decreases as degree of cure advances.

4. If you can hold viscosity at a minimum for some period of time, volatiles are allowed to escape. (Payne, Sanders and Taha pg 702)

5. Viscosity level is a dynamic variable, changes are recorded as process steps.

6. Fiber volume, resin content, autoclave pressure and vacuum on the part - compaction through pressure and vacuum at certain times during curing may reduce resin content, thus end product may have higher fiber volume than starting materials. (Net resin systems are dammed during cure, thus lose little resin.) (Warnock)

7. After some time in the cure cycle where part temperatures are rising, a polymer network begins to form, and activity within the network rises. The reaction rate increases, increasing viscosity. After reaching the gel point, the viscosity doesn't rise anymore. The polymer network is formed. Temperatures must be kept up (controlled by set point) in order to encourage crosslinking and raise the Tg of the material. (Roberts pg 754)

8. Heat and pressure cause resin to melt, flow, densify, and cure. (May pg 73)

9. Less out time leads to lower viscosity throughout cure cycle. (Warnock)

10. The sought degree of cure includes a certain degree of resin cross-linking and a certain glass
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transition temperature (Warnock), with no measurable viscosity.

11. An uneven cure may be due to uneven resin flow. This may be due to temperature
differences within the part, or to pressure differences on the part due to tooling or placement in
the autoclave (Viscosity will not be constant throughout the part. (Warnock))

12. Resin absorbs moisture, which changes its properties. (Lang pg 740) Possible changes
include lower viscosity throughout cure, gel time, and, because of the possible chemical
structure change, deactivated catalyst in the resin (an additive). (Warnock)

Comments:

Data: Voids
Reference: ASM, Payne, Hauwiller, Warnock, Adams, Konarski, Lang, Hinrichs, Roberts,
Sanders and Taha
Importance: Voids are part defects and may affect part properties.
B.D.A: After
Collectible: Collectible - during QC checks.
Manipulable: Manipulable only by proper part design and proper cure, which are difficult to
guarantee.
Range: Void sizes, void volume content in percentage, void locations and distribution, void
types.
Relationships: 1. Damping capacity is influenced by properties and proportions of resin and
fiber, size of inclusions, orientation of fibers to loading axis, and surface treatment of fibers.
(Adams pg 206)

2. Higher pressure during cure (before gel point) reduces void volume.

3. If you can hold viscosity at a minimum for some period of time, volatiles are allowed to
escape. (Payne, Sanders and Taha pg 702)

4. Voids can be caused by resin-starved plies or excessive bleeding during cure. This can be
taken care of with proper layup materials (such as bleeder plies and dams). (Konarski pg 661)

5. Slow part heating (both mid- and top-part temperatures, and set point temperature) and low
viscosity with pressure can help rid a curing part of voids. (Konarski pg 661)

6. Apply the pressure before the gel point is reached in order to consolidate the part and to rid it
of voids and volatiles.

7. If the resin viscosity is too high (temperature too low or the material advanced), flow does
not occur easily and compaction does not occur. May result in air pockets (voids).
8. Consolidation during processing can eliminate voids, increase density, and control part thickness.

9. Bridges can result in voids and dimension (size and shape) problems. (ASM pg 5)

10. A more dense material may have forced out more voids during cure.

11. Difficult layup due to inadequate drape or care can lead to voids or bridges in the part, particularly if the part has a complex contour (geometry). (Warnock)

12. Voids can be reduced by proper cleanliness and pressure within the layup room. (Lang pg 740)

13. Thicker parts are more likely to retain voids than thinner parts. (Hauwiller)

14. Increased moisture content slows exothermic reaction, (slows the formation of a polymer network), resulting in increased void content. (Roberts pg 748)

15. Too large a difference between mid-part and top-part temperatures during gelation may cause stresses, non-uniform consolidation, or trapped volatiles. (Hinrichs pg 651).

16. The time or temperature at which the vacuum bag is vented is critical to void reduction. A vacuum is needed to help hold plies together at the beginning of the cure cycle and to remove voids as much as possible. But the vacuum must be vented in order to allow full pressurization of the part, thus remaining internal voids are pressurized. (Warnock)

17. A high void content makes a part susceptible for moisture absorption. (ASM pg 662)

Comments: 1. If part is good, there are usually less than 1% voids.

2. Porosity is one synonym - it is the percent of total non-solid (void) volume to total part volume.

3. Voids are often found at the location of "ply drop-offs", that is, locations where plies are not all the same length and width. (Warnock)

Data: Weight of part
Reference:
Importance: Light weight is desired for aircraft structures.
B.D.A: After
Collectible: Collectible - weigh part.
Manipulable: Manipulable only indirectly through composite design and processing.
Range: Numerical
Relationships:
Comments:

Data: Wrinkles
Reference: ASM, Wamock
Importance: Wrinkles are surface defects.
B,D,A: After
Collectible: Collectible - visually.
Manipulable: Indirectly manipulable only through proper layup and cure, which are difficult to guarantee.
Range: Number of wrinkles, sizes, and locations.
Relationships: 1. Incorrectly drawn vacuum can cause wrinkles by causing vacuum bag to wrinkle itself and the part as the part cures. (ASM pg 26)
2. Possible causes of vacuum bag rupture include sharp edges or protrusions (wrinkles) on the laid up part, or a vacuum bag which has been stretched too thin. (Wamock)
3. Wrinkles in the part can be caused by careless layup.
Comments:

Data: Yarns, weave, float, and yarn count
Reference: ASM, Hauwiller, Wamock, Cumming, Diefendorf, Dominguez (1,3)
Importance: Different yarns and weaves give different material properties.
B,D,A: Before
Collectible: Order by design.
Manipulable: Order by design.
Range: Weave is by name, float and yarn count are numerical.
Relationships: 1. Longer float yields higher composite strength.
2. A tight weave in a ply reduces drape. (Dominguez (3) pg 149)
3. A loose weave results in decreased strength. (Dominguez (3) pg 149)
4. Unidirectional plies are higher in tensile modulus than woven plies. (Dominguez (1) pg 144)
5. Crack propagation is higher in unidirectional layers. (Hauwiller)
6. A larger filament diameter generally means a stiffer material and reduced drape. (Wamock)
7. A smaller diameter fiber has greater tensile strength, but may buckle faster under compressive stress. (Diefendorf pg 51)

8. The density of carbon fibers increases with increasing modulus. (Diefendorf pg 51)

Comments: 1. Interested in fiber type, weave, float, yarn count, filament diameter, filament length.
APPENDIX B
DEFINITIONS OF THE DATA
Data: Age of material
Definition: The age of the material consists of both when it was manufactured and how long it has been at room temperature.

Reference:

Data: Autoclave specifications
Definition: The autoclave is the "pressure cooker" in which parts are cured. It is a pressure vessel which can be heated internally.

We are interested in the autoclave's manufacturer, size, shape, and uniformity of heating, cooling, and pressurization.

Reference:

Data: Britteness
Definition: When a material deforms little before breaking, it is called brittle.

Reference: Thrower pg 137

Data: Buckling
Definition: Buckling is lateral material deflection due to compressive action.

Reference: ASM pg 6

Data: Chemical structure and additives, resin
Definition: Chemical structure: Molecules and their attachments to one another.

Additives: "Any substance added to another substance, usually to improve properties, such as plasticizers, initiators, light stabilizers, and flame retardants." Also includes curing agents and reactants.

Reference: ASM pg 3

Data: Coatings and surface treatments, fiber
Definition: Fibers used in composites may have various types of coatings and surface treatments
applied to them to achieve certain properties, such as resistance to UV light, resistance to flame, or ease of handling.

Coatings are often called finishing agents, coupling agents, or sizing.

Reference:

Data: Conductivity, Electrical
Definition: Conductance of electrical current through a material.

Resistivity is the inverse of conductivity.

Reference: ASM pg 20, Budinski pg 17

Data: Conductivity, Thermal (k)
Definition: The ability of a material to conduct heat. Thermal conductivity is measured as the quantity of heat that passes through a unit cube of material in unit time when the difference between two faces is 1 degree. It is a constant for a given material.

Reference: ASM pg 23

Data: Consolidation
Definition: Consolidation is sometimes called compaction. This means to compress to reduce voids and achieve the desired density of the composite. It is also used to achieve the desired part dimension.

Reference: ASM pg 7

Data: Corrosion, resistance to
Definition: The ability to resist deterioration by chemical reaction with the environment. Deterioration can be caused by acids, gases, salts, solvents. In the form of wear, pitting, etc.

Reference: Budinski pg 15
Data: Cracks
Definition: Cracks in the composite part may be macro (large, all the way through the part, fractures) or micro (small cracks in the resin, usually inside the part where it is not visible).

Reference:

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Data: Creep
Definition: The continuing permanent deformation of a material under stress over an extended period of time.

Reference: Thrower pg 142

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Data: Cross-linking, degree of (in resin)
Definition: Cross-linking is the attaching of polymers to each other. The degree of cross-linking is the fraction of cross-linked polymers in the resin.

Reference: ASM pg 8

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Data: Cure Process steps
Definition: Cure process steps include everything done during actual curing of the part. This starts with turning on the heat, and goes through recording and changing of temperatures, pressures, viscosity, and anything else done during the cure process itself.

Reference:

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Data: Cure, degree of
Definition: A fully cured laminate no longer has measurable viscosity, and has reached a glass transition temperature and has cross-linked polymers to the extent for which the part was designed.

Reference:

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Data: Cure, evenness of
Definition: How evenly the laminate cured. (E.g., no "well-done" spots or soft spots)

Reference:
Data: Damage tolerance
Definition: The ability of a structure to tolerate a reasonable level of damage without jeopardizing safety. For example, cracks won't grow to critical size during the structure's expected service life.
Reference: ASM pg 8, Horton and McCarty pg 259

Data: Damping Capacity
Definition: The decay with time of the amplitude of free vibration of a material.
Reference: ASM pg 8

Data: Delaminations, bridges, un/dc/disbonds, splintering
Definition: Delaminations and de/dis/un-bonds: separation of layers. Bridges: fibers don't conform to radii/corners during molding.
Reference: ASM pp 5, 8, 9, 24

Data: Density
Definition: The mass contained in a unit volume.
Reference: Vennard pg 6

Data: Drape
Definition: The ability of a material to be flexible and conform to a contoured surface.
Reference: ASM pg 9

Data: Ductility
Definition: When material deforms significantly before breaking, it is ductile. Ductility is measured by a change in length or area. Expressed in percentage.
Reference: Thrower pg 137
Data: Elongation
Definition: The increase in length in tensile testing when a specimen fractures.
Reference: Budinski pg 20

Data: Environmental conditions in layup room
Definition: This consists of temperature, moisture, cleanliness, and air pressure (just enough to keep impurities from floating).
Reference: Lang pg 740

Data: Exothermic reaction
Definition: The liberation of heat. For example, when a thick laminate is curing, at some point it begins to generate heat which adds to the heat being released into the autoclave.
Reference: ASM pg 10

Data: Fiber/Resin Volume
Definition: Fiber volume is the percentage of fibers in the part. Resin volume would be the remaining percentage. Sometimes called Fiber/resin content.
Reference:

Data: Flame, resistance to
Definition: The ability to extinguish flame once the heat source is removed.
Flammability: The extent to which a material will support combustion.
Reference: ASM pg 11

Data: Gel point
Definition: Gel temperature, gel point: The temperature at which fluid (such as soft resin) begins to gel (molecules cross-link and harden). Reactions slow after this point.
Reference: ASM pg 12
Data: Glass Transition Temperature (Tg)
Definition: The point at which a substance changes from glassy to rubbery under certain temperatures. Sometimes called the Heat Distortion Temperature.
Reference: Watson pg 99, McCarvill (1) pg 135

Data: Hardness
Definition: Resistance to wear, penetration, abrasion, or surface indentation.
Reference: Thrower pg 138, Gilkey pg 37, ASM pg 12

Data: Heat, Specific
Definition: The ratio of the amount of heat required to raise the temperature of a unit mass 1 degree to the heat required to raise the same mass of water 1 degree.
Reference: Budinski pg 17

Data: Interface, Fiber-Resin
Definition: The boundary of the fiber and the resin.
Reference:

Data: Layup Materials
Definition: Layup materials consist of materials used in preparing a part for cure. They include release films, tapes, dams, vacuum bags, breathers, bleeders, peel plies, and other materials, as well as the types and amounts of each used.
Reference:

Data: Layup steps
Definition: This consists of all of the steps necessary when preparing a part for cure, such as layering and consolidating materials, applying a vacuum, etc.
Reference:
Data: Layup Team (people, experience)
Definition: The layup team consists of one to several people with varying levels of experience in layup artistry.
Reference:

Data: Moisture Absorption
Definition: Moisture Absorption: the pickup of water from the air (or through other mediums). (ASM)
Moisture Content: the amount of moisture in a material under given conditions, expressed as a percentage of the mass of the whole moist object. (ASM)
Moisture Swelling Coefficient: similar to the coefficient of thermal expansion (CTE). A material swells with moisture. (Rosen and Hashin)
Reference: ASM pg 16, Rosen and Hashin pg 188

Data: Number, autoclave run
Definition: This number is for record-keeping. It represents a particular set of materials which were all cured together in one autoclave run.
Reference:

Data: Number, item
Definition: This number represents the particular part being cured.
Reference:

Data: Number, part
Definition: Part number is a general number for all like parts, whenever they are made.
Reference:
Data: Orientation of plies/fibers
Definition: Piles of like or different weaves may be laid up with their fibers running in any desired direction or orientation.
Reference:

Data: Out time, material
Definition: Out time is the amount of time a material is out of refrigeration. This is important in composite materials, since resins dry out.
Reference:

Data: Part geometry (part type/shape/size)
Definition: This describes the part being made--its dimensions, shape, and what the part actually is.
Reference:

Data: Plies, number of
Definition: There are always a certain number of plies that go into any part. The plies may be of somewhat different materials and they may have different types of weaves.
Reference:

Data: Ply manufacturer
Definition: The company from which prepreg materials are purchased. Prepregs are the prepared fiber and resin plies used to make some composite parts.
Reference:

Data: Poisson's Ratio
Definition: Poisson's Ratio is the ratio of lateral strain (elongation) to the axial strain (elongation), when a bar is held in tension (or compression) longitudinally. This ratio is actually a negative number since the lateral (or axial) change will be negative, but it is expressed as its absolute value. If the total volume does not change, Poisson's ratio is 0.5.
Reference: Thrower pp 144-146, ASM pg 18
Data: Polymerization, degree of
Definition: Polymer: A long chain of repeating molecules.

Degree of Polymerization: The number of monomers (structural units) in an average polymer molecule in some sample measure.

Reference: Budinski pg 40, ASM pg 8

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Data: Precursor
Definition: The precursor is the material from which fibers originated. There are a number of processes (such as carbonizing and stretching) that the material may go through before becoming a fiber.

Reference:

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Data: Pressure, autoclave
Definition: This is the actual measurable pressure being released into the curing chamber. This pressure bears down on the part, consolidating it.

Reference:

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Data: Pressure, set point
Definition: Set point pressure is the pressure the autoclave is being told to bring to bear on the part inside.

Reference:

---

Data: Resistivity, Electrical
Definition: Resistance of a material to the passage of electrical current. May be measured as the resistance per unit length and cross-sectional area or per unit length and unit weight.

Resistivity is the inverse of conductivity.

Reference: ASM pg 20, Budinski pg 17
190

Data: Rupture, vacuum bag
Definition: When a vacuum bag breaks, exposing the contents to the autoclave's atmosphere.

Also known as a "blown bag" (Warnock)

Reference: Warnock

Data: Shrinkage
Definition: The reduction in size and something distortion of shape of a part which has been densified.

Reference:

Data: Specific gravity
Definition: The ratio of material or part density to water density at a given temperature and pressure. (Vennard)

Given in pounds/feet cubed divided by pounds/feet cubed, at 60 degrees F and 1 atmosphere. (Warnock)

Reference: Vennard pg 7, Warnock

Data: Stiffness
Definition: Stiffness is also known as rigidity. It is the resistance to deformation caused by stress. The measure of stiffness is called a MODULUS, which is equal to stress/strain (strain is elongation of material based on the applied stress). For example, if stress on an object is 12.1 psi and this results in a strain (elongation) of 10%, then the modulus is 12.1 psi/0.01. If the elongation was 5%, the modulus would be 12.1 psi/0.005, and the higher modulus would indicate that the material was stiffer than at 10% elongation. A higher modulus means higher stiffness.

Moduli can be measured for fiber, resins, and finished parts. Moduli can be measured in axial (along fiber length) and transverse (across fibers) directions and can be in compressive (pushing), tensile (pulling), or shear (non-linear) modes.

Specific modulus = modulus/density.
Reference:

Data: Strength (page 2)
Definition: The other strengths of interest for this database are:

Impact strength: The amount of energy required to fracture a material. (Budinski) Impact strength is a sign of durability.

Fatigue strength: The highest unit stress to which a material can be subjected many (millions of) times without failure. (Thrower, Gilkey)

Specific strength: The ratio of strength/density. (ASM)

Reference: Budinski pg 20, Thrower pg 141, Gilkey pg 76, ASM pg 22

Data: Strength (page 1)
Definition: "Strength" means maximum tolerable stress. It can be measured in fibers, resins, and in finished parts. Part strength can be measured in axial (along fiber length) and transverse (across fibers) directions and in compressive, tensile, and shear modes (in force per unit area).

Reference: ASM pp 7, 21, 23

Data: Stress
Definition: Stress is the force applied to a material; axially or transversely; and compressive, tensile, or shear; which may cause the material to bend or fracture. Measured as force per unit area.

Stresses result from physical pressure or thermal differences within the part, and can be manifested within plies or between plies. Stresses may occur during processing or after, and residual stresses may be trapped within a cured part (for example, where different materials are molded together into a shape and the materials shrink different amounts—this leads to a pulling between the materials, even though there is no longer any outside stress being applied). (ASM)
Definition: Tack is "stickiness" that keeps plies together during layup yet allows the layup mechanic to peel the ply back if it becomes necessary to reposition the ply.

Reference: McCaivill (2) pg 139

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Definition: The actual measured temperature inside the autoclave during part curing.

Reference:

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Definition: The temperature at some mid-point in a curing part as measured by a thermocouple.

Reference:

---

Definition: Set point temperature is the temperature the autoclave is to bring to bear on the part inside.

Reference:

---

Definition: The temperature at the top of a curing part as measured by a thermocouple.

Reference:

---

Definition: The change in length or volume per unit length or volume produced by a 1 degree rise in temperature.

Reference: ASM pg 7
Data: Thickness of pan/laminate
Definition: Thickness of part either before cure or after cure is complete.

Reference:

Data: Thickness, ply
Definition: Thickness of individual plies which make up the composite part.

Reference:

Data: Time
Definition: Everything takes time. Layup. Processing. And in some parts of the process, time is critical. For example, allowing enough time at a low viscosity level is critical to removing voids from the part.

Reference:

Data: Tooling (shape, material, etc.)
Definition: Tools used to make part to prescribed shape and size.

Reference: ASM pg 16

Data: Toughness
Definition: Capacity for energy absorption (rather than damaging the part).

Reference: Gilkey pg 36

Data: Ultraviolet light, resistance to
Definition: UV light's short wavelengths can be harmful to some materials.

Reference:
Data: Use conditions of end product
Definition: Environmental conditions under which the part is expected to operate.

Reference:

Data: Vacuum level
Definition: Vacuum level is the level at which a vacuum is drawn on the part before and during curing. Vacuum contributes to the total pressure on the curing part.

Reference:

Data: Vent time (vacuum bag)
Definition: The time or temperature at which the vacuum bag inside the autoclave is vented.

Reference:

Data: Viscosity
Definition: Resistance to flow.

Reference: Levine pg 473

Data: Voids
Definition: Voids include air, water, alcohol, or gas pockets within the cured laminate (within and between plies), and other trapped volatiles, impurities, and inclusions.

Reference:

Data: Weight of part
Definition: Self-explanatory—the weight of the part (either before or after processing).

Reference:

Data: Wrinkles
Definition: Surface defects which look like wrinkles on a part.
Reference:

Data: Yarns, weave, float, and yarn count
Definition: Yarns are twisted filaments or fibers which form a continuous length suitable for weaving. (ASM)

Plies can be woven in many different ways, from unidirectional flat plies where the fibers are all oriented in one way, to three-dimensionally, with fibers in three directions.

Float is the number of yarns in a row which are not interwoven with other yarns. (Dominguez)

Yarn count is the number of yarns per inch in a ply. (Cumming)

Reference: ASM pg 26, Cumming pg 125, Dominguez (3) pg 150
APPENDIX C

DATASTAX INTRODUCTORY CARDS
Welcome! This database models relationships among different kinds of data involved in the autoclave curing of certain thermosetting composite materials.

The three boxes below delineate three classifications for the different kinds of data. Click in one of these boxes to begin exploring the data and their relationships.

<table>
<thead>
<tr>
<th>Material</th>
<th>&quot;Material&quot; refers to the prepreg materials used in laying up parts for cure in an autoclave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part</td>
<td>&quot;Part&quot; refers to the final manufactured product, for example, this could be a flat panel or an aircraft wing's leading edge.</td>
</tr>
<tr>
<td>Environment/Process</td>
<td>&quot;Environment/Process&quot; covers everything that happens around the part being made.</td>
</tr>
</tbody>
</table>

Figure 37. DataStax Introductory Card for Data and Relationships

"Material" refers to the prepreg materials used in laying up parts for cure in an autoclave. Three categories are defined below. Choose from among them to continue your exploration. (Click in the appropriate box.)

| Pile | In this database, "pile" are the preformed sheets of resin-impregnated fibers used in laying up parts for cure. |
| Resin | "Resin" is the matrix material into which fibers are embedded. |
| Fibers | "Fibers" are the materials rolled upon to give the final composite material most of its desired mechanical characteristics. |

Figure 38. DataStax Introductory Card for Material
"Part" refers to the final manufactured product. In composites, properties are not always the same in all directions (anisotropic). Five categories of part properties are shown below. Click anywhere in the box in which you are interested.

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>&quot;Physical Properties&quot; refers to the properties of the part that we can see, hear, and touch.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Properties</td>
<td>&quot;Mechanical Properties&quot; are those properties that a material exhibits when a force is applied.</td>
</tr>
<tr>
<td>Thermal Properties</td>
<td>&quot;Thermal Properties&quot; are part properties that are related to temperature.</td>
</tr>
<tr>
<td>Chemical Properties</td>
<td>&quot;Chemical Properties&quot; relate to the structure of the material and its formation from the elements.</td>
</tr>
<tr>
<td>Electrical Properties</td>
<td>In this database, &quot;electrical properties&quot; are related to resistivity and conductivity.</td>
</tr>
</tbody>
</table>

Figure 39. DataStax Introductory Card for Part

"Environment/Process" covers everything that happens around the part being made. It includes the three categories below. Click anywhere inside the box describing the category you would like to explore.

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
<th>Fabrication and use environments are important.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>&quot;Equipment&quot; includes all of the necessary tools and materials used in making certain composites parts.</td>
</tr>
<tr>
<td>Other</td>
<td>&quot;Other&quot; consists of people, time, steps in fabrication and processing, and bookkeeping data.</td>
</tr>
</tbody>
</table>

Figure 40. DataStax Introductory Card for Environment/Process
"Plies" are the preformed sheets of resin-impregnated fibers used in laying up parts for cure. There are nine kinds of data of interest specifically for plies. They are shown below.

There is more information for each kind of data. Click on the box containing the data you would like to explore.

Figure 41. DataStax Introductory Card for Plies

"Resin" is the matrix material into which fibers are embedded. The matrix holds the fibers together and protects them.

There are eight kinds of data of interest specifically for resin. They are shown below. Click on the box containing the data in which you are interested.

Figure 42. DataStax Introductory Card for Resin
"Fibers" are the materials rolled upon to give the final composite material most of its desired mechanical characteristics.

There are 10 kinds of data of interest specifically for fibers. They are shown below. Click on the box containing the one you are interested in exploring.

- Yarn, weave, float
- CTE (Coefficient of Thermal Expansion)
- Moisture Absorption
- Thermal Conductivity
- Precursor
- Stiffness
- Strength
- Density
- Specific Gravity
- Fiber Coatings

**Figure 43. DataStax Introductory Card for Fibers**

"Physical Properties" refers to the properties of the part that we can see, hear, and touch. This can be divided into the categories below.

Click on the box which contains the data you would like to explore.

**Figure 44. DataStax Introductory Card for Part Physical Properties**
"Part configuration" refers to the way the part is put together. There are four categories of "part configuration" represented in the boxes below. Click on the one in which you are interested.

[Part Geometry] [Ply Orientation] [Number of Piles] [Part Thickness]

Figure 45. DataStax Introductory Card for Part Configuration

For this database, "cure process variables" is defined as those kinds of data which change and are tracked during the process. Three kinds of data are shown below. Click on the box which contains the data you would like to explore.

[Top-Part Temperature] [Mid-Part Temperature] [Viscosity]

Figure 46. DataStax Introductory Card for Cure Process Variables
Defects may occur in any place in any part. There are five categories of defects shown in the boxes below. Click on any box in which you are interested.

![Defects Diagram]

**Figure 47. DataStax Introductory Card for Defects**

On this menu are part physical properties other than configuration, cure process variables, and defects. Click on the box which contains the data in which you are interested.

![Other Part Physical Properties Diagram]

**Figure 48. DataStax Introductory Card for Other Part Physical Properties**
PART MECHANICAL PROPERTIES

"Mechanical Properties" are those properties that a material exhibits when a force is applied. Data representing mechanical properties can be divided into "Durability" (which consists of damage tolerance, hardness, and resistance to flame, corrosion, and ultraviolet light), and the 10 properties shown in the boxes below. Click on the box which contains the data in which you are interested.

Click Here to go to "Durability" Menu

Strength
Tensile
Stress
Stiffness
Brittleness

Poison's Ratio
Elongation
Creep
Ductility
Damping Capacity

Click Here to Return to "Part" Menu

Figure 49. DataStax Introductory Card for Part Mechanical Properties

DURABILITY

For purposes of this database, "durability" consists of the five kinds of data shown below. Click on the box containing the data you would like to explore.

Damage Tolerance
Hardness
Resistance to UV Light
Resistance to Corrosion
Resistance to Flame

Figure 50. DataStax Introductory Card for Durability
PART CHEMICAL PROPERTIES

"Chemical Properties" relate to the structure of the material and its formation from the elements. Click on the box below which contains the data you are interested in exploring.

- Gel Point
- Glass Transition Temperature
- Exothermic Reaction
- Degree of Polymerization
- Degree of Cross-Linking
- Degree of Cure
- Evenness of Cure

Click Here to Return to "Part" Menu

Figure 51. DataStax Introductory Card for Part Chemical Properties

PART THERMAL PROPERTIES

"Thermal Properties" are part properties that are related to temperature. Click on the box below containing the kind of data you would like to explore.

- Thermal Conductivity
- Specific Heat
- Coefficient of Thermal Expansion

Click Here to Return to "Part" Menu

Figure 52. DataStax Introductory Card for Part Thermal Properties
In this database, "electrical properties" are resistivity and conductivity, as shown below. Click on the box containing the kind of data you wish to explore.

![Resistivity vs Conductivity](image)

**Figure 53. DataStax Introductory Card for Electrical Properties**

Fabrication and Use environments are important. Click on the one you would like to explore.

<table>
<thead>
<tr>
<th>Fabrication Environment</th>
<th>Conditions in the layup room.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use Environment</td>
<td>Product use conditions.</td>
</tr>
</tbody>
</table>

**Figure 54. DataStax Introductory Card for Environmental Conditions**
"Equipment" includes all of the necessary tools and materials used in making certain composite parts. This includes the autoclave (which consists of specifications, temperature, set point temperature, pressure, and set point pressure), tooling and molds, and materials. Click on the autoclave button to see autoclave data or on either of the boxes below.

![Click Here to go to "Autoclave" Menu](image)

**Figure 55. DataStax Introductory Card for Equipment**

Autoclave-related data consists of autoclave specifications (size, shape, manufacturer, and uniformity of heating, cooling, and pressurization), set point pressure, autoclave pressure, set point temperature, and autoclave temperature. Click on the box below which contains the data to which you are interested.

![Autoclave Specifications](image)

![Set Point Pressure](image)

![Autoclave Pressure](image)

![Set Point Temperature](image)

![Autoclave Temperature](image)

**Figure 56. DataStax Introductory Card for Autoclave**
"Other environment/process data" consists of the 10 kinds of data shown in the boxes below. Click on the box containing the data in which you are interested.

Figure 57. DataStax Introductory Card for Other Environment/Process Data