QUALITY ASSURANCE AND QUALITY CONTROL METHODS FOR RESIN INFUSION

By

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THESIS

ACCEPTANCE STATEMENT

On behalf of the Graduate Committee for Jonathan Kenerson, we affirm that this manuscript is the final and accepted thesis. Signatures of all committee members are on file with the Graduate School at the University of Maine, 42 Stodder Hall, Orono Maine.

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By Jonathan E. Kenerson

Thesis Co-Advisors: Dr. Robert F. Lindyberg, P.E. and Dr. Habib J. Dagher, P.E.

An Abstract of the Thesis Presented
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With resin infusion increasing as a method of large composite part fabrication there is a need for an industry standard in regards to quality assurance and quality control (QA/QC) methods. In terms of part quality and consistency, resin infusion as a process bridges the gap between open molding and the autoclave/pre-preg process. The chief goal of quality control methods is to reduce incoming material variability and production variability.

The primary aim of this research was to aid composite manufacturers by uncovering the major quality issues in resin infusion and identifying appropriate QA/QC practices to address these issues. To realize this aim, an investigation of the resin infusion literature was conducted to discover what key process parameters contributed most heavily to the quality of resin infused parts. Furthermore, QA/QC methods were investigated which would be suitable for controlling the most important process parameters. This was accomplished by defining the composite manufacturing QA/QC best practices contained in standards, incorporating the resin infusion specific aspects

contained in the technical literature, and investigating the actual level of implementation in the manufacturing environment.

Seven composite manufacturers from Maine were selected to participate in the industry investigation for the purpose of determining the actual level of benchmark QA/QC practice implementation. Manufacturers were selected to provide variety across several demographic categories (annual sales, company size, top management type, infusion operating period, product type, and level of customer quality requirements) in order to correlate these characteristics with the level of conformance to industry best practices. The industry investigation consisted of site visits during which manufacturers' QA/QC practices were observed and ranked on a Likert scale for conformance to the industry best practices. One company was selected for further investigation because they expressed interest in aligning their QA/QC more with the industry best practices. A statistical analysis was conducted to measure the level of significance of the correlation coefficients between demographic parameters and the ratings of best practice conformance. Conformance to the industry best practices was found to vary significantly among the manufacturers, however all manufacturers had demonstrated evidence of producing quality products.

Findings suggest that manufacturers with high levels of customer quality requirements conform more closely to the QA/QC best practices than manufacturers with lower levels of customer quality requirements. A cause and effect relationship between the ratings and customer quality requirements was observed in a case evaluation in which one manufacturer implemented a quality management system as a result of increased customer quality requirements.

Finally, three levels of QA/QC best practice implementation are presented with recommendations for manufacturers of different demographic characteristics.

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Soli Deo Gloria

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LIST OF ACRONYMS

ABS - American Bureau of Shipping (Classification Society Member)

ACMA - American Composite Manufacturers Association

A-VaRTM - Advanced Vacuum-assisted Resin Transfer Molding

CFM - Continuous Filament Mat

CSM - Chopped Strand Mat

DMA - Dynamic Mechanical Analysis

DNV - Det Norske Veritas (Classification Society Member)

EPA - Environmental Protection Agency

FTIR - Fournier Transform Infrared Spectroscopy

FRP - Fiber Reinforced Polymer

ILSS - Inter-Laminar Shear Strength

MACT - Maximum Achievable Control Technology

MOE - Modulus of Elasticity

NDE - Non-Destructive Evaluation

NDT - Non-Destructive Testing

PMCs - Polymer Matrix Composites

QA - Quality Assurance

QC - Quality Control

QMS - Quality Management System

RIFT - Resin Infusion Under Flexible Tooling

RTM - Resin Transfer Molding

SOP - Standard Operating Procedures

SPM - Semi-Porous (Permeable) Membrane

T_g - Glass Transition Temperature

TGA - Thermal Gravimetric Analysis

VARTM - Vacuum Assisted Resin Transfer Molding

VARIM - Vacuum Assisted Resin Infusion Molding

VIP - Vacuum Infusion Process

Chapter 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

This chapter presents the background for studying quality assurance and quality control methods for resin infusion. It demonstrates how this research fits into its body of knowledge and explains the potential application of the work. It presents the objectives and scope of the study and explains the outline of the thesis.

1.2 Background

Resin infusion as a method of manufacturing composite materials has increased in relation to open molding methods in recent years, while standards for resin infusion quality assurance and quality control have not. Factors which have lead to an increase in the adoption of resin infusion with respect to open molding include reduced styrene emissions, increased product quality consistency, high fiber volume fractions, and a high degree of component integration. These advantages have lead to its widespread adoption in the marine, industrial, and wind energy sectors. Current marine classification societies' construction and design standards were developed based on open molding techniques and do not specifically address quality issues for resin infusion. Review of the available literature across multiple manufacturing sectors has failed to identify a resin infusion quality assurance or quality control standard.

Resin infusion technology has reached a level where it is now being used in products which require high reliability and high quality such as aerospace primary structural components (McConnell, 2009), wind turbine spars (Griffin, 2009), railroad

bridge girders (Jacob, 2008), and high-speed NAVY vessels (Gardiner, 2008). The potential for resin infusion to serve these emerging markets depends on its ability to deliver highly reliable, high quality products.

1.3 Research Goals and Scope

The three main goals of this study were (1) to indentify issues within the resin infusion manufacturing process that lead to poor quality products, (2) to identify appropriate quality assurance and quality control (QA/QC) methods to resolve these issues, and (3) to make recommendations regarding the adoption of these methods to the manufacturers. To realize this first goal, an in depth technical investigation of the resin infusion literature was conducted to discover what key process parameters contributed most heavily to the quality of resin infused parts. The second goal was accomplished by researching QA/QC methods which would be suitable for controlling the most important process parameters. To accomplish the third goal of making recommendations, research focused on practical levels of implementation. An industry investigation was conducted in which the actual level of implementation of the QA/QC methods were observed in the shops of several manufactures. The industry investigation sought to uncover which company characteristics correlate to higher implementation of QA/QC benchmark practices in order that practical levels of implementation might be recommended. Also as a means of accomplishing the third goal the recommended QA/QC changes were implemented within a cooperating manufacturer's company and the results were monitored.

The scope of this QA/QC investigation was resin infusion with emphasis on the vacuum infusion process (VIP) due to the demographic of the composite manufacturers in the region. The VIP is used more than resin transfer molding (RTM) for large part manufacturing such as boat hulls, which is the largest application of this technology in the northeast. Research also focused on the technical level of marine manufacturing. Although resin infusion is being adopted by some aerospace manufacturers, this level of quality control was currently beyond the product requirements of the companies in the region.

Research in the Maine marine composites sector has identified resin infusion as a growing industry with technical and training assistance as the greatest needs (Lawton & Renski, 2007). Realizing the goal of making recommendations to manufacturers regarding QA/QC methods meets the stated need of resin infusion technical assistance. The ultimate purpose of this research is to be incorporated into a training curriculum as Southern Maine Community College thus meeting the other stated need of training assistance. This research is timely considering the growth of resin infusion technology adoption, the potential for its adoption into rapidly growing emerging markets, the lack of an existing quality standard for QA/QC in resin infusion and the expressed need for increased technical and training assistance.

1.4 Outline of Thesis

This thesis is structured in five chapters. Chapter 1 provides the background and goals of the study. Chapter 2 comprises the literature review of relevant issues in resin infusion. It begins with an overview of the resin infusion technology and proceeds to

cover the issues which commonly lead to poor quality products and concludes with a section on the process parameters which dominate resin infusion. Chapter 3 comprises the literature review of existing QA/QC standards. It is divided into those practices dealing with the quality management system, incoming material, in-process controls, and the final part validation testing. Chapter 4 presents the industry investigation methodology, analysis, and results. In Chapter 5 the findings of the industry investigation are used to recommend to manufactures a three tiered system of quality assurance implementation. Also in Chapter 5 recommendations for further research are presented as well as final conclusions.

Chapter 2

RESIN INFUSION

2.1 Introduction

This chapter begins with an overview of the forms, history, environmental aspects, and applications of resin infusion. Section 2.3 describes six major issues in resin infusion which lead to poor quality products: (1) voids and dry spots, (2) thickness variations, (3) resin curing problems, (4) fiber orientation problems, (5) delaminations, and (6) secondary bonding problems. Section 2.4 describes the three major resin infusion variables which can lead to quality issues if not controlled properly: (1) the permeability within the tooling cavity, (2) the pressure differential between injection and vent ports, and (3) the resin viscosity.

2.2 Overview of Resin Infusion

Resin infusion is a method of manufacturing polymer matrix composites in which dry reinforcement is placed within a mold cavity and subsequently wetted out by liquid resin driven through the enclosed cavity via a pressure differential between the injection ports and the vent/vacuum ports (CCP, 2005; Beckwith, 2007a). A schematic of a generic resin infusion setup is shown in Figure 2.1. Resin infusion belongs to a family of manufacturing processes known as closed molding due to use of two or more molds used to define an enclosed cavity (CCP, 2005, p.120). The Composites Application Guide (CCP, 2005, p. 120) divides the closed molding processes into two distinct sub-categories as shown in Figure 2.2 compression molding and resin transfer molding (i.e., resin infusion); resin infusion is further divided into resin transfer molding (RTM) and the vacuum infusion process (VIP). Compression molding uses heavy molds with large

clamping forces to inject “a pre-manufactured compound” which contains resin and reinforcement into the mold cavity (CCP, 2005, p.120). Resin infusion by contrast is capable of using less robust tooling due to the lower tooling forces; some methods require merely a thin nylon film. A trademark of the resin infusion process is that all reinforcement, cores, and inserts are placed within the mold cavity before resin infusion (CCP, 2005, p. 120). This technology is capable of meeting the needs of low to medium production volume, small to very large part size, and material properties and surface quality has been shown to rival the autoclave process (Khattab & El-Gizawy, 2006).

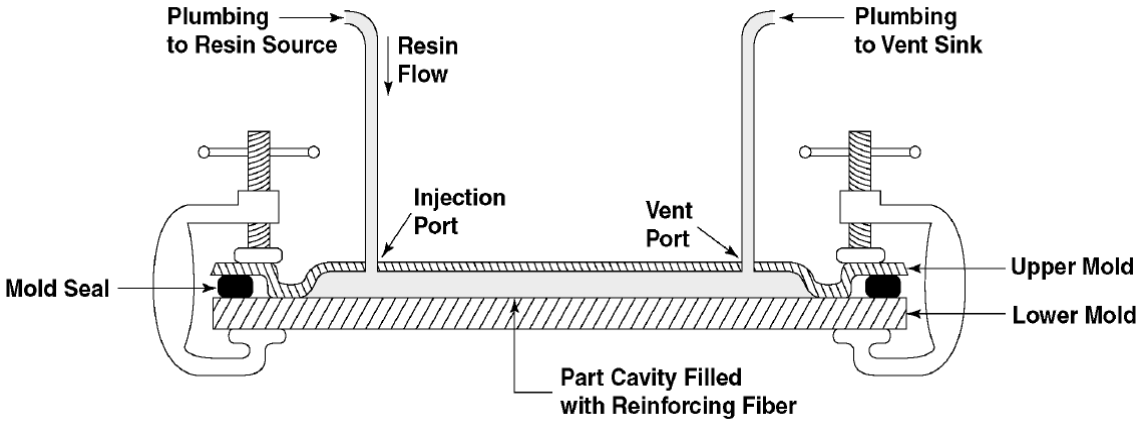

Figure 2.1 Resin Infusion Schematic (CCP, 2005, p.121)

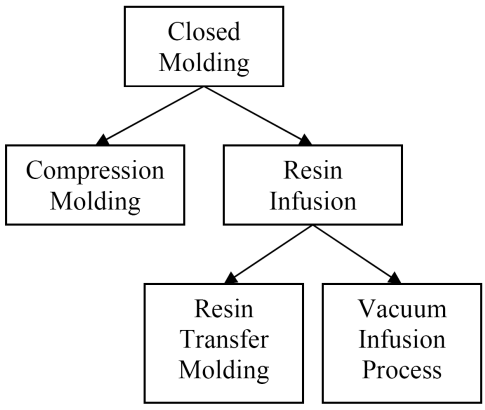

Figure 2.2 Closed Molding Processes

2.2.1 Forms of Resin Infusion

There are literally dozens of named forms of resin infusion. Variations of five key aspects of the resin infusion process can be used to delineate most of the different forms: (1) the pressure differential between the inlet and the vent ports, (2) the resin delivery method which is determined by the infusion layout, (3) the secondary mold type, (4) the mold clamping method, and (5) the method of removing the secondary mold (CCP, 2005). Even with all these forms, resin infusion is commonly divided into two general categories, resin transfer molding (RTM) and the vacuum infusion process (VIP). Table 2.1 lists the common variations and options for each key aspect.

Table 2.1 Variables Distinguishing Different Forms of Resin Infusion (CCP, 2005)

Pressure Differential (inlet to vent)	Resin delivery method	Secondary mold type	Mold clamping method	Secondary mold removal method
• Positive to positive • Positive to atmospheric • Positive to vacuum • Atmospheric to vacuum • Vacuum to vacuum	• Point • Line • Radial • Circumferential • Grid • Distribution medium • Interlaminar channels	• Metal • Rigid laminate • Flexible laminate • Multi-use silicone or elastomeric bag • Single use bag (nylon, Mylar, etc.)	• None (limited to VIP only) • Vacuum clamps • Mechanical clamps • Pneumatic clamps • Hydraulic clamps	• By hand • Mechanical lift • Pneumatic lift • Hydraulic lift

The pressure differential is the difference between the pressure at the inlet and outlet between which lies the reinforcement to be infused (CCP, 2005). The pressure differential is the force which drives the flow of resin through the tooling cavity (discussed in depth in Section 2.4.2). Resin always flows from high pressure to low pressure. Therefore as Figure 2.3 shows the pressure at the inlet can be above, at, or below atmospheric pressure and will result in resin flow toward the vent as long as the vent pressure is lower than the pressure at the inlet. Figure 2.4 compares the different scales used to measure pressure and provides common pressure units.

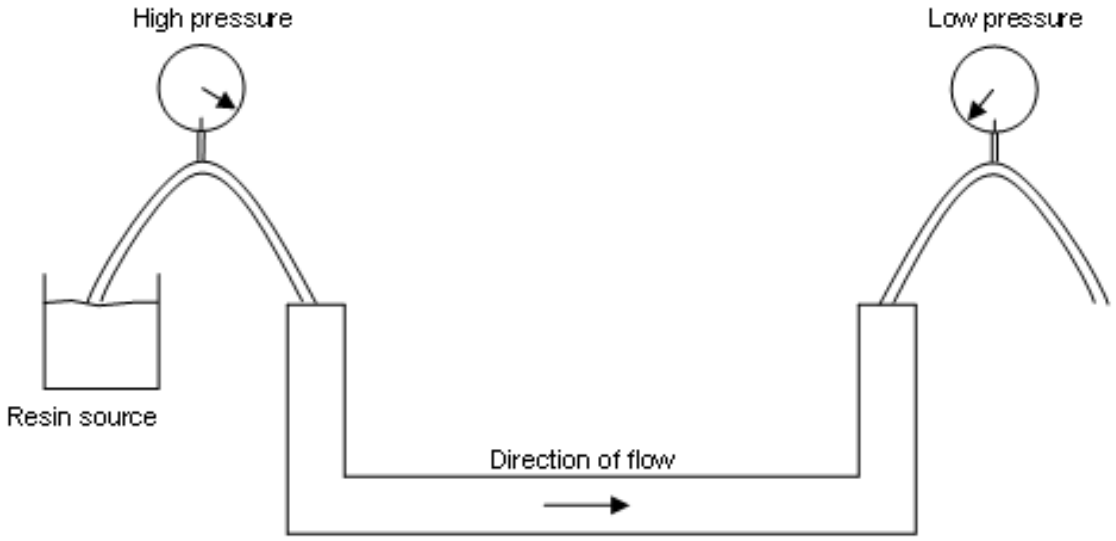

Figure 2.3 Pressure Differential Schematic

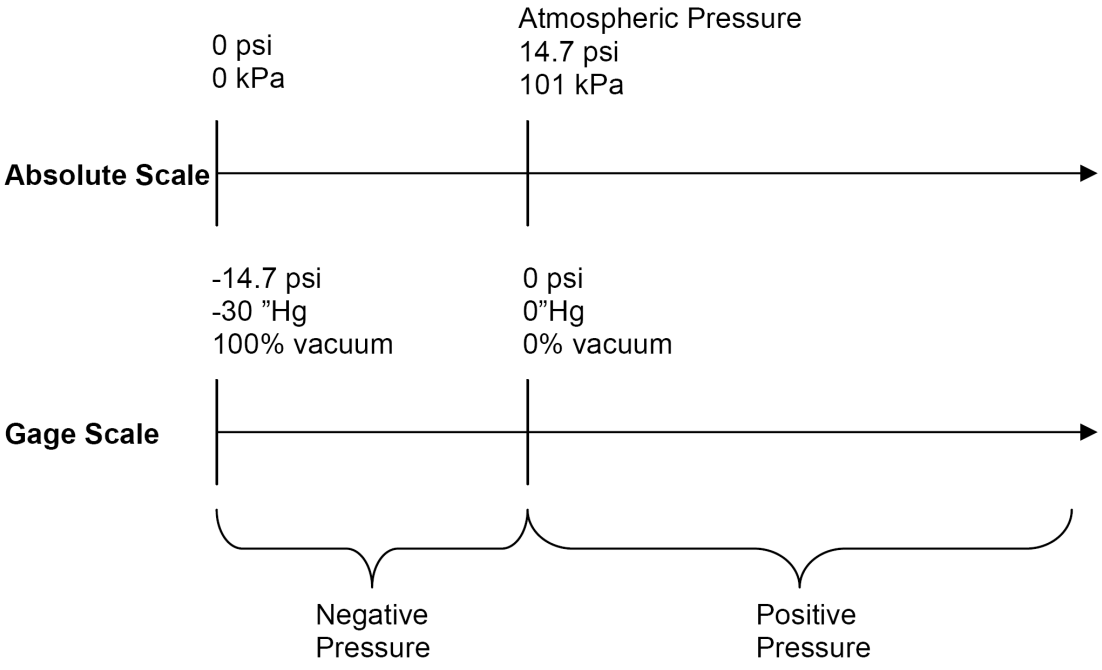

Figure 2.4 Pressure Scales and Units

Resin delivery method refers to the manner in which the resin is dispersed within the mold cavity. Usually the resin flow is enhanced by the use of feed lines (i.e., tubes or open interlaminar channels) or distribution media within the tooling cavity. These feed

lines or distribution media provide a path of least resistance for the inflowing resin which speeds the infusion process. Figure 2.5 shows five common feed line layouts which are named for the resin source location: (a) point infusion, (b) line infusion, (c) radial infusion, (d) circumferential infusion, and (e) grid infusion. Distribution flow media is a highly permeable layer in the laminate stack which increases resin flow. Flow media can be placed on the surface, which was the novel feature of the patented Seemann Composites Resin Infusion Moulding Process (SCRIMP) (Williams, Summerscales, & Grove, 1995), or it can be incorporated into the laminate stack. With flow media the resin quickly wets out this layer and then begins to infuse the laminate stack through the thickness as shown in Figure 2.6. This process is discussed in depth in Section 2.4.1.

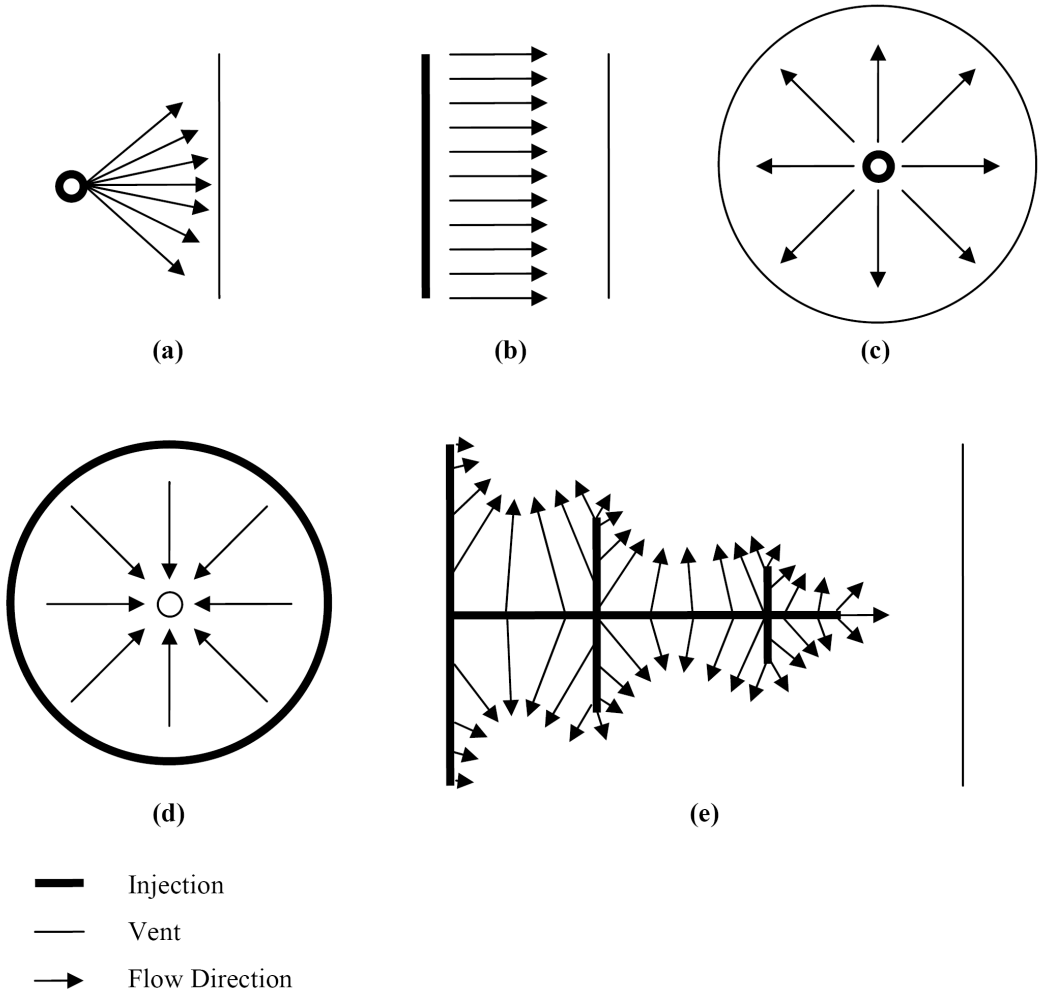

Figure 2.5 Resin Delivery Methods. (a) Point, (b) Line, (c) Radial, (d) Circumferential, (e) Grid

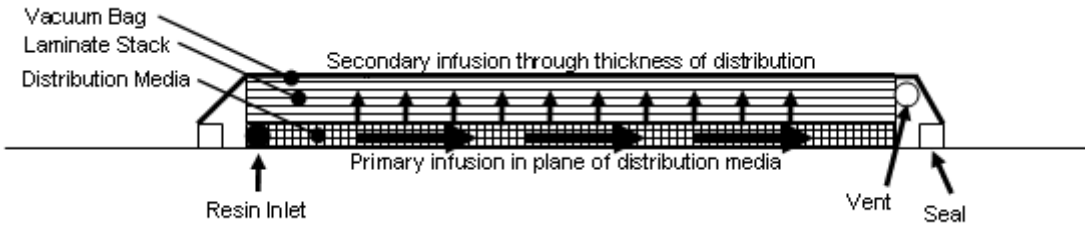

Figure 2.6 Role of Distribution Media

Resin infusion incorporates two molds to define the tooling cavity; the primary mold is generally rigid while the secondary mold type can be rigid or flexible depending on the process. It is possible to infuse into any sealed cavity, however to meet

dimensional requirements at least one of the two mold halves is usually rigid to resist movement. The half of the mold into which the reinforcement and other infusion materials are placed is referred to as the primary mold. This mold can be metal, but a rigid composite laminate or plastic is usually more cost effective. The other half of the mold is the secondary mold. In processes which utilize positive internal pressures the secondary mold must be rigid to resist the internal positive pressures. Otherwise the cavity would inflate like a balloon. In processes which utilize negative internal tooling pressures a flexible secondary mold can be used. Common flexible molds include Mylar or nylon for disposable molds, and silicone or some other type of elastomeric bag for multiuse molds.

The means of mold clamping depends on the process. In processes which utilize negative internal pressures the atmospheric pressure on the outside of the mold surfaces forces them together eliminating the need for clamping. Processes which utilize positive internal pressures require the use of force to keep the molds from separating when the positive pressure is applied in the mold cavity. This clamping force is usually applied to the flange or perimeter, but can be applied over the entire surface as in compression molding with massive metal molds. The clamping force can come from hydraulic, pneumatic or mechanical clamps. In one particular process (Light RTM) it is common to use vacuum pressure in a flange cavity to hold the mold halves together; however these must be designed such that the force of the internal cavity pressure does not overcome the force of the flange vacuum pressure.

Mold removal methods depend on the type of secondary mold and the production environment. Light flexible disposable secondary molds can be removed by hand. However heavier secondary molds or manufacturing environments utilizing reusable secondary molds are commonly removed with a hydraulic, mechanical, or pneumatic lift.

Regardless of all the possible combinations of these five key aspects, resin infusion is nevertheless divided into two general forms based on the internal tooling pressure. Those processes which utilize positive pressure are referred to as resin transfer molding (RTM) and those which utilize negative pressure are classified as the vacuum infusion process (VIP) (Beckwith, 2007a).

Even Beckwith's definition of RTM and VIP are not mutually exclusive, and attempts at industry definitions have not been entirely successful either (Beckwith, 2007a). This section clarifies the differences between the two methods and proposes a definition for the study. The Composites Application Guide (CCP, 2005) illuminates the fact that there are only the following five possible pressure schemes (inlet pressure to vent pressure) in resin infusion: (1) positive to positive, (2) positive to atmospheric, (3) positive to vacuum (i.e., negative), (4) atmospheric to vacuum, or (5)vacuum to vacuum.

Conventional RTM uses positive pressure at the injection point and atmospheric pressure at the vent point (case 2 above). It is possible to use another lower magnitude positive pressure at the vent (case 1); however this method is not commonly utilized due to the unnecessarily large tooling forces. The magnitude of the positive injection pressure is limited by the robustness of the tooling and the clamping forces; greater injection pressures lead to higher tooling forces.

It is the third case of positive inlet pressure to negative vent pressure which defies Beckwith's (2007a) definitions of RTM and VIP by incorporating both positive and negative pressures. Light-RTM falls into this category and derives its name from the use of lighter molds; a result of lower positive injection pressures (about 15psi lower than RTM) are needed to achieve the same pressure differential (Magnum Venus Products, 2007). For the purposes of this study Light-RTM will be considered an RTM method. It should be noted that Beckwith (2007a) would consider this a VIP method.

VIP is characterized by negative pressure at the vent and atmospheric or vacuum at the inlet (case 4 and 5). The term Vacuum Assisted Resin Transfer Molding (VARTM) has been traditionally used to describe the arrangement of atmospheric pressure at the inlet and vacuum at the vent (case 4) (CompositesWorld, 2009). For the purposes of this study VARTM will be considered a specific form of VIP. The fifth possible pressure combination listed in the Composites Application Guide (2005) is vacuum to vacuum. The vacuum to vacuum method (case 5) of VIP is not used in industry due to the fact that most manufacturers want to maximize the pressure differential; bringing the injection pressure below atmospheric pressure serves the opposite purpose.

Therefore for the purposes of this study RTM refers to the first three pressure combination listed at the beginning of this section and VIP to the last two. Light RTM - case 3 - is considered a subset of RTM.

2.2.2 History of Resin Infusion

The resin infusion process dates back to at least 1946 when a U.S. Navy project involving the development of 28 foot personnel boats was undertaken. The contract specified a "vacuum injection method" (Potter, 1999). A few years later in 1950 Marco Chemicals Inc. filed a U.S. patent (US Patent #2495640) for a variety of infusion techniques (Muskat, 1950). The Marco method describes resin being pushed into the cavity via pressure, sucked through via vacuum, as well as being poured into a female mold and distributed by the force of the two mold halves coming together. Potter (1999) claims that a vast degree of the RTM technological development appears in the literature prior to 1960. He cites developments such as complex part production, incorporation of inserts, multiple injection ports, and automated shut-off valves, among others. These processes did not immediately garner widespread adoption because common materials favored open molding processes and were difficult to use in the resin infusion process. Also, environmental regulation had not yet begun to influence the field (Williams, Summerscales, & Grove, 1995). Adoption, applications and variations of resin infusion began to grow during the 1970s and 1980s due to environmental legislation. Group Lotus Car Ltd. patented a vacuum infusion method (GB Patent #1432333) in 1972 in the United Kingdom which is similar to the Marco method (Williams, Summerscales, & Grove, 1995). Gotch, driven mainly by worker health concerns, produced railway coach panels with a vacuum only method in which he used an elastomeric bag for the secondary mold (Williams, Summerscales, & Grove, 1995). In 1989 Seemann was granted a patent (US Patent #4902215) for the SCRIMP method which specifies the use of a surface distribution media (Seemann, 1989). Now many composites manufacturing companies

are tailoring products to the resin infusion industry which has resulted in increased part quality. For instance, Ankarbjork (2005) claims that there are no longer any product dependent barriers to good infused surface quality. A current trend in resin infusion focuses on reducing disposables by incorporating infusion features such as feed lines into the laminate.

2.2.3 Environmental Considerations

Within the past decade in the U.S. many large composites manufacturers have been forced to switch from open to closed molding due to the Environmental Protection Agency's (EPA) Maximum Achievable Control Technology (MACT) standards. This industry-wide shift from open molding to closed molding has been largely precipitated by both environmental and worker safety considerations (Hoebergen, 2001). Both manufacturing methods use liquid resin systems, most of which contain the monomer styrene at levels generally around 40% by weight, however closed molding nearly eliminates emissions by containing the styrene within the mold cavity. Styrene readily evaporates into the atmosphere when exposed and can lead to unacceptably high concentrations. The EPA has set maximum acceptable emission levels which are regulated under the MACT standard. Styrene is known to have chronic effects including headaches, fatigue, weakness, depression, and central nervous system dysfunction to name a few. Styrene is currently classified by the International Agency for Research on Cancer (IARC) as a Group 2A, "possibly carcinogenic to humans" (EPA, 2007). Closed molding is cleaner than open molding, due to the fact that workers do not need to come into direct contact with the resin system. Manufacturers have reported increases in

employee retention and general workplace morale with a change from open to closed molding (Lazarus, 1996).

2.2.4 Applications of Resin Infusion

Resin infusion has been utilized in many manufacturing sectors including marine, automotive, armor, aerospace, sporting equipment, corrosion resistance and wind energy (Summerscales & Searle, 2005). Marine structures as large as the ERMIS², a 37 meter (121 foot) high speed luxury yacht built by McMullen & Wing, New Zealand (ShowBoats International, 2009), and the MAKO, a 25 meter (82 foot) Naval special operations patrol boat built by Hodgdon Yachts, East Boothbay, Maine, (Gardiner, 2008) have been produced using the technology. Automotive applications date back to the 1970's when Group Lotus Car Ltd. (UK) patented a vacuum infusion method. Aerospace manufacturing has been traditionally dominated by the more advanced autoclave/prepreg processes, but increases in resin infusion capabilities have lead to its adoption in this high performance application. Early applications of resin infusion in aerospace were limited to producing radomes; however, recent developments have shown promise of resin infusion of primary aircraft structural components (Khattab & El-Gizawy, 2006; McConnell, 2009)

Resin infusion has found acceptance within the realm of composites manufacturing processes due largely to its ability to meet a wide range of performance levels across a broad range of production volumes. Figure 2.7 illustrates how production volume and performance characteristics (such as material strength and stiffness per unit weight and surface quality) drive the selection of composite manufacturing techniques.

The resin infusion methods shown are RTM/SRIM (Structural Reaction Injection Molding - is a similar method to RTM but is not used for producing polymer matrix composites (Rudd, 2001)) and vacuum infusion. Increases in performance are achieved with stricter process controls and more advanced materials, while increases in production volume require reusable tooling, kitted parts, and integrated components (Mason, 2006).

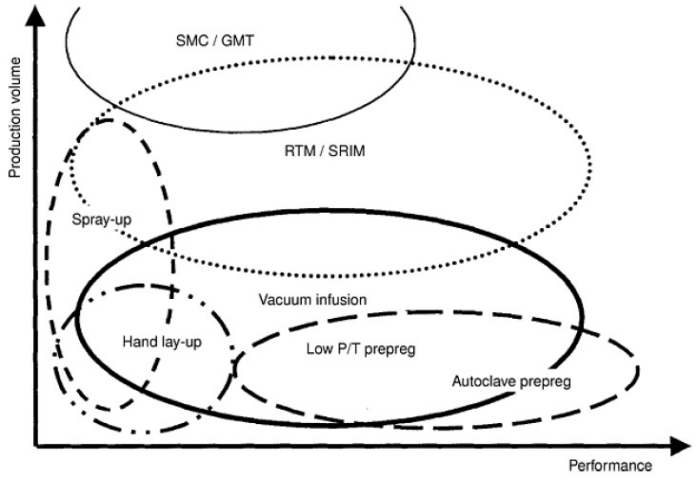

Figure 2.7 Performance and Production Volume of Composites Manufacturing Methods (Hoebergen, 2001)

2.3 Sources, Effects, and Prevention of Composites Defects

This section surveys common issues in resin infusion which lead to poor quality parts. Much research has been conducted into the affects of defects in composite materials, with most being driven by the aviation industry (Wilkins, 1984; Cantwell & Morton, 1992). Summerscales (1994) summarizes work done in this area noting that the level of structural degradation in properties varies with the following factors: defect severity, defect location and orientation, frequency of defect occurrence, component load path critically and stress state, defect idealization, design load levels and nature, defect detectability and detection capabilities, local repair capabilities, component

configuration, environmental conditions, loading history, material property variations, and acoustic vibration response. His review also highlights eight areas of concern, namely, fiber orientation, stacking sequence, fiber waviness, fiber distribution, matrix cure, voids, inclusions, and moisture effects. Racing yacht builders Landa and Sanchez (1993) identified voids, incorrect fiber volume faction, incorrect curing, incorrect lay-up, delaminations, and bonding defects as being of primary importance.

While the origin of the defects in resin infusion is sometimes of a different nature the defects themselves are largely the same as in any other composites manufacturing method. The following section addresses these common general composites manufacturing issues from the perspective of the resin infusion manufacturing process and how these issues affect material properties. The six specific issues covered in sections 2.3.1 through 2.3.6 are (1) voids and dry spots; (2) thickness and fiber volume fraction variations; (3) resin curing problems; (4) fiber orientation issues; (5) delaminations; and (6) secondary bonding issues.

2.3.1 Voids and Dry Spots

Voids and dry spots are sections of laminate which are not infused by resin. Voids are on the scale of the fabric architecture, usually a few millimeters to a few microns in diameter, and are located between or within the fabric tows. Dry spots on the other hand are large uninfused areas which are completely without resin. This section discusses the causes and effects of voids and dry spots; means of measuring voids; and methods for eliminating or controlling void and dry spot formation.

2.3.1.1 Sources and Prevention of Voids

Voids are the result of the leaks in the molds, fabric architecture, dissolved gas in the resin, boiling of styrene or other volatile resin components, or mechanical entrapment due to mixing (Afendi, Banks, & Kirkwood, 2005; Lee, Lee, & Kang, 2005; Lundström & Gebart, 1994; Kuentzer, Simacek, Advani, & Walsh, 2007). Each source of voids is explained in the following paragraphs.

Leaks in the molds must be avoided to prevent voids. In VIP the negative pressure within the tooling cavity will cause air to be pulled into the resin resulting in irreparable and severe voids. Common locations for leaks are pleats in the flexible secondary mold seal and joints or sharp corners in the primary mold. The entire seal between the two molds should be checked for leaks before infusion, but pleats are the usual culprit for leaks. An acoustic listening device is useful for performing this check. The primary mold can be checked for leaks by performing a drop test with a breather laminate. For this check a breather laminate is placed over the entire surface followed by sealing the secondary mold as usual. A vacuum is obtained within the tooling cavity and clamped off, isolating the tooling cavity. If a drop in pressure in the isolated cavity is observed over a period of time, there is a leak in the tooling provided the seal is perfect.

One of the biggest sources of void formation during the infusion process is related to the fabric architecture (Pearce, Guild, & Summerscales, 1998; Parnas, 2004; Leclerc & Ruiz, 2008). Fabric architecture refers to the method of combining the tows to form a fabric. Reinforcement fabric on the smallest scale is comprised of individual filaments which are gathered into tows which in turn form the architecture. This type of fabric

architecture is referred to as having a non-uniform microstructure. Tows are typically woven, knitted, or stitched together to form the reinforcement fabric. Other fabric architectures include chopped strand mat (CSM) and continuous filament mat (CFM) in which there are no tows, just randomly oriented individual filaments. These are called fiber mats and are of a uniform microstructure. Voids which form in the resin in between tows are referred to as matrix voids or inter-tow voids (Kuentzer, Simacek, Advani, & Walsh, 2007). Voids which form within the tows in between filaments are referred to as preform voids or intra-tow voids (Kuentzer, Simacek, Advani, & Walsh, 2007). Voids vary in size according to whether they are inter-tow or intra-tow voids with the former being on the scale millimeters while the latter is on the scale of microns as shown in Figure 2.8 from Kuentzer, Simacek, Advani, and Walsh (2007).

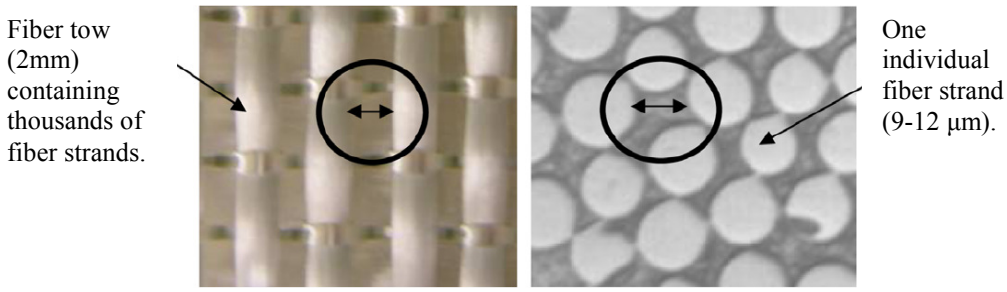

Figure 2.8 Inter-tow (left) and Intra-tow (right) Regions (Kuentzer, Simacek, Advani, & Walsh, 2007)

Much research has investigated the affects of fabric architecture on void formation (e.g., Hayward & Haris, 1989; Lundstrom, Gebart & Lundemo, 1993; Lundstrom & Gebart, 1994; Chen, Davis, & Macosko, 1995a; Chen, Macosko, & Davis, 1995b; Parnas, 2004; Lee, Lee, & Kang, 2006; Kuentzer, Simacek, Advani, & Walsh, 2007; Leclerc & Ruiz, 2008). Reinforcement fabrics with a -non-uniform microstructure have two levels of permeability, the inter-tow region and the intra-tow region.

Permeability is a geometric parameter of the fabric which quantifies how easily fluid will flow through it, higher permeability leads to higher flow volumes. Since the inter-tow regions have more open space than the intra-tow regions, they have a higher permeability. This two level permeability leads to a two level microscopic infusion which in turn can result in voids as the following explains.

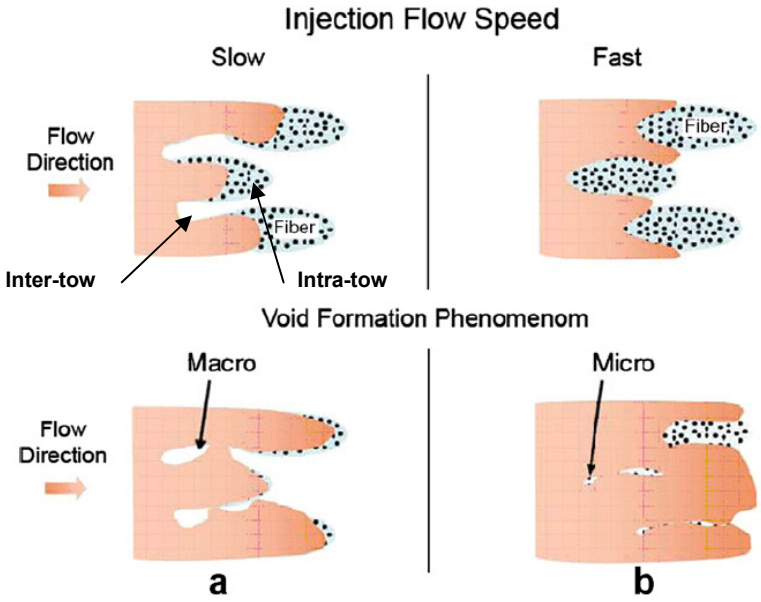

Figure 2.9 Formation of (a) Inter-tow and (b) Intra-tow Voids (Leclerc and Ruiz, 2008)

Leclerc and Ruiz (2008) show the infusion process on a micro-structural level in Figure 2.9 for (a) a slow injection flow velocity and (b) a high injection flow velocity). Void content and infusion velocity are related to the *capillary number* (Ca) which is a non-dimensional parameter defined by Equation 2.1. This study demonstrated that there is an optimal capillary number for each type of fabric which results in minimal voids.

Equation 2.1 Capillary Number, Ca

$$Ca = \frac{\mu \cdot v}{\gamma}$$

Where,

Ca = Capillary number [unitless]

*μ = resin viscosity [Pa*s]*

v = infusion velocity [m/s]

γ = surface tension at the air/resin interface [N/m]

For low resin velocity infusions (corresponding to a lower Ca) as in (a) in Figure 2.9 the driving force is from capillary action, a wicking of the resin into the tow. This results in the interior of the tow being saturated with resin while the inter-tow region contains voids that are on the order of millimeters. For high velocity infusions (corresponding to a higher Ca) as in (b) in Figure 2.9 the driving force is a viscous force, a resistance of the resin to be drawn into the tow. This results in the inter-tow region being saturated with resin while the region within the tow contains voids on the order of microns. *Inter-tow voids* (a) resulting from slow infusions can exceed 15% of the volume of the laminate, while *intra-tow voids* (b) resulting from fast infusions will be less than 2%. This means that erring on the side of a rapid infusion is preferable; however Leclerc and Ruiz (2008) emphasize the importance of determining the optimum resin infusion velocity for different types of fabric to minimize void content. For any fabric there exists an optimum capillary number which will correspond to minimization of both the inter-tow voids and the intra-tow voids.

Leclerc and Ruiz (2008) conducted experiments on two woven fabrics (a multi-axial non-crimped LIBA stitch bonded fabric and a woven fabric consisting of single end

glass rovings) to determine optimal infusion velocities. They varied infusion velocities and tested void content for the infusions. They found that for the optimal infusion velocities for the multi-axial non-crimped fabric and for the woven fabric was 7.5mm/s (0.3in/s) and 20mm/s (0.8in/s). Leclerc and Ruiz (2008) did not vary viscosity in their experiments, but do cite this as important factor to control when determining optimal infusion velocities.

Dissolved gas in the resin is another source of voids. Preventing gases from dissolving in the resin cannot be avoided. The issue is that under typical vacuum infusion pressures, dissolved gasses will over-saturate the resin and come out of solution in the form of bubbles. This bubble forming process is known as nucleation. One solution is to attempt to remove some or most of the gases from the resin prior to use via a degassing process. This can be done before and/or after mixing, however, degassing can speed the resin cure process so trial tests should be used to validate the process with a specific resin chemistry (Hoebergen, 2001). Degassing uses a vacuum to nucleate bubbles within the resin, then attempts to remove the bubbles from resin solution using nucleation object (i.e., Scotch-Brite pad), fine filters, thin films, or spinning disks (Afendi, Banks, & Kirkwood, 2005). Afendi, Banks, and Kirdwood (2005) have demonstrated that this process is capable of cutting the dissolved oxygen content in half and removing most bubbles above 500 microns in size. They subjected resin to a 27.3"Hg gage (13.4psi gage) vacuum for 15 minutes with a nucleation object added to provide a site for the bubbles to form. The nucleation agent needs to be something with a large surface area such as a Scotch-Brite pad. After nucleation, the bubbles must migrate to the surface and disperse into the air, a process which depends mostly on resin viscosity and surface

tension. They also found that increased temperatures increase nucleation; however this affects the cure characteristics of the resin system. Finally, they noted that infusion immediately following degassing (within 15 minutes) leads to increased void contents, as time is required to allow the nucleated bubbles to escape the resin.

Another cause of voids is that styrene, the liquid monomer in many resin systems, will boil under typical vacuum infusion processing conditions. The boiling point curve for styrene is shown in Figure 2.10 from Lundström, Gebart, and Lundemo (1993). They used this curve to argue that the boiling of styrene is not an issue at "typical vacuum levels" in RTM. This assessment however depends on the definition of "typical vacuum levels". When they conducted the investigation in the early 1990's, pressures below 90% of full vacuum (10^3 Pa absolute or 27"Hg gage) were uncommon in the RTM process. In VIP however it is not uncommon to achieve pressures below 95% of full vacuum (5kPa absolute or 28.5"Hg gage). From the curve it can be gathered that the pressure at which liquid styrene converts to a gas for ambient temperature (21°C or 70°F) is about 95% of full vacuum (note the log scale for pressure in the figure). Pressures below this in the shaded area will result in boiling of styrene. This was verified experimentally by Saraswat, Heider, and Song (2007) when they isolated resin within a pressure tube and observed the pressure at which bubbles formed. They found that void formation was immediately and directly related to the pressure and that for room temperature the critical pressure was 93% of full vacuum (7kPa absolute or 28"Hg gage).

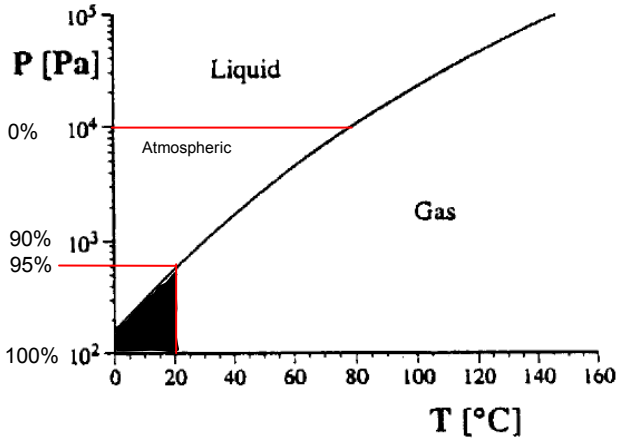

Figure 2.10 Boiling Point Curve for Styrene (Lundström, Gebart, & Lundemo, 1993)

The only way to avoid styrene boiling in VIP is to avoid dropping below the partial pressure (the pressure at which a liquid turns to a gas), which appears to be around 93% of full vacuum for styrene. Increasing the vent pressure can be undesirable due to the presence of residual air, which also can lead to voids, when only obtaining a partial vacuum (Kang, Lee, & Hahn, 2000). Due to the pressure distribution within the mold cavity between the inlet and the vent, the resin is usually only subjected to these ultra-low pressures directly at the flow front. However if the feed line is clamped off at the end of the infusion, pressures can begin to approach these ultra-low levels during post-infusion but prior to gelation (the point at which the resin turns from a liquid to a semi-solid). To address this problem in VIP, Hoebergen (2001) allows for infusing at pressures as close as possible to 100% vacuum, however he suggests increasing the absolute pressure of the internal cavity during the post-infusion process above styrene's partial pressure.

The post-infusion process is the period after resin has wetted out the fabric, but before it has cured and usually begins with clamping of feedlines and/or vacuum lines.

According to Hoebergen (2001) this absolute pressure increase is accomplished by clamping off the feed line and changing the pressure at the vent port from 100% vacuum (-30”Hg) to around 80% to 60% vacuum (-24”Hg to -18”Hg). This will allow the mold cavity to equilibrate at an absolute pressure above the partial pressure. The degree of increase will depend on the desired thickness and fiber volume fraction. According to Saraswat, Heider, and Song (2007) any absolute pressure above (keeping in mind that since this pressure is negative, above means less negative) 93% vacuum (-28”Hg) will not result in void formation.

The final source of voids is mechanical entrapment of air. This is the result of improper stirring when mixing the resin and initiator. This is usually not an issue when mixing by hand, but air entrapment can be a problem when using mechanical assistance. Power mixing blades which are designed to not introduce air should be used when mixing. A drum top pneumatic driven mixer is the best option because it will adequately turn over all the material in the drum (Lacovara, 2004). Mixing should never be done by blowing compressed air into the drum due to the possibility of introducing contaminants from the pneumatic lines (A. Cocquyt, 2007 personal communication, July 18, 2007).

2.3.1.2 Measurement of Voids

Voids are commonly measured using three methods: (1) the density method, (2) microscopic image analysis, and (3) ultrasonic attenuation. The benefits and drawbacks of each method are presented in this section

Historically the density method has been most widely used; however, the results are highly sensitive to experimental measurements and can result in negative values,

which is obviously not physically possible (Judd and Wright, 1978). ASTM D 3171 (2006) describes the density method; the void volume is calculated based on weight and density measurements of the composite, resin and fiber. Equation 2.2 is a rearranged form of the basic relation that the total sample volume is simply the sum of the resin volume, the fiber volume and the void volume. This method also fails to provide useful information about the characteristics of the voids since the measurement is representative of the entire specimen.

Equation 2.2 Void Content (Geier, 1994, p.175)

$$V_v = 100 - \left[\left(m_f \times \frac{\rho_c}{\rho_f} \right) + \left(100 - m_f\right) \times \frac{\rho_c}{\rho_m} \right]$$

Where,

V_v = *Void content as a percentage*

m_f = *Mass percentage of fiber content*

ρ_c = *Density of the composite sample*

ρ_f = *Density of the fiber*

ρ_f = *Density of the matrix*

Microscopic image analysis overcomes this shortfall by directly observing the shape, size and distribution of voids on a polished cross section of the laminate through a microscope at 200x magnification (Kuentzer, Simacek, Advani, & Walsh, 2007). Computer image analysis software is capable of measuring the voids as small as 10 microns directly from the photographic image (Kuentzer, Simacek, Advani, & Walsh, 2007). The shortfall of this method is that it is still a destructive technique, eliminating

the possibility of mechanical tests prior to or post inspection. Also a great number of cross sections must be evaluated to obtain representative and reliable results.

One non-destructive method for measuring void volume is ultrasonic attenuation which measures changes in high frequency (50kHz to 100MHz) acoustic waves traveling through a composite specimen to detect voids (Mason, 2010). Ultrasonic testing is typically divided into two levels A-scan and C-scan and it is performed with one of two methods, namely pulse-echo or through-transmission. The pulse-echo technique utilizes a transducer which is capable of both sending and receiving the frequency, while the through-transmission method uses transducers on either side of the specimen to send and receive signals. The A-scan method typically utilizes a handheld transducer to take measurements at a point, changes are observed by moving the transducer from point to point. The C-scan method measures attenuation at strategic locations and uses the field to create a map of the surface allowing easier visualization of the changes (Mason, 2010). For ultrasonic attenuation higher void content regions absorb more of the ultrasonic waves which is reflected in the receive signal. This method is highly accurate and is able to detect voids as small as 1 micron in diameter (Kuentzer, Simacek, Advani, & Walsh, 2007), however it requires calibration to a similar specimen of known void content determined with some other method (Judd and Wright, 1978). This makes it difficult to test composite specimens. Another challenge is that voids are not the only defects which affect attenuation; delaminations, resin degree of cure, and other imperfections can reduce the confidence in the correlation between attenuation and void content.

2.3.1.3 Effects of Voids

Even though void content in composites manufactured with resin infusion are usually lower than those for open molding the voids can have detrimental effect which are explained in this section. Adoption of resin infusion can decrease the void content from the 5% to 7% range typical for open molding, to less than 2% (Lewit & Wolfe, 2009). However, this 2% void content has been shown to reduce interlaminar shear strength and flexural strength by 20%, flexural modulus by 10% (Ghiorse, 1993), longitudinal and transverse strength and moduli by 2% to 3.5% (Judd and Wright, 1978) and is cited by Judd and Wright (1978) as negatively affecting compressive strength and modulus, fatigue resistance and high temperature resistance as well. While it is not possible to completely eliminate voids (Lui, Zhang, Wang, & Wu, 2006), it is important to minimize voids for any given process (Afendi, Banks, & Kirkwood, 2005).

The study undertaken by Judd and Wright (1978) is the most extensive collection of mechanical property percent-drop-off values for void content including results from over forty-seven studies. Percent-drop-off is the percent reduction of a mechanical property with an increase in one percent voids is to state the percent decrease for every percent increase in voids starting at zero percent voids. Test results show significant variability in percent-drop-off values reported for a variety of mechanical properties. For instance two studies which are cited in Judd and Wright (1978) give interlaminar shear strength percent-drop-off values of 1% and 15% for the same laminate. This large variability is attributed to the difficulty in obtaining true void content values (Judd and Wright, 1978). Variability is also due to different materials and process methods. A methodology to quantify variability of mechanical properties of marine grade composites

fabricated by the VARTM process was recently developed (Berube & Lopez-Anido, 2010).

Despite the lack of predictable effects of voids on mechanical properties, some common patterns emerge from the body of research. In general, matrix dominated material properties such as inter-laminar shear strength (ILSS) and compressive strength are more affected by voids than fiber-dominated properties (Judd & Wright, 1978). The results of studies compiled by Judd and Wright (1978) have shown ILSS percent-drop-off values to average 7 percent up to 4 percent void content at which the effect is less pronounced. The percent-drop-off values for flexural strength and modulus are similar to those for ILSS with some researchers observing drop-off rates up to 30% (Judd and Wright, 1978). Researchers (Liu, Zhang, Wang, & Wu, 2006) found that for high fiber volume fraction (65%-72%) carbon/epoxy laminates the tensile modulus was relatively insensitive to void content. A percent-drop-off value graph from work done by Ghiorse (1993) is shown in Figure 2.11 to provide an example of mechanical property degradation with increasing void contents. The graph shows flexural modulus and strength, and shear strength values about 25 to 40 percent lower at 5 percent voids when compared to a void free sample. One property which has been observed to increase with increasing void content is impact strength. Judd and Wright (1978, p. 13) claim that "this was attributed to the weakened bonding contributing to a more extensive yielding plastic zone at a propagating crack tip."

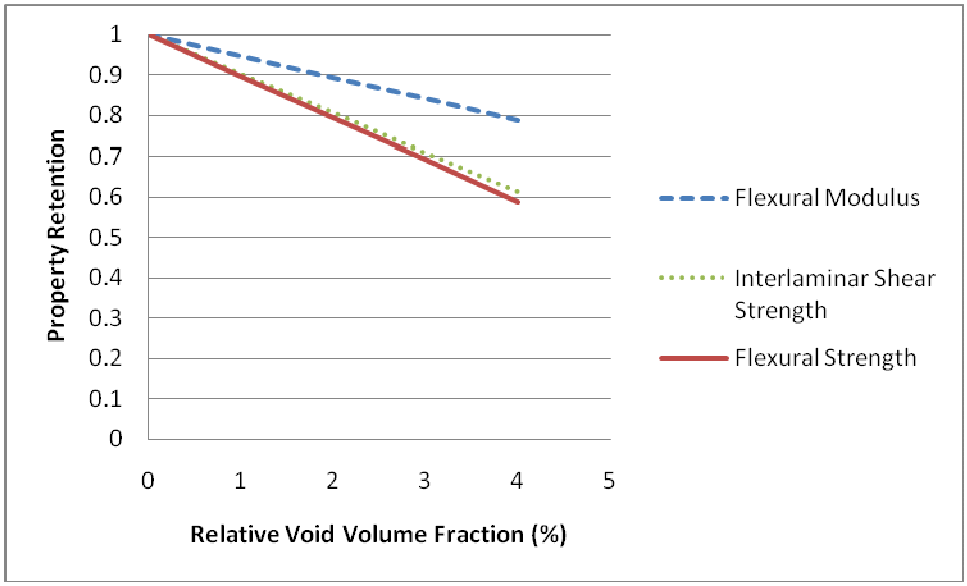

Figure 2.11 Mechanical Property Degradation for Increasing Void Contents (Reproduced from Ghiorse, 1993)

2.3.1.4 Sources and Effects of Dry Spots

A dry spot is a portion of the laminate which is uninfused by resin. They can vary in size from a small as a few dry tows (a few millimeters) to large portions of the laminate since the entire laminate begins as one large "dry spot". Dry spot formation is usually a function of poor infusion layout, mold design, and/or large scale reinforcement permeability heterogeneity (i.e., racetracking or bottlenecking) (Bickerton, Sozer, Graham, & Advani, 2000; Bickerton, Sozer, Simacek, & Advani, 2000).

Dry spot development will vary according to the infusion method used, due to the differing approaches to removing air from the part. In VIP the mold is evacuated of air prior to infusion. When the air is removed, the percentage of vacuum achieved is directly related to the percentage of air remaining in the mold cavity. A 90% vacuum (27"Hg gage) will leave 90% of the interfibril area as empty space (vacuum) and 10% air; air which will either need to be evacuated during infusion or will remain in the laminate as

voids. This is why when a section of laminate is closed off by resin flow fronts resin flow does not stop immediately. Most of the space closed off is still vacuum not air. It is not until most of the remaining space is air, which has been surrounded and confined by the resin into a small pocket, that resin flow will stop. This is due to the fact that the air pocket pressure has equilibrated with the resin pressure and without a pressure differential there is no resin flow. On the other hand, in conventional RTM, no vacuum is applied leaving 100% of the interfibril area as air prior to infusion. The air it pushed out as it is displaced by resin.

The effect of dry spots is that the fibers are not engaged by the resin, leaving the laminate without any composite action. Areas which are resin-starved should be evaluated and repaired, because the material properties will be severely compromised by the incomplete infusion. Dry spot repairs are easiest to affect in VIP while the laminate is still in the mold and under the vacuum bag. Andre Cocquyt recommends cutting a hole in the bag around the affected area and performing another micro-infusion by re-bagging over the area using new feed and vacuum lines.

2.3.1.5 Preventing Dry Spots

Preventing dry spots in resin infusion requires a working understanding of the resin infusion process parameters which affect resin flow. These process parameters are described in detail in section 2.4 Resin Infusion Process Parameters. This section does present four methods for eliminating dry spots: (1) numerically-based infusion models, (2) active control systems, (3) a pre-infusion infusion, and (4) the use of a semi-porous membrane.

Several numerically-based infusion models have been developed to predict resin flow front progression in an attempt to eliminate dry spot formation (Sun, Li, & Lee, 1998; Mathur, Heider, Hoffmann, Gillespie, Advani, & Fink, 2001; Loos, Sayre, McGrane, & Grimsley, 2001; Dong, 2006). While helpful in some cases, these tools are limited by the level of confidence of the inputs: reinforcement characteristics, resin viscosity; and pressure distributions. While the permeability of the reinforcement is not difficult to determine empirically (Section 2.4.1), in practice slight irregularities in laying the reinforcement within the tooling cavity can lead to significant variability. These irregularities can be fabric folds, overlaps, vacuum bag bridging a negative corner or racetracks all of which modify the overall laminate permeability. Racetracks, which are open areas of high permeability are the result of improper tooling design or reinforcement placement, can lead to drastic changes in the infusion pattern. This can cause unexpected and unwanted results.

Active control systems have been developed which monitor resin flow front progress and alter inlet and outlet pressures. Heider, Hofmann and Gillespie (2000) used a SMARTweave sensor fabric in the laminate stack to determine the progression of resin and then automate injection and vent openings and closings. The SMARTweave fabric determines the presence of resin by measuring conductivity between sensors; the conductivity changes with the presence of resin. They have been working on complete automation of the infusion process via information feedback (Amouroux, Deffor, Fuqua, Heider, & Gillespie, 2003).

Qui et al. (2008) proposed a simple method to predict problems in flow front progression which eliminates dependence on computer models and the data collection devices. Ethyl alcohol is injected in place of resin, flow progress is mapped and problem areas are modified. The alcohol is flushed from the laminate via vacuum, air flow, and application of heat. Once the alcohol is completely evacuated the modified or verified infusion can commence. Experiments were carried out on glass and carbon fibers using unsaturated polyester and vinyl ester resins. The use of Dynamic Mechanical Analysis (DMA), Fournier Transform Infrared Spectroscopy (FTIR), and Thermal Gravimetric Analysis (TGA) indicated that there were no appreciable differences in the resin-fiber interface. Furthermore, this study found no negative effects on mechanical properties (shear strength and modulus; flexural strength and modulus; and tensile strength and modulus) compared with the control samples due to the pre-infusion.

Another solution to the formation of dry spots in VIP is to use a semi-porous membrane (SPM) (Matienzo, Shah, & Venables, 1985; Amouroux, 2006). The SPM is placed on top of the laminate stack where the bag is usually applied, followed by a breather material, and then sealed with the vacuum bag, Figure 2.12. In this case the SPM allows passage of air and gases, but not resin. This is possible due to the molecular size of the different constituents, and works on the same principle as a modern Goretex® jacket. In the case of vacuum infusion the SPM is sealed between the vacuum bag and the laminate and connected to the vacuum port(s). Air and gasses are removed from the laminate through the thickness direction and evacuated to the vent. The advantage of the SPM is that vacuum is uniformly applied over the entire surface of the laminate. If a dry spot were to form, the vacuum would still be located above the spot allowing complete

filling. If distribution media is used it should be placed on the opposite side from the SPM due to the through the thickness pressure differential. Amouroux's (2006) experiments demonstrated the importance of qualifications testing as not all SPMs were chemically or physically compatible with the resin system. Checking with the SPM manufacturer and conducting qualifications testing will avoid problems. The SPM must physically block the resin, while allowing air through; and not degrade in the presence of the resin.

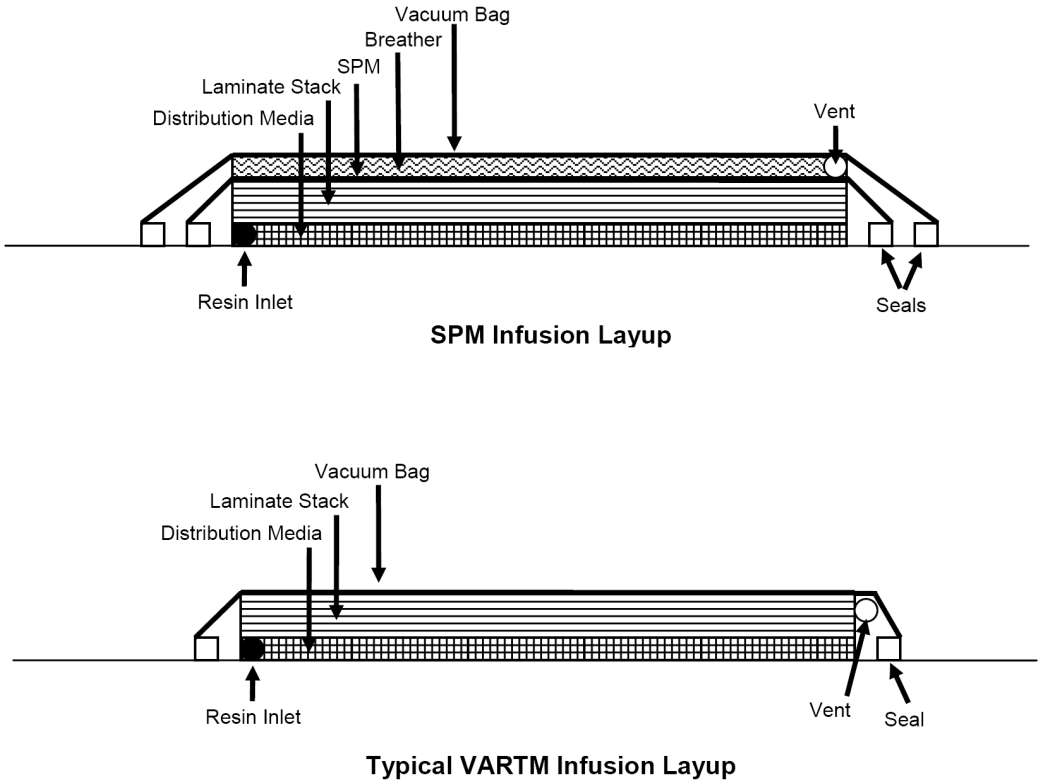

Figure 2.12 Semi-Porous Membrane Infusion Layup

2.3.2 Thickness Variations

In VIP a common observation is a change in thickness - a thickness gradient - which forms between the injection ports and the evacuation ports (Grimsley, Hubert, Song, Cano, Loos, & Pipes, 2001; Andersson, Lundström, Gebart, & Synnergen, 2003).

Thickness variations of 10% are not uncommon in the VARTM processes (Tackitt & Walsh, 2005; Amouroux, Deffor, Fuqua, Heider & Gillespie, 2003). Thickness control is a major quality concern because of dimensional control considerations, fiber volume fraction, flexural stiffness and weight reduction. Changes in thickness are directly proportional to changes in fiber volume fraction, and many mechanical properties are heavily dependent on fiber volume fraction. This section explains the causes of the thickness gradient, how it depends on the infusion layout, how to avoid and prevent it, and how it affects mechanical properties.

2.3.2.1 Causes of the Thickness Gradient

The thickness gradient has one cause which exhibits itself in two particular cases. The cause is internal variations in pressure which cause the flexible secondary mold to displace different amounts. This is exhibited when there is a pressure differential between the inlet and vent ports and also when there are variations in tooling height. These phenomena are explained in this section.

In VIP the flexible secondary mold is free to displace as pressures within the bag change. This phenomenon is particular to resin infusion under flexible tooling (RIFT). In RTM, where rigid tooling is used, the volume is fixed and it is the stresses in the tooling which will vary. In vacuum infusion the volume will vary and the tooling stresses are constant with respect to pressure. Thus in vacuum infusion the thickness gradient is inversely proportional to the pressure gradient (Tackitt & Walsh, 2005).

The thickness of the enclosed laminate is a function of a force balance equation involving the reinforcement stiffness, the applied tooling pressure, and the internal

pressure Figure 2.13. This has been modeled by researchers in an attempt to predict the compaction response. Gutowski, Morigaki, and Cai (1987) modeled the compaction of laminates as a function of the reinforcement spring constant, initial fiber volume fraction, and theoretical maximum fiber volume fraction. This model does not however take into account observations of a time-dependent response of the fabric (Kelly, Umer, & Bickerton, 2004). Robitaille and Gauvin (1998a, 1998b, 1999) have modeled the compaction response as an empirical power law fit relating the thickness to experimental observation for various fiber architectures.

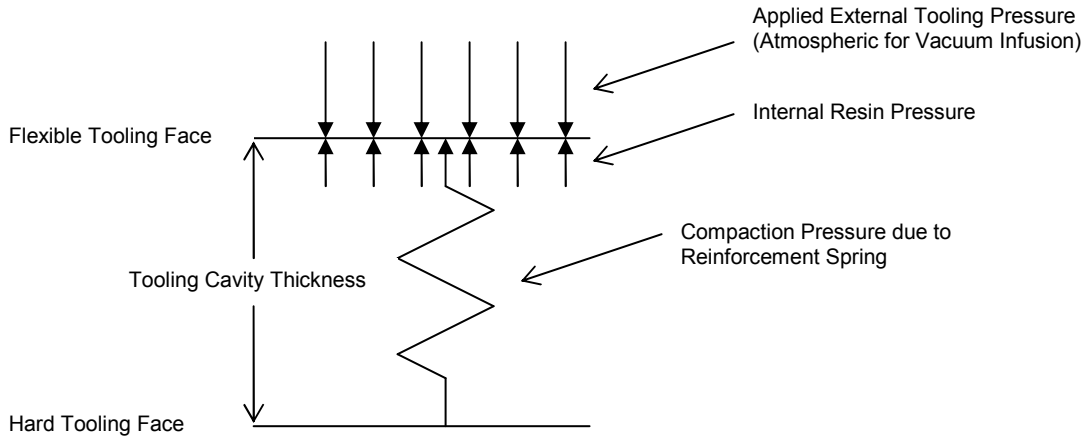

Figure 2.13 Diagram of Internal Tooling Pressures

Thickness is difficult to predict because the internal resin pressure changes throughout the different stages of infusion. In VIP there are generally five stages which affect thickness: 1) the initial response of the dry fiber reinforcement to the applied vacuum, 2) the time-dependent response of the dry fiber reinforcement under vacuum prior to infusion 3) the response to fiber wetting 4) the response to the change in local resin pressure and 5) the response to the time-dependent fiber relaxation (Yenilmez & Sozer, 2009).

In the first stage there is no internal resin pressure therefore the reinforcement compaction pressure equals the applied external pressure (atmospheric pressure for VIP). As the resin fills the vacuum it begins to increase in internal pressure and take some of the load, ranging from absolute zero at the flow front to the injection pressure at the inlet as shown in Figure 2.14 (usually atmospheric pressure in VIP). Since the force balance still applies and the applied external pressure remains constant, the increase in internal resin pressure leads to a corresponding decrease in reinforcement compaction pressure. This decrease in the compaction pressure leads to what is known as "spring-back" - the increase of thickness with increasing internal resin pressures, Figure 2.15. This was observed by Yenelmez and Sozer (2009) for all laminates at pressures above 60% of vacuum (-18"Hg). Pressures between 40% and 60% full vacuum (-12"Hg and -18"Hg) resulted in immediate "spring-back" followed by the thickness holding constant, while pressures between 40% and 2% vacuum (-12"Hg and -0.6"Hg) resulted in immediate "spring-back" followed by continued thickness increases. Laminates subjected to pressures of 80% vacuum (-24"Hg) continued to decrease in thickness; they did not experience "spring-back".

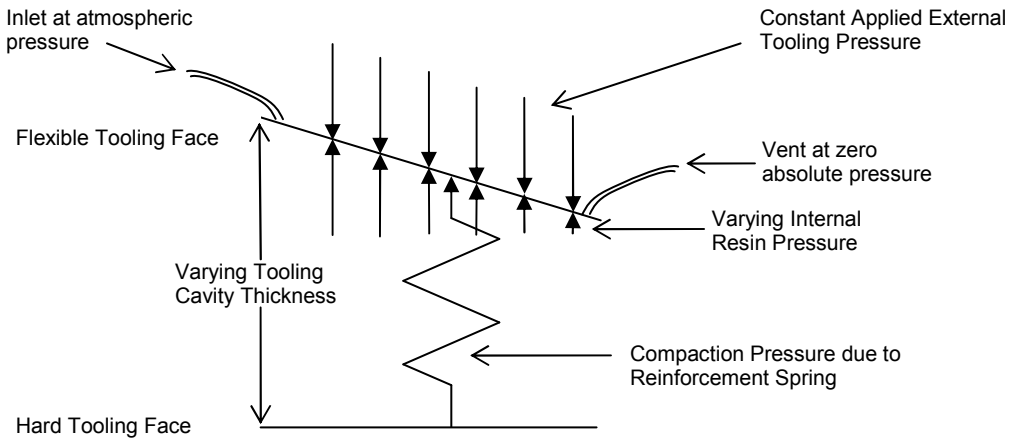

Figure 2.14 Varying Internal Resin Pressure

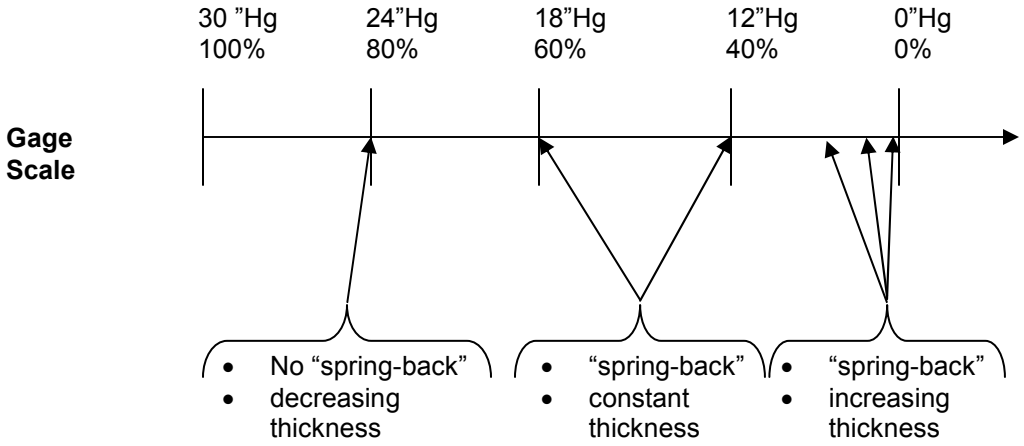

Figure 2.15 Spring-back at Different Pressures (Yenelmez and Sozer, 2009)

Yenelmez and Sozer (2009) conducted experiments simulating these different stages for vacuum infusion using different fabrics; 500g/m^2 random stitched mat, 500g/m^2 plain woven fabric, 860g/m^2 0°/90° stitched biaxial fabric and a 250g/m^2 polypropylene distribution media bulking core (about 4mm thick). They found that after initial vacuum application reinforcement stacks consisting of solid woven, biaxial,

random, and bulking core dropped in thickness by 22%, 26%, 38% and 58%, respectively, Table 2.2. Subsequent settling and wetting increased thickness reductions by only an additional 1% to 5%. The random mat changed thickness more than the other reinforcements during these stages.

Table 2.2 Thickness Reduction for Selected Fabrics Under Vacuum (Yenelmez & Sozer, 2009)

Reinforcement Type	Initial Thickness Reduction Due to Vacuum
500g/m^2 plain woven fabric	22%
860g/m^2 0°/90° stitched biaxial fabric	26%
500g/m^2 random stitched mat,	38%
250g/m^2 polypropylene distribution media bulking core	58%

Another important observation regarding the compaction response is the different response between wet and dry compaction. Wetted fibers compact more than dry fibers. This phenomenon is attributed to the lubricative affect of the fluid reducing friction between fibers (Correia, Robitaille, Long, Rudd, Simacek, & Advani, 2005).

Another source of the pressure gradient is if the tooling exhibits height variations (Juska, Dexter, & Seemann III, 1998). Thus far the explanation has been limited to infusions with relatively little height variation. However many infused parts exhibit large height variations, such as from the keel to the gunwales in a boat hull. Fluid pressure derived from an elevated source is called “head”. Just as the pressure of the ocean increases with depth, so will the internal pressure in the tooling cavity increase with increases in the heights of the resin column. The weight of elevated resin above causes increases in the internal resin pressure below. This causes “pooling” of resin at the bottom of the tooling cavity in VIP and thin, compact laminate at the top.

Equation 2.3 Pascal's Law

$$h = \frac{P}{\rho \times 12}$$

Where,

h = fluid height (feet)

P = Absolute pressure (psi)

ρ = Fluid density (lbs/in^3); vinyl ester = 0.0415 lb/in^3;

epoxy = 0.0471 lb/in^3

Atmospheric pressure is limited in the vertical distance it can push resin subjected to a vacuum. The height restriction can be calculated from Pascal's Law, a form of which is given in Equation 2.3 . Pascal's Law is limited to static fluids, but since the resin flow rate is so low this is considered a static fluid problem (Cengel & Cimbala, 2006). For a typical vinyl ester resin the theoretical limited vertical distance based on Pascal's Law with atmospheric pressure is about 29 ft, slightly less for epoxies. However, to maintain pressures at the inlet of below 80% of full vacuum (24"Hg or 11.8psi gage) - as suggested by Yenelmez and Sozer (2009) to avoid spring-back -this would be limited to around six feet as Figure 2.16 reveals. This height is determined by using Equation 2.3 and substituting 2.9psi (the absolute pressure for a vacuum pressure of 11.8psi gage) for P, and 0.0415lb/in^3 for ρ. This results in a calculation of 5.8ft or about six feet which is plotted in Figure 2.16.

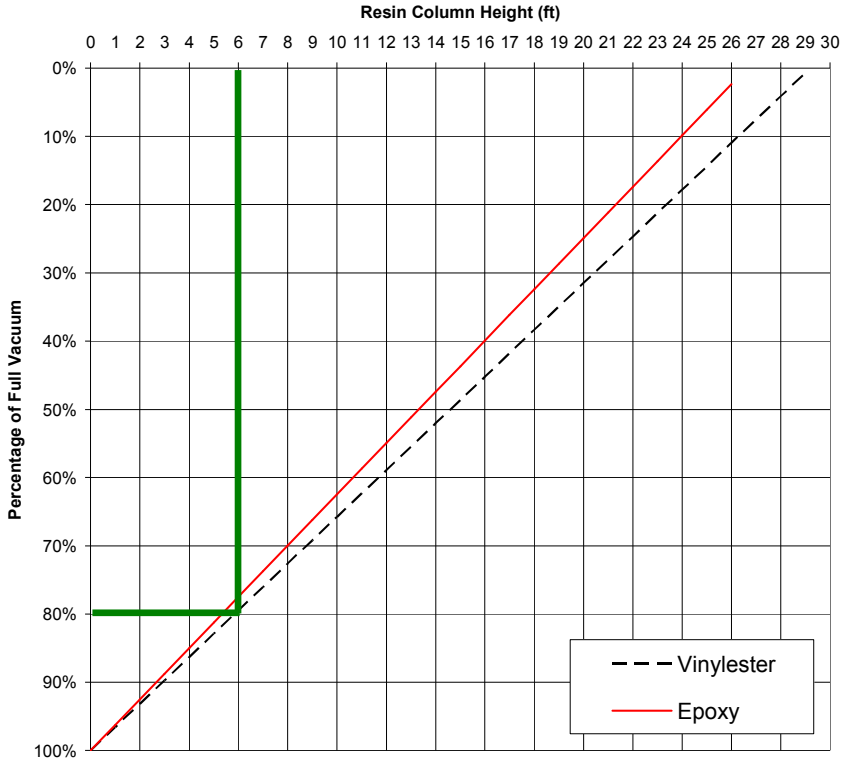

Figure 2.16 Internal Tooling Pressure for Various Resin Column Heights

To address the height limitations discussed earlier a staged infusion is often used. In this approach the height of the mold is infused in sequential stages from the bottom-up allowing the lower zones to gel while the upper zones fill. Since the lower levels have gelled and are no longer fluids they will not be subjected to the pressure increases of the increasing resin column.

2.3.2.2 Pressure Gradients for Different Infusion Layouts

The internal resin pressure which controls thickness has been shown to vary between the inlet and the vent; and for different infusion layouts this pressure curve will be different. The pressure gradient is the curve of pressure within the tooling cavity with respect to distance from the resin inlet. Tackit and Walsh (2005) present equations for the pressure

gradient curve for a line infusion and a radial infusion (Equation 2.4 and Equation 2.5), which they validated experimentally. They noted that the internal fluid pressure varies linearly between the injection port and the vent ports with respect to the area, not the distance from the injection port. They found that for a line infusion (Figure 2.5b, Page 10) the pressure gradient is constant, varying linearly between the injection and vent ports as shown in Figure 2.17. For a radial infusion (Figure 2.5c, Page 10) the pressure gradient is not constant, it varies logarithmically between the injection and vent ports as shown in Figure 2.18. Figure 2.19 shows the pressure gradient for a circumferential infusion (Figure 2.5d, Page 10). The corollary of these curves is that the thickness gradient will vary in relation to the pressure gradient and will depend on the infusion layout.

Equation 2.4 Pressure Profile for a Line Infusion (Tackit & Walsh, 2005)

$$P(x) = P_{resin\ feed} + \frac{P_{vacuumport} - P_{resin\ feed}}{L} x$$

Equation 2.5 Pressure Profile for a Radial Infusion (Tackit & Walsh, 2005)

$$P(r) = P_{resin\ feed} + \frac{P_{vacuumport} - P_{resin\ feed}}{\ln\left(\frac{R}{R_0}\right)} \ln\left(\frac{r}{R_0}\right)$$

Where,

P(x) and P(r) = Pressure at a given distance from the inlet

r and x = Distance from inlet at point of interest

$P_{resin\ feed}$ *= Pressure at inlet*

$P_{vacuum\ port}$ *= Pressure at vent*

L = Length of line infusion (distance between inlet and vent ports)

R = Part maximum radius (Radius of vent)

R_0 *= Radius of inlet tube*

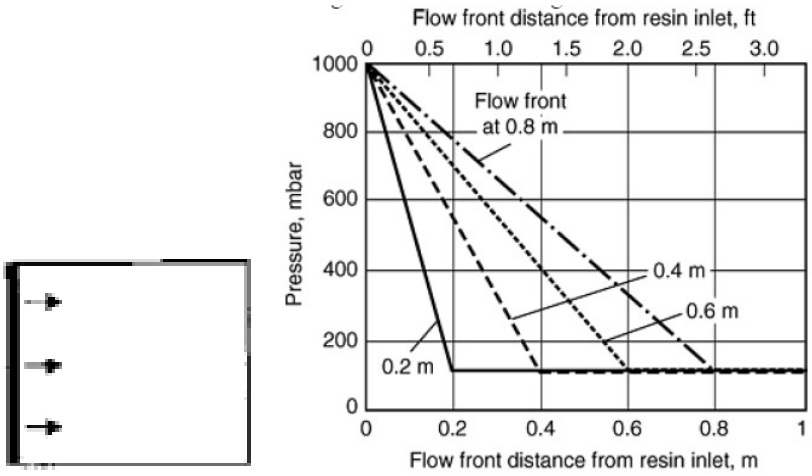

Figure 2.17 Line Infusion (Hoebergen, 2001)

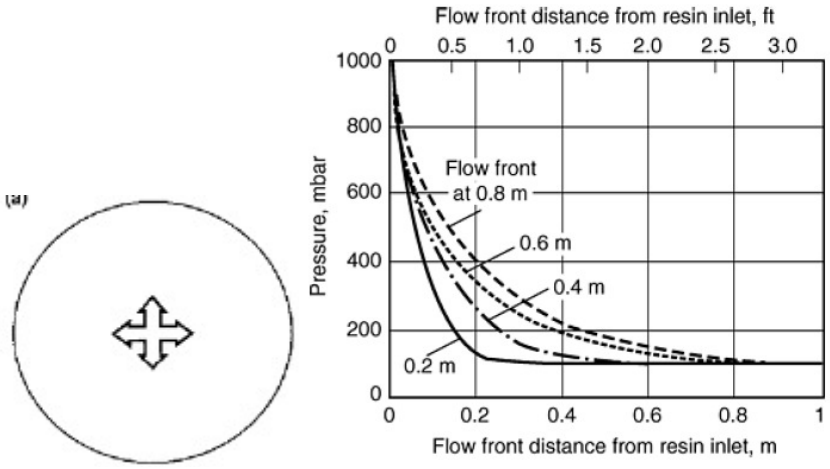

Figure 2.18 Radial Infusion (Hoebergen, 2001)

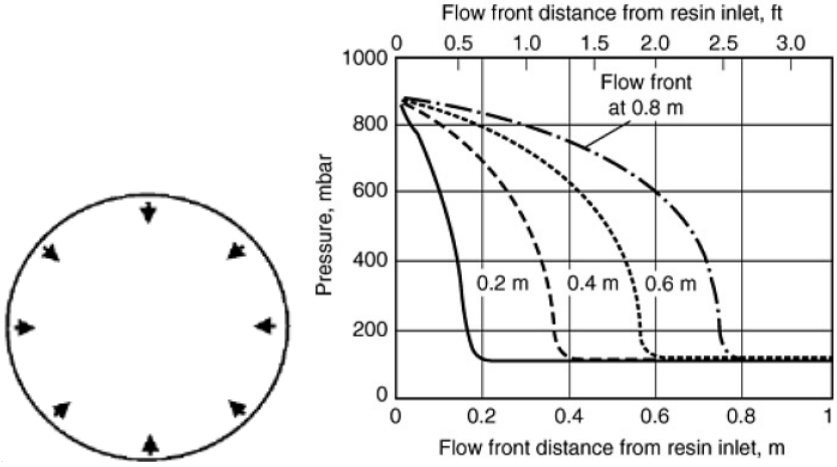

Figure 2.19 Circumferential Infusion (Hoebergen, 2001)

The previous equations are simplified in the following examples specific to VIP. Pressures can be entered in gage or absolute and will result in solutions on the same scale. For this VIP example the vacuum is assumed to be 30"Hg gage at the vent port ($P_{vacuum\ port}$ = 30"Hg) and the inlet tube is assumed to have a radius of 3/16" (R_o = 0.1875") and be at atmospheric pressure ($P_{resin\ feed}$ = 0"Hg). The length of the line infusion and the radius of the radial infusion are both assumed to equal 50". For this case Equation 2.4 simplifies to $P(x) = -0.6x$ and Equation 2.5 simplifies to the following:

$P(r) = -5.371 \ln(r/0.1875)$. The former drops off linearly moving away from the inlet while the latter does so logarithmically. This means that solving these equations a short distance away from the inlet (say r=x=5") the pressure for the line infusion is 3"Hg gage while radial infusion pressure at that point is 17.6"Hg gage, a significant difference.

2.3.2.3 Controlling Thickness the Thickness Gradient

The thickness gradient can be controlled using post-filling pressure control. The stage after the laminate is wetted by resin, but before it has gelled is referred to as the post-filling period. Hoebergen (2001) discuses common post-filling pressure control options which affect the thickness. At the beginning of the post-filling stage the pressure gradient will resemble one of those previously shown in Figure 2.17, Figure 2.18, or Figure 2.19. Clamping off only the feed line results in the pressure gradient diminishing and approaching the vacuum pressure across the entire mold, decreasing the thickness and increasing the fiber volume fraction. The downside of this approach is the formation of voids due to resin off-gassing at these low pressures (see section 2.3.1.1 Sources and Prevention of Voids). Another option is to clamp of only the vacuum line. This results in the internal resin pressure approaching atmospheric pressure, and increases in thickness and reduction in fiber volume fraction. Clamping both lines is a solution to the problems resulting from the previous two methods. The pressure will level to some intermediate value, however if there are leaks in the mold, this method will result in increase in voids. The method proposed by Hoebergen (2001) for high quality laminates is to increase the absolute pressure at the vacuum line to 80% of full vacuum (-18”Hg) prior to clamping off the feed line. This still results in a thickness gradient, however it is

small, allows the extraction of air bubbles resulting from leaks, is below the pressure at which volatiles in the resin off-gas, and will not result in spring-back.

2.3.2.4 Avoiding the Thickness Gradient

The thickness gradient can be avoided altogether if the pressure gradient is through the thickness as opposed to across the laminate. This can be achieved with a semi-porous membrane and breather material (see section 2.3.1.5 Preventing Dry Spots) over the entire laminate surface (Amouroux, 2006). This allows for uniform vacuum pressure before, during, and after the filling. The pressure gradient is now through the thickness, eliminating the thickness variation between ports.

2.3.2.5 Thickness's Affect on Mechanical Properties

The thickness variations common to VIP lead to variations in the mechanical properties, however these do not always lead to variations in the composite component's load bearing capacities or stiffnesses. The affects of thickness variations on weight, fiber volume fraction, mechanical properties, load bearing capacity and stiffness are explained in detail in the following section.

For this section the term "mechanical properties" refers to the engineering "unit properties" such as tensile, compressive, flexural and shear moduli and strength. Mechanical properties are always expressed as "force per unit area" (e.g. psi, MPa). The term "unit properties" comes from the fact that these properties have been normalized to the same area (e.g. 1 in^2, 1 m^2). A separate measure which is not normalized to area is convenient for composites; this is load bearing capacity and stiffness. Tensile,

compressive, flexural, and shear load bearing capacities and stiffnesses account for area and are given in terms of "force" (e.g. pounds, Newtons).

Thickness has a direction impact on the weight of a given laminate. When thickness varies during infusion, it is the volume of resin that is varied, not the volume of the reinforcement. Therefore increases in thickness for a given laminate stack will result in a heavier laminate with a lower fiber volume fraction. This can be a quality concern for weight critical parts such as aircraft components or racing yachts.

Fiber volume fraction (V_f) is inversely proportional to the laminate thickness and can be related using Equation 2.6, which is rearranged in Equation 2.7. Inversely proportional means that when thickness increases, V_f decreases and vice versa. The relationship of Equation 2.7 is shown in Figure 2.20 for a specific case. This shows the decrease in fiber volume fraction with increases in thickness for one ply of a 250 g/m^2 (7.4 oz/yd^2) E-glass laminate. This graph shows that the relationship is not linear. Thus a 10% increase in laminate thickness, a common VARTM thickness variation, will have a different affect on V_f depending on the V_f. For a lower V_f, the V_f is less sensitive to increases in thickness than for a higher V_f. This is also shown in Table 2.3 which presents data generated from Equation 2.7 using a laminate thickness of one unit thick and increasing the thickness by 10%. At the target V_f of 40%, a 10% increase in thickness results in a 3.6% decrease in V_f. However, at a target V_f of 70%, the same 10% increase in thickness results in a 6.3% decrease in V_f. Changes in fiber density or areal weight will only scale the results of Equation 2.7, the basic inversely proportional relationship holds true for all fiber types and weights.

Equation 2.6 Fiber Volume Fraction as a Function of Thickness (ASTM D 3171, 2006)

$$V_f = \frac{n \cdot A_f}{\rho_f \cdot t}$$

Equation 2.7 Thickness as a Function of Fiber Volume Fraction

$$t = \frac{n \cdot A_w}{\rho_f \cdot V_f}$$

Where,

n = *number of plies in laminate*

A_f = *areal weight of one ply of reinforcement*

ρ_f = *density of the fibers*

t = *cured laminate thickness*

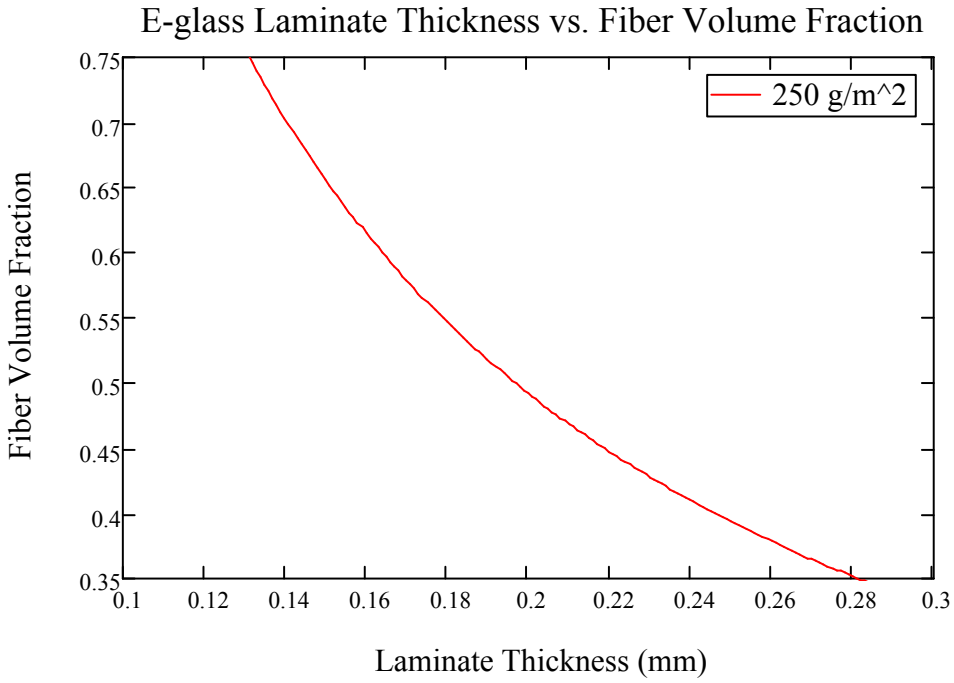

Figure 2.20 Specific Example of Thickness vs. V_f

Table 2.3 Change in V_f for a 10% Increase in Thickness

Initial V_f	Initial thickness	Final thickness	Final V_f	Change in V_f
40%	1	1.1	36.4%	-3.6%
50%	1	1.1	45.5%	-4.5%
60%	1	1.1	54.5%	-5.5%
70%	1	1.1	63.6%	-6.4%

All mechanical properties equations from composites micro-mechanics are dependent on fiber volume fraction (which has been demonstrated to be dependent on thickness) (Daniel & Ishai, 2006). For polymer matrix composites with a high fiber to matrix modular ratio (e.g. carbon/epoxy or E-glass/polyester) the fiber dominated mechanical properties (longitudinal modulus and strength) are directly proportional to fiber volume fraction. Matrix dominated properties for PMC laminates are also dependent on fiber volume fraction, but are not directly proportional. These laminates exhibit greater sensitivity to fiber volume fraction at higher fiber volume fractions.

The change in mechanical properties with changes in fiber volume fraction (i.e., thickness) is important, but is usually less so to the manufacturer than the change in load bearing capacity and stiffness. This is due to the fact that while the unit properties are decreasing with thicker laminates due to the lower fiber volume fractions the area is at the same time increasing. For tensile and compressive load bearing capacities the net increase in load bearing capacity with increasing thickness is only attributed to that load which is additionally taken by the resin. This is a small fraction of the total load for laminates with high fiber to matrix modulus ratios because load is attracted to stiffer materials (i.e. the fibers). Similarly tensile and compressive stiffnesses (which are

characterized by the product of the longitudinal modulus and the area) are not very sensitive to fiber volume fraction variations in the case of high fiber to matrix modulus ratio laminas. This is due to the fact that a thicker laminate experiencing a decrease in V_f and therefore a decreasing longitudinal modulus will at the same time experience a proportional increase in area. The product of the longitudinal modulus and the area will remain largely unchanged.

Flexural load bearing capacity and stiffness are greatly affected by changes in single skin laminate thickness. Load bearing capacity in flexural applications is related to the thickness of the laminate by the square and flexural stiffness is related to the thickness by the cube (Lewit & Wolfe, 2006). This means that small variations in thickness will result in large variations in flexural load bearing capacity and very large variations in stiffness. Equation 2.8 and Equation 2.9 (rearranged forms of beam formulae in AISC, 2008) are for the specific load case of three point bending and provide a representative example of how thickness is related to load bearing capacity and stiffness. According to these strengths of materials equations, a 10% decrease in thickness results in a 19% decrease in load bearing capacity and a 27% decrease in stiffness.

Equation 2.8 Flexural Load Bearing Capacity of a Single Skin Laminate

$$P_{ult} = \left(\frac{\sigma_{ult} b}{3L} \right) t^2$$

Equation 2.9 Flexural Stiffness of a Single Skin Laminate

$$P/\Delta = \left(\frac{4Eb}{L^3} \right) t^3$$

Where,

P_{ult} = ultimate bending load

P/Δ = bending stiffness

σ_{ult} = ultimate bending stress

b = beam width

L = span length

t = thickness of single skin laminate

2.3.3 Resin Curing Problems

Many quality related issues in composites manufacturing are related to incomplete or unpredicted resin curing. Dry spots, print through, uncured sections, tooling damage from excessive peak exotherm temperatures, under-performing mechanical properties can all often be directly attributed to a problem with the resin cure. Incomplete resin curing results in lower thermal resistance and transition temperature, lower moisture resistance, fatigue resistance, and matrix dominated strength and stiffness properties (Cain et al., 2008). Juska and Mayes (1995) also found that flexural strength is highly dependent on degree of cure. This section describes the nature of the resin curing process; common issues which lead to incomplete or unpredicted resin curing and measures for avoiding them; methods for measuring the degree of cure; the effects of post-curing; and resin shrinkage and surface quality issues.

2.3.3.1 The Nature of Resin Curing

The resin cure is different for different resin systems. In polymer matrix composites resin systems are usually unsaturated polyester resin, vinyl ester resin, or an epoxy system. The former two require an initiator to begin the process of polymer chain cross-linking which leads to gelling. The initiator starts the reaction, but does not take part in it (CFA, 2001). Epoxy resin systems on the other hand require the addition of a hardener which takes part in the chemical reaction. There are of course many different formulations and variations within each category, but these characteristics hold for each of the respective systems. Some more novel curing systems rely on microwaves, electron beams, or ultra-violet light to initiate the resin system reaction. However the use of these systems is usually limited to high performance composites and is more expensive than the traditional systems. This section will limit its focus to traditional systems.

For given chemistries and conditions resin systems have a predictable progress of cure. Progress of cure refers to the change in resin properties and temperature with time. After initiation most resin systems exponentially ramp up in temperature, reaching a maximum peak exothermic temperature, and gradually cool off. The gel time will correlate to this temperature curve. The practical portions of the resin cure are the gel time and the peak exothermic temperature.

2.3.3.2 Causes and Prevention of Resin Curing Problems

Resin curing problems arise when the resin cure is incomplete or when it does not perform as expected. The root cause of curing problems is usually one or more of three factors: (1) contaminated or expired raw material; (2) infusion conditions are dissimilar to the material qualification conditions; or (3) improper measuring and mixing.

A major cause of resin curing problems is the use of contaminated or expired material. Contamination can result from moisture condensation on the interior of the resin drums, pouring unused material from a secondary container back into the original, and a number of other situations with can generally be prevented with proper housekeeping. Resin system raw materials can age beyond recommended use resulting in unpredictable curing behavior. Polyesters and vinyl esters are formulated to cure without additional components given enough time. This aging process results in what is referred to as gel time drift. Common in pre-promoted resin systems, this process could result in a much different gel time than anticipated. Thus the initiator simply speeds up the already ongoing cross-linking process. If allowed to sit in storage beyond the manufacturer's recommended shelf life, these resins can exhibit different cure characteristics than a new system. These resins usually have a shorter gel time. Expired material can be avoided by implementing a strict inventory control system and by checking before every use.

The best way to avoid unexpected curing is to perform a gel time test immediately before infusion and compare the results with the gel time test performed upon receipt. If the gel times are the same it is safe to assume that no significant changes have occurred.

Another resin curing issue stems from the fact that products are not always used in ways congruent with material qualification tests and material qualification test may not even be performed. The only way to accurately predict the performance of a resin system is to mimic the processing conditions. Resin cure characteristics depend on many variables. Major ones include the formulation and age of the resin system; initiator ratios; the resin, mold and ambient temperatures; the mass of resin; and humidity (if

exposed to air). Gel time tests should be preformed to a standard which regulates all these parameters so that accurate comparisons can be made from one batch to the next. Infusion parameters should aim to minimize the variability of these major variables to maximize the predictability of the resin cure.

Improper measuring and mixing of initiators can result in significant changes in the resin cure. Common initiator ratios in polyester and vinyl ester resin systems require small fractions of the total weight to be measured and mixed. These percentages are usually around 1.5% to 3% of the resin and are large compared to common ratios for inhibitors and promoters which can be as low as 0.05%. Small errors in measuring these components can lead to large variations in gel time. Over or under initiating a resin system can lead to just about every resin curing problem imaginable. The Cook Composites and Polymer 2005 Composites Application Guide (CCP, 2005) lists almost thirty separate curing problems related to over or under initiation of gel coats. The smaller the resin batch (such as for gel time tests), the more pronounced this issue becomes due to the increased difficulty in accurately measuring such small amounts of materials. David Flagler (2008) recommends measuring these small amounts by volume as opposed to by weight. Volumes can be accurately measured with pipettes or medical syringes. These devices are usually graded in cubic centimeters, so using the metric system allows easy calculations of volumes needed and conversions from weight to volume. Figure 2.21 shows the gel times as a function of percentage of catalyst and temperature for a Reichhold Hydrex vinyl ester resin (Reichhold, 2004). This example shows how drastically a resin system can vary with both these parameters. In this case

the gel time of a 1% catalyzed mix at 70°F is cut in half with the addition of only a 0.5% catalyst and an increase of only 7°F.

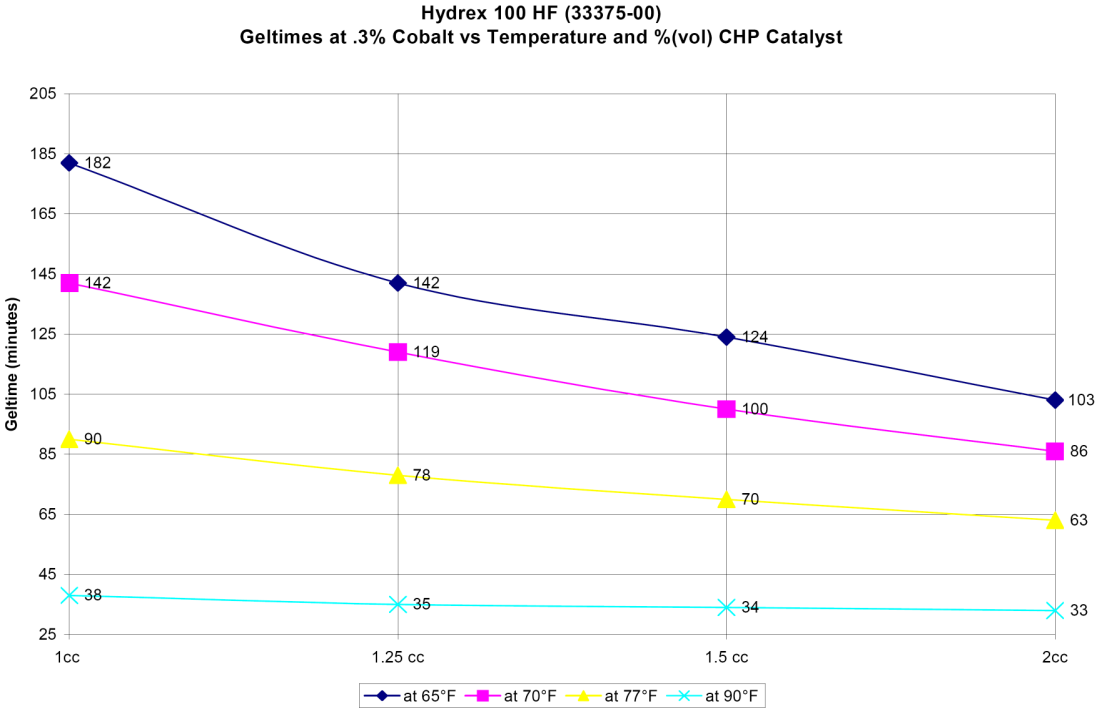

Figure 2.21 Variations in Gel Time with Temperature and Catalyst (Reichhold, 2004)

Uneven distribution of initiators, promoters, and inhibitors due to inadequate mixing can lead to portions of resin being over or under initiated. This problem can be exacerbated by the nature of resin infusion where resin is drawn into the tooling cavity through a hose. If none of the initiator reaches the bottom of the resin bucket during mixing, this uninitiated resin will be the first to be pushed into the cavity when the feed line is placed at the bottom of the bucket and this resin will never be capable of reaching full cure. Resin should be mixed long enough to ensure that the additives are evenly dispersed within the resin, at least one minute.

2.3.3.3 Measuring the Degree of Cure

Degree of cure is measured indirectly. It is determined by measuring a parameter of the resin system which can be correlated with the degree of cure. The glass transition temperature - T_g - and hardness can be measured and have been correlated to degree of cure (Cain et al., 2008; Juska & Maynes, 1995). The T_g itself is measured in a variety of different ways including Heat Distortion Temperature, Differential Scanning Calorimetry, Dynamic Mechanical Thermal Analysis, Thermogravimetric Analysis and Thermomechanical Analysis. (Aurthur Wolfe's September, 2002 article in Composites Fabrication magazine provides a good primer on these techniques) The Barcol Hardness Test measures hardness of the resin casting, but it has limited accuracy above a degree of cure of about 85% according to Juska and Maynes (1995). A more direct measurement of the degree of cure involves monitoring the cross-linking process. Cain et al. (2008) used Fournier Transform Infrared Spectroscopy (FTIR) to track the disappearance of the styrene and methacrylate double-bond. The benefit of FTIR is that it does not advance the degree of cure like thermal methods do.

2.3.3.4 Post Curing

Post curing is used to increase the degree of resin cure after the initial reaction has slowed. Typical curing diagrams show that the degree of cure for styrenated resin systems progresses exponentially, with most of the cross-linking taking place in a matter of hours, but with the potential for increased curing almost a year after when left at ambient conditions. Yang and Lee (1999) found that the mechanical properties of polyester resins were about twice as sensitive to post curing as vinyl ester resins, citing increases of 21% and 10%, respectively. Cain et al. (2006) investigated the mechanical

performance of VARTM E-glass/vinyl ester laminates with and without different levels of post curing. Findings demonstrated that the "mechanical properties are significantly affected by the degree of cure and conversion of resin constituents." Properties found to be affected by the degree of cure included static resin dominated properties such as shear strength and modulus, visco-elastic properties, and fatigue performance of fiber dominated properties. However, degree of cure, and therefore mechanical properties, of the non-post-cured laminates approached those of the post cured laminates at around 300 days of curing at ambient temperatures. Tensile strength and modulus of psudo-quasi-isotropic laminates appeared to be indifferent to the degree of cure implying that fiber dominated properties are not sensitive to degree of cure. Creep and fatigue life were greatly influenced by post-curing. This research also found that increases in post-curing temperature do not necessarily increase the mechanical performance, suggesting an optimal post curing temperature exists.

Juska and Mayes (1995) also investigated the effects of post-curing on the flexural strength of VARTM E-glass/vinyl ester laminates typical of Naval structures. The flexural strength of the non-post-cured laminates increased with time. The flexural strength of a laminate cured for six months under ambient conditions was 50% stronger than one at 24 hours. Flexural strength results pointed to a limit of the beneficial post-curing temperature; excessively high post-curing temperatures resulted in lower flexural strengths. They also found that if the post-cure temperature is increased too rapidly, the ambient temperature could exceed the glass transition temperature. This behavior could result in laminate distortions. However if the heating rate was slowly increased the material was allowed to post-cure and the T_g was able to remain above ambient

temperature. For this reason they recommended forgoing post-curing of composites for use in Naval applications unless rapid in-service temperature increases were expected. Post curing would also be beneficial if high service loads are expected soon after fabrication. It is important to note that it is not uncommon for yachts and other composite parts to experience these rapid in-service temperature increases. Boats sitting on a trailer in an asphalt parking lot in the summer sun could easily experience temperatures beyond their glass transition temperature, especially if they are dark colored. Glass transition temperatures for non-post-cured resins could be around 150°F (Juska and Mayes, 1995), while black surfaces in the sun can heat up to 180°F.

2.3.3.5 Resin Shrinkage and Surface Defects

Surface defects are usually attributable to resin shrinkage which is related to the resin system. High levels of shrinkage are mostly a problem for cosmetics and not mechanical properties, although shrinkage can affect moisture and chemical resistance. The use of styrene based gel coats can lead to "print-through", which is when the fabric architecture showing through and in the surface of the gel coat. The problem of "print-through" is amplified in infusion due to the high fiber volume fractions (Ankarbjork, 2005) and the fact that the laminate stack cures all at once as opposed to open molding in which successive layers cure in succession. Epoxy resins are known for their relatively low shrinkage, while vinyl ester and polyester resin systems can shrink as much as 7% to 10% by volume (Cao & Lee, 2003).

Excess moisture in a resin system can exacerbate shrinkage issues. Airborne moisture can be absorbed by resins if they are subjected to high humidity levels for

extended periods of time (Summerscales, 1994, p.940). Epoxies have demonstrated the ability to increase weight by several percent due to moisture uptake (Summerscales, 1994, p.940). Moisture uptake rates for particular resin systems are a function of relative humidity, temperature, and time. High relative humidity and temperature increase the moisture uptake rate (Summerscales, 1994, p.940). Moisture in resin can also be a result of condensation on the inside of a cool resin drum. For this reason resin drums should be stored sealed and at temperatures above the dew point. Relative humidity should be kept below 80% (ABS, 2006).

Studies suggest that print through can be controlled by using proper materials and layups. Yang and Lee (1999) claimed that using gel coat and veil can substantially improve surface quality. They used the roughness average to quantify the surface smoothness laminates with and without gel coat and veil. The roughness average is a quantitative measure of gel coat surface smoothness with lower values corresponding to smoother surfaces. They found that the surfaces of polyesters were much smoother than vinyl esters without gel coat or veils. This was attributed to the lower shrinkage characteristics or the low-profile DCPD polyester resin used. The use of gel coat substantially decreased the roughness average of both systems, and the use of a veil decreased the measurement even further. The work of Ankarbjork (2005) agrees with these findings, but he goes further stating that using low profile resins along with barrier coats and veil will "efficiently stop fibre print-through in the gelcoat." He concluded that given the current state of technology the mold surface is the limiting factor in surface quality for infused composites.

2.3.4 Fiber Orientation Problems

Since most reinforcement fabric in high-strength composites applications is oriented to take advantage of its anisotropic nature (having different mechanical properties in different directions) deviations in this alignment can have significant consequences. Variations in fiber orientation will lead to variations in material properties, therefore control of fiber orientation is an important quality consideration in composites manufacturing. Reinforcing fabric can deviate from the intended alignment on a large scale as in roll placement as well as on a small scale in the case of fiber waviness and wrinkles within the roll. The affects of these issues and preventative measures are explained in this section.

2.3.4.1 Sources of Fiber Misalignment

Large scale fiber misalignment can be attributed to geometric changes on the tooling surface, raw material imperfections, or process induced flaws. Geometric changes on tooling surfaces with double curvature such as a boat hull can result in misaligned fibers. In this case fibers can deviate from the axes of loading and this consideration should be taken into account in the design stage. Raw materials can contain skewed fibers as a result of processing or handling problems. Deviations of a few percent were observed in pre-impregnated materials by Potter, Khan, Wisnom, Bell, and Stevens (2008). Process induced flaws are the result of operator error during lay-up. These flaws have an unlimited potential for misalignment ranging from a couple of degrees off due to impreciseness up to 90° off because misread drawings.

Small scale fiber misalignment is in the form of fiber waviness - which can be designed into the fabric as in the case of woven or braided fabric - or wrinkles. In both cases the fibers deviate locally within the fabric. Fiber waviness has been reported to increase longitudinal tensile modulus and shear modulus, but reduce compression strength and modulus (Summerscales, 1994). Winkles could be classified as an extreme case of fiber waviness. Winkles cause stress concentrations and will drastically reduce ultimate strength values depending on the location and severity of the deviation.

2.3.4.2 Effects of Fiber Misalignment

Fiber misalignment has been shown to affect compressive, tensile, and flexural strength and moduli (Pfund, 2008; Wisnom, 1990). Compressive strength and tensile strength affected to a much greater degree than other mechanical properties. However fiber misalignment issues are minimized in laminates with more off-axis plies.

Compression strength is affected by fiber misalignment more than any other strength property. As the fibers become less aligned with the principal stress more shear stress is carried than compressive stress. The degree to which the laminate's compressive strength is affected by fiber misalignment depends on the ratio of compressive strength to in-plane shear strength. Wisom (1990) calculated the effects of fiber misalignment on unidirectional carbon/epoxy laminates and concluded that even small angles of misalignment will have a very strong effect on the compressive strength. He cites that a misalignment of 0.25° will degrade the theoretical strength by 32%. This supports the pattern found in the literature of high variability and low compressive strengths for

unidirectional laminates. He postulates that the true ultimate compressive strength may not be able to be measured.

Fiber misalignment has different effects on both the flexural and tensile strengths and moduli. Research published in Professional Boat Builder (Pfund, 2008) demonstrated that intentionally exaggerated fiber skew degraded tensile strength by almost 70%. Flexural strength was less sensitive than tensile, reduced by 23% and 36% for knit and woven fabrics, respectively. The flexural and tensile moduli were affected to a much less extent than the strength parameters. Figure 2.22, Figure 2.23, and Figure 2.24 from Pfund's (2008) article provide examples of the sensitivity of strength and stiffness to fiber misalignment.

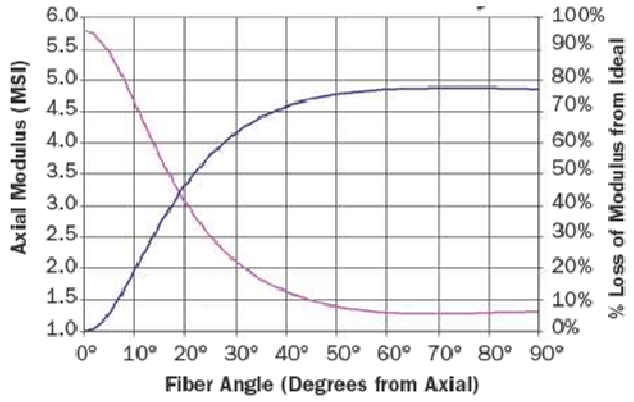

Figure 2.22 Fiber Angle vs. Axial Modulus of a Glass Unidirectional (Pfund, 2008)

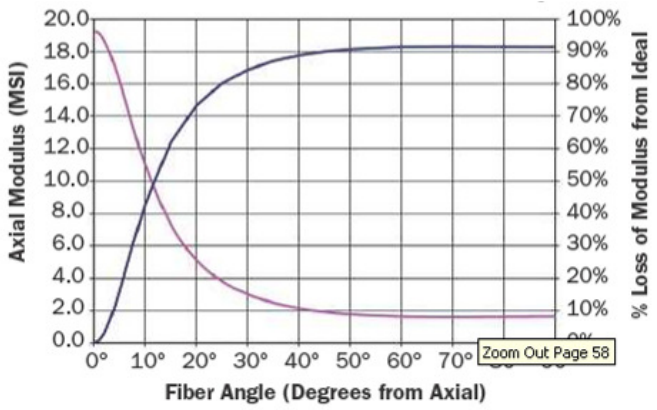

Figure 2.23 Fiber Angle vs. Axial Modulus of a Carbon Unidirectional (Pfund, 2008)

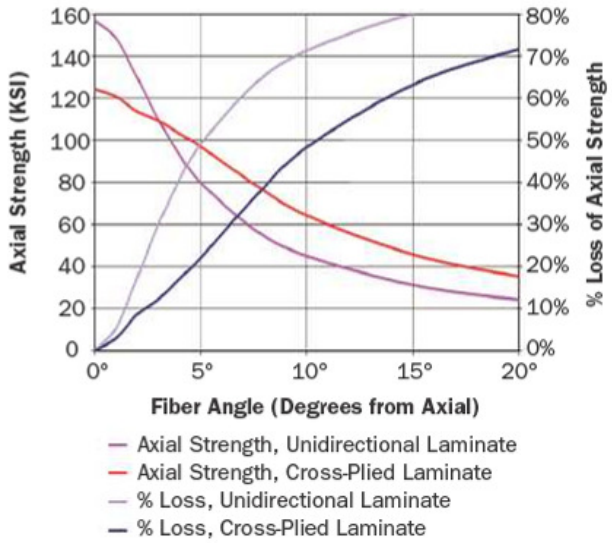

Figure 2.24 Fiber Angle vs. Axial Strength (Pfund, 2008)

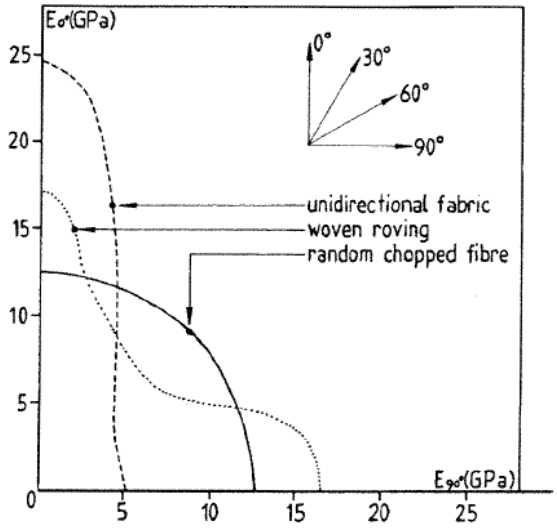

Figure 2.25 Modulus Dependance on Angle for Three Fabrics (Summerscales, 1994)

Unidirectional laminates are most sensitive to fiber orientation while random mats are not sensitive at all (random mats are quasi-isotropic - having similar mechanical properties in all directions). Increasing the number of off-axis plies decreases the laminates sensitivity to fiber orientation at shown in Figure 2.25 from Summerscales (1994).

2.3.4.3 Preventing Fiber Misalignment

Fiber misalignment can be avoided by eliminating defective material with fiber damage and by assuring that fabrics are placed within the mold at the proper orientations. One method for addressing fiber misalignment is the use of an automatic ply verification system. Blake, Purse, Talone, and Trudeau (2004) describe such a system which provides in-process quality monitoring by automatically verifying ply presence, location, material type, and fiber orientation using a laser projection system which provides a "template of light" to guide the manual placement of composite plies. The low-tech alternative is in-process inspection of laid fabric by quality control personnel.

2.3.5 Delaminations

A delamination in polymer matrix composites occurs when two adjacent plies of a laminate not being joined. This results in reduced mechanical properties due to the inability of the laminate to function as a single component. Delaminations can be the result of geometric discontinuities, sustained damage, or manufacturing errors.

Most delaminations are the result of geometric discontinuities which result in interlaminar stress concentrations (O'Brien, 2001). Figure 2.26 from the ASM Handbook on Composites (O'Brien, 2001) illustrates these common geometric discontinuities, including free edges, internal and external ply drops, sharp corners, integral stiffeners, and solid-sandwich laminate transitions. Delaminations are of most importance in parts subjected to cyclic loading due to the increased chance of crack growth, but materials with high interlaminar toughness will exhibit better delamination tolerance.

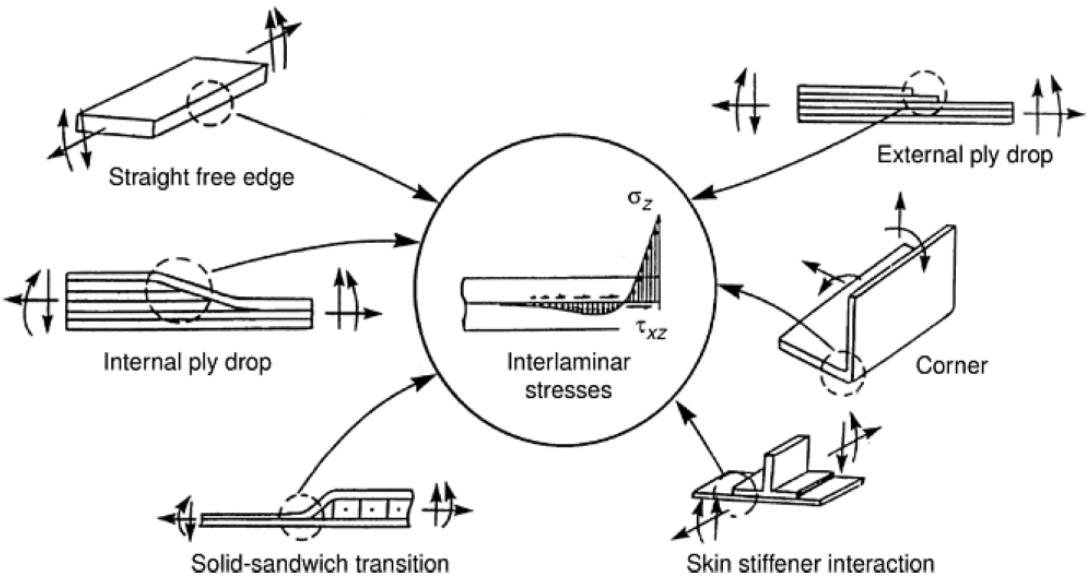

Figure 2.26 Common Delamination Locations (O'Brien, 2001)

Delaminations can also be the result of manufacturing errors. Foreign inclusions and reinforcement contamination can result in manufacturing induced delaminations. This will reduce the ability of the reinforcement to form a proper bond between layers. Summerscales (1994) identified common sources of inclusions in manufacturing environments as pre-impregnated backing, general debris, safety gloves, and even the operator's lunch. Vacuum bag or peel ply, butyl tape and tape backing, hose fittings and anything else which happens be laying around the laminating area are also potential inclusions. Common substances which could contaminate the reinforcement surface leading to delaminations include silicon lubricants used on power tools and pneumatic devices, dust and dirt, excessive tack spray, and other oily materials.

Delaminations are most detrimental at free edges or where the delamination is exposed to the surface. Interlaminar tensile stresses which lead to crack propagation have been shown to decrease away from free edges. Isolated delaminations located away from plate edges have been shown to have little effect on tensile strength if not occurring with matrix cracking (Lagace & Cairns, 1987). A plate width to thickness ratio of thirty results in negligible interlaminar tensile stresses (Sun & Zhou, 1988). Stacking sequence has been shown to influence the tensile strength of laminates with edge delaminations. Since delamination breaks a laminate down into sub-laminates, which have their own individual stiffness, strength, and stability parameters, the resulting delaminated properties are dependent on the order and arrangement of these plies.

Delaminations have been shown to have the effect of reducing compressive and tensile moduli and strengths. Compressive strength is more sensitive to delaminations

than tensile strength. Delaminations are more detrimental for highly anisotropic laminates, due to the high strain concentrations (O'Brien, 2001).

To reduce the initiation of delaminations at geometric discontinuities laminate steps should be tapered. The American Bureau of Shipping (ABS) which publishes shipbuilding standards requires that all transitions be tapered by at least a 3:1 slope, but the more gradual the transition the better (ABS Rules for Materials and Welding, 2006, Pt. 2, chap. 6, sec. 2, §3.3); for instance repairs are tapered at a 12:1 slope (ABS Rules for Materials and Welding, 2006, Pt. 2, chap. 6, sec. 6, fig. 1a).

2.3.6 Secondary Bonding Problems

Issues with secondarily bonded composites joint can lead to joint failure. Secondary bonding is laminating or bonding a new laminate to a fully cured surface. Common applications in marine construction include the hull to deck joint, the bulkhead attachments, and stringers. This is often necessary in construction due to the size and shape of some of the fabricated parts. Investigations into secondarily bonded marine joint failures revealed that filleted joints increase the strength of right angle joints, bond performance is highly dependent on surface preparation, and a chopped strand mat provides a better secondary bond surface than woven roving (Greene, n.d.).

Researchers have studied the effects of abrasion and peel ply as methods of surface preparation for secondary bonds. Matienzo, Venables, Fudge, and Velten (1985) identified the objectives of surface preparation as minimizing contamination from release agents and handling, and increasing the surface area by roughening to provide increased mechanical bonding area. They investigated the effects of silicon contamination on the

bond by performing lap shear strength tests. Surface preparations included sanding with 180 grit paper and passing a water-break-free test (observing water poured over a surface to identify irregularities); polyester peel ply; and nylon peel ply. Findings show that abrasion resulted in lap shear bond strengths more than ten times stronger than unprepared specimens. Both polyester and nylon peel ply protected surfaces resulted in even higher strengths than the abraded specimens. This is attributed to the fact that application of peel ply results in a rough surface. Also nylon peel ply was found to be completely effective in eliminating surface contamination. ABS recognizes the importance of surface preparation in secondary bonding by requiring all surfaces to be sanded, cleaned and dry before commencing bonding.

2.4 Resin Infusion Process Parameters

This section outlines the main process parameters - or variables - of resin infusion which must be controlled in order to produce quality products. While Section 2.3 discussed the issues which affect composite performance such as voids, curing problems, delaminations, etcetera; this section deals with the controllable process parameters which can lead to these aforementioned problems. Having an understanding of the resin infusion process parameters is important, because most of these parameters do not lead to defects directly, but rather through an indirect route. For example high resin viscosity will not in and of itself lead to reduced material performance, however when used in resin infusion, the resin will not flow far and could lead to substantial dry spots which in turn will drastically reduce mechanical performance.

PMCs are an engineered product, meaning that the material properties are a function of not only the raw materials but also the manufacturing process. In metal structures, one company produces the material in the form of sheets, plates and beams, while another assembles these materials into a structure. The former company is responsible for the material properties and the later for the structural properties using their different manufacturing processes. In the case of PMC construction the material properties and the structural properties are part of the same process and are the responsibility of the same company (Edwards, 1985). This means that there is greater opportunity for errors which could affect the performance characteristics of the material and that the manufacturer should understand the variations of the process.

At the center of resin infusion technology is the concept of flow of a viscous fluid (i.e., resin) through a porous medium (i.e., reinforcement). This behavior was first observed and described by the French engineer Henry Darcy in 1856, and is predicted by Darcy's Law given in Equation 2.10 (Hoebergen, 2001).

Equation 2.10 Darcy's Law (Hoebergen, 2001)

$$v = \frac{Q}{A} = \frac{K \cdot \Delta P}{\mu \cdot \Delta x}$$

Where,

v = fluid infusion velocity

Q = Volumetric fluid flow

A = cross sectional area of laminate

K = Media Permeability

ΔP/ Δx = Pressure Differential over a distance

μ = Fluid Viscosity

While it is very difficult to use this equation to directly predict and measure permeability because of the challenges in controlling all the variables, some important relationships can be extracted from it. In terms of resin infusion this law states that the resin flow is directly proportional to the reinforcement permeability and the pressure difference between the inlet and vent, but inversely proportional to the resin viscosity. This means flow speed will increase whenever (1) reinforcement permeability increases, (2) the pressure differential increases, or (3) the resin viscosity decreases.

2.4.1 Permeability

Permeability is a geometric parameter of the laminate which quantifies how easily fluid will flow through it, higher permeability leads to higher flow rates. This geometric parameter takes into account the amount of open space within a unit area of laminate cross section (porosity) and the surface area of the sides of the flow channels which are present. Porosity is the amount of void space in the laminate and is related to fiber volume fraction (Porosity = 1 – Fiber Volume Fraction) (Lopatnikov, Simacek, Gillespie, & Advani, 2004).

Permeability in resin infusion has been particularly difficult to predict and measure for a number of reasons. Firstly, fabrics with the exact same weight and designation can have a significantly different microstructure which can have large impacts on the reinforcement's permeability (A. Cocquyt, personal communication, May 2010). Secondly, resin infusion introduces variations in permeability during the infusion due to the compaction and decompaction of the laminate stack under vacuum. The reinforcement stack has a stiffness which resists compression caused by the atmospheric

pressure. During the course of the infusion the internal pressure changes which leads to changes in the permeability of the laminate stack. At the beginning of the infusion the laminate is compacted and has a lower permeability than after resin wets out the laminate and the local pressure decreases. Thirdly, permeability is difficult to measure because of the number of variables to control is large. Conversations with Andre Cocquyt regarding his research into developing standardized test methods for measuring permeability revealed that the variables which need to be controlled for conducting such a test are highly sensitive and hard to control. Variables like the specific fabric and its orientation and micro-architecture, the resin viscosity, and the infusion pressure are all very difficult to measure with the precision required to obtain meaningful permeability value calculations. Even though the exact permeability is a difficult parameter to measure accurately in the production environment, it can be measured relatively and used in the shop. The easiest method for approximating permeability is to conduct a test against a material of known permeability. Permeability values of typical infusion fabrics and hoses are given in . The permeability of the unknown fabric can easily be determined by performing two identical line infusions with the only variable being the two materials. The infusion times (t_{known} and $t_{unknown}$) for a given distance of the known and unknown materials are recorded. The permeability of the unknown material can be approximated as $K_{unknown}= K_{known}*t_{known}/t_{unknown}$. Variability in the permeability of an infusion layout is the root cause of most dry spots in resin infusion. Following are some specific problems related to permeability which lead to these dry spots.

One permeability problem is that the permeability is too low within the laminate cross section for resin to flow through at an acceptable speed. Distribution media is used

to overcome low laminate permeability by creating a three dimensional flow progression. Distribution media is simply a high permeability layer within the laminate stack allowing the resin to flow faster. Once the resin arrives at a specific location via the distribution media, it is able to flow through the thickness of the laminate, which generally has a much lower permeability than in the plane of the laminate. The method of flow progression was illustrated on page 10 in Figure 2.6.

Consolidation and compaction of the laminate layer affect fiber volume fraction as discussed earlier in section 2.3.2.1 Causes of the Thickness Gradient, and according to the Carmen-Kozeny model they in turn affect the permeability. This becomes a complex problem due to the pressure gradient present in resin infusion, which causes the permeability to not only vary in laminate space and orientation, but also with time. Studies have shown that woven and bi-axial mats are less sensitive to compaction than random mats leading to a more consistent permeability (Yenilmez & Sozer, 2009).

Racetracking is a term commonly used to describe an area or channel within the resin infusion layout with high relative permeability. Resin flow favors the path of least resistance causing drastic changes or variations in local permeability to have great influences on flow front progression. Feed lines are a good example of intentionally high local permeability allowing resin to quickly reach the intended area. Examples on unintended common sources of racetracking include vacuum bag bridging in female corners, core separation, laminate schedule transitions, and gravity induced racetracking.

To address these racetracking issues the following options are available. Racetracking occurs in female corners because the bag is not pushed tightly into the

corner to compact the laminate. This separation of the bag from the laminate creates a feed channel. Avoiding the problem is as simple as working the bag securely into negative corners during draw down eliminating any open space. Core layers should be tightly nested together and preferably filled with a bedding compound to prevent racetracking between core layers. Even tightly nested cores have a tendency to shift during drawdown causing unseen channels of high permeability. Laminate schedule transitions can also affect the permeability and for this reason it is usually beneficial to run a feed line along these contours. Treating separate areas of the laminate as distinct infusion zones will lead to fewer unexpected flow patterns. When infusing a laminate with a vertical profile it is recommended to infuse from the bottom-up rather than from the top-down. The reason for this is two pronged. Firstly, a bottom-up approach will eliminate the tendency for racetracking by using gravity to slow the resin down. Secondly, it will push any residual air up out of the cavity rather than trapping it. So in a boat hull it is recommended to infuse from the keel to the gunwales (Hoebergen, 1999).

The permeability of cores for infusion is a consideration in resin infusion. They should be perforated to allow pressure and flow equilibrium between opposite sides. Groves can be used as feed channels to increase permeability, but the size and spacing of these groves must be accurately controlled. If the grooves are too large or spaced too far apart the squares in the core will be closed off by the flow and will have voids in the center. If they are too small or too closely spaced, they will not serve their purpose as feed channels. Cores can also be cut to allow conformability to complex two dimensional curves such as a boat hull. The problem that arises from cut cores is the creation of a racetrack in the cut as it opens to conform to the contour. The solution is

once again a bedding compound. An alternative method is to use thermoformed cores which are custom fitted to the shape with heat.

The vacuum bag can have the opposite effect as racetracks and can actually choke flow in certain situations. The bag under negative pressure can be pushed down into feed channels which are meant to be left open. Such is the case with a heli-coil feed line which has been stretched out to far. The open spaces between the divided coil walls can be bridged by the vacuum bag reducing the inner diameter and therefore the permeability. This also occurs on the top layer of the laminate. A flexible vacuum bag will be pushed down into the spaces between the fibers on the top layer blocking flow. Usually caul plates, relatively stiff plates used under the vacuum bag to evenly distribute pressure, are used to prevent this minor form of flow restriction.

Another scenario of reduced flow is in male corners, especially in RTM molds. The areas have a tendency to compact around the corner decreasing the local permeability and restricting flow (Bickerton, Sozer, Graham, & Advani, 1998a, 1998b, 1999).

2.4.2 Pressure Differential

The second driving factor of Darcy's Law is the pressure differential. The pressure differential is the difference between the pressure at the inlet and outlet between which lies the reinforcement. Darcy found that there is no flow in the absence of a pressure differential across the porous media and the flow always travels from the higher pressure towards the lower pressure. As Darcy's law demonstrates the flow is directly

proportional to the pressure gradient. Therefore a doubling of the pressure differential will result in a doubling of the resin flow, and consequently the infusion speed.

Since the pressure differential is the driving force in VIP, vacuum integrity is essential to a problem free infusion. Vacuum bags are easily compromised by incorrect handling, storage, and application conditions. Bags should be stored protected and in an enclosed package. Grinding should be avoided when vacuum bags are present. Bags should never be set the floor or any other dirty surface. Once in place, never set sharp objects, such as scissors or clamps on the bag. The bag should be protected from clamps by wrapping them with cloth or suspending them so they do not come in contact with the bag. All these precautions will help prevent pin holes in the bag which are notoriously hard to locate, but are still capable of negatively affecting the infusion.

Performing a drop test is the only method of verifying a sound vacuum has been achieved. A drop test involves isolating the cavity under vacuum for a set period of time and measuring the change in cavity pressure. If there are any significant leaks in the bag or the mold the absolute cavity pressure will steadily increase. Standards for acceptable drop rates are given in pressure drop per period of time. There is a lack of published standards for acceptable drop rates, but a drop rate of 1”Hg in 5 minutes is considered acceptable for most parts (Hoebergen, 2001). Larger parts should meet a stricter standard of 1”Hg in 15 or 30 minutes depending on how large they are (A. Cocquyt, personal communication n.d.).

A major source of leaks is through the tooling and through the vacuum seal. Molds which are converted from open molding to be used in resin infusion must be

vacuum tight. This is verified by bagging the mold using only a breather material under the bag and performing a drop test. If the bag seals are airtight then any leaks will be a product of the mold. Problem areas on molds are screw and seam locations where the mold may have been joined together. Often a leaky mold can be fixed with the application of a gel coat. Vacuum seals should be checked with an acoustic listening devise to detect the presence of leaks. Pleats, where the bag has been folded over to account for complex geometries, are the location of most of the leaks in the vacuum seal. Stray fibers often bridge the vacuum seal and form a straw-like leak under the seal. This can be prevented by cleaning and then keeping covered with tape the area of the mold which will receive the seal until ready to apply the seal (Cocquyt, A. personal communication July 17, 2007).

2.4.3 Resin Viscosity

The final factor of Darcy's Law is the viscosity of the fluid. Viscosity is a measure of a fluid's resistance to shear or flow. Higher fluid viscosities result in lower flow rates. Common vacuum infusion resins are usually between 100cP and 400cP (0.1Pa*s and 0.4Pa*s since 1cP = 0.001 Pa*s). Table 2.4 demonstrates the wide range of viscosity values for common materials.

Table 2.4 Viscosities of Common Materials (cP)

Water	1
Olive Oil	80
Infusion Resin	100-400
#10 Motor Oil	500
Honey	2,000-10,000
Chocolate Syrup	10,000-25,000
Ketchup	50,000-100,000
Peanut Butter	About 250,000

It is important to be able to accurately measure the resin viscosity. It is quite difficult to determine by eye difference between a 200cP resin and a 400cP resin. However, Darcy's law predicts that the infusion speed of the 200cP resin will be twice that of the 400cP resin ceteris paribus; thus the importance of being able to measure the viscosity of the resin. The easiest method for measuring viscosity is with a viscosity cup, a common brand name is the Zahn cup. When these calibrated funnels are dipped into the resin, the time between when the fluid first starts flowing to when the draining fluid starts to break apart from a laminar stream at the base of the cup is correlated to viscosity. One EZ Zahn cups from Paul N. Gardner Supply is usually all that is needed to test infusion resins (Gardco, n.d.).

Viscosity is highly dependent on temperature. As temperature increases, resin viscosity decreases and vice versa. Resins usually respond with a change on the order of 3% to 8% per degree Celsius change in temperature (about 1.6% to 4.4% per degree Fahrenheit) depending on the type (Gardco, n.d., p. 1325). A rule of thumb is a doubling of viscosity for every drop of 17°F in styrenated resins. Epoxy resins are in general more sensitive than styrenated resins, doubling viscosity with a decrease of only 10°F (A. Cocquyt, lecture, July 16, 2007). Resin temperature should be checked prior to infusion. This can be done with an inexpensive handheld infra-red thermometer.

Of importance in addition to the temperature of the resin itself is the ambient temperature of the shop and the temperature of the tooling. The resin will equilibrate to the ambient temperature and if it is stored at temperatures different from the desired processing temperature it will need to be adjusted. It can take a 50 gallon drum of resin a

few days to reach ambient temperature depending on how cold the storage temperature was (CFA, 2001). Controlling the resin temperature and the ambient temperature alone will not help if the mold temperature deviates significantly. Tooling usually has significant thermal mass and will change temperature very slowly. For this reason tooling which is stored below optimal processing temperatures must be warmed up before being used. If room temperature resin is infused into a cold mold the resin will quickly give up its heat to the mold and assume the mold's temperature. Conversely this principle can be used to the manufacturer's advantage; heated molds can be used in environments with below optimal ambient temperatures. Energy is only needed to heat the mold and not the entire manufacturing shop. The infused resin will assume the temperature of the mold and the infusion will proceed predictably. Therefore it is important to control the resin temperature, the tooling temperature and the ambient temperature for repeatable, predictable infusions.

Thixotropic additives are common in open mold resins, but have no place in infusion resins. Thixotropes increase the apparent viscosity of a resin allowing it to resist sagging and flowing, a necessary attribute in open molding. This will however have the effect of increasing the viscosity and therefore the infusion speed when used in resin infusion.

2.5 Summary of Resin Infusion

This chapter provides an overview of the forms, history, environmental aspects, and applications of resin infusion; followed by an in depth explanation the sources,

effects, and preventative measures for major manufacturing induced defects in composites; and lastly addresses the key process parameters of the resin infusion process.

The three major process variables of resin infusion which are explained in section 2.4 “Resin Infusion Process Parameters” are (1) laminate permeability, (2) pressure differential, and (3) resin viscosity. Understanding and controlling these variables will lead to predictable and repeatable resin flow progression during resin infusion. Failing to understand and control these variables leads to incomplete infusions and dry spots which can be costly and sometimes difficult to repair.

In the resin infusion method many of the same defects that occurred in open molding manufacturing are still a threat, however the sources and means of preventing them often take on a different face. The defects addressed in this section include (1) voids and dry spots; (2) thickness and fiber volume fraction variations; (3) resin curing problems; (4) fiber orientation issues; (5) delaminations; and (6) secondary bonding issues. A summary of section 2.3 “Sources, Effects, and Prevention of Composites Defects” is provided in Table 2.5 which contains the effects of these defects, the causes, and the appropriate quality assurance and control methods.

Table 2.5 QA/QC Methods for Resin Infusion Defects

Voids

(Sec. 2.3.1.1)

Effects:

- Reduced interlaminar shear strength, longitudinal and transverse flexural strength and modulus, longitudinal and transverse tensile strength and modulus, compressive strength and modulus, fatigue resistance and high temperature resistance (Judd & Wright, 1978. p. 13; Ghiorse, 1993)
- 7% reduction in mechanical properties for every 1% increase in voids (Judd & Wright, 1978)
- Most severe for matrix dominated properties (Judd & Wright, 1978)

Source	QA/QC Methods
Fabric structure too non-uniform	• Material pre-qualification (Sec. 3.5.3)
Entrained air due to mixing	• Proper mixing techniques (Sec. 2.3.3.2) • Bubble nucleation (Sec. 2.3.1.1)
Dissolved gasses	• Bubble nucleation (Sec. 2.3.1.1)
Boiling of styrene	• Increasing the absolute pressure of the internal cavity during the post-infusion process (above -28”Hg absolute) (Sec. 2.3.1.1)
Leaks in the tooling or vacuum bag	• Leak check (Sec. 3.6.3) • Drop test (Sec. 3.6.3)

Table 2.6 Continued QA/QC Methods for Resin Infusion Defects

Dry Spots

(Sec. 2.3.1.4 & Sec. 2.4.1)

Effects:

- Eliminates interaction of fibers and resin
- All composite performance properties are reduced

Source	QA/QC Methods
Racetracking	• Proper tooling design (Sec. 2.3.1.5) • Use bedding compound on cores (Sec. 2.4.1) • Proper infusion layout design (Sec. 2.4.1) • Pre-infusion with alcohol (Sec. 2.3.1.5) • Numerically-based computer infusion models (Sec. 2.3.1.5) • Active control systems (Sec. 2.3.1.5) • Semi-porous membrane with breather (Sec. 2.3.1.5)
Bottlenecking	• Proper infusion layout design (Sec. 2.4.1) • Pre-infusion with alcohol (Sec. 2.3.1.5) • Numerically-based computer infusion models (Sec. 2.3.1.5) • Active control systems (Sec. 2.3.1.5)

Thickness Variations

(Sec. 2.3.2)

Effects:

- Significant variations for weight, dimensions, fiber volume fraction, flexural stiffness, and flexural load bearing capacity
- Significant variation in unit properties: tensile, compressive, flexural and shear moduli and strength

Source	QA/QC Methods
Pressure differential between feed and vent ports	• Can eliminate flexible tooling • Post-filling vacuum control (Sec. 2.3.1.1) • Semi-porous membrane with breather over the entire laminate (Sec. 2.3.1.5)
Tooling height variations	• Staged infusion (Sec. 2.3.2.1)

Table 2.7 Continued QA/QC Methods for Resin Infusion Defects

Resin Curing Problems (Sec. 2.3.3)	**Effects:** • Dry spots, print through, uncured sections, tooling damage, reduced mechanical properties	
	Source	**QA/QC Methods**
	Contaminated or expired raw material	• Incoming material inspection (Sec. 3.5.2) • Inventory selection is first-in first-out (Sec. 3.5.4) • Check expiry date before use (Sec. 3.5.4) • Storage in accordance with manufacturer's recommendations (Sec. 3.5.4) • Pre-infusion gel time test (Sec. 2.3.3.2)
	Construction conditions are dissimilar to the material qualification conditions	• Proof test new materials before incorporation into production (Sec. 3.5.3) • Laminating process parameters are specified in standard operating procedures (Sec. 3.6)
	Improper measuring and/or mixing	• Resin and initiator are measured with accurate balances or syringes (Sec. 2.3.3.2) • Proper mixing techniques (Sec. 2.3.3.2)

Fiber Misalignment (Sec. 2.3.4)	**Effects:** • Most significant for compressive strength followed by tensile strength • Affects flexural strength and moduli to a lesser degree	
	Source	**QA/QC Methods**
	Geometric changes on surfaces with double curvature	• Proper part and laminate cutting schedule design
	Operator error	• In-process layup verification (Sec. 3.6.2) • Automatic ply verification (Sec. 3.6.2)

Table 2.8 Continued QA/QC Methods for Resin Infusion Defects

Fiber Waviness and Wrinkles

(Sec. 2.3.4)

Effects:

- Fiber waviness increases longitudinal tensile modulus and shear modulus, but reduces compression strength and modulus
- Wrinkles lead to stress concentrations which drastically reduce strengths

Source	QA/QC Methods
Damaged raw material	• Incoming material inspection (Sec. 3.5.2)
Operator error	• In-process layup verification (Sec. 3.6.2)

Delaminations

(Sec. 2.3.5)

Effects:

- Reduced flexural and shear strength and moduli
- Poor performance in cyclic loading

Source	QA/QC Methods
Foreign inclusions	• High standards of cleanliness in the laminating environment (Sec. 3.4.5.2)
Contaminated surface	• Protect surface prior to lamination (Sec. 3.6.1)
Geometric discontinuity	• Proper part design (Sec. 2.4.1)

Secondary Bonding

(Sec. 2.3.6)

Effects:

- Failure of the bonded joint

Source	QA/QC Methods
No mechanical bonding	• Standard operating procedures for surface abrasion (Sec. 2.3.6)
Contaminated surface	• Protect surface prior to bonding (Sec. 2.3.6)

Chapter 3

QUALITY ASSURANCE AND QUALITY CONTROL

3.1 Introduction

Currently an industry standard for quality assurance and quality control in resin infusion does not exist. Therefore this chapter explores the industry best practices available to resin infusion manufacturers for quality assurance systems and quality control methods. The chapter begins in section 3.2 with a brief historical background of QA/QC approaches in manufacturing and definitions of the terms "quality assurance" and "quality control." This is followed by a description of a three-tiered system of quality assurance implementation in composites manufacturing developed by Bishop (1991) in the early 1990's. Working with Bishop's research as a basis, the remaining sections describe the elements of a QA/QC system that is appropriate for resin infusion: (1) the quality management system, (2) incoming material inspection, (3) in-process controls, and (4) final part validation testing. The first addresses the overall approach and system of quality practice implementation while the latter three focus on the specific stages of manufacturing.

An internationally recognized quality management system and international composite shipbuilding standards were used as the basis for the QA/QC best practices contained in this chapter. In regards to a benchmark quality management system, the ISO 9000 series is regarded as the international standard and is widely used and accepted in many industries. Key elements of ISO 9001:2000 include a focus on the customer, continuous improvement and process and systems approaches to management.

International composite shipbuilding standards are published by marine vessel classification societies. The American Bureau of Shipping (ABS), Lloyd's Register (LR), Det Norske Veritas (DNV), and other classification societies have been overseeing the construction of FRP vessels and holding builders accountable to industry best practices for many years. While these standards were developed for open molding FRP vessel construction, most of the general building process remains the same for resin infusion, and thus the process controls are similar as well. Many of the elements of a quality management system are specifically required in the classification societies' published rules.

3.2 Quality Assurance and Quality Control Defined

Quality is a commonly misunderstood concept due to presence of the many definitions and implications it carries. Until WWII most manufacturers inspected finished parts for quality, focusing on eliminating defective products from reaching the customer. WWII marked the beginning of a shift in approach to quality with a focus on the process and eliminating defective products from being made. Many of the leaders of this quality movement of the latter half of the 20th century emphasized different aspects of this philosophy. Crosby (1979) focused on the cost of quality and defined it in terms of conformance to requirements. Juran (1988) focused his work on quality management, but defined quality as a product's fitness for use, this being measured by quality characteristics. W. Edward Deming (1986) understood the importance of approaching product quality within the context of the production system. He advocated for an appreciation of the system through understanding how all the components interact and influence each other. He even went so far as to estimate that 94 percent of product

variations are the result of the system, with the 6 percent remainder being the responsibility of the individual worker or the faulty machine. His systems approach, allied with a use of statistical process control, earned Deming's philosophy the accolade of being classified as one of history's nine hidden turning points (Boorstin & Parshall, 1991). This new quality philosophy is perhaps aptly summarized as continuous improvement and control of the production system in order to satisfy customers' requirements.

It is out of this new quality philosophy that the concept of quality assurance was borne. A recent ASCE-ACMA (2010) publication defines quality assurance as "the administrative and procedural requirements established by the contract documents to assure that the constructed composite components and system is in compliance with applicable standards, contract documents, and manufacturer's quality control program." Compare this with the narrower term quality control, defined as "set of activities instituted by the designer, manufacturer, or contractor intended to insure that the constructed work meets the quality requirements" (ASCE-ACMA, 2010). Prior to the quality revolution of the last century most manufacturers were practicing quality control without quality assurance. Quality assurance today most often finds its manifestation in the form of a quality management system or a quality assurance manual which is the communication of the planned and systematic activities a company adopts in the pursuit of quality.

3.3 Three Levels of Quality Assurance for Composites

A desired outcome of this research was practical recommendations to composites manufacturers regarding appropriate levels of QA/QC implementation. Recognizing that not all manufacturer's needs were alike a tiered system of QA/QC recommendations was proposed as a means of presenting different levels of practices. In this way manufacturers could choose from different levels of increasing QA/QC rigor depending on their needs. The literature review failed to uncover implemented programs in which composites QA/QC recommendations are being adopted at distinct levels based on the manufacturers need. However such a program was proposed for the composites industry by Bishop (1991) in the 1990's. A personal conversation with Bishop indicated that his proposed systems were never implemented, however the recommendations and structure of the research proved a valuable starting point for this research. His work will be used to provide a framework for structuring the QA/QC practices presented in this chapter and as a basis for the recommendations presented in the next.

Bishop (1991) conducted an enquiry of small and medium-scale enterprises (SMEs) involved in the production of reinforced plastics. This enquiry sought to "…elucidate the extent to which the SMEs concerned have developed quality-mindedness… (p.18)" Bishop found that "…only a few [composite manufacturing companies] indicated that they really apply quality assurance procedures (p.18)." Bishop found that companies desired guidance relating quality assurance methods with the function of the manufactured product. This stemmed from the fact that often they either had no customer specifications or on the other extreme had customers demanding complex and expensive tests that the manufacturers considered unnecessary. Bishop

concluded that it would be helpful to introduce classification criteria which would correlate the function of the product to the level of quality assurance required for its production.

Prior to proposing any classification criteria Bishop emphasized the necessity of precise product specifications. These specifications must cover the list in Figure 3.1 according to Bishop (1991).

- basic function of the object to be produced
- outer dimensions
- outer geometry
- service temperatures (maximum, minimum, and variation)
- environmental influences (indoor or outdoor use)
- design requirements governed by function
- load regulations and standards if applicable
- electrical requirements
- chemical resistance requirements
- physical requirements
- standards and regulations if applicable
- performance proof testing
- requirements concerning the definition of design details
- service life

Figure 3.1 Specifications for Composite Materials (Bishop, 1991)

With specifications in place Bishop (1991) defined three categories or levels of quality assurance which depend on the product application and the consequence of its failure. The highest level includes products which are subjected to "extreme conditions where uninterrupted operation is required (p.19)" and products which would upon failure endanger human life or lead to very expensive repairs. Level three is reserved for high performance products which cannot fail. Level two is for products which may have a similar application to level three, but failure would not endanger human life. This level includes products which must meet specific performance properties such as chemical resistance, mechanical properties or surface quality. Level one is the base level for

quality assurance which encompasses all other composite products. This level includes products subjected to normal conditions and failure of which would result in minor or inexpensive repairs with no risk to human life. It is the recommendation of Bishop (1991) that level one is the minimum for quality assurance regardless of the product application. Examples of quality procedures for these three levels are outlined in Figure 3.2, Figure 3.3, and Figure 3.4.

Level One includes basic incoming material verifications, basic in-process controls including verifying key parameters, and basic visual inspection for final part validation.

Quality measurements	Test method
Material in	
Check for correct material	Visual inspection
Record batch number	Visual inspection
Inspect for damage	Visual inspection
Processing	
Correct ambient temperature (refer to supplier's recommendations)	Thermometer
Correct resin mix	Accurate weighing
Adequate mixing	Visual inspection
Reasonable standard of cleanliness	Visual inspection
Adequate drying	Visual inspection
Lay-up of one layer of glass at time	
Record operator's name	
Final part inspection	
Inspect for faults, voids, delaminations, inclusions, air bubbles, surface quality	Visual inspection
Defects, colour variation, channels	Visual inspection
Check dimensions	Tape rule

Figure 3.2 Level One Quality Assurance (Bishop, 1991)

Level Two incorporates advanced requirements beyond those of Level One. It adds general requirements for equipment and documentation. Incoming materials are not

only visually inspected, but is also tested to ensure conformance with specifications. These incoming tests include gel time and viscosity for resin and areal weight and thorough visual inspection for reinforcements. There are also storage requirements for materials. In-process controls are more thorough than Level One including inspections at key manufacturing points and verifications of material expiration dates. Layup is required to be performed in a dedicated area and reinforcements are required to be protected from contamination at all times. Level Two also requires the manufacture of a witness panel for destructive testing. Final inspection goes beyond visual inspection only including random destructive tests and non-destructive tests when appropriate, fiber content, degree of cure, and dimensional tolerance checks which are verified with precision equipment.

Level Three is the highest level of quality assurance proposed by Bishop (1991). This level requires equipment calibration on short intervals, that each stage of construction is checked by the QA inspector, and that the QA inspector is independent of the production personnel. Additional incoming material tests are proposed for reinforcement and resin beyond Levels One and Two. Additional in-process controls include ply checks for each ply as it's laid down and humidity control in the manufacturing environment. Final part inspection includes non-destructive evaluation of each component and extensive destructive evaluation of witness panels for each component.

Quality assurance	Test methods (where applicable)
All procedures as for level 1 plus the following	
General requirements	
All test and recording equipment to be calibrated at specified intervals. Ensure production data sheet contains all data from materials in through processing to final part inspection	
Ensure component is being produced to current drawing/specification	
Materials in	
Weight and dimensions of reinforcement	Accurate balance
Ensure certificate of conformity received	Measuring instruments
Testing of resin viscosity and gel time	
Use material in correct rotation, i. e. oldest first	
Store at recommended condition for temperature and humidity	
Inspect reinforcing material for damage or inclusions	Back lighting
Processing	
Ensure laminate lay-up sequence is correct	
Check expiry date of materials	Visual inspection
Allow sufficient time to check correct processing	
Operators to use clean gloves	
Preparare glass cloth in separate rooms	
Glass to be protected from contamination during cutting and handling in storage	
Maintain high standards of cleanliness	
Maintain correct ambient temperature	Thermometer
Prepare test panel under same conditions as component	
Final part inspection	
Materials testing to be conducted on random components	Tensile, flexural, chemical, impact, NDT, electrical (if required)
Fibre concentration	Burnoff
State of cure	Barcol hardness
Check dimensions	Metrology

Figure 3.3 Level Two Quality Assurance (Bishop, 1991)

Quality assurance	Test method (where applicable)
All procedures as for level 2 plus the following:	
General requirements	
All test and recording equipment to be calibrated at short intervals	
Each stage of production to be certified by qualified O. A. inspector Quality control personnel to be independent of production personnel	
Material in	
Determine binder solubility of fibre mat	Time to break for weighted mat in styrene
Verify construction of woven roving	Determine warp and weft ends per specified unit
Resin	Determine acid content viscosity and gel time
Processing	
Check each ply, as ist is layed, against laminate sequence	
Record change of operator or shift change	
Maintain recommended humidity	
Final part inspection	
Fault detection to be performed on each component	N. D. T., ultrasonic, x-ray
Mechanical testing to be performed on samples produced at the same time as the components, preferably on sample off-cuts from each component	As for class II

Figure 3.4 Level Three Quality Assurance (Bishop, 1991)

The recommendations Bishop (1991) gives for quality assurance practices are broken down into four categories: general requirements, material in, processing, and final part inspection. These categories form the basis for the layout of the remainder of

this chapter: Quality Management System, Incoming Material, In-process Control, and Validation Testing.

3.4 Quality Management System

A quality management system is described as "the collection of processes, documents, records, and monitoring systems that direct the work of an organization regarding product…quality" (Simply Quality, 2001). A successful quality management system (QMS) is the overarching framework into which all quality assurance and quality control practices fit. The aim of a good quality management system is to satisfy customer expectations by implementing repeatable processes and systems which are continuously monitored, analyzed, and improved. The value of such a system is that it provides a visible sign and tangible records of achieved product quality. The QMS can be as simple as a written quality statement and a list of quality control practices or as advanced as a certified ISO 9000 system depending on a company's needs. The essence of quality assurance is the customer's assurance of the capability of producing quality products.

The basis for the quality management system are documented procedures which describe how quality requirements will be met. These written procedures are summarized in a quality assurance manual. This is not unlike the Building Process Description which is required by classification societies for classification of marine vessels. It describes the level of quality required and a comprehensive list of activities used to achieve this level of quality. A robust quality assurance system will address the categories listed in Figure 3.5 which has been derived from the ISO 9000 quality

management system (Badiru, 1995). The non-production related important elements of a QMS are expounded in this section.

- Management Responsibility
- Quality System Documentation
- Contract Review
- Design Control
- Document Control
- Purchasing
- Control of Purchased Product
- Product Identification and Traceability
- Process Control
- Inspection and Testing
- Control of Inspection, Measuring and Test Equipment
- Inspection and Test Status
- Control of Nonconforming Product
- Corrective and Preventative Action
- Handling, Storage, Packaging, and Delivery
- Control of Quality Records
- Internal Quality Audits
- Training
- Servicing
- Statistical Techniques

Figure 3.5 Elements of a Quality Management System

3.4.1 Management Responsibility

The key to a successful quality management system is the full support of top management. They must value customer satisfaction above production numbers and cost. Striving for increased quality will in turn improve production numbers and lower cost, but not the other way around (Crosby, 1979). Upper management is specifically responsible to communicate the customer's requirements and expectations to all involved with producing the product and must allocate sufficient resources to meet these requirements. They are responsible for the development and maintenance of the quality management system and for establishing the quality policy and objectives. Maintenance of the quality management system involves regular review of the suitability, adequacy, and effectiveness of the system.

Management should delegate a quality assurance representative who has the authority and responsibility to ensure compliance with the requirements of the system. All personnel have the responsibility of identifying, controlling and assessing quality, but there must be one person to oversee and manage the system. It is preferable for the representative to have no other responsibilities beyond quality assurance (ABS, 2006); however this may not be practical for smaller organizations. It is important that the representative be free of production responsibilities as shown in Figure 3.6. This could be construed as a conflict of interest having the production manager double as the quality assurance representative. It may be necessary for some in-process inspections or quality control tasks to be performed by production staff, but these must be supervised or checked by the quality assurance representative (ABS, 2006).

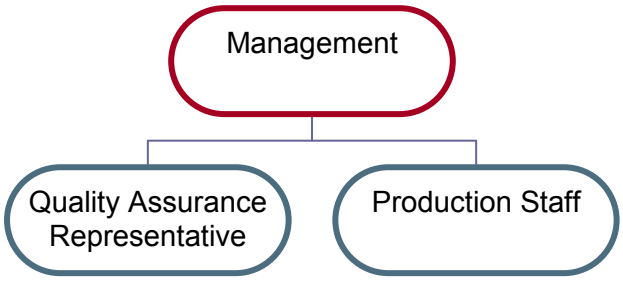

Figure 3.6 Organizational Structure

3.4.2 Continuous Process Improvement and Internal Audits

No system or process is perfect and without a means of continuous process improvement, quality will over time degrade and will fail to consistently meet customer quality requirements. Continuous process improvement includes early detection of problems, identifying and prioritizing opportunities for improvement, review of existing processes, and the establishment of long term quality goals (Badiru, 1995, p. 61). Since employees are often more qualified to make suggestions for process improvement than

management it is important to emphasize that continuous process improvement is a company wide responsibility and to provide means by which employees can make improvement suggestions.

A tool for the implementation of continuous process improvement is corrective action process. The corrective action process identifies problems, determines the underlying reason, and modifies the existing procedures to prevent reoccurrence. Whenever there is an incident in which quality standards are not met, a Corrective Action Request Form is filled out by any employee. The form documents and describes the nature of the incident. A subsequent investigation into the root cause of the problem will aid in discovering if there are any shortfalls in the processes. If the root cause can be addressed by altering the process, then changes to the appropriate SOPs are made. A lack of corrective action requests demonstrates a failure to continuously improve processes. Figure 3.7 illustrates the implementation of continuous process improvement by using the corrective action process and the corrective action report.

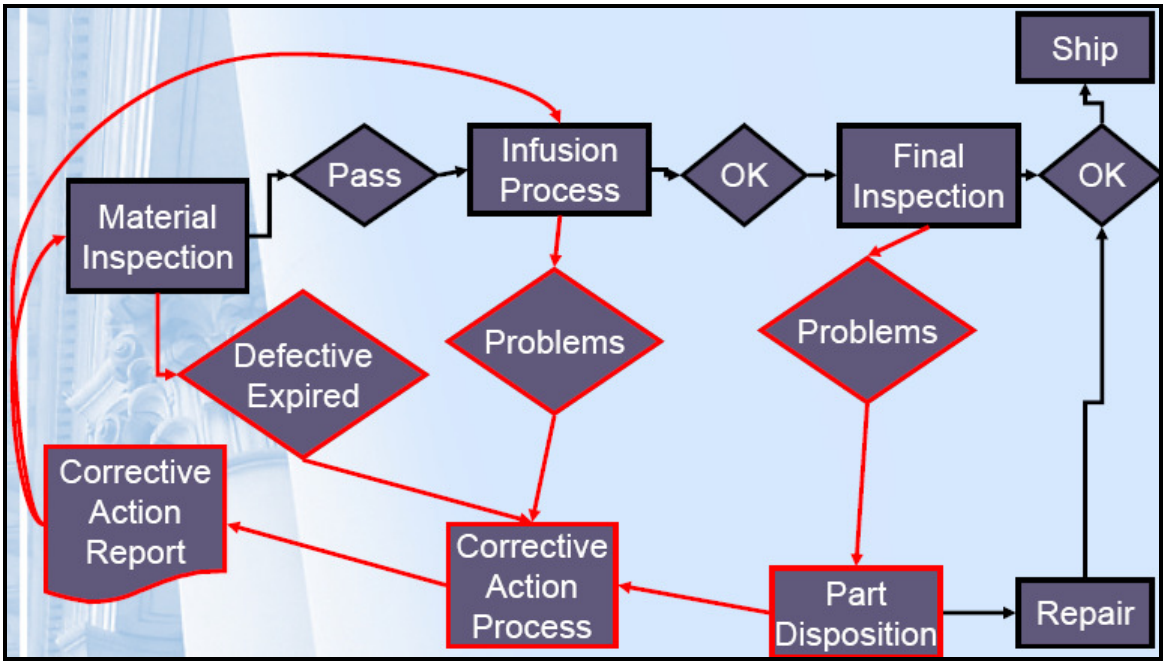

Figure 3.7 Example of a Continuous Process Improvement Implementation

A planned and documented system of internal quality audits needs to be carried out on all quality activities to assure that the current activities are appropriate and are meeting the quality requirements. Not all activities have the same level of importance and therefore do not need the same frequency of inspection, but all activities should be on a schedule and should be audited according to their level of importance. Any shortcoming found by the audit should be corrected through the corrective action process. Internal quality audits are a key element of continuous process improvement.

3.4.3 Documentation and Records

Documentation and records are the evidence of a healthy quality assurance system. Documentation refers to written processes and procedures, such as the quality assurance manual, SOPs, and inspection forms. Records are internally generated completed forms and checklists which track and demonstrate conformance to quality standards. Documentation communicates to employees and customers the way processes

are performed, while records demonstrate conformance to the processes. Without documentation or records, there is no quality system. A list of common records for resin infusion manufacturers is given in Figure 3.8, but should be customized for the specific company and type of manufacturing.

- Design Drawings
- Trained Personnel Records
- Purchase Orders
- Incoming Material Verification Records
- Key Equipment Calibration/Maintenance Records
- Material Non-Conformance Reports
- Fabrication Process Records
- In-process Inspection Records
- Corrective Action Reports
- Final Inspection Records
- Part Disposition Records
- Packaging Records
- Physical Testing Reports

Figure 3.8 Common Records for Resin Infusion

Procedures need to be in place for how records are generated, stored and disposed. Records are generated for the purpose of demonstrating quality compliance and therefore need to be legible, linked to a specific product, and available for review. They should be filed in an organized system and backed up if practical. Since it is often impractical to store records indefinitely a system should be in place which determines the appropriate length of storage time. If agreed upon, records should be available for the customer for review.

Documentation control is an important element of the documentation and record processes. Documentation control refers to the system for updating and distributing modified documents. Documents which are used in the quality assurance system will need to be changed and updated as part of the continuous process improvement process. In an effective documentation control program responsibility of issuing approved

documents is assigned to one person. Only approved documents are used and they should be clearly marked, for example with a red stamp. A master list of approved documents and their locations should be kept on file to enable collection of outdated documents upon revision. When these revisions take place it is important that old versions are quickly replaced with new versions. Each document should contain a section which describes and dates revisions. Documents can be reissued if many changes have been made (Badiru, 1995, p. 73).

3.4.4 Training

Training is an important part of quality assurance for composites manufacturing because material properties are highly dependent on the manufacturing process which is in turn highly dependent on the workers. Training as part of a quality management system must be appropriate for the tasks required of the position and should be recorded. Written job descriptions help determine what level of qualification is necessary for specific tasks be it education, training or experience. Whether training is external or on-the-job it is important to keep records for quality assurance purposes. In resin infusion, production managers should be externally trained or have significant infusion experience. ACMA now offers a Certified Composites Technician - Vacuum Infusion Process certification for the infusion process, which is an industry standard, however there are many other forms of appropriate industry training.

3.4.5 Facilities and Equipment

Classification societies' rules provide benchmarks for laminating environment conditions as well as requirements regarding equipment. Of the three classification society rules reviewed, ABS and DNV contained the most specific recommendations

regarding facility and equipment best practices (ABS: Rules for Materials and Welding, Pt.2 Ch.6 Sec.3 §3; DNV: Rules for HSLC, Pt.3 Ch.4 Sec.2 §B200). The best practices regarding facilities and equipment discussed in this section are divided into the following categories: (1) material storage, (2) laminating premises, (3) tooling construction, and (4) equipment.

3.4.5.1 Material Storage Premises

It is important to have standards in place regarding material storage practices to ensure that the material's quality is not being compromised. Material storage areas should be equipped and arranged to be capable of meeting manufacturer's storage and handling recommendations. This section covers best practices for resin, reinforcement, cores, and vacuum bags.

All materials should be stored inside, out of direct sunlight, in a clean and dry area which is protected from contamination. Temperature and humidity records should be kept for all materials at a suitable frequency (ABS, 2006, p. 110). Ideally material is stored in the original packaging if the packaging is undamaged; otherwise it should be protected against contamination.

Resins, gelcoats, initiators and additives should be stored according to the manufacturer's recommendations including ventilation, temperature, humidity and shelf life limitations. Polyester and vinyl ester resins will usually age faster in warmer environments decreasing the gel time and should therefore be stored in a conditioned space. If the resin drum temperature falls below the dew point there is a risk of condensation buildup on the inside wall of the drum. The presence of this condensed

water in the resin can alter the curing chemistry and should be avoided by maintaining recommended temperature and humidity levels. If resin is stored at temperatures below 65°F it will require acclimation prior to use (DNV, 2008). Many initiators are reactive to a wide range of conditions and materials and should therefore be stored to accommodate these dangers. Flammable liquids should be stored in an electrically grounded container to prevent static sparking.

Cores should be stored in their original packaging to be protected from moisture, contamination and mechanical damage. They should be stored at the same temperature as the laminating environment. Cores that out-gas should be stored according to manufacturer's recommendations to allow adequate out-gassing prior to lamination. New surfaces created from sanding or cutting increase out-gassing and should be given time for out-gassing prior to use (DNV, 2008).

Reinforcement should be stored at laminating temperature and humidity levels, otherwise there is a need for acclimatization prior to use; a minimum period of 48 hours is recommended (ABS, 2006; DNV 2008). Vacuum bags should be stored to prevent puncture and preferably in the original packaging. A vertical or elevated roll rack allows bags to be removed without contacting the floor.

3.4.5.2 Laminating Environment

The major elements of the laminating environment related to quality control for resin infusion are environmental control and cleanliness. Temperature and humidity should be controlled and recorded, and the laminating environment should be kept clean

to prevent material contamination. The laminating area is defined as the location where the lay-up of dry materials and the infusion takes place.

Temperature control is one of the most important parameters in the laminating environment due to its affect on resin viscosity and the resin curing characteristics. Temperature should be maintained between 60°F and 90°F according to ABS Rules for Materials and Welding (ABS, 2006), however of more importance than the specific temperature, is the *variation* in the temperature. It is the change in the temperature which causes resin to perform differently than expected. If the resin was tested and stored at 80°F for example it should be infused at 80°F for predictable results, any other infusion temperature would have unpredictable results. DNV Rules recommend limiting the temperature variation to ±9°F (±5°C).

High relative humidity is a concern in open molding lamination due to resulting condensation, and can have different affects in resin infusion depending on the method. It is generally recommended that relative humidity levels be kept below 80% (ABS, 2006; DNV 2008). Vacuum reduces the amount of moisture in the tooling cavity and is capable of removing it completely if given enough time.

Lamination environment temperature and humidity records should be kept for all laminations. An automated data logger is ideal for this application being capable of continuous temperature and relative humidity measurements; also DNV Rules require one for every approximately 16,000 square feet of lamination area. For tall laminations temperature should be recorded for at least two different levels to capture any temperature stratification (DNV, 2008).

In regards to cleanliness, the laminating area needs to be arranged and equipped such that the material manufacturer's recommendations regarding handling can be followed in addition to laminating and curing requirements (ABS. 2006; DNV, 2008). Any contamination be it dust, oils, other chemicals, tack spray, silicon spray, release agents, etcetera, has the potential of either contaminating the reinforcement or the tooling or both. The laminating area should be free of dust and isolated from all dust generating sources such as saws, sanders, grinders and such. All other contaminants should be controlled and used sparingly or not at all in the laminating environment. Ventilation filtration will reduce airborne particles, but attention should be given to the location of supply and return ducts to minimize drafts across parts. Excessive dirt on the floor can cause portable molds to jolt enough to cause to gel coat to pre-release during transportation from the gel coating booth to the laminating area (A. Cocquyt, personal communication, n.d.). Lastly, the laminating area should contain sufficient scaffolding to prevent walking on core of surfaces on which laminating is taking place (ABS, 2006; DNV, 2008).

3.4.5.3 Tooling

Ankarbjork (2005) found that resin and laminate technology for resin infusion has increased to the point where the quality of the tooling surface is now the limiting factor in the resulting quality of the finished laminate surface. For this reason the construction, storage, and maintenance of composite tooling for resin infusion is a key quality consideration.

Tooling should be constructed to accommodate the requirements of resin infusion: vacuum integrity, dimensional requirements, and cure temperatures. In resin infusion the vacuum integrity of the mold is its most important characteristic. Tooling must be free of leaks, because any leak through the mold will result in air tracing through the laminated part resulting in extensive voids. Tooling should be constructed to maintain its shape at all times being stiffened to prevent extreme distortion (ABS, 2006, p. 96). When multi-part molds are used alignment should be provided for. This includes RTM molds with a hard or semi-hard secondary tooling side. The cavity dimensions should be accurately controlled using a hard landing in addition to the seal as shown in Figure 3.9. Tooling should be constructed to withstand the expected exotherm heat from the resin reaction. Thermal expansion and contraction from high thermal shifts should be taken into consideration when selection the tooling material. Tooling material and release agents should not interfere with the resin reaction (ABS, 2006, p. 96).

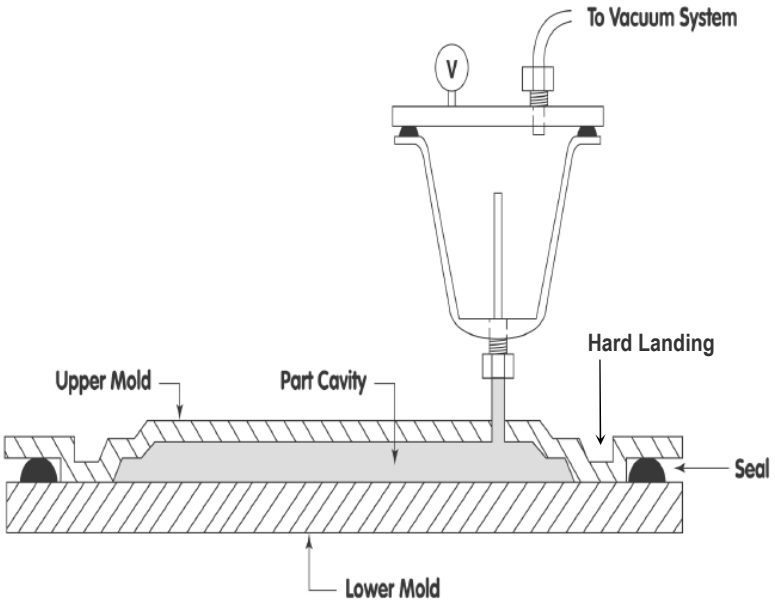

Figure 3.9 Hard Landing on RTM Tooling (Adapted from CCP, 2005)

Production tooling should be stored indoors to prevent damage from weathering. If stored outdoors it should be covered and protected from the elements. In regions where freezing will occur, tooling should be stored such that rain will not pool on the surface of the tooling because it could then expand during freezing and crack the mold. If stored at temperature different than ambient the tooling must be acclimated prior to use to prevent changes in resin viscosity.

Proper tooling maintenance is essential to keeping the molds up to the standards required for resin infusion. Tooling should be maintained on a schedule. It should be cleaned before every use if exposed to contaminants such as dirt, dust, or oils. Release agent should be used to prevent rough demolds which could damage the part or the tooling. A convenient method of checking the adequacy of the release agent is the tape test. A piece of low adhesive painter's tape is placed on the mold and removed by pulling at a shallow angle. Experience will instruct how much force is necessary to remove the tape when the tooling is adequately waxed, but the tape should "pop" off quite easily.

3.4.5.4 Equipment

Equipment must be appropriate for its intended use and maintained to ensure that it is capable of meeting the demands of use. Appropriate for its intended use means that precision equipment should be used when high accuracy is required. Testing, inspection and precision measuring equipment should be calibrated and maintained on a schedule with records being kept for each separate piece of equipment. Equipment should be labeled to identify when calibration has been performed and when it is due next. When

the precision of calibrated equipment is questionable for any reason it should be removed from use until it can be recalibrated to a traceable standard (ABS, 2006, p. 113). Examples of this type of equipment include but are not limited to the following: calipers, pressure gages, Barcol hardness tester, scales and balances, gel coat application equipment, thermometers and hydrometers. Gel coat equipment should be calibrated frequently so as to introduce a homogeneous mixture to the part (ABS, 2006, p. 98).

All manufacturing equipment should be maintained according to the manufacturer's specifications on a schedule. Vacuum pumps and compressed air lines fall into this category. The pump is an integral component in the VIP and requires routine maintenance. Compressed air lines should contain filters and moisture traps, being free of dirt, moisture or oils and undergo frequent inspection. The vacuum system should contain a large reservoir to insure against pump failure. The reservoir should have capacity to maintain vacuum pressure while a backup pump is engaged (Hoebergen, 2001).

3.5 Incoming Material

The goal of incoming material inspection is to eliminate defective products from entering inventory and making their way into finished products. To accomplish this goal purchasing documentation and technical specifications are used upon material receipt to compare the material to acceptance standards. These inspections ensure that raw materials used in production are correctly identified, undamaged upon receipt, stored and handled to preclude damage, and are in all ways capable of meeting the customer's quality requirements. These assurances are made through the use of purchasing control,

material qualification standards, incoming inspection, a material traceability system, and storage and handling standards.

Deming (1986) stressed the importance of appropriately applying incoming material inspection systems to avoid unnecessary financial burdens upon the company. He proposed a plan for minimum average total cost for testing of incoming materials and the final product wherein he compared the cost of inspection to the cost of failure. Using statistical methods he was able to recommend different levels of inspection. These methods vary for every different system, and are described in detail in Chapter 15 of his book *Out of the Crisis* (Deming, 1986). Following are benchmark industry incoming material practices assuming the system meets Deming's requirements for performing incoming material inspections.

3.5.1 Purchasing Control

Purchasing control refers to the method of checking that received material matches what was ordered. The composite manufacturer's raw material is another company's finished product. It is therefore important for composite manufacturers to select suppliers who are capable of consistently meeting raw material performance standards. Suppliers who are inconsistent or incapable of supplying conforming product should be replaced and a system for tracking performance should be in place. Purchasing documents need to contain enough information to positively identify material type and grade. When the material arrives it should be compared to purchasing records to verify that it is what was ordered. Supplier certificates of conformance and inspection records should be kept on file.

3.5.2 Incoming Inspection

At the basis of the incoming material inspection is determining if the material is acceptable or should be rejected. Upon receiving, the materials should be kept separate from material approved for production (ABS, 2006, p. 110). Prior to inspection acceptance criteria should be established for material properties. This will prevent the use of nonconforming material in production.

Nonconforming material is that which does not meet the supplier's specifications or the manufacturer's production standards. Nonconforming material can be discovered during an incoming material inspection or during an in-stock inspection. Any nonconforming material should be clearly labeled "Rejected" and immediately placed in a dedicated area isolated from production storage or returned to the manufacturer. Corrective action should be taken to deal with the root cause of the nonconforming material.

When appropriate a system of labeling should be in place such that approved incoming material can be labeled during incoming inspection and be traceable and identifiable through storage and manufacturing to the finished product. Small representative samples of each batch of material should be retained and labeled for records (Lloyd's Register, 2007, Ch.14 Sec.5.10).

3.5.2.1 Reinforcement

Reinforcement inspection includes a visual inspection and areal weight. Reinforcement packaging should be undamaged and sound. A visual inspection on incoming reinforcement should be performed on the first part of the roll. A damage

tolerance should be used to determine the acceptable level of damage. A sample of reinforcement should be checked for correct areal weight. A 12 inch by 12 inch sample is appropriate to determine weight per square foot. The reinforcement finishing or sizing should be verified to be compatible with the resin system. If there are no means of measuring the sizing a certificate of conformity from the supplier is adequate.

3.5.2.2 Resin

Incoming resin should be tested for gel time and viscosity. Gel times or viscosities outside of the acceptable range indicate faulty chemistry or improper storage or handling techniques and should be rejected. Each batch of incoming resin should be tested and labeled. All incoming resin should be within its shelf life.

Gel time is the time elapsed between the addition of an initiator to a resin system and the point when the resin turns from liquid to solid. Gel time tests should be conducted under the same conditions from batch to batch for reliable comparison. Variables which will alter the gel time for a specific sample include the size of the sample, ambient and sample temperature, and initiator ratios. Typically a 100 gram sample is initiated with the proper ratios (e.g.: 1.8 percent of a standard 9.0 percent active oxygen MEKP catalyst) in a test cup at 77°F. Since the initiator quantities are very small measuring by volume as opposed to by weight is recommended (Flagler, 2008). It is of consequence to note that since the gel time is a function of sample size it will not necessarily predict the gel time for the resin in the production part which is typically more spread out leading to a longer gel time. Peak exotherm temperature is simply

determined by recording temperature of the sample during the gel time test. This can be measured using thermocouples or a hand-held infrared thermometer.

Viscosity is indicative of resin chemistry and can be used to screen incoming material. A simple method of measuring viscosity is discussed in section 2.4.3 using a viscosity cup. More advanced and accurate methods are available for laboratory applications. The industry standard for more accurate viscosity measurements is the Brookfield viscometer shown in Figure 3.10 (CCP, 2005, p.23).

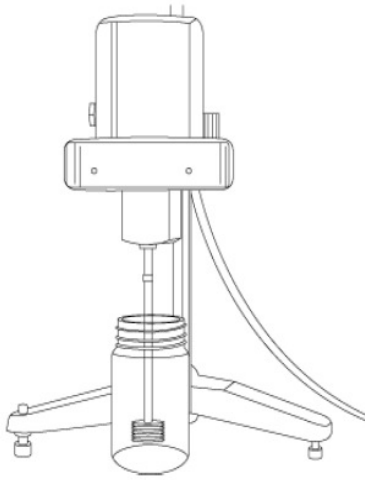

Figure 3.10 Brookfield Viscometer (CCP, 2005)

3.5.2.3 Cores

Cores should be checked for damage, density and moisture content. Balsa cores have the potential to absorb large amounts of moisture and should be checked upon receiving by weighing before and after oven drying. Density should be determined by weighing a representative sample and should be within predetermined tolerance limits.

3.5.3 Material and Process Qualification

The material and process qualification process ensures that new materials and methods used in production are capable of meeting the quality requirements. Changing materials and/or processes will affect the quality of the composite product if measures are not taken to verify that the resulting product is equivalent in all regards. The Composite Materials Handbook CMH-17 (ASTM, 2002) sets the bar for composite material and process qualification. Since qualification can be costly the system takes into account the business case for switching. The higher the required level of quality assurance, the higher the associated qualification costs will be. The stages of the system involve defining the problem to be solved, developing the business case for the change, analyzing the risk and the divergence possibilities of the new material, developing quantitative equivalency criteria, verifying production readiness, and incorporating lessons learned in an ongoing documentation process. Banisaukas, Hahn, and Wanthal (2000) attested to the efficacy of this approach after applying it in evaluating composite materials for military aircraft construction. Hoebergen (2001) recommends small scale infusion tests on flat panels to screen materials, working toward full scale simplified infusions which isolate tricky mold geometries or laminate steps, and finally implementing a full scale section infusion test to fine tune the process. This method reduces costly design errors.

3.5.4 Storage and Handling

All materials must be stored and handled in accordance with the manufacturers' recommendations. Most materials used in composites manufacturing can be easily compromised by improper storage or handling. General material storage requirements are covered in 3.4.5.1 Material Storage Premises. Arrangements should be made such

that materials can be handled without risking contamination. Clean workbenches in the lamination area allow materials to be temporarily stored to prevent contamination. All materials going into the laminate stack should be protected from contamination at all times. Reinforcement cutting should take place in a dust, dirt, and oil free location and transported to the lamination area protected. Reinforcements and cores should never be placed on the floor or walked on with soiled footwear which leads to contamination. Vacuum bags should be given the same treatment to prevent punctures. Tack spray which is used to temporarily hold reinforcements in place can become a contaminant at even moderate levels. Tack spray should be chosen such that it does not interfere with the resin reaction and should be used sparingly. Materials should be taken from storage on a first-in first-out basis to prevent significant aging. When materials are removed from storage to be used in production the shelf-life should be checked to verify that they are not expired.

3.6 In-Process Control

In-process control refers to the techniques and systems used during production to assure that parts are being constructed to the agreed upon standards. Control of the manufacturing process is usually accomplished through written instructions that generate construction related records. This section addresses the critical variables that need to be controlled in the six stages of resin infusion manufacturing: (1) tooling preparation, (2) dry laminate layup, (3) sealing the tooling cavity, (4) infusion of the laminate with resin, and (5) curing and removal of the laminate from the mold.

Standard operating procedures (SOPs) or work instructions that incorporate control forms and checklists can be used to record relevant production variables and to avoid overlooking key production points. These documents should include all of the necessary information so that different skilled workers would be able to perform the task exactly the same even having never done it before. The following information is typical of thorough work instructions: document control information, objective of the task, list of references and contacts, list of safety concerns, list of separate and related data forms or inspection sheets, and finally complete and easy to understand step by step procedural instructions. These documents should be available to laminating personnel on the shop floor.

It is important for quality assurance purposes that records are generated during the production stage. Control forms should record relevant production information such as names of workers, product identification, laminating parameters, diagrams of layout, drop test results, and other information which could be useful should a problem arise. Inspections need to be performed at critical production points. The control forms or production records should have stop points at these inspection points where a production supervisor or quality assurance representative must sign before work can continue (ABS, 2006).

3.6.1 Tooling Preparation

The first step in resin infusion manufacturing process is tooling preparation. This stage consists of inspecting, repairing, cleaning, coating the rigid molds with a mold release agent, and finally applying a gel coat called for. Prior to use molds must be

inspected for damage for areas which could cause leaks and for surface blemishes. Any surface blemishes on the mold will appear on the finish surface of the part, therefore it is important to maintain a mirror smooth finish on the mold. A leak check of the tooling can be performed in accordance with the procedure outlined in section 2.3.1.1. This inspection process is only necessary if the tooling has not been used before or if it has been stored in such a way as to induce damage. Once the vacuum integrity of the tooling has been validated it should be cleaned with a mild detergent and coated with a mold release agent. The release agent must not interfere with the resin reaction and should be applied regularly enough to avoid the use of excessive force during the demold. Molds can be checked for adequate release agent by using the "tape test" discussed in section 3.4.5.3.

Gel coat is applied after the release agent has been applied, but only after the mold has reached an appropriate temperature. Gel coat should not be sprayed on the flanges of the mold where the vacuum seal will be placed (Hoebergen, 2001). All gel coating should be performed according to best practices outlined by ACMA in their Certified Composites Technician training course (CFA, 2001). If infusion will not take place for many days, as would be the case for a very large part, Hoebergen (2001) recommends applying a hand lay-up layer. This will serve to protect the gel coat and will result in better adhesion between the gel coat and the laminate.

3.6.2 Dry Laminate Layup

The second stage of the resin infusion process is the layup of the infusion layout. This includes the placement of any distribution materials, reinforcement, core, vacuum

lines, and any other materials which are within the tooling cavity. The layout should be communicated to the laminating staff with clear precise documents. These include the laminate schedule and feed and vacuum line layouts. Lay-up sequence and orientation should be verified and recorded by quality assurance personnel. For areas where fiber orientation is critical tolerances should be given in the construction documents. Where reinforcement plies join, the overlap should be at least 2 inches and no joints should be closer than 4 inches to one another. Changes in laminate thickness should be tapered with at least a 3:1 slope (ABS, 2001, p.93).

Laminating personnel should take measures to avoid damaging material during the layup. If it is necessary to walk on the laminate protective booties should be used. Scaffolding should be utilized to avoid walking on cores (ABS, 2006) as this could cause them damage.

Where cores abut can be a huge potential flow problem in resin infusion. Voids between cores are areas of relatively low permeability and can lead to undesirable racetracking. Core scarf joints are preferable to butt joints, but all joints should be sealed with bedding putty to fill in these openings.

The final step before sealing the mold is the placement of the feed lines and vacuum lines. Correct placement is critical to the success of the infusion and can be testing using different techniques and models discussed in section 2.3.1.5. Records of the feed and vacuum line layout should be generated and kept on file. Pictures of the layout are easy to take and are clearer than hand drawn diagrams.

3.6.3 Sealing the Tooling Cavity

Sealing the tooling cavity begins with the application of the secondary mold. This stage consists of (1) applying the secondary mold, (2) checking for leaks, (3) performing a drop test, and (4) allowing time for consolidation of the laminate.

For larger parts in the VIP the secondary mold is usually a flexible bag capable of conforming to the required shape. The bag needs to free of leaks and large enough to cover the entire mold. Sealant tape should be placed around the perimeter of the part on the mold flange after it has been thoroughly cleaned. Any stray fibers caught between the flange and the seal can act as micro-straws and lead to leakage. Pleats are used to take up extra bag and should be given extra attention as they are often the source of major leaks.

After the bag is sealed and most of the air evacuated from the cavity attention should be given to the reinforcement and feed and vacuum lines to assure that nothing has shifted during the application of the bag. Negative corners should be massaged to prevent “bridging” which leads to racetracking while drawing down the part to full vacuum.

Once the part reaches full vacuum a leak check should be conducted by listening by ear for leaks at pleats or around the seal and fixing them. The use of an acoustical listening devise to detect high pitch sounds is very useful for smaller leaks or in a loud shop environment. This stage is very important because any leak in the cavity, however small, will result in voids, the massively negative effect of which was investigated in section 2.3.1.3.

Before infusion a drop test must be performed to assure a leak free mold. A drop test measures the drop in vacuum pressure within the tooling cavity over a period of time while being isolated from the vacuum source. This technique is described in section 2.4.2. Failure to pass the drop test results in another leak check followed by another drop test until the standards are met. A repeated inability to meet the drop test requirement could indicate that there is a leak in the mold.

Once full vacuum is achieved it is recommended that time be provided for consolidation of the laminate stack and moisture control in balsa cores. Kelly, Umer, and Bickerton (2004) found that the stress response of dry compacted reinforcement was visco-elastic, meaning that it is dependent on time. Yenilmez and Sozer (2009) found that the thickness change for a dry reinforcement stack under full vacuum during a fifteen minute settling period was on the order of 2% to 5% depending on fabric architecture. Moisture content of balsa cores is important to ensure proper laminate to core bonding. For resin infusion it is recommended that the moisture content of the core be between 6% and 12% with the middle of that range being preferable. Balsa will dry under vacuum with the rate of drying depending on the initial moisture content, the size of the part, the thickness of the core and the temperature. For ideal situations at least twenty minutes under full vacuum should elapse prior to infusion, and up to four hours for wetter, thicker, colder balsa in large parts (R. Elkin, personal communication June 9, 2009).

3.6.4 Infusion

The fourth stage is the infusion itself. This stage consists of preparing the resin, infusing it into the tooling cavity through the feed lines, and controlling the pressure until the resin gels.

When preparing the resin for infusion all the precautions of section 2.3.3.2 should be taken. These measures eliminate the use of contaminated or expired raw material; avoid infusion conditions that are dissimilar to the material qualification conditions; and prevent improper measuring and mixing.

To prepare for the resin to be introduced into the tooling cavity a few preparations should be made. The feed line should be shaped such that it cannot suction itself to the bottom of the resin bucket and stop flow. This can be prevented by cutting the end of the line at two different angles as shown in Figure 3.11. A technician should be specifically assigned to monitor the level of resin in the feed bucket. He/she need to ensure that the feed line does not surface above the resin and that the resin supply does not run out.

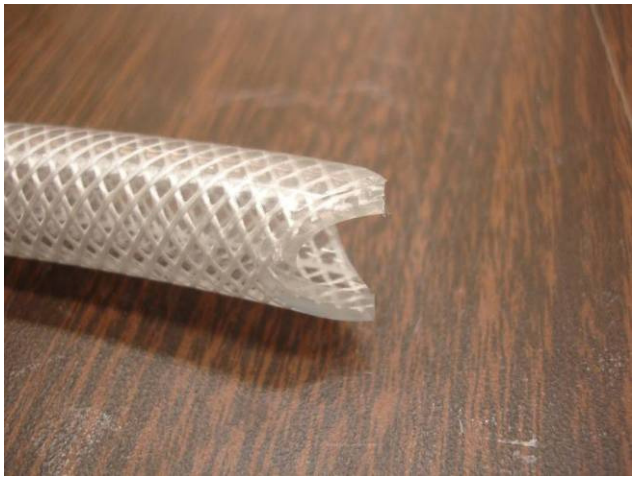

Figure 3.11 Feed Line End Cut

During the infusion certain activities should be performed. The beginning and ending time of the infusion should be recorded. As the infusion progresses technicians should search the part for air bubble trails which are indicative of a leak. These can be easily sealed with sealant tape. Dry spots can be addressed by the placement of an emergency vacuum outlet if necessary. This is described by Hoebergen (2001) as a syringe attached to a vacuum line inserted into the middle of the dry spot though tacky tape and is shown in Figure 3.12.

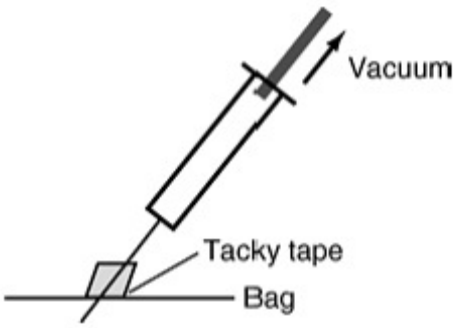

Figure 3.12 Emergency Vacuum Port (Hoebergen, 2001)

It is important to control the pressure within the tooling cavity after the infusion is complete to control fiber volume fraction, thickness and void content. Methods for post-fill pressure control are discussed towards the end of section 2.3.1.1.

3.6.5 Part Cure and Removal

ABS Rules give standards regarding part cure and removal from the mold. These standards exist to prevent the part from being removed before it can handle the stress of removal. They also give recommendations regarding the actual removal.

ABS rules state that parts should not be removed within 12 hours of laminating; that curing parts should be stored inside the workshop environment; and that degree of

cure should be verified with a Barcol hardness tester prior to demolding (ABS, 2006). Shown in Figure 3.13, this tool uses an indenter to correlate the relative depth of penetration to the hardness of a surface (ASTM D 2583-07, 2007). The 934-1 model is the most commonly used and was developed specifically for metals displaying unit-less values up to one hundred. Cured composites usually read around forty or fifty on the Barcol scale. According to ABS Rules (2006) no part should be demolded until a Barcol hardness reading of at least 40 is obtained; Lloyd's Register (2007) allows demolding after a reading of only 20, but requires that the part remain in the laminating environment until reaching a hardness reading of 35. Barcol testing is appropriate for non-homogenous materials such as composites, however results will be more varied than for homogeneous materials such as neat resin. To address the variability in softer materials it is recommended increasing the number of readings. For hardness readings below 30, twenty-five readings should be taken; for reading between 30 and 40, only twelve readings are required (ABS, 2006, p.115). The average of the readings after discarding the highest and lowest values is the Barcol hardness value. The indenter should be calibrated regularly using supplied aluminum disks. Readings should not be taken on gel coat and must be on laminates at least 1/32 inch thick. ABS rules do not recommend using the Barcol hardness tester for epoxies, which can be too soft to yield reliable values; the Barcol 936 model or a type-D Durometer would be more appropriate for that application.

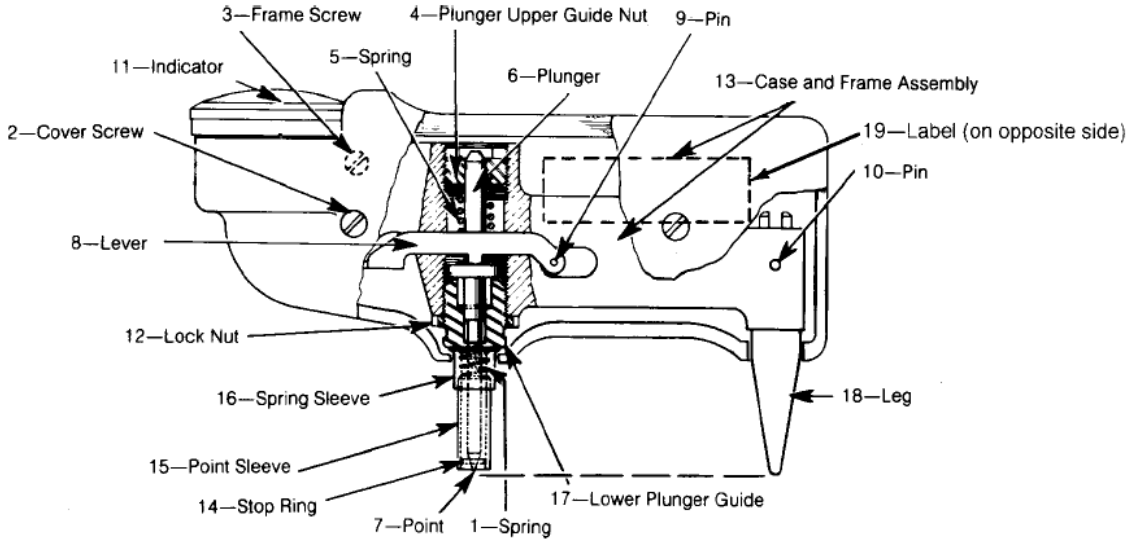

Figure 3.13 Barcol Hardness Tester (Barber-Colman Company, 2002)

Once it has been determined that the part has reached an acceptable degree of cure the part may be demolded. All parts should be sufficiently stiffened to prevent harmful flexing. For large boat hulls in female molds it is best practice to allow the part to remain in the mold while the internal stiffeners are placed to prevent distortion. For other cases it is necessary to properly brace and support the part so as to maintain its form. Moldings should be stabilized in the laminating environment for at least 24 hours prior to any curing treatments (ABS, 2006, p.103).

3.7 Validation Testing

Validation testing is the methodical approach of determining the properties of a manufactured part. Examples of properties which can provide useful information include ultimate strengths, elastic moduli, and constitutive relationships. It should be noted that this form of testing differs from design testing in which material properties are confirmed for design purposes. Engineers are not always interested in every property of the

laminate when performing validation testing, but are mainly concerned with answering the question, "Will this laminate perform acceptably in this application?" This form of assuring that a part meets specifications usually requires that the part is destroyed (also known as destructive testing). Because this method renders the part useless after testing, it is impossible to test the exact same piece that will be used in the final construction. The solution is to fabricate parts with identical lay-ups using identical procedures and in identical shop conditions. Many times a manufacturer will infuse a test panel (witness panel) concurrently with the actual part using the same procedure. Standard tests require specific geometries and a certain number of samples (usually a minimum of five) to reduce variation.

Due to the nature of composite fabrication certain properties should be checked for each part, however some properties only need to be checked depending on the use of the part and the consequence of failure (DNV, 2008, Pt.2 Ch.4 Sec.2 p.12). Bishop (1991) suggested a classed system of inspection depending on the rigors of the service environment and consequence of failure. Parts subjected to extreme service conditions and would result in loss of life or extremely high costs upon failure should undergo the most thorough inspection requirements. Parts subjected to normal service conditions and which would not be harmful upon failure should undergo a basic inspection.

Because of the wide range of composite parts and their applications and the generally high cost of testing, there is no one inspection regimen which will be adequate to meet all validation needs. The scope of the testing should be determined based on customer and regulatory requirements (Bishop, 1991). Following is an overview of the

range of available nondestructive and destructive validation testing procedures which should be considered for resin infused products.

3.7.1 Nondestructive Evaluation

Nondestructive evaluation of composite materials is still an emerging and ever advancing field. The heterogenic nature of composite material complicates subsurface damage assessment and requires significant technical training to execute advanced NDE methods and interpret their results. The most basic and important form of NDE is the visual inspection. Visual inspection can yield important information about the quality of the laminate and can focus more involved and expensive NDE techniques. Some of the most popular of the advanced NDE methods for composites include tap testing, ultrasound, thermography, thermal pulse imaging, and laser shearography. NDE aims to discover internal laminate damage or flaws such as porosity, fiber waviness, fiber misalignment, micro-cracking, core damage, interlaminar delaminations, skin-to-core disbands and others (Aoki, Sugimoto, Hirano, & Nagao, 2008; Hsu, 2008).

3.7.1.1 Visual Inspection

Visual inspection is the simplest form of testing and should be preformed to some degree on every composite part to determine the quality of the part surface. Often surface defects are indications of more serious sub-surface structural issues. ASTM D 2563 (1994) sets the standard for visual inspection of composite parts. This guide describes and illustrates the range of almost thirty defects which can be discovered through visual inspection without the aid of optical magnification. The standard discriminates three levels of acceptable defects and specifically describes the size and extent of each type of defect at the different levels.

3.7.1.2 Tap Testing and SIDER

A simple method of inspecting for delaminations and dry spots is the tap tests or the hammer test. Using this rudimentary but reliable method an inspector with a trained ear can discover faulty areas which respond with a different sound when tapped with a solid object. A large coin is often used to perform the tapping although very advanced equipment does exist to perform this test. Advanced systems use an electronic hammer and measure the response frequency of the vibrations to provide quantifiable data for this simple test (WichiTech Industries Inc, 2008). A uniform laminate will respond with a clear solid ring, while a delamination or dry spot will sound hollow and dull. This test is useful for quickly and inexpensively locating areas which require further investigation.

SIDER (Structural Irregularity and Damage Evaluation Routine) is a patented vibration response technique developed at the Naval research lab in Caderock, Maryland. This technique uses accelerometers mounted on the structure to measure the response to an impulse excitation delivered via a modally tuned impact hammer. Stiffness variations can be correlated to the vibration response, and are used to map possible structural anomalies. This technique has been used on large structures in a fraction of the time necessary for more advanced NDE techniques such as thermography and ultra-sonic testing. SIDER is useful as a pre-inspection method for these other more descriptive NDE methods, locating which areas should be given inspection priority (Crane, Ratcliffe, Gould, Johnston, & Forsyth, 2007).

3.7.1.3 Ultrasonic Testing, Thermography, and Laser Shearography

There are many advanced nondestructive evaluation techniques available for use with infused composites, however the three most popular are ultrasonic testing (UT),

thermography, and laser shearography. The equipment needed to perform these tests is usually beyond the means of a small or medium sized manufacturer. Also the expertise needed to conduct and interpret the test results is beyond the composites manufacture. For this reason these tests are performed by trained NDE personnel.

Ultrasonic testing (UT) is one of the most utilized advanced NDE methods for quality assurance inspection in composite manufacturing (Hsu, 2008). UT is capable of measuring thickness, identifying interlaminar delaminations, skin-to-core disbonds, voids, and characterizing material properties (Greene, 2007; Hsu, 2008). The technology is the same as that used in the medical field to monitor fetal development. A transducer introduces sound waves at frequencies beyond the range of the human ear; these waves propagate within the test specimen in predictable patterns bouncing off inclusions and the back surface of the material, returning to the transducer (Shull, 2002). By mapping the wave response and energy absorbed an experienced technician should be able to identify flaws within composite materials. UT is not as dependable as X-ray methods in detecting sub-surface flaws, but it has the advantage of costing orders of magnitude less for equipment.

The two most popular non-contact full-field methods of inspection for composites are thermography and shearography. Thermography is a relatively new NDE method in which a large specimen is externally heated and observed with an infrared imaging device during the cooling stage. The heat dispersion characteristics of the structure can then be correlated to the structural characteristics. Unlike UT which takes multiple measurements at discrete points, thermography is a full field method. This means that

multiple measurements are taken at once allowing for more rapid testing of larger areas. Thermography can identify voids, inclusions, and delaminations; but like UT is user sensitive and requires extensive training and experience to correctly interpret results. Thermal wave imaging is a slightly more advanced variation of this method which measures the surface temperature profiles after applying a heat pulse via a flash lamp (Hsu, 2008).

Laser shearography identifies flaws by comparing surface deformation images before and after loading. Loading can be from vacuum pressure or heat provided it induces a slight stress. According to Hsu (2008), "[a] shearography instrument detects the difference as a shift in the phase-separated optical images of the reflected laser light." This method is quite reliable for detecting sub-surface flaws using real-time optical imaging.

3.7.2 Destructive Testing

Destructive validation testing is used to physically measure through testing laminate properties. This is preferably performed on cutouts or extension tabs of the part. If there are no cutouts and there is not room for extension tabs, ABS rules (2006) permit validation testing to be performed on a witness panel fabricated under exactly the same conditions at the part. The mechanical property tests listed in Table 3.1 are required by ABS rules for new laminates. In addition to mechanical properties determination of fiber volume fraction, thicknesses, and void content are also required. Lloyd's Register (2007, Pt.2 Ch.14 Sec.3 p.9) and DNV (2008, Pt.3 Ch.4 Sec.3 p.13) require similar testing in accordance with ISO standards; however Lloyd's Register adds a test for water

absorption, ISO Standard 62. For novel laminate schedules all classification societies reserve the right to require further testing such as fatigue and environmental effects.

Table 3.1 Tests for Physical Properties of FRP Laminates (ABS, 2006, p.116)

Type of Laminate	*Properties*	*Test*
Single Skin	Flexural Strength and Modulus	ASTM D790 or D790M or ISO 178
Single Skin	Shear Strength, perpendicular and parallel to Warp	ASTM D732 85
Single Skin and Sandwich	Glass Content and Ply-by-Ply Analysis	ASTM D2584 or ISO 1172
Single Skin and Sandwich – Both Skins	Compressive Strength and Modulus	ASTM D695 or D695M or ISO 604
Single Skin and Sandwich – Both Skins	Tensile Strength and Modulus	ASTM D3039 or D638 or D638M or ISO 3268
Single Skin and Sandwich – Both Skins	Interlaminar Shear Strength	ASTM D3846
Sandwich – Core to Skin Bondline	Flatwise Tensile Test	ASTM C297
Sandwich – Core Material	Shear Strength and Modulus	ASTM C273

3.7.2.1 Reliability of Destructive Testing of Composites

Destructive testing results are highly dependent on many factors. Many of the standardized tests listed in Table 3.1 were developed for the plastics industry under the oversight of ASTM committee D20 on plastics. Since many of these standards were optimized for the plastics industry they are not always ideal for composites. Work by Dagher, Lopez-Anido, Thompson, El-Chiti, Fayad, and Berube (2007) revealed large testing variability when standard composite test methods were applied to marine grade composites. They highlighted that "variability in material properties obtained from experimental testing has three sources: material variability, fabrication variability, and testing variability." They further noted that testing variability can depend on the experimental technique and setup, specimen preparation, tabbing procedure, strain measurement system, specimen alignment, and operator expertise (Dagher et al., 2007). Their work suggests modifications to standard methods to reduce testing .

3.8 Summary of Quality Assurance and Control Literature Review

This chapter explores the industry best practices available to resin infusion manufacturers for quality assurance systems and quality control methods. It begins with definitions for *quality assurance* and for *quality control* followed by a description of the three-tiered quality assurance system proposed by Bishop (1991) and implemented by the composites companies XXX and YYY before getting into the QA/QC practices themselves. The literature review found that these practices were commonly reduced into four stages: (1) the quality management system, (2) incoming material inspection, (3) in-process controls, and (4) final part validation testing. The first addresses the overall approach and system of quality practice implementation while the latter three focus on the specific stages of manufacturing. The QA/QC practices identified in the literature review are listed in Table 3.2.

Table 3.2 QA/QC Methods

QA/QC Practice	Section Addressed
Quality Management System	
QMS is in place	Section 3.4
Quality procedures are written	Section 3.4
Thorough coverage of quality procedures	Section 3.4 Figure 3.5
Internal audits of QMS conducted	Section 3.4.1
One person responsible for QA/QC	Section 3.4.1
QA representative separate from production	Section 3.4.1
QA representative's only responsibilities are QA/QC	Section 3.4.1
Company wide approach to QA/QC	Section 3.4.1
Continuous improvement system in place	Section 3.4.2
Processes generate records	Section 3.4.3
Records on file	Section 3.4.3
Records are traceable	Section 3.4.3
Job descriptions are written	Section 3.4.4
Training records are kept	Section 3.4.4
Resin storage standards followed	Section 3.4.5.1
Reinforcement storage standards followed	Section 3.4.5.1
Vacuum bag storage standards followed	Section 3.4.5.1
Reinforcement conditioning prior to lamination	Section 3.4.5.1
Resin conditioning prior to lamination	Section 3.4.5.1
Laminating area conditions are acceptable	Section 3.4.5.2
Laminating area temperature is controlled	Section 3.4.5.2

Table 3.2 Continued QA/QC Methods

Temperature records are kept	Section 3.4.5.2
Dust is controlled	Section 3.4.5.2
Scaffolding is used to avoid damaging cores	Section 3.4.5.2
Tooling construction standards	Section 3.4.5.3
Tooling storage is appropriate	Section 3.4.5.3
Tooling conditioning prior to lamination	Section 3.4.5.3
Precision equipment is calibrated	Section 3.4.5.4
Equipment maintenance schedules are kept	Section 3.4.5.4
Compressed air is clean and dry	Section 3.4.5.4
Appropriate measuring equipment is used	Section 3.4.5.4

Incoming Material	
Purchase order validation of received materials	Section 3.5.1
Material properties compared to data sheets	Section 3.5.2
Isolate and label incoming material	Section 3.5.2
Material accept/reject criteria exist for inspection	Section 3.5.2
Nonconforming material separation	Section 3.5.2
Material traceability	Section 3.5.2
Incoming reinforcement inspection	Section 3.5.2.1
Incoming resin testing of gel time and viscosity	Section 3.5.2.2
Incoming core inspection and testing	Section 3.5.2.3
New materials and processes undergo qualification testing	Section 3.5.3
Shelf life tracking	Section 3.5.4
Material selection system in place	Section 3.5.4
Resin shelf life checked before use	Section 3.5.4

In-Process Control	
SOPs available for manufacturing	Section 3.6
Lamination records collected	Section 3.6
Process inspections and tests conducted	Section 3.6
Gel coating application standards followed	Section 3.6.1
Lamination alignment is checked	Section 3.6.2
Leak check	Section 3.6.3
Drop test	Section 3.6.3
Consolidation and degassing standards followed	Section 3.6.3
Barcol hardness test prior to demold	Section 3.6.5

Validation Testing	
Fiber volume fraction checked	Section 3.7.2
Voids checked	Section 3.7.2
Final visual inspection	Section 3.7.1.1
Mechanical properties testing	Section 3.7.2

Chapter 4

INDUSTRY INVESTIGATION: METHODOLOGY AND RESULTS

4.1 Introduction

Chapter 2 presented common composite defects and the key process parameters of resin infusion which can lead to them, and Chapter 3 presented best practices for controlling these parameters. This chapter is focused on determining which of these practices are being implemented in industry for differing levels of product requirements. If manufacturers were found to be capable of producing a quality product while adhering to some lower level of quality assurance as Bishop (1991) suggests, then recommendations could be made as to which practices to adopt based on the specific level of product requirements.

The industry investigation sought to uncover whether certain manufacturer demographic characteristics such as annual sales, number of employees, management type, infusion operating period, product type, or customer quality requirements had any correlation to the implementation and use of best practices. For this reason and since the aim of this research was to assist manufacturers, manufacturers were selected for investigation based on their specific demographic characteristics (listed above) and based on their reputation for producing quality composite products. While none of the manufacturers were implementing all best practices, all were producing quality products and enjoyed a favorable market reputation. The results of the investigation were analyzed to determine which demographic characteristics (if any) correlated with the level of conformance to best practices.

This chapter describes the investigation which assessed the level of compliance to QA/QC best practices within Maine's composites industry. It covers development of the survey instrument which was used to assess the manufacturers' level of conformance to the best practices; describes the participating manufacturers and how they were selected; includes details about the actual site visits as well as explaining the methods for collecting the data. This chapter contains a description of the data analysis and the results of the analysis and discusses the findings. Lastly this chapter describes a case evaluation of one of the manufacturers in the original assessment, who was required to develop and implement QA/QC practices in order to become compliant with the requirements set forth by a new client.

4.2 Survey Instrument

A survey instrument was developed as a tool to gather information about which quality control practices (Table 3.2) were being practiced by composites manufacturers. The best practices included in the survey instrument are those which were found in the QA/QC literature review (Chapter 3) to control the key process parameters of resin infusion (Chapter 2). The quality control best practices were broken down into the following six categories: (1) quality management system, (2) documentation and records, (3) training, (4) facilities and equipment, (5) material control, and (6) production and testing.

The survey instrument was designed to facilitate an in-person interview. It was structured as a series of open-ended questions to be asked by the researcher during a personal interview. Attention was given to wording the questions such that answers were

not prompted. The survey instrument was created in table format with numbered questions. It contains next to each question the reference of the standard or source from which the quality control practice was prescribed as well as the underlying principle which the question is inquiring about. For example question 1.10 of the survey instrument asks "Who is primarily responsible for the implementation of quality?" The researcher was not actually interested in which employee is responsible for the implementation of quality, but rather in whether or not one person is responsible for QA/QC as is recommended by ABS Part 2 Chapter 6 Section 4.13. In this manner the underlying principle is masked while an inquiry can be made about whether or not this best practice is followed by the manufacturer. In this regard the survey instrument is modeled after the ABS Guide for Hull Survey for New Construction (ABS, 2007).

4.3 Participant Demographic Parameters

Eight composites manufacturers from Maine were selected for investigation based on the diversity of their company characteristics and positive quality reputations. Seven of these manufacturers were able to participate. The intention of the selection was to be small and yet representative of most manufacturers regardless of their specific demographics. An investigation into a large number of manufactures was ruled out due to the limitation of resources. This is the reason for the small sample size as well as the geographic limitation.

Taking these limitations into consideration the selection of participants was important to obtain a sample which represents the infusion industry population. Lawton and Renski (2007) estimate that there are approximately 230 boat builders and boat yards

in Maine. They surveyed 99 of these and found that slightly less than half did any work with composites at all and only 25% of those utilized closed molding. If this rate is representative of the overall population it is not unreasonable to estimate that there are around 60 companies in Maine utilizing closed molding at any level. Of these certainly less are using closed molding at a significant level beyond accessory products. Our survey focused on manufacturers which focused significantly on composites manufacturing. Therefore seven manufacturers of a population of perhaps forty to sixty is a reasonable representation.

The sample was selected to incorporate a range of the demographic characteristics listed in Table 4.1 which were hypothesized to correlate with the level of best practice implementation. Park, Kim, Kang, and Jung (2007) conducted a similarly structured investigation into the implementation of the ISO 9000 Quality Management System within the Korean shipbuilding machinery manufacturing companies. Their demographic categories included the following six categories: (1) annual sales, (2) total number of employees, (3) type of top management, (4) ISO implementation motives, and (5) ISO operating period. This investigation used these parameters with some alterations. In their study "ISO implementation motives" were classified as the result of a "customer request" or "internal development." The parallel demographic category in this study is "customer quality requirements." This demographic category captures the level of quality expected of the manufacturer and depends on the product performance and application. Also in this study the "ISO operating period" demographic category is replaced with "infusion operating period" to quantify the years of infusion implementation. Besides these two changes, this study added a demographic category to

track the product type. The "product type" demographic category is divided into "custom" products and "production" products (the distinction is described in the following paragraph). This broad range of demographic characteristics allowed for a better representation of the overall composites manufacturing population, allowing findings to be applicable to more manufacturers. Of the eight manufacturers contacted for this study, seven were available and willing to participate in the investigation.

Table 4.1 Manufacturer Demographic Categories

Demographic Parameter	**Ranges Studied**
Annual Sales for 2007	Less than $1 million $1 to $3 million $3 to $10 million Over $10 million
Number of Employees	Small: Less than 30 Medium: 30 to 100 Large: Over 100
Top Management Type	Owner CEO Professional manager CEO
Infusion Operating Period	Less than 2 years 2 to 5 years More than 5 years
Product Type	Custom Production
Customer Quality Requirements	High Low

The only two demographic categories which were not easily quantified were "product type" and "customer quality requirements." For "product type" some manufacturers were obviously either solely production or custom builders, while others were somewhere in between and not easily classified as one or the other. Definitions for production and custom builders were borrowed and adopted from the National Association of Home Builders (NAHB, n.d.). The NAHB also recognizes the grey area between custom and production builders, but describes the differences. Attributes of custom home builders include small-volume high-value unique houses built to specific

specifications for a specific client. The trademarks of the production builder on the other hand are high-volume and limited designs. Production builders are able to turn out houses rapidly and less expensively than custom builders due to lower designs fees and economies of scale. They use stock plans to standardize the majority of the construction processes, while allowing clients to customize easily altered details. These home building definitions parallel the boatbuilding industry with production builders using stock plans to produce high-volume products while the custom builders produce low-volume one-of-a-kind products.

In regards to "customer quality requirements" definitions were adopted from the work of Bishop (1991), who concluded that product quality can be defined in terms of performance and application. Performance addresses the level of customer specifications and application refers to the consequence of failure. High performance products would be those with many strict customer specifications. Examples include mechanical performance, appearance, dimensional, or weight specifications. Products with high consequence of failure include bridges, airplane components, boat hulls, primary structural components and others which would result in severe collateral damage or personal injury upon failure.

4.4 Description of Participants

To encourage transparency and cooperation the survey results are presented anonymously, without reference to specific manufacturers. Following are brief descriptions of each manufacturer which are summarized in Table 4.2.

Table 4.2 Manufacturers' Demographic Data

Company	2007 Annual Sales ($Mil.)	Number of Employees	Type of Top Management	Infusion Operating Period (years)	Product Type	Customer Quality Requirements
Alpha	1-3	<30	Owner	2-5	Production	Low
Bravo	>10	>100	Professional	<2	Production	High
Charlie	3-10	30-100	Owner	2-5	Custom	High
Delta	<1	<30	Owner	<2	Production	Low
Echo	>10	>100	Professional	>5	Production	High
Foxtrot	<1	<30	Owner	>5	Custom	High
Golf	3-10	30-100	Owner	<2	Custom	High

4.4.1 Alpha

Company Alpha is a small (less than 30 employees) company specializing in infrastructure products with 2007 annual sales between $1 million and $3 million. Alpha has two product lines which are manufactured according to stock plans at high-volumes, classifying these as production products. These two product lines encompass the majority of Alpha's work load. Alpha also works on custom projects to increase revenue and reduce down time. Alpha is managed by the owner and as of 2007 had been manufacturing using resin infusion for four years. Resin infusion is used extensively and all production parts are produced using resin infusion.

Most products company Alpha produces are classified as having low customer quality requirements. Customers of the two product line products do not require the products to be built to any third-party standards and appearance is usually not an important factor. The two product lines are subjected to moderate environmental conditions. Failure of these products would not likely result in any collateral damage or personal injury, but would likely only require repair or replacement.

4.4.2 Bravo

Company Bravo is a large (more than 100 employees) boat manufacturing company fabricating high-end high-volume craft. Their luxury vessels are built to National Marine Manufacturer Association (NMMA) and American Boat and Yacht Council (ABYC) standards and are CE certified (for products sold in the European Economic Area). Bravo is known for their superior quality and craftsmanship with certain models winning industry design and performance awards. Bravo is in the high customer quality requirements demographic category. Annual sales for 2007 exceeded $10 million placing Bravo in the largest sales bracket in this study. A professional-manager CEO runs the company. Bravo has been in business building boats for almost forty years; however as of 2007 Bravo was only beginning the switch from open to closed molding. While none of the production parts had yet been manufactured using resin infusion, tooling was being converted and plans were in place to implement the technology.

4.4.3 Charlie

Company Charlie is a medium sized (30 to 100 employees) purely custom luxury yacht manufacturer. Grossing between $3 million and $10 million in sales in 2007 places this company in the medium-large sales demographic category for this study. Charlie currently only manufactures custom products which are high-value low-volume unique designs. Charlie has been owner operated for almost forty years, and has been building boats for longer than that. As of 2007 Charlie had been infusing parts and hulls for two years relying heavily on the experience of previously trained new employees. The

custom products they manufacture have a high customer performance and appearance specifications placing Charlie into the high customer requirement demographic category.

4.4.4 Delta

Company Delta is a small (less than 30 employees) owner operated boat manufacturer with annual sales for 2007 below the $1 million mark. While the volume of products is low due to their small size Delta is considered a production builder due to their limited designs and use of stock plans. Delta has been building boats for over twenty years and was in the process of switching from open molding to closed molding as of 2007. Delta's customers do not have high performance or appearance requirements in comparison to the other boat manufacturers. For this reason Delta is in the low customer quality requirements demographic category.

4.4.5 Echo

Company Echo is a large (more than 100 employees) manufacturer grossing over $10 million in 2007. Operated by a professional manager CEO, Echo is a production boat manufacturer in the classical definition. They produce a high-volume of limited design high-end vessels in a typical production-line environment. Echo is a veteran user of resin infusion having implemented the process for more than five years as of 2007. The award winning vessels are built to NMMA and ABYC standards with certain models capable of CE certification. Echo's customers have high performance and appearance requirements placing Echo in the high customer quality requirements demographic category.

4.4.6 Foxtrot

Company Foxtrot is a small (less than 30 employees) manufacturer in size and in sales, with 2007 revenues below $1 million. Foxtrot is owner operated and is a solidly custom manufacturer. Product designs are one-of-a-kind and are usually prototypes or limited batch production products. Products cover many sectors: marine, automotive, industrial and have recently branched into energy and aerospace. They are experienced in resin infusion having adopted the process more than five years prior to 2007. While projects are incredibly varied in terms of customer quality requirements, most customers have high expectations and standards, especially those from high-value sectors. Foxtrot's has sought these high-end customers with their high-performance and strict specifications. This places Foxtrot in the high customer quality requirements demographic category for this study.

4.4.7 Golf

Company Golf is one of the two medium sized (30 to 100 employees) manufacturers in this study also falling into the $3 million to $10 million gross revenue demographic category for 2007. Golf is owner operated and manufactures most products to custom specifications for the industrial industry. Golf's products are built to third-party industry standards, require precise dimensional control, and would result in major damage and possibly injury upon failure. High customer specifications and high consequence of failure put Golf in the high customer quality requirement demographic category.

4.5 Data Collection

The survey instrument was used to collect data during an on-site interview with the person responsible for quality control implementation at each manufacturer's shop. This was followed by a tour of the premises to allow for personal observations. Each interview was conducted by a team of two researchers. This method allowed one researcher to focus on conducting the interview while the other could focus on taking notes, resulting in a more thorough documentation of the interview.

The interviews were conducted at the manufacturer's shop for two reasons. First, a face-to-face meeting was preferred over a phone conversation because of the long length of the interview, each taking between one and two hours. Questions were left as open ended as possible to allow the interviewee's response to be unaffected by the interviewer. Second, the researchers were given a shop walk through. The tour allowed the researchers to observe the facilities and production practices first hand. This served simply to validate the interviewee's responses to the questions.

4.5.1 Assessment of Product Quality

Since the questionnaire was not structured to provide information about product quality, the use of a follow-up questionnaire was used in an attempt to obtain reliable product quality information. As means of quantifying the product quality, questions focused on rework and warranty work. They attempted to elicit the frequency of product quality issues, as well as the level of work required to rectify the non-conforming products. The result was that only two of the companies responded to the follow-up questionnaire and others claimed not to have records or estimates of this information.

Another problem with the follow-up questionnaire was the possibility of biased data due to the lack of a third party, investigation. Any information about the product quality was to be collected from the manufacturer, who could be inclined to portray their product quality in a favorable light. While there is no reason to expect that any of the companies would not be forthcoming with product quality information, the issue is that the researchers were depending on the manufacturers, themselves, for a rating of the manufacturer's product quality. This could result in a somewhat subjective and inconsistent analysis.

Therefore, in lieu of an actual product quality measurement, business performance was assumed to correlate with product quality. It was assumed that companies failing to consistently meet customers' expectations would suffer the financial consequences due to lack of repeat customers, customer recommendations, and ability to expand product lines (Garvin, 1984). Companies Bravo, Charlie, Delta, Echo, and Golf have all been in business for at least 25 years and have demonstrated steady or growing sales relative to the economy. The ability of these companies to remain viable for that amount of time was interpreted as business success. Companies Alpha and Foxtrot have been in business less than ten years. According to the owner, Alpha has demonstrated a history of steady growth in sales, number of customers, and products offered since their founding. Foxtrot's owner also attested to having steady growth in sales and number of customers since their founding as well as being able to branch into markets with higher customer quality requirements such as energy and aerospace. The ability of these two newer companies to grow steadily was interpreted as business success. While a rating of

product quality was not obtained the researcher was satisfied based on the records of business success that all companies were producing quality composite products.

4.6 Analysis

The goal of the statistical analysis was to determine if any of the demographic parameters correlated with the best practices. Correlation was determined by performing a linear regression analysis and correlation coefficients were evaluated for levels of significance using a t-statistic.

For ease of analysis the survey instrument is organized in six best practice categories: (1) quality management system; (2) documentation and records; (3) training; (4) facilities and equipment; (5) material control; and (6) production and testing, Figure 4.1. Each best practice category contains from two to twenty-four practices on which each manufacturer was rated. Each best practice category rating is the average of all the practice ratings within that category.

- Quality Management System
- Documentation and Records
- Training
- Facilities and Equipment
- Material Control
- Production and Testing

Figure 4.1 Best Practice Categories

In order to allow statistical analysis a rating rubric (APPENDIX B: RATING RUBRIC) was developed which corresponds to each best practice contained in the survey instrument. The rating rubric provided a means of a quantitative analysis of the collected manufacturers' information. Each practice was rated with a four point Likert-type scale. The traditional five point Likert scale is commonly used in questionnaires to gage

respondents' level of agreement to a statement: 1-strongly agree, 2-agree, 3-neither, 4-disagree, 5-strongly disagree (Park, Kim, Kang, & Jung, 2007). For this survey a four point scale measured level of conformance to the best practices with 1-does not conform, 2-somewhat conforms, 3-mostly conforms, and 4-fully conforms. The rating rubric contains descriptions of what each level of conformance would look like for each practice. After the site visit was complete the information collected was used to complete a best practice conformance rating according to the rating rubric. Any questions which did not apply to that particular company were left blank and were not included in the calculations.

4.6.1 Correlation

Correlation analysis helps identify a relationship between two sets of data (Ayyub & McCuen, 1997). The two sets in this study being investigated for a relationship were the best practice category ratings and the demographic parameters of the manufactures listed in bold in Table 4.3. This study aimed to determine if there was a correlation between specific demographic characteristics and conformance to best practices (indicated by the ratings). This study used correlation plots to graphically represent the relationship and hypothesis testing to statistically analyze correlation coefficients. The data were assigned the categorical values shown in Table 4.3 and Table 4.4 in order to statistically analyze the data.

Table 4.3 Demographic Category Values

2007 Annual Sales	**Category Value**
Less than $1 million	0
$1 to $3 million	1
$3 to $10 million	2
More than $10 million	3
Number of Employees	
Less than 30	0
30 to 100	1
More than 100	2
Type of Management	
Owner CEO	0
Professional Manager CEO	1
Infusion Operating Period	
Less than 2 years	0
2 to 5 years	1
More than 5 years	2
Type of Product	
Production	0
Custom	1
Customer Quality Requirements	
Low	0
High	1

Table 4.4 Demographic Category Values by Manufacturer

	2007 Annual Sales	Number of Employees	Type of Top Management	Infusion Operating Period	Product Type	Customer Quality Requirements
Alpha	1	0	0	1	0	0
Bravo	3	2	1	0	0	1
Charlie	2	1	0	1	1	1
Delta	0	0	0	0	0	0
Echo	3	2	1	2	0	1
Foxtrot	0	0	0	2	0	1
Golf	2	1	0	0	1	1

The data were plotted with the demographic category (2007 annual sales, number of employees, etc.) on the horizontal axis and the best practices category rating on the vertical axis. Each demographic category was plotted against each best practices category rating with the addition of an average for all of the best practices categories generating forty-two individual correlation plots as shown in Figure 4.2.

	2007 Annual Sales	Number of Employees	Type of Top Management	Infusion Operating Period	Product Type	Customer Quality Requirements
Quality Management System						
Documentation and Records						
Training						
Facilities and Equipment						
Material Control						
Production and Testing						
Average						

Figure 4.2 Correlation Matrix

Correlation analysis "is a measure of the degree to which the values of [two or more] variables vary in a systematic manner" (Ayyub & McCuen, 1997, p. 273). When one set of data is found to vary along with another, the two sets are said to correlate or have a high degree of common variation. Correlation can be direct (positive) where an increase in the X corresponds to an increase in Y or indirect (negative) where an increase in X corresponds to a decrease in Y (Ayyub & McCuen, 1997, p. 275). Correlation is

measured with the Pearson product-moment correlation coefficient *R* which ranges from -1 to 1 with positive values indicating a direct relationship, negative values indicating an indirect relationship, and zero indicating no correlation.

Equation 4.1 Formula for the Pearson Product-Moment Correlation Coefficient

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{s_X}\right)\left(\frac{Y_i - \bar{Y}}{s_Y}\right)$$

Where,

r = Pearson Product-Moment Correlation Coefficient

n = sample size

X_i and Y_i = sample values

X_{bar} and Y_{bar} = sample means

S_X and S_Y = standard deviation of the variables

Cohen (1988) suggested that a correlation coefficient of 0.1, 0.3, and 0.5 represent weak, moderate, and strong correlation respectively. Others have suggested that this is somewhat arbitrary and depends on the type of study and data (Weinberg & Abramowitz, 2008). A more graded, but still admittedly arbitrary scale is presented in Table 4.5 (*Pearson's R Correlation*, 2000). Weinberg & Abramowitz (2008, p.131) also note that the Pearson Correlation Coefficient is on an ordinal scale and therefore does not linearly indicate the strength of the relationship. Therefore while we can say that higher *R* values indicate a higher strength of relationship we cannot say *how much higher* the strength of the relationship is. The correlation coefficients for the correlation matrix of Figure 4.2 which were calculated according to Equation 4.1 are given in Table 4.7.

Table 4.5 Degrees of Correlation for Pearson's Coefficients

+0.70 to +1.0	Very strong positive relationship
+0.40 to +0.69	Strong positive relationship
+0.30 to +0.39	Moderate positive relationship
+0.20 to +0.29	Weak positive relationship
+0.01 to +0.19	No or negligible relationship
-0.01 to -0.19	No or negligible relationship
-0.20 to -0.29	Weak negative relationship
-0.30 to -0.39	Moderate negative relationship
-0.40 to -0.69	Strong negative relationship
-0.70 to -1.0	Very strong negative relationship

Correlation plots were used to provide a graphical representation of the data. In the plots, high correlation is indicated by steep slopes of the best fit lines and data points which fall close to that line, while shallow slopes with data points which are farther from the best fit line indicate no correlation. Plotting of the data also helps identify outliers as well as the type of relationship (e.g.: linear, quadratic, or exponential).

It is not enough to determine the correlation coefficient for correlation analysis, but it is also necessary to determine if it is statistically significant. This is determined with hypothesis testing of the correlation coefficient. To perform statistical analysis the distribution of the random variable must be known. The distribution of the correlation coefficient R is a function of both the sample size, n, and the value of R itself (Ayyub & McCuen, 1997, p. 279). It follows the t distribution with n - 2 degrees of freedom if the null hypothesis is true (Montgomery & Runger, 2003, p.402). For the hypothesis testing of R the null hypothesis and alternative hypotheses are given in Equation 4.2 and Equation 4.3, respectively. These hypotheses can be tested using the test statistic given in Equation 4.4 with the rejection criteria given in

Equation 4.5 (Montgomery & Runger, 2003). Montgomery, Runger, and Hubele (2004) argue that a P-value approach to hypothesis testing should be used (as opposed to

a pass/fail test at a given significance level) because it does not impose the researcher's predefined level of significance on the test. The level of significance α is "the probability of rejecting the null hypothesis when it is true" (Montgomery, Runger, and Hubele, 2004, p.138). The P-value is "the smallest level of significance [α] that would lead to the rejection of the null hypothesis" (p. 149) and it is appropriate to "think of the P-value as the smallest [significance] level α at which the data are significant" (p.149). Therefore P-values close to zero indicate a low probability of rejecting the "no correlation" hypothesis (accepting the alternative hypothesis that there is a correlation) when there is in fact no correlation. The importance of the P-value hypothesis test is that one can determine not only whether or not the hypothesis is rejected, but also the weight of evidence for the decision. The correlation coefficients and P-values were calculated directly using Microsoft Excel's Regression Data Analysis Tool.

Equation 4.2 Null Hypothesis

$$H_o: R = 0$$

Equation 4.3 Alternative Hypothesis

$$H_A: R \neq 0$$

Equation 4.4 Test Statistic (Montgomery, Runger, & Hubele, 2004, p.285)

$$t_0 = \frac{R\sqrt{n-3}}{\sqrt{1-R^2}}$$

Equation 4.5 Rejection Criteria (Montgomery, Runger, & Hubele, 2004, p.285)

Reject the Null Hypothesis if $|t_0| > t_{\alpha/2,n-2}$

4.7 Results

A summary of the manufacturer best practice ratings is given in contained in Table 4.6. The row labeled "Average" is the mean of the six best practice categories and represents an overall rating of conformance to industry best practices.

Table 4.6 Summary of Best Practice Ratings

Best Practice Category	Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf
Quality Management System	1.60	2.90	3.40	1.30	2.50	1.60	3.60
Documentation and Records	2.25	4.00	3.75	1.50	3.50	3.50	3.75
Training	1.00	3.00	2.50	1.00	2.50	2.00	3.00
Facilities and Equipment	2.20	3.60	3.00	2.30	2.80	2.40	3.00
Material Control	2.00	3.25	3.04	2.26	2.29	2.74	3.25
Production and Testing	2.11	3.21	3.24	1.54	2.89	2.39	3.11
Average	1.86	3.33	3.15	1.65	2.75	2.44	3.29

This overall rating is also graphically represented in on page 153 which shows the average best practice ratings for each manufacturer along with the manufacturers' demographic parameters. Error bars in the figure represent the high and low best practice category rating while the colored data bars represent the overall average rating. Overall ratings ranged from 1.65 (Delta) to 3.33 (Bravo) with an average overall rating for the seven manufacturers being 2.64.

4.7.1 Correlation

The resulting correlation plots from the correlation matrix of Figure 4.2 are completely contained in Figure 4.4 on page 153. Each plot is the result of the manufacturer data points which are described by the demographic parameters (horizontal axis) and the best practice category rating (vertical axis). Included in the correlation plots for reference are linear least squares lines.

The correlation plots on pages 154 through 156 are the same as the thumbnail plots in the bottom row of Figure 4.4. These plots have been enlarged to provide greater

detail. The graphs on pages 158 through 171 show manufacturer ratings organized by demographic parameter values. Thus for the manufacturers are arranged from left to right according to annual sales. These graphs are useful in that they contain the other demographic information for each manufacturer summarized at the bottom of each graph.

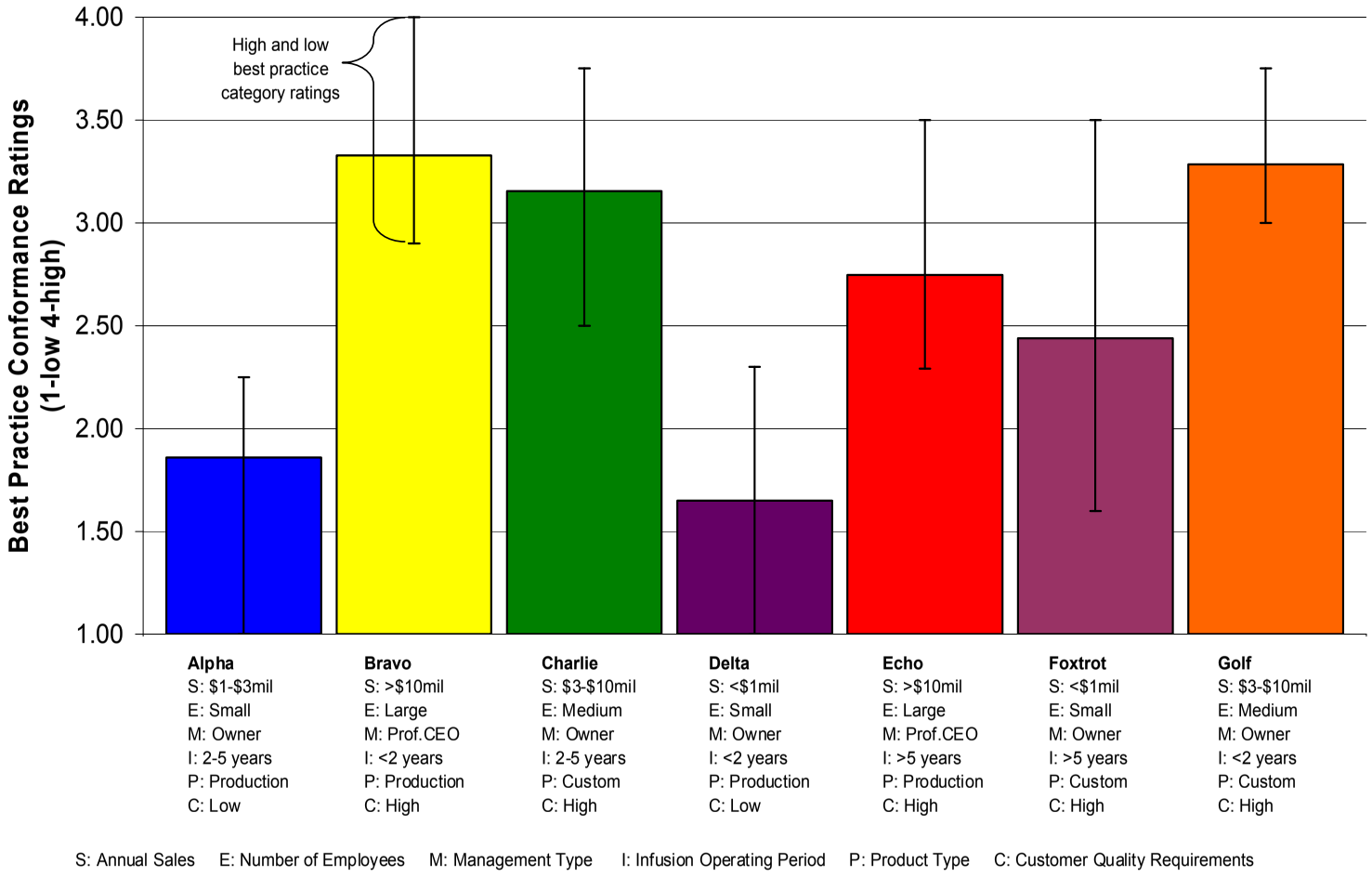

Figure 4.3 Manufacturer Best Practice Ratings

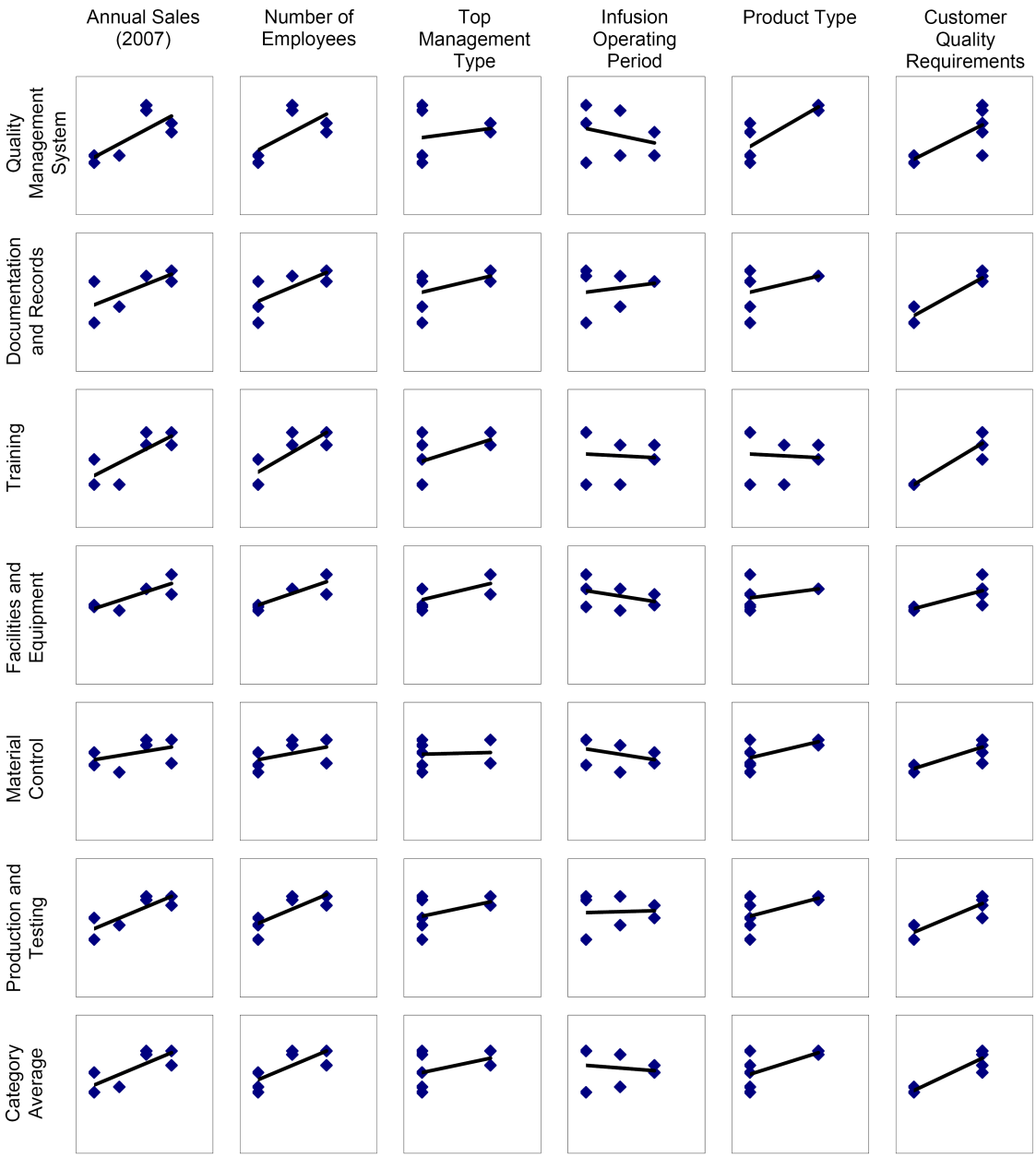

Figure 4.4 Correlation Plots with Least Squares Lines for Demographic Parameters vs. Best Practices Category Ratings

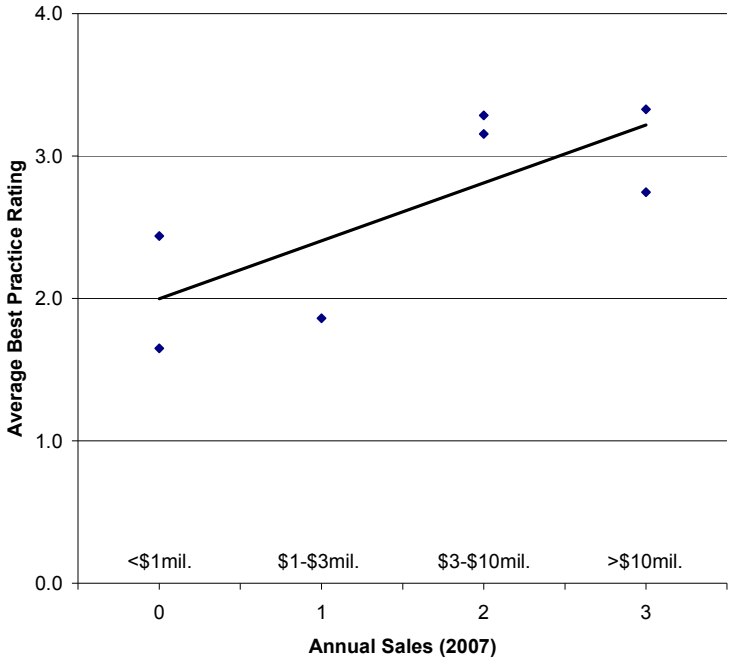

Figure 4.5 Correlation Plot of Annual Sales (2007) vs. Average Best Practice Rating

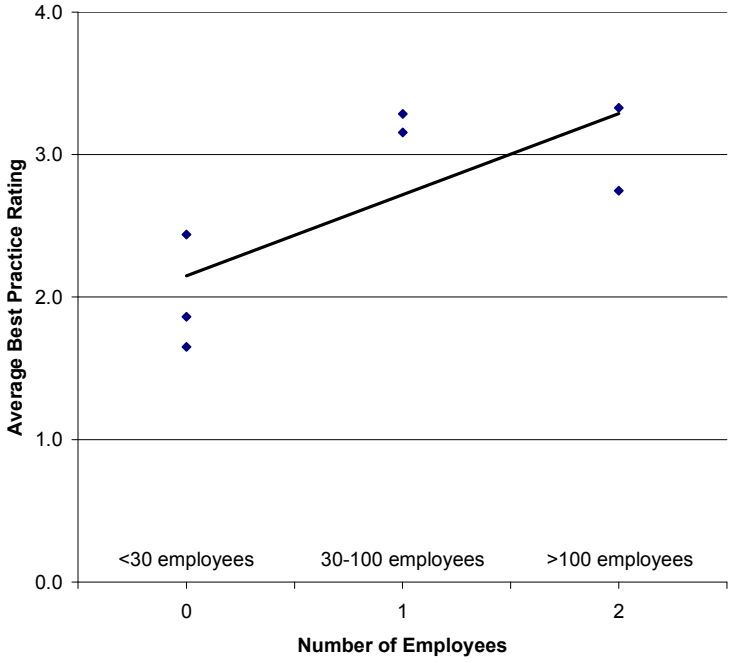

Figure 4.6 Correlation Plot of Number of Employees vs. Average Best Practice Rating

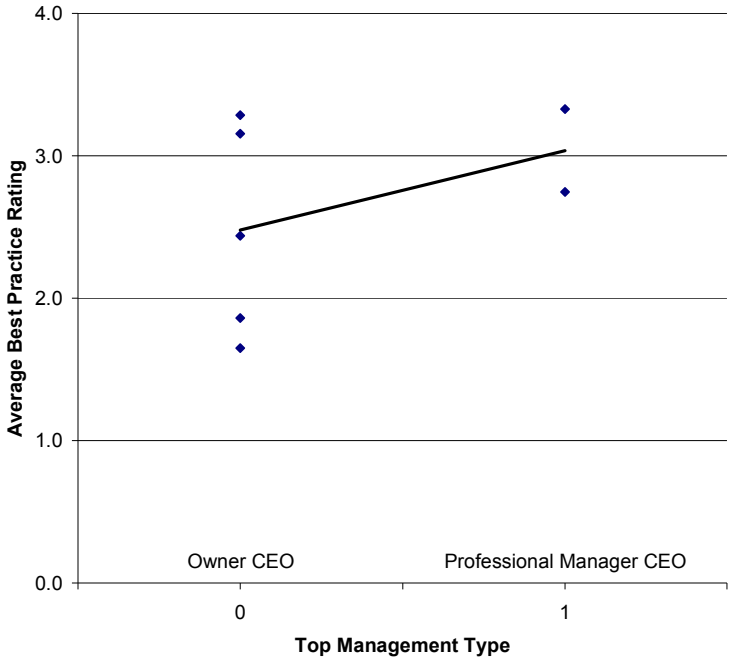

Figure 4.7 Correlation Plot of Top Management Type vs. Average Best Practice Rating

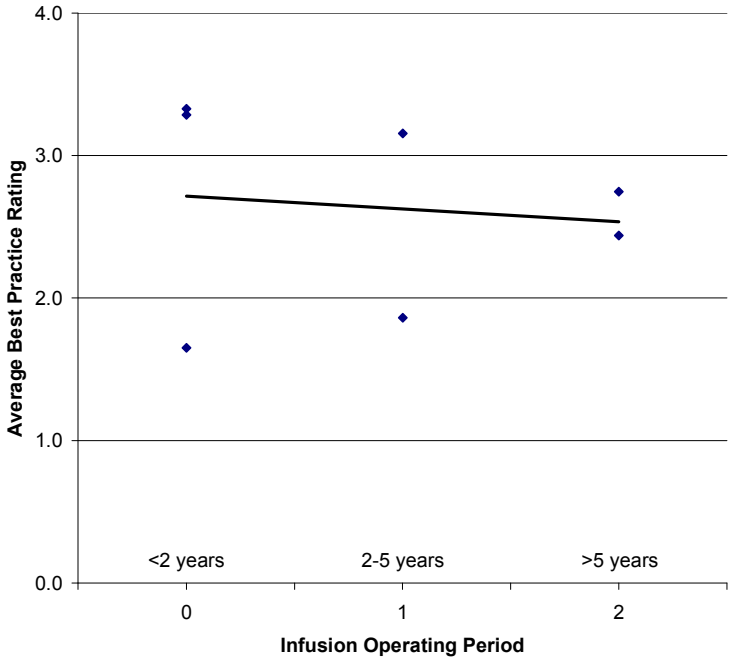

Figure 4.8 Correlation Plot of Infusion Operating Period vs. Average Best Practice Rating

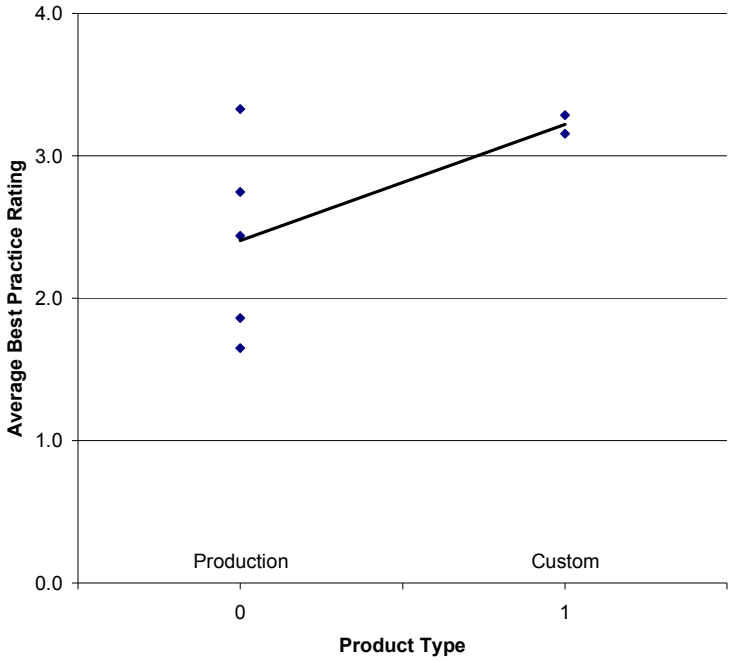

Figure 4.9 Correlation Plot of Product Type vs. Average Best Practice Rating

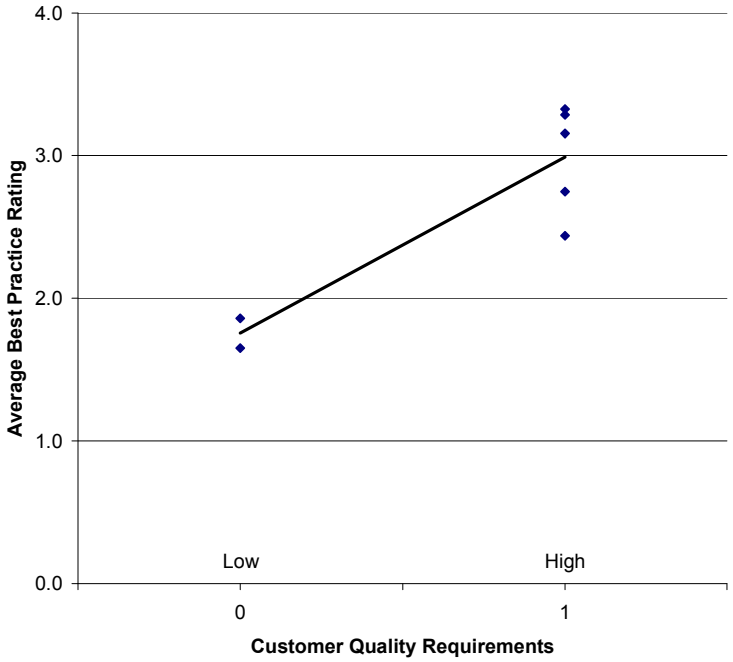

Figure 4.10 Correlation Plot of Customer Quality Requirements vs. Average Best Practice Rating

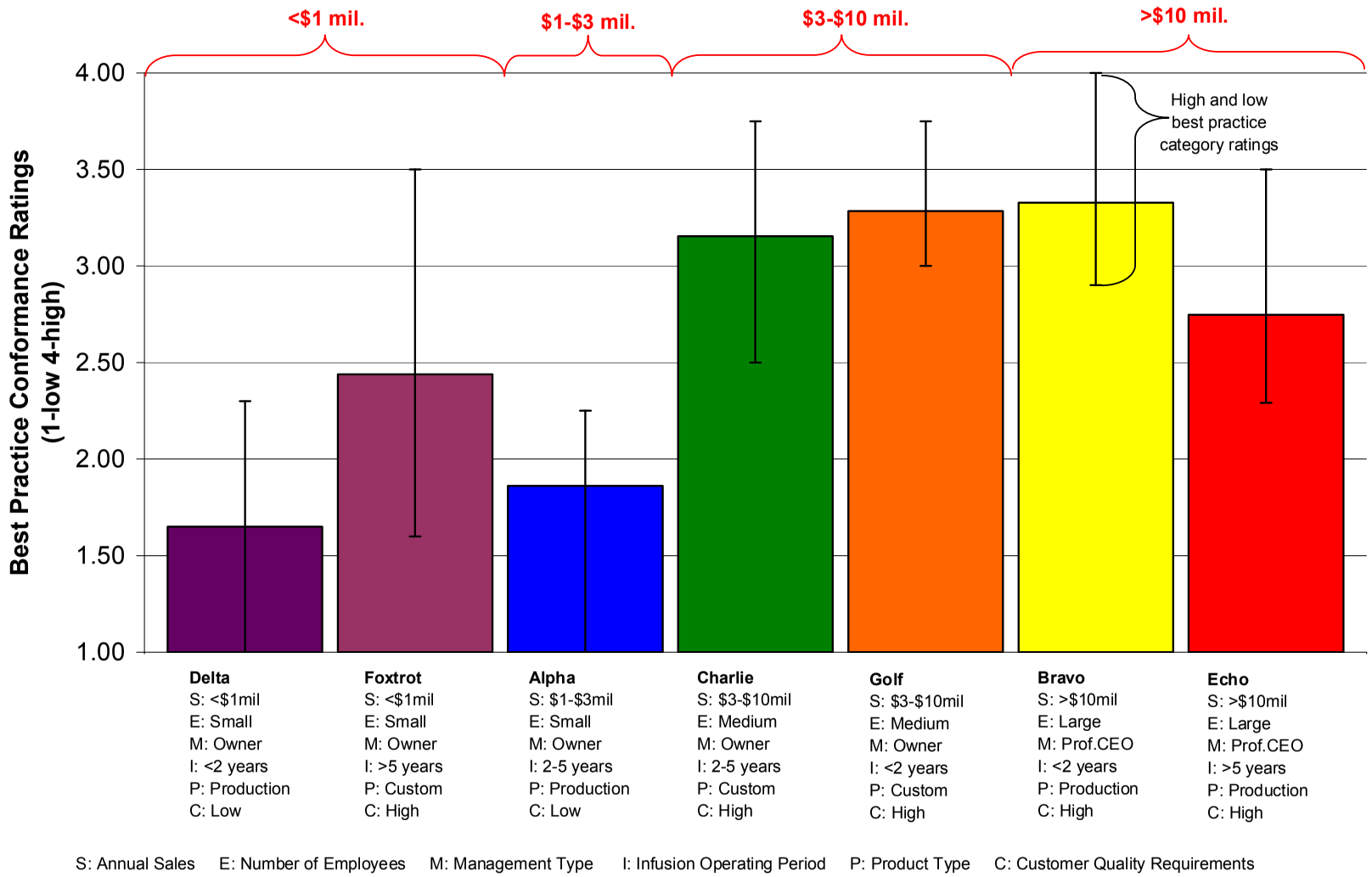

Figure 4.11 Graph of Best Practice Ratings by 2007 Annual Sales

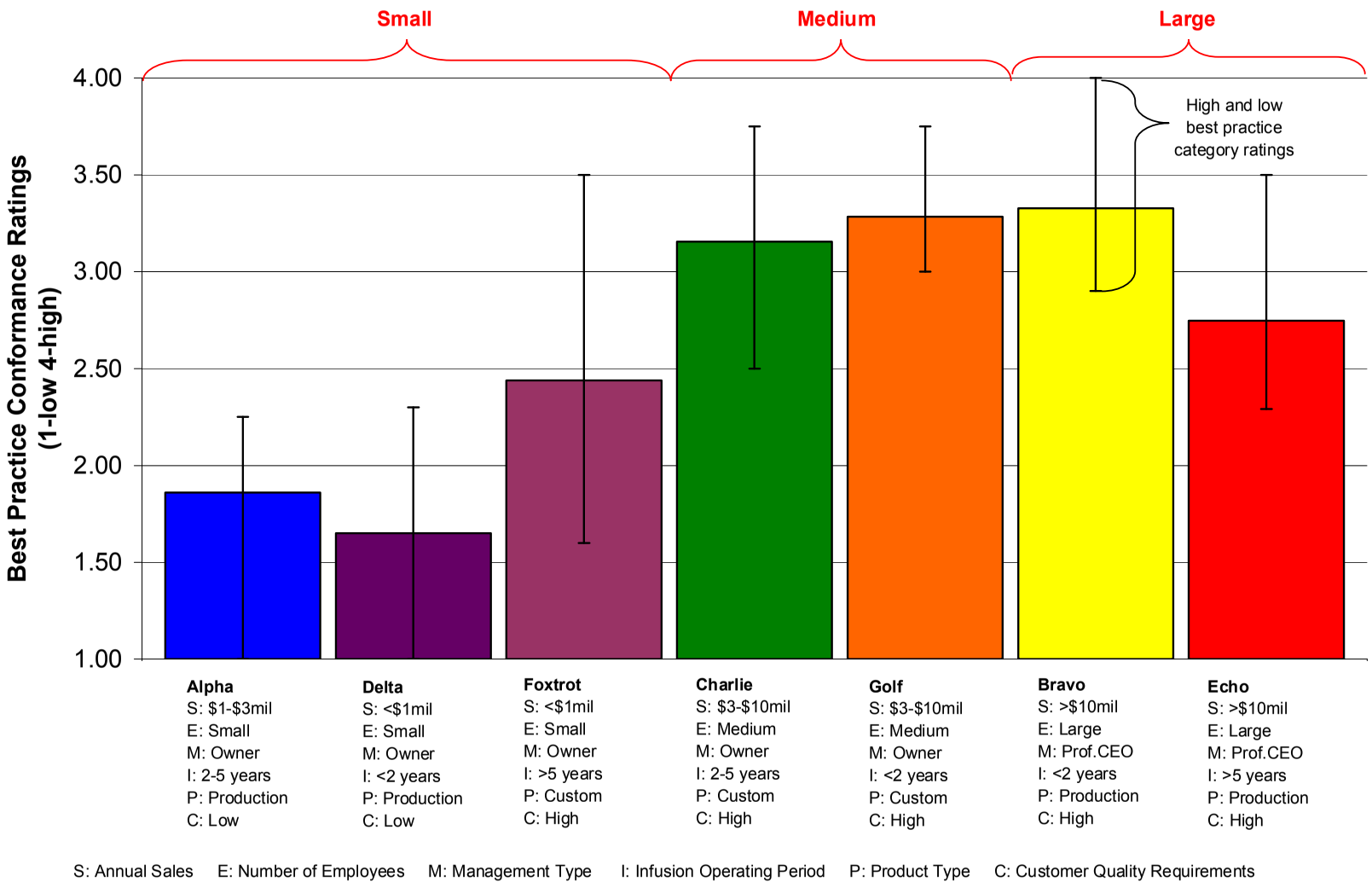

Figure 4.12 Graph of Best Practice Ratings by Number of Employees

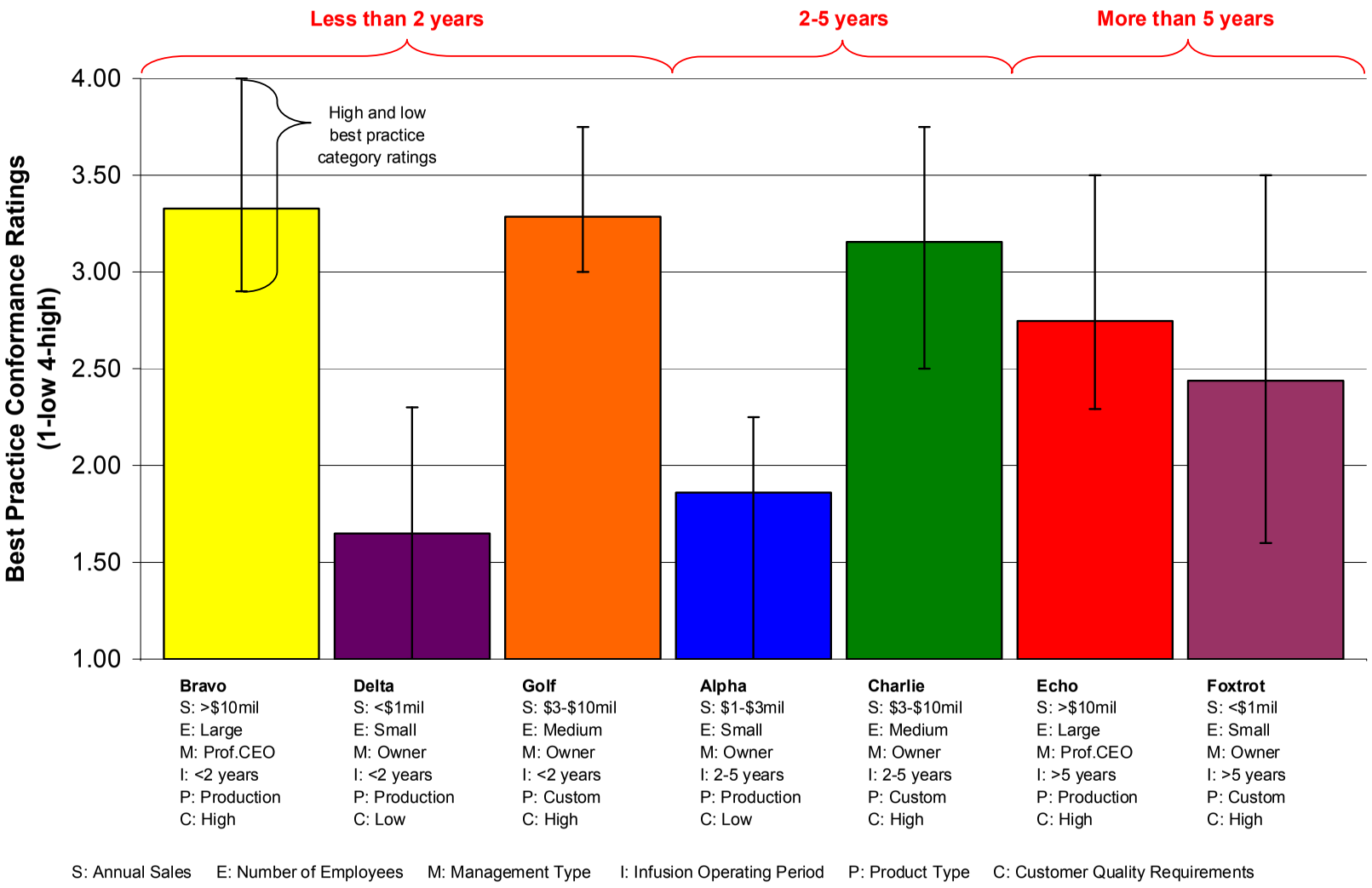

Figure 4.13 Graph of Best Practice Ratings by Infusion Operating Period

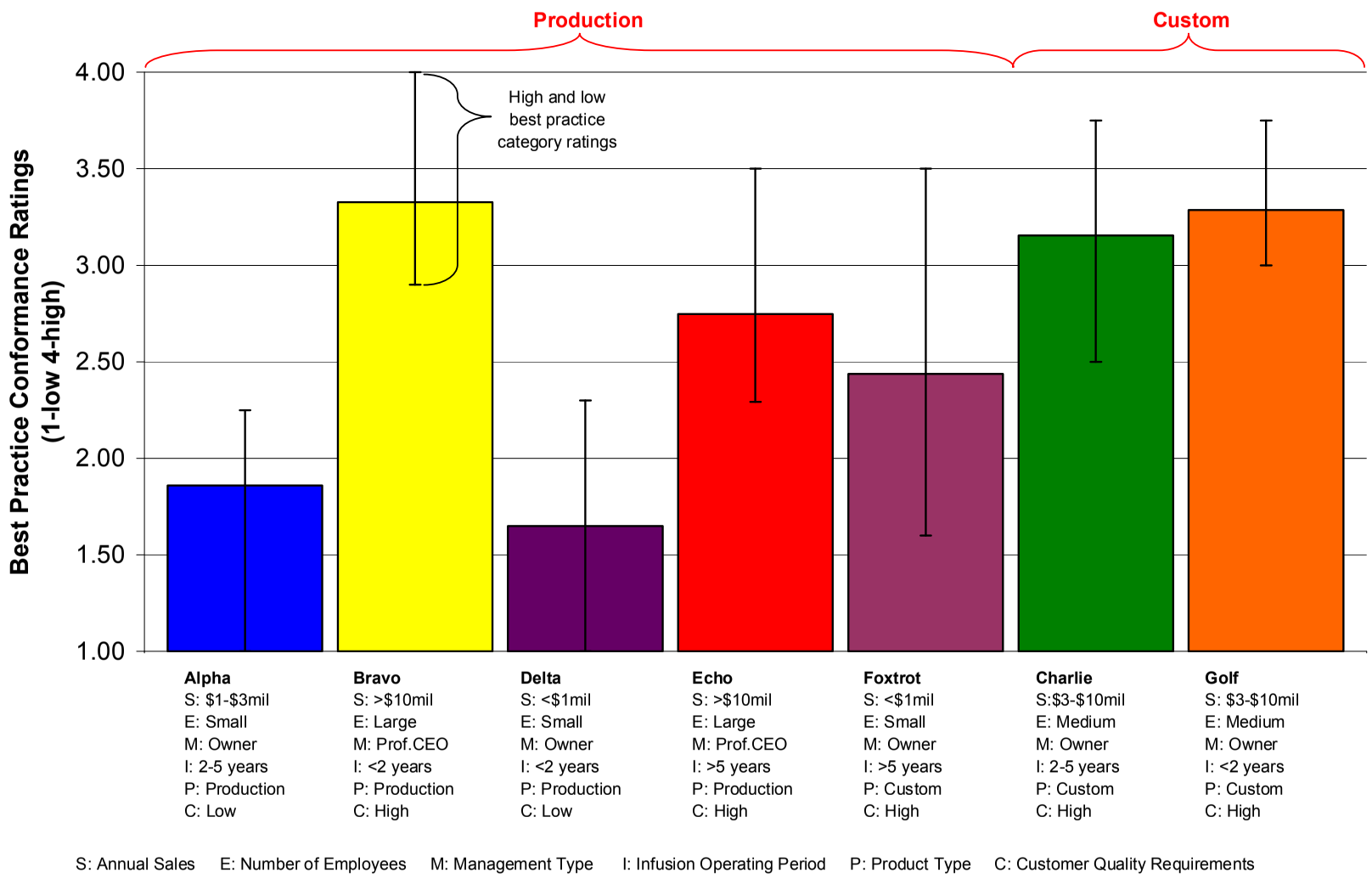

Figure 4.14 Graph of Best Practice Ratings by Product Type

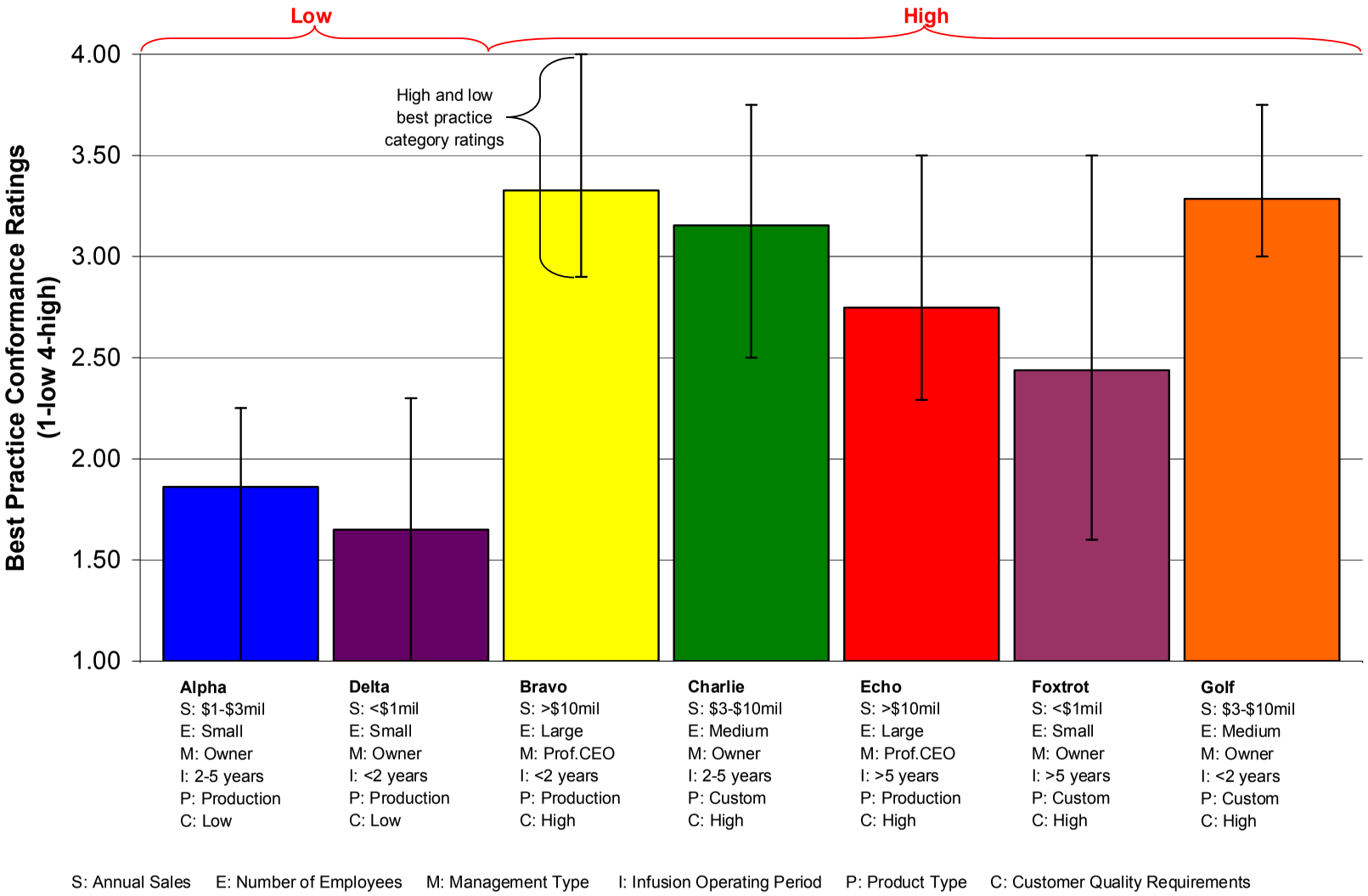

Figure 4.15 Graph of Best Practice Ratings by Customer Quality Requirements

Table 4.7 Correlation Coefficients

Best Practice Category	Demographic Category					
	Annual Sales (2007)	Number of Employees	Top Management Type	Infusion Operating Period	Product Type	Customer Quality Requirements
Quality Management System	0.738	0.660	0.210	-0.256	0.798	0.708
Documentation and Records	0.672	0.681	0.419	0.185	0.419	0.955
Training	0.758	0.792	0.487	-0.078	0.487	0.916
Facilities and Equipment	0.811	0.843	0.610	-0.352	0.334	0.698
Material Control	0.413	0.446	0.107	-0.376	0.608	0.747
Production and Testing	0.820	0.773	0.432	0.016	0.560	0.860
Average	0.758	0.750	0.400	-0.119	0.583	0.883

The correlation coefficients for the correlation matrix of Figure 4.2 which were calculated according to Equation 4.1 are given in Table 4.7. From Table 4.8 it can be shown that demographic categories 2007 Annul Sales, Number of Employees, and Customer Quality Requirements have very strong positive relationships; Top Management Type and Product Type have strong positive relationships; and Infusion Operating Period has no or a negligible relationship.

Table 4.8 Strength of Relationships between Demographic Categories and Best Practice Ratings

Demographic Parameter	Strength of Relationship
Annual Sales (2007)	Very strong positive relationships
Number of Employees	Very strong positive relationships
Top Management Type	Strong positive relationships
Infusion Operating Period	No or a negligible relationship
Product Type	Strong positive relationships
Customer Quality Requirements	Very strong positive relationships

With the correlation coefficients calculated it was necessary to conduct hypothesis testing to test for statistical significance. The P-values corresponding to the hypothesis testing described in section 4.6.1 are given in Table 4.9 and the relationship between the test statistic (t-value) the significance level (p-value) and the correlation coefficient (R) are illustrated in Figure 4.16. P-values range from zero to one; values close to zero

indicate a low probability of accepting the alternative hypothesis that there is a correlation between the two sets of data when there is in fact no correlation. P-values below 0.050 would lead to the rejection of the null hypothesis at the commonly used significance level α of 0.05. In other words, values below 0.050 lead us to conclude that there is statistical evidence behind a conclusion that there is a correlation. P-values for these relationships are denoted by an asterisk. This table shows that only the correlation coefficients between the average best practice ratings and the demographic categories "Annual Sales" and "Customer Quality Requirements" were statistically meaningful at a significance of 5%. Expanding the statistical significance level to 10% results in the inclusion of the demographic category "Number of Employees" as being statistically meaningful. There is however not enough statistical evidence at these levels of significance to conclude that there is a correlation between the average best practice ratings and demographic categories "Top Management Type", "Infusion Operating Period" or "Product Type".

Table 4.9 P-values

	Demographic Category					
Best Practice Category	Annual Sales (2007)	Number of Employees	Top Management Type	Infusion Operating Period	Product Type	Customer Quality Requirements
Quality Management System	0.058*	0.107	0.651	0.579	0.032**	0.075*
Documentation and Records	0.098*	0.092*	0.350	0.692	0.350	0.001**
Training	0.049**	0.034**	0.268	0.869	0.268	0.004**
Facilities and Equipment	0.027**	0.017**	0.146	0.439	0.464	0.081*
Material Control	0.357	0.316	0.820	0.406	0.147	0.053*
Production and Testing	0.024**	0.042**	0.333	0.973	0.191	0.013**
Average	0.048**	0.052*	0.374	0.799	0.169	0.008**

*p < 0.100

** p < 0.050

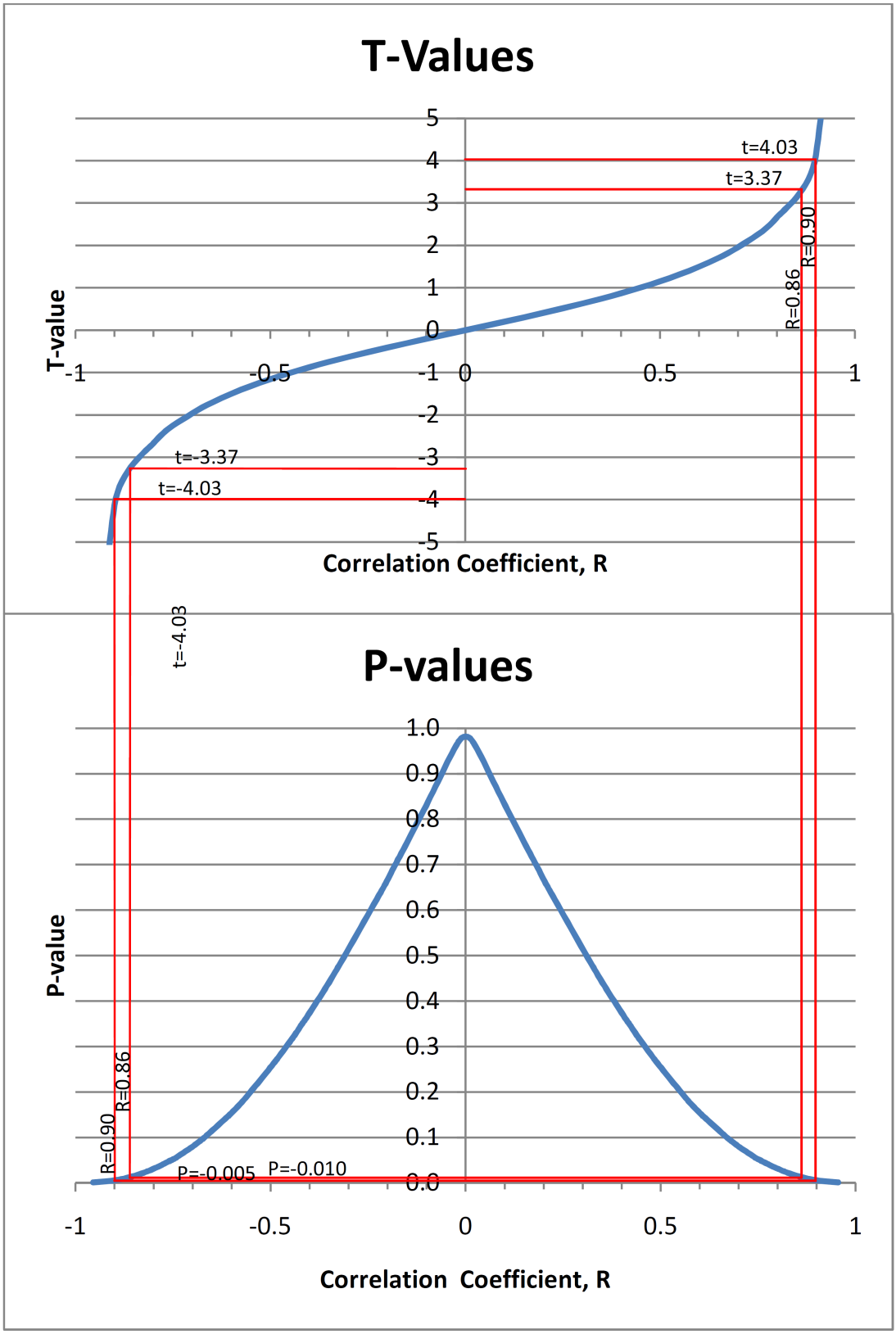

Figure 4.16 Relation of Correlation Coefficients to P-values and t-values

4.7.2 Summary of Results

The correlation analysis revealed that there is statistical evidence to conclude that at a 10% significance level there is a positive correlation between the average best practice ratings and the demographic categories "Annual Sales", "Number of Employees" and "Customer Quality Requirements".

Correlation analysis is incapable of determining a causal relationship; this must be determined using logic (Ayyub & McCuen, 1997). Therefore it is not enough to simply conclude that because there was a high degree of correlation between best practice ratings and certain demographic categories that this implies a cause and effect relationship. Each of these relationships must be examined on its own logical merits to determine if a causal relationship makes sense. The results of the correlation analyses are examined in this section with observations and remarks about the findings.

Annual Sales for 2007 and Number of Employees were found to have very strong positive correlations with best practice ratings. These two demographic parameters would be expected to share a similar relationship because they are both measures of manufacturer size. The Annual Sales parameter correlates highly with the Number of Employees parameter (R=0.96) indicating consistent size measurements. In terms of Annual Sales, the manufacturers making below $3 million had an average best practice rating of 1.98 while those above the $3 million mark averaged 3.13, a whole point difference between the small and large manufacturers (page 158).

In terms of Number of Employees the small manufacturers (<30 employees) had an average best practice rating of 1.98 while the medium (30-100 employees) and large

(>100 employees) had average best practice ratings of 3.22 and 3.04, respectively. In general the smaller manufacturers obtained ratings around 2 while the larger manufacturers were up around 3. Correlation of size to ratings makes logical sense. Larger manufacturers rely more on systems and written policies to effectively communicate within the company. When established these written policies are not usually created from scratch, but are based on precedent and best practice. Therefore it makes sense that as a company grows and develops more standard practices these are in accordance with industry best practice. This would explain the very strong correlation between size and best practice.

Management Type was found to have a "strong positive relationship" with the best practice ratings, but this correlation is not statistically significant at the 10% level. It would be logical to expect that manufacturers with professional manager CEOs would have higher ratings than owner CEOs. This was the case in this study with professional manager CEO and owner CEOs receiving ratings of 3.04 and 2.48, respectively. However there was significant variation among the owner CEO ratings. Manufacturers Bravo and Echo were the only two with professional manager CEOs. These two companies also happened to be classified as "large" in terms of size, "production" in terms of product type, and have "high" customer quality requirements. Infusion operating period is the only demographic parameter which distinguishes these two manufacturers. The fact that there was not a diversity of other demographic parameters among the professional manager CEO class means that this measure is not very robust. Even though manufacturers Charlie and Golf were classified as "owner CEO" they had

high ratings. Therefore, Management Type is not a very reliable predictor of best practice conformance.

However it is logical that the larger manufacturers would be more likely to have a professional manager CEO than the smaller manufacturers. This was found to be the case in this study. The two manufacturers that had annual sales in excess of $10 million (Bravo and Echo) were the only two that also had a professional manager CEO. Therefore the correlation between Management Type and the ratings could be due to the fact that manufacturers with professional manager CEOs tend to be larger, and manufacturer size is a logical predictor of high ratings.

Infusion Operating Period was found to have no correlation with best practice ratings. The correlation plot fails to reveal any patterns in the trending of ratings with length of time practicing resin infusion.

Product Type was found to have a "strong positive relationship" with best practice ratings, but this correlation is not statistically significant at the 10% level. Manufacturers that were production builders had an average rating of 2.41 while custom builders were at 3.22. Manufacturers Charlie and Golf are the only two custom builders in this study. This correlation analysis had the same issue that the Management Type correlation analysis did in that the only distinguishing parameter between the two manufacturers is the Infusion Operating Period parameter. The small sample size leads to a lack of robustness of this analysis. It is difficult to distinguish from this analysis whether the high ratings received by the two custom builders are because they are custom builders or because of some other parameter which they both share. This analysis would

have been made more conclusive by a larger sample size which included custom builders with other demographic parameters which were more varied. Because some production builders also received high best practice ratings (Bravo and Echo) this demographic parameter is a poor predictor of best practice ratings.

Customer Quality Requirements was found to have a "very strong positive relationship" to best practice ratings, receiving the highest correlation coefficient of any of the demographic parameters (R=0.883). Manufacturers with low customer quality requirements received an average rating of 1.76 while those with high customer quality requirements received an average rating of 2.99, a difference of 1.23. This correlation analysis has the same issues as both the Management Type and Product Type correlation analyses. Specifically the two manufacturers with low customer quality requirements (Alpha and Delta) only differed in demographic parameters of Annual Sales and Infusion Operating Period. However, this correlation analysis differs from the Management Type and Product Type analyses in that it is still a useful predictor of best practice ratings because the inter-category variation was low. This means that all the low customer quality requirement manufacturers received low ratings while all the high customer quality requirement manufacturers received high ratings. The analysis would nonetheless benefit from a larger sample size.

In summary demographic categories Annual Sales, Number of Employees and Customer Quality Requirements were found to be useful predictors of manufacturer best practice ratings. Larger manufacturers in terms of sales as well as employees were found to have higher best practice ratings. Manufacturers with higher customer quality

requirements had higher best practice ratings than those with low customer quality requirements. Infusion Operating Period did not have any correlation to best practice ratings, and Management Type and Product Type would benefit from a larger sample size.

4.8 Case Study: Company Alpha

As a case study the change in best practice conformance ratings was observed in company Alpha due to the implementation of a Quality Management System. After the initial industry investigation company Alpha was presented with the opportunity to serve a client with a high quality requirement. The prospective client was interested in having an infrastructure product manufactured which was required to meet strict dimensional and performance specifications and could possibly result in severe injury or death as a consequence of failure. The infrastructure product was required to meet a much higher level of quality than Alpha was accustomed to meeting. The client required that a quality assurance program be in place for a bid to be considered. Alpha approached the University of Maine asking for assistance in developing a quality management system. Researchers worked with company Alpha developing an overarching Quality Management System and guiding them in the development of their own SOPs, checklists, and inspection forms.

A second best practice rating was conducted immediately after the system was enacted by company Alpha. Unlike the first survey which was conducted by two researchers in an interview format with observational validation, the second survey was conducted by one researcher through direct observation. A member of management was

interviewed to provide information not able to be collected from direct observation. This second format was appropriate due to the high level of involvement of the researcher in the process of implementing the QMS.

Results of the Alpha case study are presented Table 4.10 and Figure 4.17. In regards to demographic changes Alpha experienced an increase in the level of customer quality requirements. An increase in annual sales due to the new market was projected; however this projected increase would still put Alpha in the $1-$3 million range.

Table 4.10 Case Study Best Practice Ratings

	Best Practice Conformance Ratings		
Best Practice Category	**Alpha Before**	**Alpha After**	**Change**
Quality Management System	1.60	3.20	+1.60
Documentation and Records	2.25	3.50	+1.25
Training	1.00	2.50	+1.50
Facilities and Equipment	2.20	2.70	+0.50
Material Control	2.00	3.58	+1.58
Production and Testing	2.11	3.28	+1.17
Average	1.86	3.13	+1.27

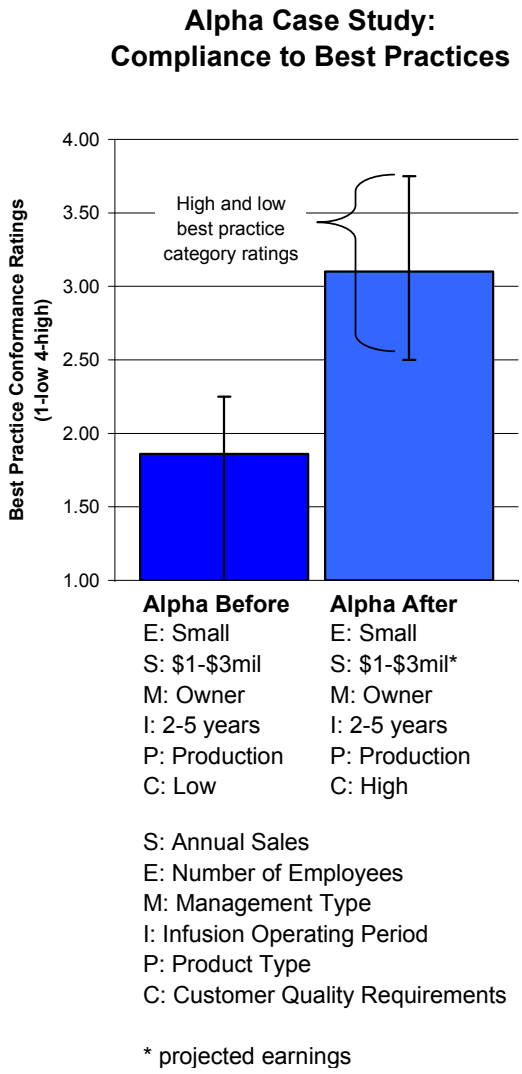

Figure 4.17 Graph of Best Practice Ratings for Case Study

The data show that Alpha's best practice ratings increased in every category contributing to an average best practice rating increase of 1.27. This pattern is consistent with the ratings observed in the Customer Quality Requirements correlation analysis. Manufacturers with low customer quality requirements received best practice ratings around 1.8, while those with high customer quality requirements were around 3.0, a difference of about 1.2. In this case Alpha's best practice rating before implementing the changes was 1.86, while the subsequent rating was 3.13. This increase in the best

practice rating with an increase in customer quality requirements is to be expected from the results of the industry analysis, and is observed in this case study.

The significance of the case study is that this data agrees with the causal relationship between the customer quality requirements and the best practice rating which was proposed in the previous section. The increase in the best practice rating was a direct result of meeting the demands imposed by higher customer quality requirements.

4.9 Discussion of Results

In this study high correlations were found between the degree of manufacturer conformance to best practices and both manufacturer size and the level of their customer quality requirements. A cause and effect relationship between the ratings and customer quality requirements was observed in a case evaluation in which one manufacturer implemented a QMS as a result of increased customer quality requirements. This implementation had the direct result of increasing conformance to best practices which was measured by an increase in their best practice rating. This observation of different levels of quality assurance implementation (conformance to best practices) conforms to the suggestions made by Bishop (1991), specifically the finding of higher levels of best practice implementation with higher customer quality requirements. Bishop (1991) suggested a three level system of quality assurance implementation depending on product performance and application. These attributes of product performance and application are embodied in this study's definition of customer quality requirements.

Since this study did not include a case evaluation of a manufacturer changing from a small to a large company, no cause and effect conclusions can be made about the

correlation between company size and best practice ratings. Table 4.11 reveals a lack of data points in this study for large manufacturers with low customer quality requirements. The effect of this hole in the data is that it is difficult to determine whether or not the correlation observed between company size and best practice ratings is a valid result. It is not possible to determine if high ratings are a result of both large size and high customer quality requirement or if these ratings are dependent on high customer quality requirements only. The presence of high ratings (close to three) for companies in this empty quadrant of the table would lead us to conclude that the ratings are dependent on both company size and customer quality requirements. However the presence of low ratings (close to two) in this empty quadrant would lead us to conclude that high ratings are independent of company size and are only dependent on customer quality requirements.

Table 4.11 Manufacturer Data Points vs. Predictor Characteristics

		Customer Quality Requirements	
		Low	**High**
Company Size	**Small**	Alpha -- 1.9 Delta -- 1.7	Foxtrot -- 3.1
	Med-Large		Bravo -- 3.3 Charlie -- 3.2 Echo -- 2.7 Golf -- 3.3

In this study manufacturers categorized as small or having low customer quality requirements uniformly received ratings near two, while those categorized as medium to large or having high customer quality requirements uniformly received ratings near three as shown in Table 4.12.

Table 4.12 Best Practice Ratings by Predictor Characteristics

Average Best Practice Ratings 1-low 4-high					
Size (Annual Sales)		**Size (Number of Employees)**		**Customer Quality Requirements**	
Less than $3mil.	**More than $3mil.**	**Less than 30**	**More than 30**	**Low**	**High**
2.0	3.1	2.0	3.1	1.8	3.0

The ratings of this study were found to be in agreement with the three tiered quality assurance recommendations of Bishop (1991). The "low customer quality requirements" category used in this study generally aligns with Bishop's (1991) lowest level of quality assurance where basic QA measures are in place. The high customer quality requirements category used in this study generally aligns with Bishop's (1991) second level of quality assurance. The requirements of Bishop's third level were not commonly required of manufacturers in this study. Using these observations it is possible to "calibrate" the best practice ratings of this study to Bishop's work. This leads to the conclusion that his first level would result in best practice ratings around two while his second level would result in ratings around three. It could be extrapolated that his third level of quality assurance would result in best practice ratings nearer to four using this study's rating system although none of the manufacturers in this study were implementing quality assurance as this level. This agreement would be expected as his

third level of quality assurance is the highest level possible for composite manufacturing and this study's rating system was based on four being perfect conformance to industry best practices.

4.10 Summary of the Industry Investigation

The purpose of the industry investigation was to determine the level of implementation of resin infusion industry best practices within the Maine composites manufacturing environment. A major goal of this study was discovering if certain manufacturer demographic parameters (annual sales, number of employees, management type, infusion operating period, product type, and customer quality requirements) correlated with best practice implementation. Manufacturers that were producing quality products were selected based on the diversity of demographic characteristics to attempt to obtain information which would be relevant to the entire composites manufacturing population. A survey instrument was used during on-site interviews to collect best practice implementation data. The data were analyzed with correlation analysis to quantify the strength of the relationships between best practice implementation and manufacturer demographic parameters.

In this study high correlations were found between the degree of manufacturer conformance to best practices and both manufacturer size and the level of their customer quality requirements. A cause and effect relationship between the ratings and customer quality requirements was observed in a case evaluation in which one manufacturer implemented a QMS as a result of increased customer quality requirements. While the statistical analysis suggested that the high correlation between best practice ratings and

manufacturer size was statistically meaningful, observations about the distribution of the data samples call this finding into question. The observation of higher levels of quality assurance implementation (higher best practice ratings) for higher customer quality requirements conforms to the suggestions made by Bishop (1991) about different levels of quality assurance implementation. It was also observed that the best practice ratings of around two in this study corresponded with Bishop's (1991) lowest tier of quality assurance implementation and that ratings of around three corresponded with his second tier. While none of the manufacturers in this study received ratings around four, these ratings would be expected to correspond to Bishop's (1991) highest level of quality assurance implementation. This is due to the fact that the rating system for this study was based on a rating of four corresponding to complete alignment with the industry best practices for quality assurance.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

In this chapter the best practices are divided into three separate levels of quality assurance and recommendations are presented for resin infusion manufacturers as to which level is appropriate based on their customer quality requirements. Recommendations regarding further research are presented and conclusions drawn.

5.2 Recommendations to Manufacturers

The primary aim of this research was to aid composite manufacturers by identifying resin infusion quality assurance and quality control (QA/QC) issues and identifying appropriate QA/QC practices. Recommendations are based on industry best practices identified in Chapter 3 and industry implementation levels observed in Chapter 4. The level of implementation was found in the industry investigation to have a very strong positive correlation relationship with the level of customer quality requirements. Manufacturers with higher customer quality requirements were more closely aligned to the industry QA/QC best practices than those manufacturers with lower customer quality requirements.

5.2.1 Three Expanded Levels of Quality Assurance

These composites manufacturing recommendations build on the three levels of quality assurance implementation recommended by Bishop (1991). He developed three levels of quality assurance that correspond to three levels of customer quality

requirements with level one being the base level and level three being reserved for very high quality products.

Level one practices represent the basic level of quality assurance for resin infusion. It is recommended that manufacturers of any infused product incorporate these practices into their production to reduce failed infusions and increase product quality. The practices for level one are given in Figure 5.1, practices originally proposed by Bishop are marked with an asterisk while those resulting from this study are unmarked. This level contains basic general requirements for organizational structure and training with minimal documentation. Incoming material practices are designed to eliminate blatantly incorrect or defective material. Processing controls are selected to control the most important sources of variation in production: resin mix proportions, temperatures, and vacuum integrity which can all lead to dry spots and voids. The final inspection relies on visual inspection to verify that there are no major flaws in the part.

Level One

General

- The responsibility to identify, control and assess quality is shared among all employees
- Details of key processes are documented
- Training is appropriate for the tasks required

Incoming Material

- Check for correct material upon receipt (visual inspection)*
- Record batch number (visual inspection)*
- Inspect reinforcement and core packaging for damage (visual inspection)*
- Materials are stored to prevent damage or contamination

Processing

- Maintain a reasonable standard of cleanliness (visual inspection)*
- Record key process parameters on control sheet to be kept on file
- Record operator(s) name(s)*
- Record correct ambient, resin, and mold temperature prior to infusion (thermometer)*
- Record correct resin/initiator proportions (accurate balance)*
- Record adequate resin mixing (visual inspection)*
- Record leak check (by ear)
- Record pressure drop test(s) (timer and pressure gage)

Final Part Inspection

- Inspect for voids, dry spots, delaminations, inclusions (visual inspection)*
- Inspect for surface quality and color variation (visual inspection)*
- Check dimensions (tape measure)*

*Bishop (1991)

Figure 5.1 Recommended QA/QC Practices: Level One

Level two practices are intended for products which are required to meet higher quality standards than level one products. Level two has much higher general requirements which are intended to increase the level of documentation and record generation. Requirements include the incorporation of an uncertified quality management system. The QMS includes requirements for a corrective action system, documentation of all processes, a system to control the use of current documentation, the use of standard operating procedures in production, the filing of process generated records. It also contains practices regarding equipment calibration and training. Incoming material practices subject incoming materials to a more thorough examination to validate properties. Practices segregate nonconforming materials from production inventory by inspection upon receipt, labeling systems, strict storage requirements, storage inspections, and pre-processing checks. Processing practices include a higher

level of cleanliness to prevent material contamination in the laminating environment. Records of the lamination alignment and sequence are generated. Temperatures are more carefully controlled and standards for consolidation time and cure time prior to demolding are followed. The final part inspection incorporates the use of destructive testing to verify as-built properties on selected or random parts and the use of inexpensive non-destructive tests on questionable parts.

Level Two - All procedures for Level One plus the following:

General

- The elements of an uncertified quality management system are in place
- Positions have written job requirements and internal and external training records are on file
- Calibrate testing and recording equipment on a schedule*
- Details of all processes are documented
- A documentation control system is in place
- Ensure product is built to current drawings/specifications*
- Standard operating procedures are used by personnel to guide processes
- Production data sheet includes batch numbers and final inspection*
- Process records are kept of file for specified periods of time
- A corrective action system is in place which affects processes

Incoming Material

- Proof test new materials before incorporation into production (building block approach)
- Separate incoming material from inventory until inspected
- Written acceptance/rejection criteria are used for incoming inspections
- Verify incoming material by matching with purchase orders
- Clearly label approved incoming material
- Non-conforming materials storage area is separate from inventory
- Material data sheets include identifying information
- Inspect sample of reinforcement roll for damage*
- Record areal weight of reinforcement sample (accurate balance)*
- Record areal weight and moisture content of core
- Record resin viscosity and gel time for each batch (Viscosity cup and gel timer)*
- Document certificate of conformity for materials*
- Inspect prepackaged kits for completeness
- Store all materials strictly according to manufacturer's recommendations*
- Check inventory material's self life on a schedule
- First-in first-out inventory selection policy is in place*

Figure 5.2 Recommended QA/QC Practices: Level Two

Processing

- Maintain high standards of cleanliness*
- Check and record expiration date of materials prior to use*
- Completely isolate dust generating sources from the laminating area
- Clean, inspect and apply release agent to tooling prior to gel coat/lamination
- Compressed air is filtered and clean to prevent gel coat contamination
- Gel coat is applied according to industry best practices (ACMA CCT Guidelines)
- Lamination is in dedicated space*
- Reinforcement is protected from contamination during cutting and transportation*
- Scaffolding is used to avoid walking on cores
- Verify laminate lay-up sequence (visual inspection)*
- Check lamination alignment (visual inspection)
- Record layout details
- Perform frequent in-process inspections*
- Feed line layout is tested prior to important infusions (building block approach)
- Maintain correct ambient, resin, and mold temperature throughout infusion (thermometer)*
- Record leak check (acoustic listening device)
- Consolidation and degassing standards are followed
- Manufacture witness panel(s) for testing*
- Record Barcol hardness readings before demolding (Barcol Hardness Tester)

Final Part Inspection

- Perform random/representative part destructive testing (mechanical properties)*
- Perform non-destructive testing on suspect parts (tap testing, SIDER)
- Perform fiber volume fraction test for representative parts (burnoff)*
- Determine degree of cure for representative parts (Barcol)*
- Determine void content for representative parts
- Check dimensions (calibrated equipment)*

*Bishop (1991)

Figure 5.2 Continued Recommended QA/QC Practices: Level Two

Level three practices are intended for infused products which are required to meet the most strict quality requirements. General QA/QC practices include a certified QMS which is subjected to regular audits and improvements. The quality assurance inspector plays an important role at this level of quality assurance. They must be independent of production, have no other responsibilities than quality assurance, and should oversee the entire production. Other general practices include frequent calibration of equipment, precisely defined product specifications, and complete material traceability. Incoming material inspection practices are very thorough and are similar to those used in the pre-

preg process outlined in *The Composite Materials Handbook CMH-17* (ASTM, 2002). Processing practices include the revalidation of resin gel time prior to processing and frequent checks of laminate sequence and alignment. Important infusion layouts are validated with computer models. The final part inspection involves the extensive use of destructive mechanical tests and frequent advanced non-destructive testing.

Level Three - All procedures for Level Two plus the following:

General

- A certified Quality Management System is in place
- Perform regular internal audits of the QMS
- One person is directly responsible for QA
- QA is independent of production*
- QA tasks are the only responsibility of the QA inspector
- Each stage of construction is certified by QA inspector*
- Calibrate testing and recording equipment on a schedule at short intervals*
- All parts are built to precise customer specifications or third party standards
- Materials are traceable from receiving to the finished part

Incoming Material

- An advanced materials qualification system is in place (e.g. CMH-17)
- Perform advanced resin characterizations tests (DMA, DTMA, DSC)
- Retain samples from each resin batch for traceability
- Verify reinforcement warp and weft ends per unit*

Processing

- Revalidate resin gel time prior to manufacturing
- Continuous temperature monitoring system is in place or laminating temperature is always kept constant
- Check each ply against laminate sequence as it is placed *
- Automatic placement of reinforcing or check lamination alignment with light templates
- Record changes in operators*
- Feed line layout is tested prior to important infusions (computer modeling)

Final Part Inspection

- Perform destructive testing of witness panels for all parts (mechanical properties)*
- Perform non-destructive testing for each component (UT, Laser Shearography, Thermography)*

*Bishop (1991)

Figure 5.3 Recommended QA/QC Practices: Level Three

5.2.2 Selecting a Level Based on Demographic Characteristics

This section provides suggestions for manufactures regarding which level of quality assurance to adopt depending on their specific demographic parameters. It should be emphasized that these are general guidelines which cannot take into consideration the specific needs of the manufacturer, client, or product. All composite products which

could in any way contribute to life safety should strive for the highest level of quality possible.

The industry investigation found that the level of implementation of quality assurance benchmark practices was highly correlated to the level of customer quality requirements. The customer quality requirements are defined by the product's required level of *performance* and the rigors of the *application* environment. Specifically performance addresses the level of customer specifications and application refers to the consequence of failure. High performance products would be those with many strict customer specifications. Examples include mechanical performance, appearance, dimensional tolerances, or weight specifications. Products with high consequence of failure include bridges, airplane components, boat hulls, primary structural components and others which would result in severe collateral damage or personal injury upon failure.

Manufacturers serving clients with very precise specifications for products with high consequences of failure should be implementing a high level of quality assurance. High consequence of failure refers to any situation where failure is completely unacceptable and includes consequences such as probable loss of life or injury. A level three (Figure 5.3) degree of quality assurance implementation would be appropriate for products where the resin infusion process is replacing the pre-preg/autoclave process. This level has traditionally been reserved for aerospace components, but could be expanded to include infrastructure, defense, and any products for which failure could result in loss of life.

A level two (Figure 5.2) degree of quality assurance implementation would be appropriate for all other high performance products which do not have a high consequence of failure. These components include those that would result in substantial repair costs or very little chance of human injury given failure. This level encapsulates the majority of the yacht production in Maine. Most wind energy components, certain corrosion resistant products, and some consumer goods products would fall into this category.

A level one (Figure 5.1) degree of quality assurance implementation would be appropriate for all components which do not need to meet particularly exacting requirements and which would result in minor repair costs and no chance of human injury as consequence of failure. These products include some marine products, most consumer goods, and some construction/architectural applications. These are usually products where the environment is not particularly demanding.

Manufacturers deciding which level of quality assurance to implement should find guidance from customers. Bishop (1991) suggested that all product specifications be agreed upon by manufacturer and client.

5.3 Recommendations for Further Research

As noted in the Discussion of Results section 4.9 extensions of this study would benefit from a larger sample size. The sample size of seven manufacturers was enough to gain important insights into the implementation of best practices within the composites manufacturing environment and to conclude that the level of customer quality requirements is a useful predictor of best practice implementation levels. However this

sample size was not large enough to determine whether or not manufacturer size is also a useful predictor of best practice implementation. This study would benefit from the inclusion of manufactures which fall into the small category in terms of size and which are classified as having low customer quality requirements according to the definition used in this study. A larger sample size would also increase the confidence of the findings.

It would also be beneficial to conduct more case evaluations like the one discussed in section 4.8. That evaluation monitored the change in best practice implementation through the course of changing customer quality requirements. It would also be beneficial to monitor the changes in best practice implementation over the course of company growth for specific manufactures. By monitoring levels of best practice implementation as a company goes from small to large it would be possible to gain insight into whether or not company size is a useful predictor of best practice implementation. If this was found to be the case the recommendation for appropriate levels of quality assurance could be extended to include guidelines pertaining to not only customer quality requirements but also company size.

5.4 Conclusions

The primary aim of this research was to aid composite manufacturers by identifying resin infusion quality assurance and quality control (QA/QC) issues and identifying appropriate QA/QC practices. The resin infusion issues were identified through an in depth investigation into the technical literature surrounding the relatively new process. The key defects found in resin infusion are (1) voids and dry spots; (2)

thickness and fiber volume fraction variations; (3) resin curing problems; (4) fiber orientation issues; (5) delaminations; and (6) secondary bonding issues. Causes and consequence of these defects were explained. An investigation into the principles of resin infusion revealed that the key variables of laminate permeability, infusion pressure, and resin viscosity determine the progress of the infusion. Thus it is important to control these variables through the use of appropriate quality control measures such as standard operating procedures.

With the issues identified from the resin infusion technical literature, the study reviewed existing QA/QC standards for composites manufacturing as well as systems for implementing quality assurance. General business practices from quality management systems such as ISO 9000 as well as shipbuilding classification society standards regarding composite manufacturing were referenced to identify common QA/QC practices which would control the key parameters identified in the resin infusion technical literature. The four general areas of QA/QC are (1) general requirements which are addressed by a quality management system, (2) incoming material inspections, (3) in-process controls, and (4) final part validation testing. These four areas cover the breadth of a thorough quality assurance program. The best practices from these sources were compiled in APPENDIX A: SURVEY INSTRUMENT and used to conduct an industry investigation.

The aim of the investigation was not only to identify the issues and appropriate QA/QC measures, but also to aid the manufacturers through communicating this information to them. Thus the industry investigation aimed to gauge the level of best practice implementation within the resin infusion manufacturing environment and

identify what manufacturer characteristics might influence best practice implementation. Characteristics such as size, infusion operating period, type of management, product type and customer quality requirements were tracked along with the levels of best practice implementation. It was found that manufacturers with high customer quality requirements consistently incorporated more quality assurance best practices than those with low customer quality requirements.

These findings were used to expand recommendations made by Bishop (1991) regarding appropriate levels of quality assurance for composites manufacturing. Three levels of quality assurance are proposed. The recommended adoption of one of these levels is based on the manufacturer's customer quality requirements with lower customer quality requirements permitting lower acceptable levels of quality assurance.

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APPENDIX A: SURVEY INSTRUMENT

Key	Area	Source	Underlying Principle	Inquiry	Response
1.01	Quality Management System	ABS 2-6-4.13 Personnel	Ideally one person is ultimately responsible for QA/QC, the quality assurance representative	Who is primarily responsible for the implementation of quality? What is the title of this position?	
1.02	Quality Management System	ABS 2-6-4.13 Personnel	The quality assurance representative should have authority over and be able to control the production environment.	Does this person have the authority to ensure that requirements are met? Can they stop production in the event of a serious quality problem?	
1.03	Quality Management System	ABS 2-6-4.13 Personnel	Other responsibilities could detract from the quality assurance representative's focus on quality.	Does this person have any other responsibilities other than the management of the quality system? If yes, explain.	
1.04a	Quality Management System	ABS 2-6-4.13 Personnel	The responsibility to identify, control and assess quality is shared among all employees.	Does production management have responsibility to identify, control and assess quality?	
1.04b	Quality Management System	ABS 2-6-4.13 Personnel	Approach to quality is company wide and is a team effort.	Please explain your company's approach to quality.	

Key	Area	Source	Underlying Principle	Inquiry	Response
1.05	Quality Management System	Lloyd's Register 8-2-1.6.1(a) Quality Assurance System	The manufacturer should have in place a quality assurance system in accordance with an international or national standard. The objective of a QMS is to measure and record compliance with approved plans and the building process description.	Does your company have a quality management system by which processes are defined and relevant records are kept? (e.g. ISO 9001:2000)	
1.06	Quality Management System	Corrective Action (Badiru, 1995, p.79)	Corrective action analyzes the systems and processes to eliminate the causes of nonconforming products	Is this system ever updated? (i.e., Is it static or dynamic?)	
1.07	Quality Management System	ABS 2-6-4.15 Internal Audit and Badiru, 1995, p.80	Audits of the QMS should be conducted on a schedule, documenting findings and implementing corrective action on uncovered deficiencies.	Do you ever perform internal audits of the quality management system? How frequently?	
1.08	Quality Management System	ABS 2-6-4.11 Documentation of Quality Assurance System	The manufacturer should establish, document and maintain a written quality management system.	Does your company have written quality procedures?	
1.09	Quality Management System	ABS 2-6-4.7 Building Process Description	The building process description should cover in detail the important production related processes.	Do these procedures cover the following: ☐ Documentation and Records ☐ Training ☐ Facilities and Equipment ☐ Inventory ☐ In-process Control ☐ Post Production (curing and testing)	

Key	Area	Source	Underlying Principle	Inquiry	Response
1.10	Quality Management System	Precise Specifications (Bishop, 1991)	Agreed upon precisely defined product standards of performance reduce misunderstandings and quality assurance expense. Third party standards are best.	Do you build parts to an agreed standard? (e.g. ASTM standards, third party inspections, a builder/buyer agreement) If so, what is the process by which agreements are made?	
2.01	Documentation and Records	ABS 2-6-4.17 Documentation	Written processes and procedures, such as the quality assurance manual, SOPs, and inspection forms should be in place before manufacturing.	What quality related documentation do you require before production? (e.g. Quality Assurance Manual, Building Process Description, Design Plans, SOPs, inspection forms)	

Key	Area	Source	Underlying Principle	Inquiry	Response
2.02	Documentation and Records	ABS 2-6-4 37.1 Records	The manufacturer should develop and maintain records that show achievement of the required quality and the effective operation of the quality system.	What quality related records do you keep on file?	☐ Quality Assurance Manual ☐ Documented procedures ☐ Work instructions ☐ Workmanship standards ☐ Internally produced standards ☐ Accept/reject criteria ☐ Representative samples ☐ Procedure approval tests ☐ List of recognized suppliers ☐ Working drawings with revision history ☐ Copies of purchase orders ☐ Records of incoming tests ☐ Records of in-process tests ☐ Records of final inspection tests ☐ Certificates of conformity for raw materials used ☐ Records of temperature and humidity ☐ Completed nonconformance reports ☐ Warranty claims ☐ Customer complaints ☐ Training records ☐ Internal audit reports ☐ Corrective action analysis ☐ Management review meeting minutes
2.03	Documentation and Records	ABS 2-6-4.37.3 Record Storage	All records should be kept in a secure environment for a predetermined period of time.	How are the records filed?	

Key	Area	Source	Underlying Principle	Inquiry	Response
2.04a	Documentation and Records	ABS 2-6-4.37.5 Records and Traceability	Records should be organized such that retrieval and interpretation is possible.	Are problems which may arise in a finished part traceable through the record keeping system?	
2.04b	Documentation and Records	ABS 2-6-4.23.3 Production	Material needs to be labeled and identifiable throughout storage for traceability.	Is material coming out of storage traceable and identifiable to the batch?	
3.01	Training	ABS 2-6-4.35 Training	Personnel involved in manufacturing, inspection, and testing should be adequately trained or have sufficient experience to meet quality requirements. This takes the form of written qualifications.	Describe the training program? (e.g. areas of training and level of training required)	
3.02	Training	ABS 2-6-4.23.17 Production Personnel	Internal and external training should be documented and kept on file.	What training is required for laminating and gel coating applicators? Is this documented and available?	
4.01	Facilities and Equipment	ABS 2-6-3.3.5.1 Laminating Premises	The laminating area needs to be fully enclosed, dry, clean, shaded, adequately ventilated and adequately lighted.	Is the shop fully enclosed? Dry? Clean? Areas generally free of scrap reinforcement and resin and surfaces and floors are regularly cleaned? Shaded? Ventilated? Adequately lighted?	

Key	Area	Source	Underlying Principle	Inquiry	Response
4.02	Facilities and Equipment	ABS 2-6-3.3.5.2 Laminating Premises	Temperature and humidity should remain relatively constant. Temperature should be maintained between 60°F and 90°F during laminating and relative humidity should be below 80%.	To what extent are the temperature/humidity maintained? In which areas are they maintained? What are the acceptable ranges before lamination, spraying etc.?	
4.03	Facilities and Equipment	ABS 2-6-3.3.5.4 Laminating Premises	Temperature and humidity should be monitored during lamination.	Are records of the shop temperature and humidity levels documented? (e.g. production records, monitoring system)	
4.04	Facilities and Equipment	ABS 2-6-3 3.5.5 Laminating Premises	Laminating areas should be remote or separated from dust creating operations.	How do you keep dust away from the laminating/gel coating areas? Do you have a dust collection system?	
4.05	Facilities and Equipment	ABS 2-6-3 3.5.6 Laminating Premises	Scaffolding should be used during lamination to prevent standing on cores or laminated surfaces.	Describe when you would employ the use of scaffolding in the laminating process.	
4.06	Facilities and Equipment	ABS 2-6-3 3.5.7 Laminating Premises	Ventilation should be adequate to control emissions and protect worker safety.	Are Hazardous Air Pollutants (HAP) and Volatile Organic Compounds (VOC) measured and monitored?	
4.07a	Facilities and Equipment	ABS 2-6-4.33.1 Calibration and Maintenance of Equipment	Production and inspection equipment should be maintained and calibrated according to the manufacturer's recommendations	Which equipment is maintained, serviced, calibrated per manufacturer's recommendations?	
4.7b	Facilities and Equipment	ABS 2-6-3.3.7.4 Equipment	Gel coat spray guns need to be regularly calibrated to ensure a proper mix ratio.	Catalyst injection accelerator of spray gun set to correct ratio and calibrated frequently?	

Key	Area	Source	Underlying Principle	Inquiry	Response
4.08	Facilities and Equipment	ABS 2-6-4.33.11 Calibration and Maintenance of Equipment	Maintenance and calibration should be done on a schedule.	How do you keep track of these schedules?	
4.09	Facilities and Equipment	ABS 2-6-3.3.7.3 Equipment	Compressed air for air operated equipment should be clean, dry and free from contaminates such as oil, moisture or dirt. The system should include traps that are cleaned and serviced frequently.	Is shop compressed air clean, dry and free of contaminants (oil, moisture, or dirt), contain traps, regularly cleaned and serviced?	
4.10	Facilities and Equipment	ABS 2-6-3.3.7.8 Equipment	All measuring equipment is to be certified and suitable for the quantity of material being measured. Valid certificates of calibration are to form part of the quality control documentation.	Is all measuring equipment certified and suitable, and documented?	
5.01	Material Control	Hoebergen, 2001	Incoming material should be proof tested off production parts.	Do you have standards that new disposables and materials must meet before being used in production?	
5.02	Material Control	ABS 2-6-3.5.3 Specifications and Data Sheets for Materials	Reinforcement data sheets should include the identifying information, fiber type and form, weave fiber orientation, weight, physical data and mechanical properties. They are available for reference.	What material specifications and data sheets do you require for reinforcements?	☐ Fiber type and form ☐ Weave ☐ Fiber orientation ☐ Weight ☐ Physical data ☐ Mechanical properties

Key	Area	Source	Underlying Principle	Inquiry	Response
5.03	Material Control	ABS 2-6-3.5.1 Specifications and Data Sheets for Materials	Resin system data sheets should include composition, storage information, and mechanical properties. Specific batches should have identification and properties. They are available for reference.	What material specifications and data sheets do you require for resins, gel coats, catalysts, accelerators, hardeners and other additives?	☐ Composition ☐ Storage requirements ☐ Cured/uncured mechanical properties ☐ Curing characteristics ☐ Properties of batch ☐ Batch data sheets
5.04	Material Control	ABS 2-6-3.5.5 Specifications and Data Sheets for Materials	Core material data sheets should include the identifying information, material type, density, and storage recommendations. They are available for reference.	What material specifications and data sheets do you require for core materials?	☐ Material specification number ☐ Material type ☐ Density
5.05a	Material Control	ABS 2-6-4. 21.1 Material Receipt, Inspection and Storage	Material should be kept separate from inventory prior to inspection and labeling.	Where do you put incoming material?	
5.05b	Material Control	ABS 2-6-4.21.1 Material Receipt, Inspection and Storage	The material is to be kept separate prior to receiving	Do you have an incoming material labeling and storage system?	
5.06	Material Control	ABS 2-6-4.21.3 Material Receipt, Inspection and Storage	Materials should be matched to a purchase order, be in good condition, tested for compliance to standards	What paperwork is involved with incoming materials? What is the inspection process?	

Key	Area	Source	Underlying Principle	Inquiry	Response
5.07	Material Control	ABS 2-6-3.7.1 Receiving Materials	Each incoming resin batch should be tested to verify properties (at least viscosity, gel time, and peak exotherm) as part of incoming material inspection. Written allowable tolerances should be stated for specific properties. Records of test results and samples should be retained.	What, if any, incoming tests do you perform on resin, gel coats, catalysts, accelerators, hardeners and other additives?	Resins ☐ Viscosity ☐ Thixotropic Index ☐ Gel Time ☐ Cure Time ☐ Peak Exotherm Temperature ☐ Weight per Gallon ☐ Wet Out Gel Coats ☐ Viscosity ☐ Thixotropic Index ☐ Gel Time ☐ Cure Time ☐ Peak Exotherm Temperature ☐ Color Consistency ☐ Weight per Gallon
5.08	Material Control	ABS 2-6-3.7.5 Receiving Materials	Core density and moisture content should be checked. Batch data sheets should be retained.	What, if any, incoming tests do you perform on cores?	☐ Visual inspection ☐ Density ☐ Moisture content
5.09	Material Control	ABS 2-6-3.7.3 Receiving Materials	Testing on incoming reinforcing materials should include a weight check and a visual inspection of a sample of the material for its physical condition. Batch data sheets should be kept on record.	What, if any, incoming tests do you perform on reinforcements?	☐ Areal weight ☐ Visual inspection of a sample ☐ Fiber finish/sizing
5.10	Material Control	ABS 2-6-4.21.13 Material Receipt, Inspection and Storage	All incoming materials should have documented accept/reject criteria.	Do you have material acceptance/rejection criteria?	

Key	Area	Source	Underlying Principle	Inquiry	Response
5.11	Material Control	ABS 2-6-4.21.13 Material Receipt, Inspection and Storage	Material which is suspected or known to be nonconforming should be separated from inventory.	What is done with material the does not meet acceptance standards?	
5.12	Material Control	ABS 2-6-4.29.3 Nonconforming Materials and Components	As part of a corrective action system nonconformities should be documented and addressed.	Is there a system in place to eliminate repetitive material nonconformance?	
5.13	Material Control	ABS 2-6-4.21.7 Material Receipt, Inspection and Storage	Materials with a limited shelf life should be used before the expiration date and in full compliance with manufacturer's recommendations	How do you track the shelf life of materials in storage?	
5.14	Material Control	ABS 2-6-3.3.1.3 Material Storage Premises	Resin must be stored in a temperature controlled environment and electrically grounded.	Describe the resin and gel coat storage requirements?	☐ Temperature control ☐ Electrically grounded
5.15	Material Control	ABS 2-6-3.3.1.3 Material Storage Premises	Initiator should be stored in a ventilated, grounded, temperature controlled, non-corrosive cabinet	Describe the catalyst storage requirements?	☐ Ventilated ☐ Grounded ☐ Temperature controlled ☐ Non-corrosive cabinet
5.16	Material Control	2-6-3.3.1.1 Material Storage Premises	Reinforcement storage area is enclosed, shaded, clean, dry, ventilated, and dust free according to manufacturer's recommendations.	Describe reinforcement storage requirements.	☐ Enclosed ☐ Shaded ☐ Clean ☐ Dry ☐ Ventilated ☐ Dust free
5.17	Material Control	Personal communication with A. Cocquyt	Vacuum bags should be guarded from abrasions and puncture threats.	How are vacuum bags stored?	

Key	Area	Source	Underlying Principle	Inquiry	Response
5.18	Material Control	Personal communication with A. Cocquyt	Materials should be used in the order that they were received to avoid prolonged storage times.	What is the process of selecting a material from storage? (e.g. first-in-first-out, first-in-last-out, none)	
5.19	Material Control	ABS 2-6-3.3.1.2 Material Storage Premises	If storage environmental conditions differ from laminating environmental conditions reinforcements should be acclimated for at least 48 hours?	What is done with reinforcement prior to use?	
5.20	Material Control	Lloyd's Register 8-2-2.5.3 Gel coats, tie coats, and water barriers	All resin should be at infusion temperature and checked for gel time drift.	What is done with the resin between storage and infusion?	
5.21	Material Control	ABS 2-6-4.21.7 Material Receipt, Inspection and Storage	Resin shelf life should be checked prior to mixing and infusion.	(should be included in above answer)	
5.22	Material Control	ABS 2-6-3.3.3 Mold Construction	Tooling should be constructed to avoid distortion, so as not to interfere with the resin cure, and to achieve the required surface quality. Alignment should be ensured for multi-part molds.	What criteria exist for mold construction quality?	
5.23	Material Control	Personal communication with A. Cocquyt	Production tooling should be stored indoors protected from damage.	How is tooling stored and moved?	

Key	Area	Source	Underlying Principle	Inquiry	Response
5.24	Material Control	ABS 2-6-3.3.5 Mold Construction	Tooling needs to be at the correct temperature and adequately waxed prior to laminating.	What criteria exist for mold use?	
6.01a	Production and Testing	ABS 2-6-4.23.1 Production	Laminators should have the necessary work instructions in the manufacturing area.	What quality assurance resources are available to the laminating staff?	
6.01b	Production and Testing	ABS 2-6-4.23.11 Production	The production staff is to have ready access to instructions on mold preparation, resin mixing, laminating, curing and release processes.	Are there standard operating procedures for common and critical production steps? What procedures are included?	
6.02	Production and Testing	ABS 2-6-4.23.3 Production	All material needs to be tracked out of storage and traceable into the finished part.	Do you keep track of material that is going into the part?	
6.03	Production and Testing	ABS 2-6-4.23.5 Production	The building process should be controlled with the use of checklists and key points should be inspected by the appropriate personnel.	How is the building process/steps controlled? Are certain people responsible for certain steps?	
6.04	Production and Testing	ABS 2-6-3.9.3.1 Laminating Procedure	Gel coat applied according to the best practices described in ACMA CCT Study Guide.	Describe the gel coating procedure.	
6.05	Production and Testing	Det Norske Veritas 3-4-2.401 VARTM and vacuum bagging	Feed and vacuum line layout should be designed based on proven experience or resin infusion software.	How do you determine the layout of vacuum and feed lines?	

Key	Area	Source	Underlying Principle	Inquiry	Response
6.06	Production and Testing	ABS 2-6-3.9.7.2 Main Lamination - Single Skin	Alignment of reinforcement layers should be verified by someone other than the laminator.	How do you assure that the reinforcement fabric is aligned correctly?	
6.07	Production and Testing	Det Norske Veritas 3-4-2.403 VARTM and vacuum bagging	The vacuum cavity should be checked for leaks, preferably with an acoustic devise.	Do you perform a leak check before infusion? How?	
6.08	Production and Testing	Hoebergen, 2001	Drop tests should be performed prior to infusion. 1"Hg/5min is a minimum standard.	Do you perform a drop test before infusion? How?	
6.09	Production and Testing	Personal communication with R. Elkin	Consolidation time standards should indicate minimum time for degassing of cores and consolidation of laminates.	Do you have a minimum time from when full vacuum is pulled to infusion?	
6.10	Production and Testing	ABS 2-6-4.23.13 Production	Times, conditions, measurements, graphical records, and other critical information should be recorded during lamination and stored in the product file.	Describe what records are kept of the lamination. What is done with this data?	
6.11	Production and Testing	ABS 2-6-4.25 Production Inspections and Tests	Inspections and tests should be conducted at critical process points as indicated on the work instructions by inspection personnel.	At what steps are inspections performed?	
6.12	Production and Testing	ABS 2-6-5.1 Gel Time	Gel time must be within specified upper and lower limits according to the manufacturer prior to use.	When and how do you conduct gel time tests?	

Key	Area	Source	Underlying Principle	Inquiry	Response
6.13	Production and Testing	ABS 2-6-5.5 Burnout and Thickness	Check fiber content on cutouts or plugs in a sufficient number of locations.	How often do you check fiber volume fraction?	
6.14	Production and Testing	ABS 2-6-5.7 Void Content	Any suspect areas should be tested for void content. Void content must be lower than 4%, and areas above 2% warrant further investigation.	Do you test for voids?	
6.15a	Production and Testing	ABS 2-6-3.9.11 Release and Curing	Parts should remain in the mold for at least 12 hours and should be removed such that damage is precluded.	How do you determine when a part may be demolded?	
6.15b	Production and Testing	ABS 2-6-5.3 Barcol Hardness	Parts should not be demolded before reaching a Barcol hardness reading of 40 or higher.	How do you perform Barcol tests? How often do you calibrate?	
6.16	Production and Testing	ABS 2-6-3-9.13 Secondary Bonding	Secondary bonding surfaces should be protected and free of contamination and should be roughened and cleaned prior to bonding.	What standards do you have for secondary bonding?	
6.17	Production and Testing	ABS 2-6-4.27 Final Inspection	Final inspection should verify that all building requirements have been met.	Describe the final inspection process.	

Key	Area	Source	Underlying Principle	Inquiry	Response
6.18a	Production and Testing	ABS 2-6-5.9 Validation Testing	Laminate properties should be determined from cut outs or witness panels. Properties include specific gravity, glass content, tensile strength and modulus, flexural strength and modulus, and shear strength.	What destructive tests do you perform? How often?	
6.18b	Production and Testing	Det Norske Veritas 3-4-2.302 Production Testing	Certain products and applications require nondestructive testing as a supplement to destructive testing.	Do you ever use nondestructive testing? What kinds and under what circumstances?	

APPENDIX B: RATING RUBRIC

1.00	**Quality Management System**				
1.01	One person responsible for QA/QC	No single person is responsible for QA/QC	Project managers oversee quality control on the floor per project	A few persons in upper management are responsible for QA/QC	One person is directly responsible for overseeing QA/QC
1.02	Quality assurance representative in control of production environment	QA and production are not distinct entities	QA is distinct, but does not have real authority over production	QA is distinct, checks some work and has authority to stop production	QA is distinct, checks all work and has authority to stop production
1.03	Only responsibilities are QA/QC	No QA/QC person	QA/QC is one of many responsibilities	QA/QC is the major responsibility, but not the only one	QA/QC is the only responsibility
1.04	Company wide approach to QA/QC	No employees have an attitude of team effort or personal responsibility for quality	A few key employees have an attitude of team effort and personal responsibility, most do not	Most employees have an attitude of team effort and personal responsibility, some do not	All employees have an attitude of team effort and personal responsibility
1.05	Quality management system	There is no QMS documentation of any kind or plans toward one	The basic elements of an uncertified QMS are in place	There is an uncertified QMS in place with supporting documentation	An international or national standard QMS is in place such as ISO 9001
1.06	Continuous improvement	There is no corrective action system in place	There is a corrective action system in place, but it is not used	There is a corrective action system in place, resulting in process alterations	There is a corrective action system in place, resulting in process alterations and scheduled reviews are conducted

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
1.07	Internal audits	There is no QMS	Internal audits are not conducted	Internal audits have been conducted before	Internal audits are conducted on a regular schedule
1.08	Written quality procedures	No quality documents exist	Some key processes are documented	Most processes are documented	There is a working quality manual
1.09	Quality procedures coverage	There are no Quality procedures	Quality procedures cover some items of level 4	Quality procedures cover most items of level 4	Quality procedures cover documentation, records, training, facility, equipment, inventory, in-process controls, testing, and other important production related processes.
1.10	Third party standards	Parts are not built to precise standards	Critical parts are built to precise standards	Critical parts are built to precise third party standards	All parts are built to a precise third party standards
2.00	**Documentation and Records**				
2.01	Documentation prior to manufacturing	There are no standard operating processes or inspection forms in place prior to construction	Few important standard operating processes and inspection forms are in place prior to construction	Majority of standard operating processes and inspection forms are in place prior to construction	Thorough written building process description, standard operating procedures, and inspection forms in place prior to construction
2.02	Process generated records	No records are generated during production	Process control forms are used to collect production data, but are used both inconsistently and lack thoroughness	Process control forms are used to collect production data, but are used either inconsistently or lack thoroughness	Thorough process control forms are used consistently for all infusions and are kept on file
2.03	Record filing	No records are prepared, maintained or available	There are major shortcomings in the record preparation, maintenance and filing system	There are only minor shortcomings in the record preparation, maintenance and filing system	All records are consistently prepared, maintained and filed securely for predetermined periods of time

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
2.04	Traceable records	No material batch specific records are kept	Material batch specific records are kept, but material is not traceable through the finished part	Material batch specific records are kept and material is traceable through the finished part for critical parts	Root cause analysis can be performed on problems which may arise in produced parts due to the organization and thoroughness of the records
3.00	**Training**				
3.01	Written job descriptions	There are no requirements for laminating or gel coating	There are flexible verbal requirements for laminating or gel coating	There are strict verbal requirements for laminating or gel coating	There are written requirements for laminating and gel coating
3.02	Training records	There are no training records	There are some training records, usually external training only	Most training records are kept, usually informal on-the-job training is not documented	All internal and external, formal and informal training records are kept on file
4.00	**Facilities and Equipment**				
4.01	Laminating area conditions	The laminating area meets none or very few of the requirements of level 4	The laminating area meets only a few of the requirements of level 4	The laminating area meets most of the requirements of level 4	The laminating area is fully enclosed, dry, clean, shaded, adequately ventilated and adequately lighted.
4.02	Temperature control	There is no temperature regulation in the laminating area	Temperature is highly variable in the laminating area due to inadequate active heating or cooling	The laminating area temperature varies slightly with the seasons due to only active heating or cooling	The laminating area temperature is always the same due to active heating and cooling
4.03	Temperature records	There are no temperature records	Temperature records are sometimes taken periodically	Temperature records are taken at every lamination	There is an automated continuous temperature monitoring system
4.04	Dust control	There is no consideration of the dust contamination to the laminating environment	Slight precautionary measures are taken to control dust in the laminating areas (i.e., point of use dust collection)	Major steps are taken to minimize dust in the laminating areas (i.e., central vacuum system and filtration)	Dust sources are completely isolated from the laminating areas

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
4.05	Scaffolding	No scaffolding is used to avoid walking on cores	Some scaffolding is used to avoid walking on cores	Extensive scaffolding is used to avoid walking on the cores	Scaffolding is always used to avoid walking on cores
4.06	HAPs and VOCs controlled	HAP and VOC levels have never been checked	The shop meets requirements but no systems are in place to control dust or VOCs	The shop meets requirements and systems are in place to reduce either dust or VOCs	The shop meets requirements and systems are in place to reduce both dust and VOCs
4.07	Precision equipment calibration	Precision equipment has never been calibrated	Only some precision equipment is calibrated regularly	Most precision equipment is calibrated regularly	Standards are in place specifying which precision equipment should be calibrated and how frequently
4.08	Maintenance schedules	No records or maintenance schedules are kept for equipment	Some equipment has a maintenance schedule	Most equipment has a maintenance schedule	All equipment has a maintenance schedule and records are kept on file
4.09	Compressed air is clean and dry	There is no compressed air filtration system	Some point of use compressed air filtration is used	Multiple moisture and oil filters are used in the compressed air system	Multiple moisture and oil filters are used in the compressed air system which are cleaned on a schedule
4.10	Appropriate measuring equipment	Measuring equipment is not appropriate for the application	Measuring equipment is appropriate but is not calibrated	Measuring equipment is appropriate and was calibrated once	Measuring equipment is appropriate and is calibrated regularly
5.00	**Material Control**				
5.01	Proof testing of new materials	New material is not proof tested	Only new material considered highly critical is proof tested off production parts	Most new material is proof tested off production parts	Without exception new material is proof tested off production parts

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
5.02	Reinforcement data sheets	Reinforcement data sheets are not available for reference	Reinforcement data sheets include general information and are of limited availability for reference	Reinforcement data sheets include specific information and are generally available for reference	Reinforcement data sheets include identifying information, fiber type and form, weave fiber orientation, weight, physical data, mechanical properties and are widely available for reference
5.03	Resin system data sheets	Resin system data sheets are not available for reference	Resin system data sheets include general information and are of limited availability for reference	Resin system data sheets include specific information and are generally available for reference	Resin system data sheets include composition, storage information, and mechanical properties and are widely available for reference; specific batches have identification and properties.
5.04	Core material data sheets	Core material data sheets are not available for reference	Core material data sheets include general information and are of limited availability for reference	Core material data sheets include specific information and are generally available for reference	Core material data sheets include the identifying information, material type, density, and storage recommendations; they are widely available for reference
5.05	Isolate and label incoming material	Incoming material is placed directly into inventory without inspection or labeling	Incoming material is inspected, but is stored close to inventory and could be confused with inventory	Incoming material is stored separately from inventory, but is not labeled so it could be used	Incoming material is stored separately from inventory until inspected, approved, and labeled as such
5.06	Purchase order validation of received materials	No purchase orders are used to check incoming material	Purchase orders are filed, but not used to verify incoming materials	Purchase orders are used to verify incoming materials and are filed, but they do not include material specifications	Purchase orders include material specifications, are used to verify incoming material conforms to the order and are kept on file

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
5.07	Incoming resin testing	There is no incoming resin testing	Resin is periodically tested for conformance to specified properties (viscosity, gel time, and peak exotherm)	Only new resin is tested for conformance to specified properties (viscosity, gel time, and peak exotherm); records are kept	Each incoming resin batch is tested for conformance to specified properties (viscosity, gel time, and peak exotherm); records are kept
5.08	Incoming core testing	Incoming core material is not inspected	Incoming core material is periodically visually inspected	Each box of incoming core material is visually inspected	Each box of incoming core material is visually inspected and areal weights are verified, moisture content is checked when a problem
5.09	Incoming reinforcement testing	Incoming reinforcement material is not inspected	Incoming reinforcement is periodically visually inspected	Each roll of incoming reinforcement is visually inspected	Each roll of incoming reinforcement is visually inspected and areal weights are verified
5.10	Material accept/reject criteria	There are no written acceptance criteria for incoming materials	Some incoming material have written allowable acceptance criteria	Most incoming material have written allowable acceptance criteria which are strictly followed	All incoming material have written allowable acceptance criteria which are strictly followed
5.11	Nonconforming material separation	There are no nonconforming material checks	Incoming but not inventory material is checked for nonconformance; it is separated but not labeled	Nonconforming material is removed from inventory but not labeled to prevent use	Incoming and inventory material is checked for nonconformance; any suspect material is labeled and separated from inventory
5.12	Nonconformities	There is no system for dealing with nonconforming material	Nonconforming material is dealt with on a case by case basis	A limited system is in place to deal with material nonconformities	A thorough system is in place to deal with material nonconformities including documentation and remedial action

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
5.13	Shelf life tracking	Shelf life is not tracked or checked before use	Shelf life is not tracked during storage, but is checked before use	Shelf life is tracked during storage and is checked before use	Shelf life is tracked during storage, inventory is checked on a regular basis for expired material, and it is checked before use
5.14	Resin storage	No consideration is given to resin storage conditions (e.g. stored outside, or in an unconditioned storage unit)	Resin is stored on the shop floor	Resin is in a dedicated room, electrically grounded and is at varying shop temperature	Resin is stored in a dedicated room, electrically grounded, with thermostatically controlled temperature limits
5.15	Initiator storage	No consideration given to initiator storage conditions	All initiators are stored in a dedicated cabinet	Initiators are stored separately based on compatibility	Initiators are stored separately based on compatibility, in a ventilated space, in a noncorrosive cabinet, and at the recommended temperature
5.16	Reinforcement storage	Reinforcement storage area meets none or very few of the requirements of level 4	Reinforcement storage area meets only a few of the requirements of level 4	Reinforcement storage area meets most of the requirements of level 4	Reinforcement storage area is enclosed, shaded, clean, dry, ventilated, and dust free according to manufacturer's recommendations
5.17	Vacuum bag storage	No consideration is given to vacuum bag storage; it is exposed to damage	Some consideration is given to vacuum bag storage (e.g. on roll rack, but exposed to sharp or abrasive materials)	Vacuum bags are left in the original packaging and precautions are taken while being accessed	All necessary precautions are taken to protect vacuum bags from any form of damage (e.g. stored on roll rack and protected)
5.18	Material selection system	There is no system is in place to control selection of materials from storage	Some system other than a first-in-first-out system is in place	A loose first-in-first-out system is in place	A strict first-in-first-out system is in place or all materials are ordered and assigned to a project

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
5.19	Reinforcement conditioning	Reinforcements are not stored in laminating environmental conditions and no consideration is given to conditioning prior to infusion	Reinforcements are not stored in laminating environmental conditions, some consideration is given to conditioning prior to infusion	Reinforcements are stored at laminating temperatures	Reinforcements are stored at laminating temperatures and temperature is checked before infusion
5.20	Resin conditioning	Resin temperature or gel time are never checked prior to infusion	Resin temperature is checked but not recorded prior to infusion	Resin temperature is checked and recorded prior to infusion	Resin temperature is checked and recorded prior to infusion and gel time is tested for resins with prolonged storage
5.21	Resin shelf life check before use	Resin shelf life is not verified prior to mixing	Resin shelf life is not consistently verified prior to mixing	Resin shelf life is always verified, but not recorded prior to mixing	Resin shelf life is always verified and recorded prior to mixing
5.22	Tooling construction	None of the considerations of level 4 are met for tooling construction	Some of the considerations of level 4 are met for tooling construction	Most of the considerations of level 4 are met for tooling construction	Tooling is constructed to avoid distortion, so as not to interfere with the resin cure, and to achieve the required surface quality; alignment is ensured for multi-part molds
5.23	Tooling storage	Most tooling is stored outside and unprotected	Most tooling is stored outside, but is protected	Most tooling is stored inside and protected	All tooling is stored inside and protected at all times or tooling is one time use and not stored
5.24	Tooling conditioning	Tooling temperature requirements not considered prior to infusion; and mold release is applied after difficult demolds	Loose tooling temperature requirements are followed and prior to infusion; and mold release is applied as needed	Strict tooling temperature requirements are always followed; and mold release is applied as needed	Strict tooling temperature requirements are always followed and recorded prior to infusion; and mold release is applied on a schedule
6.00	**Production and Testing**				

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
6.01	Work instructions in work area	There are no work instructions available to the laminators	There are minimal work instructions, but these are not commonly utilized by the laminators	There are some work instructions which are commonly utilized by the laminators	There are detailed work instructions available to and utilized by the laminators which describe all critical production processes
6.02	Material traceability	No components or materials are documented or traceable in the finished part	Sometimes critical components are documented and traceable in the finished part	Only critical components are documented and traceable in the finished part	Each piece of material is documented and traceable in the finished part
6.03	Process control forms	There is no use of process control forms or checklists	Some of the processes are controlled through the use of control forms or checklists	All of the processes are controlled through the use of control forms or checklists, but key points are not inspected for conformance to standards	All of the processes are controlled through the use of control forms or checklists and key points are inspected for conformance to standards
6.04	Gel coating application	There are no standards for gel-coat application	Internal standards are mostly followed for gel-coat application	Internal standards are strictly followed for gel-coat application	Industry best practices are strictly followed for gel-coat application
6.05	Feed line layout	A new feed and vacuum line layout is designed based on experience alone	A new feed and vacuum line layout is always designed based on proven experience and sometimes tested on a sample part	A new feed and vacuum line layout is always designed based on proven experience and always tested on a sample part	A new feed and vacuum line layout is always designed based on proven experience, tested on a sample part and verified with the use of modeling software
6.06	Lamination alignment is checked	Lamination alignment is never checked	Each lamination stack is checked by the laminator	Each lamination stack is always checked and recorded by someone other than the laminator	Each lamination layer is always checked and recorded by someone other than the laminator

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
6.07	Leak check	A leak check is never performed prior to infusion	A leak check is sometimes performed by ear prior to infusion	A leak check is performed by ear prior to every infusion	A leak check is performed and recorded prior to every infusion with an acoustic listening device
6.08	Drop test	A drop test is never performed prior to infusion	A drop test is performed and recorded prior to every infusion according to lenient leak rates (e.g. less than 1”Hg/1minutes)	A drop test is performed and recorded prior to every infusion according to moderate leak rates (e.g. less than 1”Hg/5minutes)	A drop test is performed and recorded prior to every infusion according to strict leak rates (e.g. less than 1”Hg/15minutes)
6.09	Consolidation and degassing	No consideration is given for consolidation and degassing time	Low standards are sometimes followed for consolidation and degassing time	Standards are sometimes followed for consolidation and degassing time	High standards are consistently followed and recorded for consolidation and degassing time
6.10	Lamination information	No records of laminations are kept	Conditions and some critical information is recorded during lamination and stored in the product file	Times, conditions, measurements, and other critical information is recorded during lamination and stored in the product file	Times, conditions, measurements, graphical records, and other critical information is recorded during lamination and stored in the product file
6.11	Process inspections and tests	No inspections or tests are conducted during production	Some inspections and tests are conducted at critical process points	Inspections and tests are conducted at critical process points by inspection personnel	Inspections and tests are conducted at critical process points as indicated on the work instructions by inspection personnel
6.12	Gel time tests	No gel time tests are performed before infusions	Gel time tests are periodically performed before infusions	Gel time tests are performed before most major infusions	Gel time tests are routinely performed before every infusion

Key	Area	1 – Does Not Conform	2 – Somewhat Conforms	3 – Mostly Conforms	4 –Fully Conforms
6.13	Fiber volume fraction	Fiber volume fraction is never verified	Fiber volume fraction is sometimes verified in suspect areas	Fiber volume fraction is verified in critical parts	Fiber volume fraction is verified in every part
6.14	Voids check	Void content is never checked or only visually	Void content is sometimes checked in highly suspect areas or by a tap test	Void content is always checked in suspect areas	Void content is always checked in suspect areas to allowable standards
6.15	Barcol hardness test	There are no cure standards for demolding	Cure standards are mostly followed for each part prior to demolding	High cure standards are written and followed for each part; a method of verification is not used prior to demolding	High cure standards are written and followed for each part; a Barcol harness test or other acceptable method of verification is used prior to demolding
6.16	Secondary bonding	There are no secondary bonding requirements	There are some unwritten secondary bonding requirements	There are thorough unwritten secondary bonding requirements which specify surface preparation	There are written secondary bonding requirements which specify surface preparation
6.17	Final inspection	The final product is never inspected	The final product is informally inspected during the finishing stage	The final product is visually inspected to standards prior to shipping	The final product must pass a thorough visual inspection checklist and proof tests prior to shipping
6.18	Testing	No validation testing is performed on any parts or designs	Validation testing is only performed on new designs	Validation testing is always performed on each new design and on suspect parts	Validation testing is always performed on each part

APPENDIX C: MANUFACTURER RATINGS

Key	Best Practice	Best Practice Conformance Ratings							Avg.	S.D.
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf		
1.00	**Quality Management System**	**1.6**	**2.9**	**3.4**	**1.3**	**2.5**	**1.6**	**3.6**	**2.4**	**0.93**
1.01	One person responsible for QA/QC	2	3	4	1	3	2	4	2.7	1.11
1.02	Quality assurance representative in control of production environment	1	3	4	1	2	1	4	2.3	1.38
1.03	Only responsibilities are QA/QC	1	3	4	1	3	1	3	2.3	1.25
1.04	Company wide approach to QA/QC	3	4	4	4	3	3	4	3.6	0.53
1.05	Quality management system	1	2	3	1	2	1	3	1.9	0.90
1.06	Dynamic QMS	1	3	3	1	1	1	4	2.0	1.29
1.07	Internal audits	1	2	2	1	2	1	2	1.6	0.53
1.08	Written quality procedures	2	3	3	1	3	2	4	2.6	0.98
1.09	Quality procedures coverage	2	2	4	1	2	2	4	2.4	1.13
1.10	Third party standards	2	4	3	1	4	2	4	2.9	1.21
2.00	**Documentation and Records**	**2.3**	**4.0**	**3.8**	**1.5**	**3.5**	**3.5**	**3.8**	**3.2**	**0.93**
2.01	Documentation prior to manufacturing	2	4	4	2	4	3	4	3.3	0.95
2.02	Process generated records	3	4	4	1	4	4	4	3.4	1.13
2.03	Record filing	3	4	4	2	4	4	4	3.6	0.79
2.04	Traceable records	1	4	3	1	2	3	3	2.4	1.13

Key	Best Practice	Best Practice Conformance Ratings							Avg.	S.D.
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf		
3.00	**Training**	**1.0**	**3.0**	**2.5**	**1.0**	**2.5**	**2.0**	**3.0**	**2.1**	**0.85**
3.01	Written job descriptions	1	3	3	1	3	2	3	2.3	0.95
3.02	Training records	1	3	2	1	2	2	3	2.0	0.82
4.00	**Facilities and Equipment**	**2.2**	**3.6**	**3.0**	**2.3**	**2.8**	**2.4**	**3.0**	**2.8**	**0.50**
4.01	Laminating area conditions	4	4	4	4	4	4	4	4.0	0.00
4.02	Temperature control	3	3	3	3	3	3	3	3.0	0.00
4.03	Temperature records	3	3	3	3	3	3	3	3.0	0.00
4.04	Dust control	1	4	2	3	4	2	1	2.4	1.27
4.05	Scaffolding	1	2	4	2	2	1	1	1.9	1.07
4.06	HAPs and VOCs controlled	2	4	2	1	3	2	3	2.4	0.98
4.07	Precision equipment calibration	2	4	3	2	2	2	3	2.6	0.79
4.08	Maintenance schedules	1	4	2	2	2	2	4	2.4	1.13
4.09	Compressed air is clean and dry	3	4	4	1	3	2	4	3.0	1.15
4.10	Appropriate measuring equipment	2	4	3	2	2	3	4	2.9	0.90

Key	Best Practice	Best Practice Conformance Ratings							Avg.	S.D.
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf		
5.00	**Material Control**	**2.0**	**3.3**	**3.0**	**2.3**	**2.3**	**2.7**	**3.3**	**2.7**	**0.51**
5.01	Proof testing of new materials	2	3	4	2	3	3	4	3.0	0.82
5.02	Reinforcement data sheets	2	3	3	3	2	3	3	2.7	0.49
5.03	Resin system data sheets	2	3	3	3	2	3	3	2.7	0.49
5.04	Core material data sheets	2	3	3	3	2	3	3	2.7	0.49
5.05	Isolate and label incoming material	2	4	3	1	4	3	4	3.0	1.15
5.06	Purchase order validation of received materials	2	3	4	2	3	3	4	3.0	0.82
5.07	Incoming resin testing	1	4	1	1	1	1	4	1.9	1.46
5.08	Incoming core testing	1	1	1	1	1	1	3	1.3	0.76
5.09	Incoming reinforcement testing	1	4	4	1	1	1	3	2.1	1.46
5.10	Material accept/reject criteria	1	2	2	1	1	2	3	1.7	0.76
5.11	Nonconforming material separation	1	3	3	1	1	1	3	1.9	1.07
5.12	Nonconformities	1	2	3	1	2	2	3	2.0	0.82
5.13	Shelf life tracking	2	4	4	2	3	3	4	3.1	0.90
5.14	Resin storage	2	4	3	2	1	4	4	2.9	1.21
5.15	Initiator storage	3	3	3	3	2	3	3	2.9	0.38
5.16	Reinforcement storage	4	4	4	4	4	4	4	4.0	0.00
5.17	Vacuum bag storage	3	3	3	na	3	3	3	3.0	0.00
5.18	Material selection system	1	4	4	2	4	4	4	3.3	1.25
5.19	Reinforcement conditioning	3	3	3	3	3	3	3	3.0	0.00
5.20	Resin conditioning	3	3	4	3	3	3	3	3.1	0.38
5.21	Resin shelf life check before use	2	4	4	3	3	3	3	3.1	0.69
5.22	Tooling construction	3	4	2	4	2	4	4	3.3	0.95
5.23	Tooling storage	2	4	na	2	1	na	1	2.0	1.22
5.24	Tooling conditioning	2	3	2	4	3	3	2	2.7	0.76

Key	Best Practice	Best Practice Conformance Ratings							Avg.	S.D.
		Alpha	Bravo	Charlie	Delta	Echo	Foxtrot	Golf		
6.00	**Production and Testing**	**2.1**	**3.2**	**3.2**	**1.5**	**2.9**	**2.4**	**3.1**	**2.6**	**0.65**
6.01	Work instructions in work area	2	4	4	1	4	3	4	3.1	1.21
6.02	Material traceability	2	4	4	2	4	4	2	3.1	1.07
6.03	Process control forms	2	4	4	1	4	3	4	3.1	1.21
6.04	Gel coating application	1	4	na	na	4	2	4	3.0	1.41
6.05	Feed line layout	2	na	4	na	3	3	3	3.0	0.71
6.06	Lamination alignment is checked	1	2	3	1	2	2	2	1.9	0.69
6.07	Leak check	4	na	4	na	4	3	3	3.6	0.55
6.08	Drop test	4	na	4	na	3	2	4	3.4	0.89
6.09	Consolidation and degassing	3	na	4	na	1	1	4	2.6	1.52
6.10	Lamination information	3	3	4	2	3	3	3	3.0	0.58
6.11	Process inspections and tests	2	4	3	1	2	2	3	2.4	0.98
6.12	Gel time tests	1	4	4	2	4	4	1	2.9	1.46
6.13	Fiber volume fraction	1	2	1	1	1	1	2	1.3	0.49
6.14	Voids check	2	2	2	2	2	2	2	2.0	0.00
6.15	Barcol hardness test	2	3	2	2	2	2	4	2.4	0.79
6.16	Secondary bonding	2	3	2	2	3	3	4	2.7	0.76
6.17	Final inspection	2	4	4	2	4	2	4	3.1	1.07
6.18	Testing	2	2	2	1	2	1	3	1.9	0.69

BIOGRAPHY OF THE AUTHOR

Jonathan was raised in the Bangor, Maine area attending Hermon High School and graduating with high honors. Immediately following his high school graduation Jonathan began his engineering career with a student researcher position at the AEWC Advanced Structures and Composites Center on the University of Maine's Orono campus. During his undergraduate career he married his high school sweetheart and continued on as a student researcher. Undergraduate engineering classes and hands on laboratory experience proved an invaluable educational experience and through this position he was able to lead various projects and even draft and spearhead the U.S. Patent application process for a composites related laboratory invention. He graduated summa cum laude and immediately began graduate work towards a Master's degree in structural engineering at the AEWC at UMaine. He played a role in the vetting of the Certified Composites Technician-Vacuum Infusion Process (CCT-VIP) curriculum published by the American Composites Manufacturer's Association (ACMA). Prior to graduating he was able to provide composites quality assurance consulting for the Maine DOT and a composites manufacturer striving for an improved quality assurance system. He was able to bring his expertise in the composites manufacturing process to Advanced Infrastructure Technologies, LLC (AIT) in 2009 developing and implementing a production level QA/QC program for the company's composite arch manufacturing system. He continues with AIT as a structural engineer and oversees the manufacturing division. When not focusing on AIT related work Jonathan is in Levant with his wife and two young children helping to run a successful agricultural-tourism diversified family farm. He is a candidate for the Master’s degree in Civil Engineering from The University of Maine in August, 2010.