Economics of Composite Material Manufacturing Equipment

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

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ABSTRACT

Composite materials are used for products needing high strength-to-weight ratios and good corrosion resistance. For these materials, various composite manufacturing processes have been developed such as Automated Tow Placement, Braiding, Diaphragm Forming, Resin Transfer Molding, Pultrusion, Autoclave Curing and Hand Lay Up. The aim of this paper is to examine the equipment used for these seven processes and to produce a cost analysis for each of the processes equipment.

Since many of these processes are relatively new or are fairly costly and specified to the customers need, much of the equipment is custom made to meet the requirements of the part being produced. Current pricing information for individual custom-built machines, as well as standard machinery has been provided here.

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1. Introduction

Composite materials are used in various applications where light weight, corrosive resistant, high strength materials are needed. These composites are used in lieu of metal, wood or other stock materials. The traditional method of manufacturing materials has been to remove material from the raw stock. However, composite materials are typically manufactured by building up layers of material to shape and produce the end product. Glass, carbon, boron, and aramid fibers are typically used to produce composite materials. The composite manufacturing processes that are of particular interest in this paper are Automated Tow Placement, Braiding, Diaphragm Forming, Resin Transfer Molding, Pultrusion, Autoclave Curing, and Hand Lay Up.

Since composite manufacturing methods differ from traditional manufacturing methods, unique equipment is required for these composite material manufacturing processes [3]. The equipment used is sometimes custom built because in various cases the equipment options vary depending on what product is to be produced. As the composite material industry has developed, equipment has now become standard for many processes. However, some processes are relatively young and therefore may not have standard equipment available. The standardization of equipment has allowed for the results of this study of prices and price drivers for composite materials manufacturing equipment.

1.1 Approach

The main aim of this thesis is to give a cost analysis of the equipment used in Automated Tow Placement, Braiding, Diaphragm Forming, Resin Transfer Molding, Pultrusion, Autoclave Curing, and Hand Lay Up. Graphical analysis of price and the processes discriminators are given where applicable. In order to conduct a pricing analysis of composite manufacturing equipment for the processes described above, manufacturers of such equipment were found by using various composite manufacturing guides [4]. In many cases, the manufacturers of the composite materials were contacted in order to learn where the equipment they used was purchased. The majority of the composite equipment manufacturers who were contacted provided brochures and pricing information.

1.2 Thesis Outline

In this paper, seven composite manufacturing processes have been examined in order to find the cost drivers and a cost estimation for the equipment for each of the processes. The processes examined are Automated Tow Placement, Braiding, Diaphragm Forming, Resin Transfer Molding, Pultrusion, Autoclave Curing, and Hand Lay Up.

The first section of this paper is the Introduction and it includes the aim of the paper, the process used to approach the problem, and a brief thesis outline. The Background section explains the full process and equipment required for each of the seven composite manufacturing processes listed above. Section three presents the results found and a graphical cost-analysis where applicable. The final section includes a discussion of the results shown in section three and recommendations for further studies of this kind.

2. Background

The seven composite manufacturing processes examined in this paper will be described in 2.1 Process Summary. The equipment used for these processes is described in further detail in 2.2 Equipment Description.

2.1 Process Summary

Automated Tow Placement / Tape Laying (ATP)

Automated tape or tow placement is a process by which layers of prepreg tapes are placed parallel to one another upon a tool or contour. The tape is stored on spools (reels) that are carried with the tape laying head as it places the tape. After laying the tape, the tape is cut to the desired laminate design [1].

The tape form consists of unidirectional strands of glass, carbon, and other fibers that are pre-impregnated with resin. Commonly, epoxy resins are used for this process but thermoplastics can be layed up with modifications to the process. The tape comes in various widths from about 1/8" to 1" for tow placement and 3", 6" and 12" widths for tape laying. The equipment used for this process is called a Tape Layer and typically consists of a CNC controlled multi-axis machine used to deposit prepreg tape or tows onto a curing tool or the contour of a lay-up [1].

Since ATP is often used in large-scale productions, tools are usually manufactured out of metals. The tool may either be machined out of Invar or aluminum depending on the use of the tool as a curing device or not. For the process of tape laying the tools are mainly flat or simply curved. However, for tow placement they may also feature moderate double curvature. In aerospace, ATP is used for the production of large, simple to moderately complex parts.

The use of ATP for small, complex parts would not be time efficient or economical. ATP can achieve very good part repeatability and accuracy [1].

Braiding

Braiding is a process of inter-weaving fibers to form a braided material that is shaped by a former or over a mandrel. With braiding, two or more dry or prepreg yarns, tapes or tows are introduced on carriers to be wound together [2]. For composite braiding, kevlar, fiberglass, carbon and pre-impregnated fibers can be used [5]. Two-dimensional or three-dimensional braiding can be used to make composite braids. Typically, composite braiding occurs over a mandrel or rotating and removable form, which provides the shape of the braided material [2]. A braided composite form can be seen in Figure 1.

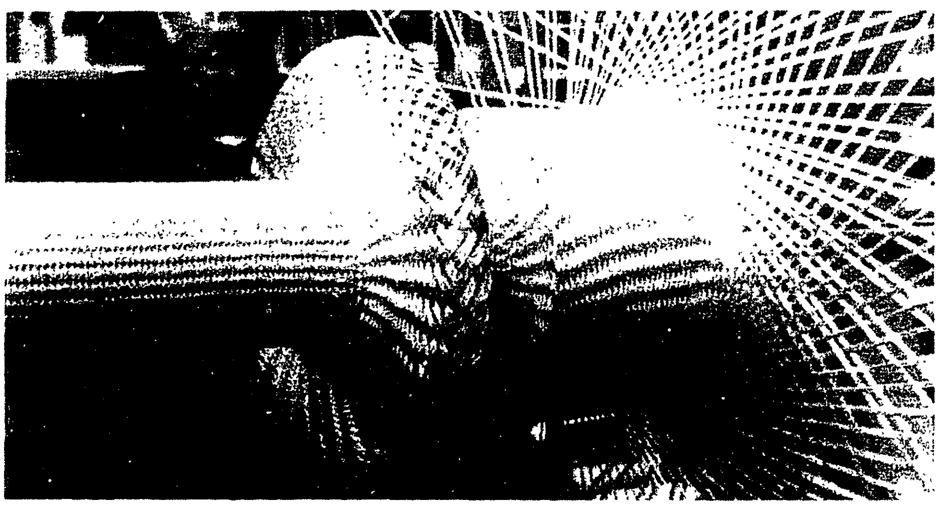


Figure 1: A braided composite over a mandrel. [2]

Braided parts are used when conformability, torsional stability, and damage resistance are required [2]. When describing the increased strength of the fabric, Composite Technology states that the strength of a braided material "comes from intertwining three or more yarns without twisting any two yarns around each other. Braids are continuously woven on the bias and have at least one axial yarn that is not crimped in the weaving process. This arrangement of yarns allows for highly efficient load distribution throughout the braid" [3]. This strength in material can also be seen in composite braids that are made over a mandrel or a rotating and removable form [2].

Diaphragm Forming

The forming process starts with a complete laminate in a flat state, which is then formed as a whole. This is dramatically different from hand lay up because the shape is not formed piece by piece, significantly reducing production time. Hydrostatic pressure is used to shape the stack of plies over a tool. Variations of the process such as single-diaphragm, double-diaphragm and matched die forming exist as well. After the part is formed, it will typically be cured in an autoclave or oven [1]. Figure 2 shows the processes involved in diaphragm forming.

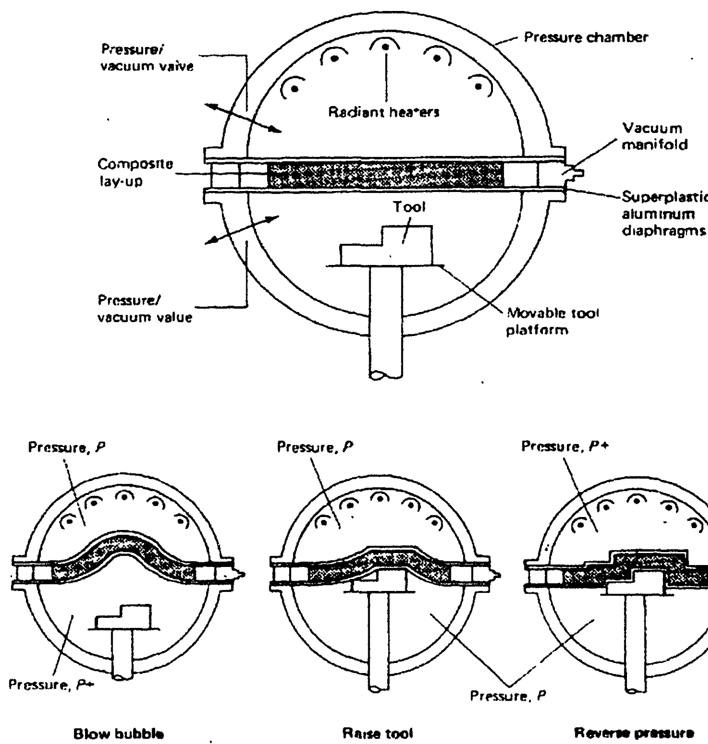


Figure 2: Diaphragm Forming [2]

Moderate financial investment is required for forming machines. However, they are often custom built for a particular product line. The machine generally consists of a tank substructure, a vacuum, a heater/cooler system, and elastic diaphragms. Diaphragm Forming is most economical and useful when used for high volume production of simply curved and slightly double curved parts [1].

Woven prepreg material or unidirectional tapes are used for Diaphragm Forming. Epoxy, vinylester or polyester thermosets or thermoplastics hold the fibers together. The tooling can be made out of wood, cast epoxy or machined metal. The material choice is dependent on the size of the production and the material's ability to withstand the forming pressure [1].

Resin Transfer Molding (RTM)

Resin Transfer Molding (RTM) is a process of injecting resin into a mold containing a fiber preform. The dry fiber preform is preshaped in a matched die mold by the processes of hand lay up, braiding, weaving, etc. After the mold is closed securely, liquid resin is injected under low pressure (approx. 100 psi) to impregnate the fiber reinforcements. The part is often cured in the mold. Several derivations of this process exist (VARI, RIM, SRIM, RRIM) depending on part size and shape [1]. Figure 3 shows the process used before resin is injected into the mold.

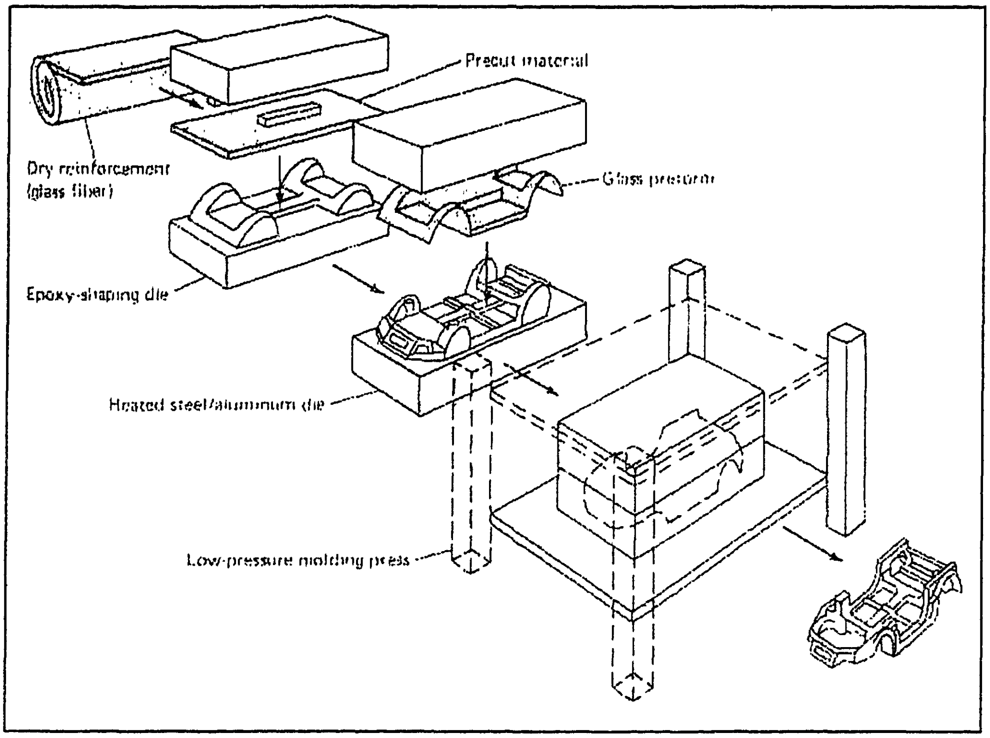


Figure 3: Resin Transfer Molding [2]

Woven, mat, and stitched unidirectional fibers are used in the mold. For injection, thermoset resin systems are typically used. The resin is usually cured at room temperature and may sometimes be cured at a higher temperature (up to 250 deg. F). Closed mold RTM tooling is typically machined out of metal in order to withstand the injection pressure due to the resin. A moderate financial investment in equipment is required to obtain the metering apparatus used it RTM. This equipment is typically responsible for storing and mixing the binder and the catalyst before the resin is injected into the tool. RTM is generally used for complex parts needing high surface finish. Production runs are typically medium to high in volume in order to be economical. RTM is usually used for the automotive and aerospace industries [1].

Pultrusion

Pultrusion is a process in which a "nonhomogenous compilation of materials (is) pulled through a die" [2]. Pultrusion is used to manufacture parts with a constant cross-section. Dry fibers are pulled through an impregnation station, and then passed through a forming die, which shapes and cures the part [1]. Material is being pultruded in Figure 4. In order to understand the steps in the process of pultrusion see Figure 5.

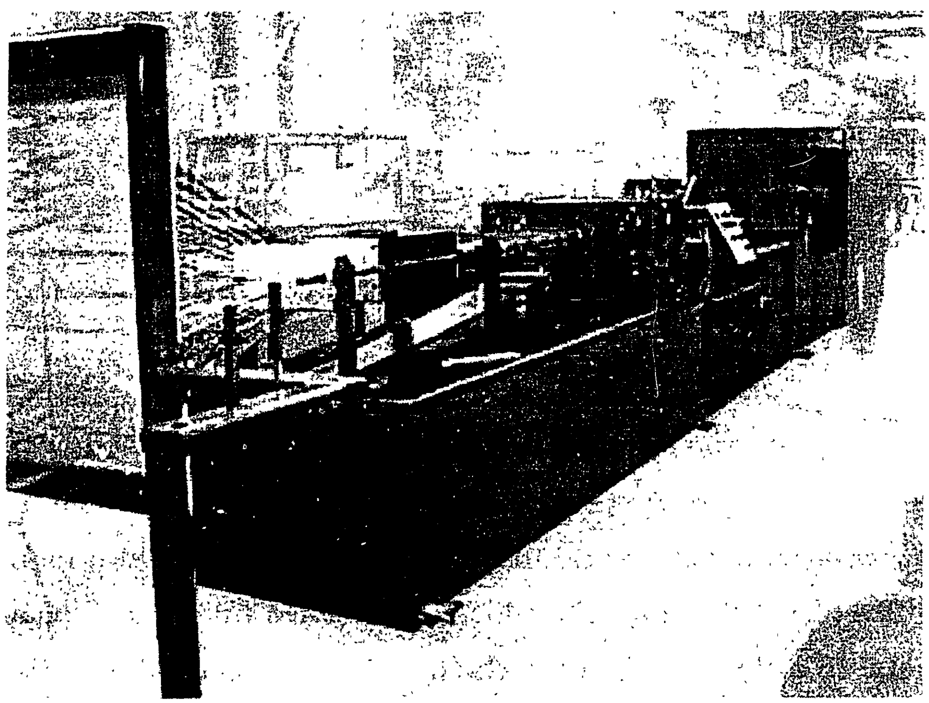


Figure 4: Pultrusion in process [7]

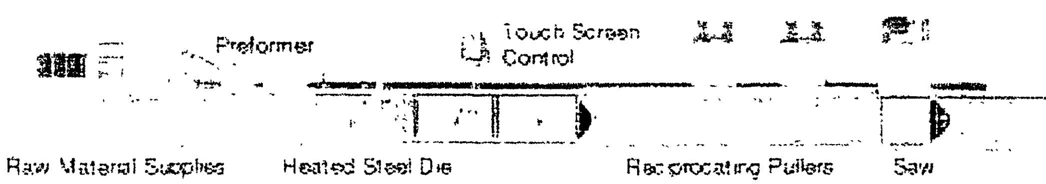


Figure 5: Pultrusion process [6]

Unidirectional glass, aramid and carbon fibers are typically used in pultrusion. The fibers are stored in dry form on creel stands. Resin systems such as epoxy, vinylester and polyester as well as fibers pre-impregnated with thermoplastic matrix are used for pultrusion.

The pultruder consists of many parts. The first part is the fibers, which are stored on creel stands. They are fed through a resin bath where they are impregnated with resin. Following this, they are formed in a die and cured. They are pulled through this machine and then cut off at pre-determined intervals. Almost any constant cross-section, simple curvature shape can be made in a pultruder. Pultruded profiles are used many applications such as buildings, bridges and electrical towers [1].

Autoclave Cure

The autoclave is a structure used as a pressurizing device and oven. It facilitates a chemical reaction that cures the composite laminate and solidifies the resin. Internal autoclave pressure and vacuum work to consolidate and bond the individual layers of the composite [1]. Figure 6 shows the set up of an autoclave with a part inside it, ready to cure.

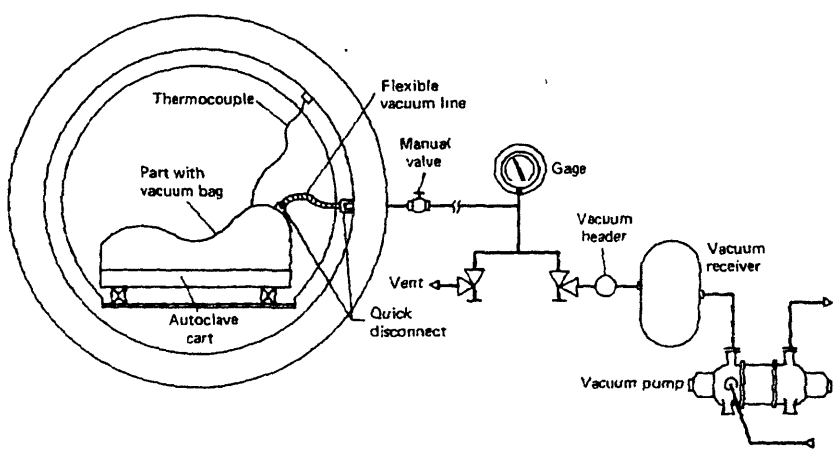


Figure 6: Autoclave with part ready for cure [2]

Thermosets and thermoplastics are used for impregnation or bonding of the laminate structures. Autoclave tooling is mainly made of metal or even composites, mostly depending on the pressure that the tool can withstand and the production run. A one sided open mold may be used in order to give the part its shape. However, the pressure applied and the ply thickness controls the thickness of the part. Autoclave curing may be used for a wide range of part sizes and complexities. Autoclaves are especially useful for parts that require superior consolidation and mechanical properties. Autoclaves are mainly used in aerospace applications [1].

Hand Lay-Up

The process of hand lay up is the process of manually depositing layer by layer of composite fibers onto a tool in order to give a part its shape. After laying down each ply, the ply is cut to the desired shape. The release film is removed before the next ply is added. The operator is responsible for ensuring proper placement and orientation of the fibers as well as the absence of wrinkles [1]. Figure 7 shows an operator laying up plies onto a tool.

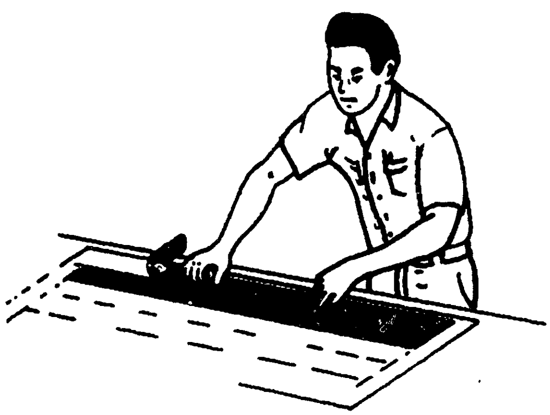


Figure 7: Operator performing Hand Lay Up [2]

Equipment used for hand lay up can vary but usually consists of cutting tools, breather plies, bleeder plies used to absorb the excess resin, peel plies or release film, vacuum bagging film and sealant tape [8]. Also, worker safety devices such as gloves are needed. Unidirectional tape and woven dry fiber mat can be processed through hand lay up. Commonly, pre-impregnated woven materials are layed up because the tackiness of the resin prevents the material from slipping on the lay-up tool and they are easier to shape [1].

Lay up tooling can be manufactured of wood, cast epoxy and metal and is usually an open mold. Unlimited part shapes are possible. Hand lay up is commonly used for low volume or prototype models especially within the aerospace and boat building industries [1].

2.2 Equipment Description

Automated Tow Placement (ATP)

The equipment used for ATP is called a Tape Layer or Fiber Placement Machine, which is used to lay pre-impregnated tapes or tows onto a tool. Fiber placement machines are intended for laying tows that are 1/8" to 1" wide and are used when greater precision is required for highly contoured parts. However, a tape layer lays tapes that are 3" to 12" in width when flatter, less contoured parts are required. Both of these machines are used to used to lay down material on a tool, compact the material, and then cut the material to the desired contour [1].

Since automated tape layers and fiber placement machines are expensive, they are mostly used for large parts requiring a great deal of strength such as in commercial and military aircraft as well as space launch applications. The machines are typically 30' x 20' or greater and have the capability of making parts as large as 26' x 140'. They are equipped with multiple tape or tow cutters and are fully automated with a seven to eleven axis CNC tape or tow placement system depending on required contourability of the part. A tape layer can lay tape at a transverse or longitudinal speed of up to 30m/min. The investment for a tape layer is usually from $1 Million to $4.8 Million. For the fiber placement machine, the fiber placement speed can range from 200 to 1200 in/min. The cost for a fiber placement machine can be as low as $3 Million and as high as $6 Million. Manufacturers of automated tow placement equipment include Cincinnati Machine Company, Ingersoll Milling Machine Company, and M. Torres. An automated tape layer can be seen in Figure 8 below.

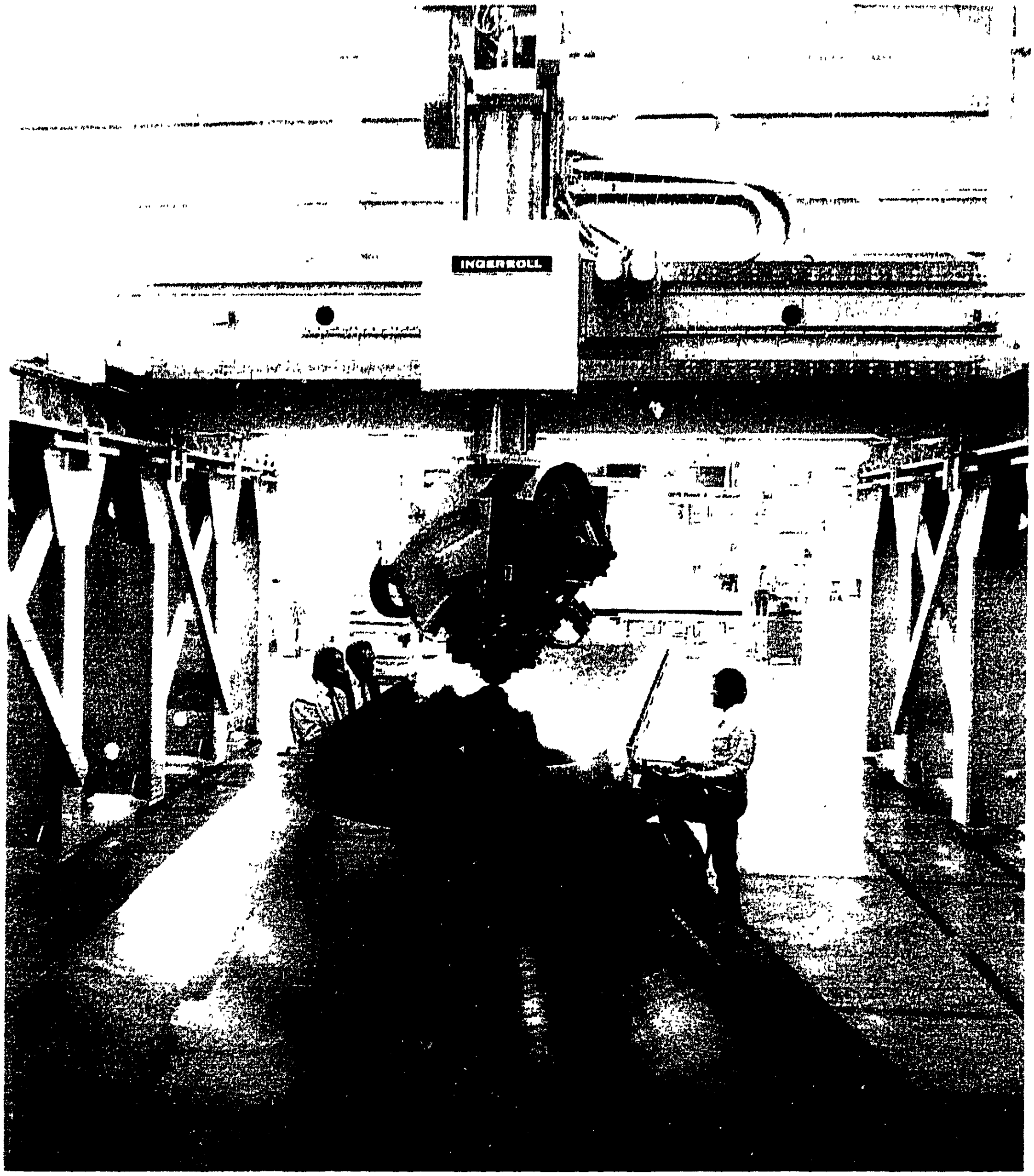


Figure 8: Automated Tape Layer [9]

Braiding

Composite braiding equipment can come in the two-dimensional or three-dimensional braiding style. Two-dimensional braiding refers to structures with two braiding yarn systems. However, three-dimensional braiding refers to a braided structure with three or more braiding yarns. Composite braiding equipment can hold from 3 to 144 yarn carriers in order to make the braided material [2]. Composite braiding equipment ranges from $25,000 to $220,000 depending most significantly on the size of the braided product. The size of the braided material can increase as the number of carriers is increased [10].

Composite braiding equipment can work on various systems. One system of braiding is called Maypole braiding where the carriers move in a criss-cross pattern around a central point to create a braid pattern. Another system for braiding is the Overhead Gantry System that includes a stationary braider with a moving mandrel. A Transverse System can either work similarly to the Overhead Gantry System by having the braider remain stationary while the mandrel moves or it can work by having a stationary mandrel while the braider moves [5]. A composite braiding machine working on the transverse system can be seen below in Figure 9. Braiding machines can either have manual or computerized controls. Manufacturers of composite braiding equipment include Wardwell Braiding Machine Company and Composite & Wire Machinery Incorporated.

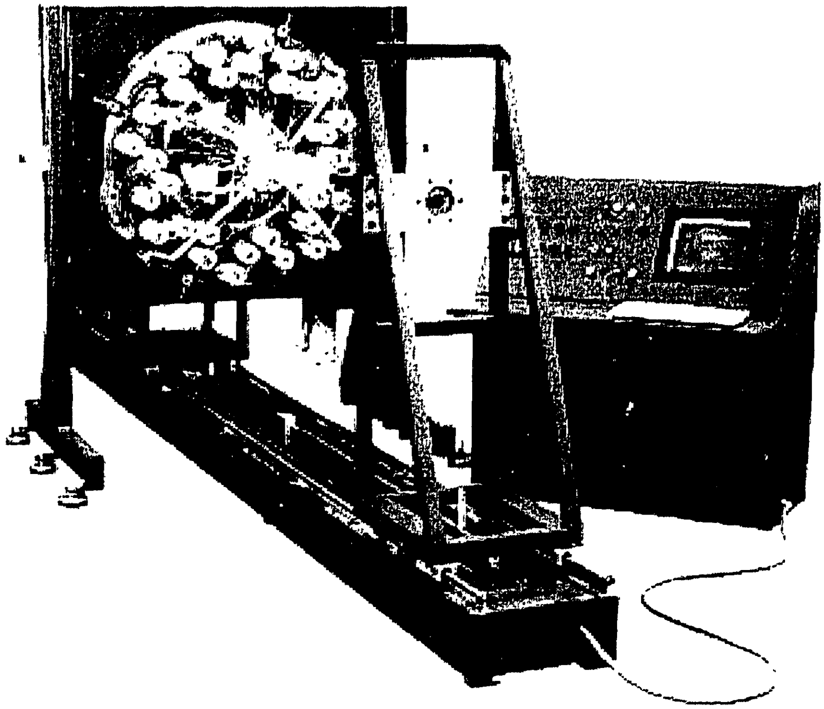


Figure 9: Composite braiding machine [5]

Diaphragm Forming

A diaphragm-forming machine includes a heater/cooler system to soften the resin prior to forming and to stiffen the part in order to lock it into its formed shape. A tank substructure is needed to encase the tool holder and a silicone rubber diaphragm seals the tank. Elastic diaphragms clamp the relatively stiff fibers with vacuum pressure in order to minimize buckling and wrinkling in the formed part. A vacuum system is required for hydrostatic clamping and forming pressure [1].

Since diaphragm forming is a relatively new process, only custom made machines are currently being made. A custom-built double diaphragm former can be seen in Figure 10. This machine was built for research purposes and works by having two diaphragms sandwich the preforms, preventing wrinkles in the double-curvature part by supporting the preforms on both sides. After being formed, the part is cured separately [11].

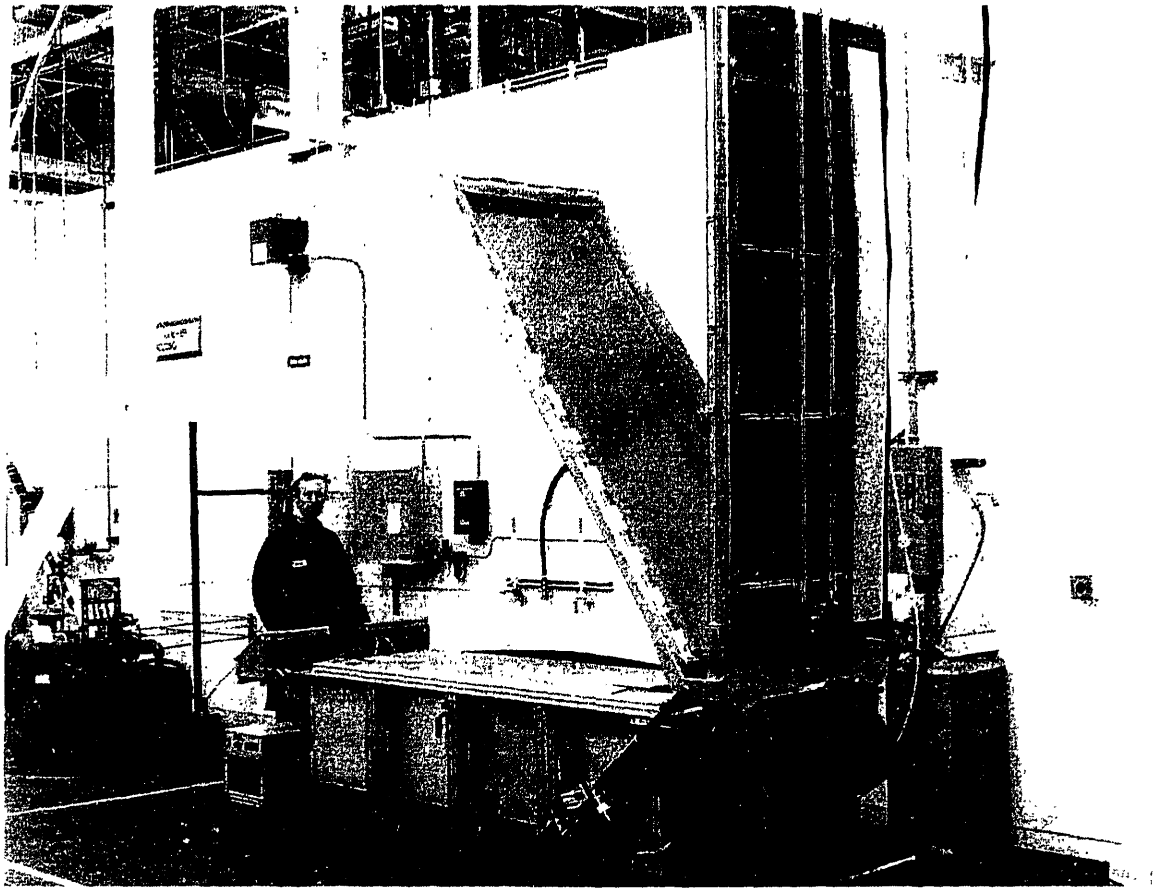


Figure 10: Custom built double-diaphragm former [11]

Resin Transfer Molding (RTM)

RTM injection equipment can vary greatly due to the capabilities of the machine. The basic machine will mix and inject the resin mechanically at pre-set mixing ratios. Some models will have additional capabilities such as the ability to store the binder and catalyst, have adjustable mixing ratios, or have monitoring devices to view the pressure or temperature of the resin. A RTM machine can dispense resin from a storage unit of 2100 cc's to 500 gallons. Resin can be injected with as little as 100 psi to as much as 600 psi of pressure. A moderate investment in equipment is required ranging from $5,000 to $100,000. Some RTM equipment manufacturers are Advanced Process Technology, Glas-Craft Incorporated, GS Manufacturing, Liquid Control Corporation, Radius Engineering, and Venus-Gusmer. A basic RTM dispensing machine is shown in Figure 11.

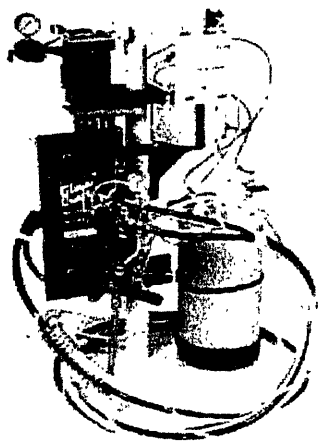


Figure 11: Resin Transfer Molding Equipment [12]

Pultrusion

The investment for a pultruder apparatus is moderate to high, ranging in cost from $100,000 to $400,000. A pultruder includes the creel stand(s) on which to store the dry reinforcement fibers and a fiber impregnation station of resin bath. A pultruder also allows for a heated forming die in which the cross-section is formed and the resin is cured. There is both a heating and cooling section of the forming die so that the part will be cooled such that it will not deform when the part is pulled. After being formed by the die, the part is grabbed by a pulling mechanism (continuous or reciprocating gripper) and is then cut to a pre-determined length. Continuous gripper pulling mechanisms cost approximately $15,000 to $35,000 more than their reciprocating gripper counterparts. The pulling force required increases with part size and can be as little as 500 lbs for a machine with an envelope area of 1 in^2. Part envelope areas can be as great as 1440 in^2. Manufacturers of pultrusion equipment include Martin Pultrusion Group (Pultrusion Dynamics), Strongwell Machinery & Licensing, and Weebee Enterprises. In Figure 12 a pultruder is shown.

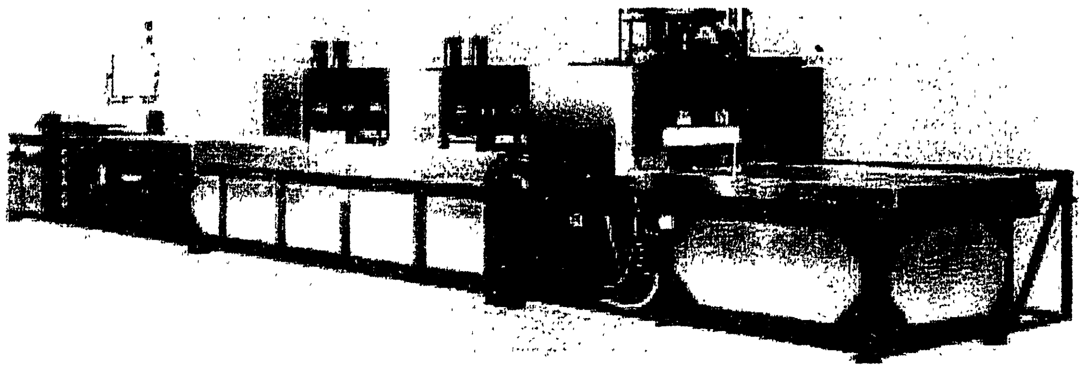


Figure 12: Pultruder [6]

Autoclave Curing

Autoclave ovens are capable of reaching very high pressures and temperatures but for autoclave curing, the pressure ranges from 80 psi - 100 psi and the curing temperatures are between 250 deg and 850 deg F. The variation is due to the resin system. Prior to the autoclave run, the part is typically sealed with a vacuum bag. The cure cycle normally lasts between 3 and 8 hrs, depending on the resin.

The investment cost for an autoclave can range from $80,000 to $2,500,000, depending on size, maximum desired temperature and pressure, computerization, and heating and cool-down rates. Autoclaves can range in size from dimensions of 3' long and 1' diameter to a machine with a 40' length and15' diameter, if not larger. In addition to the pressure chamber, compressed air and a vacuum are required. Air, nitrogen or carbon dioxide is used as a pressurizing medium. Air and nitrogen are slightly less expensive than carbon dioxide and air will only combust at temperatures of 300°F and higher. Therefore, nitrogen is typically used. Gas is usually used to heat large capacity autoclaves while electricity is used for small systems. The control and data acquisition equipment for pressure and temperature control is a major cost driver for computerized and fully automated systems [1]. ASC Autoclave Division, Thermal Equipment Corporation, McGill Air Pressure Corporation, and Melco Steel are some of the leading autoclave manufacturers. A large autoclave is shown in Figure 13.

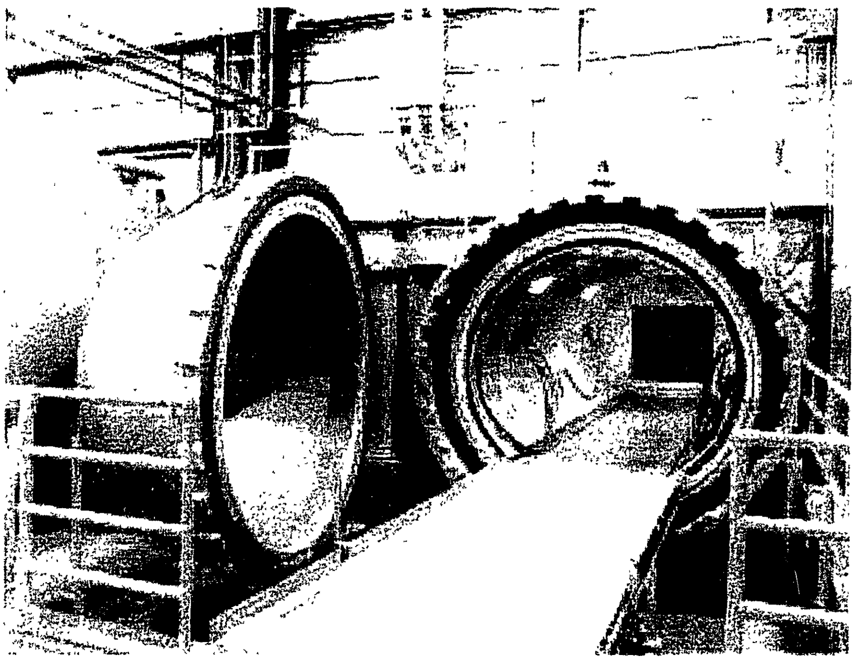


Figure 13: Autoclave [13]

Hand Lay Up

For hand lay up manufacturing equipment the cost can range from approximately $200 to $1000, depending on the size of the part, the number of workers, accuracy, etc. The tools necessary for hand lay up are peel plies or release film, bleeder plies to absorb the excess resin, breather plies, cutting tools, and gloves for worker safety. In addition, a vacuum bag is used in hand lay up procedures to compress the plies. For this, vacuum bags and sealant tape are required before the part is cured. Some manufacturers have made vacuum bagging systems that allow for hand lay up and also allow the vacuum bag to be re-used. Vacuum bagging components can be found at Airtech International, Bond Pro USA, Compasec Safety Incorporated, and Richmond Aircraft Products. Figures 14 and 15 show the vacuum bag lay-up components and an example of a vacuum bagged part.

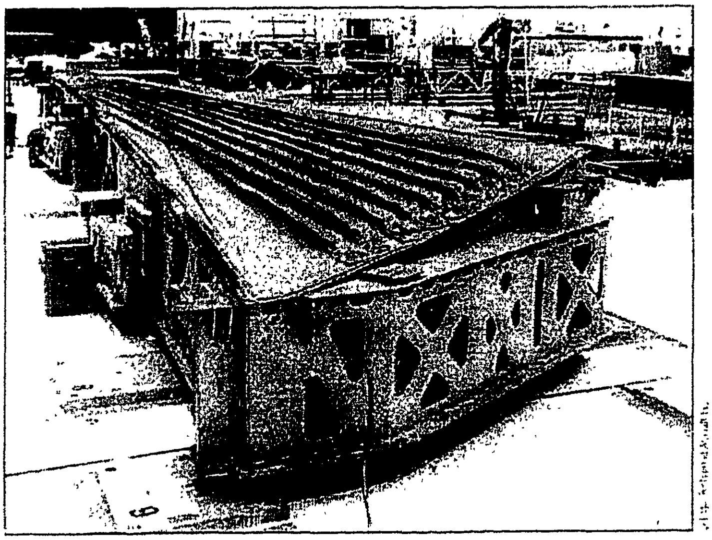


Figure 14: Vacuum bagging for the aerospace industry [8]

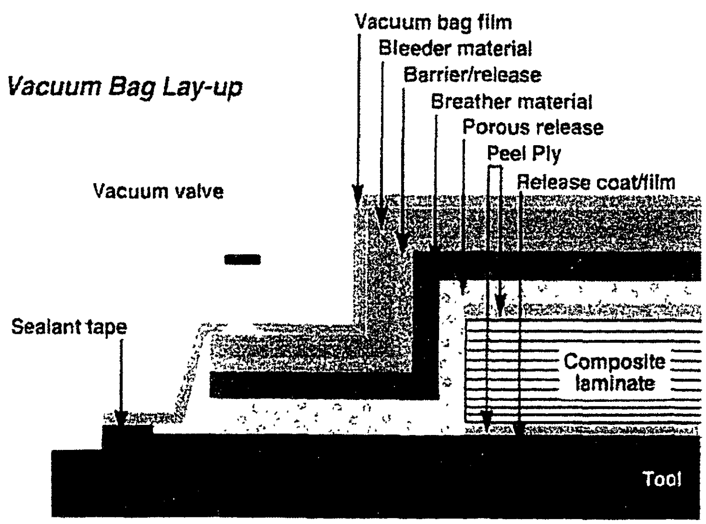


Figure 15: Vacuum bag assembly [8]

3. Equipment Costs and Results

The equipment costs for many of these processes has not become standard because of the high customization that occurs for each piece of equipment. For these manufacturers, examples of custom made machines will be given in order to understand the variations in price and to find a range of prices for such equipment. In order to obtain product prices from equipment manufacturers for the following processes, confidentiality has been requested by some manufacturers. In order to secure the identity of the manufacturer in relation to the prices here quoted, the manufacturers will be listed as Manufacturer A, B, C, etc. However, an alphabetized list of all the manufacturers whose prices have been used is given in the paragraph below.

The manufacturers who have graciously provided prices for their equipment and whose prices are shown in the results section are: Advanced Process Technology Incorporated, Airtech International, ASC Autoclave Division, Bondline Products, Cincinatti Machine Company, Compasec Safety, Inc., Composite & Wire Machinery Incorporated, Glas-Craft, Ingersoll Milling Machine Company, Martin Pultrusion Group (Pultrusion Dynamics), Melco Steel, M. Torres, Radius Engineering, Strongwell Machinery & Licensing, Thermal Equipment Corporation, Venus-Gusmer, Wardwell Braiding Machine Company, Weebee Enterprises.

Automated Tow Placement (ATP)

Since automated tow placement is primarily used in the aerospace industry for large, expensive parts, the machines are typically custom-built. An individual manufacturer may make from 0 to 3 machines per year. Currently, there are approximately 40-45 operational machines of this type worldwide [14]. The high specialization of these machines makes the pricing of the machines difficult to quantify. However, after speaking with the manufacturers, it has become clearer what the main cost drivers may be.

The main cost driver is the engineering costs for the technical complexity of the machines, which vary based on size of part, complexity of part, and speed of tape or tow placement. The consumer, typically airplane manufacturers or the military, also contributes to the high cost of the equipment because there are few consumers and also few suppliers of such equipment. This leads to nearly full customization of each machine, which in turn leads to high costs.

Added features to a basic machine will increase the price of the overall machine. Changes that are customarily made to the standard machine are changes in length, changes in width, or changes for national safety regulations. The cost to change the capabilities of length for the manufactured parts is minimal. However, the incremental cost for adding 10 feet in the width of the machine is approximately $100,000. Examples will be used to understand the pricing of tow placement and tape laying equipment due to the custom-made nature of the product.

The first tape laying machine is from Manufacturer A and has the capability of making parts as large as 25' x 120' with an accuracy of ±0.02", and was quoted with the base price of $3,500,000. This machine has an 11-axis CNC control system, can hold 6" and 12" tapes, can detect tape defects, has a tape lineup system, and cuts tapes with two ultrasonic knives. Adding software, postprocessor, part history recording, and installation costs to the same machine would raise the cost to approximately $4,182,000. To make the same machine at half the size would cost approximately 5% to 7% less than the price quoted above.

The second tape laying machine found is from Manufacturer B and is 16 feet wide, only lays flat tape, has 5-6% of material scrap, and could make parts as long as 140 feet long. This machine was quoted at a price of approximately

$2.5-$2.6 Million. However, the same machine with all features, including software, safety sensors, and two traveling shears, would cost $4.25-$4.8 Million. An addition of 20 ft in width would increase the cost by $200,000.

Manufacturer C has quoted prices for tow placement equipment, which is also referred to as a fiber placement system. The machine quoted is capable of placing as many as 32 tows of 0.125" width at a fiber placement speed of up to 1200 in/min. The machine has a seven-axis CNC placement system and has a ply orientation accuracy of ± 0.5 degrees. The travel of the machine is 30' x 28.5' x 5'. A machine of this type is priced from $4.5-$6 Million. However, tow placement machines that are capable of making smaller parts can be found for as low as $3 Million.

Braiding

New braiding equipment can cost from $25,000-$220,000. One of the main variables that affects price is the number of carriers needed for the composite braiding machine. In addition to the number of carriers, special options such as mandrel transverse systems, custom safety features, and computer or electrical control systems also affect the price of the equipment.

From Manufacturer D, a variety of quotes for new braiding equipment is provided here. The first sample braider has a price quoted for a composite braider with no carriers, drive components, or electrical controls. This machine costs $25,532. To add a Windows driven computer system and electric controls costs an additional $44,500. The second braider has 48 carriers, a gantry system, full controls, a computer system, and has overall dimensions of 16'x52"x63". The quoted price for this braider is $87,185. The third braider holds 144 carriers, has an overhead gantry mandrel transversing system, complete controls system, computer control system, central lubrication system, and warp guides. This braider has been quoted for $216,625.

Used braiding equipment, although somewhat out of the scope of this study, can be used to find the incremental costs that may occur with variations in size. Manufacturer E has provided the cost estimates for the used braiding equipment shown here. The chart below shows the prices for a basic model of a composite braider with various carrier capacities in Figure 16. To add work handling devices such as mandrel transverses or capstan pullers could cost an additional $12,000 to $150,000.

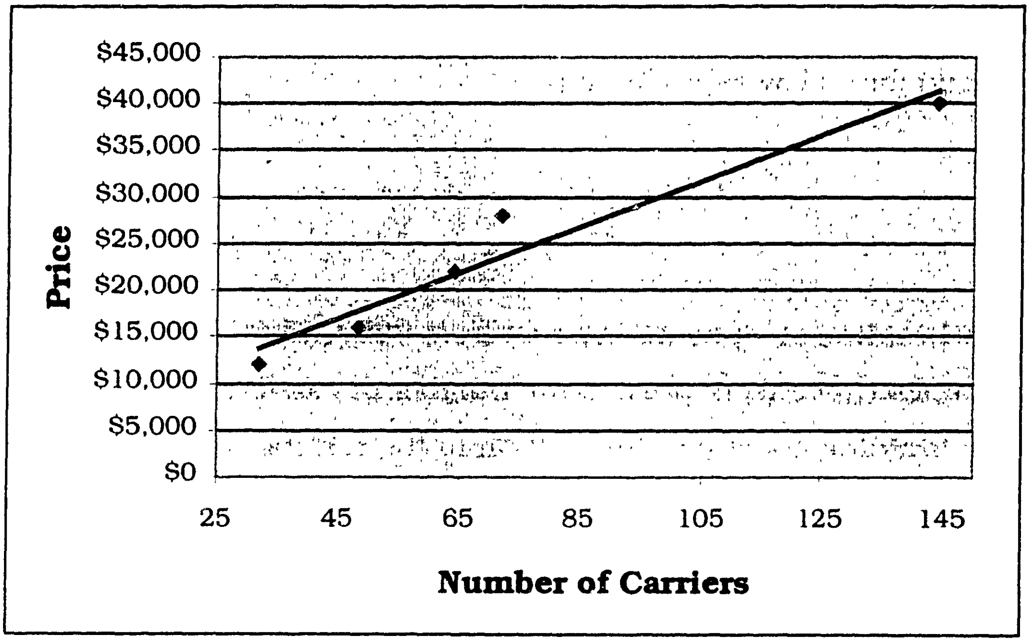


Figure 16: Used Braiding Equipment Costs (Manufacturer E)

Diaphragm Forming

The one custom-built diaphragm former that was found is a double diaphragm forming machine. This machine's approximate dimensions are 8'x 3'x 2'. Since this machine was produced for research purposes at MIT, various materials and some design changes occurred. However, the creator of the machine estimated the cost to manufacture the machine to be $80,000-

$100,000. This cost range does not include labor or engineering costs that would customarily be incurred with non-academic projects.

Another custom-built diaphragm former called the Pressclave has been developed by an assistant professor in the Netherlands. Although no specific information has been available regarding this particular project, diaphragm forming research is still in progress at the Structures and Material Laboratory at Delft University of Technology in the Netherlands.

One manufacturer of other composite manufacturing equipment, Radius Engineering, is in the initial stages of finding investors in order to manufacture diaphragm-forming equipment. The Radius representative anticipated that if the proposal is accepted, they will be manufacturing equipment within a few years.

Resin Transfer Molding (RTM)

Resin transfer molding equipment varies in resin capacity, automation capabilities, mixing ratio, temperature and pressure capacity. In order to see the cost of a basic mechanical RTM dispenser refer to Figure 17, which shows the prices for equipment with mixing ratios provided by Manufacturers F and G. These models have no features such as data acquisition or automated pressure or temperature monitoring. However, Figure 18 shows the incremental costs of various additional options.

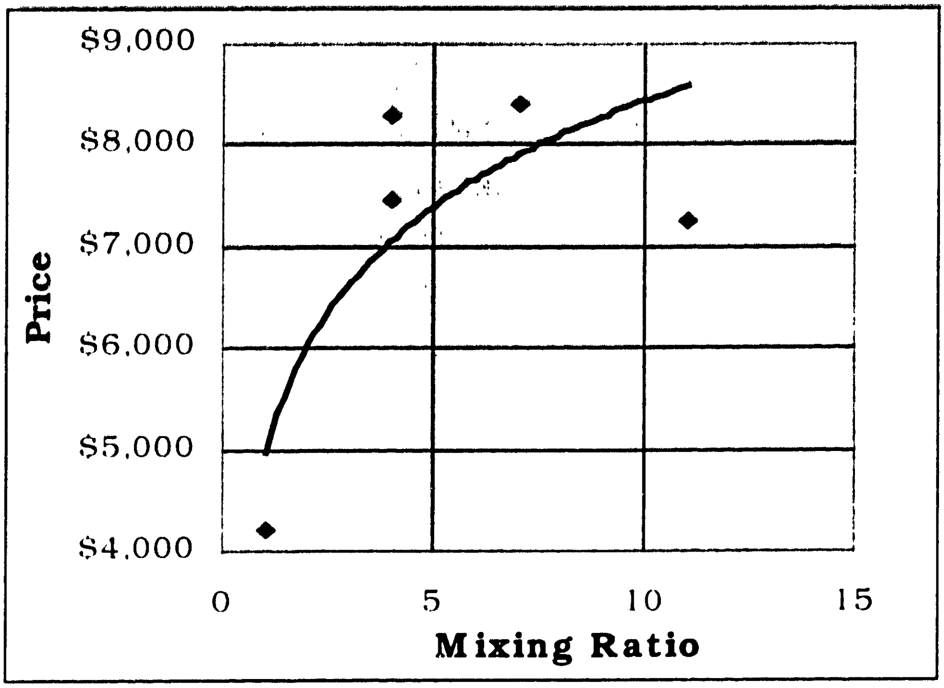


Figure 17: Non-automated RTM mixer and dispenser with varying mixing ratios.

Options	Low	High
Remote Injection:	$624	$850
Resin heater kit		$426.40
High volume material		
pump		$2.950
2 Gallon Heated Tank		$8.000
5 Gallon Heated Tank		$9.500

Figure 18: Incremental cost for added options to the non-automated systems.

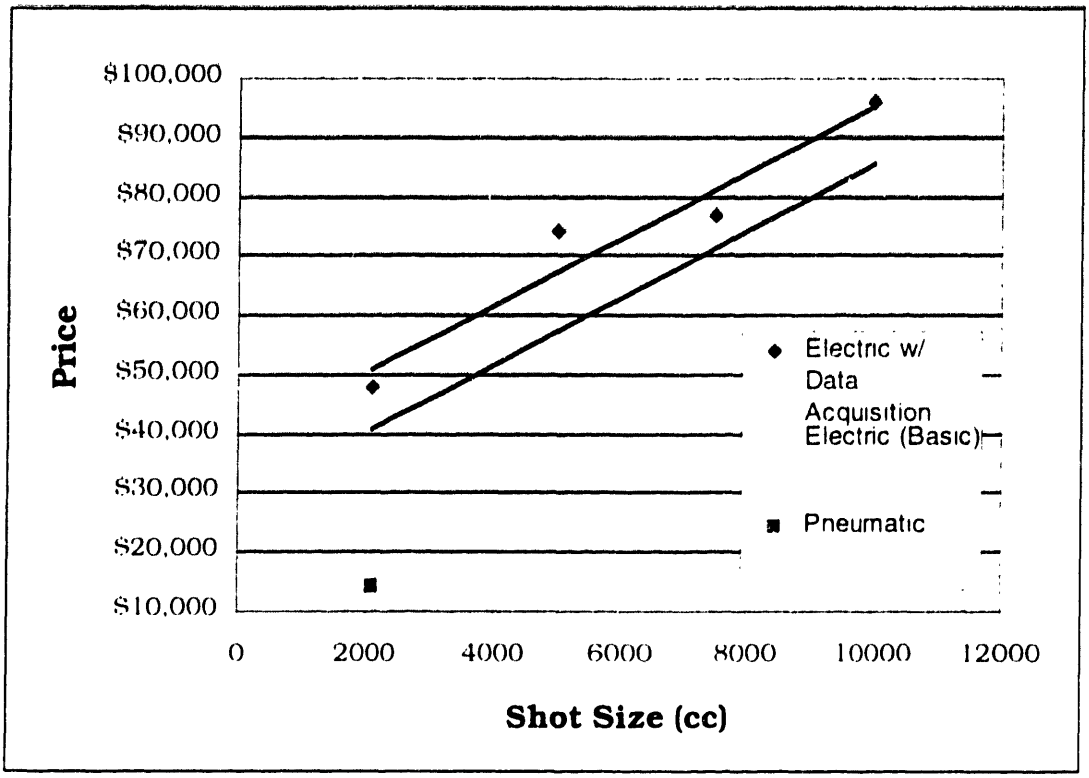


Figure 19: Automated RTM mixer and dispenser with various shot sizes

Figure 19 shows the prices for a RTM dispenser and mixer with and without data acquisition provided by Manufacturer H. Also, the prices for both a pneumatic, pressure-controlled device and an electric, flow-controlled device are shown. The figure shows how the prices fluctuate with various injector shot sizes.

Manufacturer I has provided two custom-made machine price quotes. The first price quote for an RTM metering, mixing and dispensing system is approximately $55,000. This machine includes two 5-gallon tanks for the component materials, has a maximum temperature capacity of 350°F and 600 Psi maximum output pressure. Shot size and ratio of component mixing can be adjusted manually in this machine.

The second custom-made machine, with the same capabilities as the one described above is a digital, metering, mixing, and dispensing system. This system allows for pre-sets to be saved for various molds with unique mixing ratio, shot-size, output rate, and mixer speed. This system is fully automatic and adjustable and costs from $150,000 to $225,000 depending on the complexity of the system.

Options such as a vacuum chamber sized at 18"x18"x18" would cost an additional $40,000 and are used to prevent air from entering the mixed materials, resulting in improved part quality. Pressure transducers can be added to the metering pump in order to maintain the preset pressure for a cost of $5,000 to $10,000.

Pultrusion

Pultrusion equipment costs vary most significantly by the part envelope size (in^2), the pulling capacity (lbs), and the gripper type (continuous or reciprocating). Figure 20 shows the variations in cost as the envelope area is increased. It also shows the price difference between reciprocating and continuous pulling mechanisms. The pulling capacity of the machine increases as the envelope area increases. Figure 21 shows the relationship between cost, and pulling capacity.

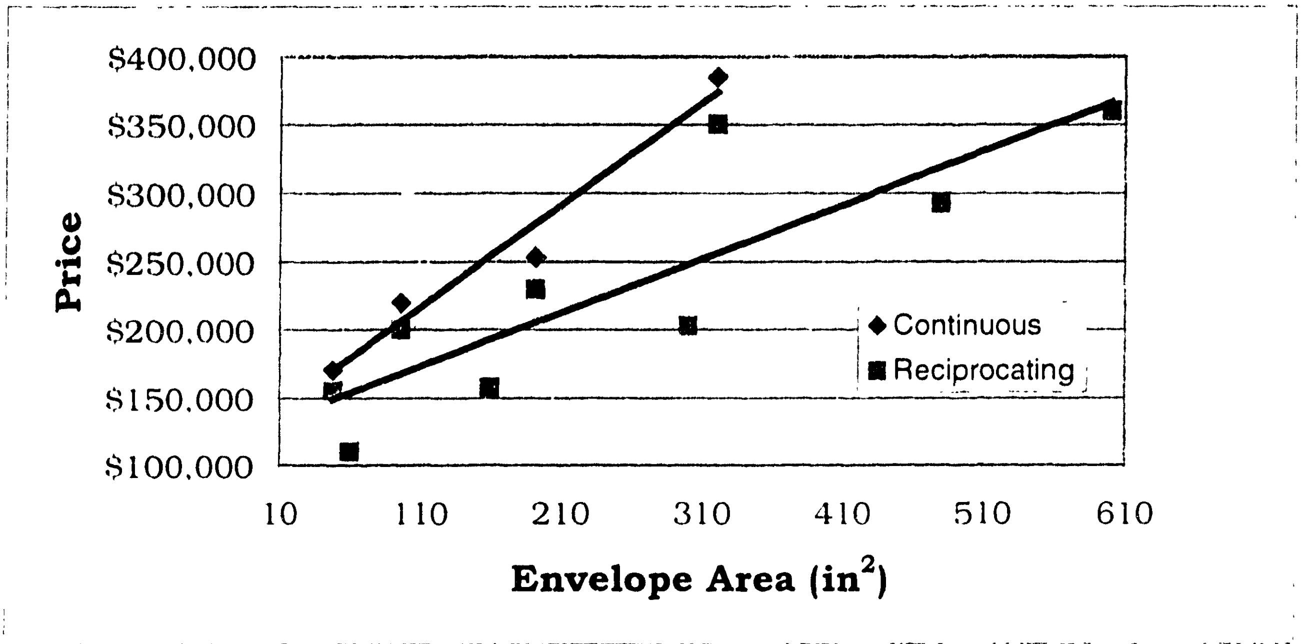


Figure 20: Pultrusion equipment costs in relation to gripper type and envelope area

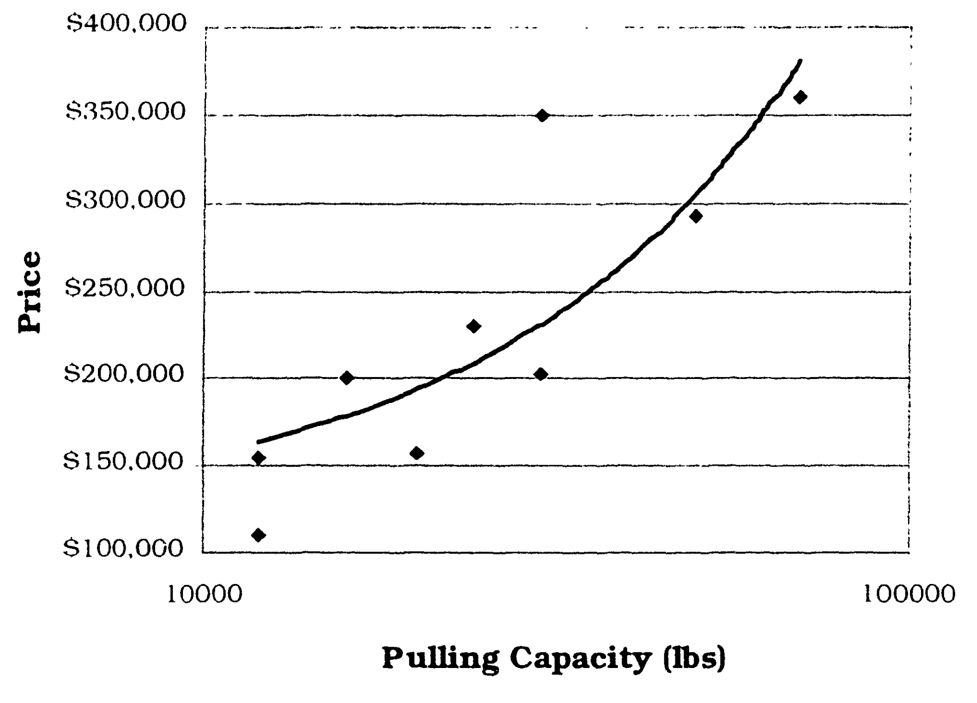


Figure 21: Pultruder cost related to pulling capacity

Autoclave Cure

Autoclave prices vary depending on maximum allowable pressure, maximum temperature, diameter of autoclave opening, length of autoclave, heat up rate, cool down rate, and computer systems. Figure 22 shows the price quote for a basic (no computerization) autoclave with various inner volumes and temperature or pressure constraints. In Appendix A, the full data from which this graph was taken is seen. In order to understand price variations to include all possible factors all prices and specifications have been shown there. In order to retain the anonymity of the manufacturers numbers have been added in parentheses showing that the prices have been quoted from either manufacturer J, K or L in the appendix.

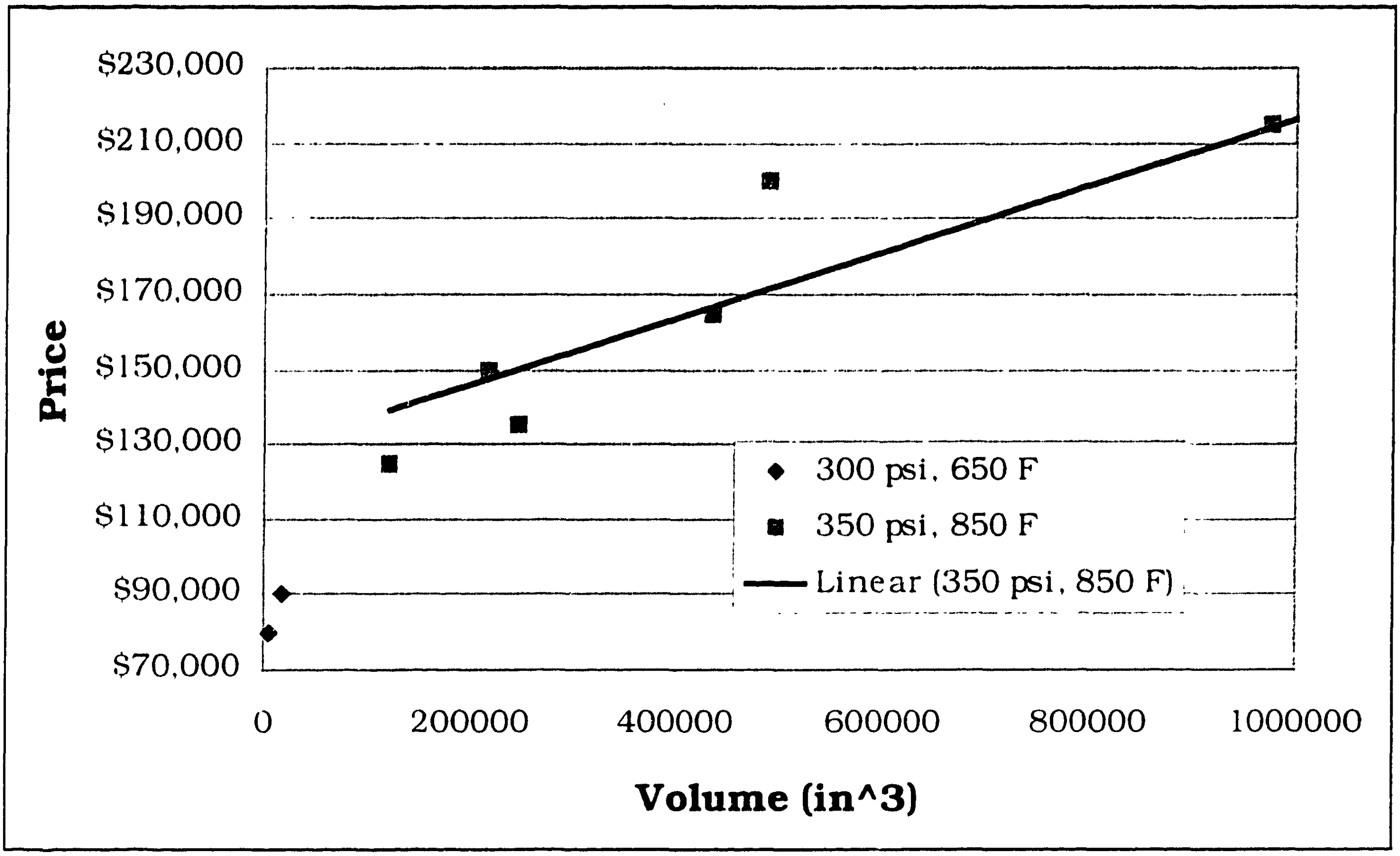
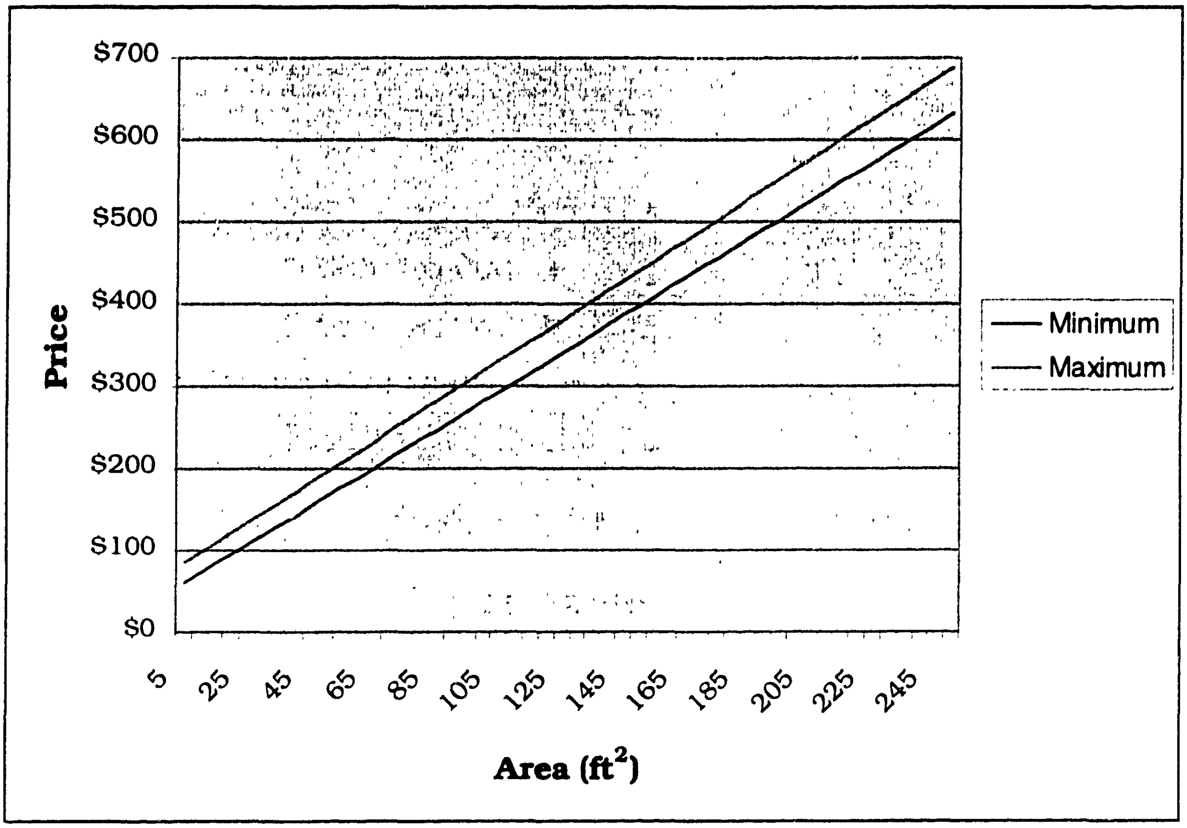


Figure 22: Autoclave pricing with various volumes.

Hand Lay Up

Hand lay up can be broken down into its component tools, and some manufacturers provide standard hand lay up systems. One quote for a re-usable vacuum bagging system costs approximately $450. Appendix B shows the prices for each product involved in the hand lay up process. Since the number of tools required depends on the number of simultaneous workers, the overall prices have been estimated for one of each tool or product needed. The fixed costs come from the cutting shears and safety gloves which are totaled from $49.20 to $73.00. Prices have been calculated assuming that vacuum bagging is the process used to compact the composite laminate and that most parts require 2' of tape for every square foot of tooling, with 10% wasted materials. The variable costs are the vacuum bagging film, sealant tape, peel ply, breather which are valued per square foot of material. This composite value is a minimum of $2.33/ft^2$ and a maximum of $2.46/ft^2$. Figure 23



shows the maximum and minimum prices for hand lay up equipment.

Figure 23: Hand lay up equipment prices

4. Discussion and Conclusion

Automated Tow Placement (ATP)

The two tape layers from Manufacturers A and B show that the base price for any machine used for tape laying will be from $2.5-$3.5 Million. The bulk of the cost of this machine appears to be in the design of custom made machinery. Additional costs to the basic machine could increase the price by at most $2.2 Million.

The cost data from Manufacturer C indicates that tow placement machines should only be used for parts requiring high precision and contourability because of the high cost (up to $6 Million) of such machines. Currently these machines are custom built but, with standardization, the overall cost of the equipment should decrease. Within five or ten years, the market for ATP equipment could improve as the need for strong, lightweight materials are required in the Aerospace industry and as the decreased equipment cost due to standardization makes the equipment more affordable.

Braiding

For braiders, it appears that the major cost variations occur with increases in the number of carriers and computer or controls systems. The computer system and controls system is the main cost driver in the automated braiding machines. An interesting future study may look at performance of braiding equipment related to cost, based on automated or controls systems.

The incremental cost of additional carriers can vary from approximately $170/carrier to $750/carrier. This estimate is from a used braiding equipment manufacturer, which means that the variation may also be due in part to availability of carriers and availability of used machines. This variation in cost shows that the relationship between additional carriers and cost is not linear. It appears that the price per carrier increases until 72 carriers are added, but after 72 the price/carrier drops. It may also be that there is a minimum cost required to expand a unit, with little significance to how many carriers will be added to the machine.

Diaphragm Forming

Due to the experimental nature of the diaphragm forming information available, further cost-analysis should be conducted once the technology has been further developed and taken past the academic environment. Although two examples of diaphragm forming equipment have been given here, they are prices quoted including experimental and developmental costs. The material cost of the double diaphragm machine would likely be reduced as standardization occurred. For a production-run machine, in addition to the cost estimated, further costs would arise from engineering, labor, and administrative needs. The Radius Engineering interest in diaphragm forming may be the beginning of diaphragm forming being used for composite manufacturing in the future.

Resin Transfer Molding (RTM)

Changes in mixing ratio have a minimal effect in price with non-automated, manual RTM equipment. As seen in Figure 17, the pre-determined mixing ratio of the RTM equipment does have a positive relationship with the cost of the equipment. Options such as remote injection and resin heating have a small additional cost as well. However, there is a large cost associated with the addition of heated tanks in which to store the component materials.

For automated systems, the base price is much higher than manual systems. However, within automated systems, the difference in price between pneumatic and electric injection systems is approximately $23,000. The added cost for data acquisition on an electric unit is rather expensive, at $10,000. There is a large positive relationship between shot size and cost in these automated systems. This is likely due to the fact that re-filling the injector is timely. Therefore, a larger shot size would minimize the number of re-fillings.

With the custom made machines, adding an automated, digital system at least triples the price of the equipment. Other quality devices such as the vacuum chamber and the pressure transducers can increase the price of the machine significantly as well. In RTM, it appears that the main sources of the costs are the computerization of the equipment as well as the optional quality and time saving devices.

Pultrusion

The main cost driver in Pultrusion equipment is the size of the part being pulled. As the envelope area increases, the cost of the equipment rises, as can be seen in Figure 20. When the envelope area increases, the pulling capacity also increases to accommodate for the larger part. Therefore, the price also increases as the pulling capacity increases. In terms of part quality, continuous pulling produces a higher quality part, which is reflected in the price. A continuous pulling mechanism costs approximately $15,000 to $35,000 more than the same puller with a reciprocating pulling mechanism, depending on the size of the machine. From extrapolating the data, the relationship between price and pulling capacity is roughly price = 3.7287*pulling capacity (lbs) + 119235.

Autoclave Cure

Autoclave pricing is dependent on maximum attainable pressure, maximum temperature, diameter, length, heat up rate, cool down rate, and computerization options. As seen in Appendix A, some of these factors are more significant than others.

To see the variation in price due to heat up and cool down rate see model 1 and 2 for an example. They are identical except for the heat up and cool down rate, which vary by 5°F/min. For Manufacturer J, there is no price difference between the two models but for Manufacturer K, there is an increase of $10,000 in price due to the same increase in cool down and heat up rate. This is inconsistent between companies and further investigation into the true price relationship of this factor is needed.

In order to see the price difference that occurs with a change in length see model 8 with 11, model 9 with 12, and model 10 with 13. In these examples, they are identical except that models 8, 9, and 10 have a length of 20' and the models 11, 12, and 13 have the length of 10'. For Manufacturer J the prices for the 20' long models are $10,000-$15,000 more than the 10' models. However, for Manufacturer J the prices for the 20' long models are $50,000-$100,000 more than the 10' model. This may be due to the increased computerization that is needed with a longer autoclave. This variation in price may also be due to under-estimation or over-estimation on the part of one of the manufacturers.

To observe the change in price due to change in diameter see models 8-13. This time however, note that the difference between models 8 and 9 and the difference between 11 and 12 is that both changes are from 3 feet in diameter to 4 feet in diameter. This one-foot diameter change increases the base price of model 8 by $30,000 and model 11 by $25,000 for Manufacturer J. For the computerized versions of the Manufacturer A autoclave, the changes are $30,000 and $55,000 respectively. However, for Manufacturer K, the change in price due to a one-foot diameter increase is $100,000 for both the 20-foot long and 10-foot model. This inconsistency suggests that the increase in diameter may affect the price of the computerized models more than the manual autoclaves.

Figure 22 shows the price as it changes with volume. The relationship between price and volume is positive and linear when pressure, temperature, cool down rate, and heat up rate are held constant. From extrapolating the data for autoclaves with maximum pressure of 350 psi and maximum temperature of 850 F with 15F/min heat up and cool down rate, the relationship between volume and pressure is price = 0.0878*volume (in^3) + 128541.

The greatest price driver appears to be size, in both diameter and length of the autoclave. From the data collected here, the range of autoclave prices are from $80,000 for model 1 with no computer system to $2.5 Million for model 7 with a computer system provided by Manufacturer K. Further research on autoclave pricing could be conducted to find the incremental cost to quality benefit of automated systems over manual systems.

Hand Lay Up

The equipment required for hand lay up can vary a considerable amount. The main price driver of hand lay up tools is the number of workers requiring tools at one time. This will adjust the fixed costs associated with safety gloves and cutting tools. The relationship between the size of the part and the cost is linearly related as can be seen in Figure 23 which gives the maximum and minimum prices depending on square foot of materials required. The price of the re-usable vacuum bagging system may be comparable to the overall price for the individual tools needed depending on how many times the system can be reused and what the part capacity is.

Additional pricing studies for hand lay up could include inquiries into equipment costs for material storage racks, a table on which a tool may lie, positioning aids for lay up, precision cutting instruments, and worker lab coats.

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Appendix A

Autoclave Prices:

Model	Maximum Pressure	Maximum Temp (F)	Diameter (ft)	Length (ft)	Volume (in^3)	Heat Up Rate	Cool Down Rate
1	150 psi	650 F	3	3	36644	15F/min	15F/min
2	150 psi	650 F	3	3	36644	10F/min	10F/min
3	200psi	650 F	3	5	61073	15F/min	15F/min
4	120 psi	500 F	5	10	339292	15F/min	15F/min
5	300 psi	650 F	1	3	4072	15F/min	15F/min
6	300 psi	650 F	2	3	16286	15F/min	15F/min
7	350 psi	850 F	15	40	1221451	15F/min	15F/min
8	350 psi	850 F	3	20	244290	15F/min	15F/min
9	350 psi	850 F	4	20	434294	15F/min	15F/min
10	350 psi	850 F	6	20	977161	15F/min	15F/min
11	350 psi	850 F	3	10	122145	15F/min	15F/min
12	350 psi	850 F	4	10	217147	15F/min	15F/min
13	350 psi	850 F	6	10	488580	15F/min	15F/min

Model	Base Price (J)	Price w/ Computer (J)	Price w/ Computer (K)	Base Price (L)
1	$80,000	$120,000	$375,000	$43,000
2	$80,000	$120,000	$365,000	
3	$83,000	$123,000	$400,000	$75,000
4	$160,000	$195,000	$500,000	$170,000
5	$80,000	$120,000	$150,000	
6	$90,000	$145,000	$200,000	
7	$1,200,000	$1,240,000	$2,500,000	
8	$135,000	$175,000	$500,000	
9	$165,000	$205,000	$600,000	
10	$215,000	$255,000	$750,000	
11	$125,000	$165,000	$600,000	
12	$150,000	$190,000	$700,000	
13	$200,000	$245,000	$800,000	

Appendix B

Hand Lay Up equipment costs:

Product Type	Material	Quantity, Size	Price	Other
Vacuum Bagging Film	Nylon	1 Roll, 60"x200'	$75.00	
Vacuum Bagging Film	Urethane	1 Roll, 60"x200'	$129.00	Re-usable
Vacuum Bagging Film		1 Roll, 60"x200'	$75.00	Release film and vacuum bag
Sealant Tape		1 Roll, 3/8"x50'	$44.00	
Peel Ply	Nylon with red tracer	1 Roll, 60"x 25 yards	$148.00	
Peel Ply	Polyester, black tracer	1 Roll, 60"x 25 yards	$128.00	
Peel Ply	Nylon, w/ silicon release agent	1 Roll, 60"x 25 yards	$156.00	
Breather		1 Roll, 60"x 25 yards	$58.00	
Shears for cutting Composite		9.5 in	$69.00	
Shears for cutting Composite		8.3 in	$53.85	
Shears for cutting Composite		7.1 in	$45.20	
Safety Gloves	Range between $2.50 and $26.00		$4.00	(Median price)
		Minimum Overall Price:	$354.20	* Prices assume one of each tool shown above
		Maximum Overall Price:	$460.00	* Prices assume one of each tool shown above

Appendix C

Pultrusion Equipment Prices:

Part Envelope	Envelope Area	Pulling Capacity - Continuous (lbs)	Gripper Type	Gripper Length	Price
4"x8"	32		Reciprocating		60,000
4"x8"	32		Reciprocating		75,000
12"x10'	1440		Reciprocating		1,000,000
10"x6"	60	12,000	Reciprocating	24"	110,000
20"x8"	160	20,000	Reciprocating	24"	157,500
30"x10"	300	30,000	Reciprocating	24"	202,500
40"x12"	480	50,000	Reciprocating	30"	292,500
50"x12"	600	70,000	Reciprocating	30"	360,000
8"x6"	48	12,000	Reciprocating	24"	155,000
8"x6"	48	8,000	Continuous	n/a	170,500
16"x6"	96	16,000	Reciprocating	24"	200,000
16"x6"	96	16,000	Continuous	n/a	220,000
24"x8"	192	24,000	Reciprocating	24"	230,000
24"x8"	192	16,000	Continuous	n/a	253,000
40"x8"	320	30,000	Reciprocating	24"	350,000
40"x8"	320	20,000	Continuous	n/a	385,000

Appendix D

Resin Transfer Molding Equipment Prices:

Options	low	High
Remote Injection:	$624	$850
resin heater kit		$426.40
high volume material pump		$2,950.00
2 Gallon Heated Tank		$8,000.00
5 Gallon Heated Tank		$9,500.00

Mechanical Models (F & G)	Mixing Ratio	Price
5-55 Gallon drum capapcity	4	$8,284.12
	7	$8,399.26
	11	$7,250.00
	4	$7,450.00
	1	$4,200.00
	Variable	$6,090.00

Automated Models (H)	(includes dispenser and mixer)	
	Shot size (cc)	
pneumatic-pressure controlled	2100	$14,200.00
electrical - flow controlled	2100	$47,800.00
	5000	$74,200.00
	7500	$76,800.00
	10000	$95,900.00

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