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Advanced Blade Manufacturing Project Final Report

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Advanced Blade Manufacturing Project
Final Report

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Sandia Contract – AN-0166

ABSTRACT

The original scope of the project was to research improvements to the processes and materials used in the manufacture of wood-epoxy blades, conduct tests to qualify any new material or processes for use in blade design and subsequently build and test six blades using the improved processes and materials. In particular, ABM was interested in reducing blade cost and improving quality. In addition, ABM needed to find a replacement material for the mature Douglas fir used in the manufacturing process. The use of mature Douglas fir is commercially unacceptable because of its limited supply and environmental concerns associated with the use of mature timber. Unfortunately, the bankruptcy of FloWind in June 1997 and a dramatic reduction in AWT sales made it impossible for ABM to complete the full scope of work. However, sufficient research and testing were completed to identify several promising changes in the blade manufacturing process and develop a preliminary design incorporating these changes.

Acknowledgments

The author would like to thank all of following people who have contributed to the successful completion of this research: Tom Ashwill, Dennis Harrison, Mike Zuteck, Dayton Griffin, Jerry Lafave, Jim Derosher, Billie Blades, Bill Bertelsen, Meade Gougeon, and Ron Roesler. While all of those listed made significant contributions, the author would like to particularly acknowledge the dedication and commitment of the ABM and AWT employees who spent many months completing this research under the constant cloud of uncertainty concerning the future of the organizations. Without their commitment and dedication it would not have been possible to complete this work.

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Executive Summary

In January, 1997 FloWind Corporation was awarded a contract by the United States Department of Energy, through Sandia National Laboratories (Sandia), to develop improved manufacturing processes for wind turbine blades. The work was to be completed by Advanced Blade Manufacturing (ABM), a FloWind subsidiary. The objective of the Sandia Blade Manufacturing Program (BMP) was to "Promote the development of advancements in the manufacturing of utility-grade wind turbine blades in ways that significantly lower blade costs and improve their quality and reliability." This report documents the work completed by ABM on the FloWind BMP project.

The original scope of the project was to research improvements to the processes and materials used in the manufacture of wood-epoxy blades, conduct tests to qualify any new material or processes for use in blade design and subsequently build and test six blades using the improved processes and materials. In particular, ABM was interested in reducing blade cost and improving quality. In addition, ABM needed to find a replacement material for the mature Douglas fir used in the manufacturing process. The use of mature Douglas fir is commercially unacceptable due to a very limited supply and environmental concerns associated with the use of mature timber.

Unfortunately, due to the bankruptcy of FloWind in June 1997 and a dramatic reduction in Advanced Wind Turbines (AWT) sales, ABM was not able to complete the full scope of work. ABM was able to complete sufficient research and testing to identify several promising changes in the blade manufacturing process and develop a preliminary design incorporating these changes.

Baseline Turbine and Blade Description

The baseline turbine is the AWT-27. It is a downwind, free-yaw machine. The blades are lofted from NREL S825/S809/S810 thick-airfoil sections and are made of wood-epoxy laminates, reinforced with carbon fiber. The rotor is a teetered, two-bladed, fixed-pitch, stall-regulated design. It has a diameter of 27.4 m (90 ft) and has a nominal speed of 53 rpm. The rotor is connected directly to the gearbox mainshaft, and the gearbox increases the mainshaft speed to 1800 rpm, driving a three-phase, 60 Hz, 480 volt, induction generator.

The blades are constructed from wood/epoxy laminates with two shells bonded together with an inner vertical shear web. Carbon fiber is used in some of the laminations on the tension side, and the shells are sealed on the inner and outer surfaces with a layer of fiberglass. The outer surface is gelcoat. The number of laminations varies along the blade length in response to the load spectrum seen by each station on the blade. Due to the length of the blade, each laminate layer has multiple span-wise joints along the length of the blade. These joints are staggered between layers. In the most highly loaded layers, the ends of the veneer sheets are scarfed to improve the strength of the joints. In less heavily loaded veneer layers the veneer sheets are placed end-end, with no pre-treatment, to create butt joints.

Summary of Findings

The research completed identified several significant improvements to the blade design and manufacturing process. The most significant findings were:

1. Pre-sealing the scarfed joints in the blade shell sufficiently increased the joint strength to allow elimination of the carbon reinforcement from the design. This resulted in a significant cost savings.
2. Use of heat during the blade molding process will accelerate the epoxy cure sufficiently to allow the existing manufacturing facility to operate on two shifts rather than a single shift. This effectively doubles blade production with a modest capital investment.
3. The use of fumed silica as an epoxy extender will permit a 20% reduction in the amount of resin used in the blade and an associated cost savings.
4. Several additional improvements in the blade manufacturing process were developed which will increase manufacturing flexibility, improve blade quality and decrease the labor required to produce a blade.
5. Both Loblolly southern pine and new growth Douglas fir were tested as candidates to replace the mature Douglas fir currently used. Neither was found to be acceptable. Loblolly Pine may be a suitable candidate if it is used in conjunction with extended epoxy to reduce epoxy absorption. This was not tested due to resource limitations. An alternative second growth Douglas fir was identified late in the program which may be a suitable candidate as well.
6. The quality of the blade laminate produced is heavily dependent on material characteristics not generally published, such as their tendency to absorb epoxy. In addition, variables such as the age of the tree from which the veneer is made appears to have an impact. These variables, coupled with the inherent variability found when working with natural materials, dictate thorough testing of any change in the materials or processes used in manufacturing the blades.

Cost Reductions Identified

For single shift operation (750 blades per year or less) the project identified improvements which would reduce blade cost approximately $500 (8%) and would require a capital investment of approximately $103,500. At full single shift capacity this would provide a first year return on investment of approximately 366%. If the plant were operating at one third capacity there would be a positive return on investment in the first year.

For higher blade capacities and dual shift operation (1,500 blades per year) the project identified improvements which would reduce blade cost approximately $875 (14%) and would require a capital investment of approximately $507,000. At full single shift capacity this would provide a first year return on investment of approximately 260%. Operation at full two shift capacity would not be required to warrant the initial investment to move to two shift operation.

Conclusions and Recommendations

This project identified several significant improvements in the technology for manufacturing wood epoxy wind turbine blades which result in substantial reductions in the cost of the blades. However, the project was not successful in identifying an alternative material to replace the mature Douglas fir presently used in the blades. Several promising candidates beyond those tested were identified by the project, but resource limitations precluded testing them.

The wind turbine market has changed substantially since this project was originally proposed and the market for AWT and ABM products has decreased. This, together with the problems associated with FloWind's bankruptcy, have resulted in AWT and ABM being shut down.

Despite the failures of ABM and AWT, the technical potential for wood epoxy technology in wind turbine blade manufacture is significant. The wood epoxy material, when properly manufactured, offers a combination of light weight, relatively low cost and high strength not available in other known materials. As wind turbines continue to develop into larger diameters, these properties are expected to become even more desirable.

The technology also continues to have serious commercial limitations. These can generally be classified as a lack of market acceptance due in part to the technical limitations of the materials. It is therefore suggested that a careful assessment of the barriers to commercialization of the technology in the wind turbine market be completed prior to any further research on the technology. The technical advantages of the technology are very attractive; however, the commercial limitations of the technology should be understood and additional technical research directed toward addressing these limitations. Areas which may warrant further research include:

- Identification of a suitable wood species which is available in many parts of the world
- Examination of approaches to making blades with easily varied lengths
- Examination of techniques for making blades which will have round roots and be more readily accepted by existing turbine manufacturers
- Examination of the benefits available from wood epoxy as turbines increase in size.

If these limitations can be addressed, or the benefits of wood epoxy can be shown to be large enough, the market will accept it and the technology can play a major role in the world wind energy industry.

1. Introduction and Background

1.1 Background

Advanced blade Manufacturing (ABM) was established in 1995 to build wood-epoxy blades for the AWT-26 and AWT-27 wind turbines designed by Advanced Wind Turbines (AWT) and marketed by FloWind Corporation (FloWind). FloWind is the parent company of both ABM and AWT. During 1995 and 1996 ABM built almost 200 sets of blades for AWT turbines utilizing technology, equipment and methods originally developed by Gougeon Brothers Incorporated (Gougeon) in the 1980's. In January, 1997 FloWind was awarded a contract from the United States Department of Energy, through Sandia National Laboratories (Sandia), to have ABM develop improved manufacturing processes for wind turbine blades. The objective of the Sandia Blade Manufacturing Program (BMP) was to "Promote the development of advancements in the manufacturing of utility-grade wind turbine blades in ways that significantly lower blade costs and improve their quality and reliability." This report documents the work completed by ABM on the FloWind BMP project.

1.2 Project Purpose

Consistent with the objectives of the overall Sandia BMP project, the primary purpose of this project was to reduce the cost, and improve the reliability, of the blades used on the AWT-26 and AWT-27 wind turbine. Specifically, the project was to evaluate opportunities to reduce cost and improve reliability by examining two major areas:

1. Improvements to the manufacturing process though either changes in the process or changes in the process controls.
2. Changes in the blade material properties, through changes in the material or treatment of the materials in the manufacturing process, which would result in a reduction in cost or an increase in reliability.

1.3 Project Scope

The original project scope was to include the following steps:

- Research to identify candidate process and design improvements
- Testing and analysis to better quantify the potential benefits of the candidate changes
- Preliminary design of the factory equipment needed to implement the process improvements
- Preliminary design of a blade incorporating the most promising material and process changes
- Detailed design of the factory equipment needed to implement the process improvements
- Detailed design of a blade incorporating the most promising material and process changes
- Construction of six prototype blades incorporating the changes
- Laboratory and field testing of these blades.

Unfortunately, due to the bankruptcy of FloWind in June 1997 and a dramatic reduction in AWT sales, ABM was not able to complete the full scope of work. ABM was able to complete all of the work outlined above through the preliminary design of a blade incorporating the most promising material and process changes. At the completion of this work, it was apparent that ABM did not have the resources required to continue with the project and it was unlikely there would be a market for the improved blades being developed by the project. As a result, the project was canceled at the request of FloWind, AWT and ABM.

1.4 Report Organization

The remainder of this report is organized into five additional major sections. Section 2.0 describes the baseline turbine and blade which are the subject of this report. Section 3.0 presents the results of ABM's research into improvements in the manufacturing process. Section 4.0 presents ABM's work identifying alternative materials and material treatments. Section 5.0 presents the preliminary blade design developed under the project and Section 6.0 presents conclusion and recommendations.

2. Baseline Turbine and Blade Description

2.1 Baseline Turbine (AWT-27)

Advanced Wind Turbines, Inc. had two turbine designs, the AWT-26 and the AWT-27. Both turbine rotors used identical wood-epoxy blades, with the AWT-27 rotor including the addition of hub extenders to increase the diameter.

The configuration of the AWT-27 wind turbine is shown in Figure 2-1. The turbine is a downwind, free-yaw, fixed-pitch machine. Rotational energy is converted to electrical power in the nacelle, which contains a speed increaser (gearbox), generator, and a programmable logic controller (PLC).

The blades are lofted from NREL S825/S809/S810 thick-airfoil sections, and are made of wood-epoxy laminates, reinforced with carbon fiber. The AWT-27 rotor is a teetered, two-bladed, fixed-pitch, stall-regulated design. It has a diameter of 27.4 m (90 ft) and has a nominal speed of 53 rpm. The rotor is connected directly to the gearbox mainshaft, and the gearbox increases the mainshaft speed to 1800 rpm, driving a three-phase, 60 Hz, 480 volt , induction generator.

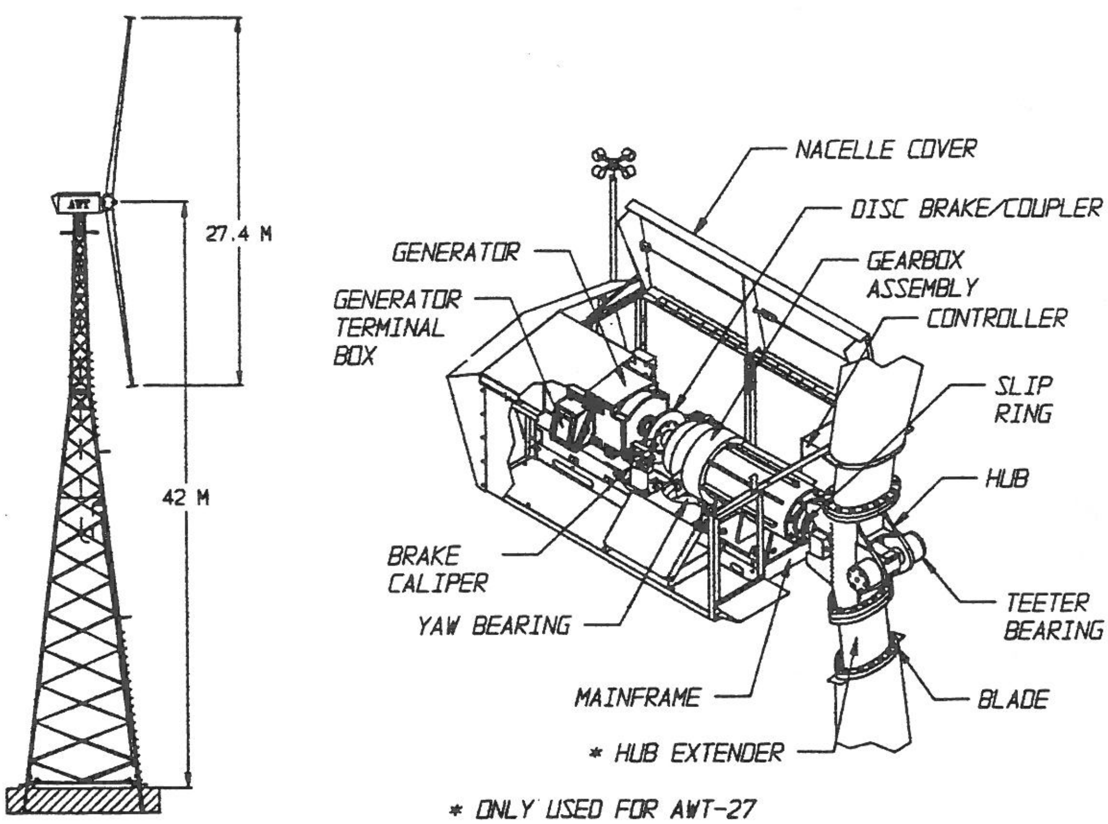


Figure 2-1 General Configuration of AWT-27 Turbine

The tower is a 42.7 m (140 ft) high free-standing, steel lattice structure. The machine is controlled by a PLC that is located in a control house adjacent to the tower. This PLC communicates with the PLC in the nacelle and also provides performance and maintenance diagnostic information. Connection to the grid is made at the switchboard enclosure in the control house.

2.2 Baseline Blade (AWT-26/27)

A drawing of the AWT-26/27 wind turbine blade cross section appears in Figure 2-2. The blades are constructed from wood/epoxy laminates with two shells bonded together with an inner vertical shear web. Carbon fiber is used in some of the laminations on the tension side, and the shells are sealed on the inner and outer surfaces with a layer of fiberglass. The outer surface is gelcoat.

The number of laminations varies along the blade length in response to the load spectrum seen by each station on the blade. Due to the length of the blade, each laminate layer has multiple spanwise joints along the length of the blade. These joints are staggered between layers. In the most highly loaded layers, the ends of the veneer sheets are scarfed to improve the strength of the joint. In less heavily loaded veneer layer, the veneer sheets are placed end-end with no pre-treatment to create a butt joint.

The blade is secured to the turbine hub with bolts which thread into steel studs bonded into the blade root.

The blade is 12.57 m (495 in.) in length and is lofted based on three basic NREL advanced airfoil sections: S815 on the inboard region, S809 on the midspan region, and S810 on the tip region of the blade. A smooth lofting process based on cubic splines was used to generate the intermediate airfoil shapes. The root region of the blade is governed by structural considerations peculiar to the wood/epoxy laminate system used to fabricate the blade shell. The anisotropic nature of the veneer limits the rate at which surface geometry can transition from an airfoil shape to a desirable shape for attachment to the hub. As a result the first basic airfoil station (S815 airfoil) is located 4.597 m (181 in.) from the center of rotation and the root shape approximates an oval.

Table 2-1 AWT-26/27 Blade Geometry

	AWT-26/27
Blade length	12,570 mm (495 in)
Hub station	533.4 mm (21 in)
Tip station	13,106 mm (516 in)
Total blade twist	6.10 degrees
Root (inboard) airfoil	S815
Midspan airfoil	S809
Tip (outboard) airfoil	S810
Furnished blade mass	447 kg (950 lb)
Maximum chord	1143 mm (45 in)
Maximum chord station	3,932 mm (154.8 in)
Tip chord	368 mm (14.5 in)
Root chord	774 mm (30.5 in)

Table 2-2 gives a summary of production costs and related figures of merit for the baseline blade. Note that a production rate of 3 blades/day may result in a 13% decrease in blade cost, relative to a 2 blades/day rate. For this report the 3 blade per day figures are used as the baseline.

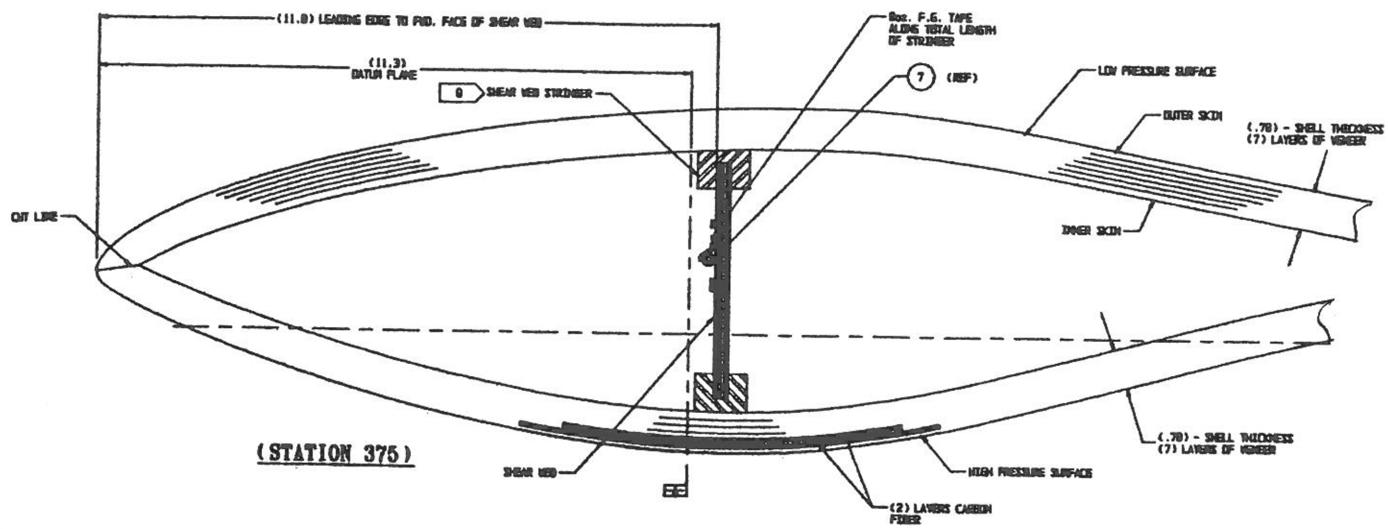


Figure 2-2 Typical Blade Cross Section

Table 2-2 Baseline Blade Costs

Cost/ Figure of Merit	Production Rate	
	2 blades/day (62.5 MW/year)	3 blades/day (94 MW/year)
Production Cost (per blade)	$7,091	$6,158
Weight (per blade)	950 lb.	950 lb.

3. Manufacturing Processes

The blades for the AWT-26/27 are constructed using a wood epoxy laminate system. High-grade, 2.5-mm (0.1 in.) thick Douglas fir veneer sheets are laminated in female molds using West System epoxy to form the high- and low-pressure half-shells. These two parts are then trimmed and bonded together, including a vertical shear web, as indicated in Figure 2-2, to form the basic blade shell.

The blade half-shells are laminated as follows:

1) outer gelcoat skin sprayed into molds (pigmented polyester gelcoat),
2) one layer of 0.75 oz/ yd^2 E glass veil cloth,
3) one layer of 12 oz/ yd^2 double-biaxial E glass,
4) laminating epoxy,
5) veneer layer,
6) carbon augmentation,

Repeat 5) & 6) as per local lay-up schedule

7) one layer of 12 oz/yd^2 double-biaxial E glass, and
8) two coats of resin/hardener to seal interior of blade shell.

Once the blade half-shells are complete and cured, they are removed from the molds, trimmed slightly and are ready for assembly with no further painting or sanding. After the shells and the shear web are bonded together, the epoxy lines at the leading and trailing edge seams are removed and the blade shells are complete with the exception of the installation of root and tip studs.

The blades are attached to the hub by steel inserts (studs) epoxied into holes bored into the end of the blade shell. The studs are tapered and contoured to effectively transfer the load from the wood/epoxy laminate blade shell through the thickened epoxy bond to the body of the steel insert without overloading any one of these three media. The studs contain pre-tapped holes accommodating bolts through the flange in the hub.

A plate for securing the tip vane mechanism is attached in a similar manner to the tip of the blade, except that the threaded studs are epoxied into the holes bored into the blade top. These threaded rods have stop nuts to provide a positive surface for the hardware to be bolted down against without pre-loading the epoxy /blade shell interface.

Carbon fiber reinforcement is used to augment the blade shells in certain locations. Only the high-pressure half of the blade shell is reinforced with carbon fiber tape along the longitudinal axis of the blade. By balancing the cross-sectional area of carbon with the cross-sectional area of wood and epoxy to ensure good load sharing, significant structural augmentation can be achieved with relatively small amounts of carbon.

The blade shell wall thickness is decreased along the span of the blade by using successively fewer veneers along the span of the blade. At the root, the shell wall is rapidly built up to a thickness of 89 mm (3.5 in.) to accommodate the load concentrations associated with the root stud inserts. The shell wall thickness at the tip of the blade is similarly built up to accommodate increased loads from the tip studs and the tip vanes.

This blade fabrication process can be summarized as the following ten principle steps, accomplished over four calendar days:

1. Laying the outer gel coat and fiberglass layers onto the blade mold.

2. Laying of the epoxy resin coated wood laminations onto the blade mold.
3. Vacuum bagging and curing the epoxy resin laminate.
4. Trimming of the newly formed blade shells, after removal from the molds.
5. Installing the shear web between blade shells and bonding of the blade shells together.
6. Machining the ends of the assembled blades and installing end caps
7. Installation of the blade root and tip stud bolts (boring, encapsulation with epoxy resin & curing).
8. Weighing and balancing blades into matched sets.
9. Finishing of the blades (edge seam finish sanding & painting, washing, final inspection).
10. Assembling and installation of the blade tip braking mechanisms

The improvements to this process evaluated as a part of the BMP were: changes in the process controls, reductions in the blade cure cycle time, use of a molded shear web, improvements in the methods used to drill the root stud cavities, and improvements in the blade machining process. Each of these are discussed in the following sections of the report. Each section includes subsections covering the baseline process condition, the research completed as a part of this project, a cost/benefit analysis of the improvements and the resulting conclusions.

3.1 Process Controls

During 1995 and 1996 ABM conducted an internal effort to ensure its quality system was in conformance with ISO 9000 requirements. During this process it became apparent that three aspects of the blade manufacturing process could benefit from more controls. These were:

1. The vacuum bagging process used during curing of the blade shells
2. Tests used to establish blade shell integrity
3. The process used to apply epoxy resin to the individual veneers

This section of the report documents the work which was completed to develop improved controls for these elements of the manufacturing process.

3.1.1 Vacuum Bag Process

After the laminated blade shells are placed into the mold a vacuum bag operation is used to compact the laminate, thus ensuring a strong bond between the laminations. The process specification requires that the blade shells be subjected to a vacuum of 18-22 Hg for an eight hour cure cycle. Excessive vacuum causes moisture to be pulled from the laminations, reducing bond strength. Insufficient vacuum also reduces bond strength due to insufficient compaction of the laminate. If the vacuum is not maintained throughout the curing cycle the laminate may pull apart, also reducing laminate strength.

In the current production process, the proper level of vacuum is established by an operator reading a mechanical gauge. The operator then sets a timer for the eight hour cure cycle and leaves the operation generally unattended. A significant portion of the cycle occurs at night, while the plant is not in operation.

To ensure process integrity and documentation it was necessary to develop process controls which would continuously monitor the status of the process, document out-of-specification conditions and alert an operator if the process falls out of specification.

To achieve this objective, an automatic vacuum monitoring instrumentation system was developed. This system provides a real time readout of the vacuum, continuously monitors and records the vacuum within the molds and sounds an in-plant alarm and notifies off-site operators in the event of an out of specification condition. The system and its estimated costs are depicted in Figure 3-1.

3.1.2 Blade Shell Integrity

As a result of several tests conducted in conjunction with the National Renewable Energy Laboratory (NREL) ABM determined that there were some problems with the quality of the laminates it was producing. This resulted in an effort to identify a non-destructive testing technique for evaluating the condition of the blade shell.

These efforts resulted in ABM adopting stress wave testing as an NDT technique for the root portion of the blade shells. Stress wave testing is an NDT technique which utilizes accelerometers to measure the transit times of shock waves (stress waves) though the laminate being tested.

To better control the manufacturing process it was necessary to establish acceptance criteria for the blade laminate. An extensive data base of Stress Wave measurement and corresponding laminate quality was developed using a Metriguard model 239A Stress Wave Tester. This resulted in an acceptance criteria being established for the blade root. After the unit was sent to Metriguard for repair and returned to ABM it was found that the calibration of the unit was different than it had been when the original database was established. Subsequent testing developed a new standard. This experience resulted in ABM establishing a more frequent calibration interval for the Metriguard testing unit.

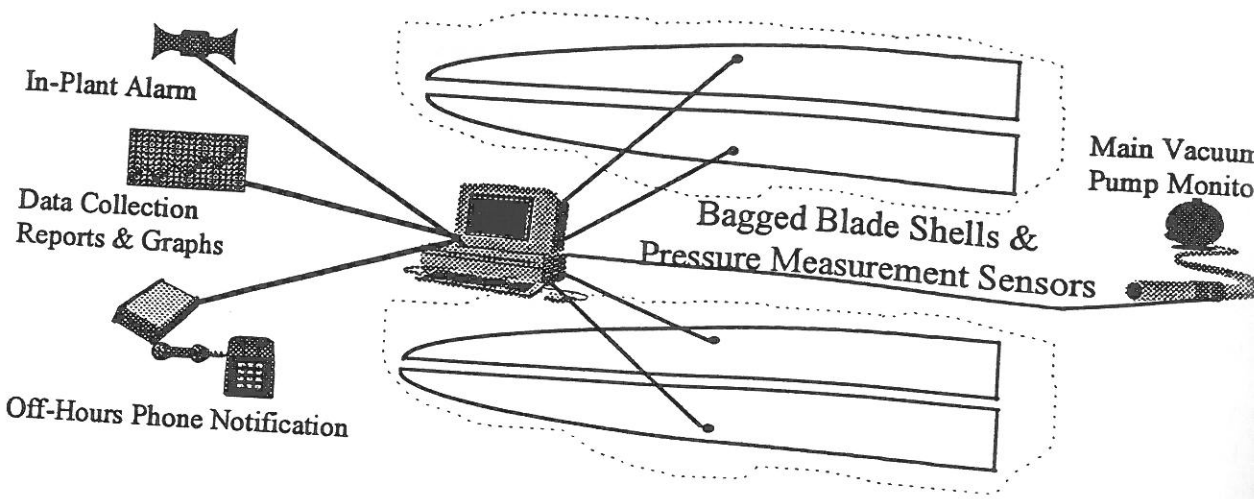
As part of this project standard testing procedures and data recording and analysis methods were also developed. Similar systems should be considered for any organization producing wood epoxy laminates where the quality of the laminate is a significant concern.

3.1.3 Resin Application Rate

In the current manufacturing process the epoxy is applied to the veneer sheets using a roll coating machine. As the veneer sheet is passed through this machine a pair of rollers, which rotate in a bath of epoxy, transfer a layer of epoxy to the veneer sheet. The amount of epoxy transferred depends on many variables including the spacing of the rollers, the viscosity of the epoxy, the condition of the veneer surface and the condition of the roller surface.

Examination of the historical blade production data showed that the standard deviation (sigma) of the application rate was approximately 1.66 grams per double glue line (g/dgl). The roll coater was typically set toward the mid point of the allowable standard of 24.5 - 30 g/dgl. When this is combined with a sigma of 1.66 g/dgl. it becomes apparent that at 3-sigma the amount of epoxy applied will be significantly outside of the allowed standard.

To address this problem it was necessary to evaluate the current process and implement changes which would ensure application rates within the standards.



Cost Estimate

The Harrison proposal for the Honeywell recording unit:

1- HONEYWELL PROGENY RECORDER MODEL 031060-A0-200-0-0E00-00 RECORDER/ CONTROLLER	$3,980
7- HONEYWELL ST 3000 SERIES 900 SMART TRANSMITTERS, MODEL STA922-A1A--00000-MB-F1D3 is $1,173.25 @	$8,213
The Michigan I & C proposal for the Control Valve (Appendix page A30):	
1 - 1/2" Baumann Control valve, 24000 SERIES, Little Scotty -	$1,338
Total Equipment Cost	**$13,531**
Installation cost estimate, including, materials, construction labor, coordination, and supervision:	
Total Installation Cost	**$14,340**
Total Project Cost	**$27,871**

Figure 3-1 Automated Vacuum Monitoring Layout and Cost

The evaluation process showed that the rollers on the roll coater had become worn and glazed from many years of use. Discussions with the manufacturer indicated that resurfacing the rollers would significantly decrease the variability in the application rate of the epoxy. The evaluation also showed that while measurements of the resin application rates were being made periodically, the data was not being evaluated in any statistical manner. So long as the data recorded was within the prescribed limits, no adjustments to the machine were made. Measurements were taken several times during the production cycle but unless an out of specification operation occurred when a measurement was made the process was considered to be within specification.

As a result of this investigation it was concluded that the rollers on the roll coater should be recovered, a process control chart should be established at the roll coater and the machine operators and plant manager should be trained in its proper use. The mean and standard deviation of the measurements taken should be used to determine if the process is within specification. Data should be maintained for each blade manufactured to ensure traceability if problems occur in the field.

3.1.4 Conclusions

The wood-epoxy blade manufacturing process is one in which there are many variables affecting the quality of the finished blades. In particular, variability in the properties of the raw materials will result in high variability in the manufacturing process. For this reason, it is critical that appropriate process controls be in place during the manufacturing process. This portion of the BMP developed several significant improvements to the process controls at ABM which can be applied to any wood-epoxy blade manufacturing operation.

3.2 Reduction in Cure Cycle Time

3.2.1 Baseline Process

Steps 2, 5, and 6 of the blade manufacturing process outlined above require the use of epoxy adhesive. For these adhesives to achieve the required strength prior to successive manufacturing operations, an extensive cure cycle is required. The baseline manufacturing process employs ambient factory conditions during the curing cycle. Of the three process steps requiring epoxy resin, the blade lamination and cure cycle (step 3) requires the longest period. The present length of this cycle restricts the ABM factory to a single blade molding operation per 24-hour period. The specific steps in this process are shown in Table 3-1.

Table 3-1 Blade Molding Cycle Time

a)	preparation of molds for lamination	300 minutes (5 Hr.)
b)	epoxy resin coating of the wood veneers and placement in the mold (per mold basis)	45 minutes (3/4 Hr.)
c)	covering the filled mold with a plastic wrapper and placing under vacuum (nearly full atmospheric pressure is applied to the mold contents) (per mold basis)	15 minutes (1/4 Hr.)
d)	maintaining the mold and contents under vacuum, ambient temperature	480 minutes (8 Hr.)
e)	vacuum bagging complete, mold & contents setting until blade shell removal	420 minutes (7 Hr.)
	Total Cycle Time	24 Hours

If the duration of this process could be reduced to a maximum of 12 hours it would be possible to operate the factory on a two production shift per day basis. This would result in a reduction in blade cost through better utilization of the equipment, facilities, and labor. The production rate would be doubled without requiring a corresponding increase in factory tooling or overhead costs. Discounting the "wait" period, which is not required to ensure product quality, the mold preparation, placement of veneer and resins into the mold, and the vacuum bagging steps require 17 hours to complete. To reduce the duration of this cycle to 12 hours will require that the vacuum duration be reduced from 8 hours to 3 hours, as the other steps are already optimized.

3.2.2 Research Completed

The following research process was followed to evaluate the potential for reducing the cure cycle time of the blade molding process.

1. Determine epoxy resin cure time vs. temperature for epoxy mixtures used in ABM operations. This was expected to allow a determination of the temperature required to sufficiently shorten the cure time.
2. Determine epoxy hardness vs. temperature profiles. This is required to ensure that the blade is not removed from its mold until the epoxy is sufficiently cured to preclude a change in blade shape when removed from the mold.
3. Utilizing the data obtained, complete preliminary engineering of the equipment required to achieve the desired reduction in cycle time.

3.2.2.1 Cure Rate Curve Determination

The Gougeon Brothers, Inc. (GBI) provided data on the cure rates of the 105 epoxy resin and 206 "slow" hardener used in the blade lamination process. This data is shown in Table 3-2.

Table 3-2 Cure Rate Data for 105 Resin / 206 Hardener

	CYCLE	CURE TIMES (min) 65°F	75°F	85°F
	START	0	0	0
POT LIFE	POT	24	18	11.5
GELLATION	GEL	300	48	42
VITRIFICATION POINT	SET	330	90	72
VITRIFICATION COMPLETE	SOLID	420	150	90

Inspection of the cure rate data indicates that the time required to reach full vitrification is strongly temperature dependent. It also indicates that at typical ambient factory temperature of 65 °F the epoxy will have achieved full vitrification prior to the end of the vacuum bagging process. An increase in vacuum bagging operating temperature to 85°F from 65°F, would result in a decrease in vacuum time required for full vitrification from seven and a half hours to one and a half hours. Since increasing the factory production to two production cycles per day is dependent on the completion of the vacuum bagging cure cycle in a maximum of three hours, it appears that performing the vacuum bagging at elevated temperatures will accomplish the objective. However, it was not clear whether the cure time information provided by Gougeon was representative of the relatively isothermal conditions experienced in much of a blade where relatively thin films of epoxy are used.

A concern with elevating the temperature during the curing cycle is that the elevated temperature of the partially cured epoxy would result in epoxy whose properties were insufficient to preclude changes in blade shape if the blades were removed from the mold before the blade had cooled sufficiently. Hardness, as

measured by a Durometer reading, is used as a criteria [illegible]
developed sufficient strength to withstand typical handl[illegible]
concerning the hardness of the epoxy resin/hardener mix[illegible]
temperature was not available.

To address these questions, a series of tests to measure the [illegible]
conditions were developed.

3.2.2.2 Hardness Testing

Three series of laboratory tests were completed, one at 65 °F [illegible]
performed at 65 °F were used as the base case, duplicating [illegible]
during the colder winter months. The tests were performed [illegible]
refrigerators and ovens. Hardness was measured utilizing [illegible]
hardness scale. Special sample containers were fabricated [illegible]
modeled the isothermal conditions experienced in the cure [illegible]
containers were constructed from 1 ½ inch thick aluminum [illegible]
3/16" Garolite sheet containing a 3/4" diameter hole bonded to [illegible]
large aluminum plate served as a heat sink to assure [illegible]
cavity contained the epoxy sample. Data (temperature and [illegible]
elapsed time intervals. The results of these tests are shown in [illegible]

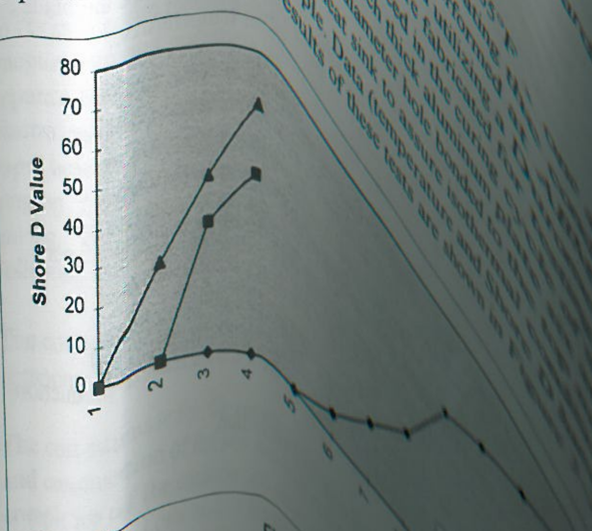


Figure 3-2 Shore D Hardness [illegible]

Examination of the data in Figure 3-2 for 65 °F [illegible]

- The epoxy resin remains very soft (< 1 on Shore D [illegible] the epoxy resin and hardener system. At [illegible] epoxy) it attained a Shore D value of [illegible] hours) the Shore D value is approximately [illegible]
- An accelerated production curing cycle [illegible] vacuum forming step and 70 by the [illegible] properties known to be successful [illegible]