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The Status of the U.S. VAWT Program*

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ABSTRACT

Vertical axis wind turbine (VAWT) technology in the United States started in the early 1970s directly from the original work in Canada. The close, and very productive relationships among laboratories, universities and industry have continued since that time. This paper briefly discusses the significant technical progress and rather dramatic programmatic changes that have occurred in the past 18 to 24 months on the U.S. side of the border.

INTRODUCTION

VAWT technology in the United States began at Sandia National Laboratories in the early 1970s, coming directly from the pioneering work of Templin and Rangi in Canada. The cooperative activities among laboratories, universities and the wind and utility industries in both countries have continued over the years, with the work described in Massé and Pastorel[1] simply being the latest example of that cooperation.

The keystone of the U.S. VAWT research and development program for the past four years has been the DOE/Sandia 34-meter VAWT Test Bed, last reported to a Canadian audience two years ago.[2] An excellent summary[3] of work conducted through early 1990 is available, and individual papers have also been presented at U.S. conferences during the intervening time. This paper highlights those results and presents progress not previously reported. Some results helped validate analytical tools, while others yielded surprises that are now providing new research directions.

The success of the VAWT research and development program led to a decision to pursue technology transfer opportunities with U.S. industry. Beginning with a public announcement

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MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED and an open workshop held in May of 1990, Sandia began a new initiative to transfer the advanced technology demonstrated on the Test Bed to private industry and to assist, where needed, in developing a next generation of commercial VAWTs. An integral part of that effort was the VAWT Point Design,[4] and this paper presents a brief synopsis of that work as well as the ongoing cooperative activities with the U.S. industrial leader/partner.

STATUS OF THE VAWT TEST BED

Since its dedication in May 1988, the DOE/Sandia VAWT Test Bed has provided vital information concerning the improvements possible for the next generation of VAWTs. The last report to this conference was in 1989,[2] and included preliminary performance data. Since that time numerous papers have been published[3] and considerable progress has been documented. A brief summary of the Test Bed characteristics includes: a diameter of 34 meters, a height-to-diameter ratio of 1.25, power rating of 500 kWe at 37.5 rpm in a 12.5 m/s wind, variable speed operation (6-40 rpm) with most testing conducted from 28 to 38 rpm, step tapered extruded aluminum blades incorporating natural laminar flow (NLF) airfoils, a versatile programmable controller, and extensive instrumentation coupled with a state-of-the-art data acquisition and analysis system. The following sections describe recent significant findings in various areas of research; some results are specific to VAWT technology while others have impacted wind turbine research and development in general.

Aerodynamic Results/Issues. The Test Bed is the first wind turbine designed to utilize the VAWT-specific SAND 0018/50 airfoil, one of a family of symmetric, natural laminar flow (NLF) airfoil sections developed by Sandia researchers and Dr. Gerald Gregorek of The Ohio State University to achieve Sandia-specified performance characteristics.[5-8] These airfoils are tailored for use on a VAWT blade near the turbine equator. A major concern regarding the use of laminar flow airfoils on wind turbines is the degradation of performance that occurs due to roughening of the blade surfaces by dust, rain, and/or the residue from insect impacts. This concern was addressed in the design of the SAND airfoils, and we concluded that the performance of the SAND airfoils, even when roughened, would be superior to the performance of NACA 00XX-type airfoils similarly roughened.[7,8]

The portions of a VAWT blade near the tower operate in a much different environment than that experienced by the equatorial portion, and the NACA 00XX airfoils are far better suited for that environment than are the SAND airfoils.

The Test Bed blade incorporates both airfoil sections: the SAND 0018/50 airfoil near the equator and the NACA 0021 airfoil near the tower. A tapered blade with a smaller chord at the equator and a larger chord at the blade roots reduces blade material stresses while maintaining high rotor energy capture. The taper also maintains a relatively constant Reynolds number over much of the equatorial section of the blade, allowing the SAND 0018/50 airfoil to operate near its design point.

The blade material is extruded aluminum, chosen both because we have had considerable experience with it and because we anticipated the resultant blades would be less expensive than if they were produced with some other fabrication method. The use of extrusions forced us to adopt the step-tapered blade configuration illustrated in Figure 1. The blade chords were too large for single-extrusion airfoils; two extrusions were required for each of the SAND 0018/50 airfoil sections, and three extrusions were required for the 1.22-m (48-in) chord NACA 0021 sections. The extrusions for each airfoil were bolted together in the spanwise direction.

The predicted performance of the Test Bed is compared with data measured in January 1990 in Figures 2 and 3. The predictions were made with SLICEIT, a conservation-of-momentum based, double-multiple streamtube (DMST) code based on Paraschivoiu's CARDAA code.[9] The code incorporates the Gormont dynamic stall model,[10] as modified by Massé,[11] and accounts for local Reynolds number effects. The Massé correction is not used for that portion of the blade comprised of NLF airfoil sections. The agreement between measurement and prediction at moderate to high wind speeds is very good. The power regulation in the high-wind regime is particularly worthy of notice. It is due to the stall characteristics of the SAND 0018/50 airfoil section, and this regulation was one of the key objectives of the Test Bed blade design effort.

The agreement at low wind speeds is not as good. We feel that this discrepancy is at least partly due to the external blade-to-blade joint design shown in Figure 4. As can be seen in this drawing, these joints are not aerodynamically smooth; exposed bolt heads, blunt leading surfaces, and sharp corners all contribute to increased drag and decreased lift from this area of the blade. These effects were not modelled in the performance calculations, but we would expect them to result in decreased turbine performance, especially at low wind speeds.

In order to improve the turbine performance, we installed small aerodynamic fairings on these blade-to-blade joints, using a lightweight epoxy material with embedded fiberglass tape to cover the bolt heads and eliminate some of the sharp corners. The fairings were hand shaped and coated with enamel paint to give them a hard, fairly smooth finish. Measurements of the rotor aerodynamic performance with the fairings installed are summarized in Figures 5 and 6 for 28 and 34 rpm, respectively. The predicted performance curves in these figures are identical to those in Figures 2 and 3. Careful examination reveals that, although the differences are small, the fairings did appear to provide a small improvement in performance in low wind speeds and a small degradation in performance at high wind speeds. We feel the performance could be further enhanced with the installation of somewhat larger teardrop-shaped fairings. But the cost would be significant, so we plan to retain our present fairings for the near-term future.

In May 1990, we ran the first extensive tests during a season when significant quantities of insects were present. After a few days of operation, we noticed that there was a large number of turbine stops due to turbine overspeed in high-wind conditions at 34 rpm. This was an unexpected situation for those operating conditions. Investigation showed the overspeed condition was caused by power production that exceeded the generator capacity (500 kWe). The turbine was producing about 540 kWe at 17 mps, and it normally produced only 480 kWe at that wind speed. A review of the data obtained at 28 rpm that same month revealed the results shown in Figure 7; once again the data obtained in May showed a significant increase in power at high wind speeds, as compared to data obtained during the winter months. An inspection of the turbine blades revealed some accumulation of bug debris, but intuition and experience argued that should cause a decrease in maximum power output, not a 15% increase!

Since the biggest difference in performance came in the power regulation portion of the power curve, we decided to collect more performance data at 18 rpm where the regulation occurs at lower and more prevalent wind speeds and to monitor any change in performance due to natural rain washing. These data, presented in Figure 8, are confined to the power regulation portion of the performance curve, and the data curves are rather rough because the amount of data acquired for each case was quite small. The data marked *7/19/90* are base-line performance data with dirty blades (bug debris and dirt accumulation from several weeks of running in the summer). The *7/24/90* data, at a slightly lower maximum power level, were obtained immediately after a heavy rain fell on the parked turbine. The *8/16/90* data were taken immediately after the turbine was run for nearly an hour during a heavy rain shower. These data show a significant decrease in the maximum power level (approximately 15% below the dirty blade level).

As seen in Figure 9, 28 rpm performance data with the rain-washed blades, obtained on 8/22/90, compare very well with performance data obtained in February, when we know the blades were free of any dirt and/or bug debris.

This evidence all indicates that the accumulation of bug debris and dirt on the Test Bed blades caused a 15% increase in maximum power output at 18 rpm during the summer of 1990. We also observed increases in maximum power output at 28 and 34 rpm, due to the dirty blades, but we do not have enough data to determine the magnitude of maximum power increase at those rotational speeds.

While this increase in maximum power output due to blade roughness is in marked contrast to the sharp decrease normally observed, it is still a problem. Any sensitivity of blade performance to roughness is undesirable, for while a decrease in power implies lost revenue, an increase in power may well lead to premature drivetrain component failure.

We speculate that the presence of the roughness on the Test Bed NLF blade sections delays blade stall and separation of the boundary layer, leading to higher maximum lift and increased maximum power. We have initiated a research effort with Dr. Gerald Gregorek at The Ohio State University to further investigate the effects of naturally occurring roughness on the performance of the SAND 0018/50 airfoil. In contrast, other experimental results to date utilizing NREL(SERI)-developed bug-roughness simulations have all yielded increased drag and decreased maximum lift. But this would correspond to decreased Test Bed maximum power output, rather than to the observed increased output.

Apparently the effect of roughness on the Test Bed blades is heavily dependent on the detailed characteristics of that roughness, and we will have to determine those characteristics before we can fully understand the roughness effects. This is probably true of HAWT blades as well, but we do not have enough data to be sure. Determining the characteristics of blade roughness is difficult, as normal contact-type methods are tedious and not very accurate, and the available non-contact systems are not well suited for this application. Obviously, those characteristics will vary from site to site and from season to season, so we need a measurement technique that is fairly speedy and easy to use. We are currently evaluating the feasibility of developing a non-contact surface mapping system specifically for this application.

Future plans call for the modification of the root sections of the current blades with the installation of vortex generators (VGs). Analytical studies, based on previous tests of vortex generators on VAWTs,[12] indicate that appropriately placed VGs could yield performance improvements of up to 5% at moderate wind speed sites.

Structural Dynamics. The Test Bed project provided an opportunity to exercise our analytical tools in a complete VAWT design process. The primary structural tools, our NASTRAN-based codes, FEVD and FFEVD, perform natural frequency analyses and steady-wind, forced-response analyses, respectively. The validation of these codes and the finite element model is an ongoing effort as operational data become available.

As reported earlier,[2,13] comparisons between measured and analytical data have been completed in several areas. For example, measured deterministic stresses, both gravitational and centrifugal (at several rotation rates), compare closely to analytical results. In addition, stationary natural frequencies were measured with a modal test and compared to FEVD predictions. The measured frequencies of the first ten modes agree with the predictions to within 2% except for a blade-edgewise mode, which differs by only 5%. Measured rotating natural frequencies also compare closely to FEVD results.

Since 1989 many hours of data have been collected at 28, 34, and 38 rpm in winds to 20 m/s. These data have been binsed and compared to predicted operating stresses.[14] The steady wind predictions (determined by FFEVD) are reasonably close to measured values in winds of up to 11 m/s, but diverge from measured values in higher winds. Figure 10 shows this for the case of a lower root, flatwise gauge. Turbulent wind predictions were determined with TRES4, a recently developed code,[15] and show good agreement to measured values at most wind speeds and rotation rates (Fig. 11). However, more work is required to determine aeroelastic damping values and aerodynamic loads in dynamic stall operation.

Upcoming tests include a rotating transient test, which will induce a known force into one blade by releasing a pretensioned cable. It will be performed at several rotation rates and in very low winds to eliminate aerodynamic loads. The measured strain-time histories will be studied to confirm predictions of aeroelastic damping.[16] These results will also be compared to calculations from VAWT-SDS, a time domain code that incorporates turbulent winds and includes both rotating effects and controls/structure interactions. Plans also include the addition to this code of nonlinear aeroelastic effects.

Fatigue. In addition to Sandia's long-term involvement with VAWT technology, several generic research areas have received considerable attention for the past several years. The largest of these is fatigue, and Sandia has been developing an analytical framework for determining the service lifetime of turbine components.[17] The Test Bed has played a key role in providing measured data for design code validation. This design code, called LIFE2, is a fatigue/fracture analysis code that is specialized to the analysis of wind turbine components. The numerical formulation of the code uses a series of cycle count matrices to describe the cyclic stress states imposed upon the turbine. However, many structural analysis techniques yield frequency-domain stress spectra, and a large body of experimental loads (stress) data is reported in the frequency domain. To permit the analysis of this class of data, a Fourier analysis module was added recently to the code. The module transforms the frequency spectrum to an equivalent time series suitable for rainflow counting by other modules in the code. The addition of the module is a major milestone in the development of the code and significantly increases its capabilities.

The Fourier analysis computation module and its associated analysis techniques are described in a paper[18] to be published soon. The application of the module to a wind turbine component is illustrated by the examination of stress spectra from the Test Bed. A typical result is shown in Figure 12. In this figure, the cycle counts from a frequency domain analysis are compared to rain-flow counted cycles from time series data and to the narrow band Gaussian model that has been proposed by Veers.[19] It should be noted that the Gaussian model presented has a different RMS value (based on a large set of time series) than the two time series presented. As illustrated by this figure, the cycle counts from the frequency domain analysis closely follow the cycle counts from the time series data and from the Gaussian model in the main body of the distribution. In the high-stress tail of the distribution of cycle counts, the ability of the analysis technique to generate relatively long time series permits the tail to be defined with a stable, finite, relatively smooth, and monotonically decreasing distribution of the cycle counts. Although the "correct" distribution of cycle-counts in the high-stress tail is still under study, the synthesis of time series data from frequency domain data is an effective technique for the determination of stress cycles imposed on a wind turbine component.

Controls. The Sandia 34-meter Test Bed is equipped with a variable-speed/constant frequency (VSCF) generator system, which is controlled by an Allen-Bradley programmable controller. A personal computer is used to communicate with the controller and to display the current control parameters. This system offers a unique capability to evaluate various control algorithms. For example, the controller can be programmed to operate the system as a fixed-speed, a two-speed, or a variable-speed wind turbine. Tests can be performed to quantify the advantages and disadvantages of each mode of operation. Control algorithms implemented to date include operator-selected, fixed-speed operation; variable-speed operation; full automatic operation; and regenerative braking. All of these control modes include algorithms for the avoidance of structural modes within the operating range of the turbine. The next generation of control algorithms will include artificial intelligence, adaptive control, and "fuzzy logic" concepts. The flexibility of the Test Bed will also allow us to implement these algorithms so that the enhancements in energy production and fatigue life can be determined.

The Test Bed also provides the capability to verify a design code called ASYM.[20] The code permits a designer to examine the effects of various control strategies on the production of energy and the consumption of fatigue life for a wind turbine. ASYM uses a random wind as input to a wind turbine model. The model can be set up to use various control algorithms, as well as various material fatigue and output power characteristics. ASYM is used to select optimal values for start and stop control decisions based on wind speed, power production, and/or fatigue damage rate. With the capability to operate in different control modes and with its extensive instrumentation, the Test Bed gives us the capability to verify the analytical models used in ASYM.

VAWTs AND TECHNOLOGY TRANSFER

As a result of the technical successes of the Test Bed program discussed above, a decision was made in FY90 to initiate a major effort to identify an industry partner and, through cooperative agreements, translate the demonstrated improvements into a commercial product. This intent by Sandia was publicly advertised, and more than a hundred direct contacts with industry were made. The technology transfer strategy included conducting fairly detailed performance and structural designs on a "pre-commercial" version of the Test Bed -- the Point Design[4] -- and then presenting the results and proposed plans to interested parties at an open workshop. The remainder of this section first discusses details of the Point Design, then presents some aspects of how cooperative agreements are implemented in the U.S.A. and finally describes the nature of the new commercialization activities.

VAWT Point Design. In developing a point design it was appropriate to use the best features of the Test Bed to develop a design that eliminates the research items, reduces component weights and lowers costs. Although the size of the rotor was not optimized, a 34 meter diameter turbine was chosen based on our experience with the Test Bed, its known costs, and the quality of comparisons between measured and analytical data. The design philosophy of a point design is much different than that of a research machine. The design goals of the Test Bed were:

1. To provide a conservative design. This was the first time our full suite of design tools was used for a design process, and their accuracy was not completely known.

2. To incorporate a modular design. This feature allows change-outs of components, including individual blade sections.

3. To realize that the turbine is a one-of-a-kind construction. Detailed optimization to manufacturing methods and mass production techniques (as would be done for a commercial machine) was not emphasized.

4. To allow for single-blade operation without counterbalance. This meant larger bearings and bearing housings were required to withstand the inherent eccentric loading.

On the other hand, our point design goals were:

1. To minimize the changes from the existing, tested configuration, and maintain the operating stress levels. We recognize that this is just a single design, which is useful in economic studies, but is probably not the optimum design.

2. To maintain a maximum power output level of between 500 and 600 kW and incorporate power regulation by retaining the laminar flow blade sections.

3. To reduce oversized items.

4. To minimize the number of blade joints.

5. To reduce costs by using off-the-shelf items wherever possible.

6. To keep the tower and cables stiff enough to place the tower in-plane 3P resonance above the operating speed.

Figure 13 shows a drawing of the 34-m Point Design and the features that distinguish it from the Test Bed. The major changes from the Test Bed are the following:

1. Tower: The tower is smaller (2.1-m diameter instead of 3.0-m), which was possible because the turbine was assumed to have two blades.

2. Blades: A laminar flow blade with a 0.91-m (36-inch) chord and SAND 0018/50 profile for the equatorial section maintains the power regulation. The

root sections remain a 1.22-m (48-inch) chord, NACA 0021 profile. This configuration eliminates the 1.07-m (42-inch) transition sections on the Test Bed and two major blade-to-blade joints on each blade. One additional minor blade-to-blade joint in the 0.91-m (36-inch) chord equatorial section on each blade is necessary due to limits on the lengths of extrusion (24 m). Possible extensions to this extrusion length or slight reductions in the overall turbine size would eliminate this joint.

3. Generator: Operation occurs at 36 rpm in a single-speed mode. Two-speed operation is possible, but the variable-speed option is eliminated because of its current high cost.

4. Others: Due to the elimination of the requirement for single blade operation, the bearings, bearing housings, and bearing shafts are significantly lighter. The use of off-the-shelf brakes will lower costs substantially compared to the Test Bed brakes, which were designed and built in-house.

Aerodynamic Characteristics. Figure 14 shows the predicted performance for both the Point Design and the Test Bed at 36 rpm. The Point Design shows a power curve very similar to that of the Test Bed. It exhibits power regulation and actually has higher power levels at high winds due to the longer 1.22-m (48-inch) NACA section. Peak shaft power is 585 kW at 17 m/s.

Structural Characteristics. Structurally, the goal was to keep the operational stresses of the Point Design to levels no higher than those of the Test Bed and maintain the tower in-plane mode crossing of the 3P harmonic above the operating speed.

Several iterations between the aerodynamic code, CARDAA, and the structural codes, FFEVD and FEVD, indicate that we can place the mode slightly above 40 rpm and still retain a rotor that achieves a maximum power of 585 kW at 36 rpm.

Predicted operating stresses at 36 rpm and 11.2 m/s (25 mph) for both the Point Design and the Test Bed were examined, and, as expected, the stress distribution along the blades is very similar for both cases.

In conclusion, the Point Design differs minimally from the Test Bed which has proven performance and thus low technological risk. Initial hardware cost for the Point Design was estimated at $800,000, but with a more detailed design and quantity production, this cost should be more than halved. The Point Design is a first step towards a Test Bed-based commercial machine that would be competitive with conventional sources of power in the mid-1990s.

Cooperative Mechanisms Between National Labs and Industry. Recent growth in the federal wind program has focused on cooperative and/or cost-shared efforts involving the wind industry and the national labs; in fact, the two-year growth in funding from \$8.6M in FY90 to \$20.4M in FY92 has been almost exclusively earmarked for these areas. Since certain aspects of cooperative activities between national laboratories and private industry in the United States may be unfamiliar, this section briefly describes the general kinds of collaborative agreements that can be employed and indicates those chosen for our current technology transfer activity.

Several mechanisms have existed for years to encourage certain types of cooperation and/or cost sharing between the national labs and private industry. First, conventional, competitively bid proposals can require cost-sharing from the industry participant. In this case, contract awards are based on both technical merit of the proposal and the level of cost sharing proposed. The best example of this type is the series of Advanced Wind Turbine solicitations (a three-phase program) being directed by the National Renewable Energy Laboratory (NREL), formerly SERI. In this arrangement, the private company must provide a significant fraction of the total costs and <u>may</u> request assistance from the national labs as part of the activity. Another form of cooperation involves a no exchange of funds (NEF) agreement whereby an effort of mutual interest to industry and the DOE is undertaken, and the parties agree to fund their own efforts and share the results. Finally, industry can request support from a national lab by agreeing to fully pay for the work (which must be done on a non-interference basis by the laboratory). The advantage of this kind of agreement, called work for others (WFO), is that all results are the exclusive property of the funding party and can be kept proprietary.

Unfortunately, the above mechanisms have not always proven to be effective, particularly for the emerging wind industry, which has been severely undercapitalized and often lacking in technical staff. Late in 1989, the President signed into law a new mechanism, which promises to complement the above processes and encourage more effective technology transfer. The result of the law is a new Cooperative Research and Development Agreement (CRADA), which has several unique features. First, CRADAs are made directly between the industry partner(s) and the DOE laboratory, with the DOE providing only initial approval. No funding can flow from the government (through the laboratory) to industry, but money can flow from industry to the laboratory. But the laboratory can provide staff, hardware or protected property (e.g., patents and copyrights). Important aspects of CRADAs are that the industry partner can be given exclusive rights to produce a product, and that intellectual property can be held proprietary (i.e., exempt from the Freedom of Information Act) for up to five years. Equal opportunity to participate in a CRADA must be provided if the laboratory initiates the technology transfer effort; but industry is also allowed to initiate the process, and in this case no open solicitation is required.

The Industry Partner. As a result of a response to the publicly announced workshop mentioned above, FloWind Corporation of Pleasanton, California, was chosen as the industry partner for the advanced VAWT technology transfer process. Because a CRADA could not be formalized in the required timeframe, a combination of existing cooperative mechanisms was chosen for the initial set of tasks. First, a FloWind-funded effort was initiated under a WFO for Sandia to assist in an evaluation of a repair program for FloWind's existing fleet of over 500 VAWTs in California. This effort also includes the design, procurement and installation of data acquisition systems, including both stationary and rotating units. The installation of the stationary units was completed in mid-October, while the rotating, RF-based system was successfully demonstrated on the Test Bed in early October and will soon be moved to California.

At the same time the WFO was implemented, a FloWind/Sandia NEF was also created with the primary purpose of applying some of the improved components demonstrated on the Test Bed to a product improvement program. Specifically, the copyrighted analytical tools that have been validated by the Test Bed, as well as specific components such as the NLF airfoils, are being incorporated into an improved design based on the existing FloWind F-19 turbine.

The final element of this cooperative activity is a plan to optimize the entire Test Bed configuration into a commercial product. The Point Design discussed above is almost certainly not this optimum, but it will be used as the starting point for determination of what the most cost-effective VAWT for the mid-1990s and beyond should look like. This collaboration is just getting underway and will probably take the form of a CRADA.

SUMMARY/CONCLUSIONS

Since the 1989 CANWEA conference, significant technical progress has been demonstrated for VAWT technology in the United States; and the VAWT Test Bed has proven to be the cornerstone for that progress. Of even greater long-term significance, however, is the renewed role of FloWind Corporation in efforts to commercialize this progress. The collaborative efforts between Sandia and FloWind are characteristic of the new emphasis in the DOE Wind Program to combine the federal and private sectors in efforts to improve energy security, positively impact the environment and increase U.S. economic competitiveness in the energy sector worldwide.

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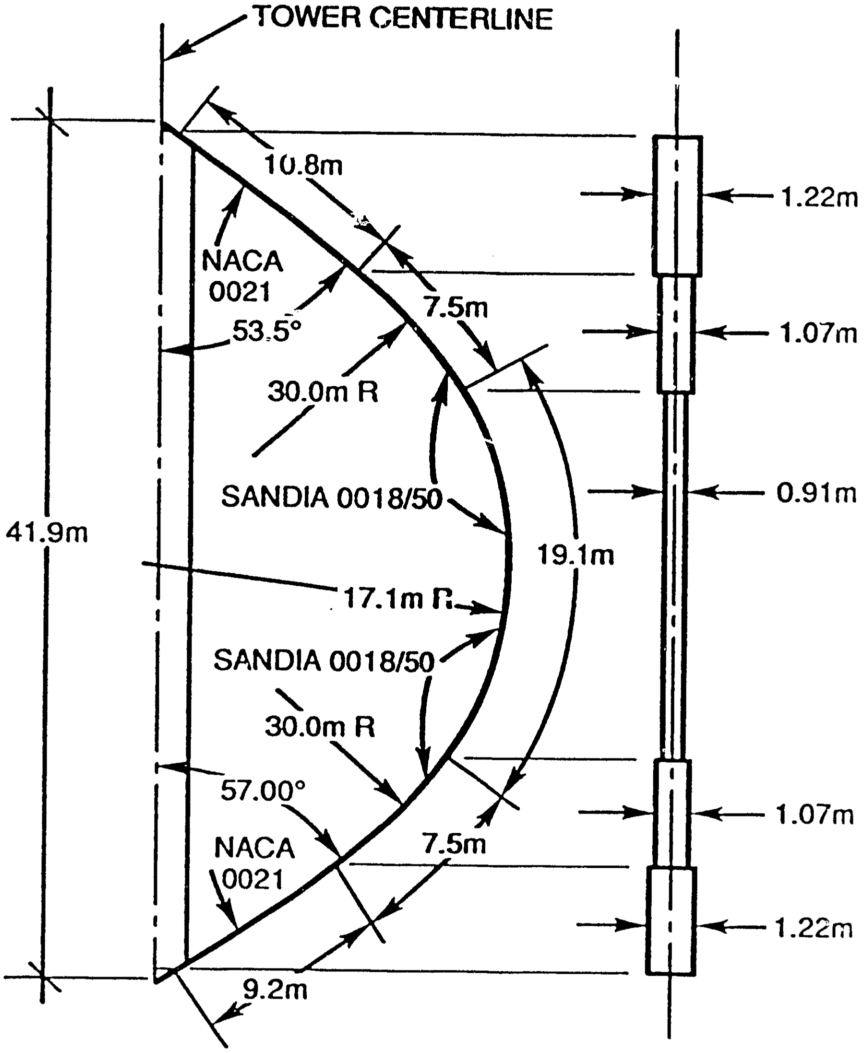

Figure 1. Test Bed Blade Configuration

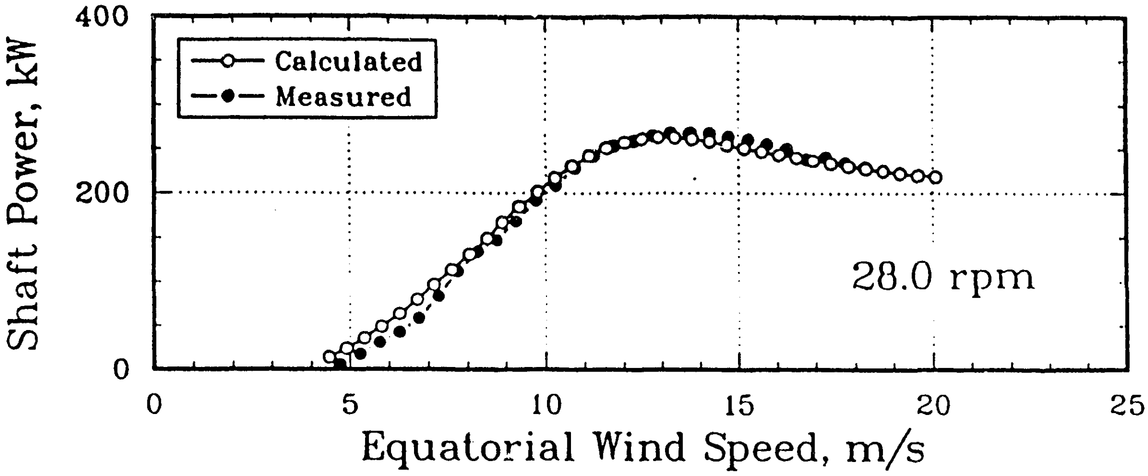

Figure 2. Test Bed Performance at 28 rpm

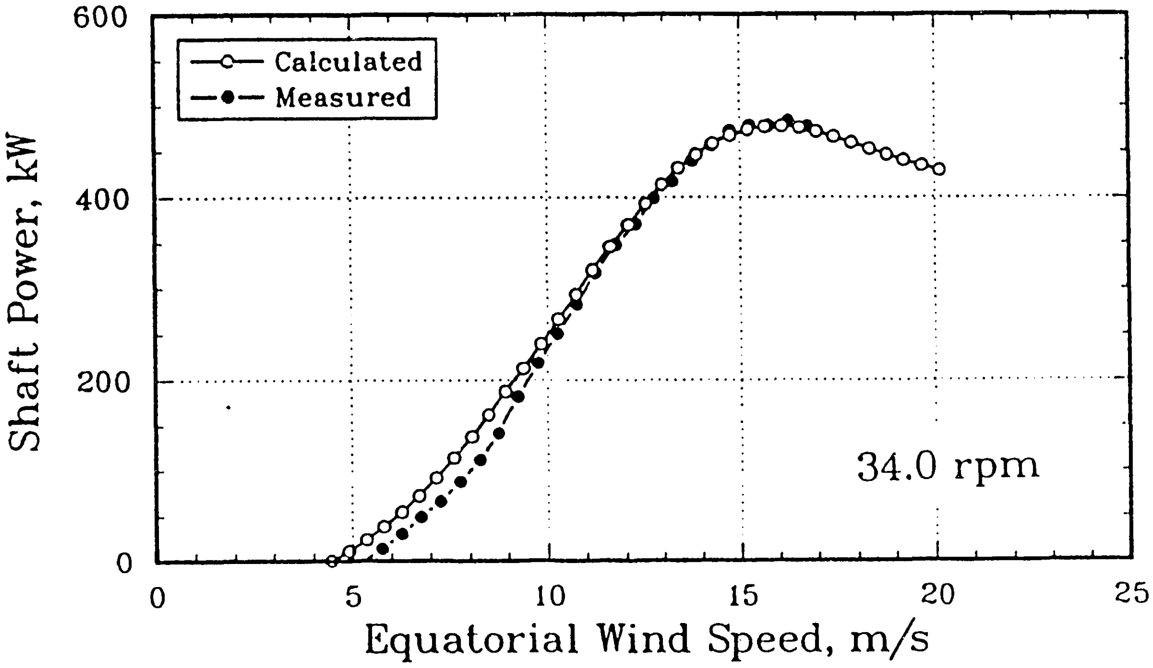

Figure 3. Test Bed Performance at 34 rpm

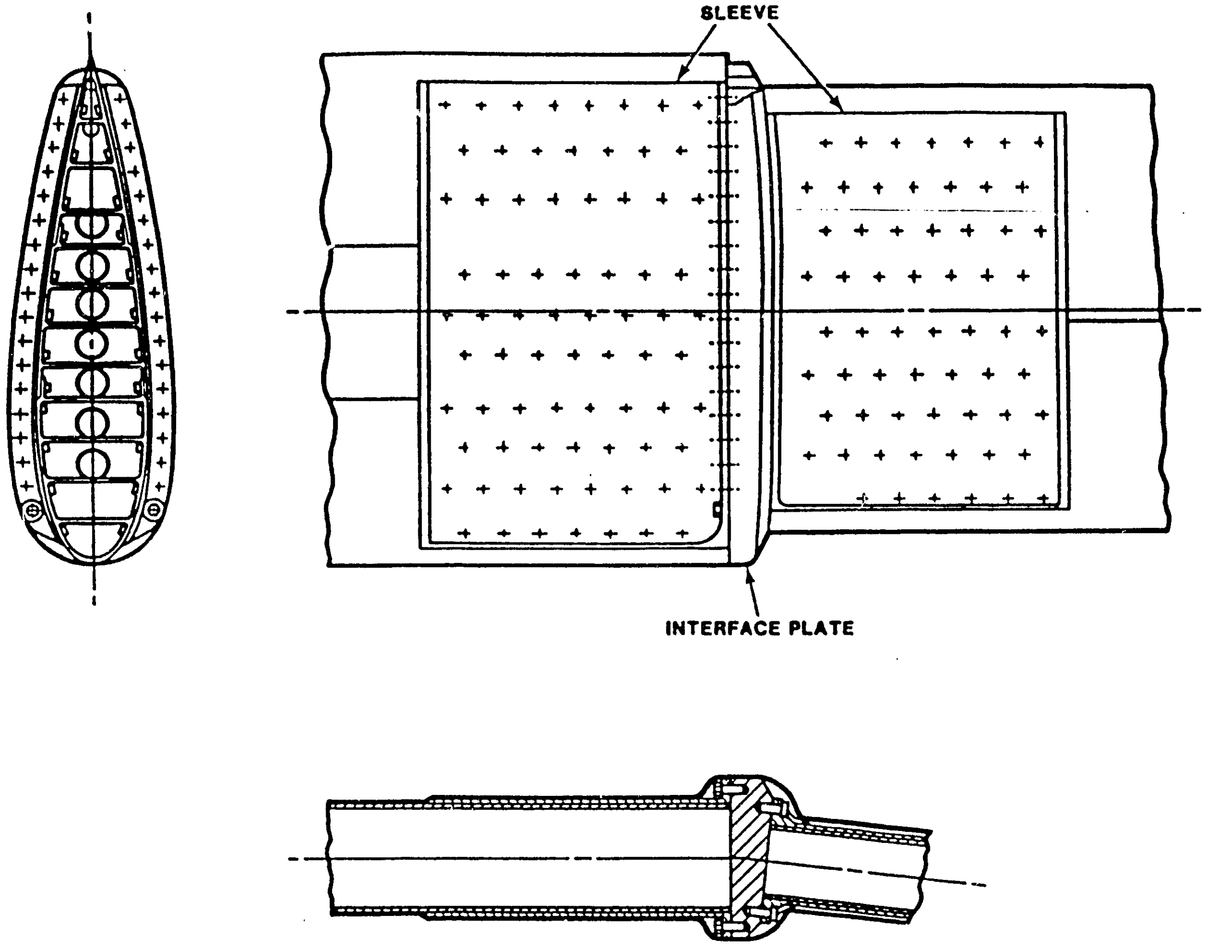

Figure 4. Blade-to-blade Joint Configuration

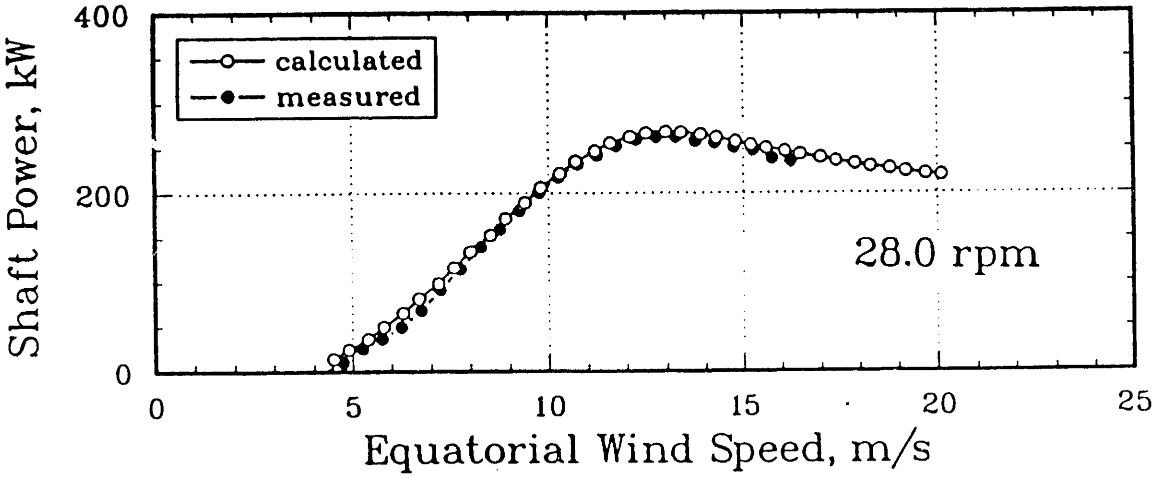

Figure 5. Test Bed Performance with Fairings at 28 rpm

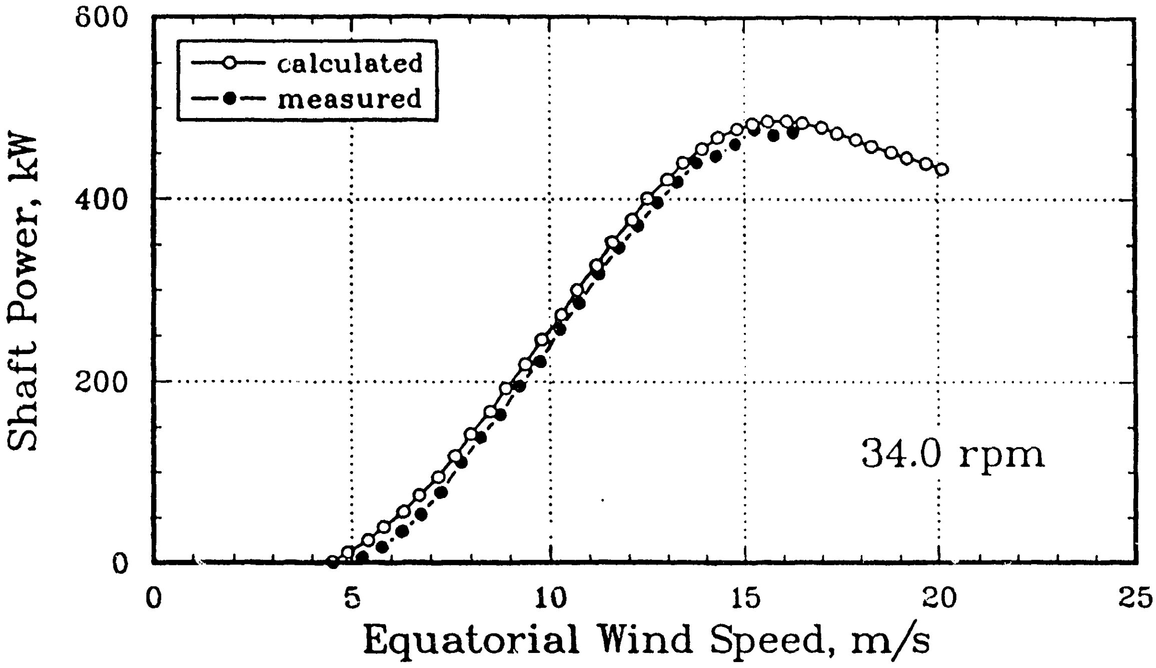

Figure 6. Test Bed Performance with Fairings at 34 rpm

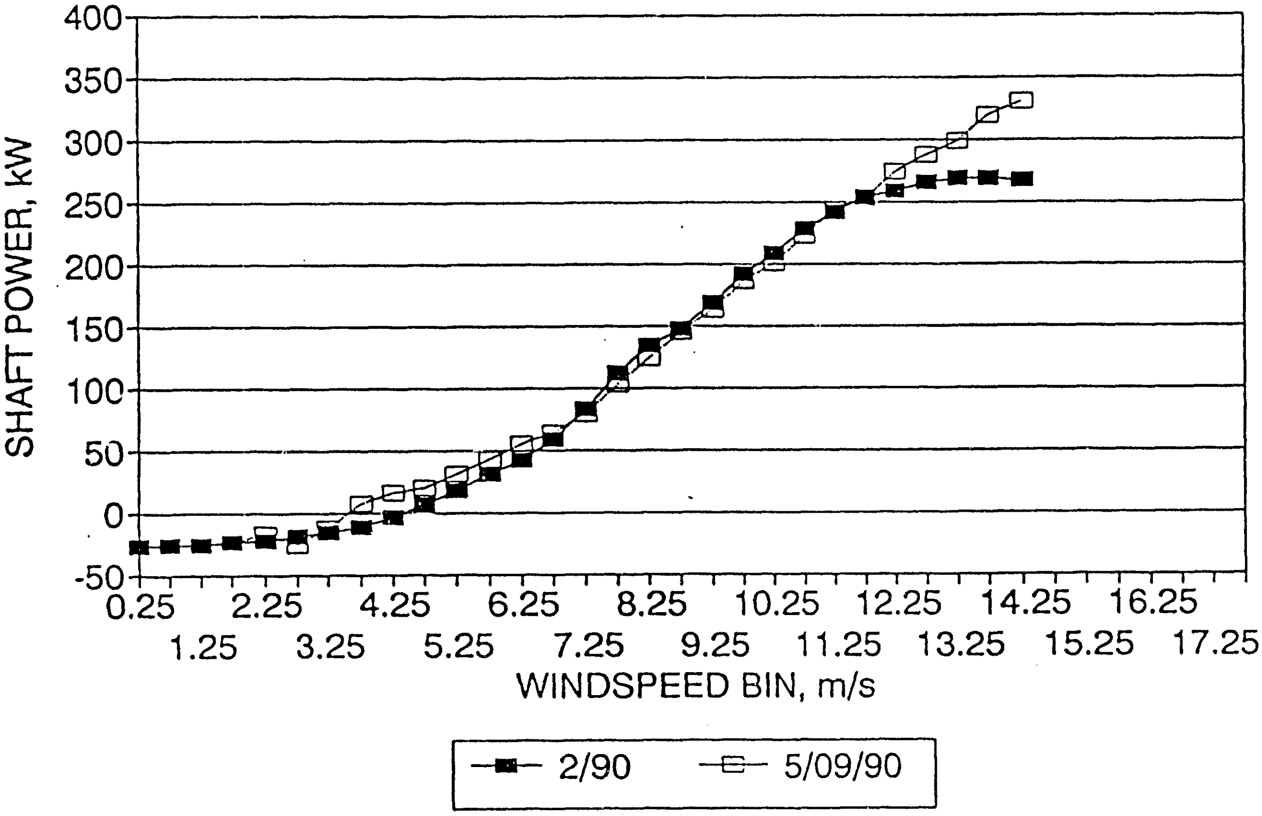

Figure 7. Turbine Performance at 34 rpm.

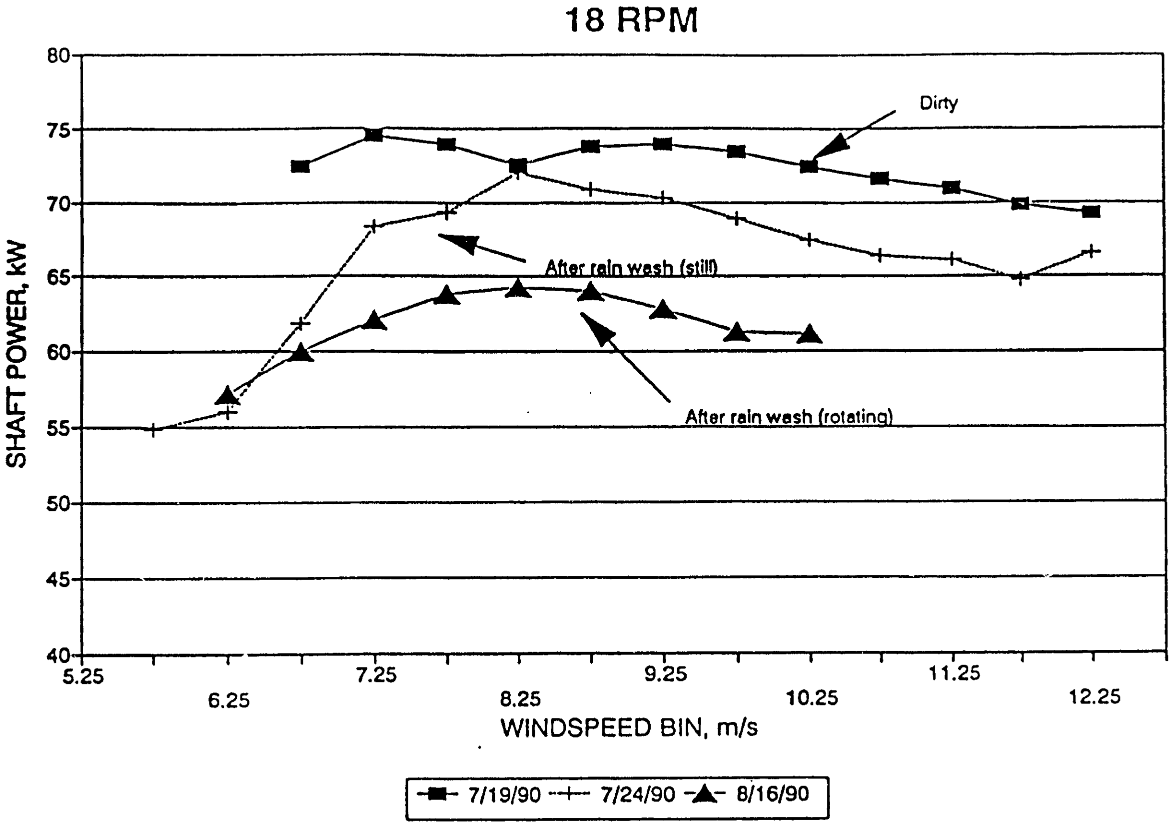

Figure 8. Effect of Rain Washing on Turbine Performance at 18 rpm.

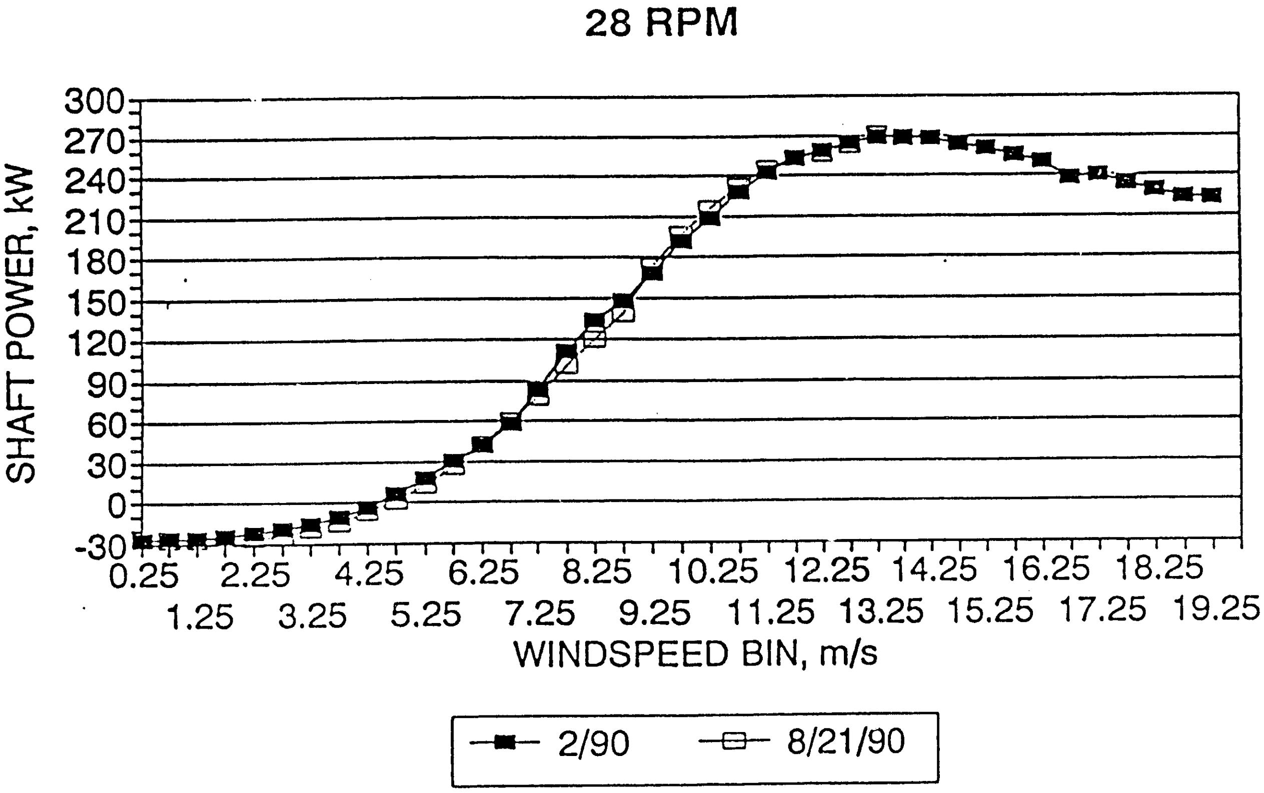

Figure 9. Turbine Performance with Clean and Rain-Washed Blades.

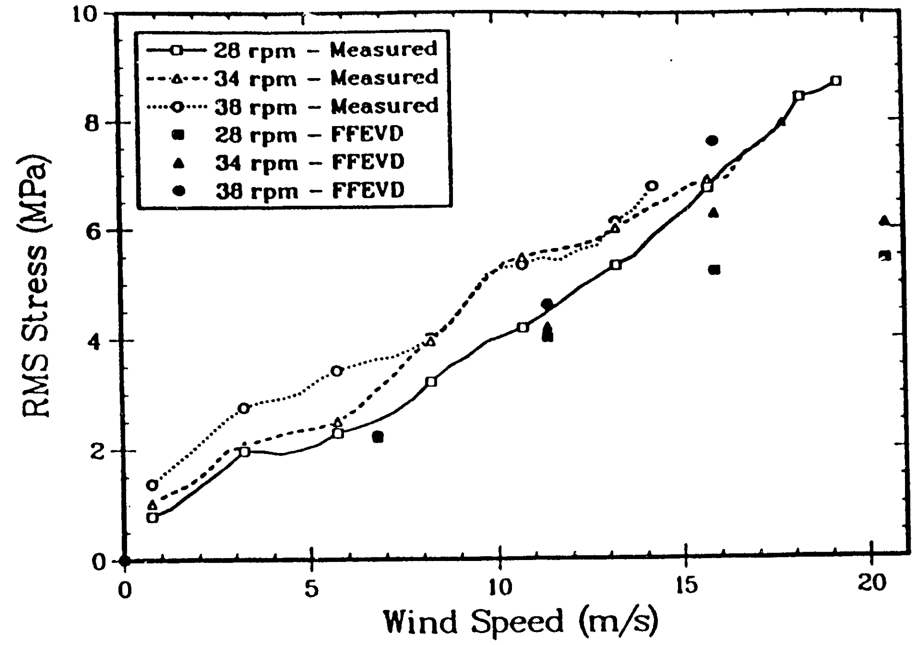

Figure 10. Lower Blade Root Flatwise RMS Stress vs. Wind Speed: Measured and Analytical (FFEVD) Without Turbulence

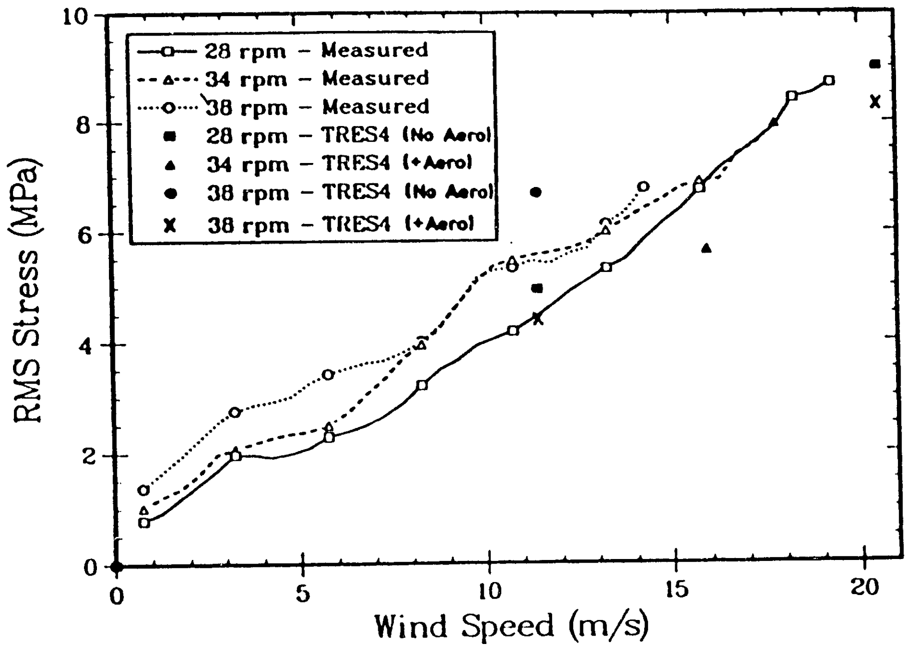

Figure 11. Lower Blade Root Flatwise RMS Stress vs. Wind Speed: Measured and Analytical (TRES4) With Turbulence

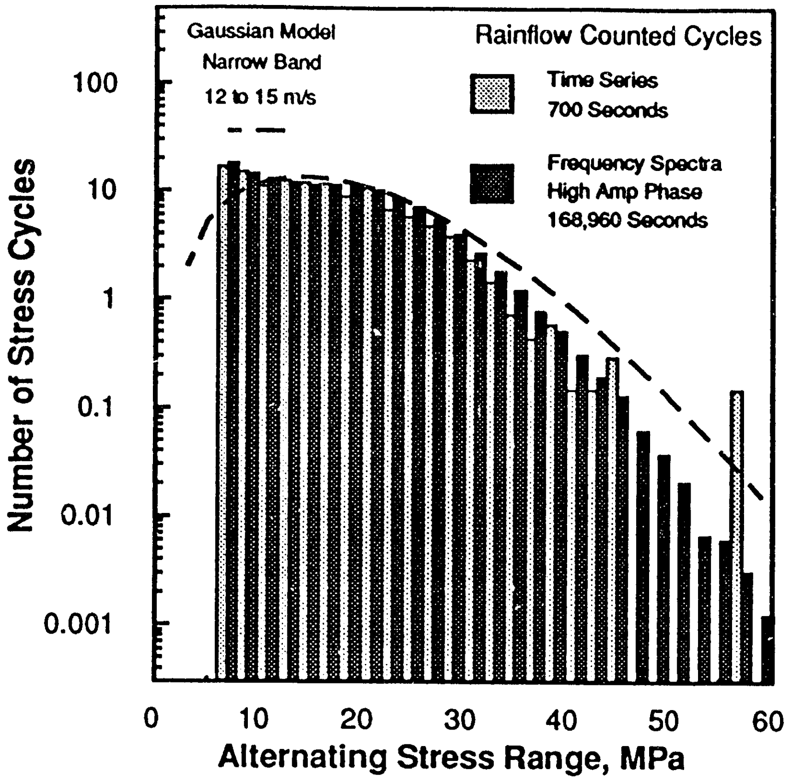

Figure 12. Cycle Counts for the Test Bed Upper Blade-to-Tower Joint (cycle count per 100 seconds).

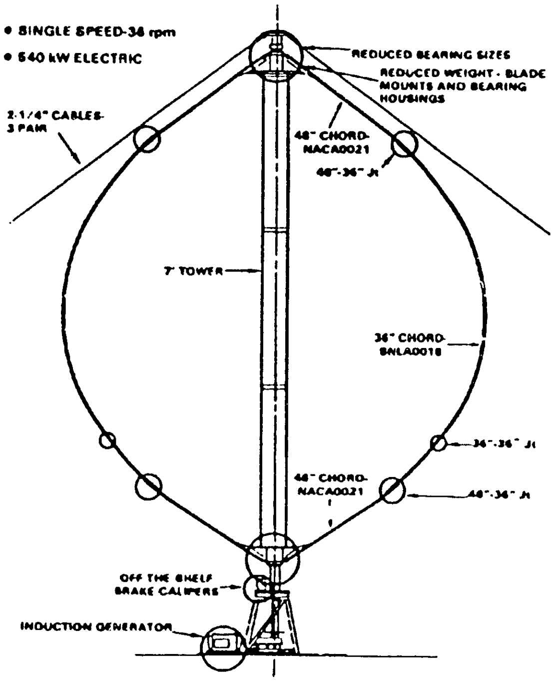

Figure 13. Details of Advanced VAWT Point design

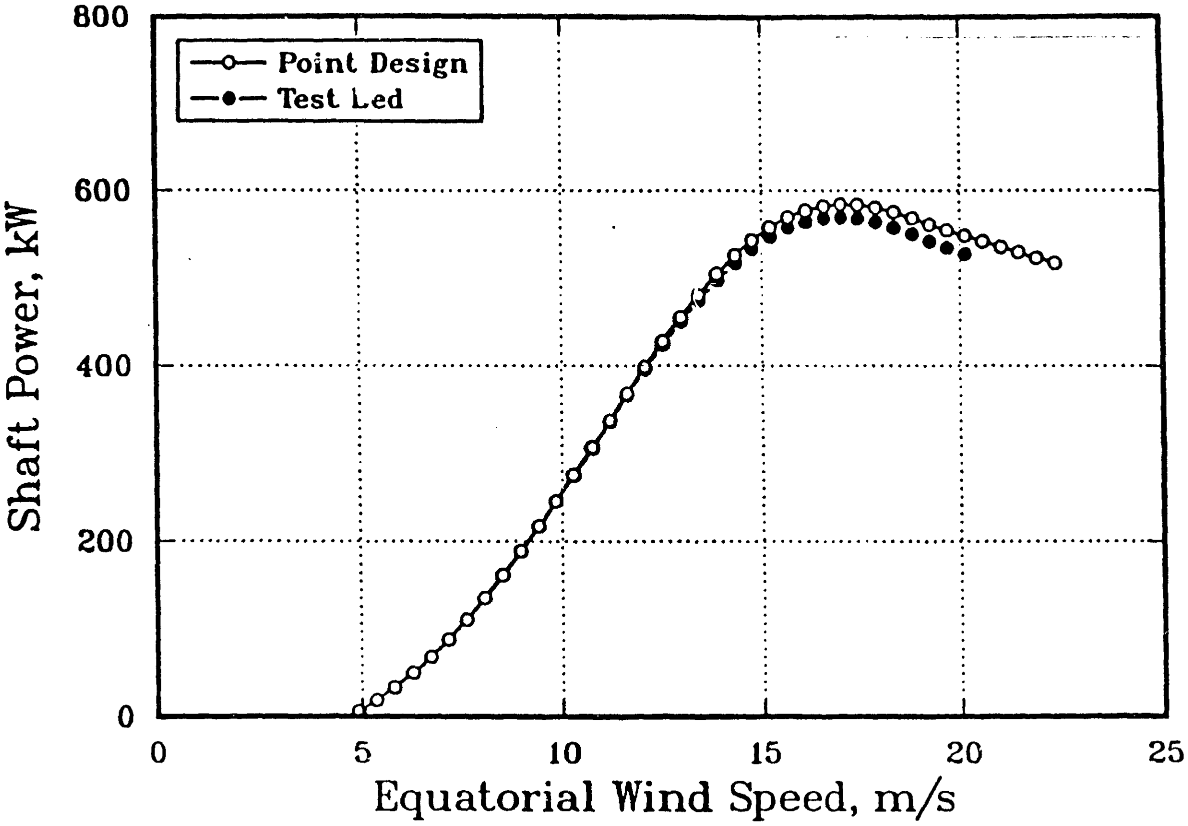

**Figure 14. Predicted Shaft Power at 36 RPM:
34-m Point Design vs. 34-m Test Bed**

END

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