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Aerodynamic Performance of the 17 Meter Diameter Darrieus Wind Turbine

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AERODYNAMIC PERFORMANCE OF THE 17-METRE-DIAMETER DARRIEUS WIND TURBINE

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ABSTRACT

A two-bladed 17-metre Darrieus vertical-axis wind turbine was field-tested at the Sandia Laboratories wind-turbine site. Performance results for seven constant operating speeds are presented along with a discussion of the trends. Predicted performance and experimental test data for two constant speeds are also compared.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A_s	Turbine rotor swept area
c	Blade chord
C_p	Coefficient of performance
f	Wind frequency
H	Height
J	Advance ratio
K_p	Power coefficient
L	Blade length
n	Number of sampled data points
N	Number of blades
p	Freestream barometric pressure
P	Turbine rotor output power
Q	Turbine rotor output torque
Q_o	Density-adjusted Q
R	Maximum turbine radius
Re_c	Reynolds number based on chord
T	Freestream air temperature
V_∞	Freestream windspeed
X	Tip-speed ratio
μ_∞	Freestream air viscosity
ρ_∞	Freestream air density
ρ_o	Reference freestream air density
ω	Turbine rotor rotational speed
σ	Rotor solidity

Note: Any variable subscripted with an "i" refers to a windspeed bin.

AERODYNAMIC PERFORMANCE OF THE 17-METRE-DIAMETER DARRIEUS WIND TURBINE

Introduction

The Darrieus wind turbine was originally patented in the United States by D. J. M. Darrieus in 1931. Until recently, this particular wind turbine received little or no attention. The energy awareness of this decade and the projected shortages of energy have stimulated a revived interest in wind energy and, along with this, the Darrieus wind turbine. Sandia Laboratories, together with the Department of Energy (DOE), has been involved both technically and economically with the Darrieus wind turbine over the past several years. Currently three Darrieus wind turbines with approximate diameters of 2, 5, and 17 m are being field-tested by Sandia.

The DOE/Sandia 17-m turbine was completed and first operated in March 1977. It is funded by the DOE to obtain field performance test data of a large Darrieus turbine, to verify analytical studies, and to provide firsthand experience in the construction and operation of a large Darrieus wind turbine.

This report presents field performance test data obtained from the 17-m turbine in the two-bladed configuration. Testing involved seven constant turbine speeds from 29.6 to 52.5 rpm. Performance test data presented are only of the turbine rotor and do not include drive train or electrical generation performance. It is assumed that the reader is already familiar with the Darrieus wind turbine operating in a synchronous mode with the power grid.[1] A general physical description of the DOE/Sandia 17-m turbine is provided here to familiarize the reader with the physical components of this particular wind turbine.

Description of the DOE/Sandia 17-Metre Darrieus Wind Turbine

Rotor

Figure 1 shows the 17-m turbine in the two-bladed configuration. This wind turbine is located within Kirtland Air Force Base on the west side of the Sandia Mountains in Albuquerque, New Mexico. The rotor geometry is formed by straight-circular-straight blade sections that approximate a troposkein curve (the shape that a perfectly flexible blade would assume under centrifugal forces). Struts, the straight sections forming an X, were included to give additional stiffness to the rotor structure. All the blade sections including the struts are of an NACA 0012 airfoil section with a 21-in. chord. Figure 2 shows a cross section of the blades. Leading and trailing edges are aluminum extrusions, and the center is a honeycomb/fiberglass structure.

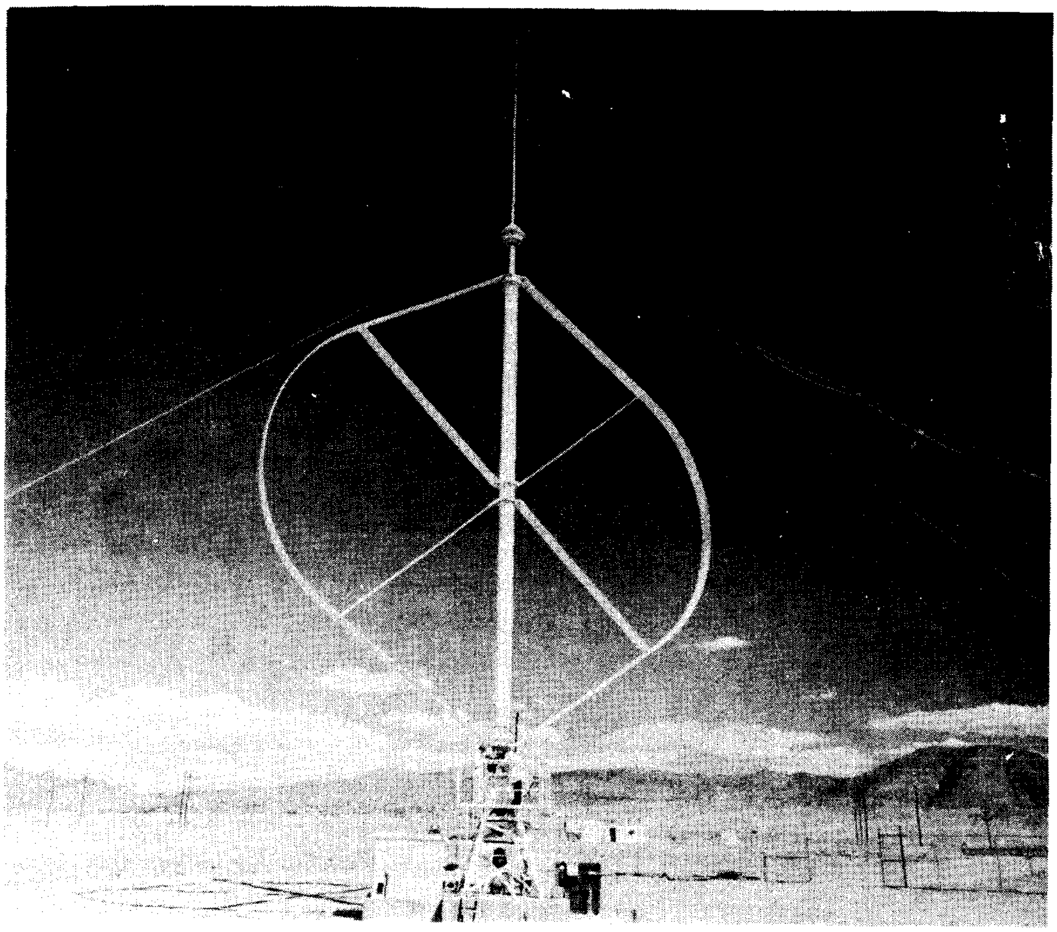

Figure 1. DOE/Sandia 17-Metre Darrieus Wind Turbine

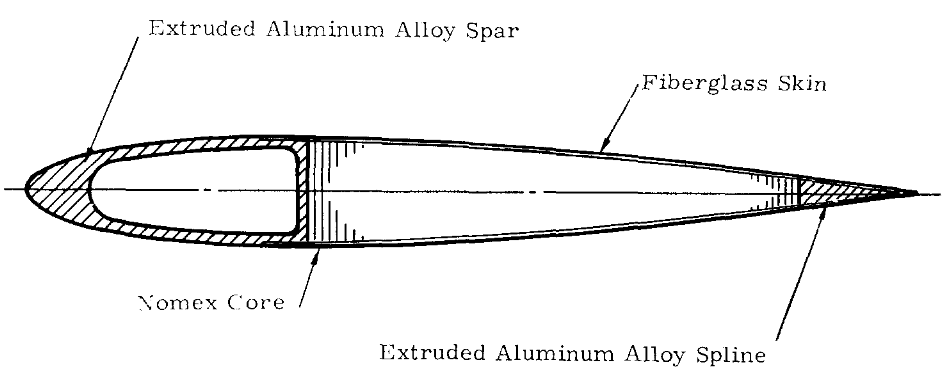

Figure 2. Blade Section Cutaway

Blade sections are pin-attached at all points including the central rotating steel tower. The tower is supported top and bottom by tapered roller bearings. Four guy cables attached to the housing of the top bearings provide the necessary tower support.[2] Visible in Figure 1 is a slender pole projecting from the top bearing. Two pairs of anemometers and wind-direction sensors located at heights of 94 and 110 ft on this pole record wind conditions near the turbine during testing.

A lightning protection system was also installed on the 17-m turbine. Because of its height, this turbine is susceptible to possible lightning strikes.[3] From the top of the turbine, there are five paths to ground, four guy cables, and the turbine tower. The protection system is basically concerned with the bearings of the tower. A parallel path around each tower bearing is formed by using sliding carbon brush contacts. The brushes around the lower tower bearing are connected directly to ground. The grounds for each of the guy cables and the lower set of brushes consist of buried metal lattices. In this manner, much of the current of a lightning strike is drawn away from the tower bearings and lower turbine components. The turbine has sustained two lightning strikes since it began operating, which underscores the need for lightning protection.

Brakes

Two disk brakes, visible in Figure 3, are located immediately below the blades on the turbine rotor shaft. The steel disks have a diameter of 36 in. and a thickness of 1 in. There are four hydraulic calipers on each disk. The top disk brake in Figure 3, called the proportional brake, provides a varying braking moment typically from 3,000 to 48,000 lbf•ft. The proportional brake is used for normal shutdown procedures and occasionally to help engage the synchronous generator. The second disk brake, located just below the proportional brake and partly visible in Figure 3, is the emergency brake. This brake operates from an accumulator that is independent of the proportional system. The emergency brake operates automatically in case of electrical failure or when any one of several emergency stop buttons are depressed either in the control building or at the turbine site. This brake provides a braking moment of 48,000 lbf•ft. A more thorough discussion of the braking system is found in Reference 4.

Drive Train

Two flexible couplings surrounding a torque sensor are located below the bottom tapered roller bearing of the turbine tower. The flex couplings, composed of rubber shear sandwich mountings, provide for shaft misalignment, protect the torque sensor from mechanical shock, and help attenuate torque ripple in the drive train through reduced torsional stiffness.[5] This torque sensor is used to determine the performance of the turbine. Figure 4 shows these components.

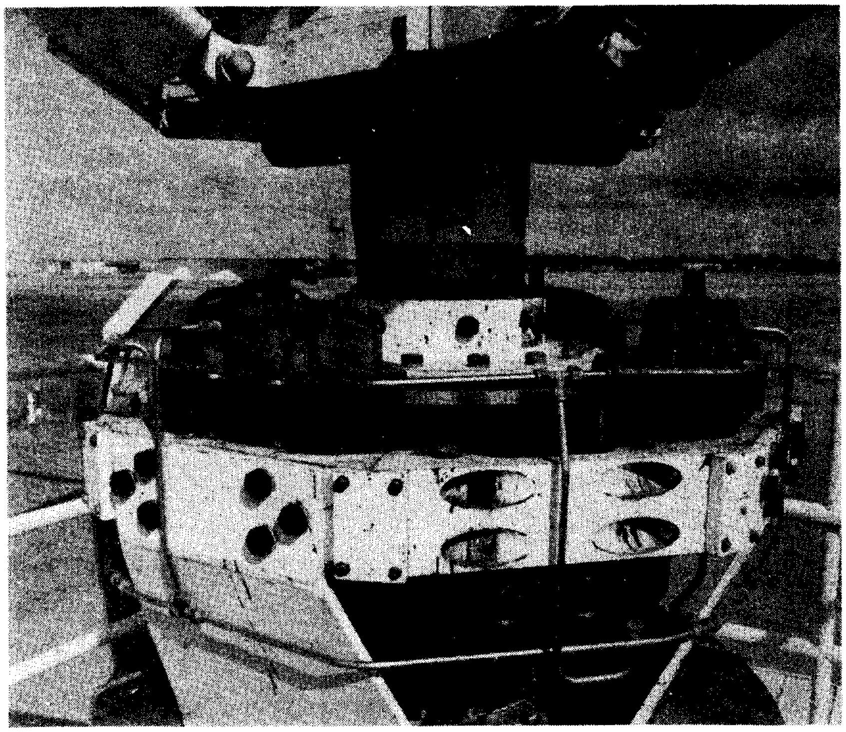

Figure 3. Brake Arrangement

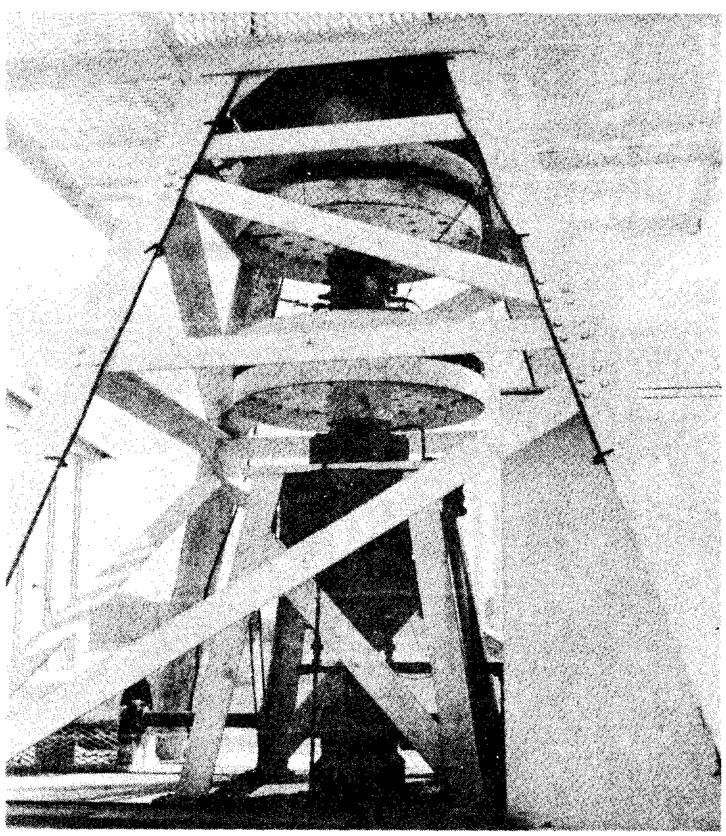

Figure 4. Drive-Train Components

The speed increaser visible in the lower part of Figure 4 is a three-stage vertically mounted planetary gearbox with an overall ratio of 42.87:1. This particular gearbox was modified to operate with a dry sump lubrication system to reduce internal viscous losses. A right-angle bevel gearbox with a ratio of 1:1 is located directly beneath the speed increaser.

It was stated earlier that the 17-m turbine operated at constant turbine rotor speeds ranging from 29.6 to 52.5 rpm. The overall drive-train gear ratio is varied by using a timing belt and toothed pulleys as seen in Figure 5. Using pulleys of different diameters can vary the gear ratio of this stage from 0.706:1 to 1.417:1 in 13 discrete steps. The overall gear ratio of the drive train then can be varied from 60.81:1 to 30.25:1 corresponding to constant turbine rotor speeds of 29.6 to 59.5 rpm. The highest speed used for performance testing was 52.5 rpm.

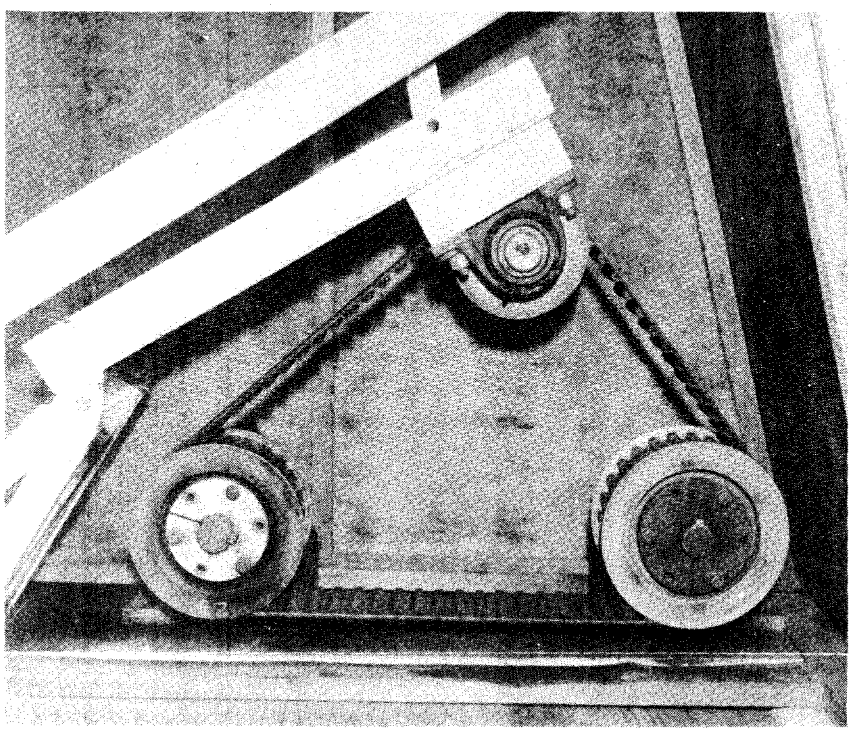

Figure 5. Toothed Pulley Arrangement

Generators

The generators are located on the output shaft of the toothed pulleys (Figure 6). On the right is a synchronous generator and on the left an induction generator coupled in tandem by an electric clutch. Both are 480-V three-phase generators rated at 60 kW. The operating speed is 1800 rpm for the synchronous generator and 1825 rpm for the induction generator. Either machine can function as a generator or as a motor depending only on whether the turbine rotor drives the machine (sufficient winds, generating) or the machine drives the turbine (very low or no winds, motoring). In either case, the synchronous machine operates at a steady 1800 rpm. The induction machine, by its nature, experiences a slip of 1.4% at rating. In a motoring mode the speed is thus slightly below 1800 rpm, and slightly above 1800 rpm in a generating mode.

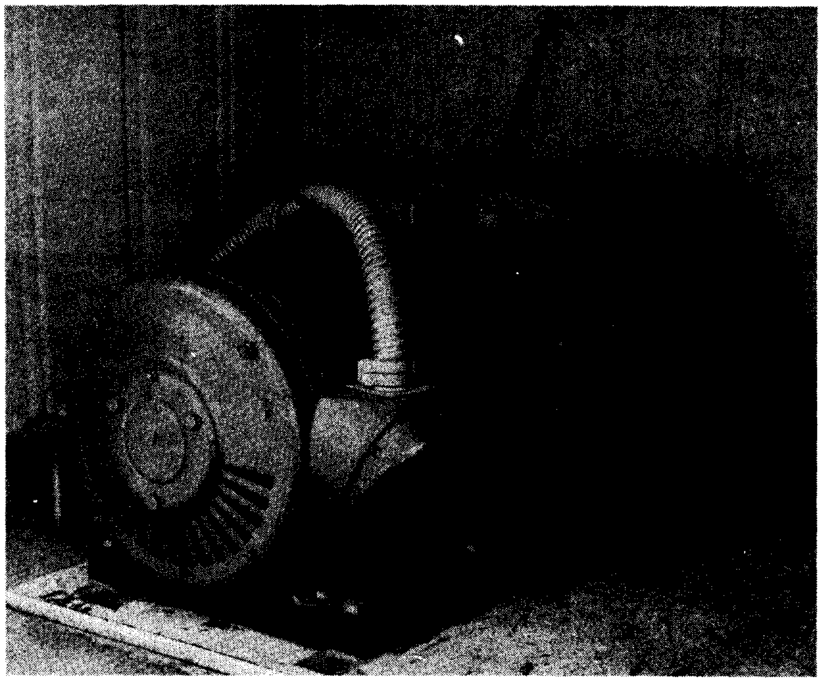

Figure 6. Induction and Synchronous Generators

Two generators were installed so that tests could be performed using either synchronous or induction power generation. When the induction generator is being used, the field of the synchronous generator is left unexcited to effectively decouple it from the turbine. When the synchronous generator is being used, the induction generator simply idles at the synchronous speed of 1800 rpm. The induction generator at this point can be uncoupled from the system by the electric clutch if desired.

Because of the inability of the Darrieus turbine to self-start reliably, it is brought up to speed by the induction machine, which possesses better starting characteristics than does the synchronous machine. Once the turbine attains operating speed, either generator can be used in testing. References 1 and 6 discuss the application of the Darrieus wind turbine to synchronous power generation.

Performance data presented in this report were obtained using only the induction generator. It was stated earlier that the performance data are only of the turbine rotor. These data are therefore independent of which generator is being used so long as a constant rotational speed is maintained. Since the induction generator experiences a 1.4% slip at its rating, this allows the turbine rotor to operate at a rotational speed 1.4% higher than the exact synchronous speed. All performance data presented in this report are based upon the assumption that the rotational speed is unvarying regardless of output. This introduces a negligible error.

Instrumentation and Data Acquisition

Anemometry

Currently 10 anemometers are paired with wind-direction sensors at the wind-turbine site. Two pairs are located atop the 17-m turbine and five more pairs are mounted on a meteorological tower located ~ 270 ft from the 17-m turbine. Instrument pairs are located at heights of 12, 33, 43, 59, and 98 ft on the tower. Whenever a particular anemometer is used in the performance evaluation of the 17-m turbine, it is corrected for wind shear to a reference height of 44 ft, the exact centerline of the 17-m turbine. The relationship used for wind shear correction is

$$\frac{V_{\infty_1}}{V_{\infty_2}} = \left(\frac{H_1}{H_2}\right)^{0.1} \qquad (1)$$

where

V_∞ = freestream windspeed, and

H = height.

Reference 7 discusses the experimental determination of the exponent used in Eq. (1).

Test results presented in this report are all based upon anemometry atop the 17-m turbine at the 94-ft level. It is believed that the anemometer atop the 17-m turbine and those on the meteorological tower are not affected by the presence of the operating turbines at the test site. In support of this, Figure 7 is presented. This figure is actually a representation of Eq. (1) in that the log of anemometer height is plotted as a function of the log of the average windspeed measured by the anemometer. The points in Figure 7 represent anemometers located on the 17-m turbine, the meteorological tower, and on the 5-m turbine. Each point shall fall on a straight line where the slope is the exponent of Eq. (1). The exponent was originally determined with the turbines not operating, while Figure 7 is with the 5- and 17-m turbines operating. There is no apparent effect of the turbine operation upon the slope of the line, which is the same as originally measured. To say that the presence of the turbines has no effect at all upon the anemometers is unjustified, but whatever effect exists is small. Reference 7 goes into more detail concerning the wind characteristics of the test site.

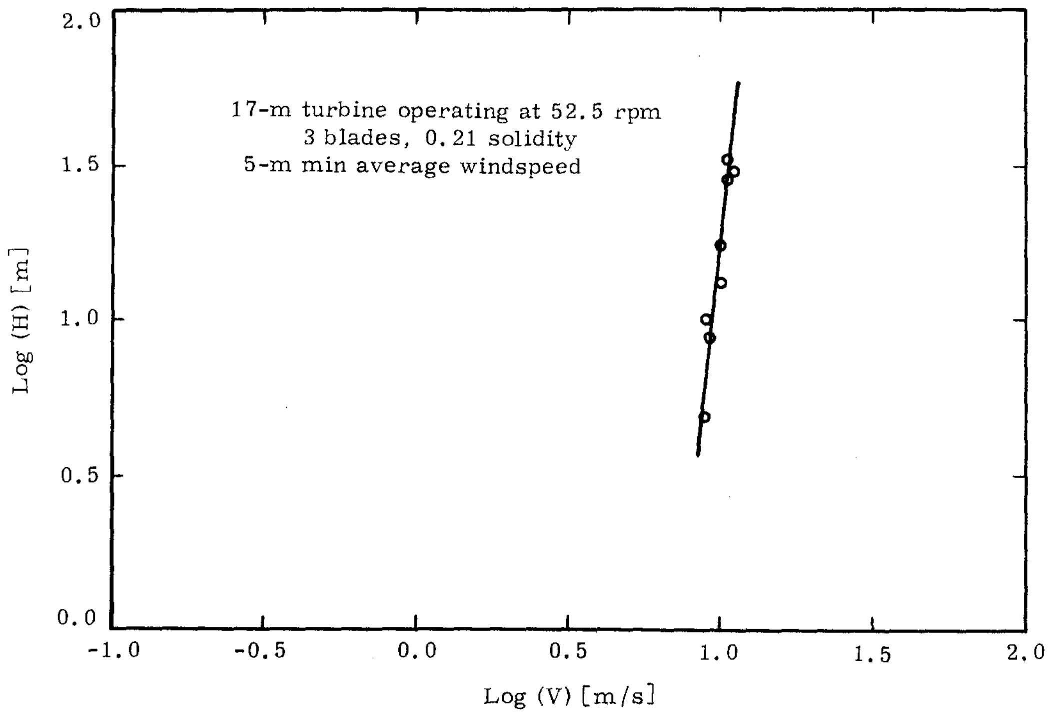

Figure 7. Experimental Anemometer Height and Windspeed Relationship

Torque Sensors

Two torque sensors were installed on the 17-m turbine. One is located directly beneath the lower tower bearing on the turbine rotor shaft; the second is on the high-speed shaft immediately upstream of the generators. Performance data are based upon the former torque sensor, which will not reflect any losses in the drive train that is below it. However, a certain tare torque is associated with the tower bearings of the 17-m turbine; this was measured and found to be 333.0 lbf·ft. This tare torque value is added to the torque-sensor output to give the actual turbine rotor torque without frictional losses. Both torque sensors also have a shaft rpm output.

Air Density

The air density during testing is determined from the following:

$$\rho_\infty = \frac{(0.03915)\, p}{T + 460} \tag{2}$$

where

ρ_∞ = freestream air density (lbm/ft^3) ,

p = barometric pressure (mbar) , and

T = air temperature (°F).

Both p and T are recorded at the onset of testing and are periodically checked during testing to detect any changes.

Strain Gages

The blades on the 17-m turbine are fully instrumented with strain gages to monitor the stress levels due to the combination of aerodynamic, rotational, and gravitational loading.[8] The signals are fed into a pulsed code modulator and then transmitted through a set of slip rings on the turbine rotor shaft to the control building. Although strain gage data are not recorded during performance testing, they are periodically checked as a precaution.

Minicomputer

The focal point of the data acquisition system is a minicomputer. Through this device it is possible to monitor and record several data inputs simultaneously and also to provide rapid data reduction and convenient data storage.[9] This system is used in the performance evaluation of both the 2- and 5-m turbines along with the 17-m turbine at the test site.

Method of BINS

The unsteady nature of the wind required development of a statistical method of determining turbine performance.[10] The formal name of the method is BINS; it is written as a code used in the previously mentioned minicomputer. The method consists of allocating 120 windspeed bins to correspond to a wind range of 0 to 60 mph. The width of each velocity bin is 0.5 mph. During testing, the minicomputer is instructed to sample both windspeed and turbine output torque simultaneously at a rate of four samples per second. The windspeed bin associated with the sampled windspeed is located and the corresponding turbine torque output measurement is entered into the bin. Each bin records the number of entered measurements, n, and calculates the average torque. Additional information entered into the program for each test is the turbine rotational speed, air temperature and barometric pressure, the anemometer to be sampled, tare torque of turbine tower bearings, the number of blades on the turbine, and the time and date.

The result of the data-acquisition process is a listing of the windspeed bins and the average torque, Q_i, in each bin. Several other parameters are listed for each windspeed bin.

The turbine output power of the bin is given by

$$P_i = Q_i \omega \tag{3}$$

where

ω = rotational speed of the turbine rotor.

The tip-speed ratio is defined as

$$X_i = \frac{R\omega}{V_{\infty_i}} \tag{4}$$

where

R = maximum turbine radius

V_{∞_i} = average windspeed of the bin.

The coefficient of performance is given by

$$C_{p_i} = \frac{Q_i \omega}{\frac{1}{2} \rho_\infty A_s V_{\infty_i}^3} \tag{5}$$

where A_s is the turbine rotor swept area. The power coefficient[6] is defined as

$$K_{p_i} = \frac{Q_i \omega}{\frac{1}{2} \rho_\infty A_s (R\omega)^3} \; . \tag{6}$$

Here the freestream windspeed has been replaced by the equatorial speed of the blades. K_{p_i} will reach a peak value (indicating maximum power output of the turbine) at a particular windspeed. Since K_{p_i} does not involve the cube of an experimentally measured windspeed, it is not as error-prone as C_{p_i}.

Another parameter to be defined is the advance ratio

$$J_i = \frac{V_{\infty_i}}{R\omega} \; . \tag{7}$$

As can be seen, this is simply the inverse of X_i. The Reynolds number used in all testing is based upon blade chord and is given by

$$Re_c = \frac{\rho_\infty R\omega c}{\mu_\infty} \tag{8}$$

where

c = chord length

μ_∞ = freestream viscosity .

For each separate test run the freestream air density, ρ_∞, at the time of the test was determined so that Cp_i and Kp_i could be calculated. The compiled performance record for each discrete turbine rpm is actually the combination of several separate test runs. To combine these records, a standard reference freestream air density, ρ_o, is selected and each test run is adjusted to this. ..pecifically, this required adjusting the average torque in each bin by the ratio of the reference freestream air density to the freestream air density of the particular test run and replacing ρ_∞ by ρ_o in Eqs. (5), (6), and (8):

$$Q_{o_i} = Q_i \frac{\rho_o}{\rho_\infty} . \tag{9}$$

This then is nearly equivalent to having performed all the testing at the same air density. There are slight changes in Re_c that have a small effect on performance from day to day.

Rotor solidity, the ratio of blade planform area to swept rotor area, is given by

$$\sigma = \frac{NcL}{A_s} \tag{10}$$

where

A_s = rotor swept area,

L = blade length,

N = number of blades.

For the two-bladed 17-m, $\sigma = 0.14$.

Test Results

The compiled performance records of the 17-m turbine in the two-bladed mode are presented in Appendix A for turbine rotational speeds of 29.6, 33.6, 37, 42, 45.5, and 52.5 rpm. The results are all based upon anemometry at the 94-ft level atop the 17-m turbine and upon the torque sensor immediately beneath the turbine rotor. The tare torque of the tower bearings was added to the torque sensor readings. The data were sampled at a rate of four per second. All records are adjusted to $\rho_o = 0.0625$ (lbm/ft^3), which is the freestream air density corresponding to T = 60°F, and p = 830 mbar for an altitude of 5440 ft, the elevation of the test site. All windspeeds are based upon a reference height of 44 ft, the exact centerline of the turbine rotor. The induction generator was used in all testing.

One compiled performance record is shown in Figures 8 through 12. This particular record is for 48.4 rpm and is comprised of eight individual test runs. Figure 8 shows a listing of the records along with the compiled tabular results. In accordance with the BINS method, there is a listing of windspeed bins (mph at 44 ft) with the corresponding number of data points, n_i , and the wind frequency of the bin, f_i , P_i[KW], X_i , C_{p_i}, J_i , and K_{p_i}. As can be seen from Figure 8, the windspeed of this compiled record ranged from 0.5 to 37.5 mph and bins above 32.5 mph contained less than 300 samples. When a windspeed bin contains less than 300 samples, the corresponding performance parameters, P_i, C_{p_i}, and K_{p_i}, should not be taken in a literal sense because there are not enough samples to give a true representation. The total number of samples for the compiled record is 88,143, which would correspond to 6.12 hr of testing.

17. M TURBINE, COMBINED DATA, RPM=48.4
NUMBER SAMPLES IN ACCUMULATION = 88143.
DATA RECORD NAME(S)= 60272. 60276. 60321. 60721. 82521. 82621.
83021. 90621.

V	N	F	POWER(KW)	RW/V	CP	V/RW	KP	RMS
.5	361.	.004	-2.9815	189.63	-2851.52	.01	-.0004	
1.5	6260.	.071	-3.3136	63.21	-117.377	.02	-.0005	
2.5	6876.	.078	-3.2805	37.93	-25.100	.03	-.0005	
3.5	3625.	.041	-3.6400	27.09	-10.150	.04	-.0005	
4.5	2797.	.032	-3.9663	21.07	-5.204	.05	-.0006	
5.5	3220.	.037	-3.7341	17.24	-2.683	.06	-.0005	
6.5	3336.	.038	-3.4474	14.59	-1.501	.07	-.0005	
7.5	3443.	.039	-2.5505	12.64	-.723	.08	-.0004	
8.5	3941.	.045	-1.5587	11.15	-.303	.09	-.0002	
9.5	4404.	.050	-.3524	9.98	-.049	.10	-.0000	
10.5	4598.	.052	1.1444	9.03	.118	.11	.0002	
11.5	4909.	.056	2.8274	8.24	.222	.12	.0004	
12.5	4892.	.056	4.4804	7.59	.274	.13	.0006	
13.5	4448.	.050	6.1526	7.02	.299	.14	.0009	
14.5	3665.	.042	8.4193	6.54	.330	.15	.0012	
15.5	3332.	.038	10.6320	6.12	.341	.16	.0015	
16.5	3419.	.039	12.3099	5.75	.328	.17	.0017	
17.5	3216.	.036	14.3598	5.42	.320	.18	.0020	
18.5	2812.	.032	17.0662	5.13	.322	.20	.0024	
19.5	2242.	.025	19.3547	4.86	.312	.21	.0027	
20.5	1700.	.019	21.9028	4.63	.304	.22	.0031	
21.5	1442.	.016	24.7191	4.41	.297	.23	.0035	
22.5	1412.	.016	27.7034	4.21	.291	.24	.0039	
23.5	1216.	.014	29.6096	4.03	.273	.25	.0042	
24.5	1151.	.013	31.3259	3.87	.255	.26	.0044	
25.5	1025.	.012	34.5583	3.72	.249	.27	.0048	
26.5	865.	.010	36.6357	3.58	.235	.28	.0051	
27.5	650.	.007	39.1332	3.45	.225	.29	.0055	
28.5	549.	.006	42.3501	3.33	.219	.30	.0059	
29.5	555.	.006	45.2303	3.21	.211	.31	.0063	
30.5	479.	.005	46.1648	3.11	.195	.32	.0065	
31.5	431.	.005	47.8924	3.01	.183	.33	.0067	
32.5	350.	.004	49.0697	2.92	.171	.34	.0069	
33.5	271.	.003	49.6130	2.83	.158	.35	.0070	
34.5	156.	.002	50.1809	2.75	.146	.36	.0070	
35.5	67.	.001	49.5770	2.67	.132	.37	.0070	
36.5	23.	.000	51.1987	2.60	.126	.38	.0072	
37.5	5.	.000	48.3047	2.53	.110	.40	.0068	

Figure 8. Performance Data at 48.4 rpm

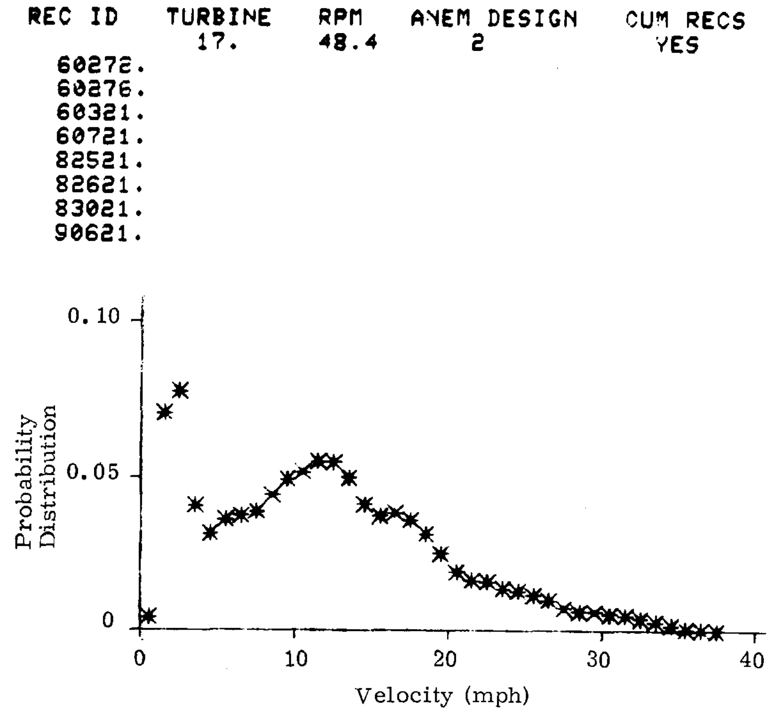

Figure 9. Wind Frequency at 48.4 rpm

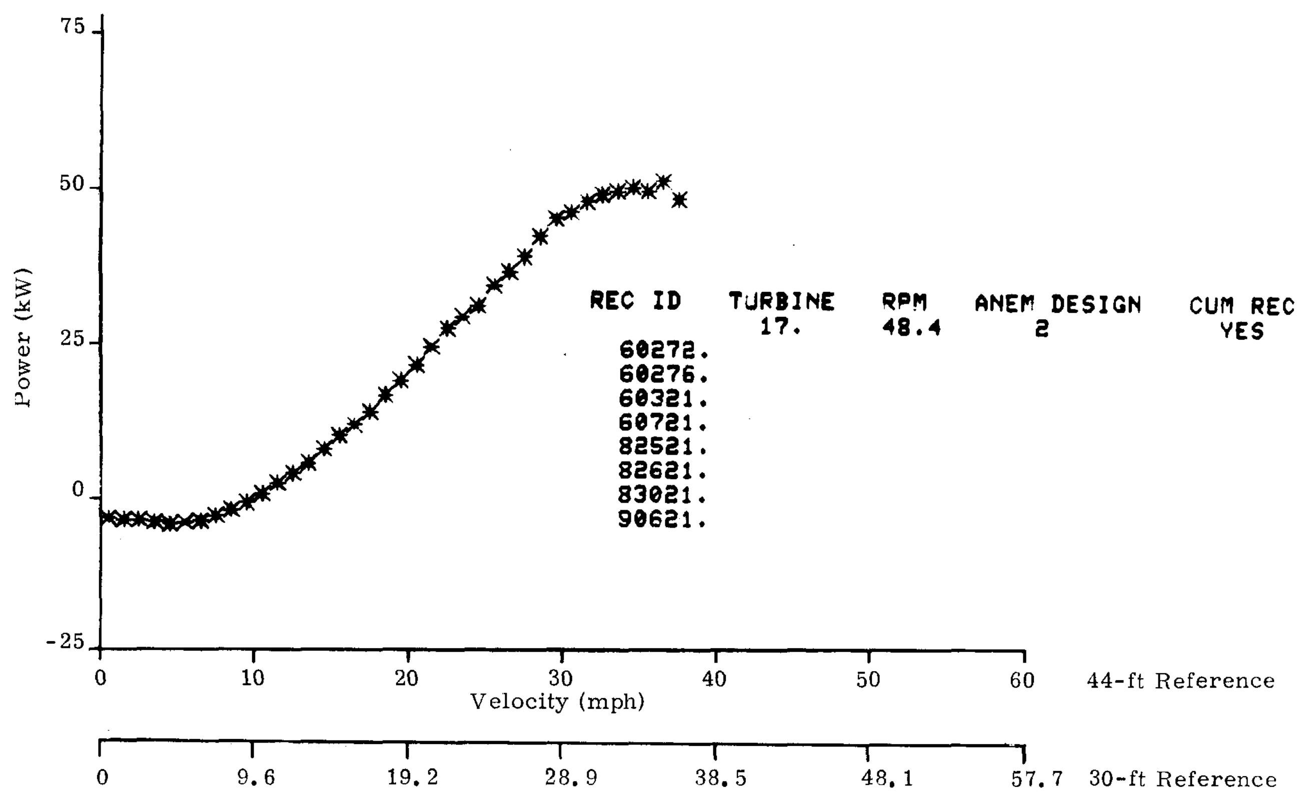

Figure 10. Turbine Rotor Power as a Function of Windspeed at 48.4 rpm

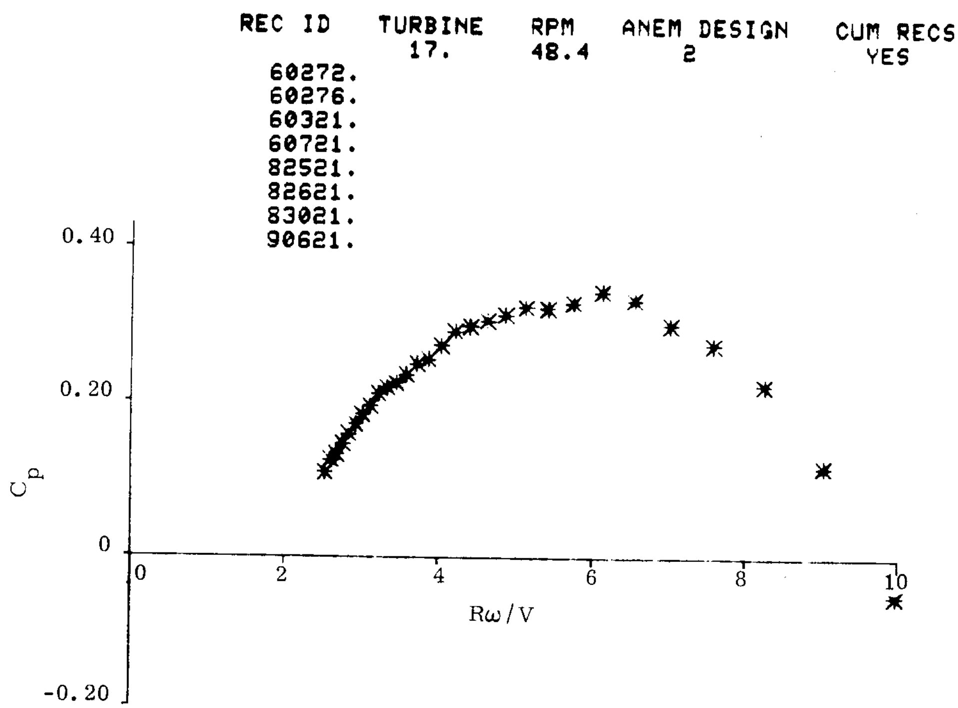

Figure 11. C_p as a Function of Tip-Speed Ratio at 48.4 rpm

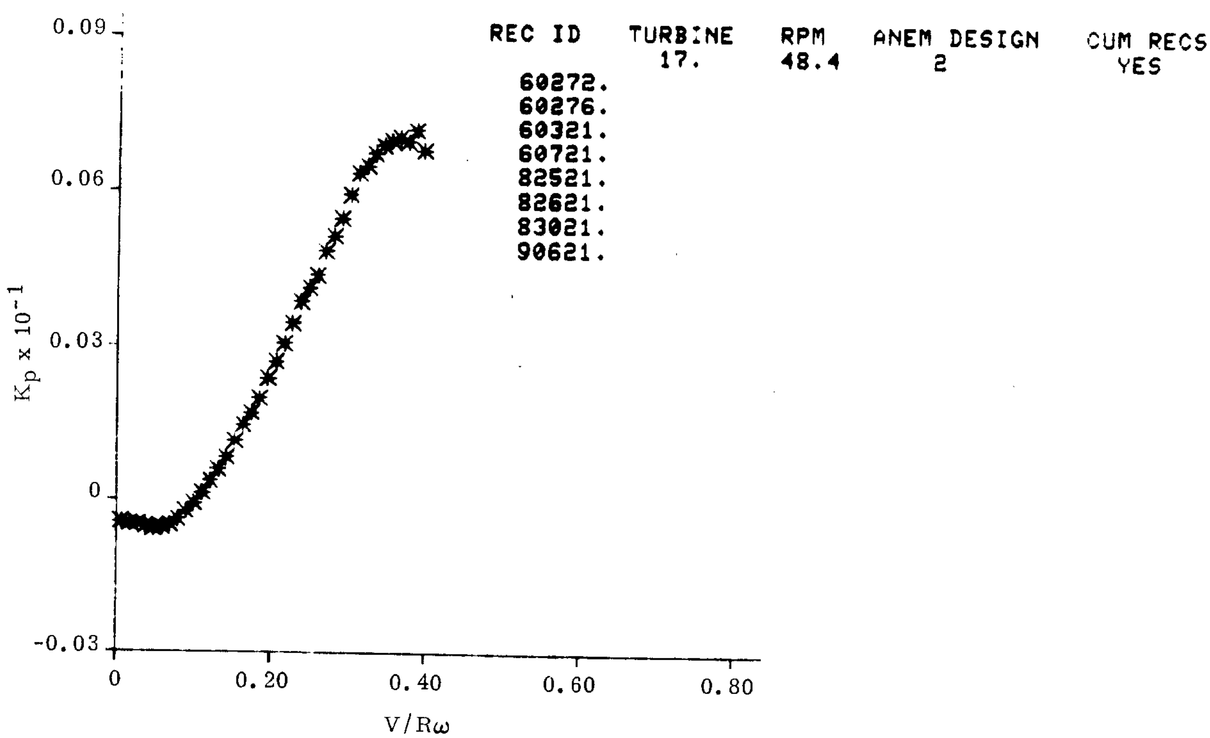

Figure 12. K_p as a Function of Advance Ratio at 48.4 rpm

Figures 9 through 12 are graphical representations of the tabular data of Figure 8. Figure 9 shows the distribution of the wind frequency of the bins. Figure 10 plots the turbine rotor output power against windspeed. As can be seen, the turbine would start to produce a positive output at approximately 10 mph and reach a maximum at roughly 33 mph. This illustrates one of the characteristics of a synchronously operating Darrieus wind turbine in that the turbine output will peak at a certain windspeed depending upon rotational speed, airfoil section, turbine solidity, and Reynolds number. This characteristic is perhaps better seen in some of the other performance records in Appendix A.

Figure 11 shows C_p plotted as a function of X. This is probably the most familiar plot of wind-turbine performance. The maximum C_p here is 0.341 at X = 6.12, which corresponds to a windspeed of 15.5 mph. K_p plotted as a function of J is shown in Figure 12. Here the maximum value of K_p was 0.0069 at J = 0.34. This corresponds to a power output of 49.1 kW at a centerline windspeed of 32.5 mph.

A plot of C_p as a function of X for 29.6, 42, and 52.5 rpm is shown in Figure 13. The speed of 29.6 rpm yielded a narrow C_p curve while the two higher speeds were roughly equivalent. As can be seen, 42 rpm gave a higher $C_{p_{max}}$ than did 52.5 rpm. In fact, the highest $C_{p_{max}}$ (0.38) occurred at 37 rpm, which can be seen in Figure 14. This figure illustrates $C_{p_{max}}$ as a function of Reynolds number, which is correlated to turbine rotational speed by the bottom scale. $C_{p_{max}}$ at 45.5 rpm is significantly lower than the other rotor speeds tested. The trend of Figure 14 is fairly well defined, and it is felt that an error was involved at 45.5 rpm. This will be discussed in a later section.

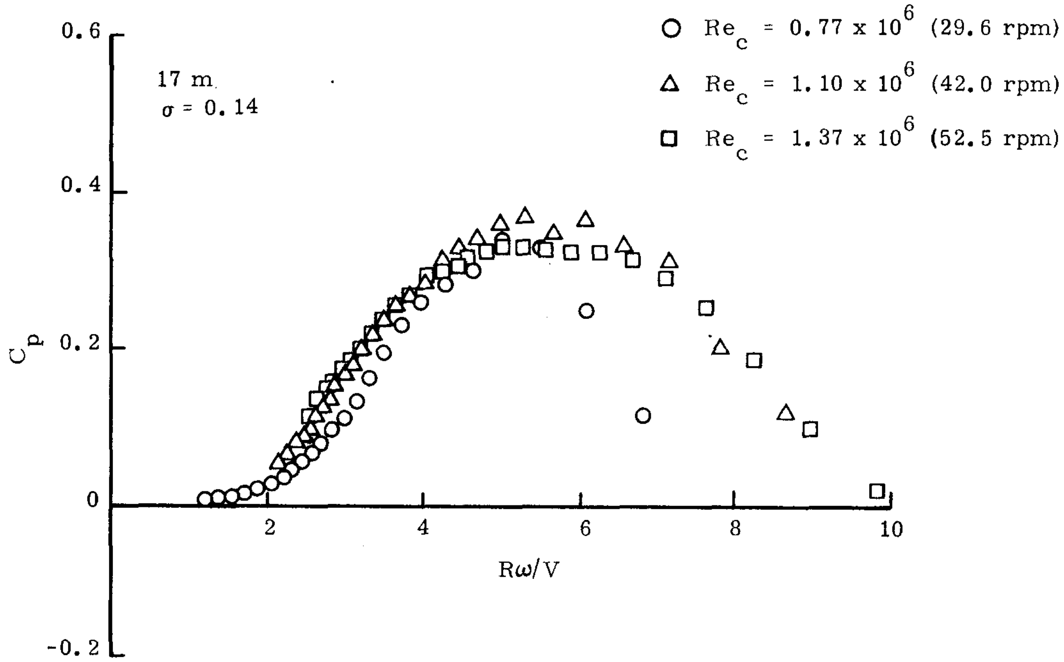

Figure 13. C_p as a Function of Tip-Speed Ratio of 29.6, 42, and 52.5 rpm

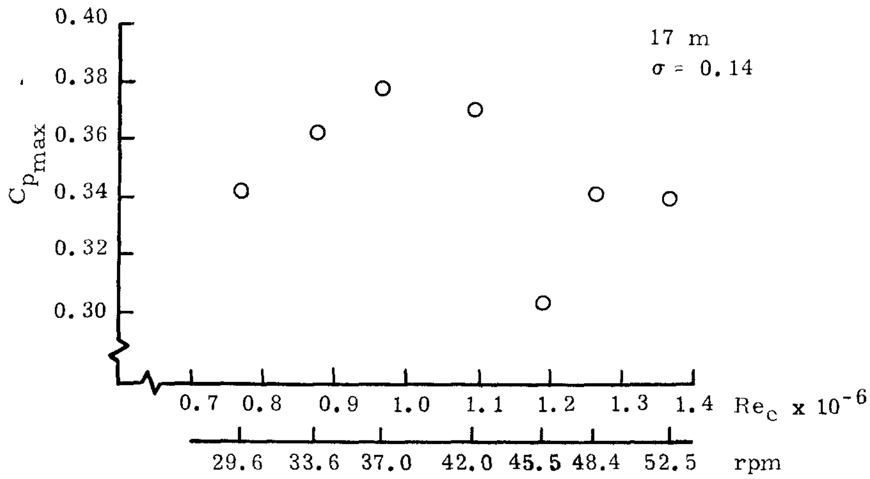

Figure 14. $C_{p_{max}}$ as a Function of Reynolds Number

A plot of K_p as a function of advance ratio for 29.6, 42, and 48.4 rpm is shown in Figure 15. The most important aspect to be noted here is that each rpm would achieve a peak K_p and then decrease even though the advance ratio increases (ambient wind increases). This is very important from the standpoint of synchronous operation in that the turbine is self-limiting when maintained at a constant rotational speed. The $K_{p_{max}}$ for each rpm is shown in Figure 16. The trend here is for $K_{p_{max}}$ to increase with Reynolds number (turbine speed). $K_{p_{max}}$ for 52.5 rpm was the highest obtained at that rotational speed but is not the highest that could have been attained due to the lack of the necessary windspeed (> 32 mph) to achieve $K_{p_{max}}$.

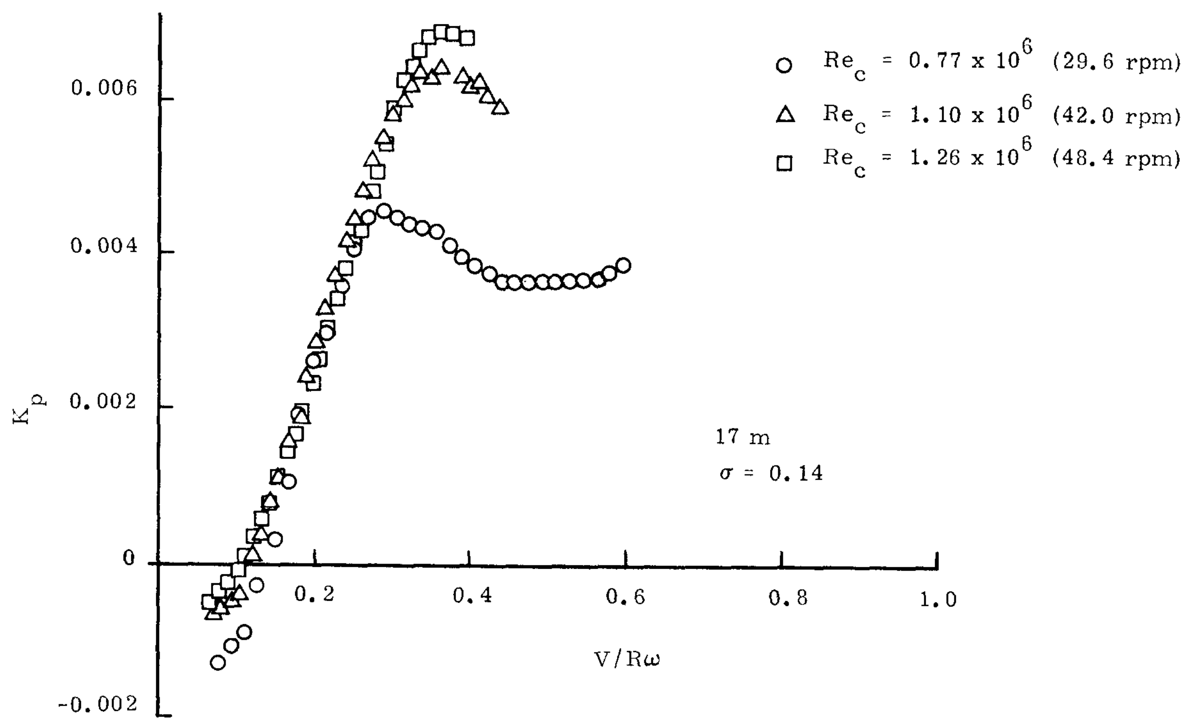

Figure 15. K_p as a Function of Advance Ratio at 29.6, 42, and 48.4 rpm

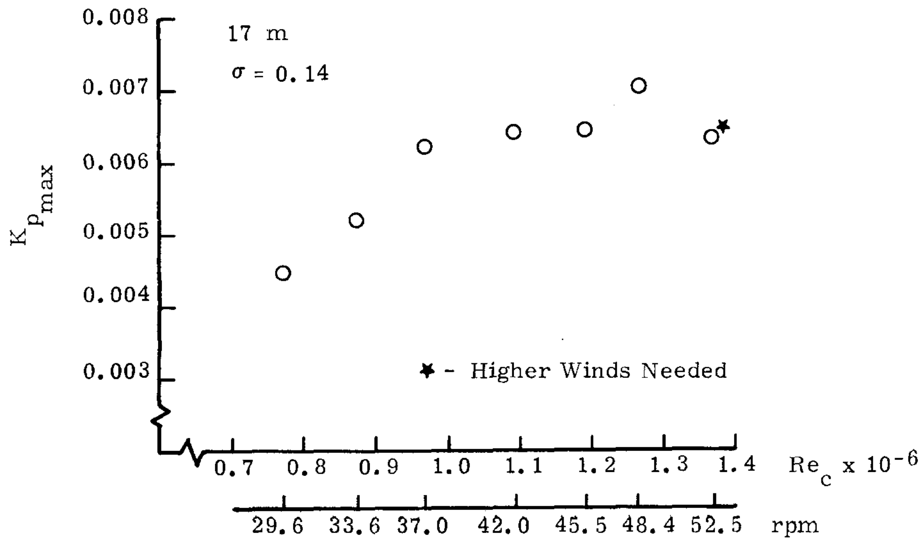

Figure 16. $K_{p_{max}}$ as a Function of Reynolds Number

Discussion and Conclusions

The purpose of this particular test sequence was to ascertain experimentally the aerodynamic performance of the DOE/Sandia 17-m Darrieus wind turbine. Except for 45.5 rpm, the efficiencies were quite reasonable, reaching a high of 38% for 37 rpm at V = 12.5 mph. The peak power produced by the turbine was 57.3 kW at 32.5 mph for 52.5 rpm. This peak power would have been higher if the ambient windspeed during testing at 52.5 rpm had been higher.

The characteristic of a synchronously operating Darrieus turbine to achieve a peak output and then level off is clearly evident in the data presented in Appendix A. The record for 29.6 rpm is particularly illustrative of this. The power, C_p, and K_p plots of the performance records generally had smooth shapes except for the end points. Data scatter was more prevalent here due to lack of data points for averaging.

One significant discrepancy in the data was a low Cp_{max} for 45.5 rpm. In fact, when the entire efficiency curve for this speed is examined, there is a noticeable dip centered around X = 5.3. This seems to be unique to this one test speed. Individual test runs that comprise the overall record for 45.5 rpm were reviewed. It was found that one test run record included roughly 40% of the total sample points of the dip, and the C_p values were uncommonly low. The reason for this is not immediately clear but probably some form of error was present in the instrumentation or possibly in the data acquisition. Cp_{max} for 45.5 rpm occurred at X = 4.57, while Cp_{max} for 42 rpm and 48.4 rpm occurred at X = 6.09 and X = 6.12, respectively. X for Cp_{max} at 45.5 rpm appears to be lower than expected. It is also possible that some unusual condition existed at the time of testing that affected the data.

Predicted and experimental power output was compared for 37 and 48.4 rpm in Figures 17 and 18, respectively. The predictions are from a computer aerodynamic model called PAREP.[11] Figure 17 indicates very good agreement up to an output of 17 kW where the theoretical curve overpredicts the experimental results. There appears to be a slight shift in the windspeed for peak power output between the theoretical and experimental curves. Figure 18 indicates excellent agreement at 48.4 rpm. Results here are encouraging.

Future performance testing of the 17-m turbine will include the addition of a third blade to increase the rotor solidity to 0.21. This will allow performance comparisons between different solidities. An effort will also be made to address overall turbine performance, including drive-train and generator efficiencies.

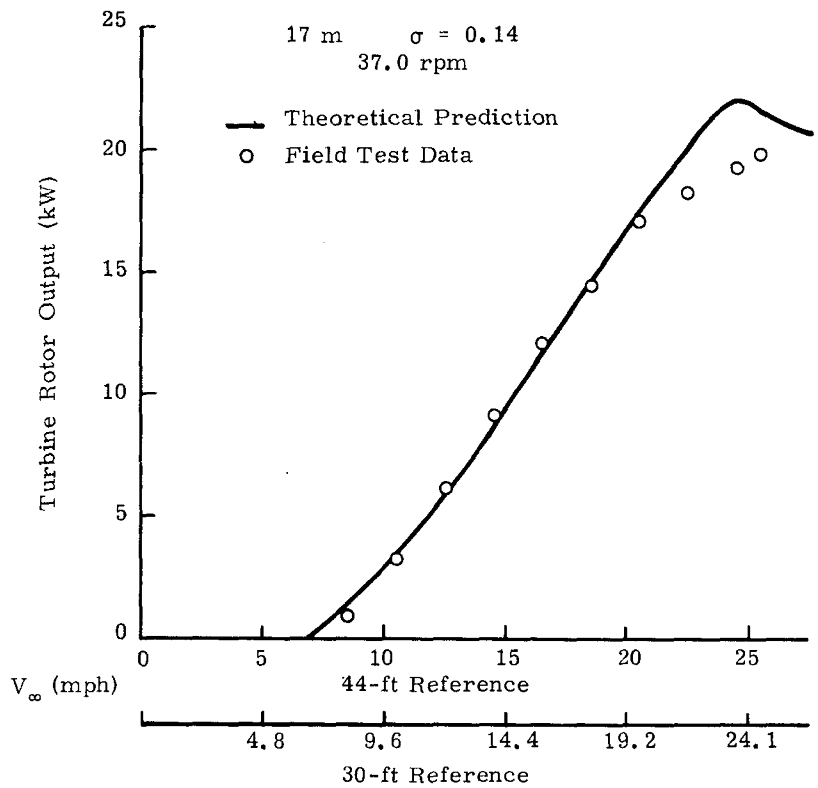

Figure 17. Comparison of Predicted and Experimental Power Output at 37 rpm

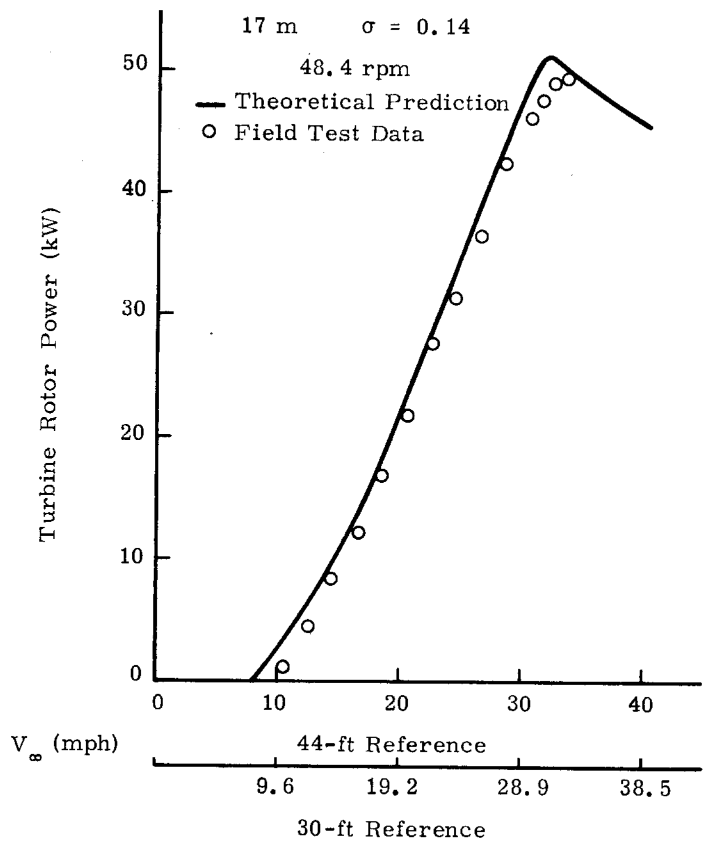

Figure 18. Comparison of Predicted and Experimental Power Output at 48.4 rpm

References

1. J. F. Banas, E. G. Kadlec, and W. N. Sullivan, Application of the Darrieus Vertical Axis Wind Turbine to Synchronous Electrical Power Generation, SAND75-0165, Sandia Laboratories, Albuquerque, NM, March 1975.

2. R. C. Reuter, Vertical Axis Wind Turbine Tie-Down Design with an Example, SAND77-1919, Sandia Laboratories, Albuquerque, NM, December 1977.

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7. R. E. Akins, Wind Characteristics at the VAWT Test Facility, SAND78-0760, Sandia Laboratories, Albuquerque, NM, September 1978.

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10. R. E. Akins, Performance Evaluation of Wind Energy Conversion Systems Using the Method of Bins - Current Status, SAND77-1375, Sandia Laboratories, Albuquerque, NM, March 1978.

11. P. C. Klimas and R. E. Sheldahl, Four Aerodynamic Prediction Schemes for Vertical-Axis Wind Turbines: A Compendium, SAND78-0014, Sandia Laboratories, Albuquerque, NM, June 1978.

APPENDIX A

Performance Data

29.6 rpm

2 Blades, $\sigma = 0.14$

Wind Range 1.5 to 37.5 mph

17. M TURBINE, COMBINED DATA, RPM=29.6
NUMBER SAMPLES IN ACCUMULATION = 42494.
DATA RECORD NAME(S)= 33072. 33176. 40172. 40174. 40578.

V	N	F	POWER(KW)	RW/V	CP	V/RW	KP	RMS
.5	68.	.002	-2.1740	115.97	-2079.22	.01	-.0013	
1.5	427.	.010	-2.4243	38.66	-35.875	.03	-.0015	
2.5	323.	.008	-2.2757	23.19	-17.412	.04	-.0014	
3.5	1518.	.036	-2.0762	16.57	-5.789	.06	-.0013	
4.5	2238.	.053	-2.0077	12.89	-2.634	.08	-.0012	
5.5	1828.	.043	-1.6468	10.54	-1.183	.09	-.0010	
6.5	1098.	.026	-1.3538	8.92	-.589	.11	-.0008	
7.5	931.	.022	-.3926	7.73	-.111	.13	-.0002	
8.5	839.	.020	.6023	6.82	.117	.15	.0004	
9.5	598.	.014	1.7910	6.10	.250	.16	.0011	
10.5	702.	.017	3.2108	5.52	.332	.18	.0020	
11.5	770.	.018	4.3464	5.04	.342	.20	.0027	
12.5	888.	.021	4.9271	4.64	.302	.22	.0030	
13.5	1237.	.029	5.8745	4.30	.285	.23	.0036	
14.5	1377.	.032	6.6418	4.00	.260	.25	.0041	
15.5	1349.	.032	7.2956	3.74	.234	.27	.0045	
16.5	1386.	.033	7.4156	3.51	.197	.28	.0045	
17.5	1462.	.034	7.3331	3.31	.164	.30	.0045	
18.5	1853.	.044	7.1676	3.13	.135	.32	.0044	
19.5	1895.	.045	7.0904	2.97	.114	.34	.0043	
20.5	1772.	.042	6.9982	2.83	.097	.35	.0043	
21.5	1458.	.034	6.6963	2.70	.081	.37	.0041	
22.5	1341.	.032	6.4856	2.58	.068	.39	.0040	
23.5	1171.	.028	6.3076	2.47	.058	.41	.0039	
24.5	1329.	.031	6.1703	2.37	.050	.42	.0038	
25.5	1448.	.034	6.0301	2.27	.043	.44	.0037	
26.5	1418.	.033	6.0053	2.19	.039	.46	.0037	
27.5	1368.	.032	6.0066	2.11	.035	.47	.0037	
28.5	1172.	.028	6.0023	2.03	.031	.49	.0037	
29.5	1074.	.025	5.9839	1.97	.028	.51	.0037	
30.5	983.	.023	6.0190	1.90	.025	.53	.0037	
31.5	822.	.019	6.0245	1.84	.023	.54	.0037	
32.5	795.	.019	6.0248	1.78	.021	.56	.0037	
33.5	697.	.016	6.1461	1.73	.020	.58	.0038	
34.5	676.	.016	6.3448	1.68	.018	.59	.0039	
35.5	536.	.013	6.2385	1.63	.017	.61	.0038	
36.5	441.	.010	6.3054	1.59	.016	.63	.0039	
37.5	351.	.008	6.3278	1.55	.014	.65	.0039	
38.5	259.	.006	6.5236	1.51	.014	.66	.0040	
39.5	203.	.005	6.6640	1.47	.013	.68	.0041	
40.5	165.	.004	6.8628	1.43	.012	.70	.0042	
41.5	121.	.003	6.9696	1.40	.012	.72	.0043	
42.5	59.	.001	6.8784	1.36	.011	.73	.0042	
43.5	29.	.001	7.7079	1.33	.011	.75	.0047	
44.5	10.	.000	7.6585	1.30	.010	.77	.0047	
45.5	6.	.000	8.1346	1.27	.010	.78	.0050	
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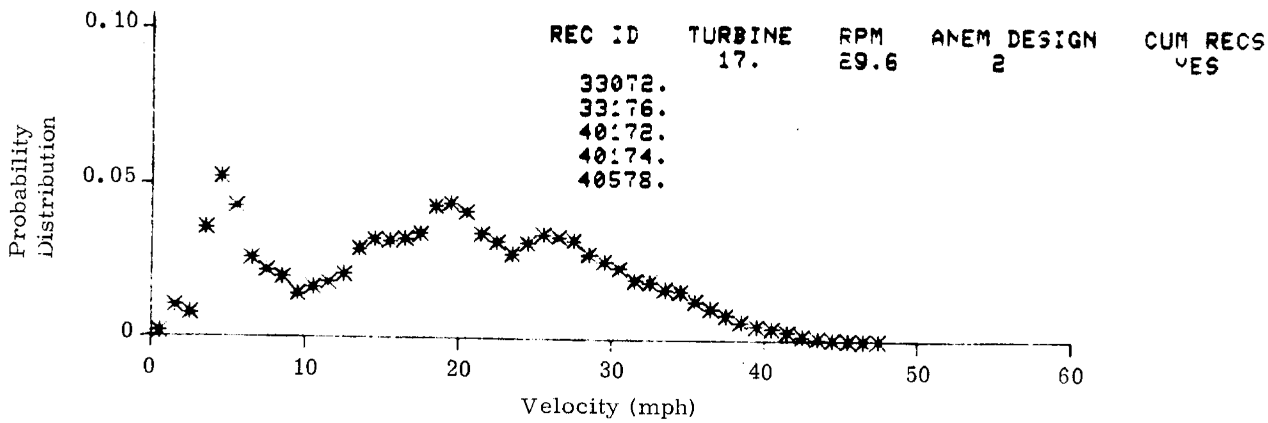
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40172.
40174.
40578.
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RPM
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ANEM DESIGN
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Probability Distribution
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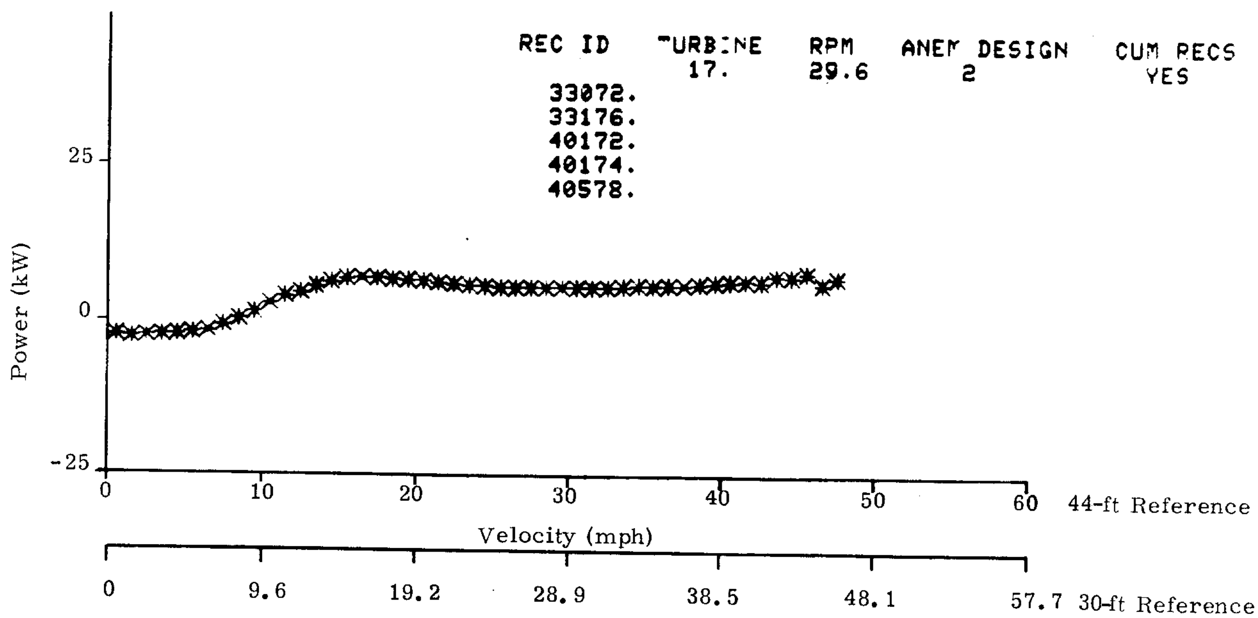
20
30
40
50
60
Velocity (mph)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RPM
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ANEM DESIGN
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CUM RECS
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Power (kW)
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20
30
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38.5
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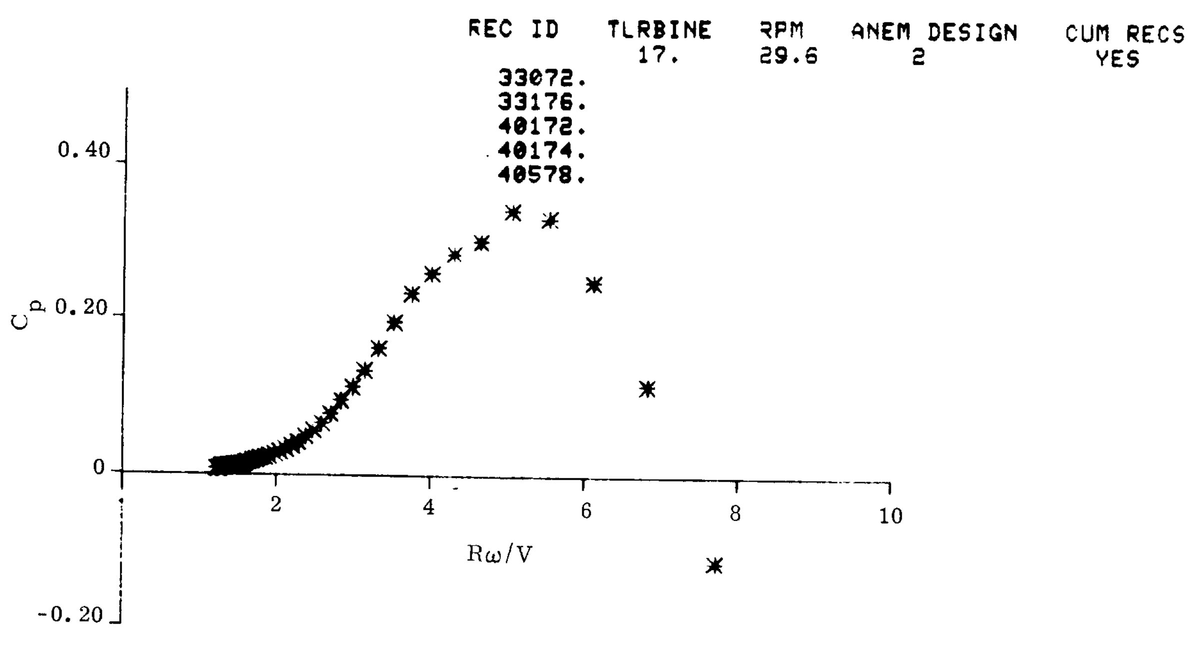
57.7
30-ft Reference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RPM
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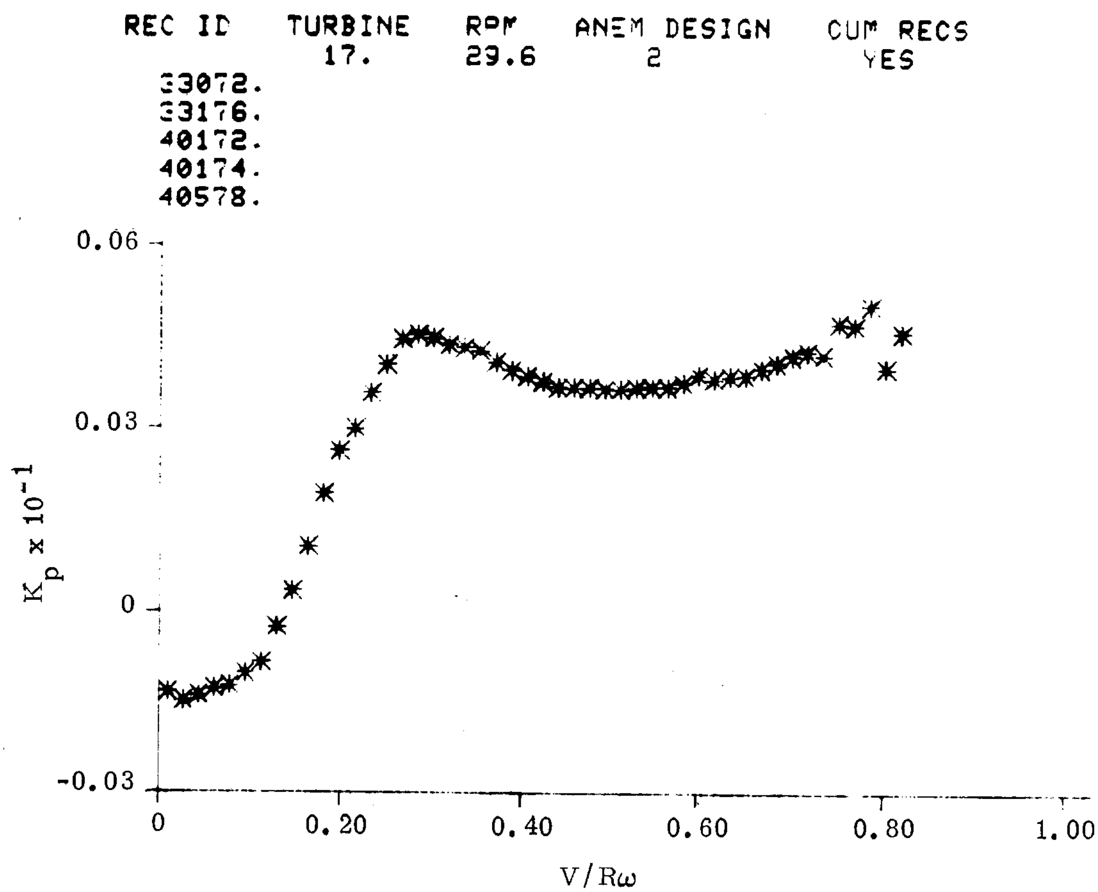
6
8
10
Rω/V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40174.
40578.
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0.03
0
-0.03
$K_p \times 10^{-1}$
0
0.20
0.40
0.60
0.80
1.00
V/Rω

33.6 rpm

2 Blades, $\sigma = 0.14$

Wind Range 1.5 to 35.5 mph

17. M TURBINE, COMBINED DATA, RPM=33.6
NUMBER SAMPLES IN ACCUMULATION = 102239.
DATA RECORD NAME(S)= 40178. 40472. 40572. 40772. 40972. 41072.
41172. 41174.

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1.5	424.	.004	-2.3798	43.88	-84.301	.02	-.0010	
2.5	953.	.009	-2.1751	26.33	-16.642	.04	-.0009	
3.5	1893.	.019	-1.6245	18.81	-4.530	.05	-.0007	
4.5	2670.	.026	-1.5196	14.63	-1.994	.07	-.0006	
5.5	3542.	.035	-1.3645	11.97	-.981	.08	-.0006	
6.5	3869.	.038	-1.0837	10.13	-.472	.10	-.0005	
7.5	3770.	.037	-.4271	8.78	-.121	.11	-.0002	
8.5	3482.	.034	.3353	7.74	.065	.13	.0001	
9.5	3097.	.030	1.6807	6.93	.234	.14	.0007	
10.5	3430.	.034	3.1192	6.27	.322	.16	.0013	
11.5	3352.	.033	4.5999	5.72	.362	.17	.0019	
12.5	2880.	.028	5.9040	5.27	.361	.19	.0025	
13.5	2667.	.026	7.0268	4.88	.341	.21	.0029	
14.5	2705.	.026	8.5209	4.54	.334	.22	.0036	
15.5	3449.	.034	9.9956	4.25	.321	.24	.0042	
16.5	3542.	.035	10.9373	3.99	.291	.25	.0046	
17.5	3986.	.039	11.8592	3.76	.265	.27	.0050	
18.5	4275.	.042	12.3101	3.56	.232	.28	.0052	
19.5	4307.	.042	12.3226	3.38	.199	.30	.0052	
20.5	4546.	.044	12.2275	3.21	.170	.31	.0051	
21.5	4500.	.044	12.0243	3.06	.145	.33	.0050	
22.5	4605.	.045	11.6469	2.93	.122	.34	.0049	
23.5	4250.	.042	11.3722	2.80	.105	.36	.0048	
24.5	4269.	.042	11.1434	2.69	.091	.37	.0047	
25.5	4030.	.039	10.7068	2.58	.077	.39	.0045	
26.5	3791.	.037	10.5030	2.48	.067	.40	.0044	
27.5	3272.	.032	10.3084	2.39	.059	.42	.0043	
28.5	2515.	.025	10.1783	2.31	.053	.43	.0043	
29.5	2143.	.021	10.1793	2.23	.047	.45	.0043	
30.5	1797.	.018	9.9838	2.16	.042	.46	.0042	
31.5	1405.	.014	10.0789	2.09	.039	.48	.0042	
32.5	977.	.010	10.2380	2.03	.036	.49	.0043	
33.5	699.	.007	10.2117	1.96	.032	.51	.0043	
34.5	463.	.005	10.1760	1.91	.030	.52	.0043	
35.5	306.	.003	9.8731	1.85	.026	.54	.0041	
36.5	165.	.002	9.6204	1.80	.024	.55	.0040	
37.5	84.	.001	9.7377	1.76	.022	.57	.0041	
38.5	63.	.001	10.1979	1.71	.021	.58	.0043	
39.5	34.	.000	9.9382	1.67	.019	.60	.0042	
40.5	11.	.000	13.0545	1.63	.023	.62	.0055	
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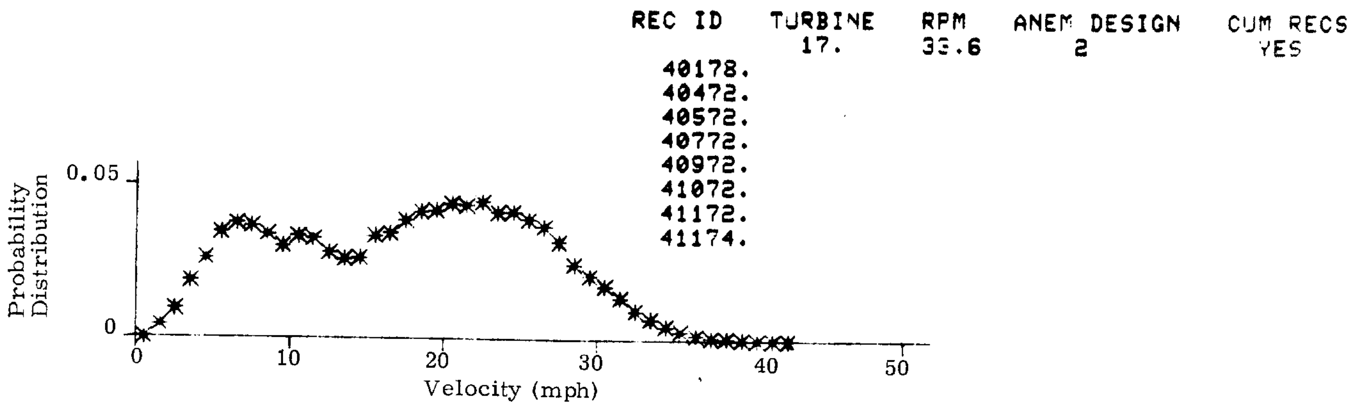
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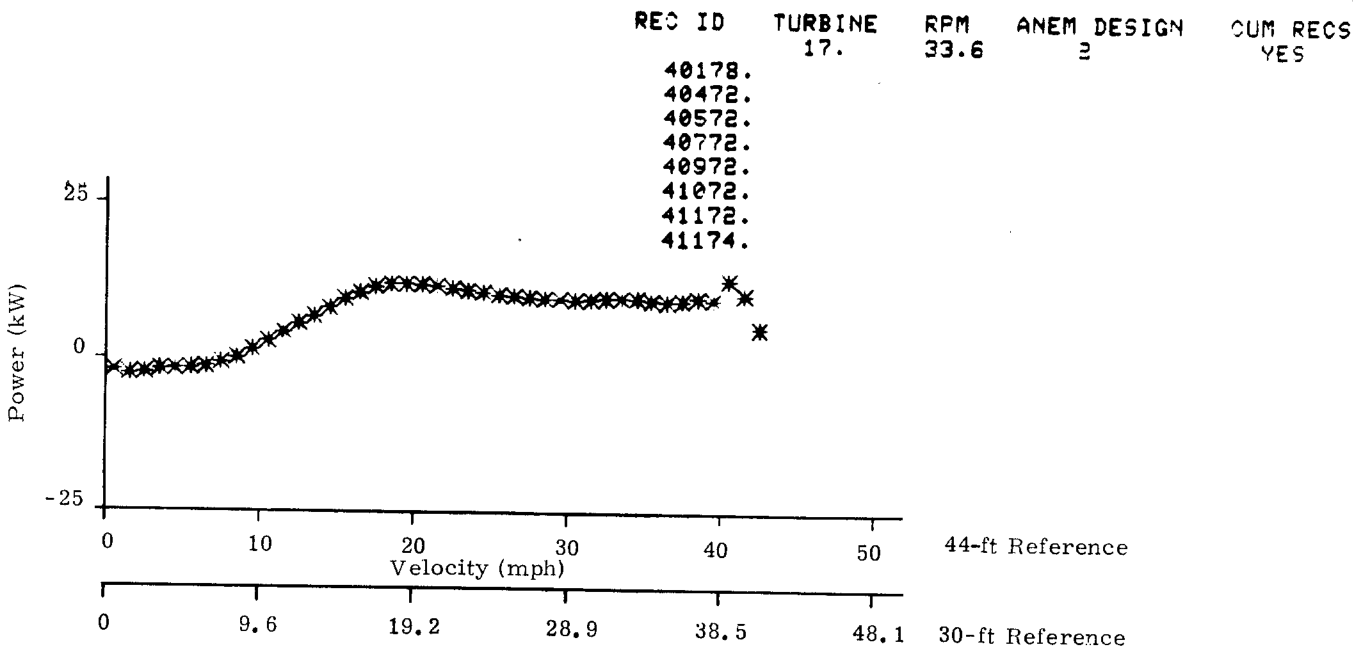
Velocity (mph)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RPM 33.6
ANEM DESIGN 2
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Power (kW)
25
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Velocity (mph)
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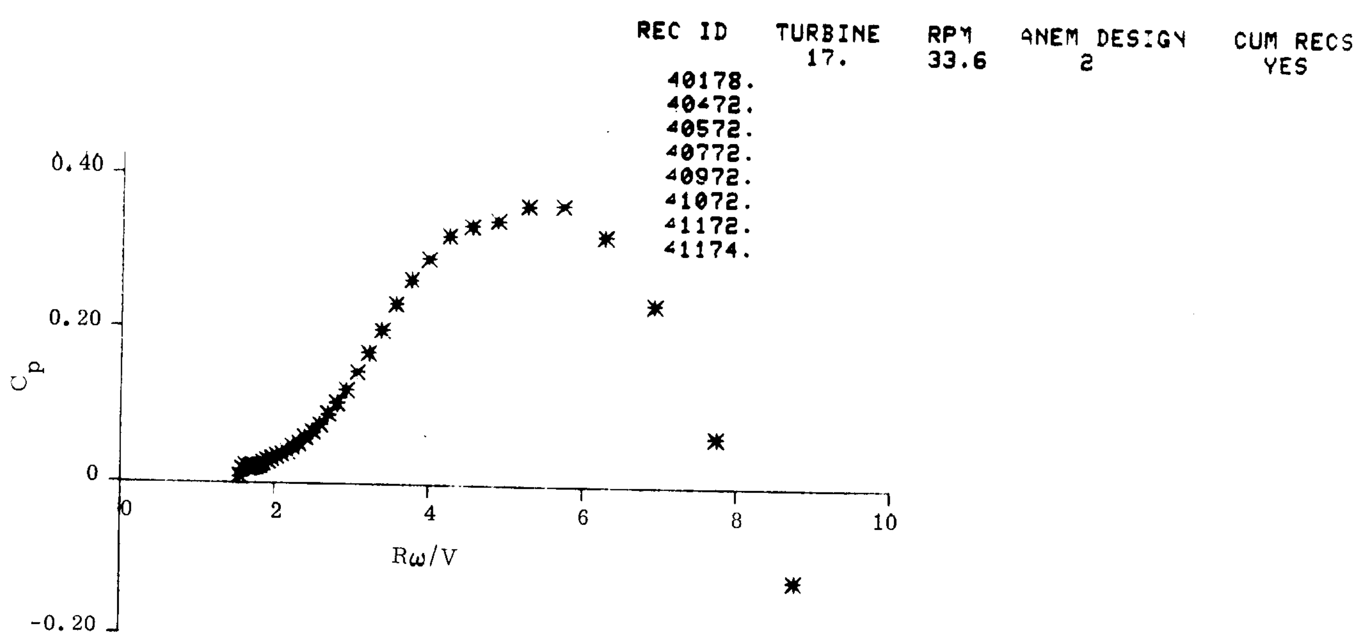
48.1
30-ft Reference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ANEM DESIGN 2
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0
2
4
6
8
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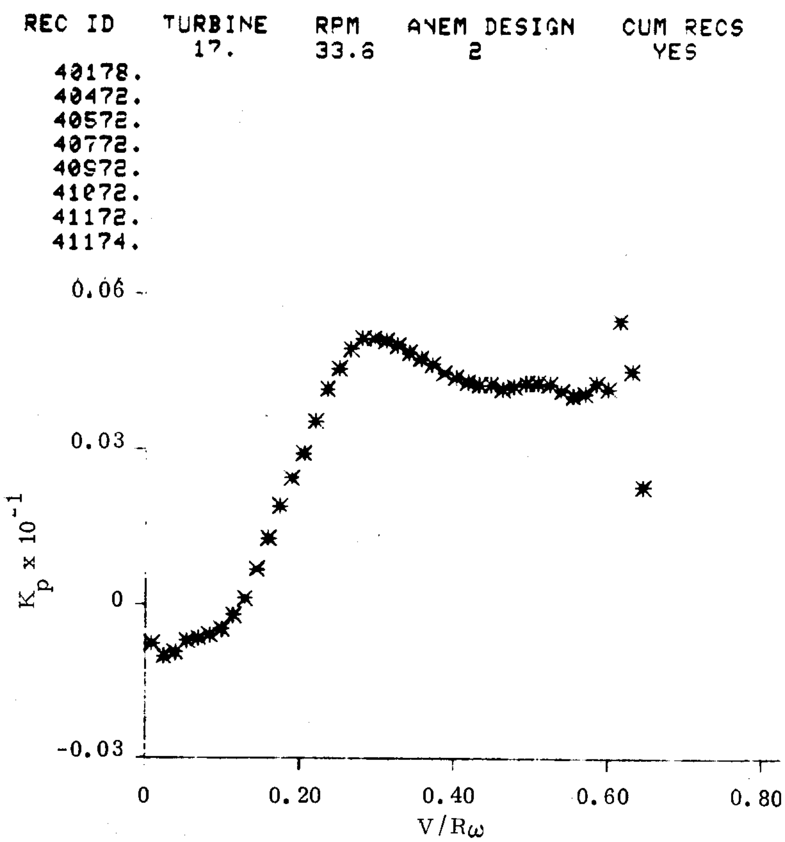
Rω/V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40572.
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40972.
41072.
41172.
41174.
0.06
0.03
0
-0.03
$K_p \times 10^{-1}$
0
0.20
0.40
0.60
0.80
V/Rω

37.0 rpm

2 Blades, σ = 0.14

Wind Range 2.5 to 25.5 mph

17. M TURBINE, COMBINED DATA, RPM=37.0
NUMBER SAMPLES IN ACCUMULATION = 55735.
DATA RECORD NAME(S)= 40672. 41372. 41472. 100921. 102021. 102221.

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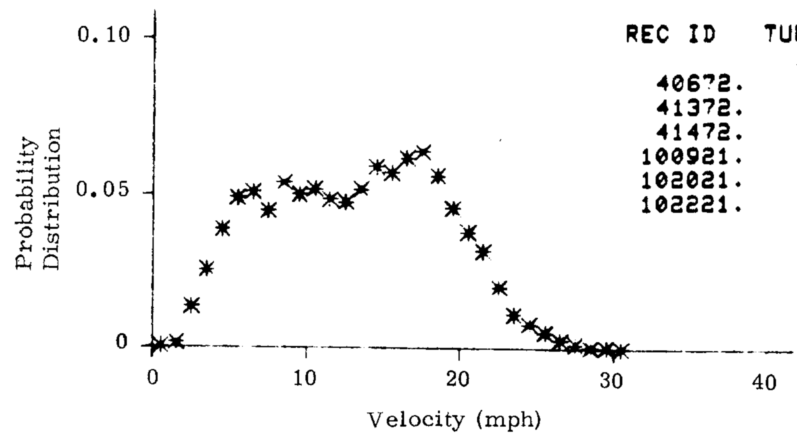
2.5	758.	.014	-2.3704	28.99	-18.137	.03	-.0007	
3.5	1426.	.026	-2.3827	20.71	-6.644	.05	-.0007	
4.5	2170.	.039	-2.2113	16.11	-2.901	.06	-.0007	
5.5	2747.	.049	-1.8594	13.18	-1.336	.08	-.0006	
6.5	2859.	.051	-1.3976	11.15	-.608	.09	-.0004	
7.5	2509.	.045	-.7000	9.66	-.198	.10	-.0002	
8.5	3025.	.054	.8462	8.53	.165	.12	.0003	
9.5	2809.	.050	1.9667	7.63	.274	.13	.0006	
10.5	2906.	.052	3.3811	6.90	.349	.14	.0011	
11.5	2733.	.049	4.6962	6.30	.369	.16	.0015	
12.5	2670.	.048	6.1661	5.80	.377	.17	.0019	
13.5	2910.	.052	7.7322	5.37	.376	.19	.0024	
14.5	3325.	.060	9.1472	5.00	.359	.20	.0029	
15.5	3222.	.058	10.7755	4.68	.346	.21	.0034	
16.5	3490.	.063	12.1525	4.39	.323	.23	.0038	
17.5	3602.	.065	13.3414	4.14	.298	.24	.0042	
18.5	3164.	.057	14.4334	3.92	.273	.26	.0045	
19.5	2581.	.046	16.1095	3.72	.260	.27	.0051	
20.5	2139.	.038	17.0484	3.54	.237	.28	.0054	
21.5	1806.	.032	17.9536	3.37	.216	.30	.0056	
22.5	1126.	.020	18.2298	3.22	.191	.31	.0057	
23.5	630.	.011	18.4900	3.08	.170	.32	.0058	
24.5	441.	.008	19.5392	2.96	.159	.34	.0061	
25.5	297.	.005	19.7938	2.84	.143	.35	.0062	
26.5	156.	.003	19.1654	2.74	.123	.37	.0060	
27.5	76.	.001	19.3395	2.64	.111	.38	.0061	
28.5	26.	.000	20.6935	2.54	.107	.39	.0065	
29.5	14.	.000	19.8973	2.46	.093	.41	.0062	
30.5	2.	.000	23.3802	2.38	.099	.42	.0073	



REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
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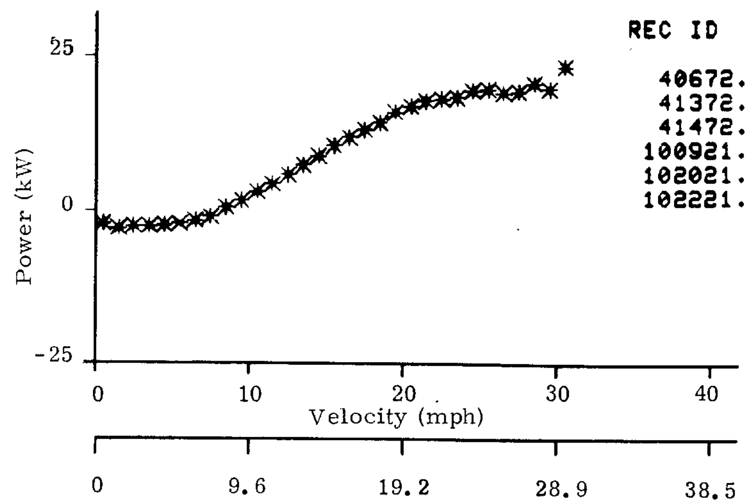
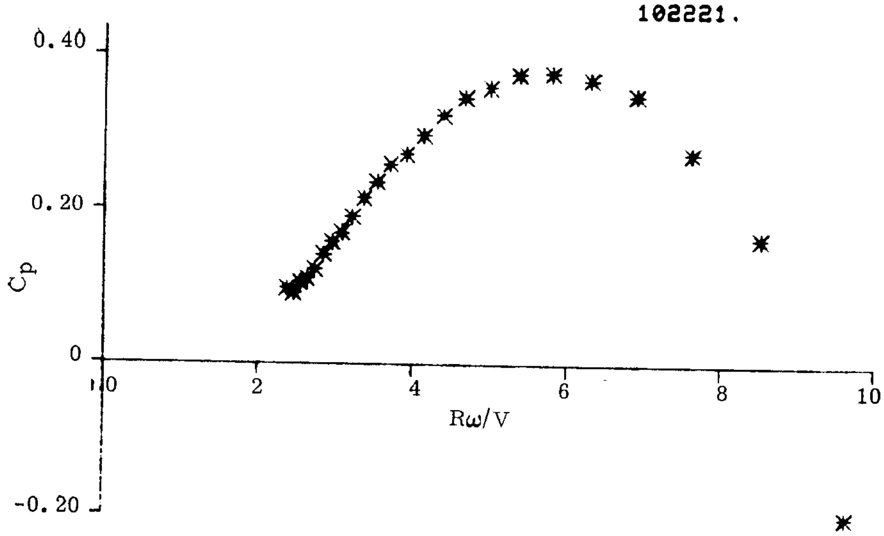
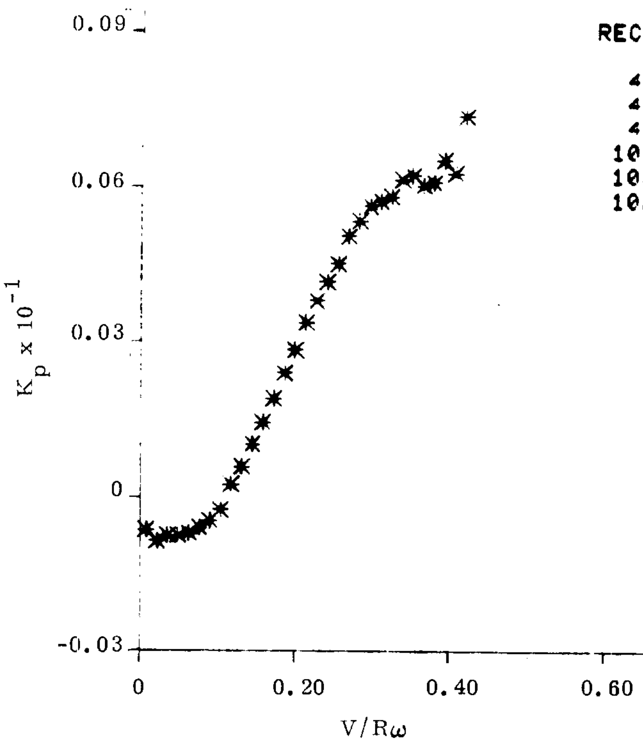
40672.				
41372.				
41472.				
100921.				
102021.				
102221.				



REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	37.0	2	YES
40672.				
41372.				
41472.				
100921.				
102021.				
102221.				

REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	37.0	2	YES
40672.				
41372.				
41472.				
100921.				
102021.				
102221.				





REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	37.0	2	YES
40672.				
41372.				
41472.				
100921.				
102021.				
102221.				

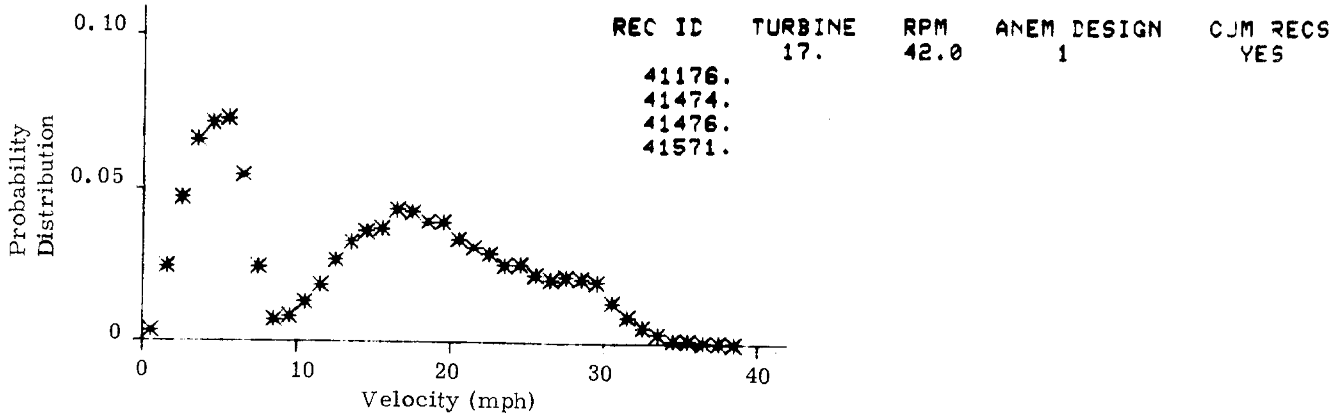
42.0 rpm

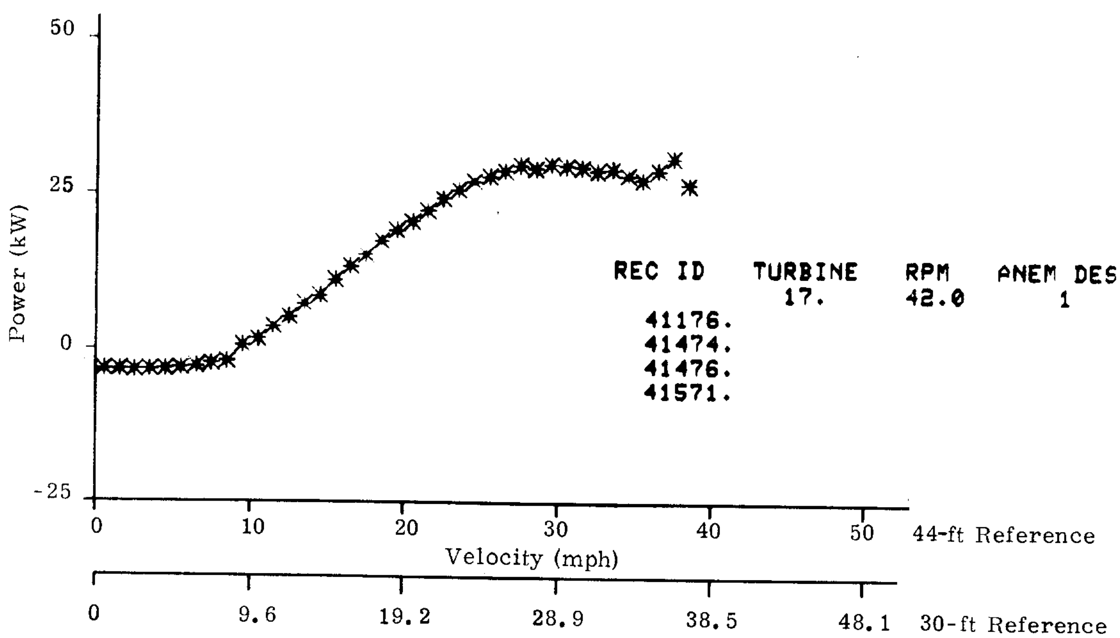
2 Blades, σ = 0.14

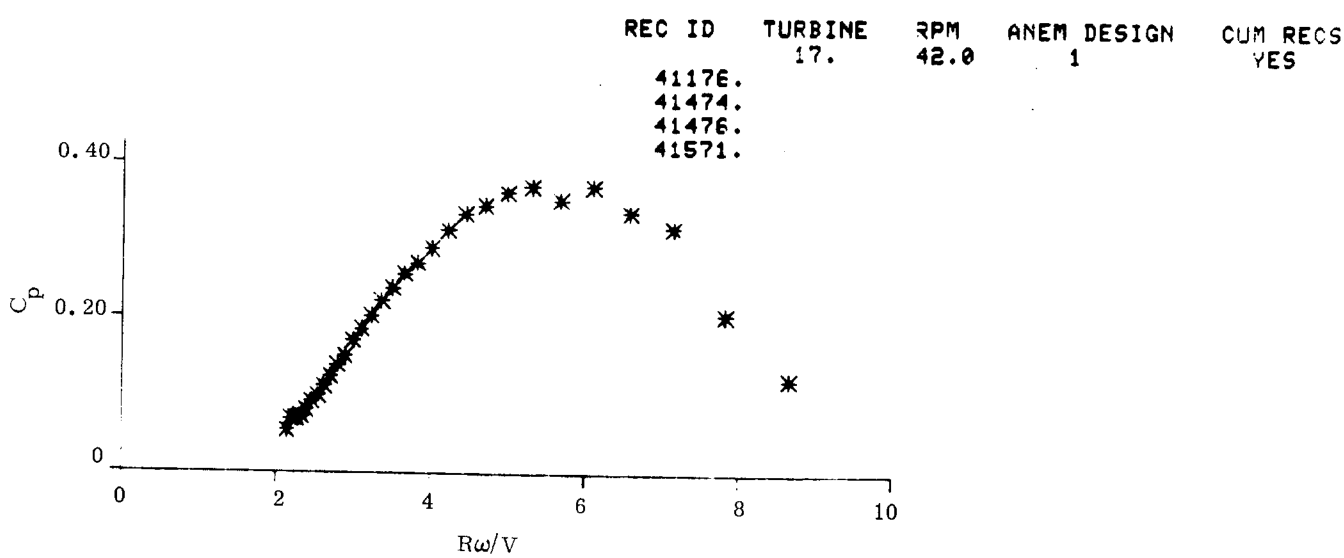
Wind Range 1.5 to 31.5 mph

17. M TURBINE, COMBINED DATA, RPM=42.0
NUMBER SAMPLES IN ACCUMULATION = 49044.
DATA RECORD NAME(S)= 41176. 41474. 41476. 41571.

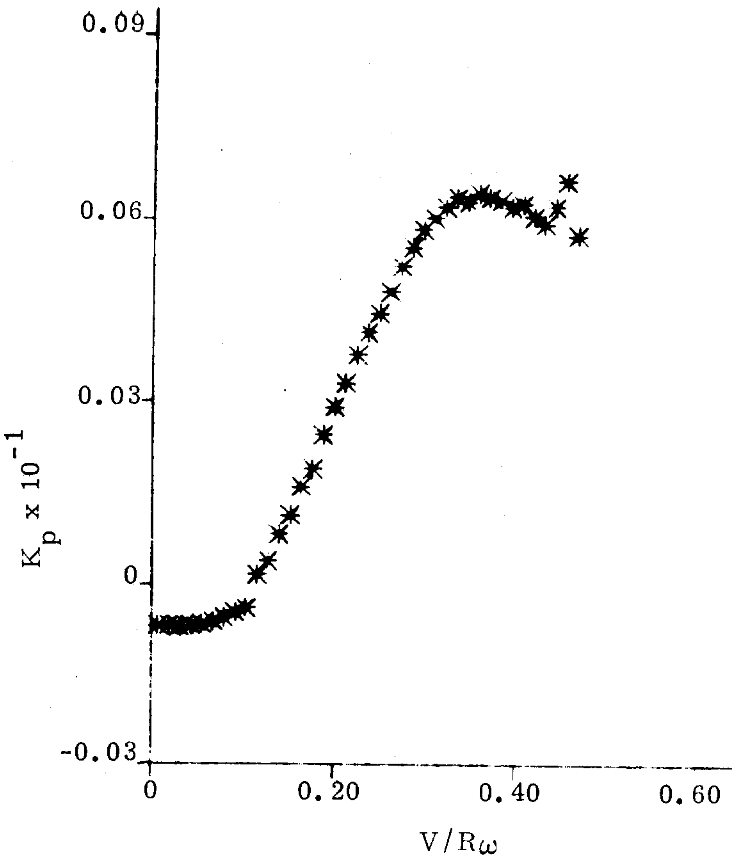
V	N	F	POWER(KW)	RW/V	CP	V/RW	KP	RMS
.5	168.	.003	-3.1408	164.56	-3003.89	.01	-.0007	
1.5	1200.	.024	-3.0918	54.85	-109.520	.02	-.0007	
2.5	2322.	.047	-3.1734	32.91	-24.281	.03	-.0007	
3.5	3259.	.066	-3.1211	23.51	-8.703	.04	-.0007	
4.5	3536.	.072	-3.0258	18.28	-3.970	.05	-.0006	
5.5	3596.	.073	-2.7899	14.96	-2.005	.07	-.0006	
6.5	2696.	.055	-2.5096	12.66	-1.093	.08	-.0005	
7.5	1205.	.025	-2.0419	10.97	-.579	.09	-.0004	
8.5	356.	.007	-1.7115	9.68	-.333	.10	-.0004	
9.5	407.	.008	.8785	8.66	.122	.12	.0002	
10.5	643.	.013	1.9866	7.84	.205	.13	.0004	
11.5	915.	.019	4.0216	7.15	.316	.14	.0009	
12.5	1326.	.027	5.4819	6.58	.336	.15	.0012	
13.5	1627.	.033	7.6096	6.09	.370	.16	.0016	
14.5	1792.	.037	8.9713	5.67	.352	.18	.0019	
15.5	1844.	.038	11.5154	5.31	.370	.19	.0025	
16.5	2152.	.044	13.6118	4.99	.362	.20	.0029	
17.5	2120.	.043	15.4464	4.70	.345	.21	.0033	
18.5	1954.	.040	17.6479	4.45	.333	.22	.0038	
19.5	1953.	.040	19.3957	4.22	.313	.24	.0042	
20.5	1676.	.034	20.8448	4.01	.289	.25	.0045	
21.5	1544.	.031	22.5070	3.83	.271	.26	.0048	
22.5	1435.	.029	24.4480	3.66	.257	.27	.0052	
23.5	1252.	.026	25.8656	3.50	.238	.29	.0056	
24.5	1263.	.026	27.2523	3.36	.222	.30	.0058	
25.5	1091.	.022	28.0663	3.23	.202	.31	.0060	
26.5	1010.	.021	28.9317	3.10	.186	.32	.0062	
27.5	1059.	.022	29.7271	2.99	.171	.33	.0064	
28.5	1032.	.021	29.3207	2.89	.151	.35	.0063	
29.5	986.	.020	29.9531	2.79	.139	.36	.0064	
30.5	651.	.013	29.6213	2.70	.125	.37	.0064	
31.5	426.	.009	29.4294	2.61	.113	.38	.0063	
32.5	255.	.005	28.8715	2.53	.101	.40	.0062	
33.5	153.	.003	29.1745	2.46	.093	.41	.0063	
34.5	52.	.001	28.2176	2.38	.082	.42	.0061	
35.5	48.	.001	27.5840	2.32	.074	.43	.0059	
36.5	24.	.000	28.9449	2.25	.071	.44	.0062	
37.5	11.	.000	30.8984	2.19	.070	.46	.0066	
38.5	5.	.000	26.7404	2.14	.056	.47	.0057	


REC ID
41176.
41474.
41476.
41571.
TURBINE
17.
RPM
42.0
ANEM DESIGN
1
CUM RECS
YES
Probability Distribution
0.10
0.05
0
0
10
20
30
40
Velocity (mph)


Power (kW)
50
25
0
-25
REC ID
41176.
41474.
41476.
41571.
TURBINE
17.
RPM
42.0
ANEM DESIGN
1
CUM RECS
YES
0
10
20
30
40
50
44-ft Reference
Velocity (mph)
0
9.6
19.2
28.9
38.5
48.1
30-ft Reference


REC ID
41176.
41474.
41476.
41571.
TURBINE
17.
RPM
42.0
ANEM DESIGN
1
CUM RECS
YES
C_p
0.40
0.20
0
0
2
4
6
8
10
Rω/V

REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	42.0	1	YES
41176.				
41474.				
41476.				
4157[illegible].				



45.5 rpm

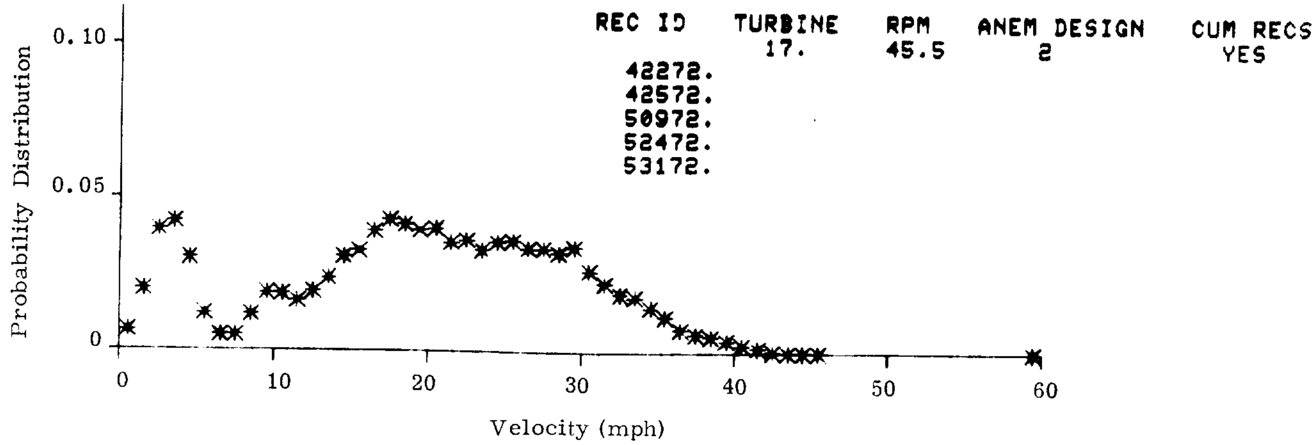
2 Blades, σ = 0.14

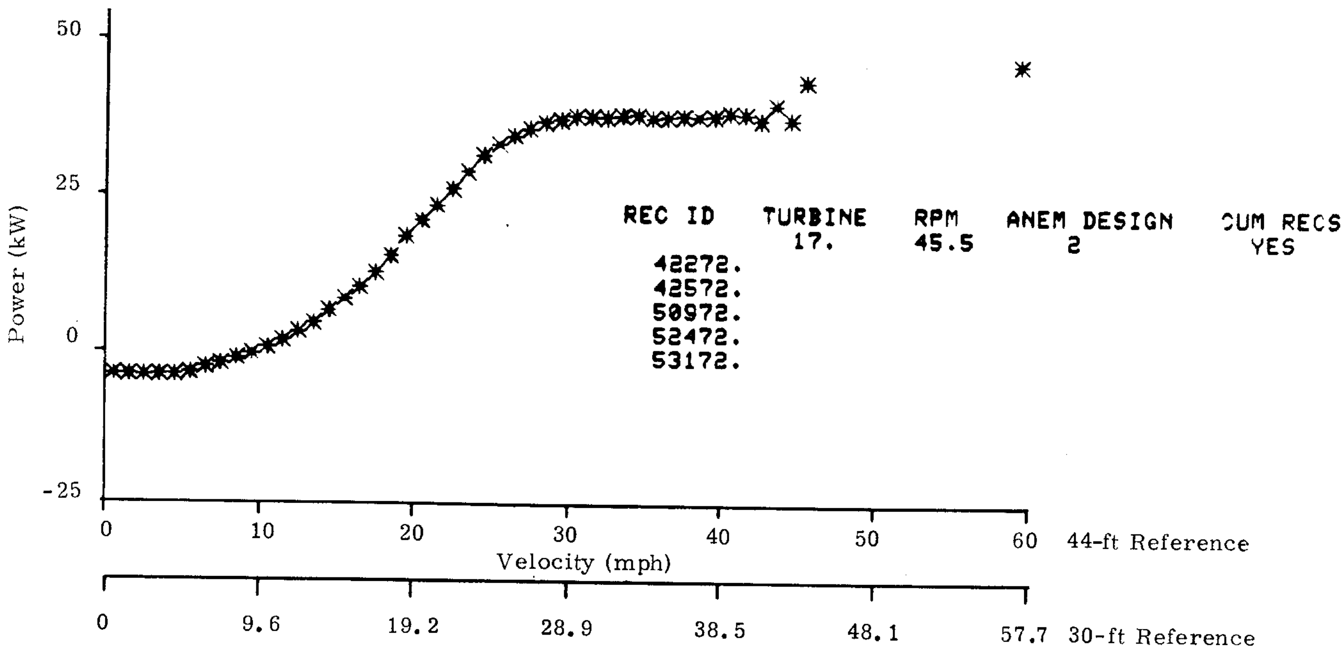
Wind Range 1.5 to 38.5 mph

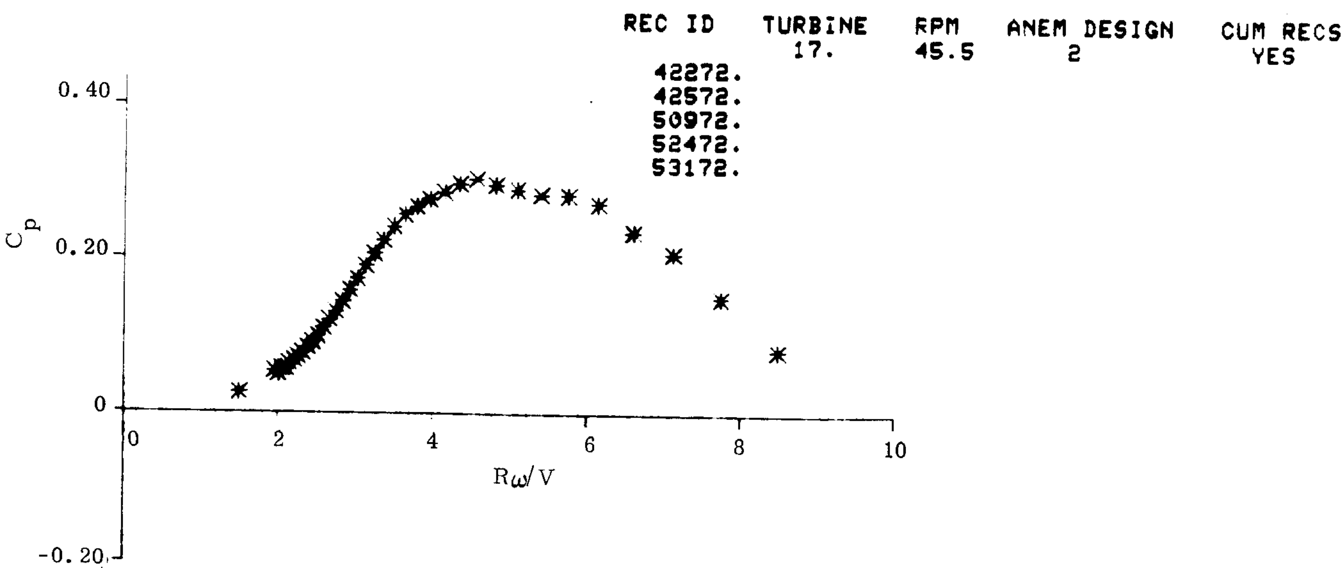
Possible Error or Unusual Testing Condition Involved

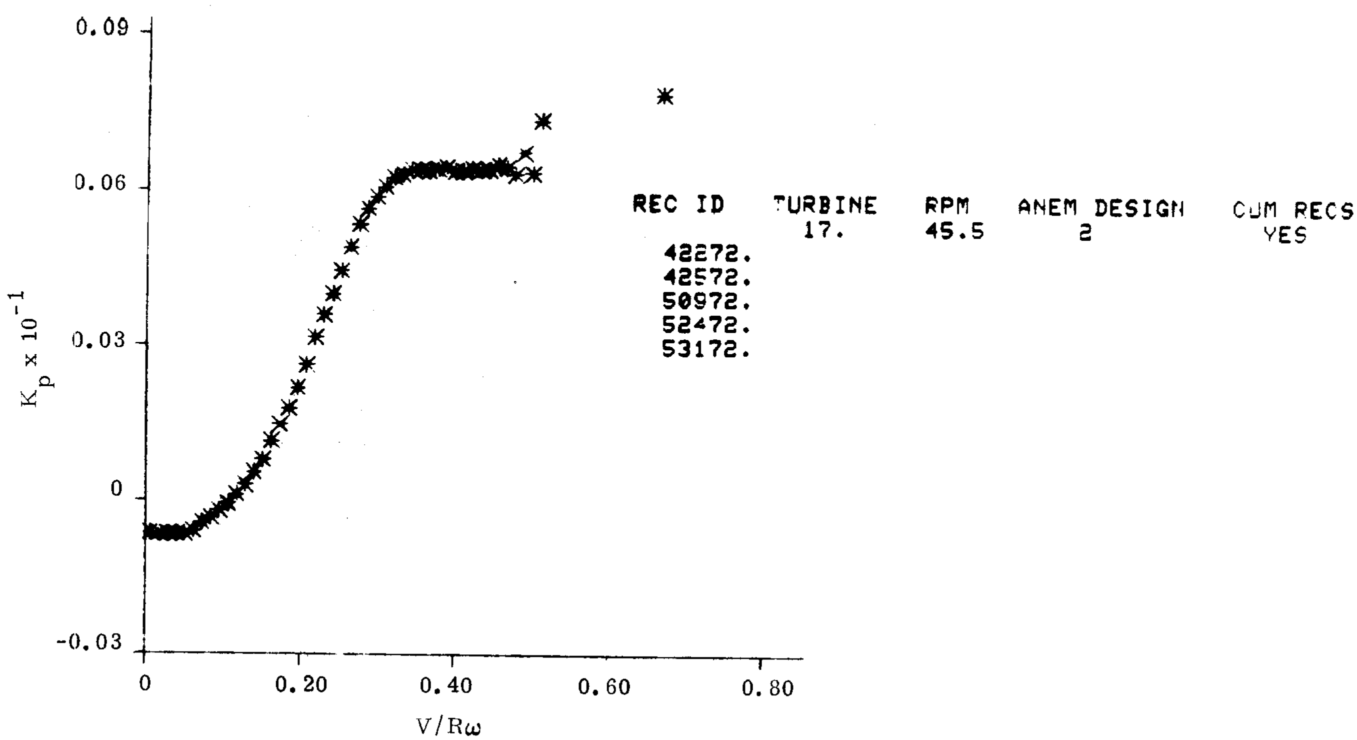
17. M TURBINE, COMBINED DATA, RPM=45.5
NUMBER SAMPLES IN ACCUMULATION = 70178.
DATA RECORD NAME(S)= 42272. 42572. 50972. 52472. 53172.

V	N	F	POWER(KW)	RW/V	CP	V/RW	KP	RMS
.5	447.	.006	-3.7022	178.27	-3540.86	.01	-.0006	
1.5	1412.	.020	-3.7679	59.42	-133.470	.02	-.0006	
2.5	2785.	.040	-3.8563	35.65	-29.506	.03	-.0007	
3.5	2975.	.042	-3.8354	25.47	-10.695	.04	-.0006	
4.5	2143.	.031	-3.8291	19.81	-5.024	.05	-.0006	
5.5	858.	.012	-3.4426	16.21	-2.474	.06	-.0006	
6.5	357.	.005	-2.4827	13.71	-1.081	.07	-.0004	
7.5	364.	.005	-1.9004	11.88	-.539	.08	-.0003	
8.5	841.	.012	-1.0354	10.49	-.202	.10	-.0002	
9.5	1340.	.019	-.2288	9.38	-.032	.11	-.0000	
10.5	1328.	.019	.8107	8.49	.084	.12	.0001	
11.5	1165.	.017	1.9242	7.75	.151	.13	.0003	
12.5	1381.	.020	3.3922	7.13	.208	.14	.0006	
13.5	1693.	.024	4.8398	6.60	.235	.15	.0008	
14.5	2188.	.031	6.9155	6.15	.271	.16	.0012	
15.5	2325.	.033	8.7748	5.75	.282	.17	.0015	
16.5	2786.	.040	10.6207	5.40	.283	.19	.0018	
17.5	3054.	.044	12.9584	5.09	.289	.20	.0022	
18.5	2944.	.042	15.6199	4.82	.295	.21	.0026	
19.5	2811.	.040	18.7676	4.57	.303	.22	.0032	
20.5	2857.	.041	21.3534	4.35	.296	.23	.0036	
21.5	2534.	.036	23.7611	4.15	.286	.24	.0040	
22.5	2590.	.037	26.4308	3.96	.277	.25	.0045	
23.5	2349.	.033	29.0577	3.79	.268	.26	.0049	
24.5	2548.	.036	31.6786	3.64	.258	.27	.0053	
25.5	2575.	.037	33.4353	3.50	.241	.29	.0056	
26.5	2396.	.034	34.8075	3.36	.224	.30	.0059	
27.5	2391.	.034	35.9113	3.24	.206	.31	.0061	
28.5	2295.	.033	37.0089	3.13	.191	.32	.0062	
29.5	2431.	.035	37.3651	3.02	.174	.33	.0063	
30.5	1880.	.027	37.9245	2.92	.160	.34	.0064	
31.5	1600.	.023	37.8844	2.83	.145	.35	.0064	
32.5	1360.	.019	37.7766	2.74	.132	.36	.0064	
33.5	1285.	.018	38.0342	2.66	.121	.38	.0064	
34.5	1052.	.015	38.1508	2.58	.111	.39	.0064	
35.5	837.	.012	37.6683	2.51	.101	.40	.0064	
36.5	550.	.008	37.7608	2.44	.093	.41	.0064	
37.5	440.	.006	37.9378	2.38	.086	.42	.0064	
38.5	379.	.005	37.8066	2.32	.079	.43	.0064	
39.5	292.	.004	37.9316	2.26	.074	.44	.0064	
40.5	180.	.003	38.4319	2.20	.069	.45	.0065	
41.5	109.	.002	38.2013	2.15	.064	.47	.0064	
42.5	35.	.000	37.3286	2.10	.058	.48	.0063	
43.5	12.	.000	39.8071	2.05	.058	.49	.0067	
44.5	1.	.000	37.4752	2.00	.051	.50	.0063	
45.5	2.	.000	43.4360	1.96	.055	.51	.0073	
59.5	1.	.000	46.4163	1.50	.026	.67	.0078	


REC ID
TURBINE 17.
RPM 45.5
ANEM DESIGN 2
CUM RECS YES
42272.
42572.
50972.
52472.
53172.
Probability Distribution
0.10
0.05
0
0
10
20
30
40
50
60
Velocity (mph)


REC ID
TURBINE 17.
RPM 45.5
ANEM DESIGN 2
CUM RECS YES
42272.
42572.
50972.
52472.
53172.
Power (kW)
50
25
0
-25
0
10
20
30
40
50
60
44-ft Reference
Velocity (mph)
0
9.6
19.2
28.9
38.5
48.1
57.7
30-ft Reference


REC ID
TURBINE 17.
RPM 45.5
ANEM DESIGN 2
CUM RECS YES
42272.
42572.
50972.
52472.
53172.
C_p
0.40
0.20
0
-0.20
0
2
4
6
8
10
Rω/V



0.09
0.06
0.03
0
-0.03
$K_p \times 10^{-1}$
0
0.20
0.40
0.60
0.80
V/Rω
REC ID
42272.
42572.
50972.
52472.
53172.
TURBINE
17.
RPM
45.5
ANEM DESIGN
2
CUM RECS
YES

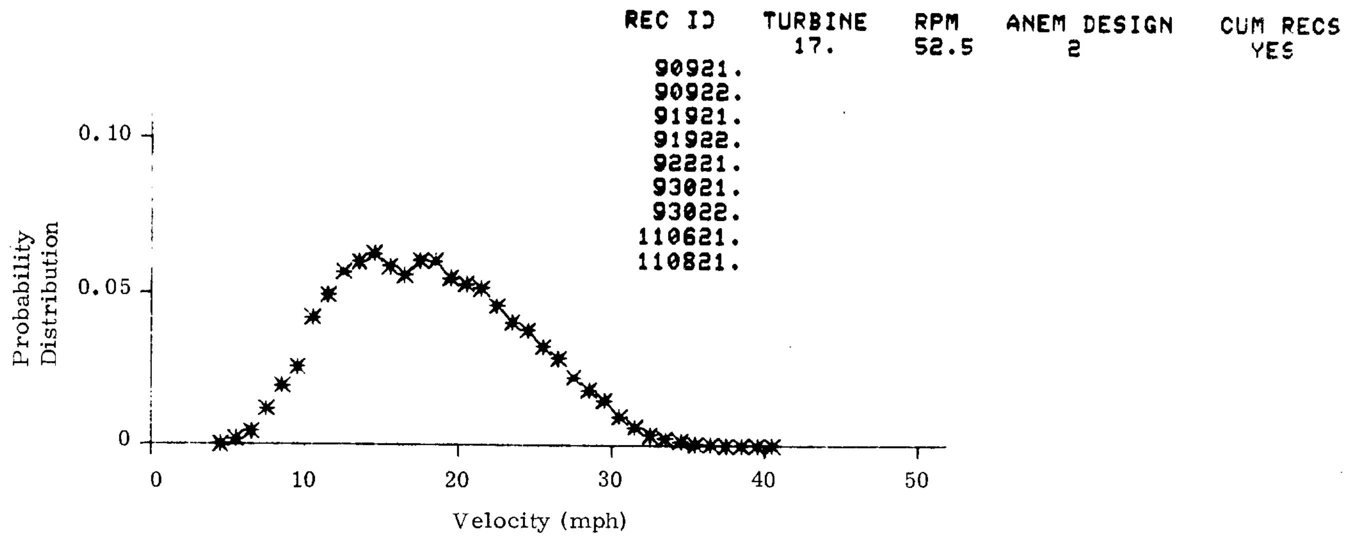
52.5 rpm

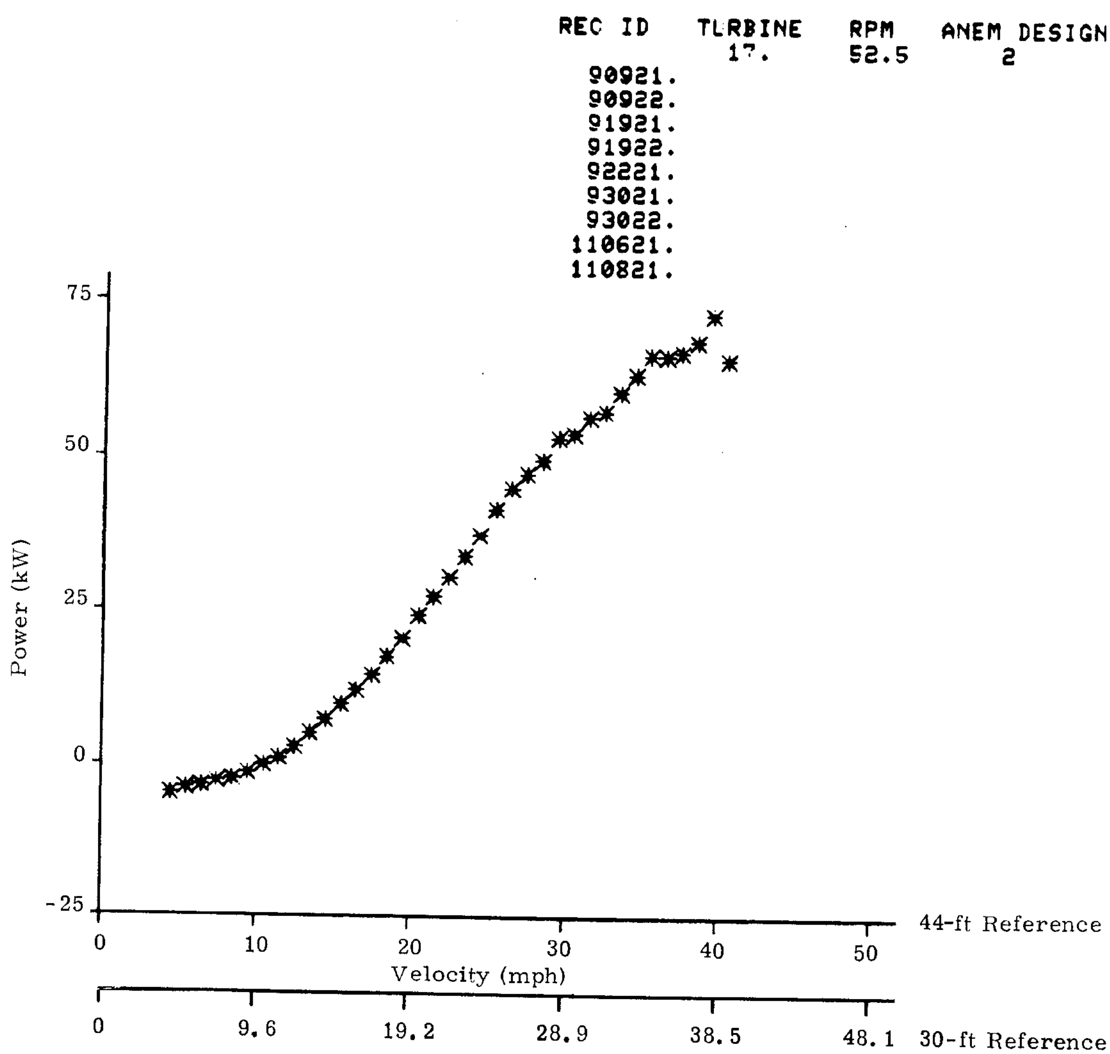
2 Blades, $\sigma = 0.14$

Wind Range 6.5 to 32.5 mph

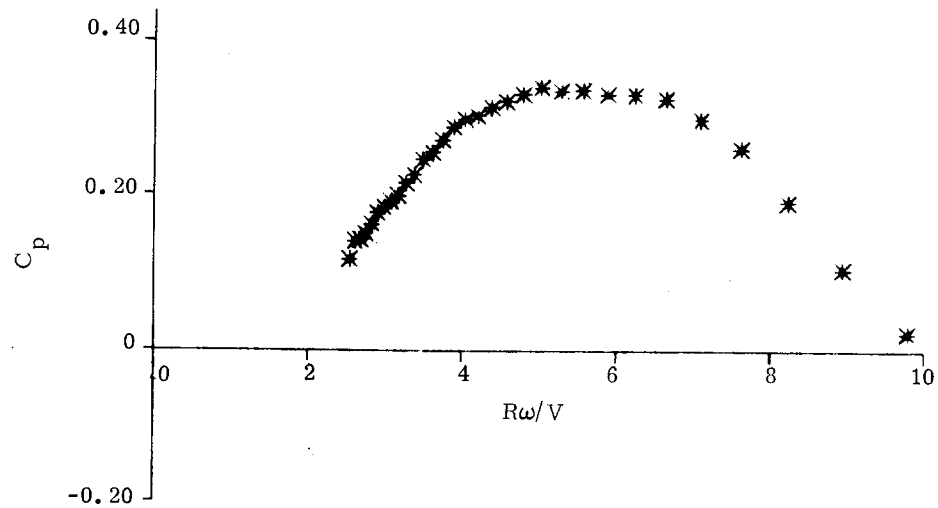
17. M TURBINE, COMBINED DATA, RPM=52.5
NUMBER SAMPLES IN ACCUMULATION = 100716.
DATA RECORD NAME(S)= 90921. 90922. 91921. 91922. 92221. 93021. 93022. 110621. 110821.

V	N	F	POWER(KW)	RW/V	CP	V/RW	KP	RMS
4.5	17.	.000	-4.6123	22.85	-6.051	.04	-.0005	
5.5	192.	.002	-3.6353	18.70	-2.612	.05	-.0004	
6.5	438.	.004	-3.2481	15.82	-1.414	.06	-.0004	
7.5	1185.	.012	-2.4960	13.71	-.707	.07	-.0003	
8.5	1969.	.020	-2.1135	12.10	-.411	.08	-.0002	
9.5	2609.	.026	-1.0757	10.83	-.150	.09	-.0001	
10.5	4247.	.042	.2381	9.79	.025	.10	.0000	
11.5	5006.	.050	1.3445	8.94	.106	.11	.0001	
12.5	5770.	.057	3.1221	8.23	.191	.12	.0003	
13.5	6087.	.060	5.3483	7.62	.260	.13	.0006	
14.5	6344.	.063	7.5752	7.09	.297	.14	.0008	
15.5	5933.	.059	10.0952	6.64	.324	.15	.0011	
16.5	5665.	.056	12.3987	6.23	.330	.16	.0014	
17.5	6136.	.061	14.8186	5.88	.331	.17	.0016	
18.5	6102.	.061	17.7889	5.56	.336	.18	.0020	
19.5	5563.	.055	20.7867	5.27	.335	.19	.0023	
20.5	5372.	.053	24.4840	5.02	.340	.20	.0027	
21.5	5232.	.052	27.5486	4.78	.331	.21	.0030	
22.5	4649.	.046	30.6790	4.57	.322	.22	.0034	
23.5	4095.	.041	34.1216	4.38	.314	.23	.0037	
24.5	3842.	.038	37.3307	4.20	.303	.24	.0041	
25.5	3301.	.033	41.4648	4.03	.299	.25	.0046	
26.5	2923.	.029	44.9736	3.88	.289	.26	.0049	
27.5	2278.	.023	47.2551	3.74	.272	.27	.0052	
28.5	1843.	.018	49.4861	3.61	.256	.28	.0054	
29.5	1494.	.015	53.0216	3.49	.247	.29	.0058	
30.5	952.	.009	53.7297	3.37	.226	.30	.0059	
31.5	603.	.006	56.4063	3.26	.216	.31	.0062	
32.5	355.	.004	57.3069	3.16	.200	.32	.0063	
33.5	233.	.002	60.4141	3.07	.192	.33	.0066	
34.5	153.	.002	63.2066	2.98	.184	.34	.0069	
35.5	53.	.001	66.3278	2.90	.177	.35	.0073	
36.5	38.	.000	66.1844	2.82	.163	.35	.0073	
37.5	13.	.000	66.7610	2.74	.151	.36	.0073	
38.5	13.	.000	68.4870	2.67	.143	.37	.0075	
39.5	8.	.000	72.7470	2.60	.141	.38	.0080	
40.5	3.	.000	65.6640	2.54	.118	.39	.0072	

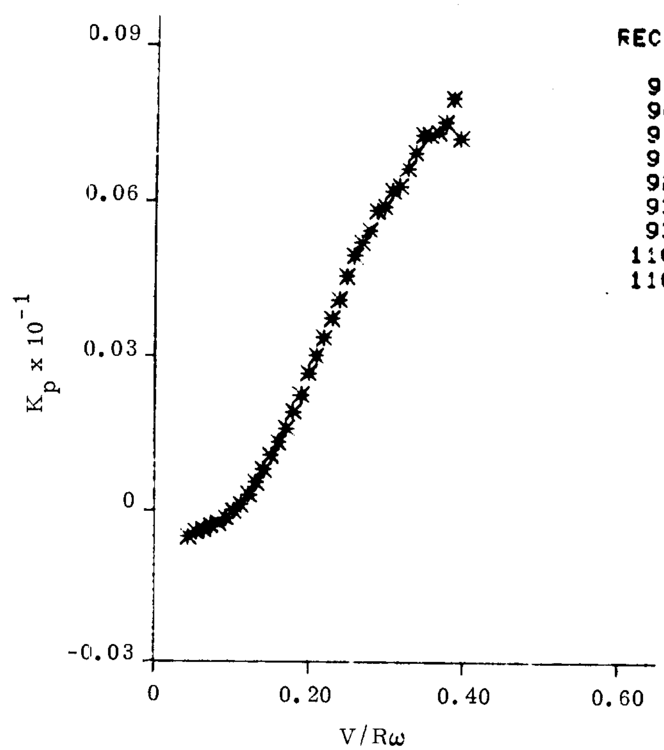

REC ID
90921.
90922.
91921.
91922.
92221.
93021.
93022.
110621.
110821.
TURBINE
17.
RPM
52.5
ANEM DESIGN
2
CUM RECS
YES
Probability Distribution
0.10
0.05
0
0
10
20
30
40
50
Velocity (mph)


REC ID
90921.
90922.
91921.
91922.
92221.
93021.
93022.
110621.
110821.
TURBINE
17.
RPM
52.5
ANEM DESIGN
2
CUM RECS
YES
Power (kW)
75
50
25
0
-25
0
10
20
30
40
50
Velocity (mph)
44-ft Reference
0
9.6
19.2
28.9
38.5
48.1
30-ft Reference

REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	52.5	2	YES
90921.				
90922.				
91921.				
91922.				
92221.				
93021.				
93022.				
110621.				
110821.				



REC ID	TURBINE	RPM	ANEM DESIGN	CUM RECS
	17.	52.5	2	YES
90921.				
90922.				
91921.				
91922.				
92221.				
93021.				
93022.				
110621.				
110821.				



APPENDIX B

DOE/Sandia 17-Metre Darrieus Wind-Turbine Rotor Specifications

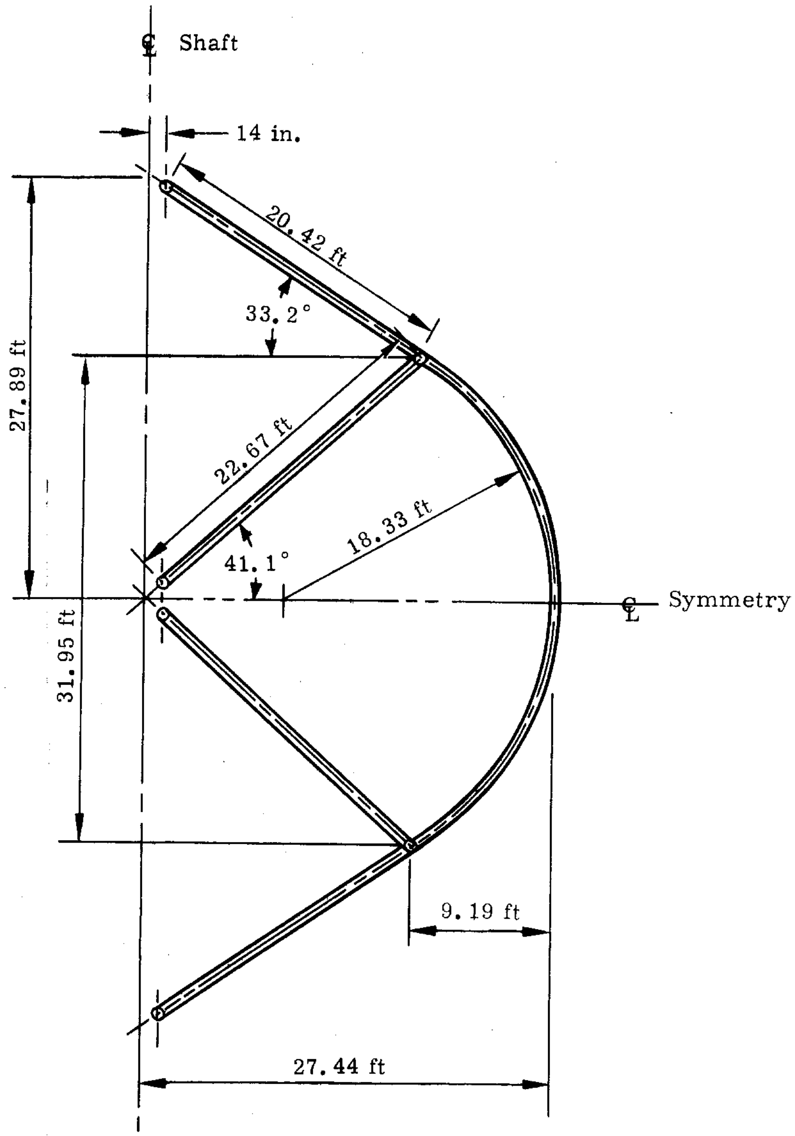


Figure B-1. 17-Metre Rotor Geometry

Summary of Rotor Specifications

Rotor Diameter	54.9 ft	Blade Circular Section Weight	299 lb ea.
Rotor Height	55.8 ft	Blade Strut Section Weight	223 lb ea.
Base Height	16.0 ft	Tower OD	20 in.
Rotor Swept Area	2014 ft^2	Tower Wall Thickness	1 in.
Airfoil Section	NACA 0012	Tower Weight	11,500 lb
Chord Length	21.0 in.	Guy Cable Size	1-in.-diameter, 19-strand
Rotor Solidity (neglecting struts) 2 blades	0.14	Guy Cable Tension	14,000 lbf
Blade Straight Section Weight	207 lb ea.	Guy Elevation Angle	35°

DISTRIBUTION:

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Alcoa Center, PA 15069
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