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Mod-2 Wind Turbine Field Operations Experience

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E-2901

SUMMARY

The Mod-2 wind turbine project is a development and research test operations program sponsored by the U.S. Department of Energy (Office of Solar Electric Technologies), managed by the NASA Lewis Research Center. The development of the turbine was initiated in 1977 under a contract NASA awarded to the Boeing Engineering Company (now Boeing Aerospace Co.). The three-machine, 7.5 MW Goodnoe Hills cluster, located near Goldendale, Washington, is now in a research/experimental operations phase that offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid; and the environment. Following a brief description of the turbine and project history, this paper addresses major problem areas and research and development test results. Field operations, both routine and nonroutine, are discussed. Routine operation to date has produced over 13 379 000 KWh of electrical energy during 11 064 hr of rotation. Nonroutine operation includes suspended activities caused by a crack in the low speed shaft that necessitated a redesign and reinstallation of this assembly on all three turbines. With the world's largest cluster back in full operation, two of the turbines will be operated over the next several years to determine their value as energy producers. The third unit will be used primarily for conducting research tests requiring configuration changes to better understand the wind turbine technology. Technical areas summarized pertain to system performance and enhancements. Specific research tests relating to acoustics, TV interference, and wake effects conclude the paper.

SYSTEM DESCRIPTION

The Mod-2 wind turbine is a horizontal axis machine utilizing a 300-ft diameter partial span control, upwind rotor, as shown in figure 1.

The rotor's center of rotation is 200 feet above ground level. It is coupled to the low speed shaft through an elastomeric teeter bearing. A 2500 kW synchronous generator is driven via a step-up planetary gearbox and "soft" quill shaft for torque transmission. The generator, gearbox, hydraulic systems, electronic controls and other support equipment are enclosed in a nacelle mounted atop a cylindrical steel tower. The nacelle can be yawed (rotated) to keep the rotor oriented correctly into the wind as the wind direction changes. A hydraulic pitch control system is used to control the position of the movable rotor tips. The movable rotor tips are used to obtain a constant rotational speed of 17.5 rpm and to maintain the proper power output at wind speeds above rated wind speed (27.5 mph at hub), and to provide for shutdown by feathering of the rotor tips (ref. 1).

The Mod-2 is controlled by an electronic microprocessor. The microprocessor is designed to allow unattended operation of the WTS at a remote site by monitoring wind conditions and the operational status of the wind turbine.

Equipment failures result in automatic safe shutdown of the WTS. The system status is monitored at the utility substation, from which maintenance crews are dispatched as needed.

PROJECT HISTORY

The U.S. Department of Energy (DOE) Office of Solar Electric Technologies has overall responsibility for conceiving and directing research and development of wind energy systems. The DOE has delegated project management responsibility to the NASA Lewis Research Center (LeRC), in Cleveland, Ohio, for the design fabrication, and field testing of large (100 kW and larger) horizontal-axis wind turbine systems (WTS) for utility applications. The ultimate objective of the Federal Wind Energy Program and the projects by which it is implemented is to develop the technology base necessary for private industry to generate cost effective wind-powered electricity.

The Mod-2 wind turbine project was initiated in 1977 for the design, installation, and research testing of an experimental wind turbine system under a contract with Boeing Engineering and Construction (now Boeing Aerospace Co.). Eventually, three turbine systems were erected at a single site near Goldendale, Washington to evaluate interactive and turbine/grid effects of multiple, identical, turbines integrated into a utility network. The first rotation of a Mod-2 turbine occurred in November 1980. The cluster was dedicated in May 1981 and final acceptance occurred in October 1982.

In November 1982, a generic failure of the low speed shafts in the Mod-2 turbines occurred necessitating redesign of the shaft (discussed later). In April 1985 the entire cluster was returned to service.

To date the Mod-2 cluster has generated 13.3 GWh while operating for 11 064 hr. Specific synchronous hours and energy produced by each turbine, as well as maximum periods of continuous/simultaneous operations, are noted in table I.

PROBLEM AREAS

Two major incidents have occurred during the course of this project: (1) overspeed failure on Turbine No. 1 and (2) low speed shaft failure on turbine 1.

Overspeed Failure

On June 8, 1981, a planned emergency shutdown test of Turbine No. 1 was initiated. A failure occurred in the Emergency Shutdown System (ESS) that can be summarized as follows:

1. While the machine was operating at a rated power of 2500 MW, a failure shutdown was initiated by commanding the emergency shutdown system through the emergency stop button located on the manual control panel at the base of the tower.

2. Both blade tips failed to feather, but the generator was, as designed, automatically disconnected from the utility grid removing all load from the drive train.

3. The rotor accelerated from the operating speed of 17.5 to 29.5 rpm resulting in damage to the drive train.

4. Both blades started emergency feather at T + 28 sec, shutting the machine down safely without major structural damage.

The NASA Failure Review Committee concluded the cause of failure to be that both start-stop valves experienced silting due to contaminated hydraulic fluid (or one was presilted) during the 4-hr run. Consequently, the valves failed to operate when the 120 V were removed and prevented the feather valves from supplying the emergency accumulator hydraulic oil to the blade tip actuators. No evidence was found to show that the electrical system failed to interrupt the command circuit.

Corrective actions were incorporated in all of the turbines with Turbine No. 2 and Turbine No. 3 returned to service in October-November 1981. Design changes included the continued connection of the generator until low generator output power occurs, the addition of yet another independently sensed emergency feather control (IESS), and keeping the servo valves active in the system to provide redundancy to the IESS.

Low Speed Shaft Failure

On November 12, 1982, Turbine No. 1 shut itself down during normal operation, while producing approximately 2.0 MW of power in gusty winds averaging 18 mph.

Subsequent investigation revealed a large crack in the low speed shaft that supports the turbine rotor. The NASA Failure Review Committee concluded the failure to be low-stress, high-cycle fatigue of the low speed shaft. Fatigue cracks in the shaft started at stress concentrations around multiple holes and progressed from hole to hole during normal operation. The cause of failure was inadequate design of the low-speed shaft and of the hydraulic tubing/electrical conduit hole details in the shaft resulting in a negative design margin of safety. A contributing cause was the presence of working fasteners in the mounting holes.

The primary recommendation for returning to remote, unattended, automatic operation was to redesign and retrofit the low-speed shafts on all turbines. However, limited-attended operations prior to retrofit were conducted with minor hardware reworks and frequent inspections. The redesigned low speed shaft with equipment modules is shown in figure 2.

Other Operational Problem Areas

During the operation of this experimental cluster, other minor problem areas have been encountered, as noted in table II. As researchers know, this is not uncommon with experimental hardware. Many valuable lessons are learned with builders of the next generation of turbines using the solutions. The fixes noted in table II have been incorporated on the Mod-2 turbines and have also been factored into the design of the Mod-5 wind turbine - the third generation of large, multimegawatt wind turbines.

RESEARCH AND TECHNOLOGHY DEVELOPMENT TESTING

As previously noted, NASA researchers installed three Mod-2 turbines at a single site to test and evaluate interactive and machine/grid effects of multiple, identical turbines integrated into a utility network. Specifically, this research testing has been structured initially to emphasize three test project areas.

1. Performance
2. Environment
3. Wind Data/Wake Effects

These tests are being conducted under the auspices of a Test Project Review Board with lead participation from Boeing Aerospace Co. (BAC), Bonneville Power Administration (BPA), Pacific Northwest Laboratory (PNL), Solar Energy Research Institute (SERI), described in reference 2.

To make the most of the research opportunities afforded by the Mod-2 turbines and site, NASA designers assigned the turbines separate primary test functions, while the turbines were still working as part of an energy producing, multi-unit cluster. As shown in figure 3, Turbines No. 1 and 3 are dedicated to full, continuous operation in available winds with a goal of achieving 5000 to 10 000 hr of operating time on either or both turbines in CY 85/86. Turbine No. 2 is the machine where advanced research will be first tested to develop large wind turbine technology further. Hence, configuration changes will be made only on this turbine.

Performance

Baseline. - The power variation with wind speed for Unit No. 2 is shown in figure 4. This is typical for the three Mod-2 units at Goldendale, Washington. The power shown in figure 4 was measured at the generator output terminals and the wind speed was measured at the 195-ft-level of the BPA meterological tower on the site.

Computer analysis reduced the data from the magnetic tape recordings. Each data point represents an average value for a 10-min interval, selected by searching the real time, brush recorder charts from the site. For operation below rated power, the pitch angle throughout the entire time interval was either +3 or +5°. To minimize data scatter, NASA and Boeing researchers selected intervals where the wind was reasonably smooth. The total variation in power during any time interval was usually less than 500 kW.

Enhancement. - In the Summer of 1983, researchers conducted a power-conversion enhancement research test using vortex generators on the blades. These small tabs, bonded to the rotor as shown in figure 5, are quite similar to those used on aircraft wings to improve performance. As summarized by reference 3 and shown in figure 6, the performance enhancement test results indicated that the addition of vortex generators (VGs) to the Mod-2 rotor blades resulted in a significant increase in power and predicted annual energy capture. Application of VGs to the fixed portion of the rotor reduced the wind speed at which rated power is reached from about 16 to 13.8 m/sec as shown in figure (6) and increased projected annual energy capture by 11 percent. The addition of VGs out to the rotor tip reduced rate wind speed an additional 0.5 m/sec and increased projected annual energy capture an additional nine percent. This performance increase came at little cost in increased cyclic loads. No significant difference in cyclic loads was found between the two VG configurations tested. A slight increase in blade cyclic loads in below rated power winds was found after the addition of VGs. However, because the addition of VGs also results in a decrease in peak steady loading, the overall effect of adding VGs is probably to increase blade fatigue life. Long term operation of Turbine No. 3 (full VG configuration operation) compared to similar operation of Turbine No. 1 (no VGs) during CY 85/86 will provide the experimental versus predicted energy capture comparisons.

Environmental (Acoustics/Television Interference). - SERI conducted a 6-week series of tests to measure the acoustic noise emission and effects during single and multiple wind turbine operations. The tests included the use of noise measuring instrumentation on the ground, on the wind turbine tower, and airborne, using a balloon. Sufficient data were obtained to show that the sound is broadband, rather than impulsive, in nature. Within the cluster, the sound level is approximately that of a moderately busy street (60 dBA); it decreases to a residential street level (53 dBA) about a quarter mile downwind. Personal observations corroborate that the sound cannot be perceived 16 rotor diameters (4800 ft) downwind in a 15 to 25 mph wind.

SERI, the UniversitY of Michigan, and BPA collaborated in measurements of television interference from the Mod-2 wind turbine system. Specific measurements were taken to determine (1) Received field strength, (2) Static or Blade Scattering, (3) Dynamic (Operating) Blade Scattering. Although the signal strength is considered to be very weak at Goodnoe Hills, background noise interference was judged to be acceptable. Equivalent scattering was found to be very close to model predictions.

Wind data/wake effects. - The plot plan was specifically configured to support tests on wake and energy capture degradation caused by spacing. As shown in figure 7, the three turbines are on a triangular grid of 1500 ft (5D), (2100 ft) 7D, and 3000 ft (10D) spacing.

Battelle Pacific Northwest Labs coordinated wake testing being performed by Flow Industries, AeroVironment, and Oregon State University. Qualitative and quantitative data were obtained using smoke generators and balloon/kitesupported instrumentation (refs. 4 and 5). Although wakes were observed by all techniques, correlation of the results was difficult due to terrain effects. To date, no load effects have been noted on downwind turbines at spacings of 7-10 rotor diameters. This year NASA researchers are placing primary. emphasis on two follow-up studies: (1) establishing terrain effects on wakes and wake characteristics for 2-5 rotor diameters; (2) determine the degradation, if any, in energy capture at these respective spacings.

The prevailing winds flow from Turbine WT 2 toward WT 1. The design mean wind (Weibull) distribution is compared to the measured Goodnoe Hills distribution in figure 8. The latter was measured over approximately an 18-month interval. It is obvious that the design distribution is more severe in that a larger percentage of time is spent at the higher wind speeds. Hence, the site winds are forgiving regarding turbine life but unfulfilling with regards to annual energy capture.

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4. Baker, R.W.; and Walker, S.N.: Wake Studies at the Goodnoe Hills Mod-2 Site. DOE/BP-182, Oct. 1982.

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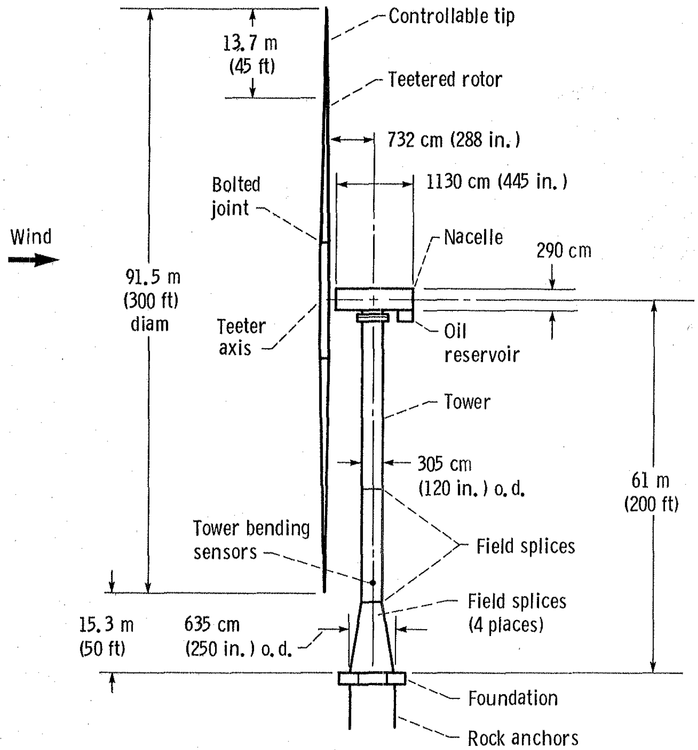
TABLE I. -GOODNOE HILLS OPERATING SUMMARY (AS OF DEC. 31, 1985)

	Turbine 1	Turbine 2	Turbine 3	Cluster
Hours of operation	3276	3165	4623	11 064
Hours of generation	3061	2964	4296	10 321
Energy generated, MWh	3871	3821	5687	13 379
Average power, kW	1265	1289	1324	1 296
Maximum continuous run time, hr	51	59	36	------
Maximum simultaneous run time, hr, for -				
Two units	37	37	----	------
Three units	18	18	18	------

TABLE II. - SUMMARY OF SOME MOD-2 OPERATIONAL PROBLEM AREAS AND FIXES

Problem	Fix
Emergency shutdown system failure	System design changes; Improved pitch hydraulic system components
Low speed shaft failure	Improved shaft design
Control instability	Revised pitch control law to preclude operation beyond maximum rotor Cp
Pitch actuator seal	Replaced Buna-N seals with improved Viton seals
Pitch hydraulic system burst disk	Replaced disk with 300 psi relief valve
Low speed shaft bearing seal	Improved seal
Low gearbox oil pressure	Revised indicator system, adjusted pressure regulator
Worn generator bearings	Installed pressurized lubrication system
Tester brake caliper failure	Removed tester brake (found not required)
Low speed shaft slip ring shorting	Modified brush block to prevent graphite dust buildup
LSS slip ring brush wear	Reduced brush pressure and installed new material
Bolt failure at blade field splice joint	Shimmed flange and joint
Control system over-sensitive to gearbox oil level	Installed 1 sec time delay
Yaw gearbox case failure	Reduced motor torque



Rated power, kW	2500
Rotor diameter, m (ft)	91.5 (300)
Rotor type	Teetered - tip control
Rotor orientation	Upwind - 2.5^{o} tilt
Rotor airfoil	NACA 230XX
Rated wind at hub, m/sec (mph)	12.5 (27.5)
Cut-off wind speed at hub, m/sec (mph)	20 (45)
Rotor tip speed, m/sec (ft/sec)	83.9 (275)
Rotor speed, rpm	17.5
Generator speed, rpm	1800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height, m (ft)	61 (200)
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient (max.)	0.382

Figure 1. - Features and dimensions of Mod-2 wind turbine.

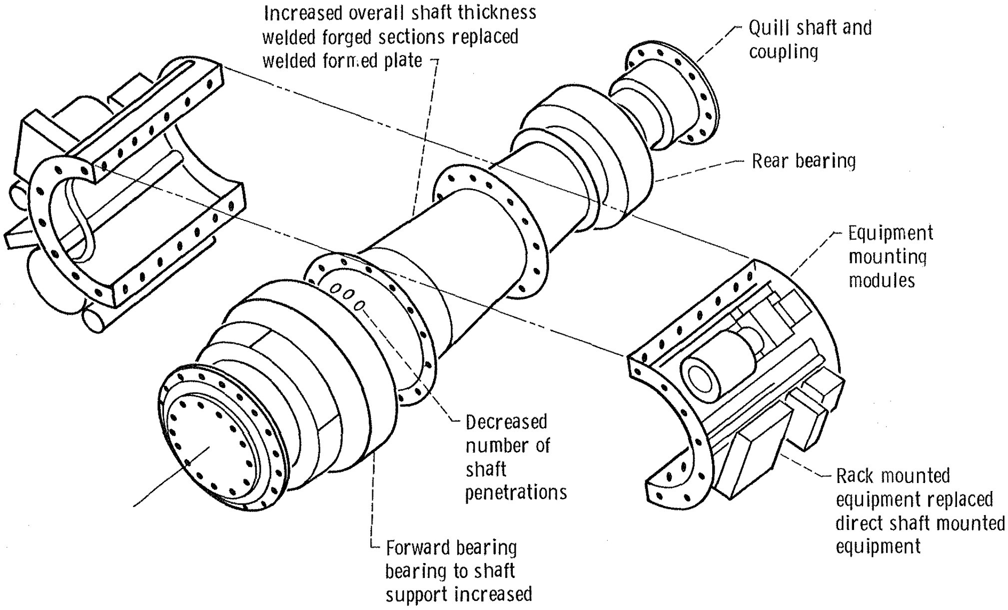


Figure 2. - Mod-2 redesigned low speed shaft.

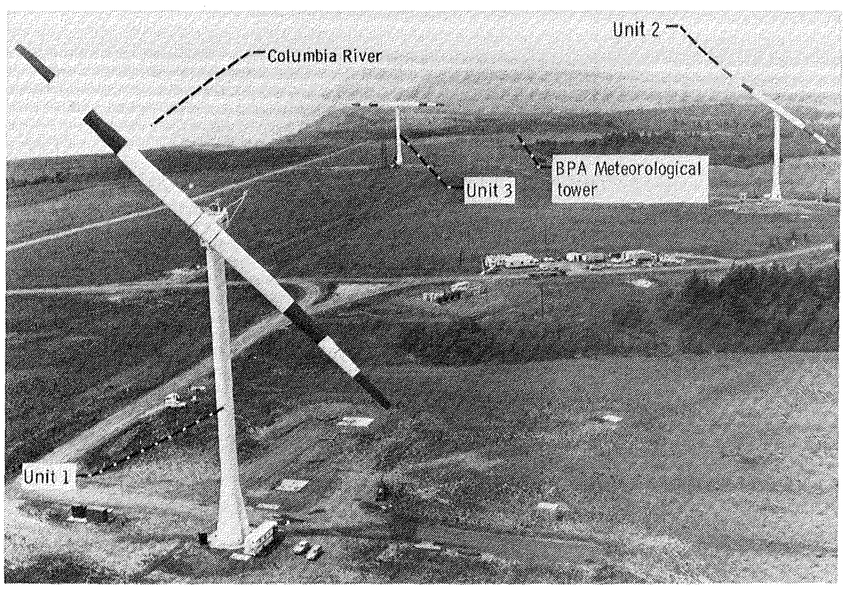


Figure 3. - Mod-2 wind turbine cluster test site at Goldendale, Washington.

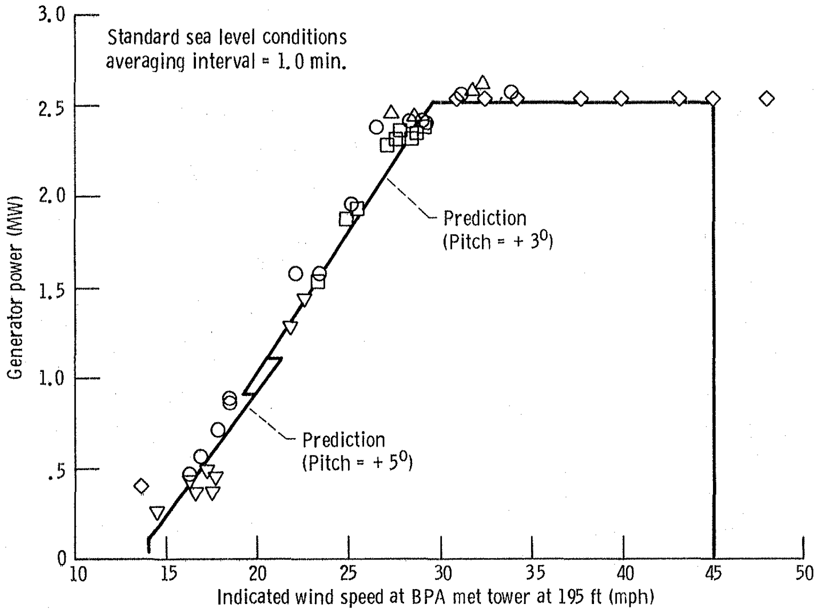


Figure 4. - Performance curve for Mod-2 (turbine 2).

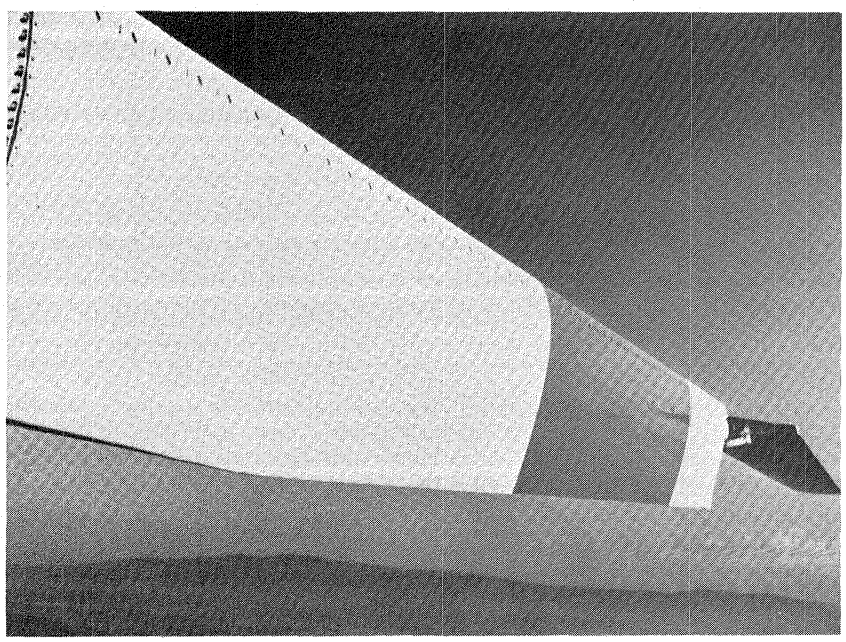


Figure 5. - Vortex generators.

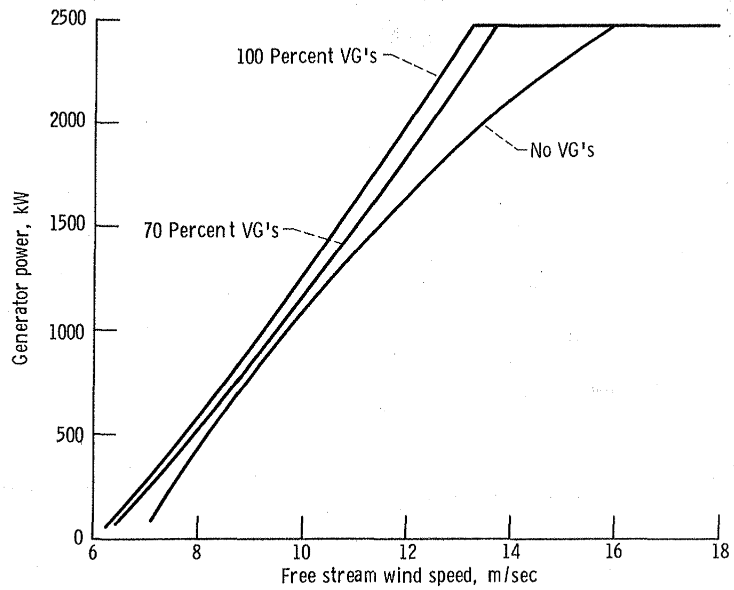
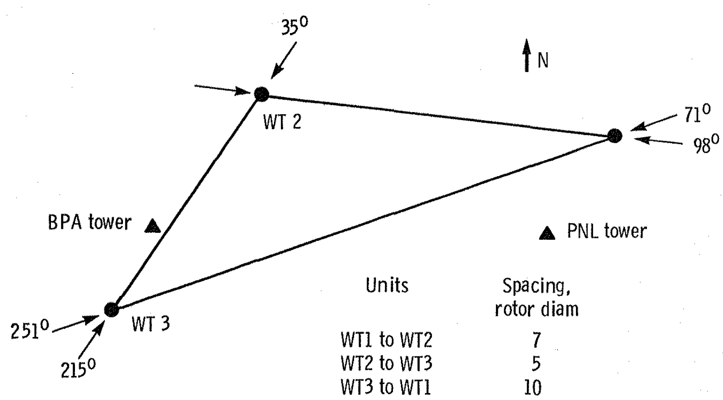


Figure 6. - Comparison of performance data curve fits from vortex generator tests. Site standard conditions: air density, = 1.127 kg/m^3.



Units	Spacing, rotor diam
WT1 to WT2	7
WT2 to WT3	5
WT3 to WT1	10

Figure 7. - Mod-2 cluster layout.

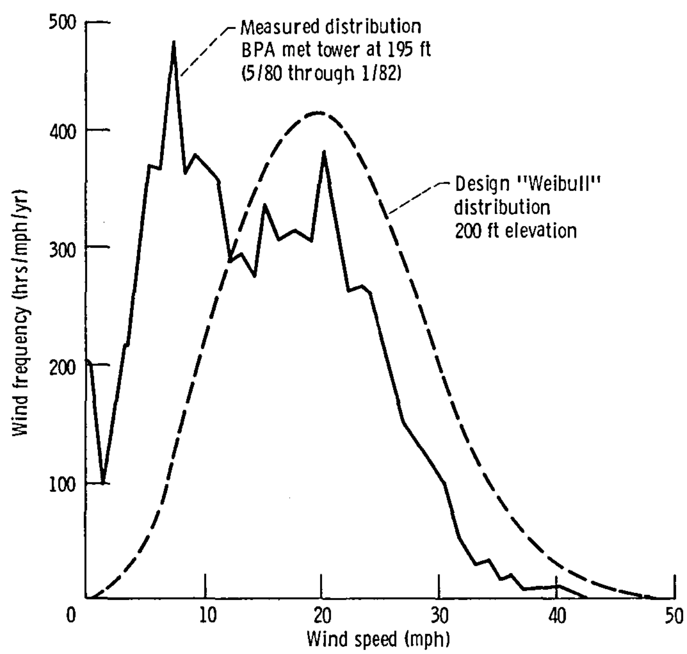


Figure 8. - Mod-2 wind speed frequency distribution.

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16. Abstract
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