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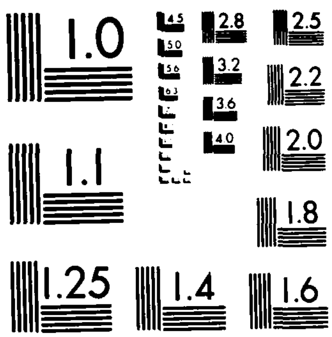

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AD-A174 887

THE MAINTENANCE AND OPERATION OF A SMALL WIND GENERATOR IN THE MARINE ENVIRONMENT

WARREN HEERLEIN

U.S. COAST GUARD RESEARCH AND DEVELOPMENT CENTER
AVERY POINT, GROTON, CONNECTICUT 06340-6096

FINAL REPORT
July 1986

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16. Abstract

This report discusses the maintenance and operation of a wind turbine generator that has been undergoing tests as a source of energy for remote Coast Guard lighthouses. The report documents both the effects of operating the wind machine in the marine environment and the maintenance that it required. Design parameters and performance records of the generator are also evaluated.

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METRIC CONVERSION FACTORS

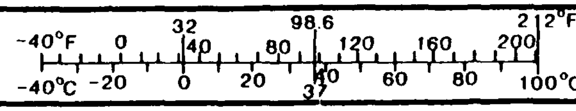
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13 10 286

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

Mission and History

This report discusses the maintenance and operation of a wind turbine generator (WTG) that has been undergoing tests as a source of energy for remote lighthouses. The wind machine, according to preliminary design (Reference 1), would function as one of several power sources (diesel, solar, fuel cell, etc.) incorporated into a hybrid system. It is the intent of this report to document both the effects of the marine environment on this WTG and the maintenance that it required. Wind machine performance and site-selection guidelines will also be addressed.

In 1980, the United States Coast Guard (USCG) contracted with the Applied Physics Laboratory (APL) of the John Hopkins University to conduct a feasibility study for powering remote lighthouses with alternative energy systems. A mainframe computer model was developed using the APL language. The results (Reference 1) indicated that at certain locations wind turbines would be economically feasible as an electrical power source contained within a hybrid system. Several assumptions concerning the wind machine were introduced as parameters into the computer program. Among these assumptions were: (1) maintenance allotted for the wind machine would be restricted to one visit per year, and (2) wind velocity data for powering the turbine would be grouped by latitude (Northern, Southern, and Alaskan areas, etc.) rather than be site specific. A description of this effort and its results are contained in a final report prepared for the Coast Guard (Reference 1).

To validate these results it was decided to construct a prototype hybrid energy system employing a wind generator. Requirements of the WTG were defined by priority to: (1) have the ability to operate reliably and unattended for at least one year in a harsh marine environment, and (2) produce DC power in the range of 2 kw to 4 kw for battery charging. The North Wind Power Company's (NWPCo) model HR2 was selected jointly by Coast Guard and APL personnel. It appeared to be the best commercially available candidate after surviving the Department of Energy's "Rocky Flats" test program (Reference 2).

The HR2 was installed at Cape Henry Light, Virginia Beach, Virginia in October of 1981. From October of 1981 to January of 1983 the HR2 was operated while connected in parallel to a customized dummy load center. APL was responsible for maintenance and data collection during this period. The objectives of testing were to gain real-time operating experience in the type of marine environment normally found at Coast Guard lighthouses and to better understand wind machine performance and control requirements (Reference 3).

In 1984 the HR2 was configured with a diesel generator set, lead acid storage batteries, and controls to make up the prototype hybrid power system. This system became the operational power source for Cape Henry Light in September 1984. At this time, the USCG Research and Development Center (R&D Center), Avery Point, Groton, Connecticut assumed the responsibilities for maintenance and data collection on the entire system. This prototype operated until mid-May 1985.

The WTG was later moved and reinstalled at the R&D Center in September 1985 following termination of the Cape Henry portion of testing. The machine is currently operating there at the time of this writing as part of a test being conducted on a reconfigured cycle/charge system.

HR2 DESCRIPTION

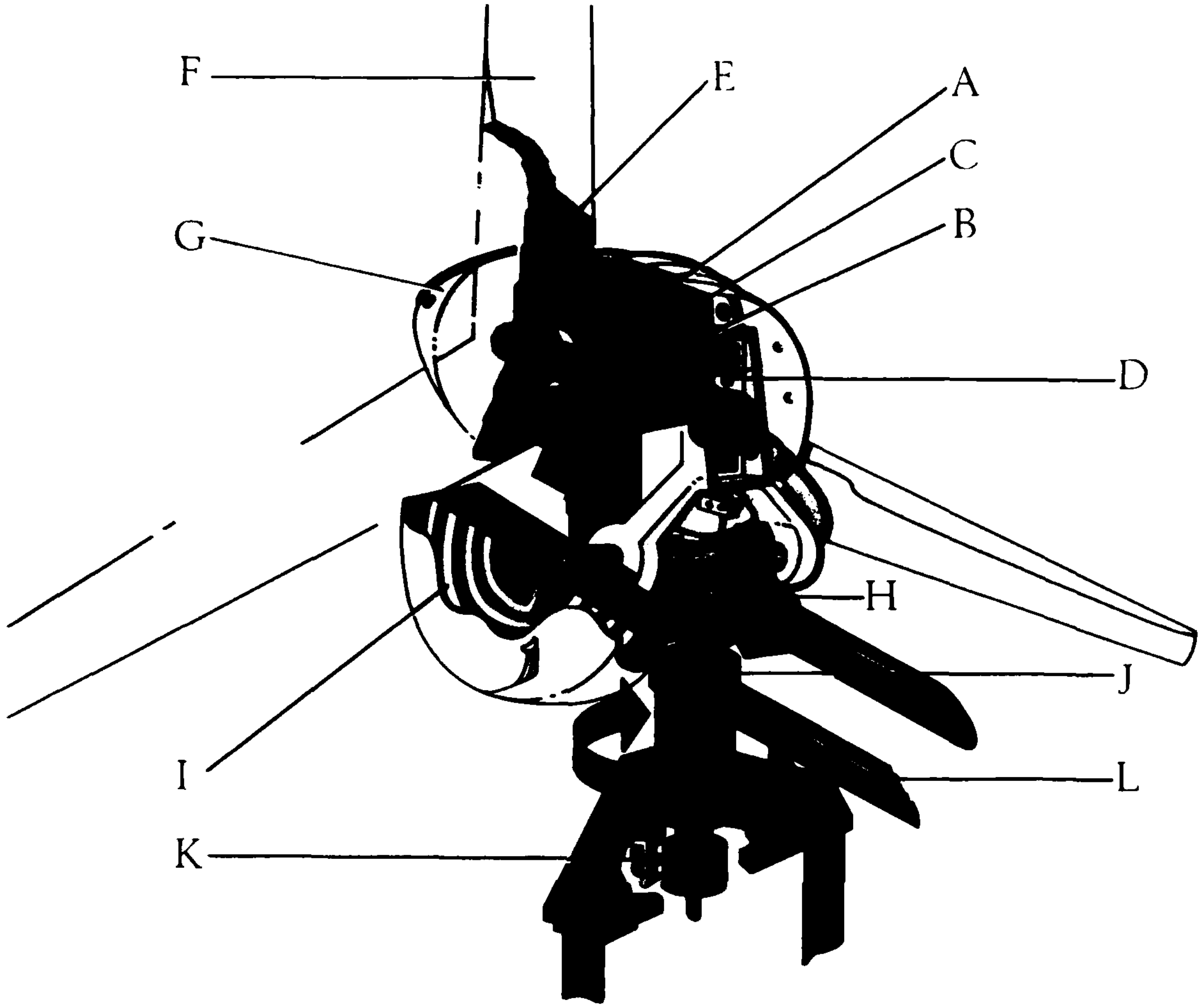
General Operation

The HR2 is a horizontal axis, upwind oriented, three bladed wind machine. It is equipped with a direct drive system that allows the kinetic force captured by the propeller to be converted directly into rotational force driving the main shaft. This shaft spins a magnetic field within the stationary power windings of the alternator. The rotor and stator are physically comprised of wire wound coils encased by steel alloy castings that have magnetic retention qualities. These two components make up a three phase alternator that produces AC voltage. The three phases of AC voltage are then fed through a silicon diode full-wave bridge rectifier and delivered to the load as direct current (DC). The HR2 is configured to produce 2200 Watts at a shaft speed of 250 RPM, or equivalently at a wind speed of 20 mph (see

Specifications in Appendix A). The HR2 can be viewed as having three sub-components: the blade and hub assembly, the alternator and overspeed control system, and the saddle/yaw control system, (see Figure 1).

The three blades are constructed of a birch wood laminate and offer a 16.4 foot (5 m) diameter wind capture area. They are machined to an aerodynamic taper and twist and then sealed and painted. The blades, although constructed separately, are considered as a system. For reasons of centrifugal force, it is necessary to balance the blades for a minimum of destructive vibration. Individual blades of a group are weighed and balanced. Lead weights are then screwed to them to account for mass and moment differences. Aircraft type blade tape is applied to the tips and leading edges to prevent erosion and cracking due to frictional wear. The blades are then fixed to a welded steel hub (sprocket) with 1/2 inch zinc-plated steel hardware. The completed sprocket assembly attaches to the main shaft and is secured with a 7/8 inch hub nut.

The alternator (described above) and the overspeed control system make up the second sub-component. It is understood that excessive and destructive shaft RPM can be obtained in high winds, so to prevent overstressing of the electrical and mechanical components it is necessary to use overspeed control in all wind machines. The HR2 accomplishes this with a unique system called a VARCS (Variable Axis Rotor Control), (see Figure 2). The HR2 alternator and blade/hub system are allowed to tilt out of a near-vertical plane about a shaft and bearing mechanism. The VARCS is a torsion spring and hinge mechanism that acts against the lifting dynamics of the spinning blades. As high winds or gusts tilt the alternator about the hinge, the VARCS's spring opposes this force and regulates the blades angle of attack into the wind; the propeller's RPM drop when tilted because of the feathering action. If the wind subsides, the force of the VARCS spring drives the alternator assembly down and presents the blades back into the wind. A hydraulic damper regulates the rate at which the HR2 returns back into normal operating position. Under loaded conditions the HR2 should not exceed a maximum of approximately 300 RPM; 400 RPM is the expected maximum with no load, (Reference 4).



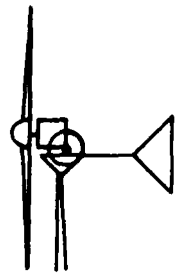
Cutaway view of the HR2, illustrating the Generator, Turbine and Saddle Assemblies, and the VARCS:

A. Stator
B. Lundel rotor
C. Field coil
D. Full wave solid state bridge
E. Rotor
F. Blade
G. Nose cone
H. Saddle
I. VARCS spring
J. Yaw bearing
K. Slip rings & collector brushes
L. Tail

FIGURE 1. CUTAWAY VIEW OF THE HR2

The VARCS spring and the pitch-hinge mechanism are matched with the characteristics of the rotor and alternator to achieve the following functional modes:

STANDARD OPERATIONAL MODE



Pitch angle at start-up: 9.5° to permit safe tower clearance for blade deflection

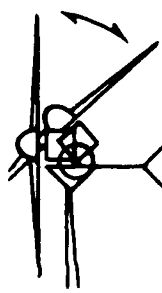
Cut-in wind speed: 8 mph

Max wind speed at this mode: 21 mph

Max power output at this mode: 2200 watts

Max rpm at this mode: 250 rpm (loaded), 400 rpm (no load)

OVERSPEED CONTROL MODE

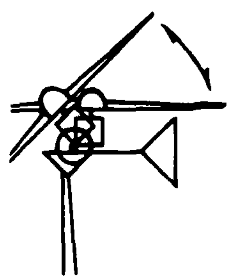


Control initiated: 21 mph (loaded), 17 mph (no load)

Max power output at this mode: 2500 watts

Max rpm at this mode: 300 rpm (loaded), 400 rpm (no load)

HIGH WIND SHUTDOWN MODE



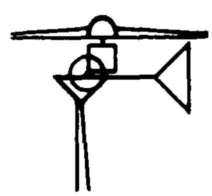
Windspeed: 105 mph and above

Pitch angle shutdown: 90° for minimal rotor loading

Power and rpm's approach 0

Spring tension resets rotor on horizontal axis as gusts subside

SERVICE & MAINTENANCE MODE



Manual shutdown from tower base

FIGURE 2. NORTH WIND PROMOTION ON VARCS PROCESS

The third sub-component is the saddle/yaw control system. The HR2's base, or saddle, contains a large bearing and tail/vane assembly that allows the generator to rotate and stay directed into the wind. The saddle provides the pivot axis for the VARCS hinge, (see Figure 3). Also included in this piece is the electrical power connection through a brush and ring system that allows unlimited turning of the machine without the limit stops necessary with directly connected wires.

Design Critique

The fixed blade pitch and wood laminate construction offered with the HR2 is an excellent choice for a remote application. Optimum power collection cannot be accomplished without varying blade pitch, but the benefits of having fewer mechanical parts far outweighs the added energy that may be collected. Wood composite blades also offer the highest strength factors (bend, flex, rupture) (Reference 5) when compared to fiberglass or metal alloy blades. The three blade versus two blade design reduces shaft vibration, and also delivers higher torque to the shaft for a lower speed cut-in. It appears that the North Wind Power Company has a firm technical grasp on blade aerodynamics and construction, as evidenced by the low vibration and zero catastrophic failures observed over the five year test period. Other demonstration projects have shown blade design to be a critical area and cause for failures. (Reference 5)

The alternator and overspeed control are also evidence of strong and innovative engineering. The simplicity offered with the HR2 of having direct drive (as opposed to a geared transmission) once again supports a remote application with a minimum of moving parts. Bearings for support of the main shaft and yaw are still a requirement and are a natural weak point since bearings have reduced life in the marine environment. The HR2 requires annual lubrication of the main shaft and yaw bearings, (see Appendix D). Although the North Wind Power Company uses oversized bearings (Timpkin brand-roller type), and they were properly maintained, evidence of considerable wear on the main shaft's front bearing was noted during a scheduled overhaul in September 1985. Furthermore, according to the Navy's small wind energy conversion system's (SWECS) experience, roller bearings of

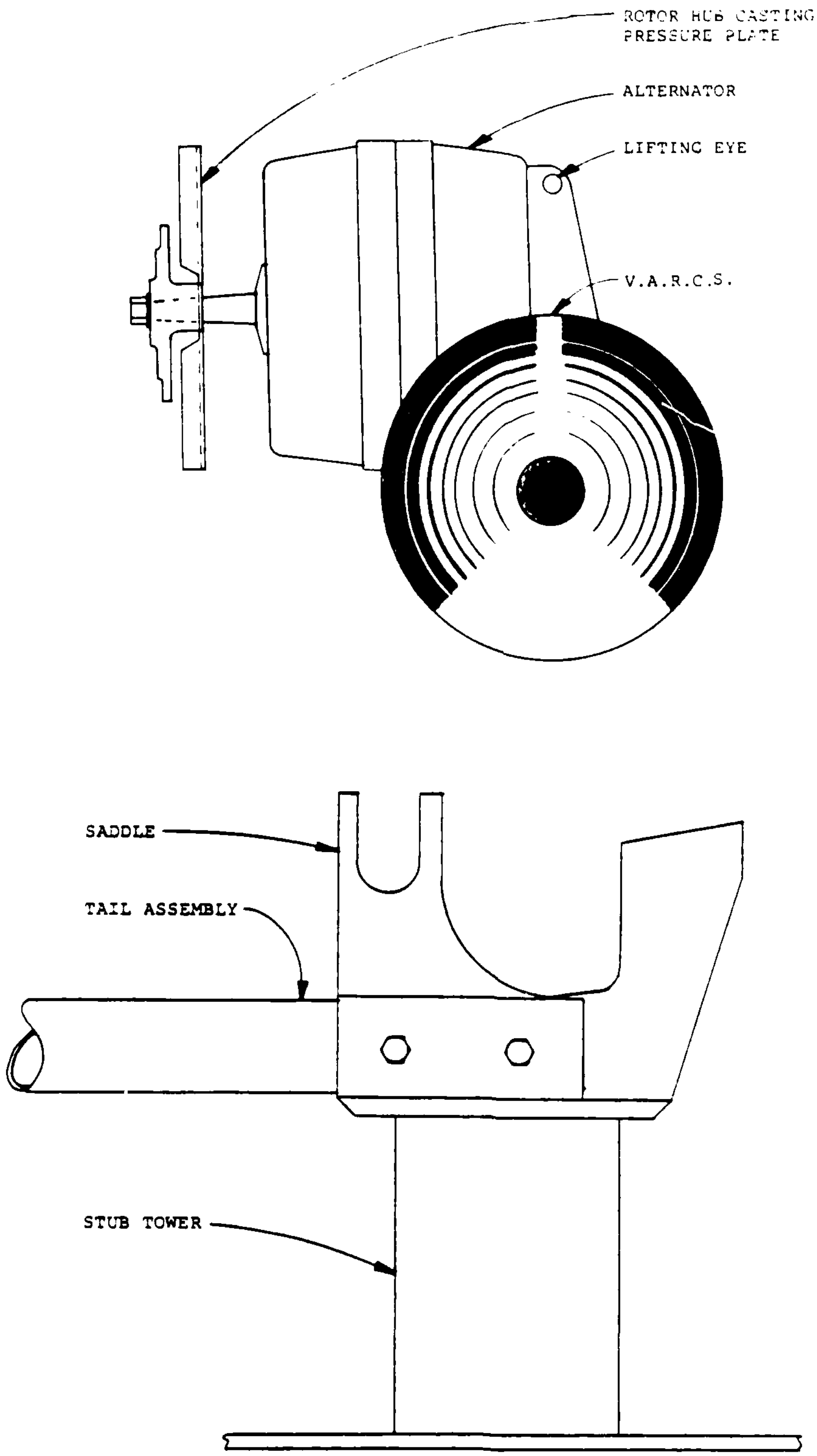


FIGURE 3. HR2 ASSEMBLIES

the type used in the HR2 will fail after about 50,000 hours or after approximately five years. (Reference 5)

The alternator design with a self-exciting rotor offers a standard common to the electric motor industry. The field coil rotor allows for voltage regulation through field current control. A drawback to having the main shaft as the horizontal axis is the need to translate the power through brushes and rings. AC voltage also requires rectification to produce DC. The alternative is to employ a DC generator, but it too requires brushes and does not lend itself to easy voltage regulation which is always necessary in battery charging applications. To eliminate the yaw brush and slip ring assembly it would be necessary to place the alternator on the vertical axis and use gears to redirect the rotating forces.

The VARCS overspeed control is a rugged and dependable control mechanism. Again, it can be shown that at times this design could limit energy collection (by its inherent reaction time being dependent on spring tension and not instantaneous wind conditions). However, for a remote application it offers a strong and positive answer to overspeed design demands. An added benefit to the tilt-back design associated with the VARCS is the ability to run a cable to the ground for manual stowing of the generator when maintenance or repairs are required at the tower's top. Alternative options for overspeed control can range from hydraulic dampers to braking systems, all requiring more parts susceptible to wear and failure.

The last design component for the HR2 is the saddle/yaw control system. It is commonly believed that tails alone are not the best method for directing a wind generator, (Reference 5). Tails are too responsive to sudden wind gusts and this sudden gyroscoping can exert failure-magnitude stresses on the blade and bearing systems. Fortunately, the Coast Guard has not experienced this type of failure. Furthermore, a single large bearing is responsible for turning. Failure of this bearing could cause catastrophic failure, although in the four year's experience at Cape Henry there were no failures of this bearing. Design alternatives for yaw control are to switch to the downwind style machine, however tower interference brings into play different and significant operating problems.

Miscellaneous: (Towers, Regulators, Reverse Current Diodes)

Towers are required to raise wind generators to safe and efficient operating heights. Tower selection is crucial in several areas: engineering to the generator's static and dynamic loads, cost, space and installation requirements, and not least of all, the ease of maintenance accessibility to the wind machine. Towers come in several materials and designs. Two generic types are classified as free-standing or guyed. Guyed towers require a large land area to secure the guy wires. Either type requires significant footings or ballast to anchor the structure. This can pose serious implications in a remote site where concrete and other construction materials may not be readily available. For example, both Coast Guard installations (Virginia and Connecticut) utilized a steel reinforced concrete foundation approximately 400 cubic feet in volume. The tower selected for the Coast Guard installation was a Unarco-Rohn SSV Class-II 60 foot free-standing tower, organized into three twenty foot sections. The tower is a galvanized steel pipe and angle iron trussed unit. It may be assembled piece by piece in place or constructed on the ground and lifted by crane onto its foundation. In both cases the Coast Guard utilized a crane for tower installation. Hinged towers have been successfully used in other programs (Reference 5), but the Coast Guard has no current experience with these units. It should be noted that the tower and generator installation will likely be beyond the scope of the Coast Guard's expertise and would require contracted services. Furthermore, specific training in tower work and safety procedures would have to be initiated before Coast Guard personnel could proceed with maintenance. Another concern which must be more fully understood is the radio wave interference caused by towers. Testing at the Cape Henry site revealed no problems with radio receivers or transmitters, (Reference 3).

The voltage regulator supplied with the HR2 is electronic in design. Its purpose is to protect connected loads from overvoltage. The HR2's rectified alternator voltage is fully impressed across the field coil during periods of low shaft speed. The residual magnetism in the rotor castings creates a magnetic field and it produces an electromotive force (emf) in the stator windings when the rotor turns. Since the field is shunt connected to the output terminals at this time, the field coil current also increases. As RPM increase, the alternator voltage and the field coil current increase in symbiotic fashion; when the power supply on the voltage regulator card comes up to 5 VDC, the control transistors become energized and pulse width modulation begins. The frequency of the field voltage modulation is one (1) megahertz. The pulse width, the part of this period when the field circuit is energized, will vary with the loading on and the RPM of the alternator so as to maintain the voltage set point. The regulator's adjustable maximum voltage setting offers flexibility in battery charging. Pulse width modulation is an electric motor industry standard for voltage control with alternators.

The reverse current diode (RCD) provided with the HR2 is a GE model #A70PB(1N3296), (see Figure 4). It is rated at 150 amps and its peak reverse voltage (PRV) is rated for 1400 volts. The RCD is necessary for a battery charging application to prevent reverse current flow from the batteries to the HR2.

Manufacturer's Specifications

See Appendix A.

PERFORMANCE EXPERIENCE

Performance Data

Extensive data has been collected on the HR2's performance.

The basic result of the experience reported here is that when the HR2 is operating properly it can produce useable quantities of energy, but the range of wind velocities that will produce this energy differs dramatically from the initial assumptions used for design and this mismatch has limited the utility of the machine. The machine was apparently conservatively rated as its peak power output exceeds the manufacturer's specifications, (see Appendix A). The manufacturer's data indicates peak power operation of the HR2 corresponding to a wind speed of 35 mph and having production distributed over the speeds of 7 to 90 mph. APL and USCG data (see Figure 5) show a very different distribution, revealing little or no power generated below wind speeds of 10 mph or over 30 mph.

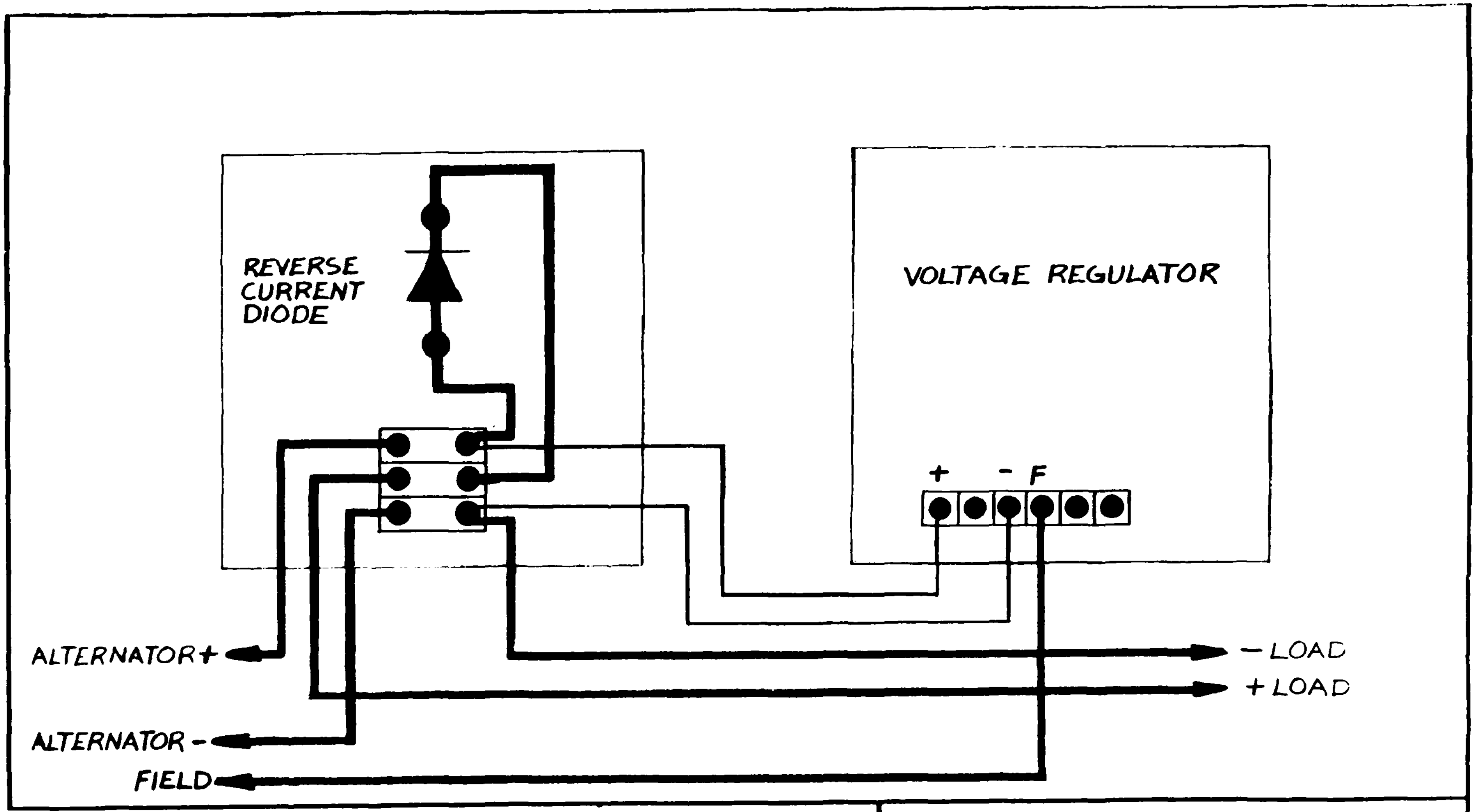


FIGURE 4. VOLTAGE REGULATOR AND RCD WIRING SCHEMATIC

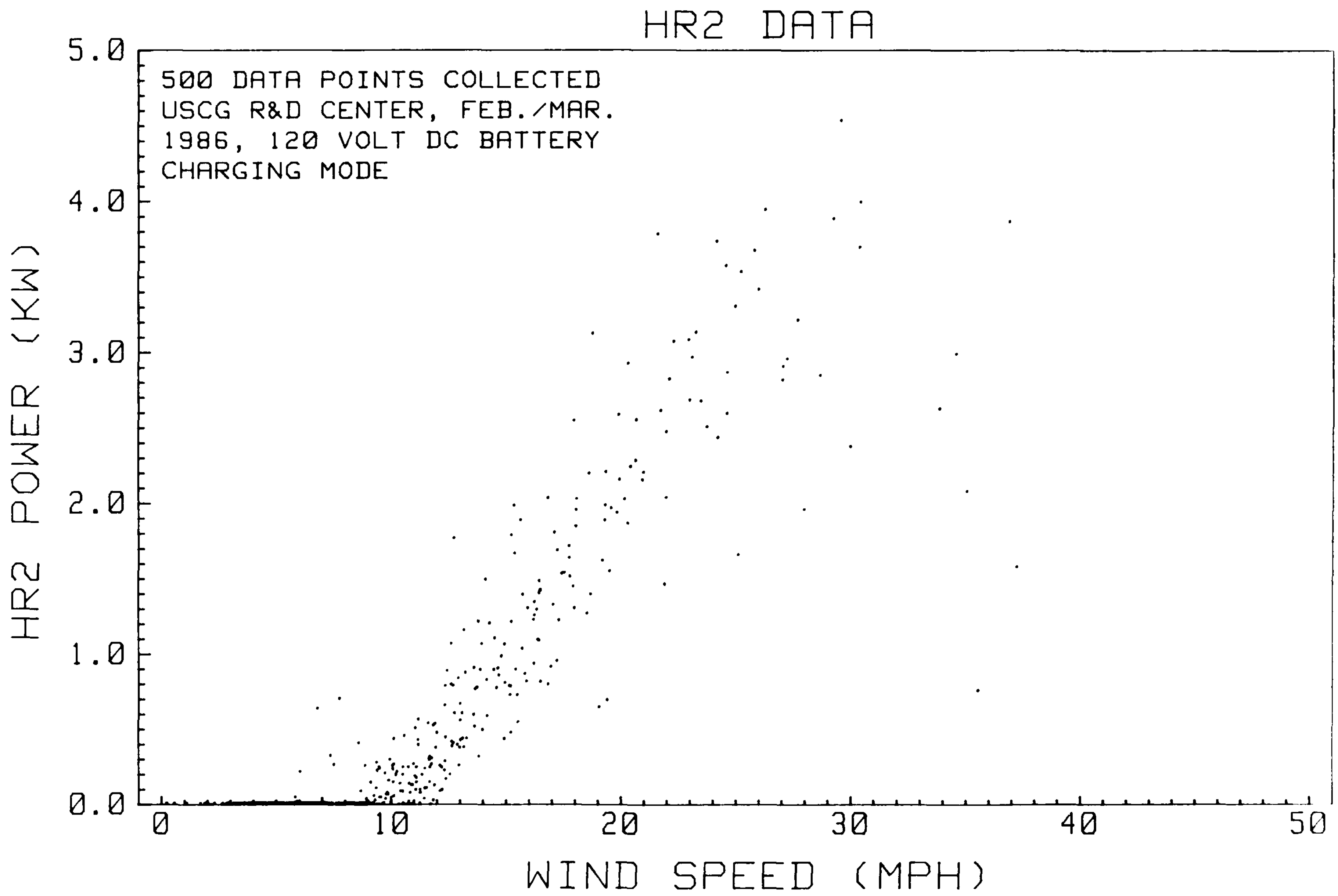


FIGURE 5. HR2 POWER DISTRIBUTION WITH WIND SPEED

Of much more importance is the averaged wind velocity. If the mean wind speed fits into this 10 to 30 mph window or if site-specific data shows a favorable seasonal frequency distribution in this range, it is possible for the HR2 to supply significant energy. A common sense approach indicates that wind speeds in excess of 30 mph are usually of short duration and frequency (gusts) and even possibly destructive. In fact, it appears the VARCS spring actually cuts out power production around 40 mph instead of the rated 105 mph likely to the benefit of the HR2. Wind speed data for Cape Henry was analyzed and shown to have a Rayleigh distribution around a mean of 8 mph with little seasonal variation (Reference 6). These data would suggest this site to be marginal for installation of a wind machine. As a counter example, information gathered by the Thirteenth Coast Guard District (Reference 7) shows an annual wind speed of 15 mph at Cape Flattery Light, Tatoosh Island, Washington. This would be an example of a site fitting into the projected power window. A major cause for not being able to model each individual lighthouse in question is the lack of organized data describing the wind regime at each site.

Actual power produced by the HR2 seems to follow closely the ratings of the machine when loaded to conditions required for peak power production. As an example, data points can be found on Figure 5 that correspond to the manufacturer's mean power rating at 10, 12, and 16 mph. They are respectively 500, 760, and 1150 watts.

A compounding circumstance in the analysis of power produced is the application of the wind generator as a battery charger. If a battery is at a high state of charge (i.e. high voltage) then this battery presents a high resistance to the wind generator. (A reverse current diode prevents the battery from discharging into the wind machine.) Since the battery's voltage must be exceeded by the HR2 before charging current can flow to the battery, power from the HR2 was sometimes less than it might be expected to have been by reason of wind speed alone. To illustrate the above conclusions, recent data records from the HR2 are shown in Figures 6 through 9. Figure 6 shows wind speed samples collected at 15 minute intervals overlayed by a moving average of the wind speed. The final average wind speed of 9.1 mph for the

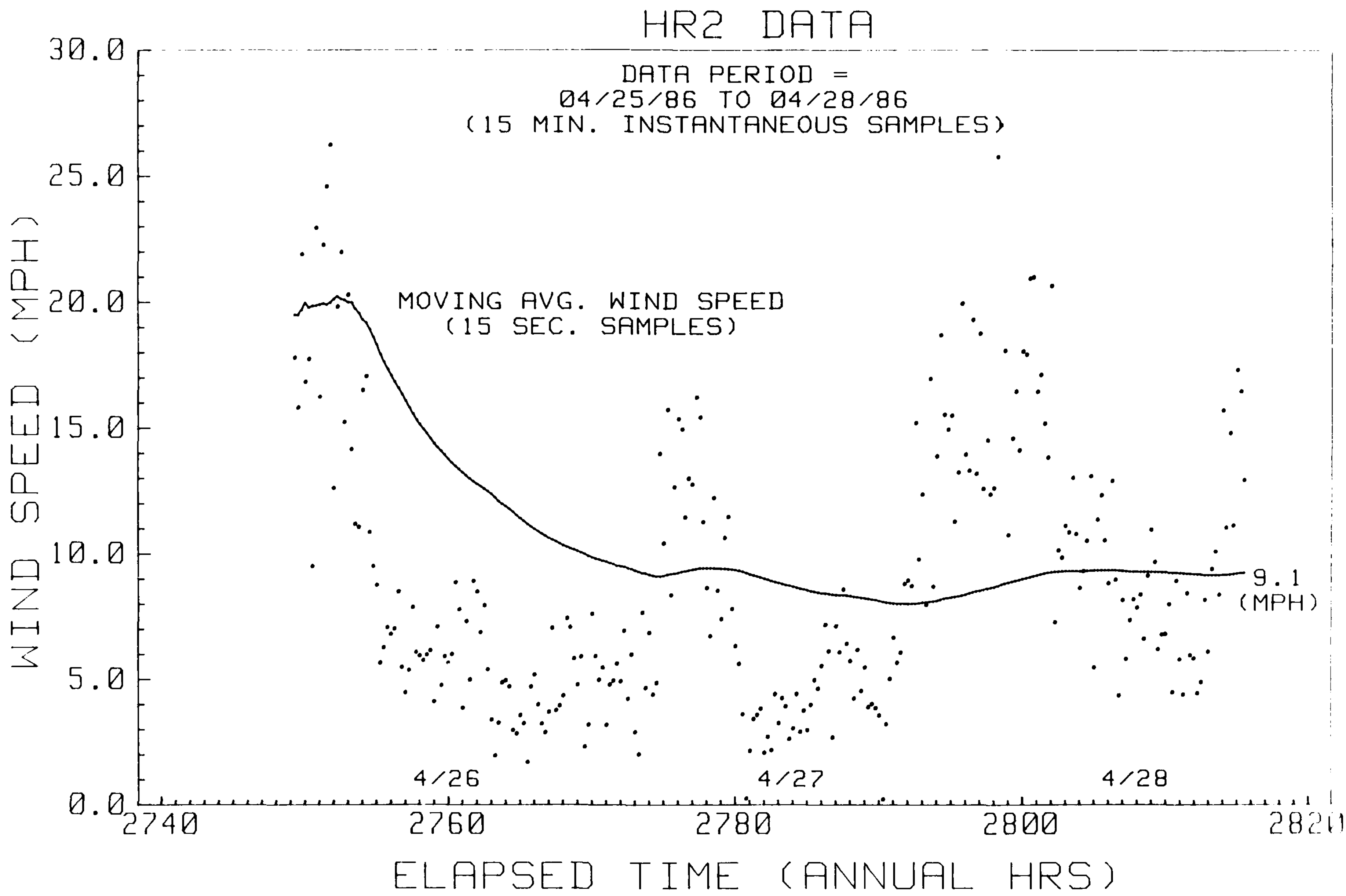


FIGURE 6. WIND SPEED DATA RECORD

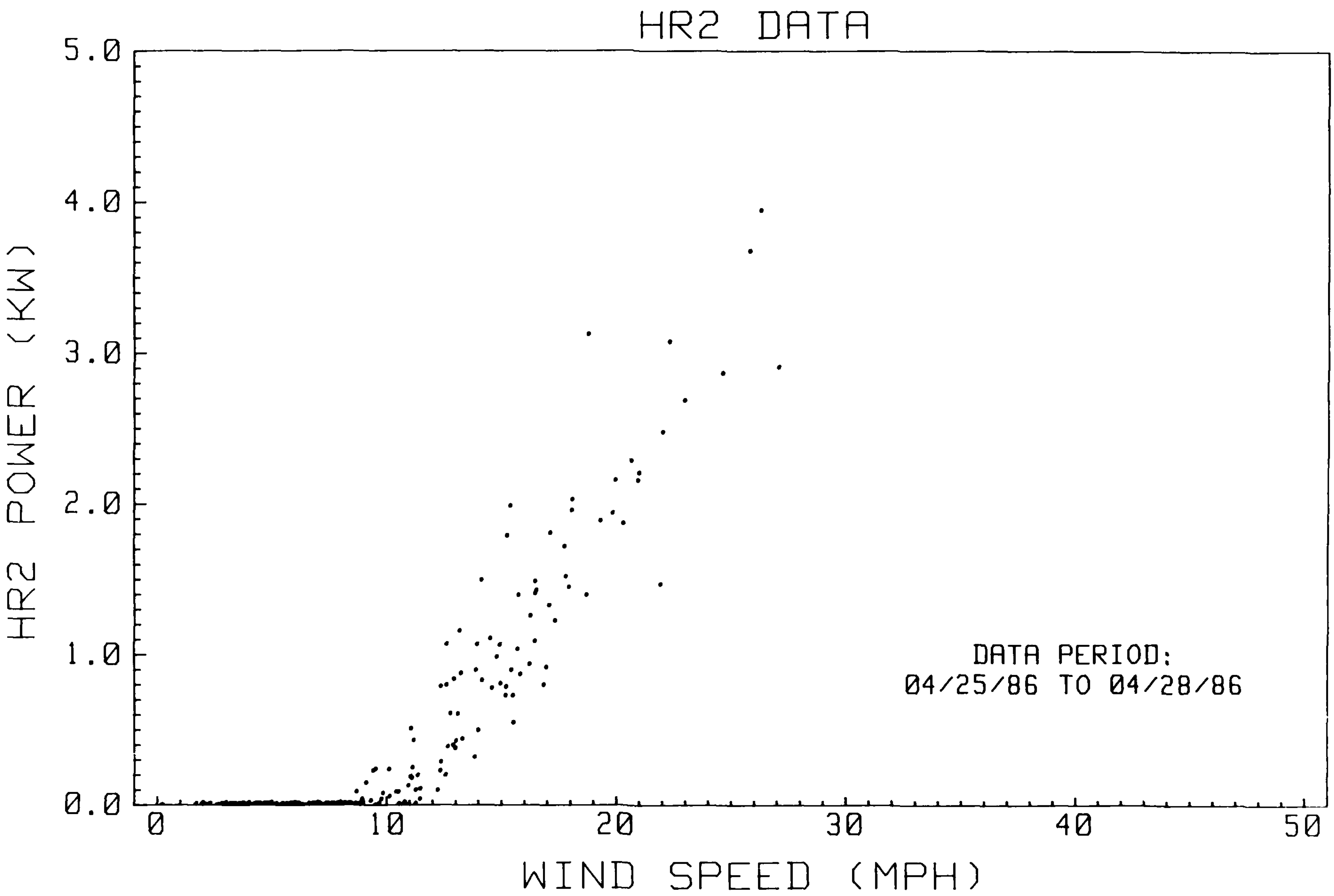


FIGURE 7. HR2 POWER DISTRIBUTION DATA RECORD

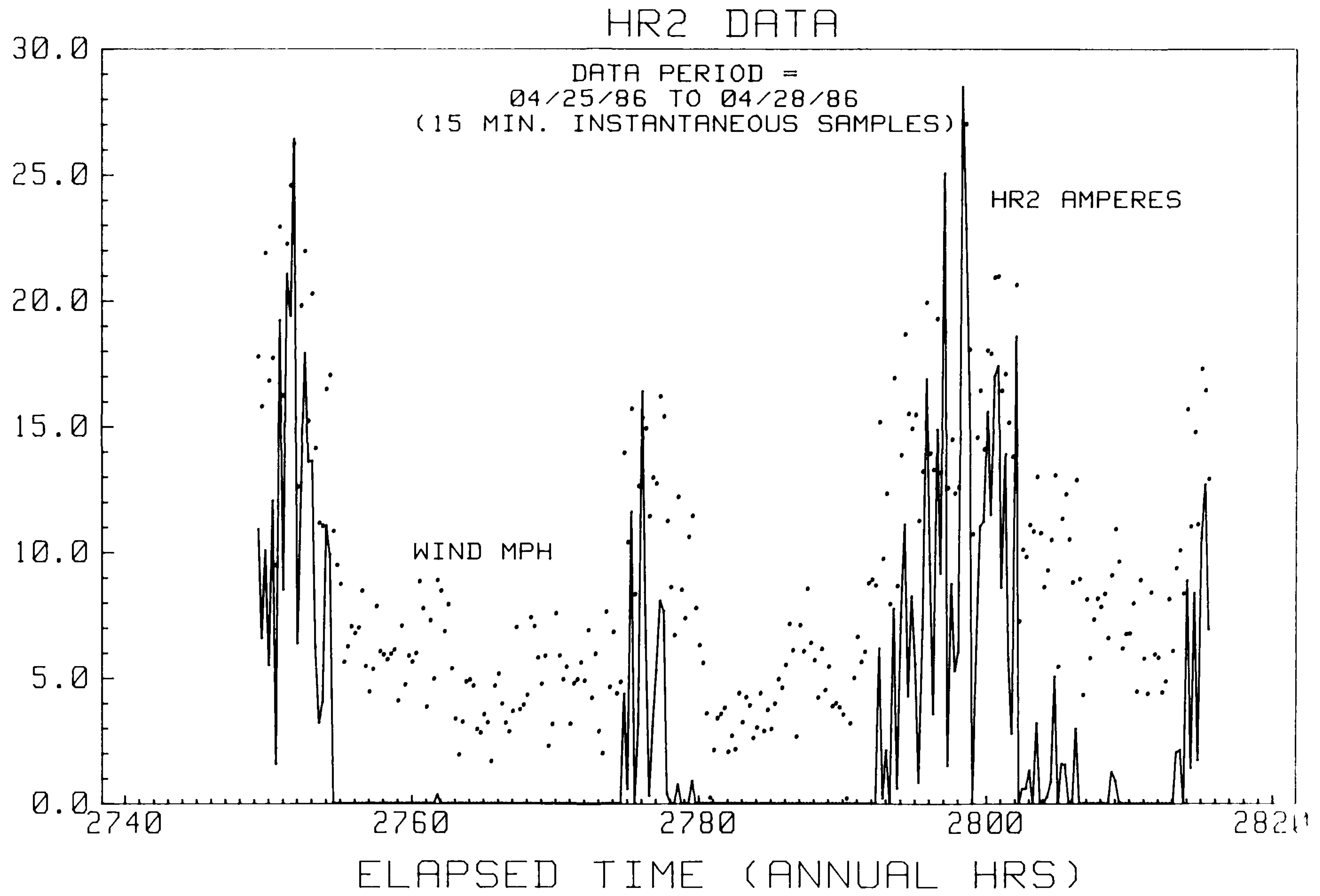


FIGURE 8. HR2 AMPERE DATA RECORD

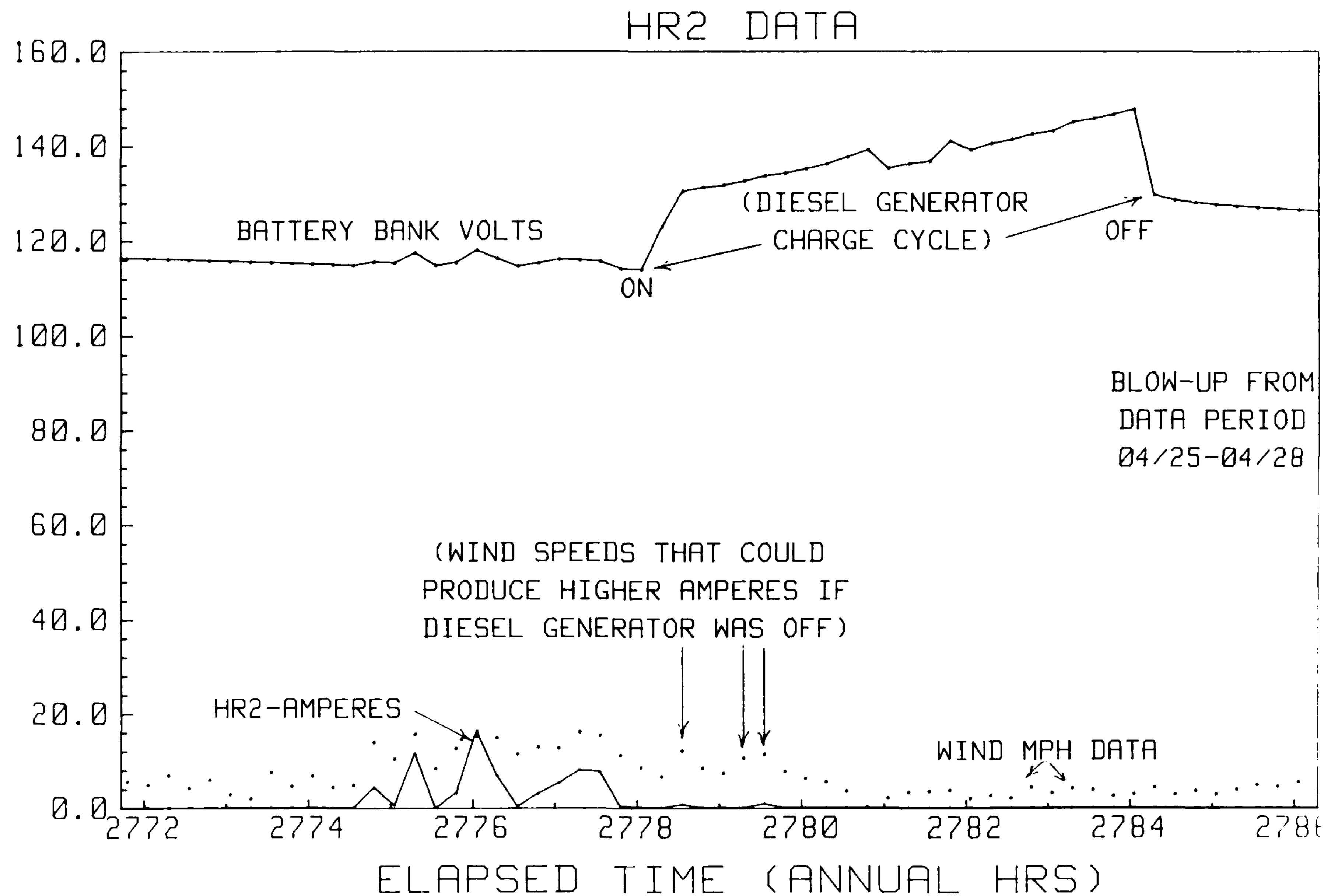


FIGURE 9. HR2 HYBRID SYSTEM DATA RECORD

period shows the Avery Point test site to be just outside of the measured 10 to 30 mph window during the sample period. Diurnal variations are wide as indicated by the instantaneous samples. Figure 7 reinforces the power production window. Figure 8 shows current flow into the batteries and its magnitude overlayed to the instantaneous wind data. This graphic presentation is an alternative method of viewing the HR2 performance as previously shown with kw in Figures 5 and 7. Figure 9 shows the effect of battery resistance on power production. Wind speeds around hours 2778.50, 2779.25 and 2779.50 would normally be high enough to produce peak power but happened to come along when the diesel generator was charging the batteries and bank voltage was artifically high.

It can be concluded from the collected data that the HR2 will produce only a fraction of its rated power on an average basis. Data collected and reported by APL claim users should expect about 15% of rated power as an annual average, (Reference 6). As explained above, wind speed variations and battery charging conditions account for this fact. The HR2 is a dynamic machine developed for durability and simplicity, but dependent on wind resources. It takes a 16 mph wind speed to produce approximately 1 kw of power and certain loading conditions may further lower this value, (see Appendix A).

MAINTENANCE EXPERIENCE

Routine Maintenance

Routine maintenance was provided to the HR2 during all phases of testing as outlined in North Wind's Assembly, Operation, & Maintenance Manual, (see Appendix C). This maintenance was performed by both APL and the USCG R&D Center personnel.

HR2 Event and Maintenance Log

October, 1981

The HR2 was installed by APL at Cape Henry Light (USCG light number 152) located in Virginia Beach, Virginia in the presence of consulting North Wind representatives. The HR2 was electrically loaded by a custom-designed, resistor network used as a load center. Verification of proper operation was made using the operating manual and no maintenance was performed.

November 1981

The HR2 voltage regulator was found failed during monthly APL inspection. The voltage regulator was replaced under warranty with the suspected cause of failure to be APL's load center or possible water damage from a poorly sealed enclosure.

February 1982

The manual stowing assembly was noticed to have evident rusting. APL hand greased the chain but did not replace it with a new chain supplied by North Wind, (see Figure 10).

July 1982

APL data collection revealed a low power output in relationship to wind speeds.

September 1982

A complete interruption of HR2 output occurred because of low field slip ring-to-field brush conductivity. Since an annual maintenance visit was scheduled for the following month and HR2 design updates were planned for this visit it was decided to accelerate and combine these two activities.

The field brushes were replaced. Power output out of the the HR2 was observed and verified to be normal in the field, concluding that this was indeed the cause of unit failure. North Wind observed through measurements that the positive field brush was worn unevenly, having 0.940 inches on the lagging edge and 0.708 inches on the leading edge. Both of these measurements are within the operating tolerance for acceptable brush wear (0.625 inches

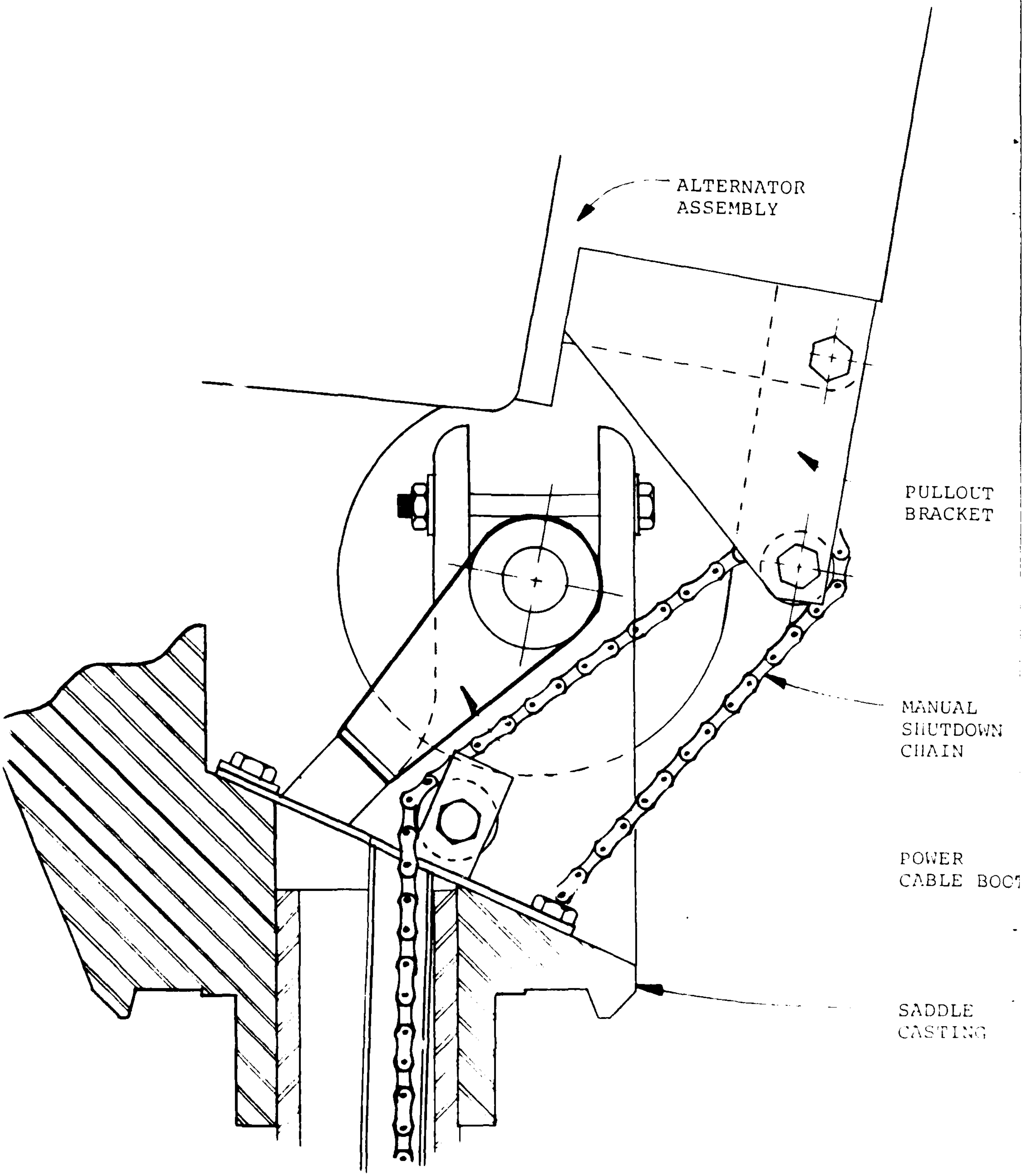


FIGURE 10. MANUAL STOWING ASSEMBLY

minimum), (see Appendix C). The negative brush showed 0.853 inches on the lagging edge and 0.781 inches on the leading edge, once again within tolerance. This discrepancy between advertised tolerance and observed failure was not addressed except to be noted that North Wind Power Company was conducting accelerated life tests on brushes at a 24 VDC potential and early results had indicated one year wear was reasonable to expect. The brushes we installed were a Helwig 692 type. The rings were not changed at this time, however, a new VARCS spring with 874 inch-pounds of pressure was installed with a Helo shock absorber to act as a damper. The VARCS pivotal mounting hardware was upgraded from 3/8 inch hardware to 1/2 inch. These modifications were manufacturer's design updates. Annual bearing lubrication and inspection was also completed during this visit.

October 1982

The HR2 completes first year of field testing.

January 1983

APL manually stowed the HR2 and the USCG R&D Center assumes responsibilty for the HR2.

February 1983

The manual stowing chain that was observed to be rusting has failed. Repair work is dangerous until the wind machine can be manually feathered. The HR2 continued to produce power while repairs were planned.

May 1983

The manual stowing chain was repaired by USCG personnel.

July 1983

The HR2 is operating properly. USCG personnel remove and measure field and yaw power brushes. All are within manufacturer's tolerances.

October 1983

The HR2 completed its second year of operation. Blades were changed to a newer design and lubrication/inspection was done on the system in preparation for hookup to a different load center. Brushes and rings were inspected and found to be within manufacturer's tolerances. The replacement blades were of a new construction and sealing process and represented the second design update on the HR2 since its installation. This work was accomplished by R&DC personnel. During this month, the HR2 survived hurricane Dean which passed through the Virginia Beach area. Reported gusts were in excess of 80 miles per hour.

May 1984

The HR2 experienced a complete power output failure when the yaw slip ring and brush assembly disintegrated and caused a short circuit to ground. The assembly is a plastic (non-conducting) housing that holds and separates the different conducting rings and provides support posts for their respective brushes. The assembly slides over the yaw shaft (orthogonal to main shaft) and is fastened with a guide bolt to the saddle base and fixed to the yaw shaft with two lock bolts. Apparently the guide bolt (originally designed as 3/8 inch hardware) allowed for slippage and wobble around the yaw shaft on which it is mounted. It eventually wore down and melted the plastic components because of frictional heating. At this time the rings short circuited and caused even more severe burning and melting of the conductors and associated hardware. North Wind Power Company provided personnel to replace this assembly. The guide bolt had since been upgraded to 1/2 inch hardware and this represented the third design change to the original HR2. Unfortunately, the appropriate hardware was not available to the repair technicians and a temporary solution evolved where a 3/8-inch bolt was "built up" with electrical tape to make up the difference to 1/2-inch hardware. At this juncture the field slip rings and brushes were replaced giving the HR2 a complete set of new rings and brushes. It was also observed that the air and dust vents for the brush/ring assemblies were badly corroded and could result in moisture buildup around these pieces. After repair and modification, the HR2 was left freewheeling.

May 1984

When the HR2 was connected to the load, the fuse on the voltage regulator failed repeatedly. It was discovered that the North Wind personnel who were at the site the previous week had incorrectly wired the new slip ring assembly which was causing the high amperage short. North Wind then provided an additional site visit to correct the wiring problem. At this time, the yaw brush/ring assembly was provided with the proper 1/2-inch shoulder bolt and new breather plugs were installed. Correct operation was observed.

July 1984

Coast Guard personnel observe normal tower vibration during site visit probably due to system harmonics, (see Figure 11).

September 1984

The final HR2 maintenance inspection and lubrication was conducted by R&D personnel before the start of prototype systems testing (battery load). Air and dust vents on the HR2 were changed out again due to corrosion.

October 1984

The HR2 completes its third year of operation.

December 1984

North Wind personnel conduct inspection of the HR2 and find the unit operational with brushes/rings within specification.

May 1985

The reverse current diode failed twice (once each in two consecutive weeks) rendering the HR2 with no output. Lightning strikes or voltage spikes from associated equipment is suspected as the cause. Coast Guard personnel replace the diode once, and after the second failure the HR2 was left in the

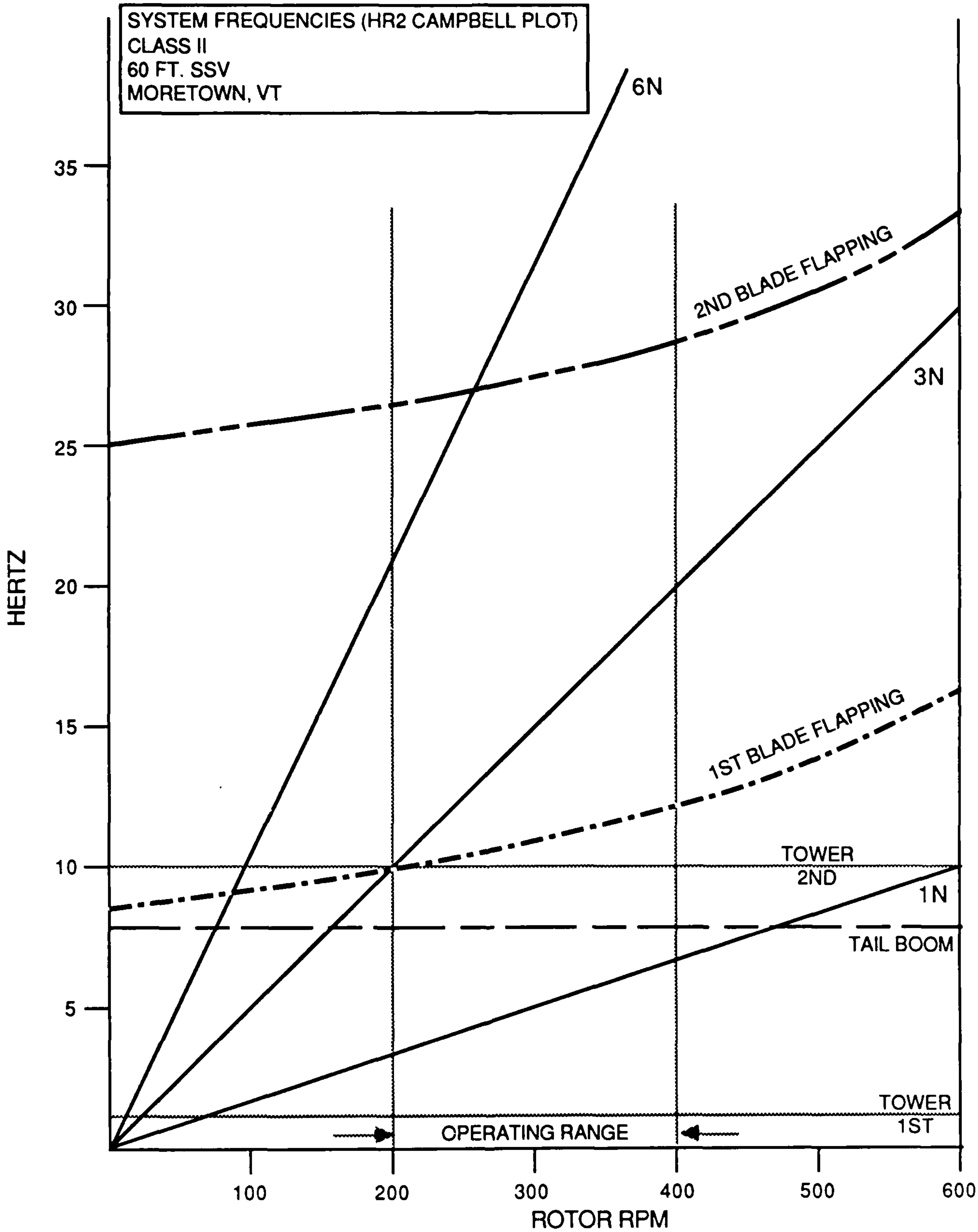


FIGURE 11. TOWER HARMONICS AS RELATED TO HR2 RPM

stowed position. The Cape Henry system's test was terminated at this point because of fiscal restraints on travel and because it was felt sufficient data had been collected to base conclusions on.

August 1985

The HR2 was removed from the Cape Henry site and forwarded to North Wind facilities in Vermont for a rebuild and analysis prior to installation at the R&D Center in Connecticut. (Reference 8)

September 1985

The HR2 was reinstalled at the R&D Center and placed back into operation as a battery charger. The WTG survived hurricane Gloria, although at the peak of the storm the machine was manually stowed. Estimated wind speeds seen by the WTG were in excess of 80 mph. Note: The wind machine was feathered at the peak of the storm because the project officer concluded that it would be more purposeful to the Coast Guard to have the machine in tact for further testing than to risk a real-time test of its high wind survivability.

October 1985

The HR2 completes its fourth year of operation, but has undergone a major overhaul under shop conditions. (Reference 8)

November 1985

Capacitor bank within NWPCo's voltage regulator failed due to a technician improperly switching the alternator's loads while the HR2 was running. Repairs were made by USCG personnel. This failure was due to improper maintenance procedures.

January 1986

The HR2 suffered a complete output failure when the regulator field fuse opened. The resistance of the field coil was measured at 22 ohms instead of the normal 42 ohms. North Wind personnel with assistance from Coast Guard technicians replaced the shaft, field coil, and bearings without removing the HR2 from the tower. A gin pole was employed to rig heavy loads from the ground to the tower top. The field coil was later found to have internal shorts, most likely from manufacturing defects, although improper switching during November 1985 may have been to blame. North Wind accepted warranty responsibility and the repaired HR2 operated properly. The HR2 was deployed as a battery charger in conjunction with a test being conducted on a commercially available power controller.

June 1986

The HR2 continues to operate properly.

Maintenance Critique

From its installation in October 1981 to the time of this report, June 1986, the HR2 experienced four major failures. Two of these failures (RCD, May 1984 and field coil, January 1986) can be traced to the manufacturer's original design. The two other failures (brush/rings September 1982 and May 1984) are of a more serious nature because they reflect on the design limits of the machine. From all observations, the weakest "link" in the HR2's design is the two sets of brushes and rings (field and yaw). The yaw brushes and rings allow the positive, negative, and field current to run down the tower length and then be translated 90 degrees at the tower top. They are not subject to the large number of revolutions that are seen by the field brush and ring assembly on the main shaft, but affected by wind direction only. Based on our data, we conclude that barring catastrophic failure such as was experienced in May 1984 this yaw brush/ring assembly will survive for a full year without service. The field brush reliability for a one year service interval cannot be stated with such certainty. The initial set of brushes put in the machine apparently began to fail after nine months and power output was nil by eleven months. The second set of brushes ran for 16 months with at least two months of no-load (higher RPM) operation. When they were removed for the rebuild in August of 1985, they measured just within specification at 0.680 inches, (see Figure 12). They may survive one year of operation.

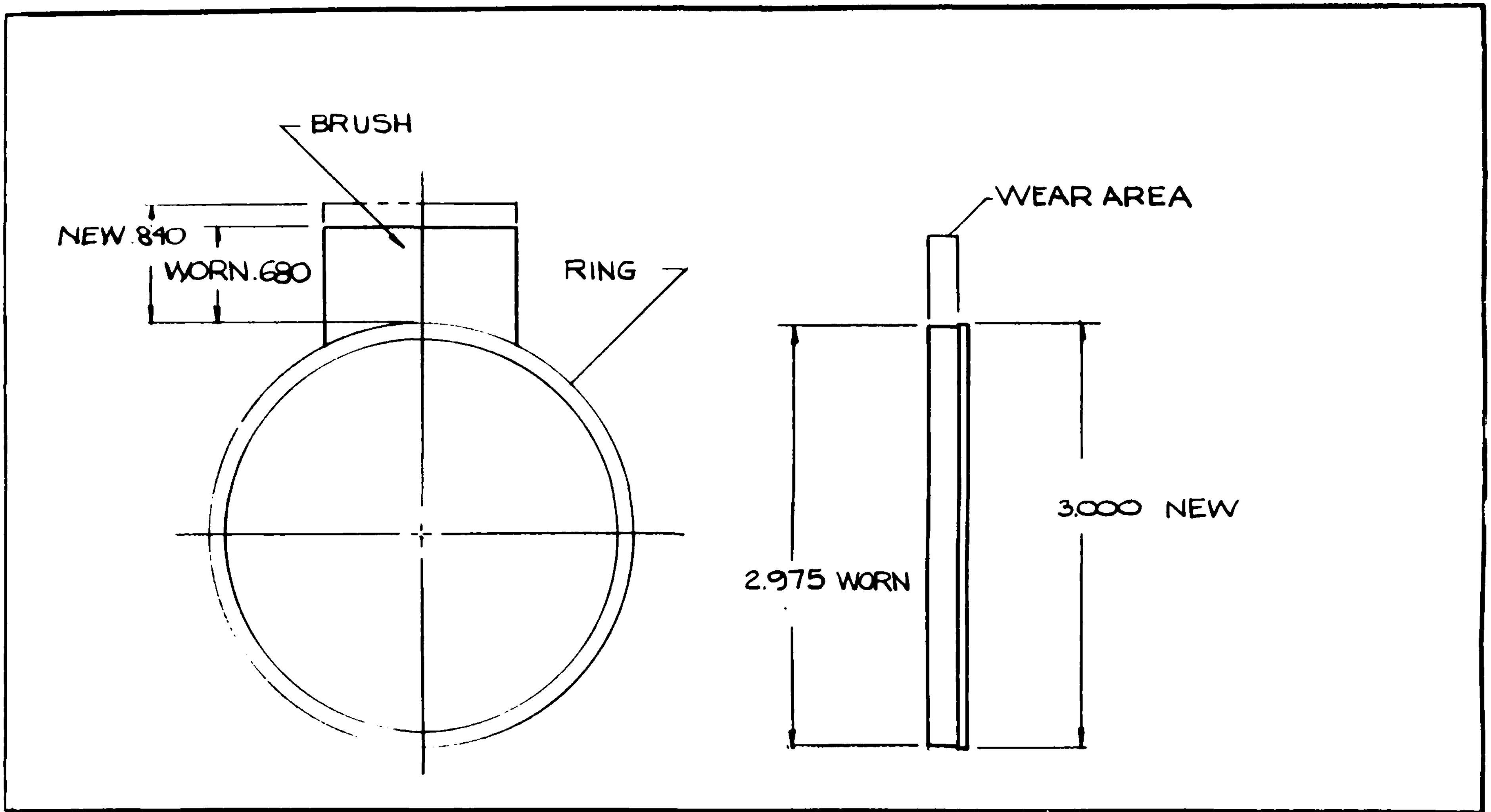


FIGURE 12. HR2 SLIP RING WEAR

Of lesser but still critical importance is the ventilation of the brush/ring enclosures. In all incidents of inspection or maintenance, heavy amounts of carbon debris (dust) could be found within the enclosures. This is a by-product of brush wear and unavoidable. When moisture builds up inside these enclosures and joins with this carbon dust, it is possible short circuits could develop over these unintentional paths. Air and dust vents that ventilate and carry away this moisture and dust have been replaced twice and appear to be susceptible to heavy wear in marine environments. They should be included as an annual maintenance item, and possibly be manufactured from a more corrosion resistant material.

The second weakest link in terms of maintenance is the continual failure of the manual stowing mechanism. This device is subject to full marine environmental stresses. Left unused for long periods of time it often fails when it is needed the most. The Coast Guard replaced the North Wind plastic coated wire rope with 1/4-inch stainless steel wire with a 6100 pound rating. Thimbles were employed at all turns. Since this change was made no failures have been experienced.

The third area of design concern in the HR2 is the bearings. HR2 bearings are not self lubricating. They require lubricating grease at least once per year. There are seven bearings in the HR2. Three bearings are located on the main shaft, two on the VARCS's hinge and two on the yaw shaft. During the rebuild conducted in September 1985, all bearings were measured for wear. The only piece to exhibit unusual wear was the single roller bearing supporting the front end of the main shaft. Observations indicated the bearing developed minor longitudinal (along the shaft) play and was beginning to breakdown due to friction and misalignment of the rollers. Rust and scoring pointed to a lack of lubrication although maintenance had been provided as required by the operating manual. The operating manual makes no mention of the consequences of long term stowing of the HR2, but North Wind mechanics pointed out that this bearing was not designed to be sealed from the elements and that excessive stowed time would allow water to enter the bearing and induce corrosion, (Reference 8). The machine was stowed for two months starting in January 1983 and again for three months starting in May 1985. North Wind now provides an oil seal to protect this bearing. This represents another design change to HR2. Despite the advanced wear on this bearing the shaft could still be rotated by hand. Starting torque on the main shaft was measured at 30 foot-lbs, well above the 2.5 foot-lbs specification.

The two opposed taper roller bearings on the rear of the main shaft were in excellent condition and will provide much longer service life. There was evidence of good lubrication in and around the races. The VARC's and yaw bearings were in equally good condition. The seventh bearing is a non-roller type "rulon" plastic that acts more as a guide for the lower portion of the yaw shaft. It exhibited wear of the scoring or turning nature, but in no way reduced the yawing action of the HR2.

The VARC's assembly performed according to design, but as was pointed out in the performance section, may reduce the output of the HR2 more than the manufacturer designed it to. The 1/2-inch steel bolt that pins the VARC shaft in place showed extreme wear on its outer surfaces, (see Figure 13). The bolt could have failed (broken) within a short period of time and this would have left the HR2 in a stowed position with no reactive force to push it back down. Power output would have been interrupted. North Wind has upgraded this bolt to 5/8-inch steel grade 8, and it will become an annual replacement item.

The blades that were installed in October 1983 were closely examined after removal from Cape Henry in August 1985. They had been in the air just short of two years. The finish on the blades showed an assortment of nicks and scratches but nothing of any major consequences. The blade tape had held up very well except for the tip chord where one would expect the major amount of erosion. The white painted surface appeared chalky and a dusty film could be picked up if one wiped a finger over the blade surface. Tests revealed no moisture buildup in the blades. North Wind personnel have recommended an annual inspection and waxing of the blades, (Reference 9).

Bolting hardware suffered from galvanic (dissimiliar metals) and marine environmental stress. For example, when changing out blades it often became necessary to "break" the bolts because of corrosion. Without the proper tools and experience this can become a difficult and dangerous task to perform on

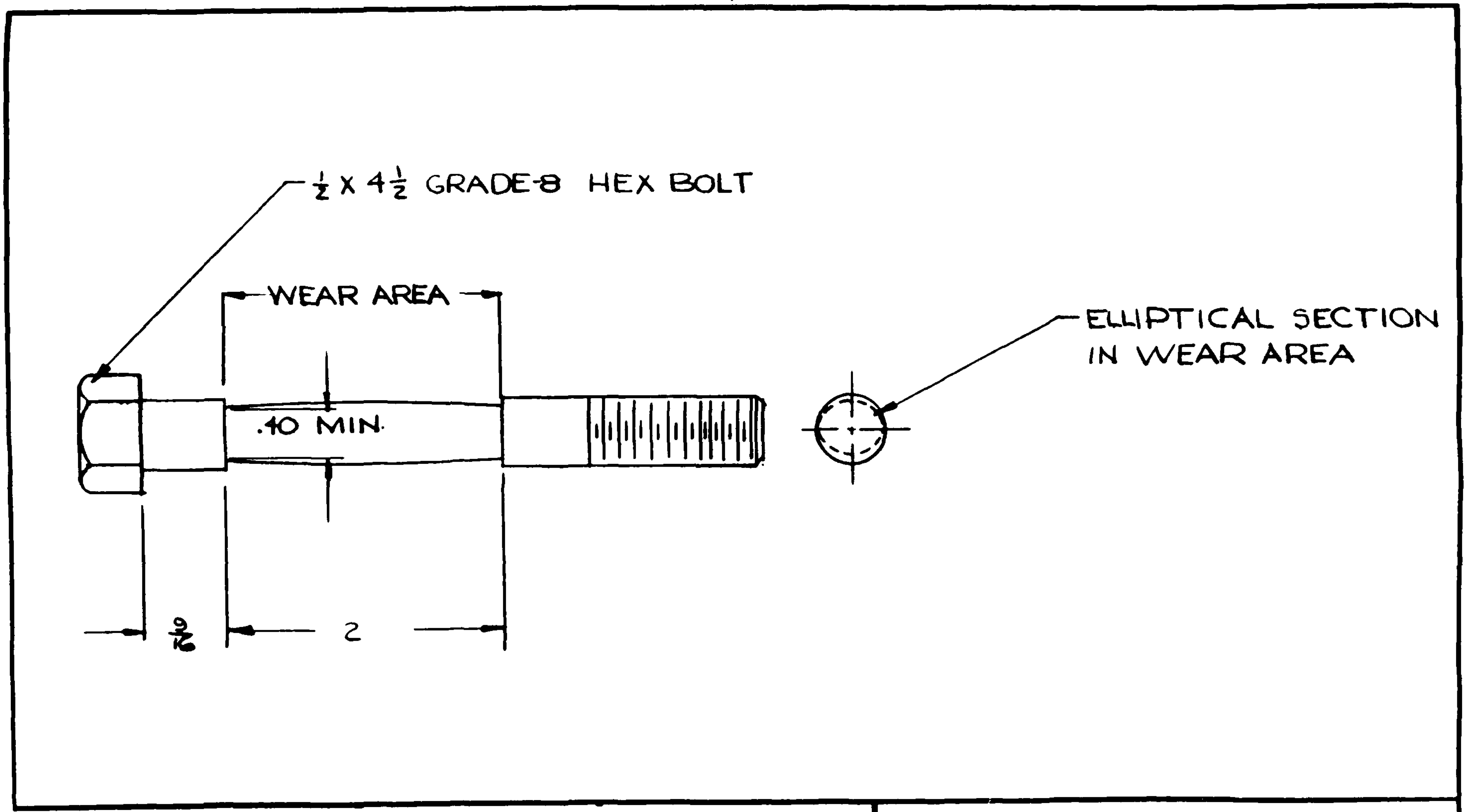


FIGURE 13. HR2 VARCS MOUNTING BOLT WEAR

NORTH WIND POWER		
HR-2 # 354-COAST GUARD VARCS BOLT WEAR		
SIZE A	CODE IDENT NO.	
SCALE		SHEET

top of a tower. In general, the materials used for the HR2 are of a durable and adequate construction. The Unarco-Rohn support tower showed very little corrosion although random rust spots could be seen developing. The hot dipped galvanized finish seems to be a good choice for a marine environment. The overall paint finish on the HR2 did not hold up as well, developing moderate rust.

Electronic components supplied with the HR2 also experienced failures. Most notably of these were the two consecutive failures of the reverse current diodes in May 1985. Although a storm passed through the region at the time of failure, we were never able to pinpoint the exact cause of failure. A curious coincidence was the simultaneous failure of the DC/AC inverter. This could indicate the possibility the failure was brought on by transients induced by the inverter. One solution to this problem would be to use redundant diodes, although recent operating experience at the R&D Center has not revealed further problems with this design.

The voltage regulator experienced problems in the early phases of the experiment (APL) but since that time has performed adequately. The rectifying diodes have never experienced failure and during the rebuild tested at close to their normal resistance measurements, (Reference 8).

To summarize the maintenance critique, the following observations can be made:

(1) Rings and brushes used with the HR2 may operate for at least one year without maintenance.

(2) Blades deployed on the HR2 will survive normal use for at least three years given normal maintenance.

(3) Roller bearings currently used in the HR2 will survive for at least five years if lubricated according to the manufacturer's schedule.

(4) Vent and dust plugs used for ventilation are inadequate and do not hold up well in the marine environment.

(5) The manual stowing cable as delivered from North Wind is not acceptable and must be re-engineered.

(6) Electronic hardware (voltage regulator, rectifiers, diodes, etc.) associated with the HR2 are of adequate design and reliability.

(7) The VARCS system is a reliable controller of overspeed conditions.

(8) The Rohn self supporting tower can survive the marine environment and offers a strong platform for deploying the HR2.

(9) The HR2 can be maintained safely by properly trained mechanics.

Availability

The HR2 was found to have an overall availability of 91%. The method of computing this figure can be found in Appendix E.

CONCLUSIONS

Introduction

Given the fact that no fewer than five manufacturing updates were performed on the HR2, it is difficult to judge the machine's continuous performance as a singular machine over the five year test period. For each update performed there were no reoccurrences of that particular problem. Given the maturity of the wind generator industry a certain improvement in reliability must be expected. Except for future refinements from suppliers, it can be said the HR2 is currently in the final stages of evolution. During the most recent testing, conducted 15 January to 15 June 1986, the HR2 has operated without failure as a battery charger incorporated into a commercial cycle/ charge system.

Since the HR2 was tested as part of a system it was sometimes difficult to distinquish how other sub-components could affect the HR2. For example, when both RCDs failed, the DC/AC inverter component of the system also failed.

Testing at the R&D Center using only a DC bus (no inverter) has not recorded any further RCD problems. We speculate that the inverter introduced voltage spikes of sufficient magnitude (about 1400 volts) to destroy the RCDs. Earlier in the testing, similiar switching transients could have explained the voltage regulator failure. Our field notebooks have also documented cases of switching loads while the HR2 was running instead of stowed in direct violation of the North Wind operation manual. It may be concluded that some failures of the HR2 as a subsystem were the effect of other components in the hybrid system or from operator negligence.

The North Wind Power Company provided exemplary assistance in all requests for maintenance and information. They have demonstrated a dedication to upgrading and evaluating their machine on a continuous basis, and providing superior assistance to their customers.

The conclusions reached in this report were not influenced by any economic factors. It is assumed that these factors will be considered last, once a site has been identified as viable for a wind installation. Based on our experience the following conclusions have been reached:

General

(1) The HR2 as modified will meet the requirements of one site visit per year for general maintenance and will survive the effects of operating in a marine environment.

(2) The HR2 has encountered operating failures during the test period unrelated to maintenance. This has caused its availability of 91% to be less than the desired 99% for a remote application.

(3) The HR2 would be ineffective at a site where the average annual wind speed was not between 10 and 30 mph.

(4) The HR2 will probably not perform for any longer than five years without a rebuild because of the probability of bearing wear. A

program of having a "spare" HR2 that would be rebuilt and ready to be switched out on a maintenance visit would have to be adopted.

RECOMMENDATIONS

(1) The HR2 should continue to be operated at the R&D Center for at least a period of one year to ascertain if past design improvements incorporated into the machine during the Cape Henry testing have indeed improved the reliability of the generator as recent operations indicate. Other wind machines have performed well in the U.S. Coast Guard's Aids-to-Navigation environment, most notably the Aerowatt 300 machine at Cuttyhunk, Massachusetts that has been operating reliably for five years. We expect that the modified HR2 will exceed that performance.

(2) An extensive program should be executed to gather wind data (digital) for each candidate lighthouse prior to deployment. A computer model should then be employed using the specific load characteristics to determine if wind machines have potential at these sites.

(3) Further study into wind generators and site-specific options for turbine installations should be conducted, as well as efforts to maintain currency in the wind generator technologies.

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SPECS · HR2

General

Rotor Configuration:	Horizontal axis, upwind, 3-bladed
Power Output (rated):	2200 watts at 9 m/s (20 mph)
Mean Power Output (MPO)*	500 w @ $\overline{V}$ = 10mph(4.5 m/s)
	760 w @ $\overline{V}$ = 12mph(5.4 m/s)
	1150w @ $\overline{V}$ = 16mph(7.2 m/s)
Voltage (nominal):	24, 32, 48, 110 vdc
Interface Requirement:	Battery storage
Transmission:	None required (direct drive)
Yaw Control:	None required (free yawing)
System Weight (excluding tower):	356 kg (785 lb)
Tower Height (minimum):	12 m (40 ft)
Tower Weight (12 m):	545 kg (1200 lb)

Wind Turbine

Rotor Diameter:	5 m (16.4 ft)
Blade Material:	Wood composite
Cut-in Wind Speed:	3.6 m/s (8 mph)
Rated Wind Speed:	9 m/s (20 mph)
Speed Control Initiation:	9.3 m/s (21 mph)
System Shutdown:	47 m/s (105 mph)
Axial Thrust (maximum):	2800 N (630 lb)
Overspeed Control:	Variable Axis Rotor Control System (VARCS)

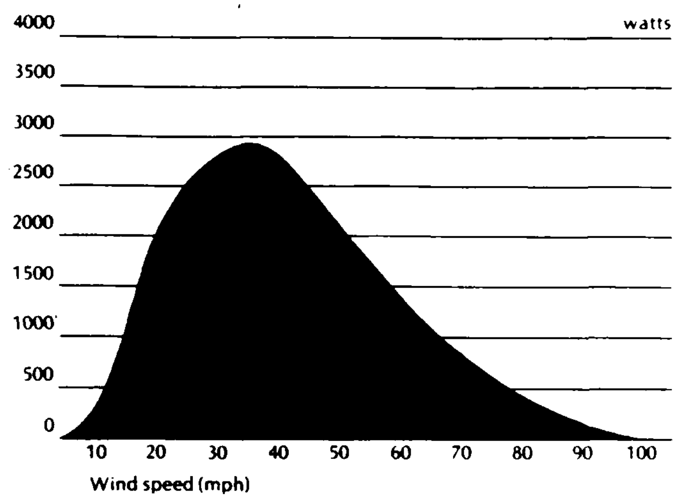
Electrical System

Generator Type:	3 phase, synchronous alternator with wound stator
Field Configuration:	Lundel type, shunt-connected
Rated Output:	2200 watts at 250 rpm
Maximum Output:	3000 watts
Rectification:	Silicon diode full-wave bridge
Voltage Regulation & Battery Protection:	Solid state field control with over-voltage protection

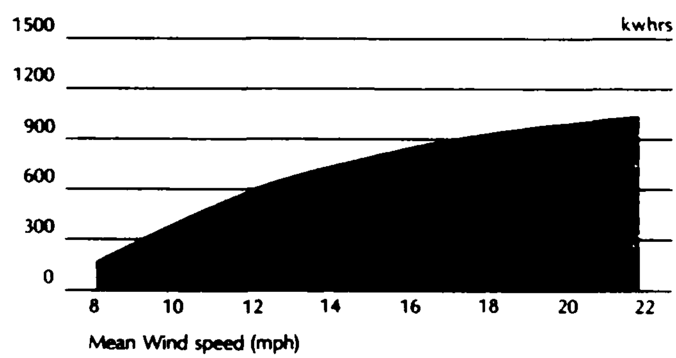
Environmental Conditions

Temperature:	-60°C to 60°C (-70°F to 140°F)
Wind, steady:	54 m/s (120 mph)
Wind, gusting:	75 m/s (165 mph)
Rain, dust, industrial atmosphere, salt water spray	Sealed construction; weather-tight fittings and connectors; corrosion resistant materials

HR2 Power Curve



HR2 Output/Month



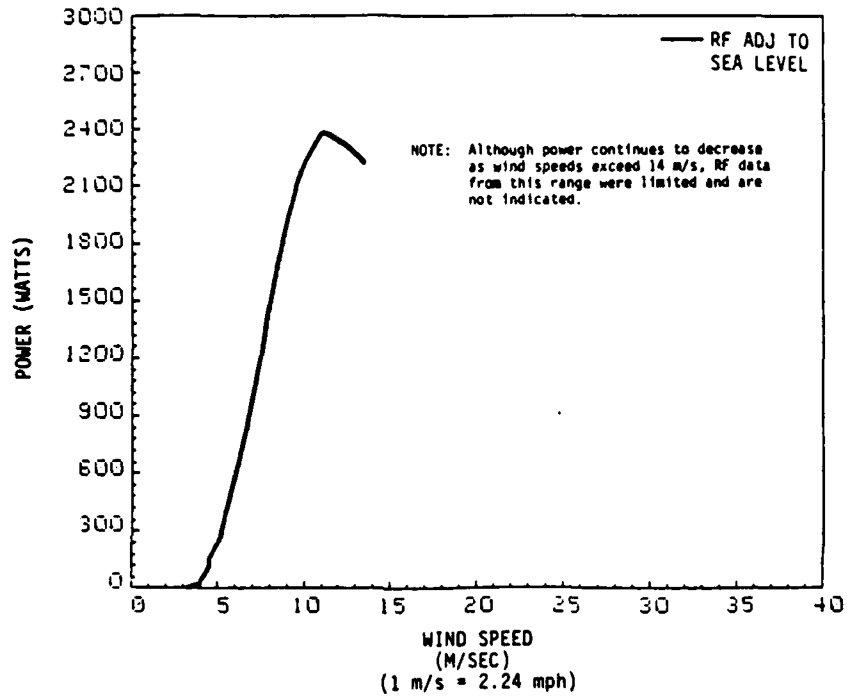
APPENDIX B

ROCKY FLATS PERFORMANCE DATA

North Wind HR2

MEASURED CHARACTERISTICS
(ADJUSTED TO SEA LEVEL)

CUT-IN WIND SPEED.. 3.5 m/s (7.8 mph)
CUT-OUT WIND SPEED.. Not Measured
SURVIVED WIND SPEED.. 52 m/s (116 mph)
OUTPUT @ 9 m/s (20 mph) .... 1980 Watts
OUTPUT @ 9.3 m/s (21 mph) .... 2020 Watts
ANEMOMETER HEIGHT.. 7.9 m (26 ft)



ESTIMATED ANNUAL ENERGY PRODUCTION
(USING A RAYLEIGH WIND DISTRIBUTION)

AVERAGE WIND VELOCITY (m/s)	(mph)	ANNUAL ENERGY OUTPUT (kWh)
3.58	8	1600
4.47	10	3300
5.36	12	5400
6.26	14	7400
7.15	16	9000

Note: *The annual energy output is based on the measured Rocky Flats power curve for this machine and 100% availability. The power curve is superimposed on a Rayleigh velocity duration curve which is then integrated over time to obtain energy. Energy output will vary at specific sites due to variations in wind characteristics and other factors.*

SUMMARY

Atmospheric testing of the North Wind HR2 was accomplished from October 1980 to June 1982. During this period, two (2) separate machines were tested under a number of configurations. The power curve shown above reflects only the performance of the latest (and presently marketed) configuration, with the VARCS spring tension set to 850 in/lbs. Since this particular system was tested for a short period of time, quantities of data for wind speeds above 14 m/s (31 mph) were limited. The only problem experienced was a loss of residual magnetism after periods of non-continuous use. This has resulted in subsequent manufacturer modifications to the system. Also, as a result of manufacturer modifications to the VARCS during testing, power output of the HR2 improved over the test period and was close to the manufacturer's predicted for the range of wind speeds experienced. The HR2 survived wind speeds of 52 m/s (116 mph) during testing at RF.

APPENDIX C

NORTH WIND POWER COMPANY OPERATOR'S MANUAL EXCERPT
HR2 MAINTENANCE SCHEDULE

MAINTENANCE

Introduction

The following maintenance procedure should be conducted on the wind system at least once within any 365 day period to assure proper operation and long life of the wind plant. NOTE: No preliminary maintenance required at installation.

Annual Maintenance Procedure

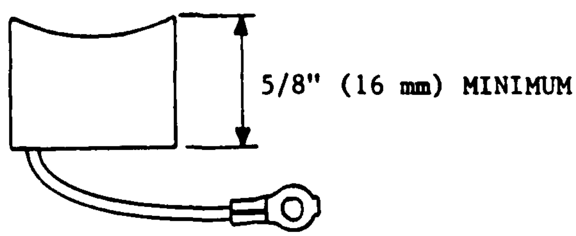
1) Observe operating machine in winds in excess of 9 mph (4 m/s). Look and listen for any irregular operation, e.g.:
   (a) Erratic pitch or yaw motion
   (b) Rotor or system vibration
   (c) Tower vibration
   (d) Power output significantly reduced
   (e) Unusual noise

2) Crank machine into service position (90 degree pitch-back).

3) Inspect and tighten, as necessary, all mechanical fasteners. (See Installation Section for bolt torques).

4) Check blade surfaces for cracks, breakage, erosion. Replace blade set, if indicated.

5) Inspect all brushes and sliprings for wear. Replace brush sets if there is less than 5/8 inch (16 mm) remaining (see sketch below). Be careful not to lose the spring from the inside of the housing during inspection.



6) North Wind lubricates all bearings with Shell "Aeroshell" 14 at the time of manufacture. Bearings should only be lubricated with Aeroshell 14 or compatible equivalent. Grease fitting locations are 1) at the top of the stub tower (40 pumps), 2) on the front face of the alternator at the shaft (10 pumps), 3) at the rear of the alternator shaft, accessible by removing the diode cover (20 pumps). (See Figure 10)

7) Return machine to operating mode slowly.

APPENDIX D

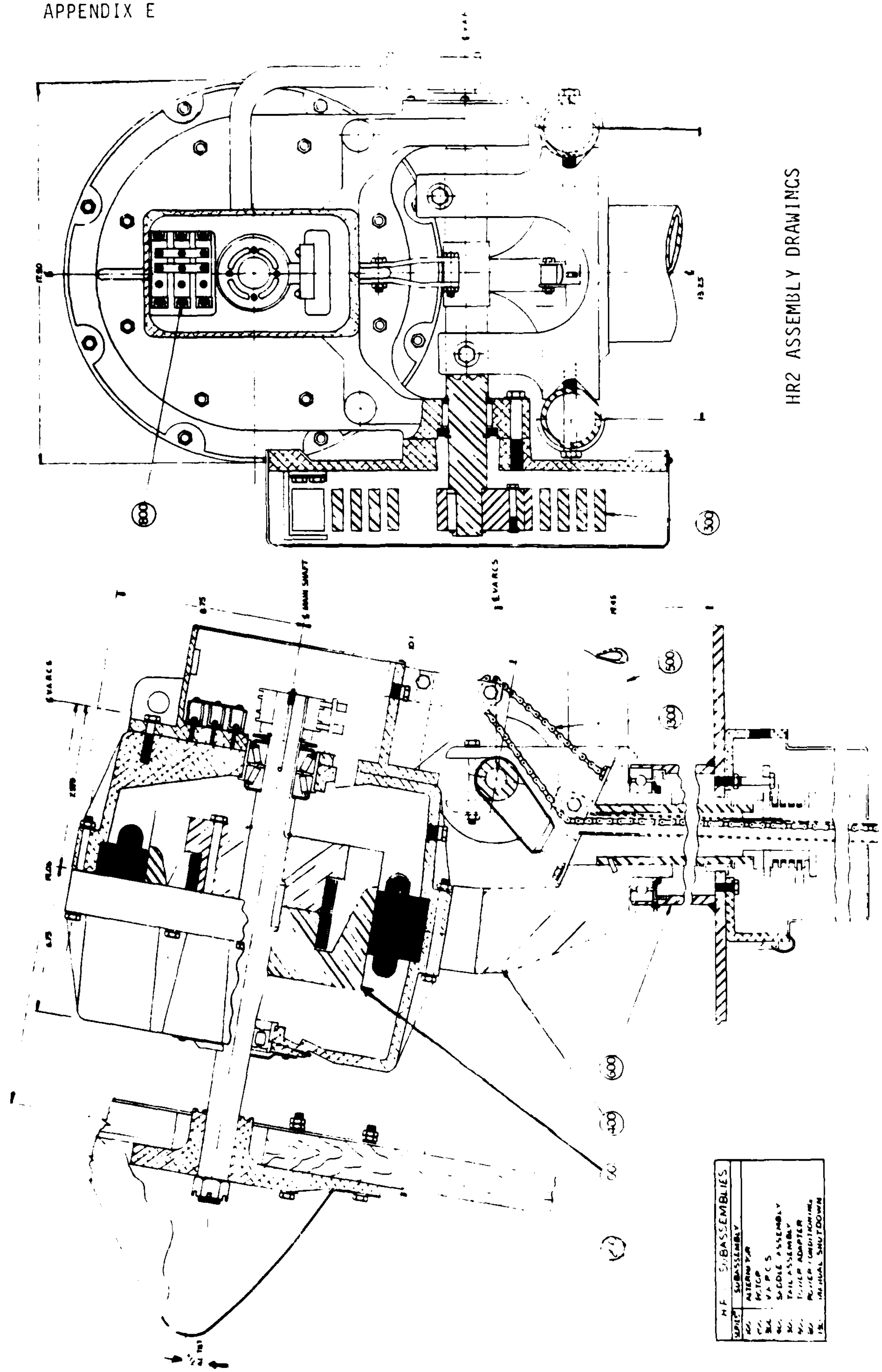
HR2 AVAILIBILITY
(Based on number of days operating over total project days.)

	1981	1982	1983	1984	1985	1986
JAN	-	31/31	31/31	31/31	31/31	16/31
FEB	-	28/28	28/28	28/28	28/28	28/28
MAR	-	31/31	31/31	31/31	31/31	31/31
APR	-	30/30	30/30	30/30	30/30	30/30
MAY	-	31/31	31/31	7/31	8/31	31/31
JUN	-	30/30	30/30	30/30	-	-
JUL	-	31/31	31/31	31/31	-	-
AUG	-	0/31	31/31	31/31	-	-
SEP	-	9/30	30/30	30/30	-	-
OCT	15/15	31/31	31/31	31/31	31/31	-
NOV	30/30	30/30	30/30	30/30	30/30	-
DEC	31/31	31/31	31/31	31/31	25/31	-
PERCENT	100	89	100	93	88	90

TOTAL: $\frac{\text{1388 days}}{\text{1525 days}}$

PERCENT AVAILABLE = 91

APPENDIX E



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