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ASI/PINSON
1 KILOWATT HIGH RELIABILITY
WIND SYSTEM DEVELOPMENT

Phase I - Design and Analysis

Executive Summary

March 1982

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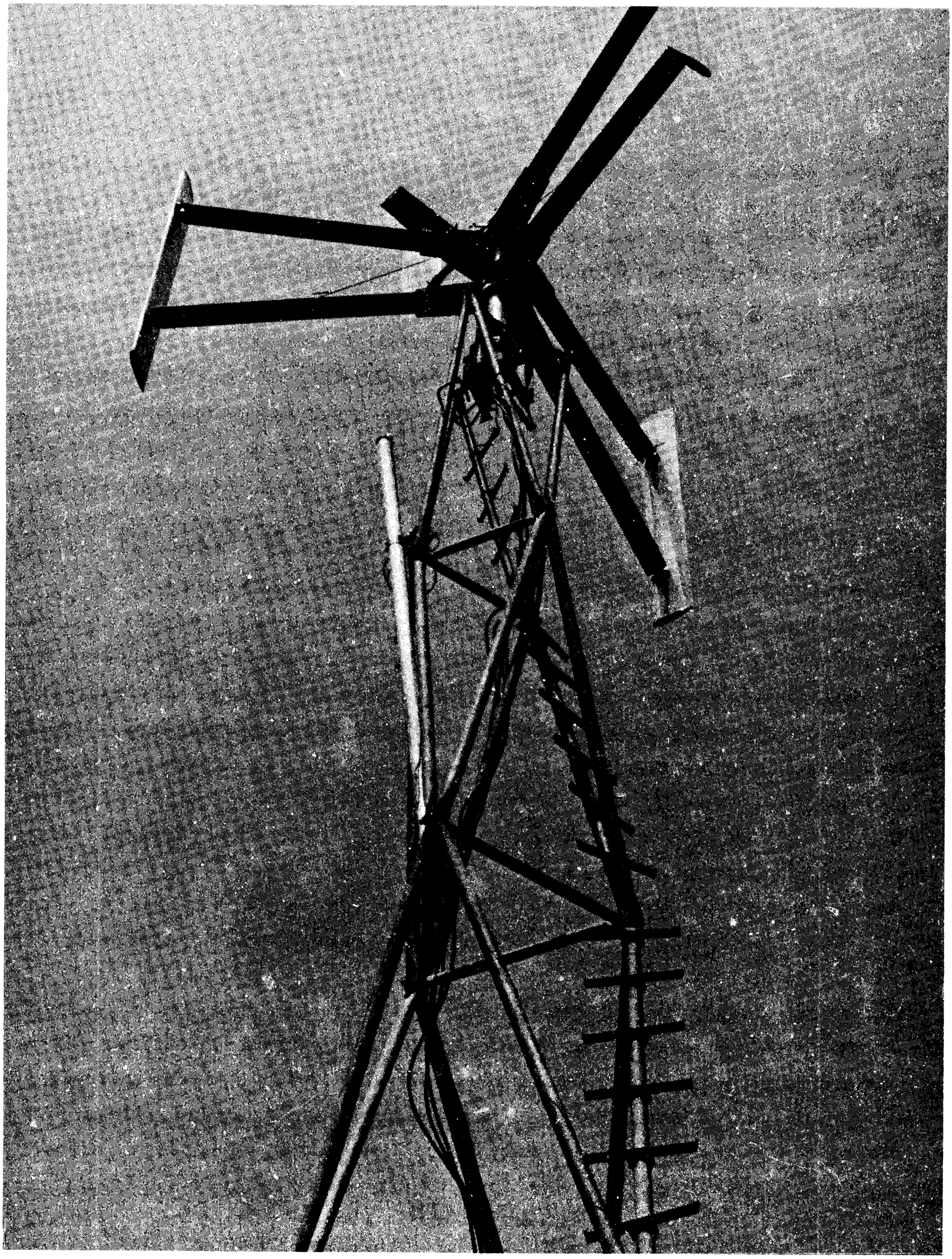

ASI/Pinson 1 Kilowatt High Reliability Cycloturbine
(Prototype - 1979 Photo)

FOREWORD

This report was prepared by Aerospace Systems, Inc. (ASI), Burlington, Massachusetts as prime contractor, and Pinson Energy Corporation (PEC), Marstons Mills, Massachusetts and Natural Power, Inc. (NPI), New Boston, New Hampshire, as subcontractors for Rockwell International, Atomics International Division, Golden, Colorado under Contract No. PF71777-F. Rockwell International operates a Department of Energy installation at Rocky Flats, Colorado. The study was sponsored by the Energy Systems Group at the Rocky Flats Plant. Mr. Warren S. Bollmeier, II served as Technical Monitor of the contract.

This report, issued in two volumes, summarizes Phase I, Design Evaluation, of the design and development of a 1-kW High Reliability Cycloturbine small wind energy conversion system (SWECS). The first volume presents an executive summary of the effort. The second volume presents the design philosophy, analysis and tests; reviews the selected configuration and construction; and examines the costs associated with production of the selected design.

The effort was directed by Mr. John Zvara, President and Program Manager of ASI. Mr. Richard B. Noll served as Project Engineer. Mr. Paul Soohoo was responsible for development of computer software and the computation of design loads and performance. Dr. Norman D. Ham, Director of the V/STOL Technology Laboratory at MIT, contributed to the program as technical consultant and co-investigator. Dr. Ham was primarily responsible for the development of the aerodynamic and performance analyses which were based on his unpublished work in those areas. Development of the rotor system was conducted under subcontract to Pinson Energy Corporation under the direction of Mr. Herman M. Drees, President of PEC. The electrical system was developed under subcontract to Natural Power, Inc. Mr. Richard L. Katzenberg, President of NPI, served as the NPI Program Manager and Mr. Leander B. Nichols served as their Project Engineer.

The design effort was facilitated by a number of consultants to ASI. Professor Ernst G. Frankel of the Department of Ocean Engineering at MIT consulted on the reliability aspects of the program. Dr. James L. Kirtley, Jr. of the Electric Power Systems Engineering Laboratory in the MIT Department of Electrical Engineering was responsible for investigation of alternator modelling and test. Mr. Walter S. Harrington of Helio Precision Products, Inc., Bedford, Massachusetts and Mr. Paul A. Thibodeau consulted on the rotor and electrical system, respectively, in the area of manufacturing technology. Finally, Dr. F. A. Fisher and Mr. Edward C. Schrom of the General Electric High Voltage Laboratory, Pittsfield, Massachusetts reviewed the lightning protection aspects of the design.

ABSTRACT

Aerospace Systems, Inc. (ASI) joined with Pinson Energy Corporation (PEC) and Natural Power, Inc. (NPI) to develop a high-reliability version of a unique vertical-axis machine called the Cycloturbine.® The final design is a 15-ft diameter turbine with three straight 8-ft blades controlled by a tilt-cam mechanism. The tilt-cam mechanism controls blade cyclic pitch amplitudes in a manner similar to a helicopter swash plate. The turbine has a power coefficient of 0.4 at an optimum tip speed ratio of ~3.0 which results in a rotational speed of 112 RPM in a 9m/sec wind.

The electrical system provides 1-kW of 24V DC power in a 9m/sec wind by means of a flux-switching alternator. The electronic circuitry, designed with high-reliability components, consists of a voltage regulator and a power rectifier. A dump-load circuit is provided as an option. Two transient protection networks are included, one on the tower for the alternator and the other to protect circuitry in the control building.

The unique configuration of the Cycloturbine necessitated the development of aerodynamic, performance, and structural analyses to evaluate the design. The resultant analyses were implemented on a computer. The alternator proved to be a non-linear device and, therefore, a semi-empirical approach was used in its analysis.

The theoretical analyses were complemented with various tests. A commercial Cycloturbine was instrumented and tested to verify the aerodynamic, performance and structural analyses. The alternator was tested to provide data to characterize its performance. A number of towers were tested to determine their dynamic characteristics before a 42.5-ft Octahedron tower was recommended for use with the 1-kW SWECS.

Manufacturing costs were evaluated and the design scrutinized to improve cost. The estimated total cost for the 1,000th production unit (in 1977 dollars) was $1,994.

Completion of the design of the 1-kW High-Reliability Cycloturbine SWECS constitutes Phase I of the joint effort. Fabrication of three prototype units for testing will be done during Phase II.

®Cycloturbine is a registered trademark of the Pinson Energy Corporation.

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SECTION 1

INTRODUCTION

Rockwell International, under contract with the Department of Energy (DOE) to manage the Small Wind Systems Program, has initiated programs to develop prototype wind machines in the one-, eight-, and forty-kilowatt (kW) ranges. Rockwell manages the program for DOE at the Rocky Flats Plant near Golden, Colorado. In particular, the program for the 1-2 kW size wind machine has the following objectives:

- To develop a technology base for design, fabrication, and production of a high-reliability wind machine in the 1-2 kW size range for use in rural and remote applications.
- To provide fabrication cost data in sufficient detail to determine economic viability of wind machines in 1-2 kW size range.
- To fabricate and deliver three high-reliability 1-2 kW prototype wind machine units for testing at the Rocky Flats Wind Systems Test Center.

ASI joined with Pinson Energy Corporation (PEC) and Natural Power, Inc. (NPI) in offering a unique vertical-axis wind machine for development as a high-reliability SWECS. The wind turbine developed by PEC is called the Cycloturbine and is pictured in Figure 1. The turbine has three untwisted, straight blades which are held to a central shaft by streamlined support struts. The blades follow a preset schedule of angle changes during each revolution of the rotor. This cyclic blade pitch motion is activated by a cam mechanism which is oriented relative to the wind by a wind-direction tracking vane (similar to a weather vane) mounted above the machine. By introducing sufficient initial blade angle into the cyclic pitch schedule, the Cycloturbine, unlike the vertical-axis Darrieus turbine, becomes self-starting. In high winds, it is possible to pivot the blades to a position of least wind resistance making the rotor aerodynamically self-limiting. This is achieved through a mechanism which, at high centrifugal loads associated with increased rotational rate, changes the cyclic pitch schedule so that the blades are aerodynamically stalled. Another convenience of the configuration of the Cycloturbine is that it can be cantilever-mounted on top of a tower without the need of auxiliary guy wires.

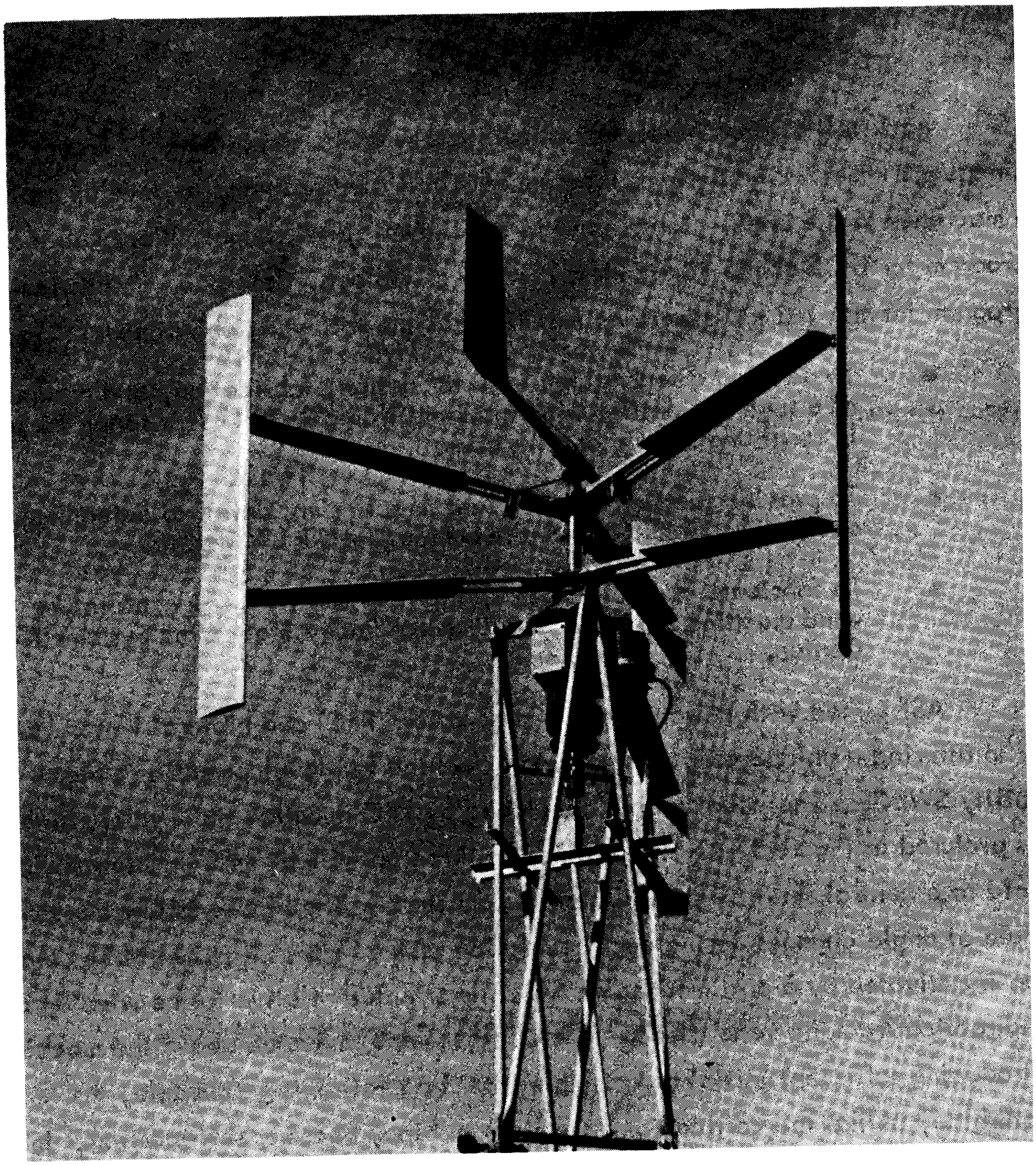


Figure 1. Pinson Energy Corporation Cycloturbine, Model C2E.

(Machine developed prior to high reliability prototype design)

Reliability considerations significantly impacted the design. A 1-kW output design was selected due to the unavailability of a sufficiently reliable and efficient 2-kW alternator with 24V DC output. Similarly, high-reliability power diodes for a 2-kW output were not commercially available. The tilt-cam mechanism was selected as the preferred design because of reliability. Higher quality bearings were also required in order to meet the reliability specification.

The Cycloturbine wind energy system is one of three designs presently being developed for Rockwell International to meet the objectives of their low-cost, high reliability program. The joint effort which is managed and integrated by ASI (see Figure 2) is being conducted in two phases, Phase I providing for the design and development of a 1-2 kW system by October 31, 1978; and Phase II providing for the construction of three prototype units for testing by Rockwell at its wind systems test center.

The design and development in Phase I were conducted by the schedule shown in Figure 3. Significant milestones are indicated in the schedule, the overall effort being paced by the three design reviews, namely: 1) Task 7, Preliminary (PDR); 2) Task 14, Critical (CDR); and 3) Task 20, Final (FDR).

Features of the SWECS design approved for fabrication in Phase II are summarized in Table 1.

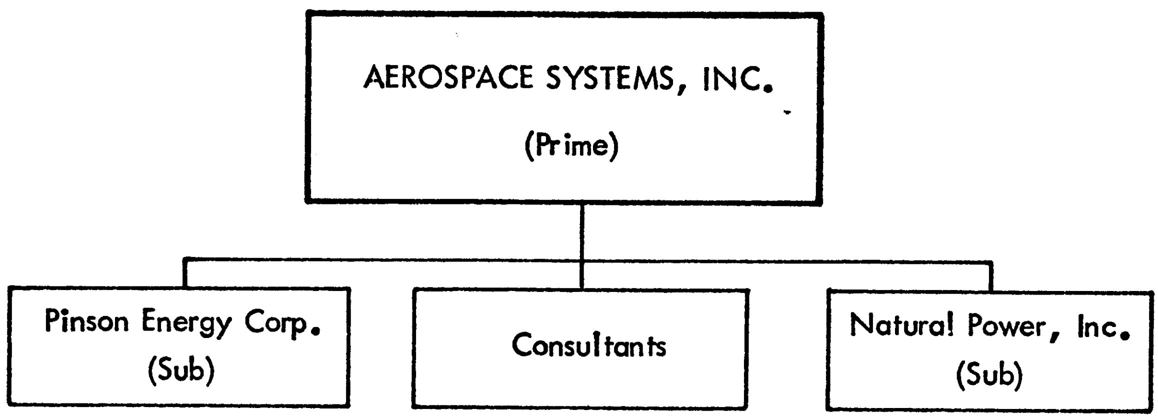
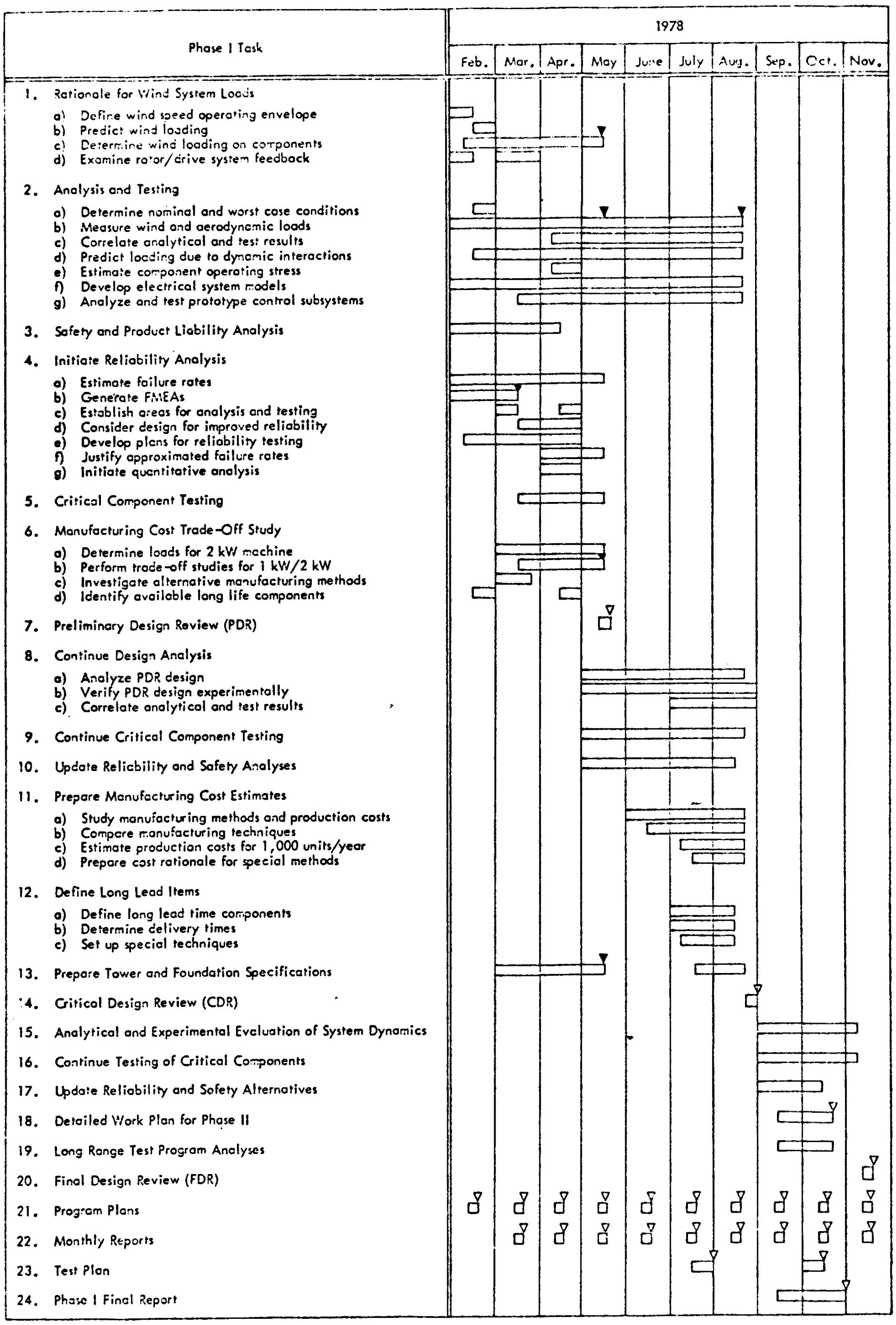


Figure 2. 1-kW High-Reliability SWECS Program Organization.



∇ Milestone ▼ Critical Milestones

Figure 3. Phase I - Master Schedule for 1-kW High-Reliability SWECS Program.

Table 1. 1-kW High-Reliability Cycloturbine Design Features.

Turbine:

- Vertical axis: 15-ft diameter
- Three (3) 8-ft blades
- Swept area: 120 ft^2
- NACA-0015 section with 1-ft chord
- Aluminum blades and struts
- Steel main shaft
- Weight: 508 lbs
- C_P = 0.4 at 9 m/s
- Cut-in velocity: 5 mph
- Cut-out velocity: 40 mph
- Cyclic control
- Aerodynamic/centrifugal shutdown control

Transmission:

- 25:1 speed increaser gearbox

Generator:

- 1-kW at 9 m/s
- 24V DC

Electronics:

- Voltage regulator and rectifier
- Two (2) transient suppression networks
- Dump load

Cost:

- $1,994 for 1000th unit

SECTION 2

DESIGN DESCRIPTION

2.1 REQUIREMENTS

The design requirements established for the 1-kW high-reliability SWECS consisted of design specifications and extreme environmental conditions which had to be withstood. The key design specifications are outlined in Table 2 and the extreme environmental conditions are established in Table 3. Design specifications which were particularly important were reliability and the capital cost goal whereas temperature range and lightning protection were the most important environmental conditions driving the design.

Table 2. Key Design Specifications.

Reliability:	MTBF 10 Years Minimum.
Maintainability:	One Maintenance Day/Year.
Durability:	Continuous Operation in Extreme Weather.
Power Output:	1-2 kW at 9 m/s (20 mph) Wind Speed.
Power Form:	26 ± 2 Volts DC with Voltage Regulation to Control Charging of 24 Volt Battery System.
Survival Wind Speed:	Steady Winds 54 m/s (120 mph), Gusts 75 m/s (165 mph).
Rotor Speed and Yaw Control:	Optional Design.
System Life Goal:	25 Years.
Capital Cost Goal:	$1,500/kW at 9 m/s (20 mph) Wind.

Table 3. Extreme Environmental Conditions.

Temperature:	-70°C to +60°C (-94°F to 140°F).
Rain:	Torrential Downpour with Winds.
Snow, Sleet, Icing:	Ice Buildup to 60 mm (2-1/2 in) Thick on Rotor System.
Hail:	Impact by Hail up to 40 mm (1-1/2 in) Diameter.
Wind:	Steady Wind 54 m/s (120 mph), Gusts 75 m/s (165 mph).
Salt Water Spray:	Heavy Ocean Spray.
Dust:	Fine Sand and Dust with Wind Gusts to 45 m/m (100 mph).
Corrosive Atmosphere:	Heavy Industrial Atmosphere Coupled with Salt Fog or Spray.
Lightning:	Repeated Strikes During Severe Thunderstorms.

NOTE: Values Represent Probable Extremes from Worldwide Applications.

Trade-off studies concentrated on the determination of the best size machine to build in terms of cost and reliability. A comparison of costs for both a 1-kW and a 2-kW machine was made to determine the feasibility of these power levels. Preliminary studies indicated that both machines could meet the cost goals for the thousandth unit but that the reliability of the 2-kW design would be less and probably would not meet the contract requirements.

In these preliminary studies, the reduced reliability for the 2-kW machine occurred largely in the electrical system. Primary factors influencing the electrical system reliability were the efficiency and reliability of available alternators and the availability of high-reliability power rectifiers. The following factors for a 2-kW design influenced the decision to recommend a 1-kW machine:

Alternator:

- Limited availability of alternators producing 24V DC.
- Available machines inefficient.
- Available machines use slip rings and brushes which, for the specified application, are unreliable.
- Development of a 2-kW alternator to meet the contract goals was considered to introduce undesirable uncertainties relative to reliability, performance, and schedule.

Power Diodes:

- Available in JAN TX quality (high quality) up to $I_f = 35$ amps (about 70 amps required for 2-kW machine).
- Reliability data on power rectifiers above 50 amps scarce.
- Rectifiers for $I_f < 35$ amps have a quality factor 5 times that of those for $I_f > 35$ amps.
- Rectifier bridge for a 1-kW machine has a failure rate about 2.5 failures/10^6 hours less than that for a 2-kW machine.

Design of the components of the Cycloturbine was directed towards reducing time of their manufacture. Extrusions and castings are employed to reduce labor hours in production. The struts and blade leading edges are aluminum extrusions which provide a high strength, low weight structure and simplifies fabrication. Steel is used in the main shaft, hubs and bearing cartridge where high strength is needed and weight is less important. These steel assemblies are the most labor intensive parts of the turbine because of the number of components which must be cut, welded and/or machined. To enhance electrical system costs, the dump load circuit was considered as optional.

Low temperature requirements affected the choice of grease, oil, seals, and protective coatings. Silicone oil and silicone grease, both of which meet the temperature specification, are used in the gearbox and roller bearings, respectively. Teflon was specified for the gearbox and bearing seals and for pivot bearing lining in the tilt-cam linkage and in the blade pivots. These latter applications also lessen the maintenance requirements for these bearings. Low temperature is generally not a problem for the electronic circuitry; however, components are not guaranteed below the stringent military requirement of -55°C.

Electronic circuitry is affected by high temperature which reduces the performance and the reliability of the components. Heat sinks were employed to dissipate expected heat rise in the circuits. Also, performance was achieved by proper circuit design; however, the design was constrained by possible reductions in reliability of these more complex circuits.

In order to provide a maintenance-free capability for extended periods (up to one year), it was essential to protect the SWECS electrical system from high-energy transients such as those caused by lightning strikes. A lightning rod and ground cable were provided to help protect against direct strikes. The electrical system required two transient suppression networks for lightning protection. One was placed near the alternator on the tower to deter lightning-induced energy from entering the alternator. The second was placed near the transmission cable entrance to the control building to deter transients from damaging electronic circuitry and the batteries located there.

2.2 CONFIGURATION

The 1-kW high-reliability SWECS designed by the ASI team consists of two major subsystems, namely: 1) rotor/transmission; and 2) electrical system.

The physical relationship of the assembled SWECS is shown in Figure 4. The rotor, transmission and the alternator and its transient suppression network are located on the tower. The remaining electrical components are located in the control building with the batteries.

The turbine has three blades with an NACA-0015 airfoil section set 120 degrees apart on a 7.5-ft radius. The blades extract energy from the wind in the form of aerodynamic loads which cause a torque on the main shaft. The aerodynamic load is controlled by controlling the pitch angle of each blade. Each blade is mounted on two struts which are bolted to twin hub plates welded on the main shaft. A stay passes from the upper hub to the lower strut to provide additional support to resist ice loads.

The main shaft is the central support for the struts and blades. The shaft turns in two flange-mounted ball bearings set in either end of the bearing cartridge. The lower end of the shaft is affixed to the gearbox transmission and the upper end of

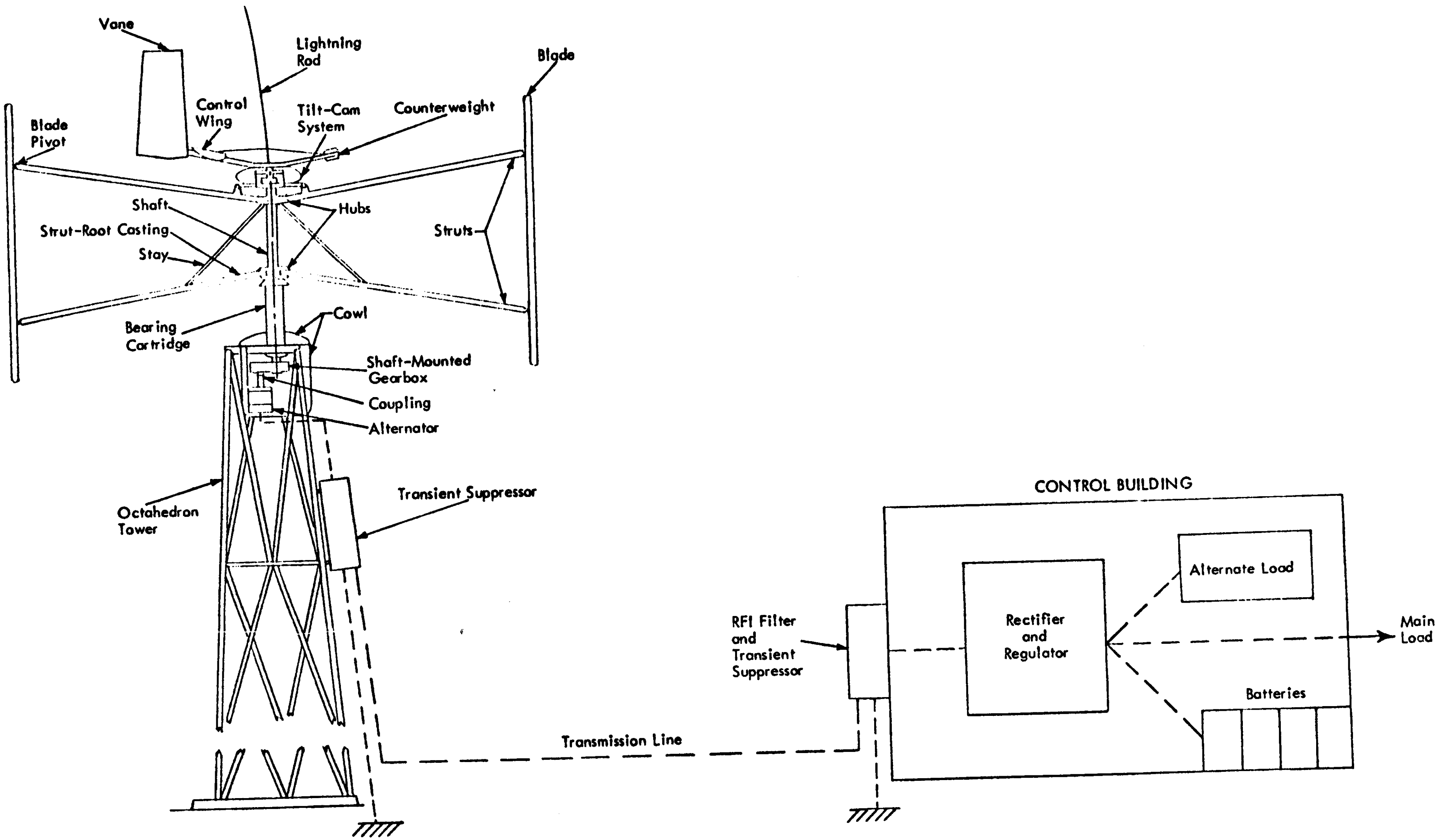


Figure 4. High-Reliability Cycloturbine Components.

the shaft houses two cam steady bearings which support the tilt-cam control system. The tilt-cam rotates independently of the main shaft. The steel bearing cartridge which houses the main bearings is part of a welded triangular steel structure which bolts to the top of the tower.

The actuation control system consists of a tilt-cam and a series of mechanical linkages which activate pull rods (located in the upper struts) which in turn rotate the blades about their hinge point. The purpose of the control system is to provide a prescribed angle-of-attack, that is, the angle between the blade chord and the relative wind, for each of the blades as they rotate through each cycle. As the main shaft rotates, the tilt-cam mechanism causes the blade position to change. Thus, the tilt-cam introduces an eccentricity into the system which acts like a mechanical cam.

The vane and wing assembly provides orientation and shutdown control for the tilt-cam actuation control system. The vane is attached to a boom which, in turn, is rigidly attached to the tilt-cam. As the wind changes direction, the aerodynamic loads on the vane cause it to rotate, thereby, reorienting the tilt-cam. This action ensures that the blade angle schedule is oriented relative to the wind.

The wing is an aerodynamic surface mounted horizontally to the vane boom. It is designed to produce a download with increasing wind velocity. At a prescribed aerodynamic load, calibrated to a selected wind speed, the download on the wing offsets the balance weight located at the end of the boom. This causes the tilt-cam angle to increase which results in a reduction in the blade pitch angles. The effect is to decrease the aerodynamic forces on the blades which reduces the torque and causes the Cycloturbine to shut down. The same effect will occur if the wing is heavily loaded with ice.

The transmission is a commercially-available Morse gearbox with a 15:1 step-up ratio. The gearbox is mounted on the tower top structure and is driven directly by the main shaft. A coupling is attached to the gearbox output and connects it to the NPI 1-kW alternator.

The rectifier converts the three-phase AC power from the alternator to direct current and provides the power to excite the alternator field through a separate rectifier. The rectifier is located in the central building to group it with the other semiconductors that need to be protected from low temperature extremes.

The voltage limiter control (or regulator) is designed to regulate the output voltage of the alternator between 24 and 28 volts in the event that the main load or dump load associated with the voltage controlled relay cannot dissipate all the energy available.

The voltage controlled relay circuit (dump load) is used to increase the load on the turbine when the battery becomes fully charged. This unit is set to operate just before the voltage limiter.

The transient suppressors and RFI filters are designed to protect the devices (alternator and the electronic circuitry in the control building) at the transmission line terminations from transient voltages (such as from lightning strikes) and high frequency electromagnetic radiation.

SECTION 3

PERFORMANCE

The performance of the 1-kW high-reliability SWECS was determined using analyses developed by ASI and implemented on a digital computer.
The predicted performance for the 15-ft diameter turbine is shown in Figure 5. The curve was derived from a modified analysis based on test results for a similar configuration Cycloturbine. Performance analyses conducted for the preliminary turbine design with a 12-ft diameter indicated that the power derived from the wind might be marginal. As a result the design diameter was increased to 15-feet.

The power output of the machine in terms of kilowatts delivered to the batteries is shown in Figure 6 as a function of the wind speed. The annual kW-hr production available from the 1-kW SWECS is shown in Figure 7 for various average wind speeds.

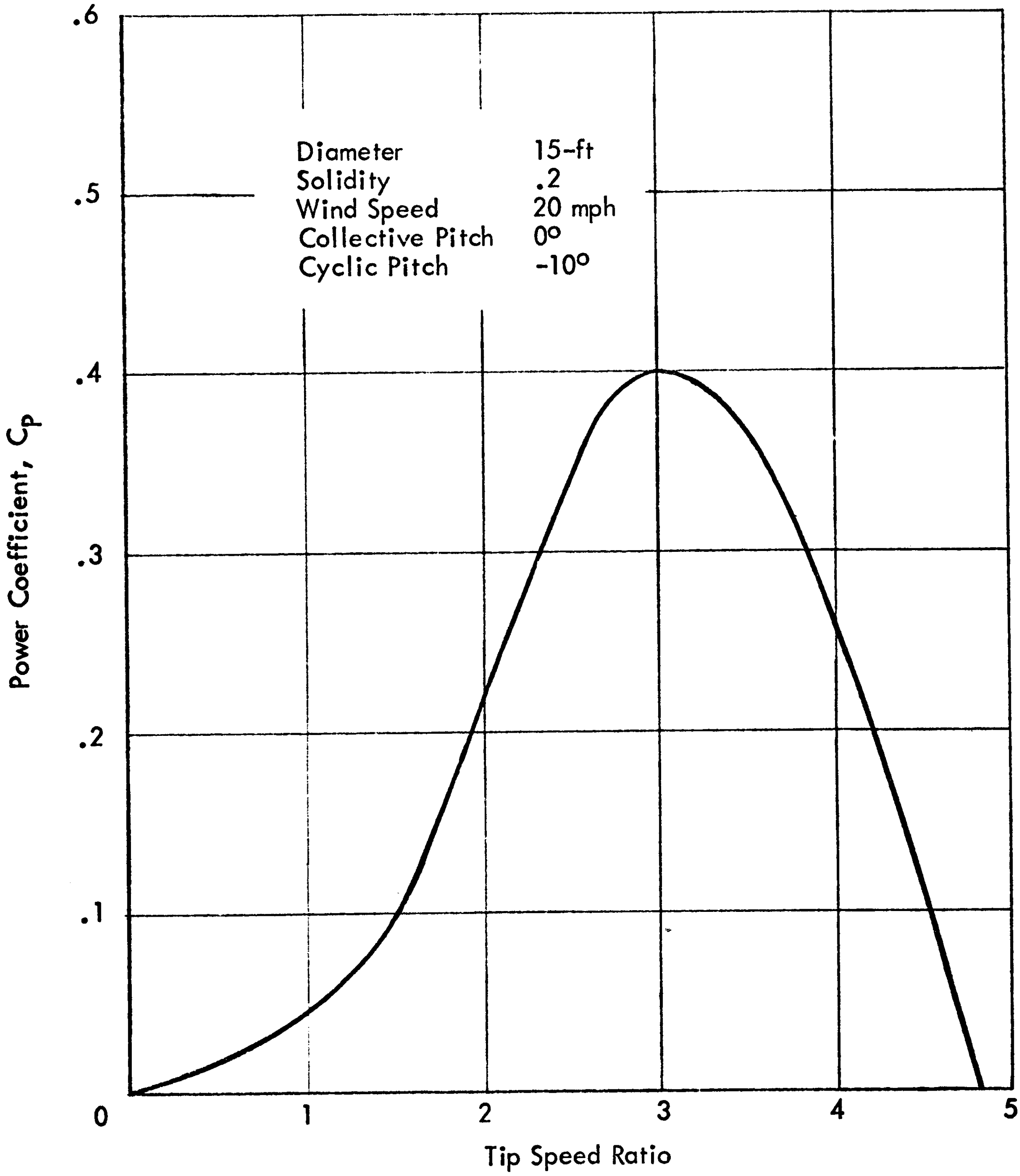


Figure 5. 1-kW High-Reliability Cycloturbine Performance.

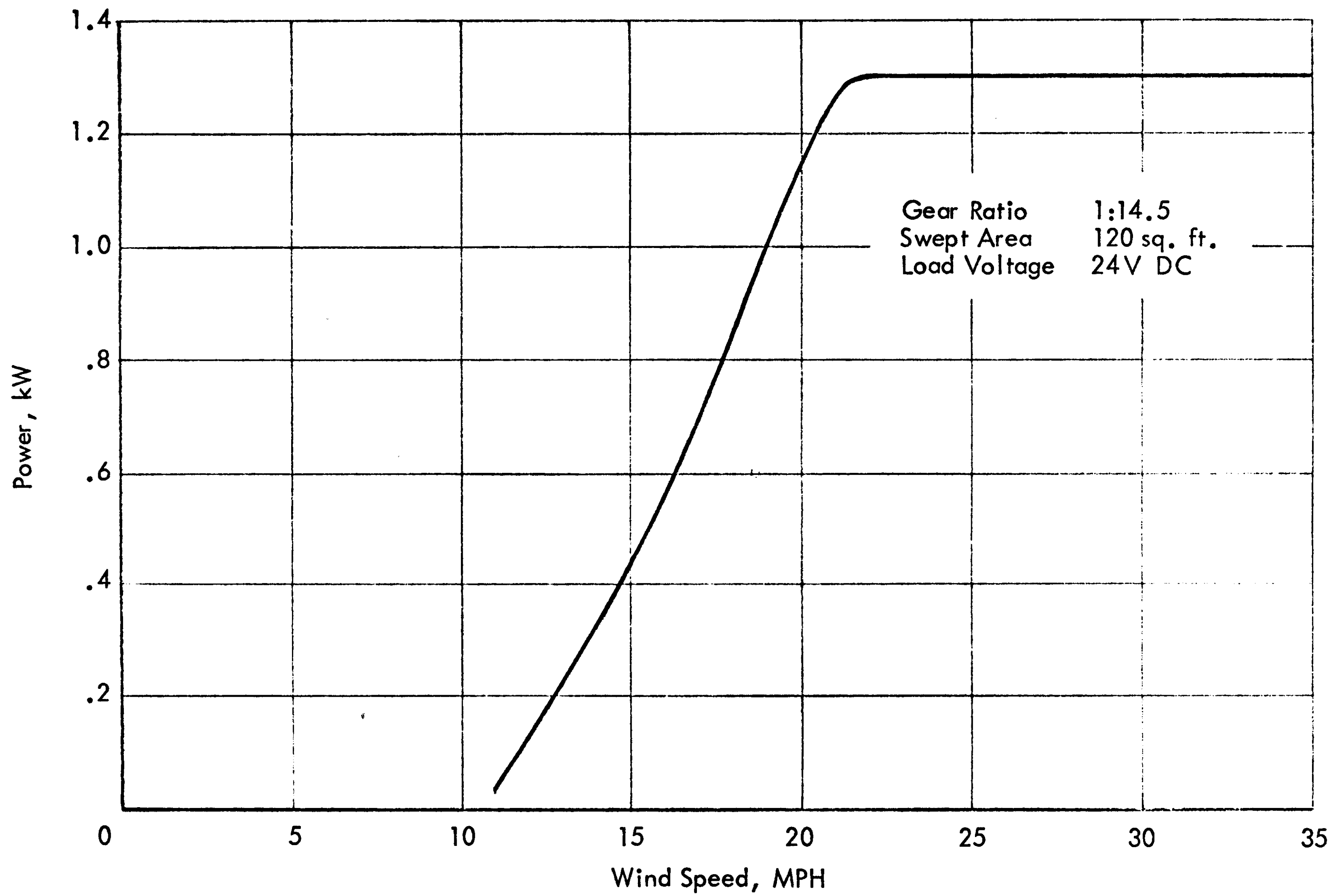


Figure 6. High-Reliability Cycloturbine Power Output.

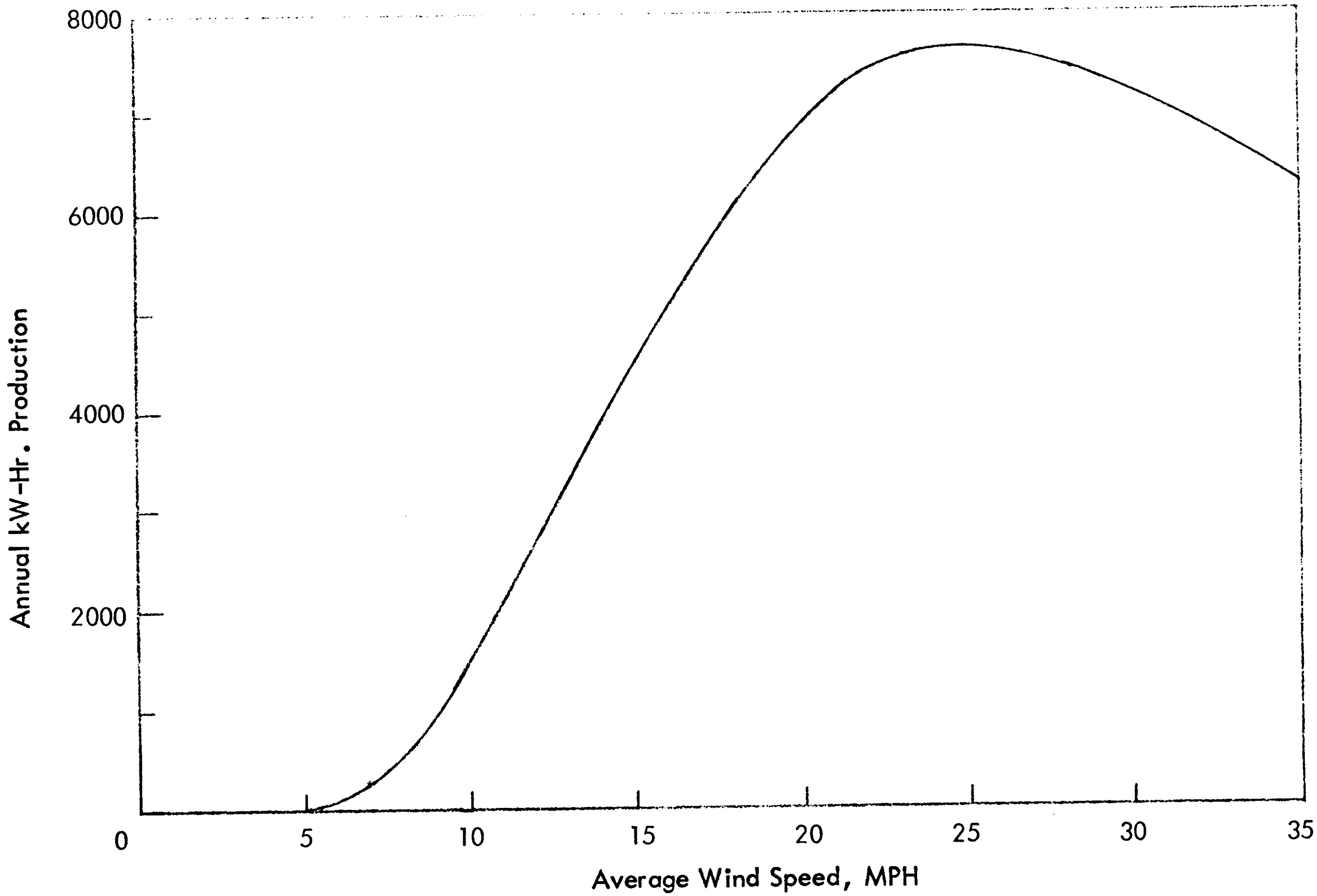


Figure 7. High-Reliability Cycloturbine Annual Energy Production.

SECTION 4

STRUCTURAL LOADS

A structural design analysis was developed for the vertical-axis turbine and implemented on the ASI computer. The analysis was used to check critical areas for the stresses imposed by aerodynamic, centrifugal and inertial loads. Critical structural loads were determined at points where bending moments and/or combined axial loads reach a maximum. These points include the center of the blade spar, the blade/strut connection, the strut root, the main shaft at the main bearings, and the pull rods in the control actuation system. The selected design was checked over the various operating ranges specified in Table 4 and was found to provide positive margins of safety for all conditions.

Table 4. 1-kW High-Reliability Cycloturbine Operating Ranges.

Operating Range	V (MPH)	Ω (RPM)	Collective Pitch (Degrees)	Cyclic Pitch (Degrees)
Nominal	20	112	0	-10
No Load	0-5	0-28	0	-10
Normal	5-28	28-160	0	-10
RPM Limited	28-40	160	0	-10
Stalled	40	160	-45 (collective) 0 (tilt-cam)	10 10
Static (Stopped)	40-120	0	-45 (collective) 0 (tilt-cam)	10 10
	165 (120 mph and 45 mph gust)	0	-45 (collective) 0 (tilt-cam)	10 10

SECTION 5

RELIABILITY

Reliability of the 1-kW SWECS was determined in order to verify that the design qualified as a high-reliability machine. To meet the reliability, maintainability, durability and system life goals (see Table 2), a reliability program was established. The program consisted of the following elements:

- A failure mode effects analysis (FMEA) to identify critical components.
- Determination of areas requiring specific analysis or test.
- Estimation of failure rates for individual components.
- Justification of failure rates which had to be approximated.
- Quantitative prediction of overall system reliability.
- Establishment of a maintenance schedule.
- Establishment of test procedures to establish failure rates and to predict component life.

Reliability was of particular importance in the selection of bearings. Bearings were chosen to have high load-bearing capacity, to have long life, and to be maintenance free, if possible. Electrical system reliability affected the choice of alternator and was constrained by the lack of available power rectifiers of the required reliability grades.

Quantitative prediction of overall system reliability for the 1-kW SWECS was determined in terms of the mean time between failure (MTBF) which was based on failure rate data for various components. Failure rates were calculated for electronic components using standardized equations. Rates were estimated for Cycloturbine bearings using manufacturer's bearing life data. These data reflect a minimum wear condition of the bearings. Failure rates were also estimated for various structural components and for the gearbox.

The approach used in the reliability analysis by ASI was to determine the probability of nonfailure of the system where failure is defined as excessive wear. Thus, the MTBF defined for the Cycloturbine is one in which the machine would continue to function but with parts exceeding wear tolerances, the result of which would eventually lead to degraded performance or failure of a more serious nature. Results for the quantitative reliability analysis based on wear failure data and failure rate estimates are given in Table 5.

Table 5. 1-kW High-Reliability Cycloturbine SWECS Reliability.

Assembly	Failures/ 10^6 Hrs.	MTBF (Yrs.)	One-Year Reliability
Turbine (bearings and structure)	5.613	20.39	.95215
Gearbox (includes coupling)	.110	1041.17	.99904
Alternator	.824	138.97	.99283
Electronic circuits (includes dump load)	4.181	27.38	.96413
Tower and foundation	.011	9999.50	.99990
Total SWECS	10.739	10.66	.91045

Evaluation of the reliability of the 1-kW high reliability Cycloturbine showed that the requirement of MTBF of 10 years (Table 2) is satisfied even when the tower and foundation are included which was not a design requirement. This result is based on wear failure data.

SECTION 6

MANUFACTURING COSTS

Manufacturing cost estimates were determined for both prototype units and a mass-produced 1000th unit. Cost estimates for a prototype Cycloturbine were readily obtained based on the experience of PEC in the manufacture of commercial units. Learning curves and company growth estimates were combined with this experience to arrive at estimates for the 1000th production unit. A similar situation exists for production of the alternator by NPI. However, for the electronic portion of the electrical system, estimates for the 1000th unit were based on established production figures which are available for mass-produced electronic components. The Cycloturbine and electrical system manufacturing costs for the 1000th production unit are presented in Table 6. All costs are in 1977 dollars.

Table 6. 1-kW High-Reliability SWECS Cost Elements.

1000th Production Unit

1977 Dollars

Cost Elements	Cycloturbine	Electrical	Total
Direct Material	$ 720	$570	$1,290
Material Overhead (10%)	72	57	129
Direct Engineering Labor	8	4	12
Engineering Overhead (150%)	13	7	20
Direct Manufacturing Labor	70	68	138
Manufacturing Overhead (100%)	70	68	138
Other Costs	18	16	34
Subtotal	$ 971	$790	$1,761
General and Administrative Expenses (5%)	48	39	87
Subtotal	$1,019	$829	$1,848
Profit (8%)	80	66	146
Total Price per Unit	$1,099	$895	$1,994

SECTION 7

TOWER SPECIFICATION

It was necessary to specify a tower which is compatible with the 1-kW SWECS design. A wind machine mounted on its tower represents a coupled dynamic system which can experience adverse interactions or excessive response to unsteady wind inputs. A SWECS cannot be considered reliable and totally safe under all environmental conditions without studying the coupled tower/rotor system. Therefore, a dynamic response analysis was conducted for the Cycloturbine/tower system which showed that significant response could occur.

Tests were conducted on two candidate towers, a heavy-duty Octahedron and a Rohn SSV, to determine their dynamic characteristics. This was necessary to ensure that the towers would not introduce dynamic response problems with the 1-kW SWECS. It was concluded that both towers are acceptable for use in the 1-kW high reliability Cycloturbine test program. However, the Octahedron tower was recommended because it can be erected more easily by hand at remote locations and because PEC has more experience with the Cycloturbine on Octahedron towers.

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