DOE/NASA/9404-76/1
NASA CR-134936
R-1382

NASA-CR-134936

DESIGN STUDY OF WIND TURBINES 50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS
Executive Summary

See also:
NASA-CR-134937
for Analysis & Design

Kaman Aerospace Corporation

July 1977

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-19404

for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Solar Energy

M78-14785

NOTICE

DOE/NASA/9404-76/1
NASA CR-134936
R-1382

DESIGN STUDY OF WIND TURBINES 50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS

Executive Summary

Kaman Aerospace Corporation
Old Windsor Road
Bloomfield, Connecticut 06002

July 1977

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Under Contract NAS 3-19404

for
U. S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Solar Energy
Washington, D. C. 20545
Under Interagency Agreement E(49-26)-1010

Page intentionally left blank

Page intentionally left blank

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

FOREWORD

This executive summary describes a study of wind energy conversion systems for electric utility applications. Complete details are presented in Design Study of Wind Turbines, 50 kW to 3000 kW, for Electric Utility Applications, NASA Report CR-134937, Kaman Aerospace Corporation Report R-1382, hereafter referred to as the "Design Study." The nine-month program was conducted under contract NAS3-19404, awarded by the National Aeronautics and Space Administration (NASA), Lewis Research Center, in November 1974, as a part of the Energy Research and Development Administration's Federal Wind Energy Program. John Sholes was the NASA project manager and provided valuable review and guidance throughout the program.

Special acknowledgement is made to Northeast Utilities and their personnel who assisted in the project. Michael Lotker served as the project coordinator for Northeast Utilities. Valuable assistance was also rendered by the Colorado Springs Public Utilities and by the Connecticut Department of Environmental Protection.

The Mueller Engineering Corporation and The Lightning and Transient Research Institute contributed critical specialized technical assistance. In addition, numerous equipment and structure suppliers furnished technical and cost data for the study.

Many personnel at Kaman Aerospace Corporation contributed to the study. Those who led the effort and wrote the final report were: Donald Brierley, Robert Collins, Thomas Cook, Herbert Gewehr, George McCoubrey, Richard Meier, Robert Paterson, Arved Plaks, John Schauble and Charles Wirth. George Neu prepared this summary.

INTRODUCTION

Concern over environmental pollution, the 1973 oil embargo, and the dramatic increase in imported oil prices in recent years have rekindled interest in harnessing the wind to produce electricity. The Energy Research and Development Administration (ERDA), as part of its overall plan to reduce U. S. dependence on overseas energy resources, delegated to the National Aeronautics and Space Administration (NASA) administrative and technical direction of programs to develop large-scale wind generator systems compatible with existing electric utility grids. The purpose of the program was to study and analyze various sizes of wind-energy generators, configurations of rotors, generating and control components and support structure (towers and foundations). From this study, Kaman was to develop two preliminary wind turbine designs to produce electrical energy at the lowest cost per kilowatt-hour. These optimized designs were to include a low-power system between 50 and 500 kilowatts, and a high-power system between 500 and 3000 kilowatts.

NASA established certain guidelines to focus and control the program. In its broad essentials, the wind generator systems (WGS) were to have a horizontal axis propeller or rotor on one end of the system (input) and a normal public utility electric grid on the other end (output). In between, Kaman was free to design and optimize the system, including the rotor itself, to produce power at lowest cost per kilowatt-hour.

The specific guidelines established by NASA were:

1. The WGS should produce power at a cost competitive with other power generating methods, and must be compatible electrically with existing electric utility grids.
2. Only horizontal-axis, propeller-type rotors are to be considered. However, the number of blades, the hub type, blade control, type of tower, number of rotors on a tower, and rotor size are unspecified.
3. The WGS must operate automatically without an attendant on-site. It must also be capable of being started (providing wind speed is sufficient) and stopped from a remote location.
4. Designs will not include provisions for storage of power. Power will be fed directly into a standard utility network.
5. State-of-the-art, available technology is to be used to the maximum, and off-the-shelf commercial parts, components, and subsystems used whenever possible.
6. Government-furnished wind data are to be used. Sites with median wind speeds of 12 and 18 mph are to be used for preliminary design and evaluation.

7. A 30-year life for rotor, drive and generating subsystems, and a 50-year life for structure are required.

8. Costs are to be calculated for production quantities of wind generating systems.

Kaman established some additional guidelines:

1. Use proven rotor and rotor control designs.

2. Apply known, low-cost rotor fabrication techniques.

3. Coordinate closely with an operating utility.

4. Use subcontractors and consultants to augment in-house capability, particularly in critical electric utility institutional cost estimating.

The program was divided into three phases for control purposes, and the phases subdivided into major tasks. Phase I consisted of two tasks:

1. Conceptual Design. Identify and evaluate feasible WGS design alternatives and based on estimates of sizes, weights, efficiencies and costs, select the best to be optimized.

2. Computer Program. Develop a parametric computer program to optimize the concept selected.

Phase II also had two tasks:

1. Concept Optimization. Use the computer program to optimize the selected concept within the constraints and guidelines.

2. Utility Applications and Requirements. Study the technical interface requirements of the WGS with a utility system and the economic considerations affecting its operation in an existing power grid. Explore the difficulties of using a new power-generating technology such as WGS.

Phase III consisted of the preliminary design of a high- and low-power system, and further refinement of subsystem development and production costs in order to derive accurate capital and energy costs.

The body of this executive summary will proceed chronologically by phase and task. It will describe how the work was performed, the major considerations and rationale for concept selection and optimization, and the key factors affecting system, subsystem, and component preliminary design and selection. Conclusions supported by the study will be listed, and recommendations made.

PHASE I

CONCEPTUAL DESIGN

Many basic concepts within the broad ground rules were studied at the outset of the conceptual design phase in arriving at a basic configuration. From these studies, the subsystems were identified and an arrangement of components emerged as follows:

1. A rotor subsystem to extract energy from the wind and convert it to useful torque to drive the electric generator.
2. A controls subsystem to position the WGS relative to the wind direction, start and stop the WGS, control the rpm of the rotor, regulate power output, monitor the system for faults and initiate emergency shutdown, and record and transmit certain data to a control station.
3. A structure subsystem to support and protect the generating components. The structure includes foundation, tower, turntable upon which the generating components rest and which interfaces the stationary structure with the rotating structure, and an enclosure to protect the generating components from the elements.
4. A drive subsystem to transfer and convert the high-torque, low rpm of the rotor to the low-torque, high rpm input to the generator. It includes the rotor drive shaft, speed-increaser gearbox, and shafting from the gearbox to the generator. Ancillary items also considered part of the drive subsystem include blade pitch control mechanism, turntable drive mechanism, parking brake and a hydraulic power system for the orientation and pitch controls.
5. The electrical subsystem to convert the energy of the rotor to electric current and feed the electricity to the grid. It includes the generator, cables, protective relaying equipment and controls, a transformer, and main circuit breakers.

A considerable number of concepts for arrangement and placement of subsystems were eliminated during the course of the study because of technical complexities and cost disadvantages. As one example, intuitively it might seem desirable to house heavy generating equipment on the ground, thus saving weight and space atop the tower. However, such an arrangement requires a high-torque, high-angle gearbox and considerable shafting, with bearing supports, to route the output torque of the rotor to the generating equipment. No such gearboxes are presently available commercially, and even if they were, they would be very heavy, thus largely offsetting the weight of the generating equipment. Therefore, to keep cost and risk low, the decision was made to house the generator in the enclosure atop the tower.

This analysis is typical of many which were necessary to pin down a concept within the guidelines of the program. Certain considerations were amenable to specific analysis while others were based heavily on engineering judgment.

As the analysis expanded, the general outline of the WGS and its elements took clearer form, and is shown schematically in Figure 1.

Candidate Systems

From consideration of feasible alternatives, eight candidate systems evolved which met the study guidelines and from which all major component options, except the structure, could be evaluated consistently. The candidates included various combinations of rotor, gearbox, and generator and are listed in Table 1. Choices for the structure, which includes the tower itself, the turntable which carries and orients the dynamic components, and the foundation, were not considered a part of the candidate configurations in the study, since it was determined very early that the type of tower and foundation could be selected largely independently of the dynamic components, then sized to accommodate these components and the imposed loads. Alternatives for structural configurations are discussed separately.

As shown in Table 1, candidate concepts consisted of various combinations of the three principal components: rotor, gearbox and generator. The rotor, because of its inherent mechanical and aerodynamic complexity and its sheer size, was the critical element influencing the overall design. Therefore, the rotor became the pacing component and the other parts of the dynamic system were selected to be compatible with it.

Rotor - Rotor concepts considered, apart from obvious consideration of diameter, number of blades, number of rotors per tower and the like, were characterized by their operating mode and method of torque regulation. The operating mode may be either constant or variable rotational speed. Torque regulation is necessary to limit rotor output torque at wind speeds higher than the rated wind speed for which the system is designed, to prevent mechanical and electrical limits from being exceeded.

A rotor with fixed pitch blades is very attractive in terms of simple, low-cost blade and hub design. Such a rotor would normally operate at a variable rpm which changes with the wind speed, resulting in operation at peak aerodynamic efficiency. However, it requires additional complexity in the gearbox and generating subsystems, so that the electric power generated is at the constant frequency required for the power grid.

Constant rpm rotors, on the other hand, usually have more complicated variable pitch blades and a more complicated hub. The operating rotor rpm is then chosen to maximize aerodynamic efficiency at a particular wind speed. Aerodynamic efficiency, therefore, suffers a small penalty at all other wind speeds. As noted below, aerodynamic efficiency is not an important factor when operating in wind conditions higher than rated wind speed.

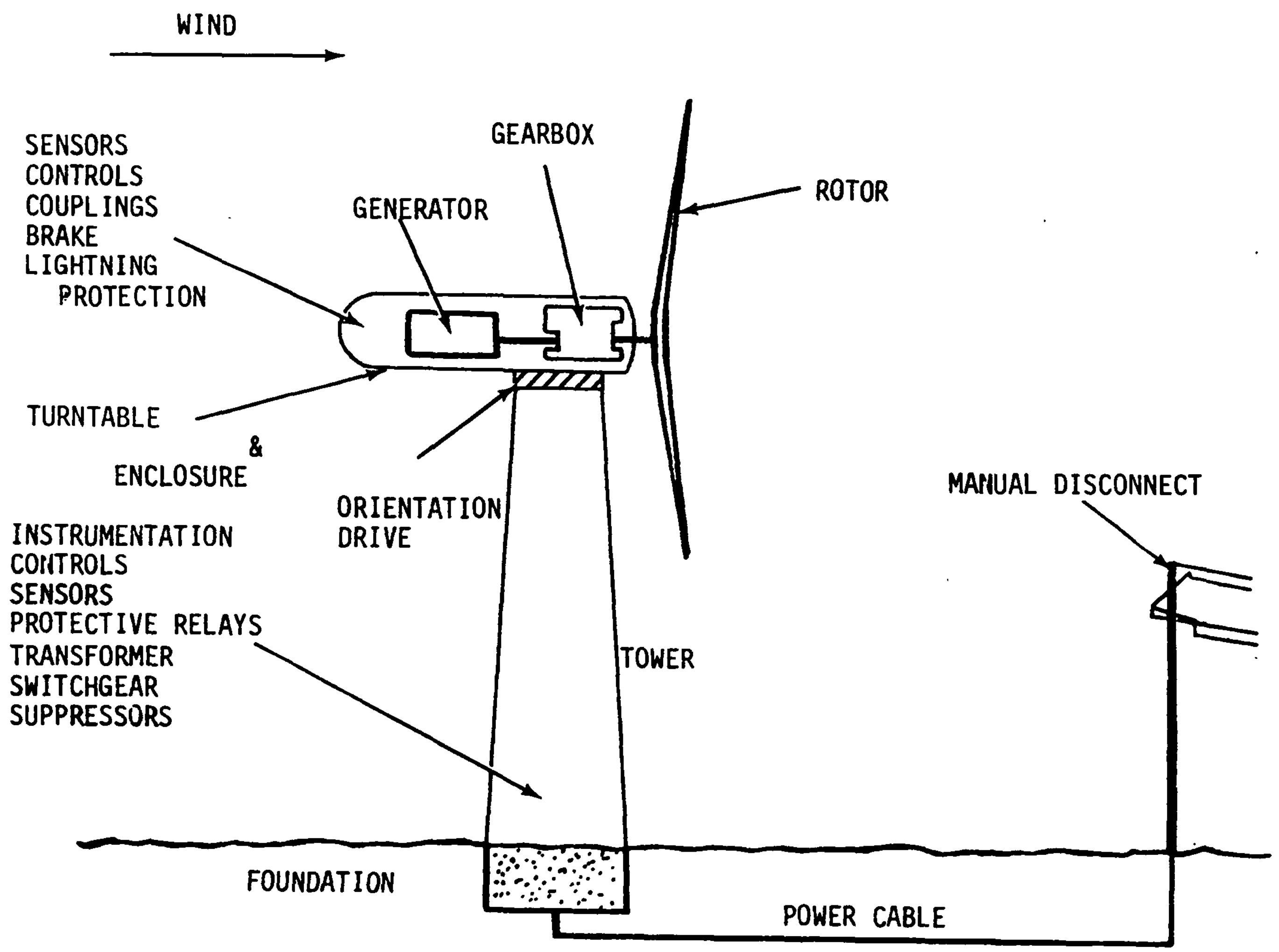


Figure 1. Typical Wind Generator System Elements

TABLE 1. CANDIDATE CONFIGURATIONS

CONCEPT	ROTOR	GEARBOX	GENERATORS
1.	VARIABLE PITCH CONSTANT SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS
2.	VARIABLE PITCH TWO SPEED	TWO SPEED RATIO GEAR	AC SYNCHRONOUS
3.	FIXED PITCH CONSTANT SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS
4.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	DC GENERATOR DC MOTOR/AC GENERATOR
5.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS TRANSFORMER AND RECTIFIER DC MOTOR/GENERATOR
6.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS TRANSFORMER AND RECTIFIER SOLID STATE INVERTER
7.	FIXED PITCH VARIABLE SPEED	VARIABLE RATIO (HYDROSTATIC)	AC SYNCHRONOUS
8.	FIXED PITCH CONSTANT SPEED VARIABLE DIAMETER	FIXED RATIO GEAR	AC SYNCHRONOUS

For constant rpm rotors, the drive and electrical subsystems are simplified and are more efficient, which compensates for the reduced aerodynamic efficiency. This type of rotor is controlled by a synchronizing torque through the AC generator, which causes the rotor to maintain the selected rpm.

As mentioned previously, rotor torque regulation is necessary to prevent drive train and generator limits from being exceeded when the wind speed is higher than rated. This may be done several ways. Blade pitch variation can be used to reduce aerodynamic efficiency, either by direct mechanical control of the blade root or indirectly by varying the pitch of a servo flap near the blade tip. Either method is applicable to the constant rpm, variable-pitch rotor, but not to the fixed-pitch variable rpm. Torque regulation for the latter could take the form of drag flaps, aerodynamic spoilers, or a mechanical variation in blade length. Of course, any of these techniques adds complexity which tends to negate the simplicity ostensibly enjoyed by the fixed-pitch rotor.

Gearbox - A speed-increasing gearbox is required to convert the relatively low rotor shaft rpm (less than 50), to the high rpm (greater than 1000) required by the generator. Methods considered include belt and chain drives, variable-ratio hydrostatic devices, two-speed gearboxes, and fixed ratio gearboxes. The belt and chain drives available simply do not have enough torque capacity and were dropped from consideration. The simplest, least costly gearbox has a fixed ratio. It is readily available commercially in a variety of sizes. The variable-ratio and two-speed gearboxes, also available commercially, were initially considered feasible alternatives, and were retained in the candidate concepts.

Generator - For a constant speed gearbox output, the AC synchronous generator and the induction generator are attractive candidates since they are designed to operate with a constant rpm input. The AC synchronous generator is most widely used and accepted in the industry, although the induction generator also has applications. A variable-speed input to the synchronous generator, such as would result from a variable-speed rotor driving a fixed-speed or two-speed gearbox, required additional devices to synchronize the frequency of the generator output to that of the electric grid. For those rotors, the conversion of rotor power to the desired constant frequency electric output can be accomplished by using the variable-speed rotor to generate DC power, either by a DC generator or a combination of an AC synchronous generator with a transformer and rectifier, then converting the DC power to 60 Hz AC to feed the grid. This latter step can be done either by the DC motor driving an AC synchronous generator or a solid state inverter. Each of these variable rpm rotor approaches suffers from efficiency, weight, and cost penalties compared with a constant rpm rotor driving a synchronous AC generator.

From the considerations just discussed, the eight feasible candidate concepts of Table 1 were retained for further evaluation.

Evaluation of Candidate Systems

Candidate Systems - Systems were evaluated by sizing them with a consistent set of ground rules. They were sized for the two prescribed median wind speeds. A 100 kW system was used for the 5.4 meters per second (m/s) (12 mph) median wind speed, and a 1000 kW system for the 8 m/s (18 mph) median wind speed. Rated wind was defined as the lowest wind speed at which the WGS develops rated power. The yearly energy output, weight, and costs were determined with emphasis placed on distinguishing differences between concepts. In the evaluation, the main criterion was energy cost, although capital cost was also an important consideration. Both are shown for each concept in Figure 2 on a relative basis, with concept 1 used as a base for normalization. Both the 100 kW and 1000 kW systems showed the same relative cost characteristics. For example, in Figure 2, candidate system 4 (fixed pitch, variable rpm) shows a relative direct capital cost ratio of about 1.26 and a relative energy cost ratio of about 1.04. The relative costs apply to both the 100 kW and 1000 kW systems. The results of this analysis, therefore, are largely independent of rated power and hence, median wind speed.

Figure 2 shows that those systems which drive the AC synchronous generator directly (concepts 1, 2, 3 and 8) have the lowest energy and capital cost. Of these, the variable diameter rotor (concept 8), though feasible, has high technical risk. The two-speed rotor (concept 2) also has greater technical risk due to the need to design the rotor and tower to avoid sustained operation at rotor and tower resonant frequencies. This leaves concepts 1 and 3 as the most attractive. However, it seemed prudent also to carry one of the variable speed candidates through conceptual design for more detailed evaluation prior to final concept selection. Of those, concept 5 was chosen from among the 4 variable-speed candidates primarily on the basis of lowest costs.

It should be pointed out that in addition to the cost considerations, good technical reasons exist for eliminating most of the candidates. Any variable speed electrical system requires converting variable shaft rpm into the constant frequency required to feed the utility grid, as discussed above. Although there are several combinations of equipment that can be used to perform the conversion, cost and weight favor a variable-rpm AC generator driving a transformer-rectifier, driving a DC motor, driving an AC generator or a solid-state inverter. Obviously, this system, with a number of elements in series, suffers several major disadvantages. DC machinery is substantially heavier and more expensive than AC equipment of equal capacity. It is also less efficient, especially at partial power, and requires more maintenance. The solid state inverter offers the potential of better reliability and lower maintenance, but still suffers substantial cost penalties. The cost of controls and protective equipment also goes up. Finally, cascaded components reduce the net efficiency of the system considerably.

	ROTOR	TRANSMISSION	ELECTRICAL
1.	VARIABLE PITCH CONSTANT SPEED (BASELINE)	FIXED RATIO GEAR	AC SYNCHRONOUS GENERATOR
2.	VARIABLE PITCH TWO SPEED	TWO SPEED RATIO GEAR	AC SYNCHRONOUS GENERATOR
3.	FIXED PITCH CONSTANT SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS GENERATOR
4.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	DC GENERATOR DC MOTOR AC SYNCHRONOUS GEN
5.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS GEN TRANSFORMER & RECTIFIER DC MOTOR/AC SYNCH GEN
6.	FIXED PITCH VARIABLE SPEED	FIXED RATIO GEAR	AC SYNCHRONOUS GEN TRANSFORMER & RECTIFIER SOLID STATE INVERTER
7.	FIXED PITCH VARIABLE SPEED	VARIABLE RATIO HYDROSTATIC	AC SYNCHRONOUS GENERATOR
8.	FIXED PITCH CONSTANT SPEED VARIABLE DIAMETER	FIXED RATIO GEAR	AC SYNCHRONOUS GENERATOR

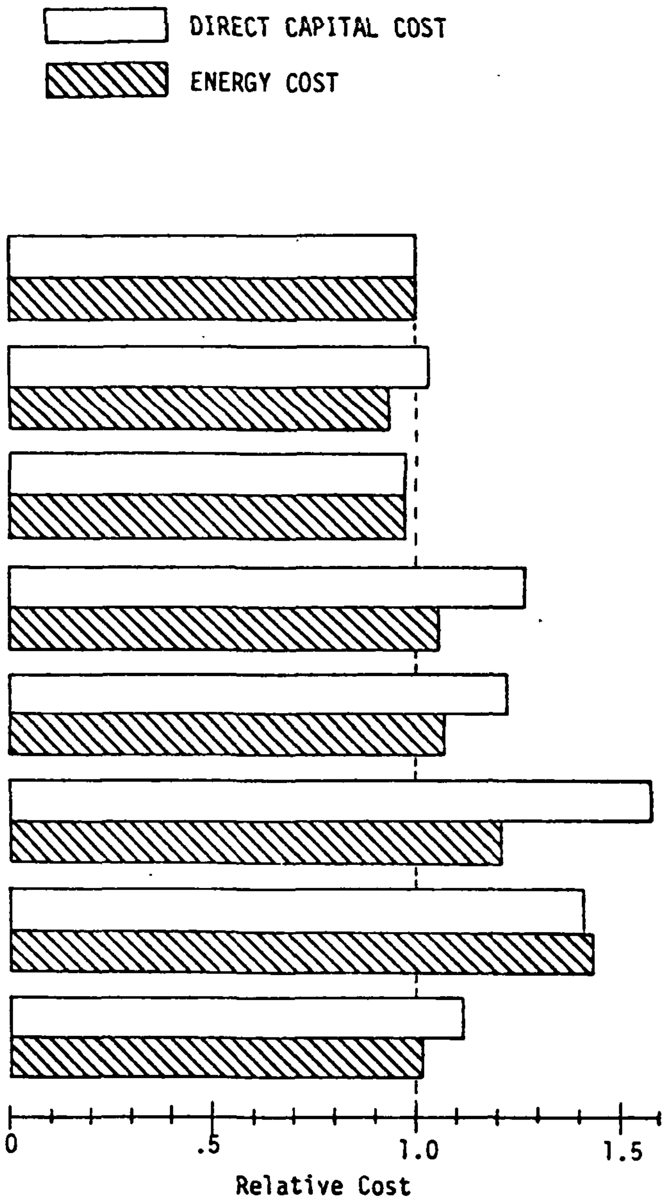


Figure 2. Results of WGS Concept Evaluation Phase

Tower

The tower supports the rotor and generating subsystems and serves as the fixed platform upon which they rotate and are oriented into the wind. It must absorb the static and vibratory forces imposed by the rotor and resist the wind forces acting on the tower itself. The fatigue strength of the tower must be great enough to withstand the rotor-induced vibratory loads, including effects of startup and shutdown cycles, gust variations, tower shadow, and gravity for a 50-year service life. The stiffness of the tower must be selected so that coupled rotor-tower natural frequencies avoid integral multiples of the rotor operating frequency.

As stated previously, it was determined that the candidate concepts for the dynamic components could be formulated and evaluated independently of the structure. However, several tower configurations were considered and evaluated. To minimize cost, existing commercial materials and standard construction techniques were used for all tower concepts. This limited the practical choices to structural steel and concrete, so the focus was on configuration rather than materials. Candidate concepts were:

> Steel Truss - This concept uses commercial structural steel beams. Its advantages are low cost, ease of modification if necessary during the development program, and wide availability. The main disadvantage is appearance, but another is the fact that the stairs to the nacelle are exposed. The truss was the most promising concept at this point.
>
> Steel Shell - This is a truncated circular cone, fabricated from rolled conical segments, field-welded in position at the site. The principal advantage is its appearance, while disadvantages are high cost and limited availability. Although the steel shell was less competitive, it was retained for further study.
>
> Guyed Pole - This design consists of a circular steel cylindrical shell of relatively small diameter supported by pre-tensioned steel cables at the top and intermediate levels. To achieve enough stiffness to carry the bending loads imposed by the rotor, the support cables must have a large preload. This increases the foundation loads, particularly the foundation for the pole. Consequently, the foundation costs drive the cost of the structure subsystem up so that it becomes more expensive than either the steel shell or steel truss. Further, it was found that this design was not practical for a high power system because it required many large diameter cables at a high angle relative to the pole to produce an acceptable natural bending frequency, and such an arrangement makes it difficult to avoid interference between rotor and cables. Consequently the guyed pole was eliminated early in the study.

Reinforced Concrete - This is also a truncated circular cone shell cast at the site. It requires heavy steel reinforcing for adequate strength and stiffness. Its advantages include ready availability, good appearance, and a sheltered stairway. However, the walls have to be thick, and the required reinforcing drives up weight and cost. This concept was also retained for further study.

Pre-Cast, Post-Tensioned Concrete - This consists of a truncated circular cone, constructed of factory-cast, matched segments, minimally reinforced for handling. Provisions are made during casting for inserting steel tensioning rods at the site during erection. Factory casting permits use of high strength concrete. Post-tensioning assures that the concrete remains in compression under all conditions of load, but this does not require as much steel as the reinforced concrete concept. Advantages are good appearance, sheltered stairs and low cost in mass production when the cost of the forms is amortized over many units. The prime disadvantage is the high cost of small production quantities. This tower was also considered a promising alternative.

Table 2 shows the results of an early conceptual design study. Later, during concept optimization and preliminary design, additional studies of the various tower and foundation types were made, and are discussed in Phase III of this volume.

Selection of System for Optimization

Evaluation of the eight concepts left three feasible alternatives from which one was to be chosen for optimization. This required the conceptual design of those three candidates. The three systems were sized and evaluated on the basis of energy and capital costs. Results are shown in Tables 3 and 4. Concept 5, the fixed pitch, variable-speed candidate that was carried along in spite of early indications that it was not a favorable choice, is clearly shown to be inferior. Besides being heavier and more costly, it has significantly higher development risk.

Concepts 1 and 3 differ principally in the method of regulating torque. Concept 1 does this with a pitch control actuated by a servo flap, while concept 3 uses a fixed-pitch drag flap system.

Concept 3 holds an insignificant weight and cost advantage. This is, however, offset by the technical considerations. Even without pitch change bearings, the mechanism to actuate and control the drag flap is as complex as the mechanism to actuate and control a servo flap. The fixed pitch rotor also presents a difficult problem when starting in low winds and stopping in high winds because of the inability to feather the blades. Pitch feathering mechanisms or augmented starting would likely be required. This rotor also operates at substantially higher thrust, thus increasing structural requirements. Finally,

TABLE 2. SUMMARY OF TOTAL TOWER COSTS, $.

	TRUSS		SHELL		GUYED POLE	
	100 kW	1000 kW	100 kW	1000 kW	100 kW	1000 kW
Tower Structural Cost	7700	34200	23900	69800	17300	---
Foundation Cost	17300	31200	16600	35600	22900	---
Basic Cost	25000	65400	40500	105400	51200	---
Auxiliary Provisions Cost	13799	23100	13700	23100	14800	---
TOTAL Tower Costs	38700	88500	54200	128500	66000	---

TABLE 3. WEIGHT SUMMARY, kg (1b)

(WEIGHT ABOVE FOUNDATION)

	CONCEPT #1 VARIABLE PITCH CONSTANT SPEED		CONCEPT #3 FIXED PITCH CONSTANT SPEED		CONCEPT #5 FIXED PITCH VARIABLE SPEED	
	100 KW	1000 KW	100 KW	1000 KW	100 KW	1000 KW
ROTOR	3858 (8505)	14630 (32252)	3343 (7370)	12689 (27975)	4414 (9732)	16155 (35615)
DRIVE SYSTEM	2451 (5404)	14605 (32198)	2451 (5404)	14605 (32198)	3038 (6697)	17429 (38424)
ELECTRICAL SYSTEM	1334 (2941)	3459 (7626)	1334 (2941)	3459 (7626)	1479 (3261)	3808 (8396)
CONTROL SYSTEM	347 (765)	372 (820)	347 (765)	372 (820)	347 (765)	372 (820)
TOTAL, DYNAMIC SYSTEM	7990 (17615)	33065 (72896)	7475 (16480)	31125 (68619)	9278 (20455)	37764 (83255)
PINTLE AND DRIVE	5645 (12445)	19465 (42912)	5645 (12445)	19465 (42912)	5645 (12445)	19465 (42912)
WEIGHT ON TOWER	13635 (30060)	52531 (115808)	13120 (28925)	50590 (111531)	14923 (32900)	57229 (126167)
TOWER*	6841 (15082)	29166 (64300)	6841 (15082)	29167 (64300)	7847 (17300)	31026 (68400)
TOTAL SYSTEM	20476 (45142)	81697 (180108)	19961 (44007)	79757 (175831)	22770 (50200)	88255 (194567)

*EXCLUDING FOUNDATION

TABLE 4. CONCEPTUAL DESIGN WGS COSTS - ($)

	CONCEPT #1 VARIABLE PITCH CONSTANT SPEED		CONCEPT #3 FIXED PITCH CONSTANT SPEED		CONCEPT #5 FIXED PITCH VARIABLE SPEED	
	100 KW	1000 KW	100 KW	1000 KW	100 KW	1000 KW
ROTOR						
BLADES AND FLAPS	30,105	68,945	29,920	66,440	38,125	83,335
HUB	20,025	88,865	19,645	86,165	24,900	109,560
	50,130	157,810	49,565	152,605	64,025	192,895
TOWER						
STRUCTURE	7,950	35,440	7,950	35,440	9,745	38,530
EQUIPMENT	13,615	23,040	13,615	23,040	14,110	23,540
FOUNDATION	25,300	41,200	24,300	41,200	29,000	43,700
	46,865	99,680	46,865	99,680	52,855	105,770
PINTLE AND DRIVE	12,960	52,090	12,960	52,090	12,960	52,090
DRIVE SYSTEM	19,475	110,150	19,470	110,115	23,980	130,675
ELECTRICAL SYSTEM	28,695	79,740	28,695	79,740	53,960	219,685
CONTROLS SYSTEM	11,160	11,630	11,160	11,630	11,160	11,630
TOTAL WGS	169,285	511,100	168,715	505,860	218,940	712,745
ERECTION AND INSTALLATION	16,160	24,625	16,160	24,625	17,525	33,725
TOTAL INSTALLED COST	185,445	535,725	184,875	530,485	236,465	746,470

a fixed pitch rotor must often operate in the vortex ring state, an aerodynamically unstable regime with possible wide fluctuations in thrust. This characteristic is extremely difficult to predict and could cause serious control problems.

These technical difficulties cause the risk of the variable rpm rotor to be considerably higher than the constant rpm candidate, without offsetting saving. The choice, therefore, was clearly for concept 1, the variable pitch, constant rpm rotor driving an AC synchronous generator through a fixed ratio gearbox.

The steel truss tower was selected for the optimization phase. Its low cost, ready availability, ease of modification, and low risk, made it the obvious choice.

COMPUTER PROGRAM

A mathematical model of the wind generator system and its environment was developed concurrently with the conceptual design task. In its entirety, the model describes the interrelationships of environmental variables (median wind speed, altitude and wind shear gradient, for example), rotor parameters (diameter, tip speed, chord, etc.), drive system (number of gear meshes), generating equipment (speed, efficiency), and structure (height, type), to produce a particular rated power. It yields weights and costs for the components, and calculates key economic and operational parameters required to evaluate the system, such as unit energy cost, direct capital cost and plant factor (plant factor-sometimes called capacity factor-is defined as the fraction of energy actually produced by the system compared to the amount that could be produced if the system operated at rated power all year). Typical model inputs and outputs are listed in Tables 5 and 6.

Other computer programs derive performance figures, such as rotor lift and drag, and analyze dynamic characteristics of the system, for example, shear, bending moments and vibratory frequencies.

The relationships used in the model are analytically or statistically derived from standard performance and scaling laws and industry-supplied statistics, except for the site wind characteristics which were supplied by NASA.

The rotor is represented by an efficiency map of a rotor with cambered airfoil, standard roughness blade surfaces and tapered planform. The power generation components include a gearbox with an efficiency consistent with best commercial quality. Commercial electrical component efficiencies are represented as functions of rating and load factor. Weight equations are included for all components when required, and are used for calculating costs, as well as for sizing of other weight- and size-dependent components. Most of these relationships are based on industry-supplied statistics, except for the rotor, for which detailed analytical relationships were derived. This was necessary to represent adequately the rotor weight, and hence cost, since the rotor represents the largest single cost element of the system. No commercial data was available for the rotor, because none of this size has been built.

TABLE 5. TYPICAL INPUT PARAMETERS

Rated Power

Rated Wind Speed, or Rated Wind to Median Wind Speed Ratio

Environment	Median Wind Speed
	Annual Wind Speed Frequency Distribution
	Density Altitude
	Terrain (Wind Shear Gradient)
Rotor	Diameter
	Solidity (Blade Area/Disc Area)
	Tip Speed or Rotational Speed
	Number of Blades
	Aerodynamic Efficiency (represents blade geometry)
	Inclination to Wind (Shaft Tilt)
Drive	Efficiency
Generator	Speed
Cable	Size (Area of Cross Section)
Tower	Rotor Ground Clearance
	Aspect Ratio (Height/Base)

TABLE 6: TYPICAL OUTPUT PARAMETERS AND DIMENSIONS (DETERMINED BY THE MODEL)

Site	Effective Wind Speed at Rotor
Rotor	Rotor Power
	Chord
	Velocity Ratio for Maximum Aerodynamic Efficiency
	Thrust Coefficient, Thrust
Drive	Gearbox Gear Ratio
	Rated Torque
Electrical	Component Ratings
	Component Losses at Rated Condition
Tower	Height
	Base Width
	Projected Area of Tower and Enclosure
System	Output Power
	Component Weights
	Component Costs
	Plant Factor
	Energy Costs

Since component costs, and hence system costs, must be minimized to assure greatest WGS economic feasibility, great emphasis was placed on deriving these relationships for the model. Equations were derived to relate component costs to their weight, dimensions or ratings. These equations are, for the most part, based on industry-supplied statistics and assume 1000 unit production levels. Major effort was devoted to constructing the rotor blade cost relationships. Blade cost equations are based on an analytical method which has been correlated with independent industry and U. S. Army estimates of helicopter blade costs, and are considered accurate. Hence, it was reasonable to extrapolate these data to account for the greater blade lengths, and use them as the basis to calculate WGS rotor blade costs.

The cost equations cover the entire WGS up to the utility grid connection, including all auxiliary equipment, installation of all components on site, land acquisition and site preparation. Thus, the total of all costs for a given system is the direct capital cost which is most often expressed on a per rated kW basis. Yearly operating cost includes carrying charges and operations and maintenance costs. Carrying charges express the annual cost of the initial capital investment. In this model, the carrying charge rate used is 15% and includes depreciation, debt service, return on equity and taxes. The operations and maintenance costs are expressed as percentages of initial costs for each subsystem or group of subsystems. These cost relationships were supplied by Northeast Utilities, with the exception of rotor maintenance cost, which was estimated conservatively from helicopter experience. The unit energy cost is simply the result of dividing the yearly operating cost by the yearly energy output.

Direct capital cost is the cost to the utility, assumed to be acting as its own prime and general contractor, for purchase and installation of all WGS components and subsystems, including the WGS site. In arriving at the direct capital cost for a complete wind generator system on a production basis, it was assumed that complete subassemblies would be provided essentially off-the-shelf by a well-established, mature, wind energy industry. Such an industry would provide the utility with major components that could be simply bolted in place without the need for additional manufacturing or subassembly operations. Installation costs included in the parametric cost analyses reflect this concept.

It was assumed that all components and subassemblies would be procured from vendors and suppliers as direct material purchases, not as construction or fabrication procurements. Therefore, direct labor and overhead rates, general and administrative expenses, and fees were assumed to be included in vendor pricing on which the parametric cost models were based. Direct capital cost presented herein does not apply multiple cost burdens which result from multi-level subcontractor procurements. The assumption that the utility acts as its own prime and general contractor also eliminates fees normally charged by such agencies. No allowance has been made for costs incurred internally by the utility for its prime and general contractor activity, for start-up costs, interest on construction loans, or contingencies.

Direct capital costs of individual WGS components are calculated in the parametric model using analytically or statistically derived equations, each representing the cost in terms of the component rating, weight or dimensions. The costs are estimated in constant 1975 dollars. The WGS direct capital cost is the sum of the individual costs. The direct capital cost, when divided by the WGS rated power, results in direct capital cost per kilowatt($/kW). The direct capital cost and its elements also form the basis of determining yearly energy costs of the system.

To size a WGS for a given rated power output and rated wind speed, the model uses the efficiencies of all the components to compute the rotor power input required to deliver the rated power output at the grid. It then calculates the rotor size that it takes to produce this power at the specified median wind speed. Once the system is sized, the energy output at any given wind speed is determined as the product of the hours per year that particular wind speed occurs and the output power at that wind speed. The total yearly energy production is then the integral of the energy output over the WGS operating wind speed regime. After the model sizes the system and determines its yearly energy output, the weights and costs of the other WGS components are determined consistent with specified design criteria. From these weights and costs, the operational and cost parameters listed in Table 6 are determined. Of these, WGS energy cost is given most emphasis in optimizing the system.

The parametric model was programmed for use with ZODIAC, a Kaman-developed computer program which allows calculations to be programmed in a very flexible, easy-to-use language. ZODIAC does not presuppose any input format; equations are easily modified, added, or deleted, and output is printed by a simple print statement with values automatically identified. General expressions are essentially the same as with FORTRAN, but many of the characteristics which tend to make difficult the changing of a model or logic in FORTRAN are eliminated. Programs executed using ZODIAC are slower in terms of central processing unit time, but time required for programming, debugging, and modifying is reduced many fold. This makes ZODIAC a very flexible and valuable calculating tool for the engineer.

The use of ZODIAC for the study facilitated continuous updating of equations and adapting of the output to the requirements of the many tradeoff studies conducted.

PHASE II

CONCEPT OPTIMIZATION

Basic Considerations

The mathematical model discussed in the preceding section was the vehicle for the optimization task. WGS major components and subsystems were optimized iteratively, and tradeoff and sensitivity analyses were made. The output variable that was optimized (minimized) was energy cost (¢/kWh). The concept optimization task included several cycles conducted to bring the major system parameters successively closer to their final values. The values selected for the preliminary design phase which followed were either the result of optimization or were determined from other design considerations.

It should be kept in mind that the optimization used a parametric model which had limited configuration detail. Inputs to the model were shaped by results of numerous separate detailed studies and tradeoffs. In order to proceed to the preliminary design phase, many more decisions were made which used the results from the model and detail studies, as well as Kaman's and Northeast Utilities' background knowledge and experience.

Major Parameters Affecting Energy and Direct Capital Costs

During the optimization phase, three parameters were found to be dominant. Most important is median wind speed ($\bar{V}$), since it determines the amount of energy available to generate power. The other two are system rated power (P_R) and the wind speed at which the WGS produces rated power, the rated wind speed (V_R). Rated power sizes the drive and electrical subsystems. Rated wind speed dictates rotor diameter and tower height. Thus, these three factors determine WGS size and yearly energy output.

The median wind speeds investigated ranged between 3.6 m/s (8 mph) and 10.7 m/s (24 mph), but the emphasis was on examining 5.4 m/s (12 mph) and 8 m/s (18 mph). Rated power ranged from 50 kW to 3000 kW.

Figure 3 relates energy and capital costs to the median wind speeds of 3.6 m/s (8 mph) and 10.7 m/s (18 mph) for the selected rated wind speeds of 9.3 m/s (21 mph) and 11.5 m/s (26 mph), respectively. The curves shown were drawn using data developed during preliminary design and, therefore, represent the best information available.

Two important conclusions can be drawn from the plots of Figure 3. First, site median wind speed is the most important parameter affecting energy and capital costs. Second, and of equal significance, for given median wind speed and rated wind speed, energy cost and capital cost do not change rapidly with changes in rated power when the cost is near its minimum. To illustrate, consider the $\bar{V}$ = 8 m/s (18 mph) curve on the energy cost plot. Energy cost is a

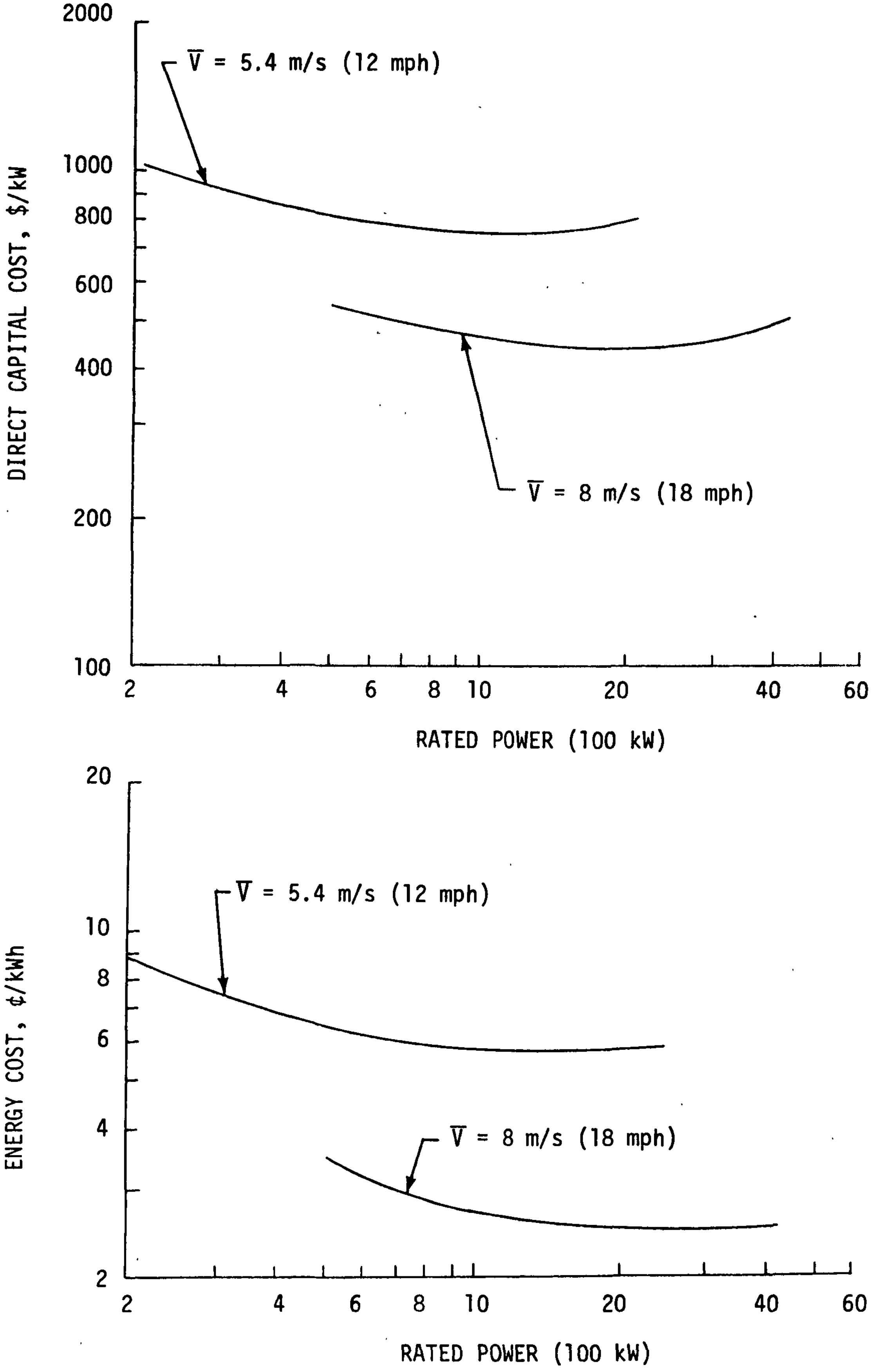


Figure 3. Energy and Capital Cost Variations With Rated Power

minimum for a rated power of approximately 2300 kW. The curve is quite flat in the neighborhood of this point so that rated power can be varied several hundred kW in either direction without causing a significant change in energy cost. This is fortunate because it allows considerable latitude in selecting other system parameters, such as direct capital cost, rotor diameter, and cut-in wind speed with minimal impact on energy cost. It allows the designer flexibility in selecting variables to meet particular user requirements, technical risk limits, unit cost goals and operational requirements.

Systems Selected for Preliminary Design

The optimization program, and other qualitative and quantitative considerations, led to selection of the characteristics of the two wind generator systems. A low power system rated at 500 kW and a high power system of 1500 kW were selected for the preliminary design phase. The 500 kW system has a 45.7 m (150 ft) diameter rotor and is optimized for the site with 5.4 m/s (12 mph) median wind speed. The 1500 kW system has a 54.9 m (180 ft) rotor and is designed for an 8 m/s (18 mph) median wind speed (see Table 7).

A description of the preliminary design effort and the results thereof is found in the section of this summary entitled "Phase III."

Site Adaptability

The two systems selected are adaptable to sites whose median wind speeds cover a range from about 3.6 m/s (8 mph) to about 10.7 m/s (24 mph). This is illustrated by Figure 4. The locus of optimized systems line is drawn through points plotted for systems optimized (systems minimizing energy cost) at sites with a range of median wind speeds. The 500 kW system was optimized at 5.4 m/s (12 mph) and hence, intercepts the locus of optimized systems at point A. The 1500 kW system intercepts the locus at point B at its 8 m/s (18 mph) design median wind speed. The significant point about this figure is that together, the selected systems cover a range of median wind speeds from 4 m/s (9 mph) to 10 m/s (22.4 mph) with less than one-half cent per kWh penalty attributable to their not being optimum at a particular median wind speed. The 500 kW system could be used up to about 6.3 m/s (14 mph), where the 500 kW line intersects the 1500 kW line (point C), and the 1500 kW system from that point on.

The conclusion that can be drawn from this discussion is that only two WGS designs should provide adequate coverage for sites with a wide range of median wind speeds, spanning most of the attractive locations in the United States. This means only two standardized WGS are needed, with the resulting economies of large-volume production of standard components.

COSTS OF MAJOR SUBSYSTEMS

The costs of major subsystems are presented simply as functions of rotor diameter or rated power, whichever is more appropriate for the particular subsystem under consideration. For example, rotor subsystem cost, Figure 5, is primarily a function of rotor diameter, whereas drive subsystem cost, Figure 6, is

TABLE 7. SYSTEMS SELECTED FOR PRELIMINARY DESIGN

	LOW POWER SYSTEM	HIGH POWER SYSTEM
Median Wind Speed, m/s (mph)	5.4 (12)	8 (18)
Rated Power, kW	500	1,500
Rated Wind Speed, m/s (mph)	9.3 (21)	11.5 (26)
Rotor Diameter, m (ft)	45.7 (150)	54.9 (180)*
Rotor Solidity	.03	.03
Rotor Speed rpm	32	34
Energy Cost, c/kWh	7.0	2.8
Capital Cost, $/kW	846	499
Unit Cost, $	423,100	749,000
Plant Factor, %	29	43

*Selection of 180 ft diameter rotor is supported by minimum energy cost calculations made subsequently, which were based on preliminary design data. See Figure 3.

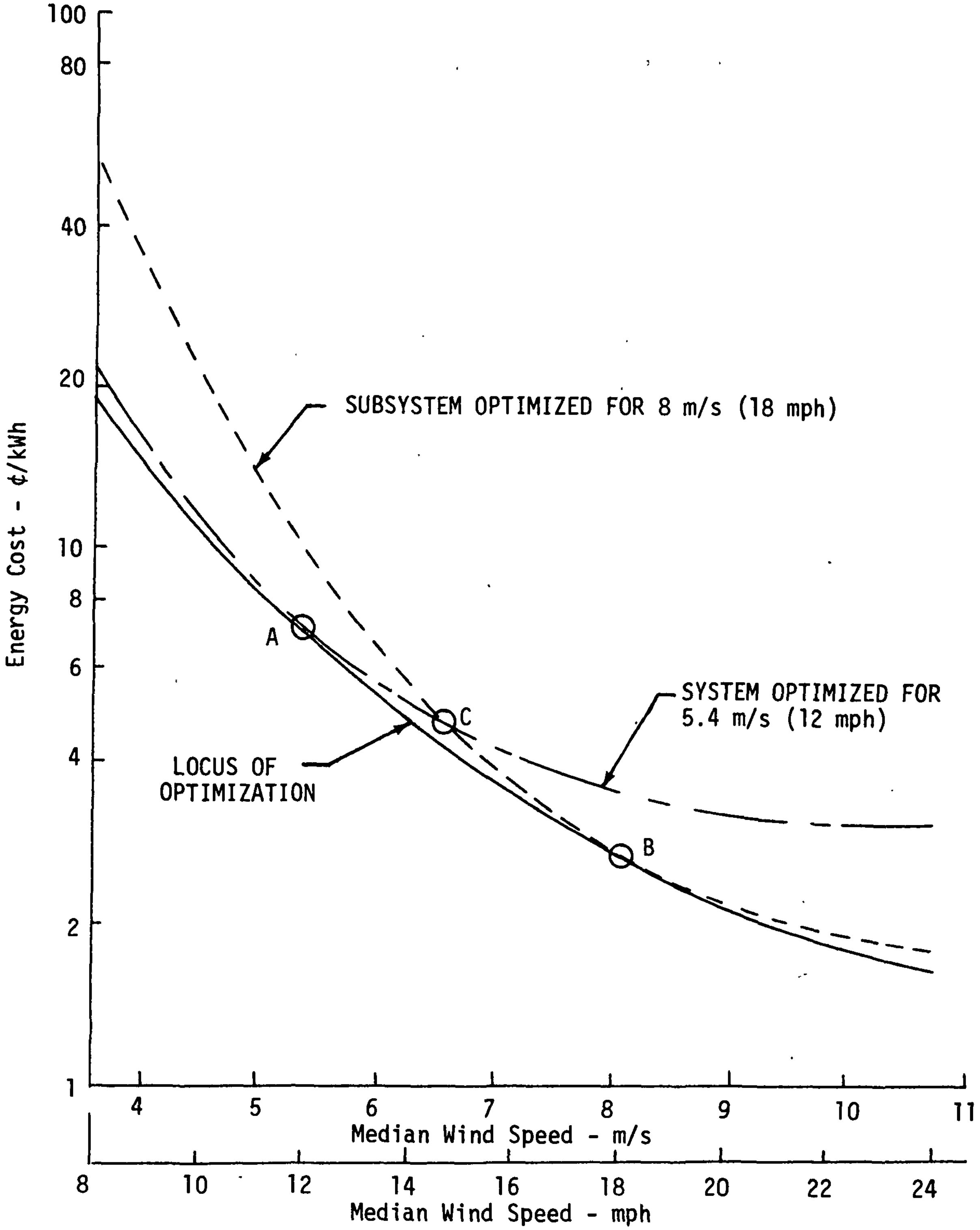


Figure 4. Energy Cost Variation With Median Wind Speed

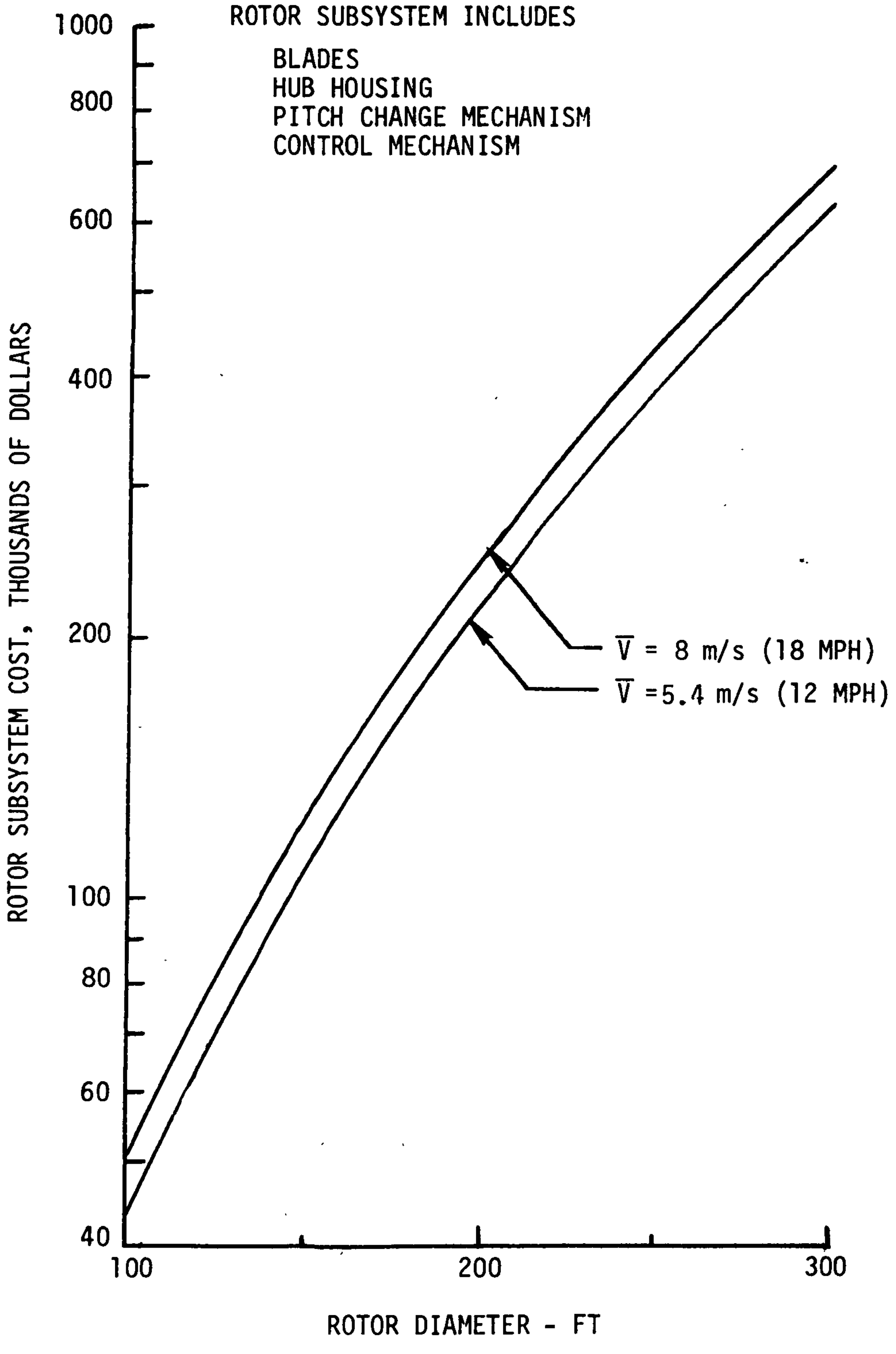


Figure 5. Rotor Subsystem Cost

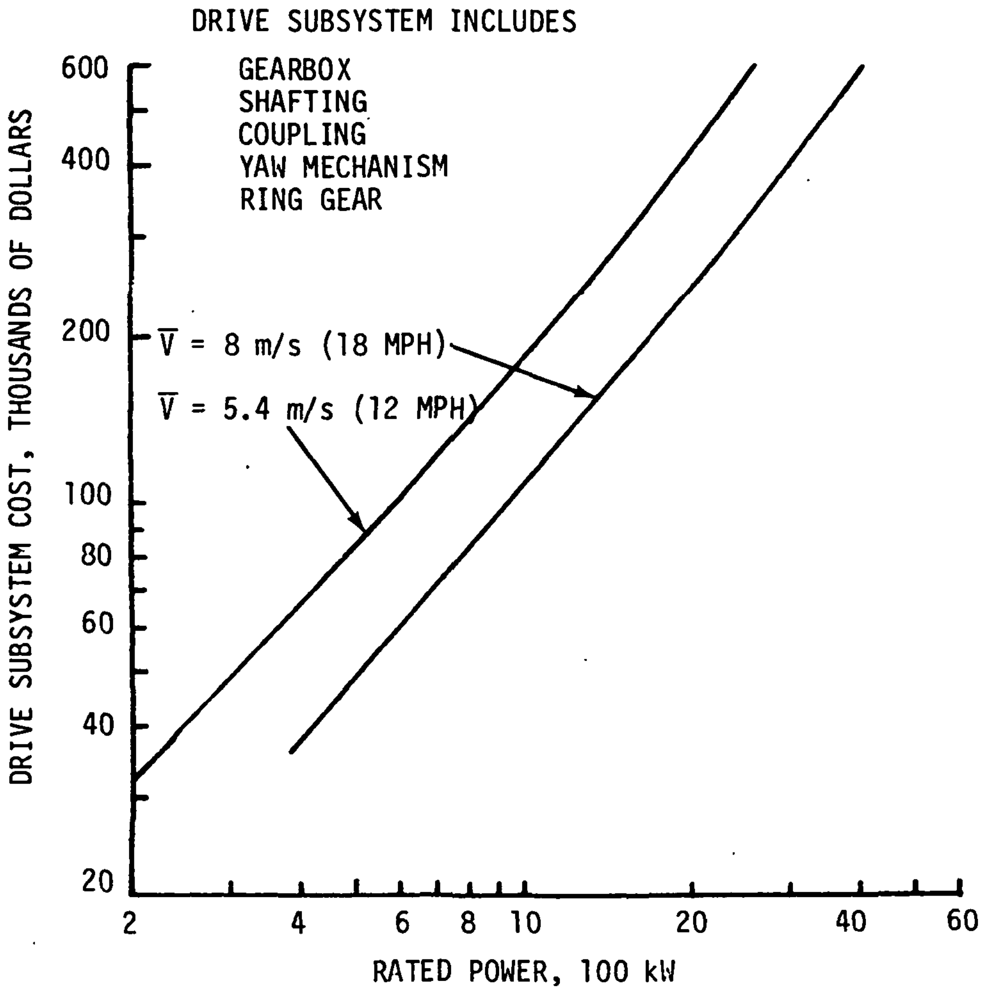


Figure 6. Drive Subsystem Cost

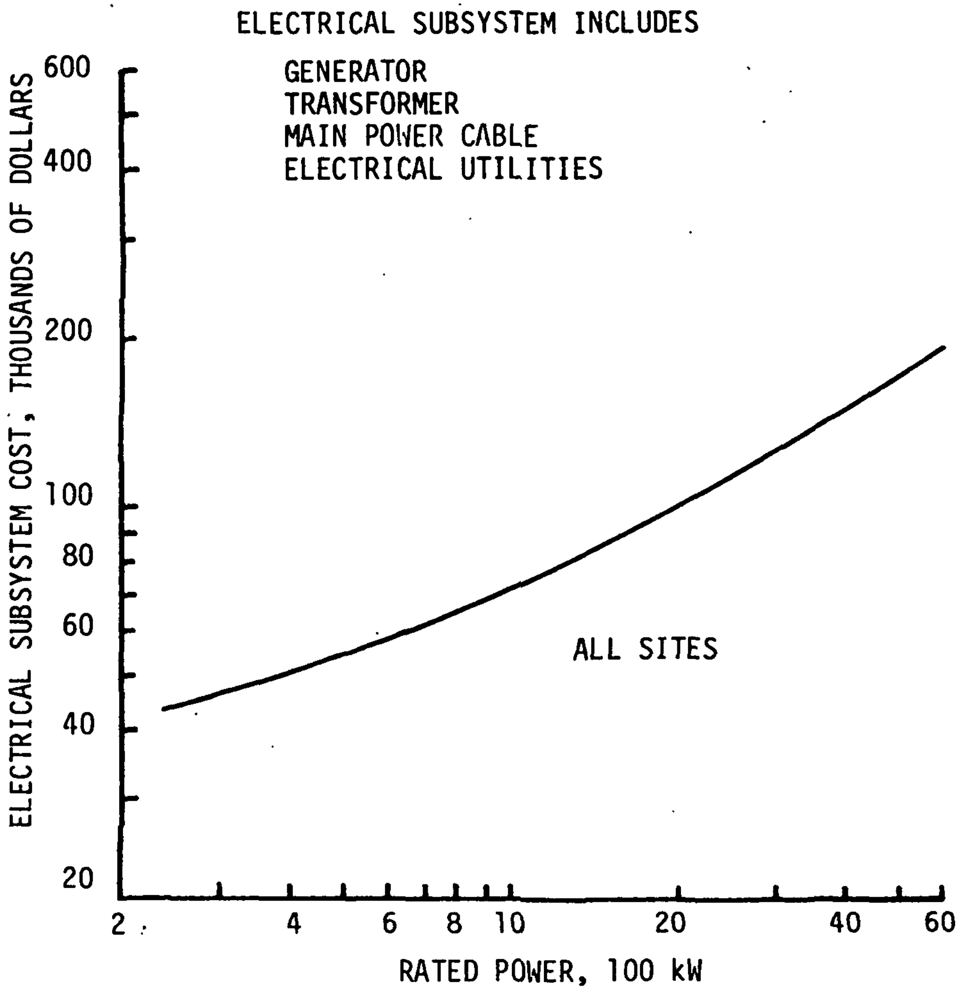


Figure 7. Electrical Subsystem Cost

primarily a function of system rated power. These costs are shown in Figures 5 through 9, based on the results of parametric cost analyses of the preliminary design, performed after the main body of work on the study was completed. Figure 10 shows energy cost as a function of rotor diameter.

More specific definition of the WGS subsystem components, particularly the rotor subsystem, during preliminary design provided the basis for costs which were used in the preliminary design parametric model.

Component costs associated with two median wind speeds (12 and 18 mph) are shown, representing the influence of wind frequency distribution on optimum WGS sizing. Drive system costs are considerably higher for low wind speed applications because optimum rotors are larger in diameter and slower turning, thereby producing higher drive system torques, the primary factor in drive system cost. For structure subsystem costs, it was assumed that rotor ground clearance is 50 feet for all cases.

The control subsystem is not included among the curves relating costs to major parameters. Control subsystem cost is assumed to be constant, independent of both rotor size and rated power. The control system is described later in this summary, and includes only the electrical and electronic devices that govern rotor and yaw mechanism operation, telemetry and supervisory functions, and fault monitoring.

SYSTEM COST TRENDS

The preceding subsystem cost trends for the preliminary design parametric model were summed to obtain cost trends for the entire WGS. Direct capital cost as a function of rated power is shown in Figure 3, and energy cost as a function of rotor diameter and as a function of rated power is shown in Figure 10. Note that systems having minimum energy cost (¢/kWh) do not necessarily have the lowest direct capital cost ($/kW).

REQUIREMENTS AND APPLICATION IN UTILITY NETWORKS

For wind generators to assume a significant role in the production of electric energy in the future, they must be economically competitive with other forms of power generation and must be accepted by the utilities and the public. In addition to the economic question, utilities are concerned that wind generators be readily adaptable to the existing power grids and that they operate safely and reliably. Public acceptance will depend mainly on safety, environmental considerations, and how the wind generators affect monthly electric bills.

There are many complex issues raised by the introduction of highly-visible wind generators into a utility network. Some of the more important are:

1. Basic attitude of utilities toward wind generators.
2. Integration into the financial and operational structure of utilities.

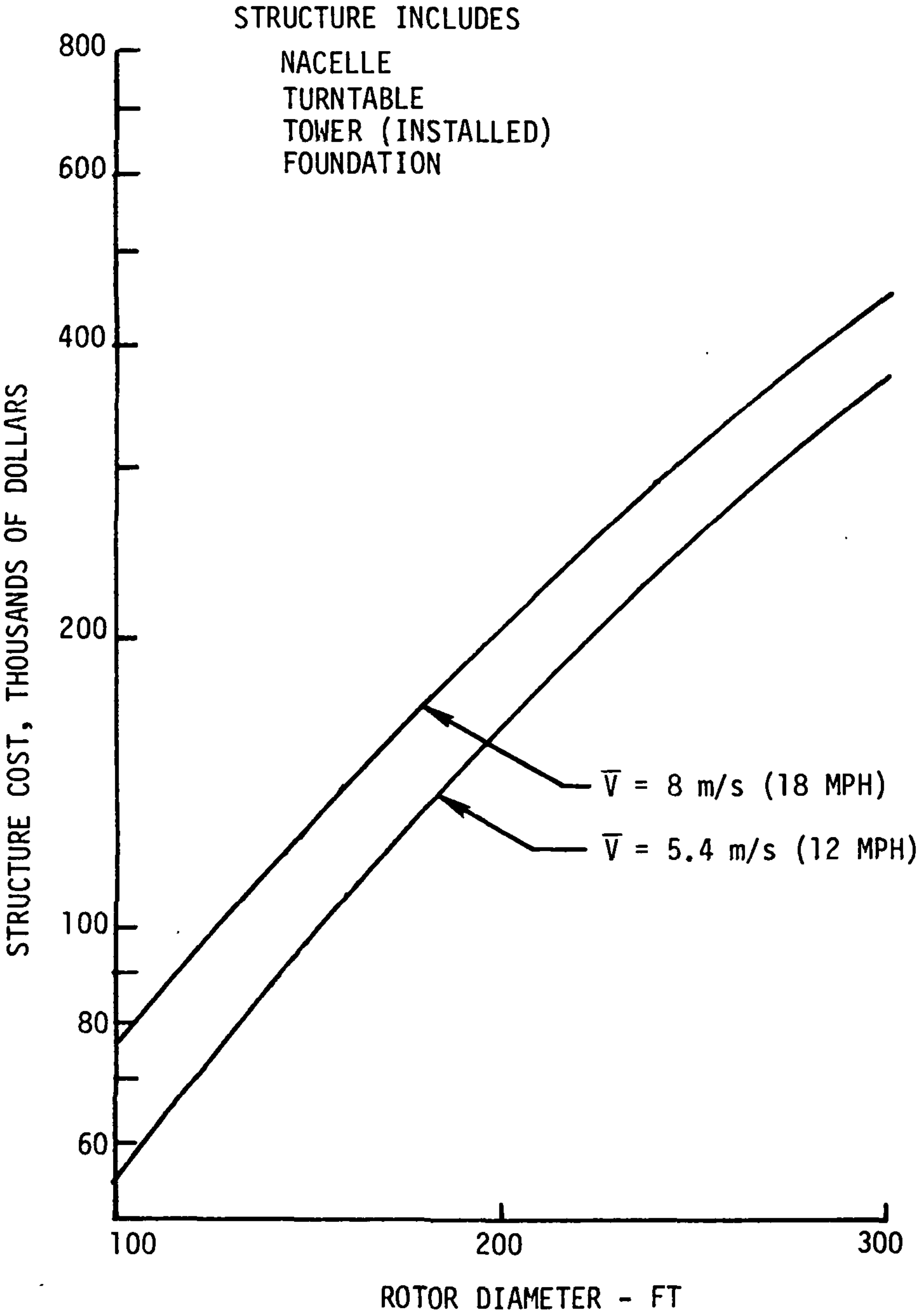


Figure 8. Structure Cost

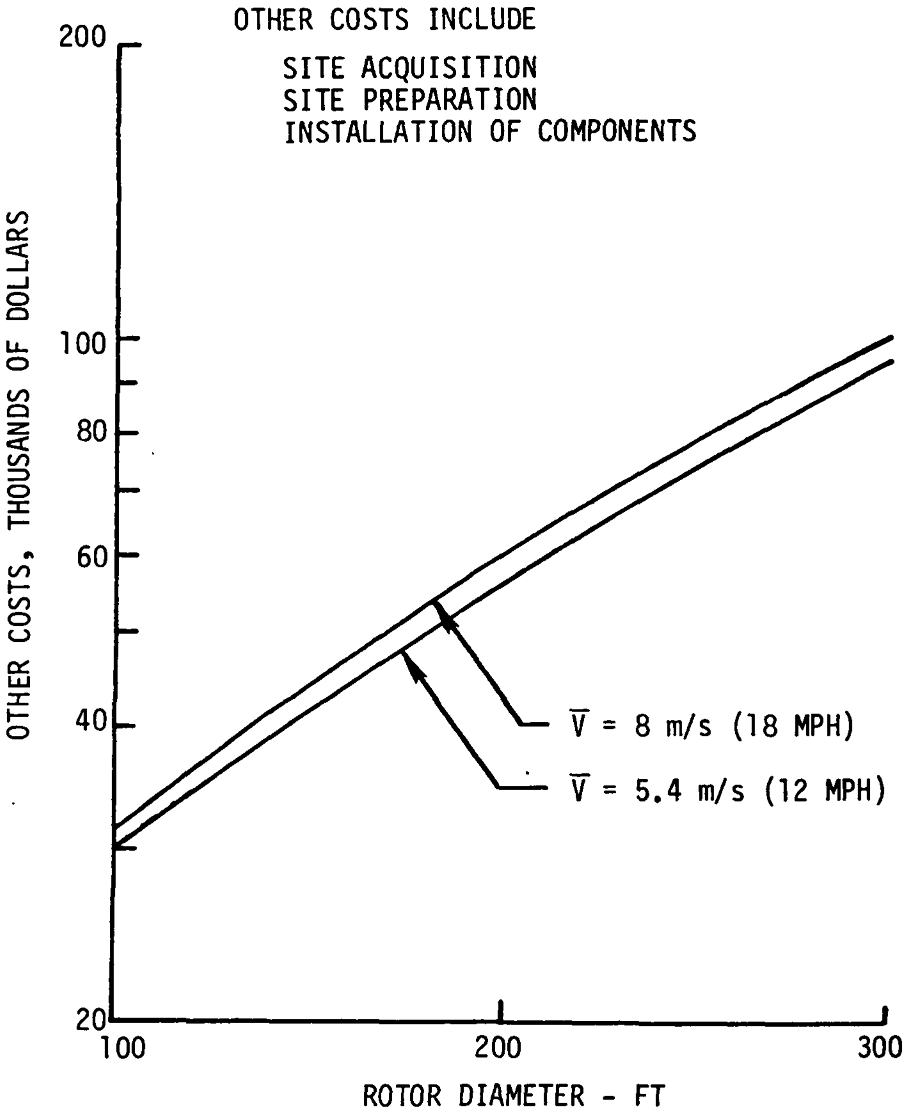


Figure 9. Other Costs

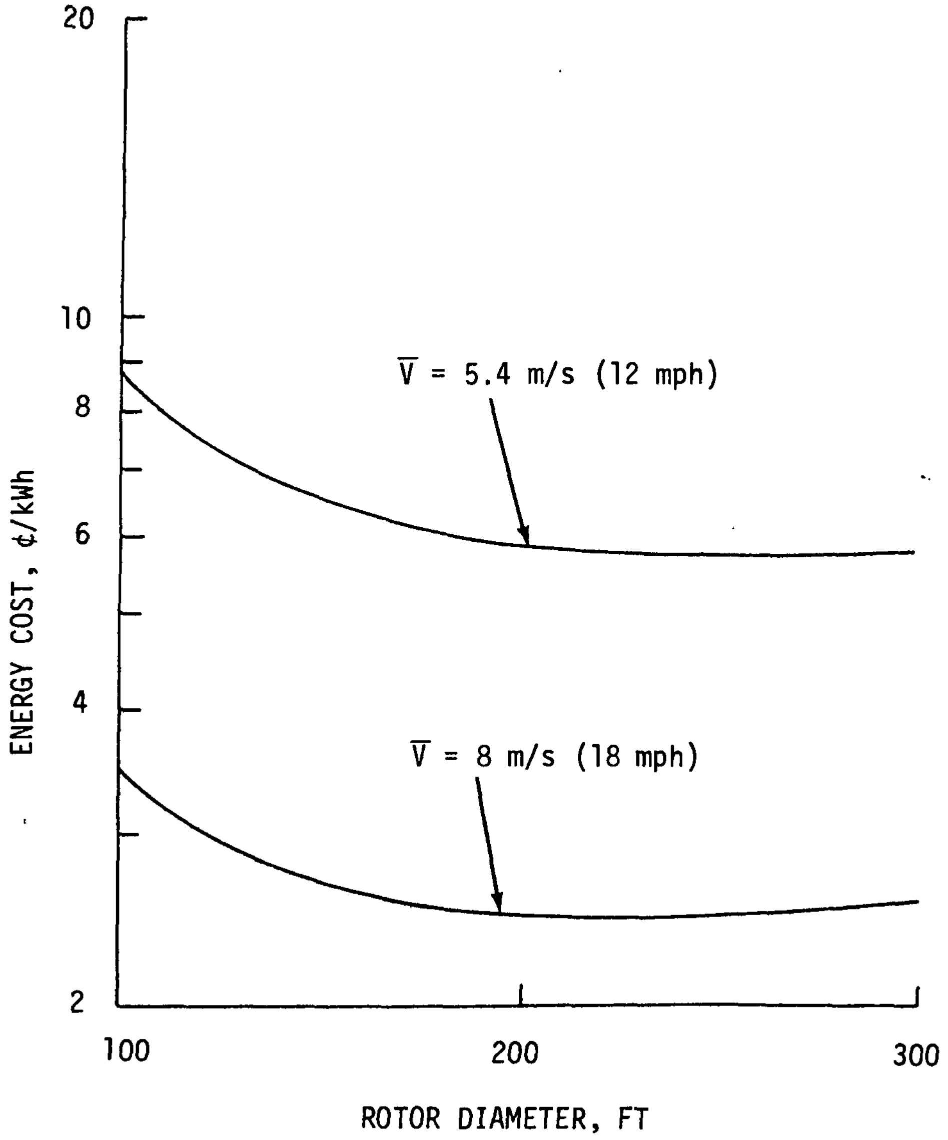


Figure 10. Energy Cost Variation With Rotor Diameter

3. Federal and state regulations, including licensing and safety.

4. Environmental impact and public acceptance.

These questions had never been studied in detail previously. Therefore, a preliminary study was made to acquire a basic understanding of these issues from the point of view of the utility industry and to apply this knowledge in the analysis and preliminary design. Much of the information came from Kaman's utility consultant, Northeast Utilities Company. Colorado Springs Public Utilities also contributed. Providing assistance from the standpoint of Government were the Connecticut Department of Environmental Protection, Connecticut Aeronautics Commission and OSHA.

Attitude of Utilities Toward Wind Generators

The two utilities consulted on the prospective use of wind generators gave insight into the question from two very different perspectives. Northeast Utilities is a large company with a total capacity of 5500 megawatts (mW), including 1100 mW of nuclear plant. Future expansion is expected to be mainly in the form of more nuclear capacity. Colorado Springs Public Utilities (CSPU), on the other hand, is a municipal utility with a modest 320 mW capacity. This company is converting the majority of its gas- and oil-fueled capacity to coal. Most of CSPU's projected capacity expansion will also be coal-fueled. From Kaman's discussions with officials of these two companies, the following important factors were determined to affect utility views of wind generators and their future.

Fuel Costs - This is the major factor. Indeed, it is the impetus behind this research. However, it is felt more acutely by some utilities than by others. Those utilities heavily dependent on oil, particularly imported oil, are suffering most. Those who use low sulphur coal, hydroelectric and nuclear power are much less affected. Obviously, the former category is more likely to be attracted to wind power in the near future.

Environmental Problems - In response to public outcry, and now by law, utilities are giving increased attention to the environment, both from the standpoint of air and water pollution, and aesthetics. In the future, these considerations may preclude the construction of the optimum generating plants they prefer. As utilities consider ways to solve these problems, they may well become more attracted to wind generators, despite possible disadvantages in economy and efficiency.

Load Pattern and Growth - Utilities believe that until major improvements are made in energy storage systems the primary role of wind generators will be fuel savings. When wind is available, wind generators can be put on line to displace fuel-fixed units, thus reducing fuel costs. The value of the wind generator is obviously related to the cost of fuel saved and the comparative efficiency of the generating units displaced. Further, because it is impractical to shut down and start up large base-load installations such as nuclear reactors, wind generators will have minimum value as fuel savers during periods of low demand. Alternatively, when they can replace the least efficient and most costly generators which are brought on line during periods of peak demand, their value will be greatest.

Thus, it may well be that daily and seasonal variation in the demand pattern will be compared with the daily and seasonal wind pattern to determine the overall value of wind generators to a particular utility's needs. Ideally, of course, the most windy periods, daily and seasonally, would coincide with peak demand.

Anticipated load growth will also be a factor. Utilities with surplus capacity for the future would probably elect to bear high fuel cost rather than invest in more unneeded capacity. This is particularly likely if increased wind generator R & D is perceived as yielding cheaper, more efficient units in the future. Under such conditions, a utility with adequate near-term capacity would likely opt for postponement of wind generator capability.

In summary, there does not appear to be utility bias against wind generators. They are seen primarily as fuel savers. Those utilities facing critical fuel shortages and very high fuel costs, and those which need increased capacity soon, are likely to be the most receptive to a fuel-free energy source in the near future.

Utility Cost Estimating

Energy costs and direct capital costs to acquire and operate wind generators are based on standard utility cost procedures and the assumption of large-scale production. Table 8 shows the factors and assumptions supplied by NASA for the study.

TABLE 8. ECONOMIC PLANNING FACTORS AND ASSUMPTIONS

PARAMETER	FACTOR OR ASSUMPTION
Useful life, dynamic components	30 years
Useful life, structure	50 years
Financing	50% debt, 50% equity
Return on investment	9% on debt, 11.5% on equity
Depreciation	Straight line over 30 years
Corporate tax rate	48%

Direct capital cost includes procuring, transporting, erecting and readying the system on a site, the site and its preparation, supporting facilities and security.

Average cost of the energy produced over the life of the system includes:

- Recovery of capital
- Interest
- Taxes
- Operation and maintenance expenses

Cost subroutines compatible with Northeast Utilities cost estimating procedures for annual carrying charges for capital recovery, interest and taxes were included in the parametric model developed during Phase I of the study. Operation and maintenance (O & M) costs were those established by Northeast Utilities for comparable generating plants and equipment, with the exception of rotor maintenance cost, which was based on Kaman's helicopter experience. A conservative estimate of rotor maintenance cost was assumed due to the lack of field experience with rotors of this size.

Based on guidance from Northeast Utilities, yearly operating cost was estimated at 1.5% of direct capital cost. This covers the cost of operating personnel, supervision, and related indirect and overhead costs.

Public and Operating Safety

Neither public nor operating safety appears to be a significant problem. One concern is the possibility of the rotor shedding ice, which could be a hazard. Although this is a remote possibility, state and local zoning laws might require a buffer zone.

There is always the threat of vandalism or sabotage, especially since the sites are to be unattended. A peripheral fence, lighting and other common security measures minimize the threat, but can never absolutely preclude it. A shell tower with stairs on the interior would also contribute to security by keeping unauthorized persons out of the tower and hence, farther from the dynamic components.

The rotating blades will present a tempting moving target to would-be marksmen, but the construction of the blades makes them very tolerant of small arms bullet strikes.

Air traffic safety is not considered a problem. The wind generator will not likely be located close enough to airports to be affected by terminal area obstruction restrictions.

Operating safety becomes a consideration primarily during maintenance of the system. Requirements for personnel safety will be imposed on the design through compliance with OSHA and industry standards. Established utility practices prescribe standard safety procedures for personnel performing maintenance on various types of equipment. Doubtless such practices would be expanded to accommodate the unique requirements of the wind generator. Therefore, no significant operating safety problems are anticipated.

Maintenance

With the possible exception of the rotor, maintenance appears to present no unusual problems. The power train and generating subsystems and associated controls have counterparts in many of the facilities presently being maintained by the utility companies and are within their existing maintenance capability.

The wind generator will operate remotely and unattended for long periods. Therefore, reliability and long operating life are viewed as particularly important. Also important is the capability to detect critical faults and to initiate shutdown automatically and safely. Reliability and fail-safe provisions must be designed into the system.

Routine preventive maintenance and servicing should be kept simple and be required no more frequently than every 30 days. A major inspection, possibly involving some component tear-down and parts replacement, would be performed annually. Upkeep of the tower and associated structure would be scheduled at 10 year intervals.

The design must stress in-place repair of heavy components to avoid removing them from the tower. The need for special tools, equipment and skills not normally available to a utility is to be avoided.

Overhaul of major dynamic components off-site should be only on the basis of observed wear and deterioration, rather than according to a fixed operating-hour schedule.

Environmental Impact

In recent years, environmental considerations have loomed large in utility development plans. Views on environmental impact of various utility facilities vary greatly with the locale, the relative influence of the organizations involved, and the weight of other priorities. Threats to the environment, real or imagined, tend to be measured against other problems of energy production, so that shortages and high energy cost have a mitigating influence on environmental concerns. These are exactly the conditions likely to spur the initial use of wind generators. Further, wind generators avoid the problems of air and water pollution with which utilities are presently contending. There are two possible environmental problems remaining--noise and aesthetics.

Noise - Rotor, bearing, and generator noise were considered. It is believed that this noise will be below objectionable levels, and that the units will be located far enough from population centers to eliminate noise as a major concern.

Aesthetics - Visual acceptability is the environmental issue most likely to spark controversy. It is unlikely that large wind generators in large numbers can be situated so as to avoid creating a displeasing visual effect. It is generally felt that public acceptance will decline with increasing numbers in a given locale. Unfortunately, the solution is not as simple as siting wind generators far from population centers. The population centers need the energy, whereas remote siting with accompanying transmission losses reduces the efficiency of wind generators. It will be desirable, therefore, to seek locations in sparsely populated areas and to subdue the presence of the generators where possible by spacing and use of natural cover. Again, unfortunately, the most windy locations may not be the most unobtrusive.

Background blending may be of some help in mitigating the presence of these units. Colorado Springs Public Utilities has used this technique in some applications. They have used paint schemes, decorative plantings, rustic fencing and panels to disguise the base of transmission towers and transformer centers with some success.

Tower design is considered another important factor. The consensus is that the shell tower will be more appealing (or less objectionable) than the steel truss.

Human nature being what it is, people will want the benefits of cheaper, more plentiful power as long as the wind generator is in the other fellow's back yard. Utilities will have to use every technique available to make the wind generators as unobtrusive as possible.

Licensing

Securing the necessary approval for a new generating plant can be a long and costly procedure for a utility. There are few, if any, precedents for licensing wind generators, so the requirements are unknown. Utilities agree, however, that wind generators will be licensed as generating plants and through state agencies. Whether each site will require a separate license or whether one will suffice for a total system of several sites is not known. Of course, if each site must be separately licensed, costs will be higher.

Applications

Ultimately, economics will decide what application, if any, will be feasible for wind generators. With this in mind, a preliminary analysis was made to evaluate the relative cost of wind generators when used in three typical applications. The basic approach was to calculate the break-even cost of the wind generator for replacing an existing fuel-fired unit.

Fuel Saver - This is the most obvious immediate application. The wind generator is connected directly into the grid during periods of available wind and when fuel-fired units of equivalent output are shut down. Any number of units can be used as fuel savers.

Break-even cost of the WGS was computed as a function of the energy cost of the fuel saved, and is displayed in Figure 11. A 1500 kW wind generator, at approximately $480/kW direct cost, is competitive with a gas turbine generator burning relatively expensive #2 oil, but not with coal or #6 oil-fired units. The wind generator would have to cost about $180/kW or $300/kW, respectively, to compete with coal and #6 oil.

With Base-Load Capacity - A wind generator could be credited with base-load capacity when some or all of its power output is available to meet the utility's daily base-load or basic energy demand with a high level of assurance.

WGS use for base-load capacity necessarily assumes a number of wind generators disposed to benefit from wind variability over a large geographic area. Energy produced in excess of the rated base-load capacity could be credited toward fuel savings.

Analysis of wind generator break-even cost with base-load capacity with fuel savings was performed for a 1000 mW system with 100 mW credited toward base-load at .7 plant factor. This means a .7 probability that at least 100 mW will be available to meet base-load requirements at all times. For a total system plant factor of .35, the system would have an effective fuel-saver plant factor of .315. This is obtained by subtracting the 10% of the 1000 mW system's plant factor which is credited to base-load from the total plant factor.

The analysis used a displaced base-load energy cost of 3.5¢/kWh and a displaced fuel cost of 2.35¢/kWh. The results predicted a wind generator system cost of approximately $510/kW for base-load capacity plus fuel savings, which compares closely with the $480/kW for saved gas turbine fuel in the fuel saving application alone.

With Storage - This application considers storing in some manner (not defined) energy generated with considerable wind variability, and gives capacity credit for peak load periods. Peak load capacity is the same as base-load capacity, except that wind generator power displaces the costly peaking units, such as gas turbines. In addition, surplus energy not needed for storage goes for fuel saving as before. Sufficient energy production to charge storage on at least 90% of available days is assumed. Besides the factors bearing on fuel savings, the analysis of the peak load application also considers the system yearly and daily capacity factors, storage efficiency and the displaced peak unit energy cost. The break-even cost in this case has the cost of the storage system included. Figure 12 presents the results of the analysis. Break-even cost is shown as a function of system daily capacity for two storage efficiencies. Results indicate that both the daily plant factor and storage efficiency affect system break-even and cost significantly.

Discussion

The results of the economic analysis of possible utility company applications of wind generating systems are more meaningful when interpreted in light of the

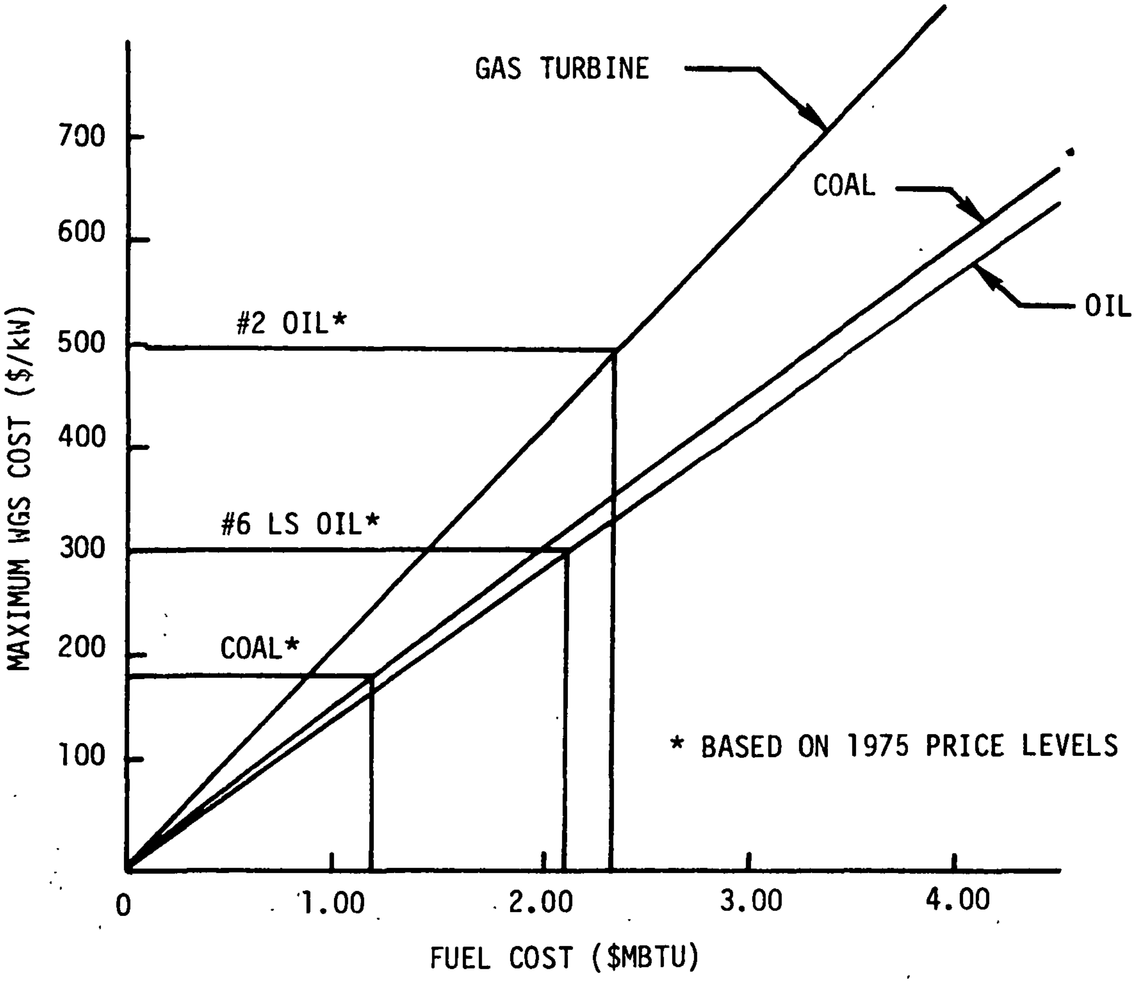


Figure 11. Break-Even Costs - WGS Vs Fuel Costs

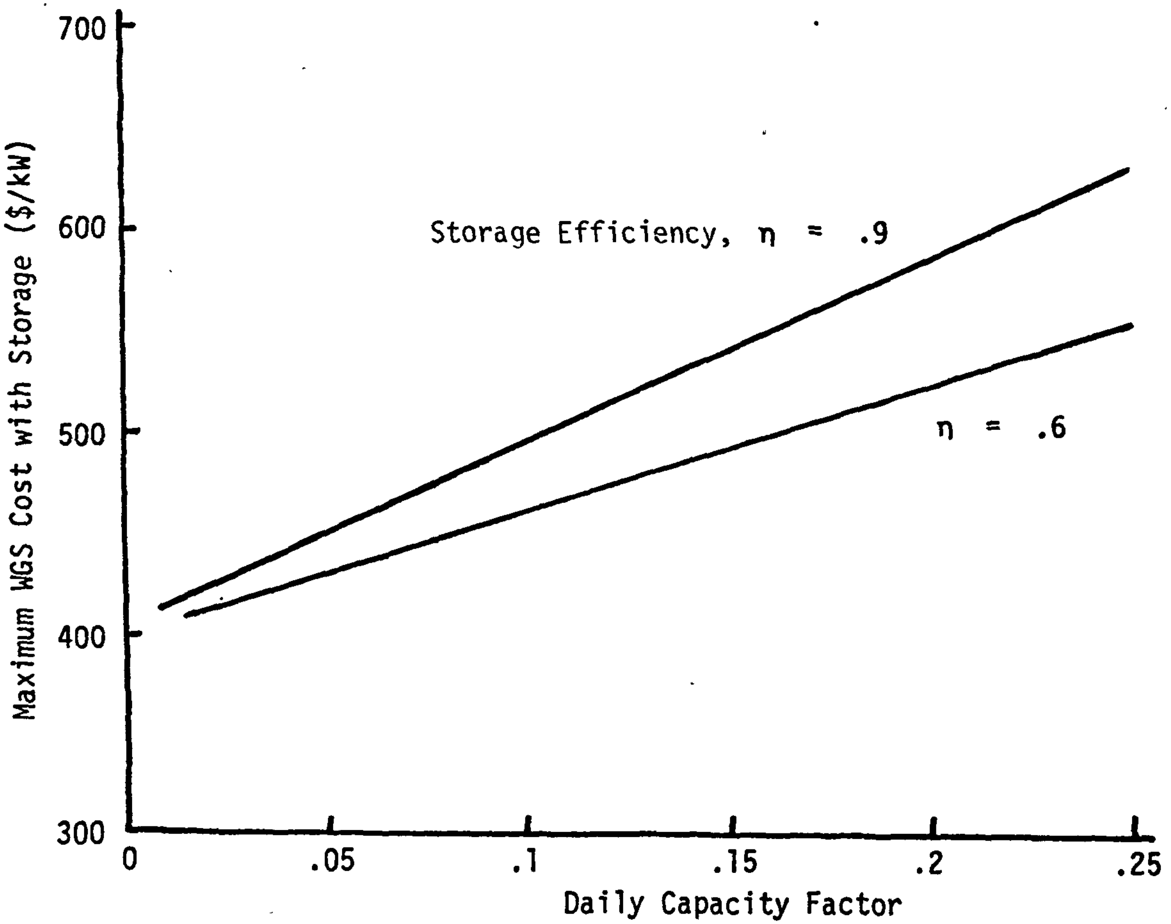


Figure 12. Value of WGS with Storage.

Factors:

Daily Peak Load = 500 MWH
Alternate Peak Energy Cost = $.0485/kWh
Cost of Off-Peak Fuel Saved = $.025/kWh

system cost analysis performed for the 500 kW and 1500 kW WGS designs during the study program. This detailed cost analysis predicts direct capital costs of approximately $900 per kilowatt for the 500 kW wind generator and $480 per kilowatt for the 1500 kW system. Obviously, the larger WGS is more attractive economically.

The $480 per kilowatt capital cost of the 1500 kW WGS compares favorably with the estimated $500 per kilowatt break-even cost required in fuel saving applications for displacing gas turbine generating systems. However, compared to systems using coal and #6 oil as fuels, the 1500 kW WGS is not competitive at present. Whether this system will be more competitive with the lower cost fuels in the future depends on how high fuel costs will rise and how much WGS costs might be reduced through continued development.

Fuel saving is judged to be the most promising application of wind generators at the present time. Systems for this application could range in size from a single wind generator to large multi-unit installations and, therefore, might find widespread use by both large and small utility companies.

For the fuel saving plus base-load capacity application, the predicted capital cost of the 1500 kW WGS is slightly under the estimated break-even cost of $510 per kilowatt. The assumptions made in the analysis are optimistic, however. Even if the necessary wind conditions could be found, a very large number of WGSs would be required and transmission costs associated with such a system, which were not accounted for in the predicted WGS capital cost, would increase this cost further. Despite the large number of wind generators required to satisfy the application, only about 10% of the total installed power, based on the example chosen, would be added to the user's base-load capacity. In effect, such a system is still primarily a variable output fuel saving system. Because of the large number of units required and the rather small base-load capacity afforded by the system, it appears that this application offers limited promise of being economically feasible for a typical utility in the foreseeable future.

The 1500 kW WGS predicted capital cost is roughly equal to the break-even cost computed for the fuel saving plus peak load application. It should be noted, however, that the 1500 kW WGS capital cost is optimistic for this application since allowances for system downtime are not included. The analysis of break-even cost assumed also that the stored wind energy would displace high-cost gas turbine-generated energy. If a less costly generating source is displaced, the WGS break-even cost would be correspondingly lower. The viability of the WGS in this application appears to be contingent upon the development of inexpensive and efficient storage systems.

The applications analysis has attempted to evaluate, in gross relative terms, the economic worth of a wind energy system to a typical electric utility. Because it has been conducted in the context of a utility operation, it did not explore applications requiring departures from present-day industry practice and regulation. Some of the regulations affecting utility operations, such as those governing rate structures and reserve capacity, do not easily accommodate variable or intermittent generating capacity, even though this type of power might be entirely feasible in specific applications. Using the wind generator as a variable energy source for selected segments of the market that could operate with anticipated power interruptions, and structuring the rates accordingly, might open up new areas of application.

Wind energy costs in the applications analysis have been based on capital, operations and maintenance, and fuel costs currently anticipated by a relatively large northeastern utility and on present-day projections of future fuel availability. These factors vary considerably among other utilities in different parts of the country and might change drastically in the future due to unforeseen circumstances. Should the supply of oil and natural gas approach depletion more rapidly than predicted and the cost escalate accordingly, wind energy would become increasingly more competitive in the United States. In other areas of the world, primarily the non-industrialized nations and even in some remote areas of the United States, conditions today may be such that wind energy is technically and economically a competitive alternative.

PHASE III

This section summarizes the work performed during the preliminary design phase of the study. This work followed that of Phases I and II and was a natural continuation thereof.

As the work progressed, understanding of the problem and available alternatives increased. Therefore, changes in the original optimized configuration were introduced which make the preliminary design different in some respects from the optimized WGS.

This section includes a brief summary of the design approach, a description of the overall system and characteristics which the preliminary design established, and then more detail on the design and operation of the major subsystems. Also discussed are considerations and rationale for the design of the subsystems. Considerably more detail is, of course, available in the Design Study.

PRELIMINARY DESIGN APPROACH

The optimized system characteristics from Phase II formed the basis for the start of the preliminary design. They call for a 500 kW WGS for a median wind speed of 5.4 m/s (12 mph) and a 1500 kW system for a median wind speed of 8 m/s (18 mph).

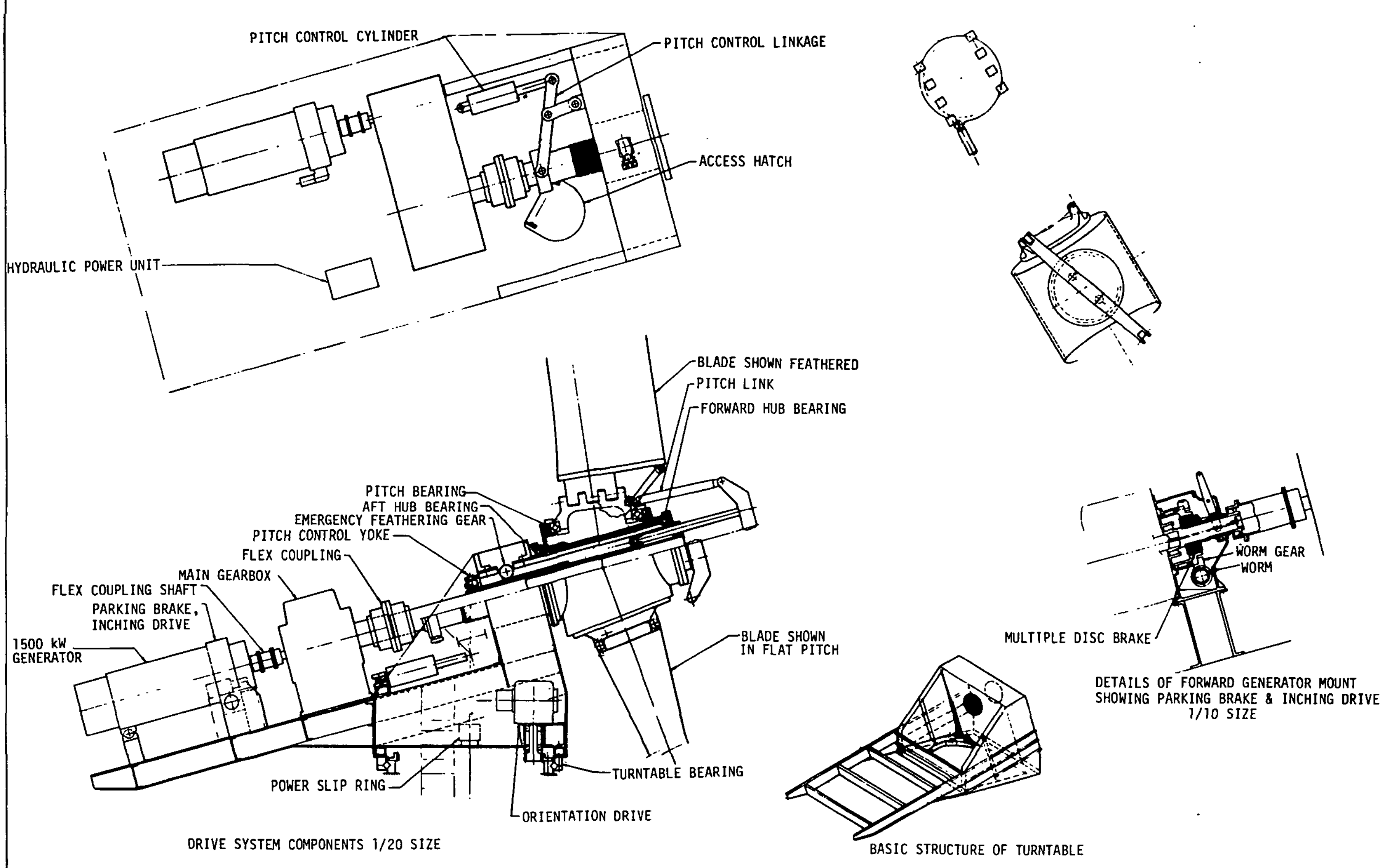
Advantage was taken of the relative insensitivity of energy cost to rotor diameter in the 46 m - 55 m (150 ft - 180 ft) range (Figure 10), and consideration was given to capital cost, plant factor, rotor model sensitivity and its adaptability to different sites, in choosing the rotor diameter.

The 1500 kW system's 54.9 m (180 ft) rotor diameter was chosen primarily to improve plant factor, but also to provide an eventual test unit with a significantly larger rotor than that of the low-power system. Designing and evaluating two different size rotors also allows flexibility in interpreting and applying the results of the study. For instance, if due to the evolution of manufacturing techniques, rotor blade cost is reduced, the optimum rotor size will increase. Two distinct rotor diameters give an indication of effect of rotor diameter variation on the system.

SYSTEM DESCRIPTION

A layout of the dynamic components of the 1500 kW WGS is shown in Figure 13. The 500 kW system has essentially the same configuration and is omitted in this summary in the interest of brevity. 500 kW system details are in the Design Study.

Both systems have a 2-bladed, variable-pitch, constant rpm rotor mounted downwind of the tower. The rotor consists of filament wound composite blades with hingeless attachment to a rigid hub. The hub is a rugged, welded structural steel assembly. Blade pitch is controlled by a linkage actuated by a hydraulic cylinder which rotates the blades on pitch bearings mounted on the hub.



DRIVE SYSTEM COMPONENTS 1/20 SIZE

DETAILS OF FORWARD GENERATOR MOUNT SHOWING PARKING BRAKE & INCHING DRIVE 1/10 SIZE

BASIC STRUCTURE OF TURNTABLE

Figure 13 Drive System Components, 1500 kW WGS

The hub is supported by crossed roller bearings mounted on a fixed spindle. This allows the non-rotating spindle to carry the high bending moments produced by the rotor without large bearings to support a rotating shaft. The rotor torque is transmitted to a triple mesh commercial gearbox by a quill shaft running through the center of the static spindle. The gearbox is connected to a commercial AC synchronous generator of the type commonly used by utilities, with a parking brake/inching drive assembly located between the gearbox and the generator. This assembly is used to stop the rotor from low rpm and to position the rotor after the system is shut down.

The control system uses a microprocessor for all sequencing and data reporting functions, including WGS startup, shutdown, operational monitoring and failure reporting. Conventional electro-mechanical controls are used for blade pitch and positioning the rotor relative to the wind. The rotor is provided with a hub-mounted mechanical blade feathering capability so that if the control system fails or is overpowered by gusts, the blades are automatically feathered, preventing system overspeed and damage.

The generating machinery and controls are housed in a closed nacelle mounted on a structural steel turntable which, in turn, is mounted on top of the tower through a crossed roller bearing assembly. The assembly is oriented to the wind by a hydraulic motor driving a worm gear which engages a large ring gear on the top of the tower (Figure 13).

The tower can be either a structural steel truss type or a pre-cast, post-tensioned concrete shell type. The steel truss tower has a distinct advantage in small quantities. The pre-cast, post-tensioned shell tower, while still slightly more expensive (about $5000 - $6000 for the 1500 kW system) when 1000 are produced, is considered to be better aesthetically, and hence could be the choice for a production run.

Another important tower effect must be considered. This is the aerodynamic blockage of the wind which causes a wake area behind the tower. Since the rotor is mounted on the downwind side of the tower, each blade passes through this wind wake, or "tower shadow" once per revolution and experiences a vibratory load input. Kaman selected a value of 30% wind velocity reduction in treating the effect of the tower shadow on the blades' preliminary design.

(NOTE: Since this study was carried out, experimental findings from the NASA wind tunnel tests have quantified wind velocity reduction as a function of tower structural design. Although the downwind rotor placement continues to appear advantageous with open truss towers, the use of shell towers now is considered unlikely, since their tower shadow effects cannot readily be reduced to the values necessary for long blade fatigue life.)

The choice of a foundation is highly dependent upon soil conditions and the tower type and size. This study assumed standard soil conditions, described in paragraph 6.4.3.1 of the Design Study. With this assumption, pile foundations are cheaper for the 1500 kW system, but mass concrete is competitive with piles for the 500 kW system. However, the analysis is quite sensitive to changes soil parameters. Therefore, the choice of foundation will likely be governed by soil condition at the particular site under consideration.

Most of the electrical protective and power conditioning equipment is mounted on a pad at the base of the tower, along with the microprocessor, related control equipment, and the data recording and transmission equipment.

PRELIMINARY DESIGN RESULTS - SUMMARY

The characteristics of the low (500 kW) and high (1500 kW) power WGS resulting from the preliminary design phase are summarized in Table 9. Table 10 lists weight breakdowns for both systems, assuming a steel truss tower. The costs of the two systems are shown in Table 11.

The predicted costs shown on Table 11 are based on quantity production in a fully developed market for wind generators. The costs of first units, in a preproduction-prototype configuration with a limited market have been estimated separately and are presented in Appendix A of this Executive Summary.

ROTOR

The rotor subsystem, which includes the blades, hub and controls, is the largest single cost element of the WGS. It is the most technically demanding subsystem and unlike the others, is not available commercially. Further, little or no experience exists in design and fabrication of rotors as large as these. Finally, all other subsystem designs are influenced directly or indirectly by the rotor.

For these reasons, rotor design and analysis received great emphasis throughout all phases of the study. Particular attention was placed on evolving a rotor design that could be mass-produced at low cost with latest state-of-the-art technology, without neglecting the stringent technical requirements of the rotor.

The following discussion on the rotor subsystem will include some design considerations and rationale that were employed during the concept evaluation and optimization phases. This is necessary because of the difficulty in compartmentalizing the various phases, and also because an understanding of what was done then is essential to understanding the final preliminary design which resulted.

Requirements

To be a competitive alternative for electrical energy production, the rotor must extract maximum energy from the available wind. It must operate in a wide range of weather conditions, including extremes of temperature and all types of precipitation. It must survive lightning strikes and hurricane winds. To be cost effective, the rotor must be economical to build, require little maintenance, and have a long operating life. With these requirements, the following design objectives were established:

TABLE 9. SYSTEM PRELIMINARY DESIGN TECHNICAL CHARACTERISTICS

	LOW POWER SYSTEM	HIGH POWER SYSTEM
SYSTEM		
Rated Power, kW	500	1500
Site Median Wind Speed, m/s (mph)	5.4 (12)	8 (18)
Rated Wind Speed, m/s (mph)	9.3 (21)	11.5 (26)
Yearly Energy Output, kW-hrs	1.3×10^6	5.7×10^6
Plant Factor, %	29	43
Minimum Wind Speed, m/s (mph)	4.5 (10)	5.4 (12)
Cut-out Wind Speed, m/s (mph)	14 (30)	20 (45)
Design Maximum Wind Speed, m/s (mph)	54 (120)	54 (120)
ROTOR SUBSYSTEM		
Design Shaft Output Power, kW	560	1648
Rotor Diameter, m (ft)	45.7 (150)	54.9 (180)
Rotor Solidity, %	3	3
Rotor Precone, Deg.	8	10
Rotor Speed, RPM	32.3	34.4
Blade Root Chord, m (ft)	1.5 (5.1)	1.9 (6.1)
Blade Tip Chord, m (ft)	.75 (2.5)	.95 (3.1)
DRIVE SUBSYSTEM		
Maximum Orientation Drive Speed, RPM	1/3	1/3
Gearbox Input Torque, Nm	166×10^3	456×10^3
(ft-lb)	(122×10^3)	(357×10^3)
ELECTRICAL SUBSYSTEM		
Generator Rating, kW	510	1522
Generator Output Voltage, KV	2.4	4.16
Generator Output Frequency, Hz	60	60
Generator Speed, RPM	1800	1800
CONTROL SUBSYSTEM		
Rotor Pitch Rate, Deg/sec	5	5
Orientation System Yaw Rate, Deg/sec	2	2
STRUCTURE SUBSYSTEM		
Tower Height, m (ft)	33.5 (110)	38 (124)
Tower Base Span, m (ft)	9.5 (31)	10.7 (35)

TABLE 10. PRELIMINARY DESIGN SYSTEM WEIGHT

STEEL TRUSS TOWER

	WEIGHT*, kg (lbs)			
	500 kW		1500 kW	
ROTOR SUBSYSTEM	8,020	(17,680)	17,430	(38,430)
BLADES	3,080	(6,800)	5,160	(11,390)
HUB	4,940	(10,880)	12,270	(27,040)
DRIVE SUBSYSTEM	16,780	(37,000)	35,180	(77,560)
GEARBOX	9,890	(21,800)	20,860	(46,000)
OTHER	6,890	(15,200)	14,320	(31,560)
ELECTRICAL SUBSYSTEM	2,820	(6,210)	6,950	(15,320)
CONTROL SUBSYSTEM	20	(50)	20	(50)
STRUCTURE SUBSYSTEM	44,950	(99,100)	69,360	(152,900)
STRUCTURAL STEEL	37,470	(82,600)	52,210	(115,100)
OTHER	7,480	(16,500)	17,150	(37,800)
TOTAL WEIGHT ON FOUNDATION	72,590	(160,040)	128,940	(284,260)

*WEIGHT ON FOUNDATION

TABLE 11. PRELIMINARY DESIGN SYSTEM COST
STEEL TRUSS TOWER
1000 UNITS

	COST PER UNIT, $			
	500 kW		1500 kW	
SYSTEM INTEGRATION	14,400		25,100	
ROTOR SUBSYSTEM	110,000		194,900	
BLADES		(76,600)		(122,000)
HUB, including hub-mounted controls		(33,400)		(72,900)
DRIVE SUBSYSTEM, including gearbox, shafting and couplings, ring gear and yaw mechanism	78,000		181,000	
ELECTRICAL SUBSYSTEM, including generator, transformer, cable, utilities	43,800		64,800	
CONTROL SUBSYSTEM	31,400		31,400	
STRUCTURE SUBSYSTEM, including bedplate, enclosure, ladders, tower (installed), foundation	97,400		134,600	
TOTAL WGS UNIT COST	375,000		631,800	
OTHER CAPITAL COSTS, including site acquisition and clearing, shed, installation of components	75,670		89,000	
DIRECT CAPITAL COST, $	450,670		720,800	
DIRECT CAPITAL COST, $/kW	901		481	
ANNUAL COSTS:				
15% Direct Capital Cost*	67,600		108,120	
Operation and Maintenance	23,280		45,350	
TOTAL YEARLY COST, $	90,880		153,470	
YEARLY ENERGY OUTPUT, kW-hr.	1.28×10^6		5.68×10^6	
ESTIMATED ENERGY COST, ¢/kW-hr	7.1		2.7	

Subsystem components are described in the appropriate subsystem sections of this report. Subsystem cost trends are shown in Figures 5 through 9.

*Includes Income Taxes, Debt Service, Return on Equity and Depreciation.

1. Maximize aerodynamic efficiency.

2. Select the simplest design that will achieve desired aerodynamic performance objectives.

3. Ensure that the rotor will operate satisfactorily in temperatures from - 51°C to 49°C (- 60°F to 120°F), in precipitation, in salt spray, in winds up to the maximum anticipated gusts during operation, and survive 53.7 m/s (120 mph) hurricane winds in the stowed position.

4. Be impervious to lightning strikes.

5. Survive foreign object damage such as bird strikes, stones, and small arms fire. Operate in sand and dust storms without leading edge erosion.

6. Have 30-year operating life for blades, hub and grips.

7. Use available technology to the maximum. Minimize production cost and development risk and reduce development costs for any new technology.

The design does not provide protection against freezing rain and structural ice. It is expected that the rotor will be shut down during those infrequent periods when heavy ice accumulates. However, operation during periods of light icing is permissible, though efficiency will be reduced.

Design Approach

The approach to the rotor design is similar to that of the other subsytems. During conceptual design and evaluation, several feasible rotor configurations were examined and one selected which offered lowest cost and risk while meeting technical requirements. The optimization of this concept included evaluation of rotor component options in greater depth. Finally, preliminary designs were prepared with drawings, weight estimates, cost estimates, specifications, and supporting analyses.

Throughout the study, the latest state-of-the-art technology was selected to minimize cost and risk. Rotor configurations were proven concepts adapted from helicopter designs. When feasible, these designs were simplified to eliminate unnecessary elements. Standard commercial parts, such as pitch bearings, were selected whenever possible and low-cost fabrication was emphasized.

Particular attention was paid to those operating conditions and regimes which have significant effects on rotor design. Starting operations, rotor-tower clearance, low rpm stability, transients during gusts, and load loss are examples. Emphasis was placed on avoiding operating the rotor near its natural frequencies to preclude high vibratory loads.

Candidate Concepts and Evaluation

A number of options for rotor blades, controls, and hub were examined during the conceptual design. The decisions made were reevaluated throughout the study and some were modified or changed as the work progressed.

Blades - Blades are the single largest contributor to rotor cost. Of primary importance to the economical design of the blades are the materials and technique for fabrication.

Conventional metal construction represents inexpensive, well-established technology. Metal blades, however, are not easily optimized for aerodynamic efficiency due to the difficulties of manufacture with optimum twist, taper and thickness distributions. Of equal importance is the length limitation of extruded metal spars. Current extrusion technology sets an upper spar length limit of 15 to 18 meters (50 to 60 ft), considerably below the spar length required. Hence, had metal construction been chosen, spars would have had to have been fabricated in sections and joined in some manner. These joints would give rise to a number of problems, including adverse dynamic effects, stress concentrations and added weight. These considerations make the use of composite fabrication techniques and materials attractive. In particular, filament wound composite construction can be used to fabricate blades of the size required for this application with little cost penalty for selecting optimum twist, taper and airfoil section. Additionally, use of filament wound composite construction facilitates achieving a close balance between the blade center of gravity (cg), feathering axis, and aerodynamic center (a.c.) without using balancing weights. Experience has shown that serious dynamic instabilities can occur if the blade cg falls behind its a.c. Hence, blades balanced with cg and a.c. at the quarter chord (25% of distance between leading and trailing edge) and having the feathering axis near the quarter chord axis are traditional in helicopter blade design. These considerations were found to apply to WGS blades; hence a cg/a.c./feathering axis match was considered a design requirement. The result of these requirements was selection and retention of composite, filament wound blades.

Pitch Mode - Variable pitch wind-driven rotors can be operated in either of two control modes--positive pitch or negative pitch. The former produces high thrust loads along the rotor axis which are non-productive, while the latter is primarily a torque-generating mode. The positive pitch mode at low wind speeds and low power levels is subject to rotor thrust instabilities familiar in the helicopter industry as the vortex ring state of rotor wake interference. The vortex ring state is a condition in which the descent velocity of a lifting rotor approximates the rotor downwash velocity, causing development of a large recirculation vortex around the periphery of the rotor disc. For the wind generator system rotor, a similar condition exists when the thrust-induced wake velocity is approximately equal to the wind velocity. Thrust fluctuations associated with the vortex ring state could cause vibratory loads at the top of the tower up to ± 60% of the steady thrust load. Large blade tip deflections also occur, increasing the danger of blade tip intersection with the tower. For these reasons, the negative pitch control mode was selected for the WGS.

Controls - The rotor requires some method of torque and speed control. The variable pitch rotor was chosen over the fixed pitch rotor because its characteristics permit the blade to be rotated about its feathering axis from almost flat pitch to full feather. This facilitates startup and shutdown, permits effective torque control and stowing of the rotor in full feather in case of high winds. Also, the variable pitch rotor can be designed to avoid sustained operation at potentially hazardous resonant conditions during startup. As discussed earlier, these considerations dictated selcction of the variable pitch rotor. The blade pitch, of course, must be controlled.

Blade pitch can be changed and controlled either by directly driving the blade root mechanically, or by using aerodynamic forces by moving a servo flap near the blade tip. The relative merits of the two systems will be discussed later.

Hub - A flex plate hub with low out-of-plane stiffness to give bending moment relief, and high in-plane stiffness to provide the needed characteristics to operate under relatively high gravity loads, was selected initially. During preliminary design, however, the out-of-plane natural frequencies were found to be too close to the operating speed, increasing vibratory response of the out-of-plane bending moments. A teetering type of articulation was then studied, but found not to be cost effective, as will be discussed later. The end result was a rigid hingeless configuration, which gave the necessary root end stiffness.

During conceptual design and optimization, several major analyses were made to examine significant component and configuration alternatives. These investigations are summarized below.

Airfoil Section - Several airfoil sections were evaluated during the conceptual design and optimization phases. These included NACA 4412, 23012, 23018 and 63_2-615 sections. Characteristics used were from NACA Report No. 824 under standard roughness conditions at Reynolds number of 6 million, approximating that of the outer portion of the blades. Although lift-to-drag ratios of NACA 4412 and 63_2-615 airfoils are higher than the 23012, the rotor optimization study yielded very little difference in aerodynamic efficiency for the entire rotor. Consequently, other considerations, such as lower aerodynamic pitching moments, satisfactory past performance, and especially better producibility, led to selection of the 230-series airfoil. This series is easier to make because of the absence of reflex curvature on the under surface, which would make filament wound composite fabrication more difficult.

The 230-series airfoil was retained through the preliminary design. Blade tuning required the bending stiffness at the root to be increased, which led to increased airfoil thickness ratios inboard.

Rotor Size and Solidity - Early analysis indicated that minimizing rotor solidity (total blade planform area divided by rotor disc area) minimized the energy cost for large rotor diameters. A range of diameters at various solidities was examined to determine the limits of solidity and diameter. Results showed there were no inherent technical limits for solidity less than .02 and diameter less than 76.2 m (250 ft). However, it was found that with solidity below .03, complex and costly construction methods and materials were indicated for the thick root sections required. It was also found that .03 solidity was near the lower bound for significant energy cost savings, and that below that solidity, starting characteristics were affected adversely. Therefore, .03 solidity was tentatively selected and was carried through preliminary design. The rotor diameters considered during this analysis also bracket those selected for preliminary design.

Number of Blades - With the cost advantage of minimum solidity and the rotor diameter necessary to generate rated power at rated wind speed, consideration was given to a 3-bladed rotor. It was found that although a 3-bladed rotor reduces vibratory loads on the drive shaft, gearbox and tower, this was not an important enough advantage to offset the higher costs of the third blade. The 2-bladed rotor was selected and retained.

Blade Geometry - The filament wound composite construction permitted most of the feasible options of blade airfoil shape, twist and taper with minimal cost impact. Two geometry studies were made after final solidity and diameter were selected for the preliminary design. The studies covered planform taper, important for structural and tuning reasons, as well as cost, and twist distributions. Final planform was optimized with a 3:1 taper rate from mid-span to tip. It was found that a linear twist of from 10° - 12° results in a rotor efficiency only slightly less than that for an ideal twist. The linear twist reduces blade tooling complexity and difficulties that might arise in removing ideally twisted mandrels from the fabricated blades. Although optimum twist was retained, linear twist can be used with negligible effect on energy cost.

Blade Life - An important factor in rotor system design is selection of the most economical blade life for the particular application. The tradeoff between blade life and initial cost is usually conducted on a total life cycle cost basis, where the cost of maintenance and replacement of the blade at periodic intervals is traded off against the unit cost of the blades.

Such a trade off study was conducted on the WGS blade, even though a 30-year life was a design specification. The results show that no savings in capital cost or energy cost will result from a blade with a life of less than 30 years.

Teetering vs Hingeless Hub - Although the flex plate hub selected during conceptual design offered blade root bending moment relief, some form of articulated blade could further reduce it, and possibly lead to weight and cost savings. A teetering hub was examined for possible advantages.

The teetering hub reduces out-of-plane vibratory bending moments substantially below those of the flex plate hub, but has no appreciable effect on in-plane bending moments. These results suggest that the teetering hub might offer some saving in weight and cost if the design requirements are dominated by out-of-plane bending. However, the out-of-plane static bending moments at the 54 m/s (120 mph) maximum wind condition are the critical bending moments driving the blade design. Blade structure which meets the static maximum wind requirement results in low, non-critical fatigue stress levels under normal operating conditions, even for the higher bending moments imposed by the hingeless configuration. When the additional complexity of the teetering hub was considered in this light, it was dropped from further consideration. Analysis conducted during preliminary design strengthened this conclusion. Blade stiffness distributions needed to tune blade natural frequencies imposed structural requirements on the blade more severe than those imposed by the hingeless rotor vibratory bending moments. Therefore, whether blades are sized for stiffness or high wind conditions, fatigue stress levels are low enough to achieve the required 30-year life.

Servo Flap vs Direct Pitch Control - The conceptual designs of the first phase of the study used a servo flap for blade pitch control. Subsequent analysis proved that although the servo flap alone would be very effective in alleviating wind loads and adequate for pitch regulation during normal operation, it would not serve for startup and shutdown. In these modes, the servo flap was found to lack adequate controllability and pitch resolution. To compensate for this shortcoming, auxiliary pitch control devices and special operational procedures would be required. Because direct blade root pitch control can accomplish the task across the operational spectrum unaided, it was incorporated into the preliminary design instead of the servo flap.

However, if blade wind load alleviation becomes an important factor for cost or operational reasons, the servo flap offers a possible alternative.

Stability - Blade flutter and divergence boundaries were defined and analyzed. The rotor was free from flutter and divergence for the rated operating conditions examined. Similarly, rotor/tower stability was investigated and found to pose no threat over the operating regime of the system.

Overspeed - Rotor overspeed beyond the design rpm for normal operation can occur during large and rapid wind velocity changes associated with strong gust conditions; when the generator is abruptly disconnected from the network, or in the event of a rotor control system malfunction. Loss of the balancing torque load imparts a net accelerating torque on the rotor, causing overspeed. A moderate rate of change of blade pitch angle, 5 degrees per second, was found adequate to provide the necessary overspeed and overtorque control. This insures that the maximum rotor overspeed under the worst combination of conditions is not greater than 150% of rated rpm, the structural limit of the generator. All other components have structural limits above 150%.

Tuning - The structural configuration and thickness distribution of blades were dictated largely by blade tuning requirements. Of particular concern in the overall blade tuning problem is the need to avoid lower order resonance crossings during rotor startup in marginal wind conditions. Under such conditions, rotor acceleration to normal operating rpm will be quite slow, particularly in the 80% to 100% rpm range, where accelerating torques are low. This requirement resulted in selecting blade configuration details, such as root-end airfoil thickness and blade stiffness, which tune the blade to eliminate these problems.

Fatigue Life - A potential for the accumulation of fatigue damage in WGS rotors exists in many regimes of operation. However, since 30 years is the required design life, almost all operation must occur below the blade endurance limit. Accordingly, a design goal was established which placed the endurance limit above all operating conditions, including startup, shutdown, and strong gusts in wind up to cut-out wind speed, leaving the possibility of occurrence of fatigue damage only for extremely severe conditions, which are seldom encountered. The calculated fatigue strength for unlimited life for both rotor blade designs, compared with loads for the maximum gust above cut-out speed, shows large margins between allowable and expected loads. This indicates that the design fatigue life will be achieved.

Tower Shadow - The wind wake downwind of a tower is proportional to the drag coefficients and solidity of the structure. A dense tower will generate a sharp wind velocity reduction which produces a pulse input to the airload distribution of a downwind rotor as the blade passes through the tower wake. This pulse occurs at exactly 1/rev frequency and will, therefore, generate harmonic forces at all integral multiples of rotor speed, 1/rev, 2/rev, 3/rev...n/rev. Blade bending and torsion responses will occur at all of these frequencies. The magnitude of response will depend upon the amount of damping in the various bending and torsion modes, their proximity to multiples of rotor speed, and the strength of the tower wake.

The study reported herein used a 30 percent wind velocity reduction for tower shadow, based on available literature information. This value of tower shadow was not critical for fatigue at any wind velocity examined, from minimum wind speed to well beyond cut-out speed.

(NOTE: Subsequent information, obtained from NASA testing after completion of this study, quantified wind velocity reductions behind towers having high solidity and angular structural elements. The wind shadow behind such towers can produce substantially higher blade bending moments, with associated reductions in blade fatigue lives. Therefore, it is considered essential that tower design criteria include the requirement for minimum shadow effect by minimizing tower solidity and selecting structural elements having low drag coefficients.)

Preliminary Design and Analysis

Rotor preliminary design was supported by configuration, operational and structural analysis. Configuration analysis included blade geometry optimization studies which led to the selection of blade thickness, planform and twist distribution. The major operational analyses included pitch control mode selection, overspeed limit calculations, blade tuning analyses, determination of blade flutter and divergence boundaries, and whirl resonance analyses. The major structural analyses covered the blade design, fatigue analysis and hub design.

Designs for both the 500 kW and 1500 kW rotors are similar, hence only the 1500 kW unit is illustrated in this summary.

Blades - Details of blade geometry are shown in Figures 14 and 15. In construction, three separate mandrels are successively wound with S-2 fiberglass at angles ranging from ± 45° to ± 60° to the blade centerline, with unidirectional layers interleaved spanwise during the winding process. The third mandrel is used to position aluminum honeycomb blankets and a trailing edge spline, after which the entire assembly is filament wound to form the complete structure. The outboard section of the blade leading edge is protected from erosion by a neoprene guard. Aluminum mesh screen embedded in the aft blade surface protects against lightning.

Head Assembly - The rotor head is shown in Figure 16, with a cutaway view including controls shown in Figure 17. The rotor head is a rigid, hingeless assembly supported by tapered roller bearings on a non-rotating hollow spindle shaft which reacts out-of-plane bending moments. A central quill shaft transmits rotor torque to the gearbox. A linear-travel blade pitch control mechanism is supported by the rotating quill shaft within the spindle shaft. The pitch control system is linked directly to a clevis in each grip. Linear movement of the pitch control beam causes a blade to rotate about its pitch axis. Travel is sufficient for blade pitch control throughout the operating range, including full feathering. Multiple-lug blade grips and pitch control bearings complete the rotor head assembly.

Blade Grips - Forged aluminum grip fittings connect the blades to the hub. These fittings redistribute blade loads into the pitch bearings and pitch control linkage. Connecting the grips to the hub is a crossed roller pitch bearing, capable of reacting large moments as well as thrust. Blades are connected to the grips by a double-pinned multi-lug joint which picks up the main spar fitting. A truss to the blade trailing edge fitting carries trailing edge spline loads.

Hub - The hub is constructed as a weldment of three large rolled plate cylinders. The larger two cylinders have axes coincident with the rotor blade pitching axes and furnish the mounting for the blade pitch bearings. These cylinders are pierced by a smaller cylinder containing the hub bearings. The bearings are a tapered roller pair in which all thrust is carried by the aft bearing.

The welded structure was selected to reduce construction costs. Low stress levels are achieved throughout the hub by providing generous cross sections.

CONTROLS

The controls subsystem conceptual design, optimization and preliminary design are discussed below. A primary tool for this process was a failure modes and effects analysis (FMEA) which is presented in the Design Study. The FMEA was used to guide the concept selection and design of the control system, based on the types of failures which might occur, the severity of their effect on the WGS, and the ability to detect and compensate automatically for such failures.

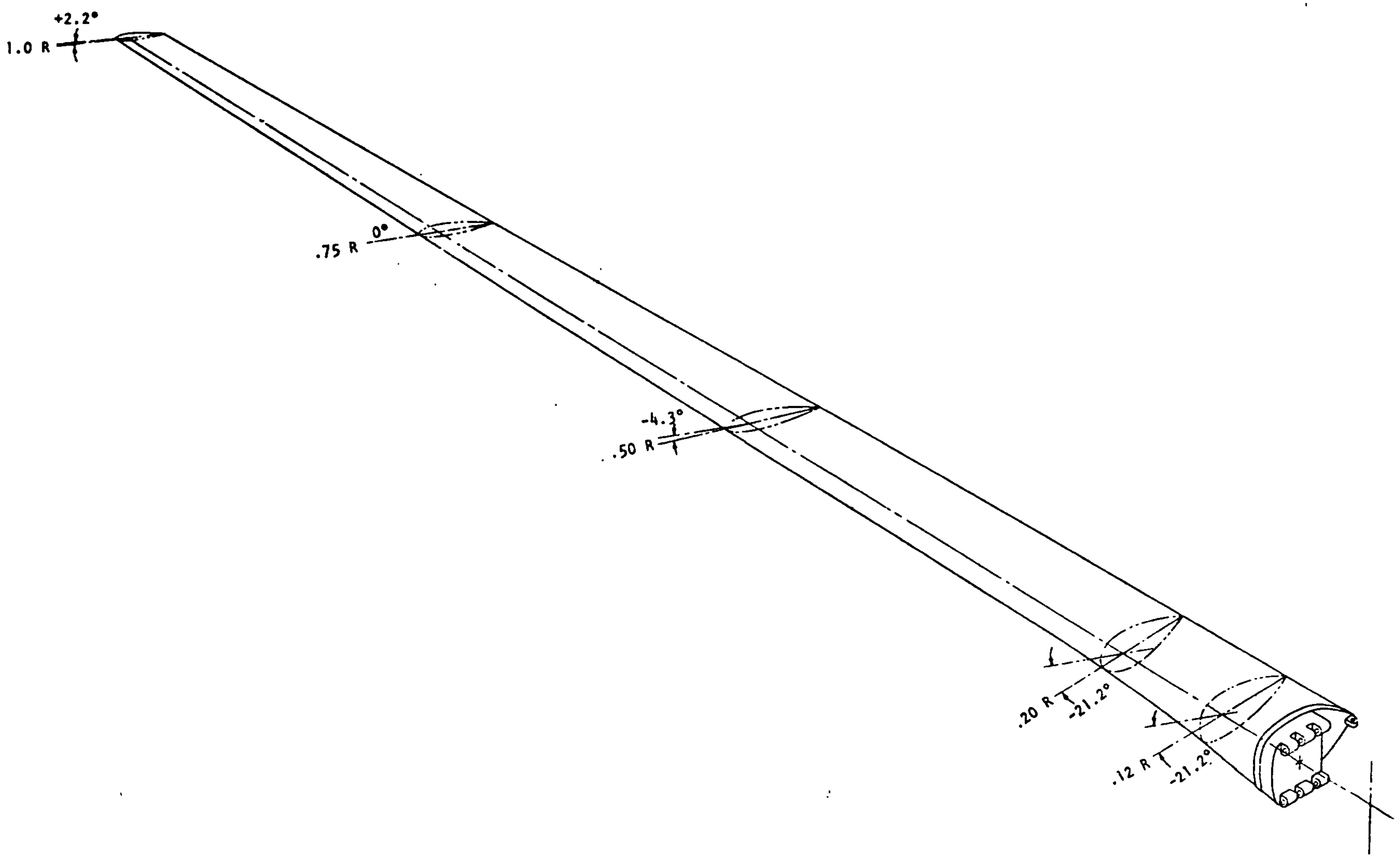


Figure 14. Isometric View of Blade, 1500 kW WGS

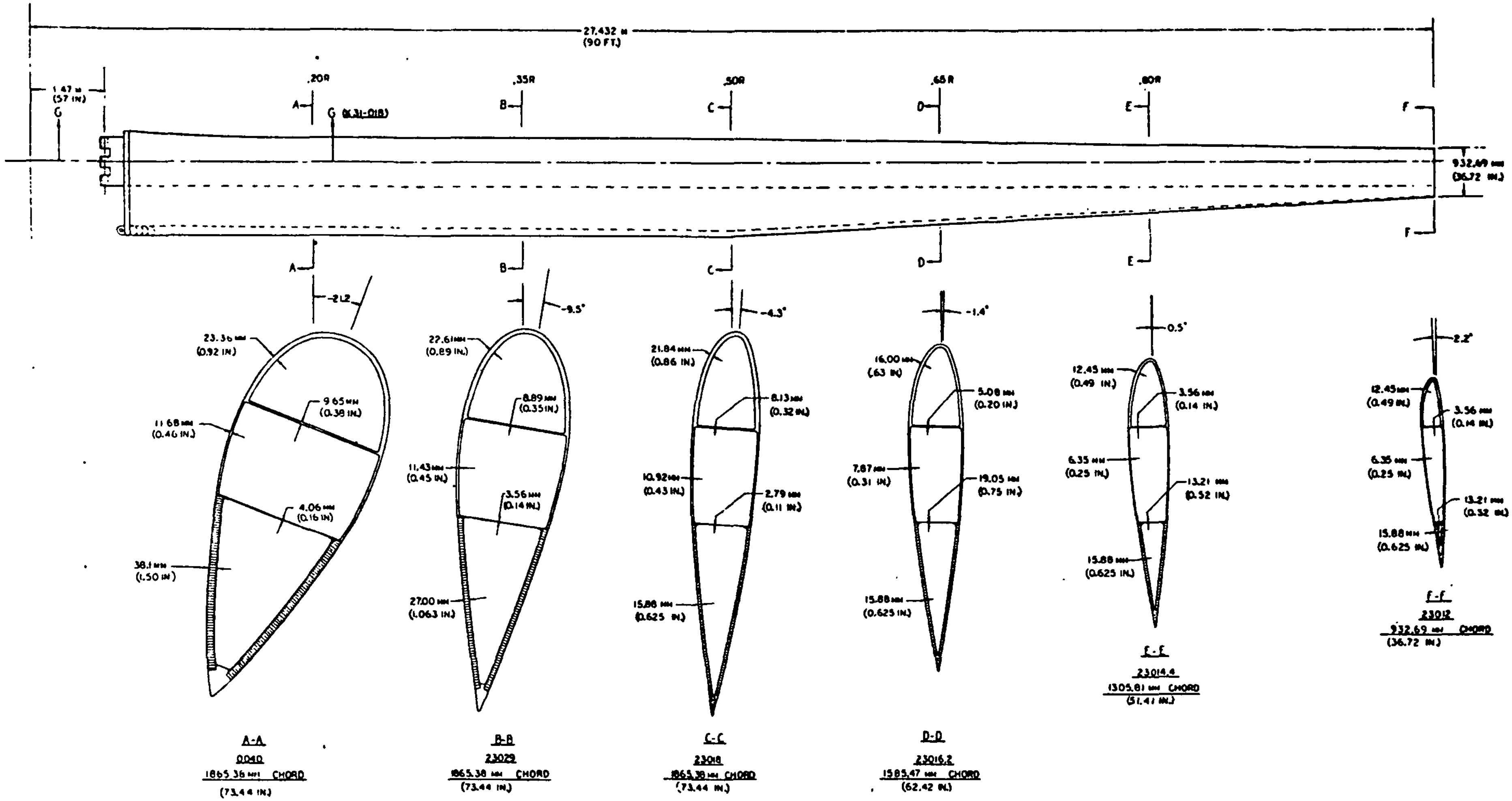


Figure 15. Planform View of Blade, 1500 kW WGS

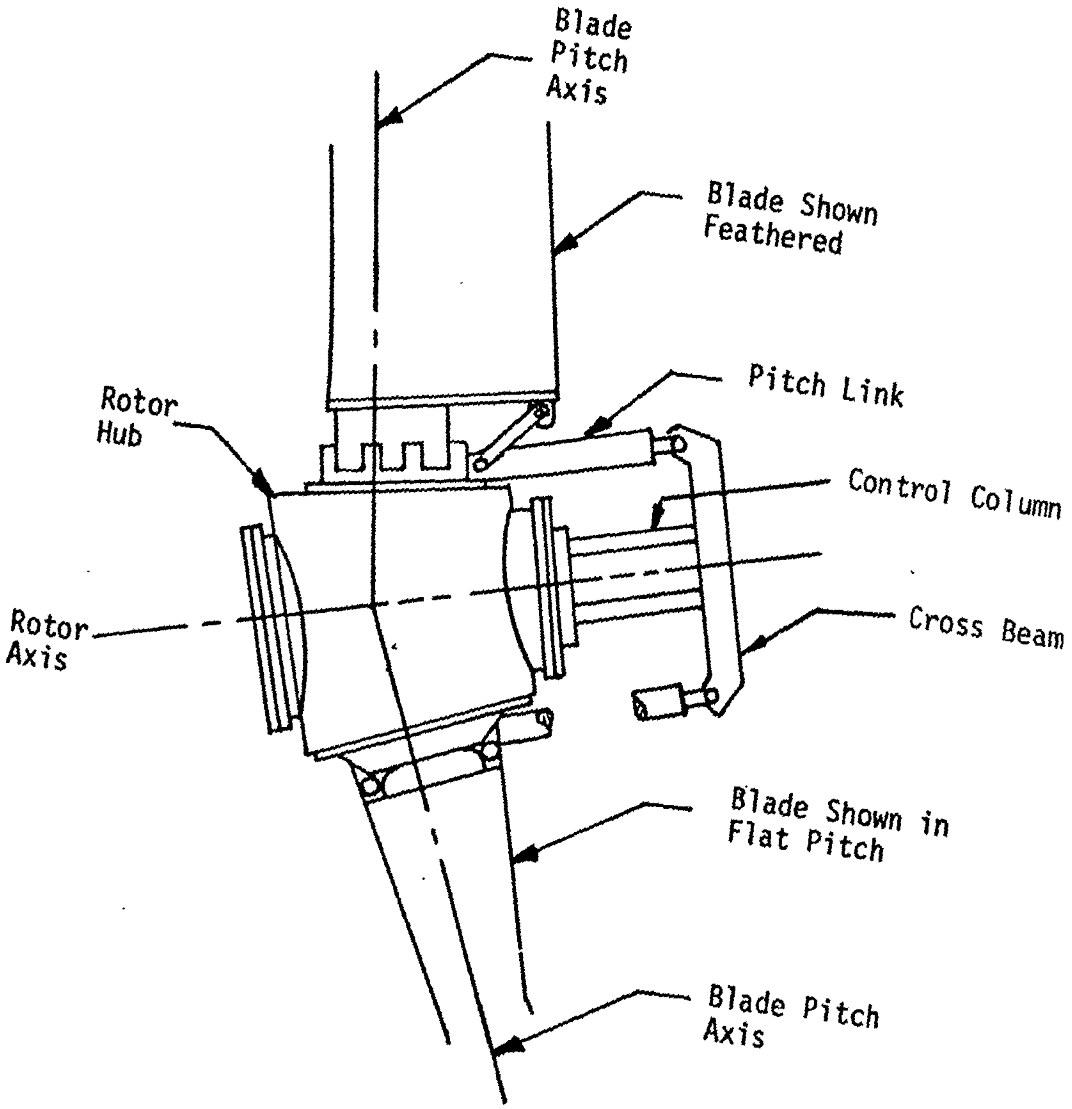


Figure 16. WGS Rotor Head Assembly

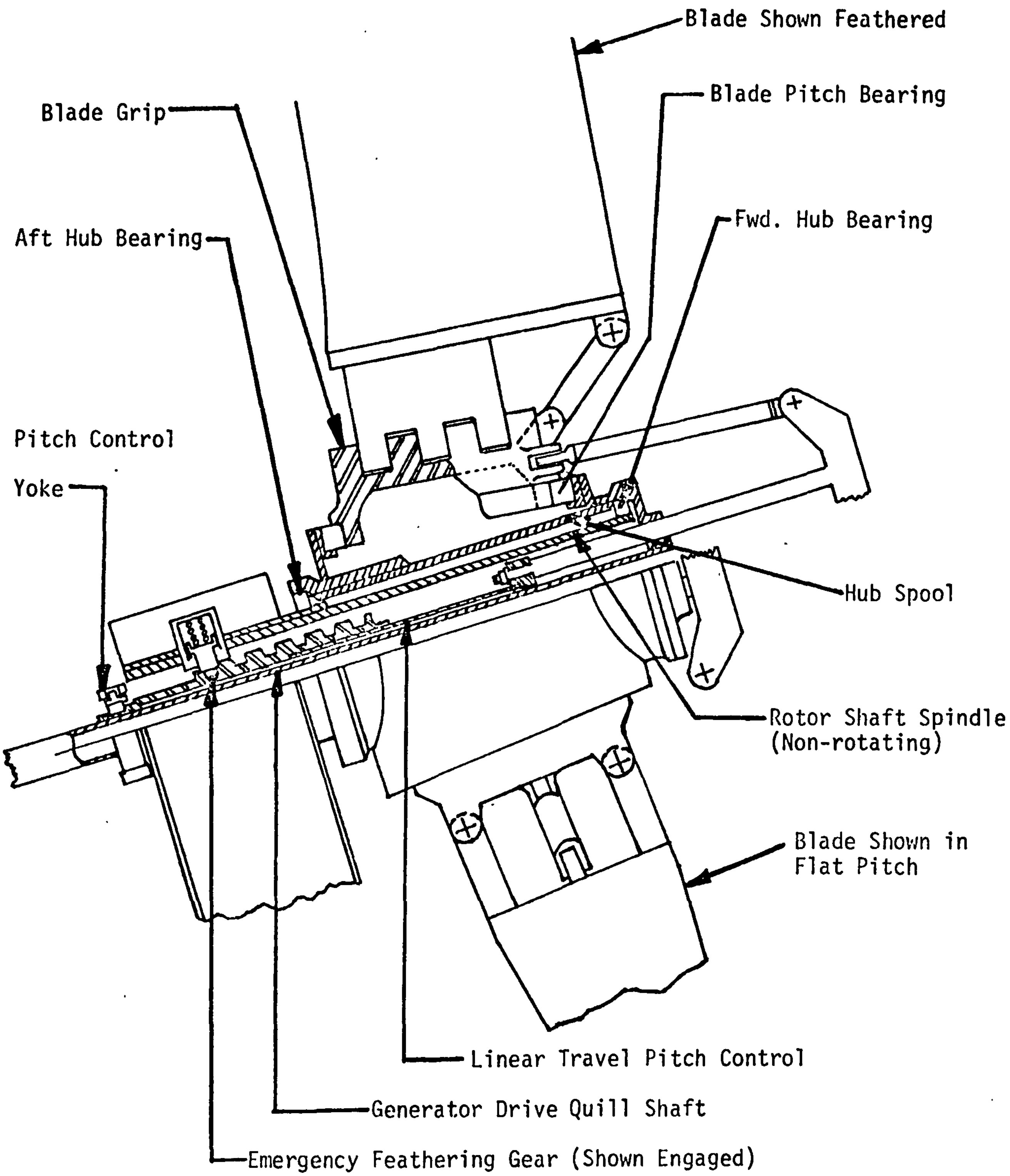


Figure 17. Rotor Head Assembly, Cutaway View

The control system uses a microprocessor for data telemetry and for startup and shutdown sequencing, with hydraulic servos and analog equipment for the primary rotor controls. A purely mechanical control backup is provided for emergency feathering and shutdown of the rotor.

Requirements

The controls subsystem must be designed for operation at a remote, unattended site. The subsystem must be fail-safe and self-monitoring; that is, it must be capable of detecting any failure within the WGS which may cause secondary damage to subsystems and take appropriate protective action. The controls must operate the system under extreme environmental conditions, such as wind gusting, and protective functions must be executed independent of the availability of external power. The controls must also be conservatively designed to maintain high reliability and be properly protected against induced transients from the power line or from lightning strikes.

The control subsystem must do the following:

1. Start up the WGS from rest to design rotor speed.
2. Shut down and secure the WGS.
3. Control blade pitch to regulate the rpm of the rotor when disconnected from the utility network.
4. Control blade pitch to regulate power output when connected to the utility network.
5. Control the yaw orientation of the nacelle.
6. Monitor operating parameters and telemeter information to a central control point.
7. Determine when a fault exists within the WGS or the utility line and take appropriate action to protect the system.
8. Record significant data at the WGS site.

Many different functions are required of the control system, ranging from continuous fast-response proportional control to discrete fault detection and sequencing. Since the various control functions also have differing degrees of importance from a safety and reliability standpoint, the same equipment will not be optimum for all functions. Therefore, the control functions were categorized for purposes of concept selection and the optimum equipment was selected for each category.

The cost and weight of the electrical portion of the control subsystem are only a small percentage of the total subsystem cost and weight. Therefore, these were not major factors in the evaluation of control subsystem concepts. The major considerations in the evaluation of the candidate control concepts were reliability and safety. Other criteria included acceptability to electric utilities, compatibility with the specified environment, simplicity, life, and maintenance. In the case of critical functions, predictability and ease of detection of failure modes and the ability to initiate protective or backup action without external power were important considerations.

Design Approach

Types of equipment examined included fully-mechanical sensing and actuation devices, electrical devices, including AC and DC analog servo systems, standard digital logic, and digital microprocessors. Several actuation methods were also investigated, including aerodynamic, electrical, mechanical, pneumatic and hydraulic approaches. The sensing devices considered depended primarily on the parameter being sensed. However, preference was given to devices which do not require slip rings or commutators. Preference was also given to readily available, off-the-shelf components and concepts which have a firm and proven experience base in the rotary wing or power generation fields.

As the WGS design concept evolved through the conceptual design, parametric optimization and preliminary design phases, the control subsystem concept was developed and modified. The essential control subsystem concepts were selected at the outset of the preliminary design phase and then refined in concert with other subsystems.

Candidate Concepts and Evaluation

Critical Controls - Hydraulic servos supplied with pressure from a pump driven directly by the main gearbox were selected for the primary rotor controls. Standard analog servo amplifiers were selected to control the hydraulic actuators, primarily due to their large experience base in utility applications and their compatibility with automatic failure detection. The blade pitch control linkages from the actuator to the blade were selected as simple mechanical linkages to provide high reliability and safety. This linkage approach also permits use of the stored energy in the rotor to provide an emergency shutdown capability in the event of a power failure or control failure during operation.

Non-Critical Components - A microprocessor-based computer system was selected to control the startup and shutdown sequencing of the WGS, and also to handle the data formatting and communications for telemetry and supervisory functions. This equipment is ideally suited to these functions, and is presently being used by utilities in a similar role. Since the utility experience base with this equipment is not extensive, the microprocessor was limited to the functions described and was excluded from the primary rotor controls and the electrical protective and relaying equipment. Field experience with these devices indicates a satisfactory performance can be obtained in a remote site environment if proper precautions are followed, such as isolating inputs and outputs against transients, and special coding provisions to provide high noise immunity for the telemetry links. The microprocessor can also draw its power from a non-interruptible battery source.

Monitoring - Critical sensing, signal processing and actuation functions can be continuously monitored for failures, and appropriate action taken to prevent secondary damage in the event of a failure. This monitoring includes, as a minimum, the blade pitch servo control, the yaw servo control, the wind speed and direction sensing, the rotor rpm sensors and the critical portions of start-up and shutdown sequences.

Preliminary Design and Analysis

The following description covers the electronic and electrical portions of the controls. The mechanical and hydraulic portions of the system are described in the drive subsystem section.

Yaw Control - The yaw servo keeps the shaft axis of the rotor aligned with the average wind when the rotor is turning. The yaw rate is limited to approximately 1/3 rpm to prevent sudden motions of the tower head which could result in large forces on the system due to gyroscopic effects. The yaw servo is only intended to trim the system to the average wind direction. A wind vane coupled to a synchro is used to sense wind direction error. The error signal is then amplified and used to operate hydraulic solenoid valves, which control the flow of hydraulic power to the yaw servo motor. Automatic fault monitoring of the yaw servo during operation is provided by independently monitoring the average wind direction error and checking for proper servo response to changes in the average direction of the wind.

Blade Pitch Control - The blade pitch servo amplifier provides a proportional DC output signal to operate the blade pitch hydraulic servo valve. The amplifier is automatically reconfigured for each mode of operation:

1. Startup - programmed pitch change for rotor acceleration.
2. Standby/Synchronize - pitch controlled to regulate rpm.
3. Operate - pitch controlled to regulate power output to utility.
4. Normal Shutdown - programmed pitch change for rotor deceleration.

During both the standby/synchronize and operate modes, gross positioning of blade pitch is accomplished by providing the servo with a signal which is a function of the component of wind speed along the axis of the rotor shaft. For the operate mode, a power signal derived from the generator power output monitor provides a fine adjustment to hold the power output at the rated set point for wind speeds above rated. RPM is used to control pitch for the standby/synchronize mode.

Continuous fault monitoring of the pitch servo during startup, standby/synch and operate modes is required to prevent possible overspeed/underspeed and/or reverse thrust on the rotor due to pitch control failures. The monitor must be capable of differentiating between pitch control failures and sudden or unusual motion of the controls due to wind gusts. This is accomplished by a monitoring device which checks for proper average blade pitch position via an independent blade pitch feedback sensor.

Several analyses of the control system were used to establish the rates and limits of the control components. The most important of these included the establishment of the rotor blade pitch rate, which is the basic system power control parameter. To establish the pitch rate required, an analysis of rotor response under gust conditions was conducted. The wind gust model used for this analysis was supplied by NASA.

When the generator is connected to the utility network, an increasing gust will cause increasing torque and power output, whereas a decreasing gust will cause decreasing torque and power output, and may also cause an undesirable thrust reversal on the rotor if the pitch control system is not sufficiently responsive. Using the static control characteristic of the rotor, in conjunction with the wind gust model, it is possible to estimate the effect of gusts on the system and to derive the control response requirements. The analysis indicated that the torque overload limit was the controlling requirement on pitch rate and showed the required pitch rate to be about 5 degrees/second.

When the generator is disconnected from the network, the sudden loss of load, combined with a gust, can cause an overspeed condition. The overspeed analysis also showed a pitch rate requirement of about 5 degrees/second to limit maximum overspeed to 150% of rated, the generator limit. Thus, analyses of both critical control conditions determined that a 5 degree/second pitch rate is adequate to control the rotor under extreme conditions. Ultimately, more detailed analysis may indicate somewhat faster rates are needed. However, the pitch rates should not be made faster than necessary, since excessively fast rates pose a greater hazard in the event of control system failure at the highest pitch rate position.

STRUCTURE

The WGS structure subsystem includes the tower and its foundation, and the turntable. Various tower configuration concepts were investigated in depth before selecting the final concepts for preliminary design. Preliminary designs of both steel truss and concrete shell towers were prepared for the 500 kW and 1500 kW systems, since both types offer attractive combinations of cost, appearance and modification flexibility.

Requirements

The structure must support the power generating subsystems and controls, allow the rotor disk to be oriented normal to the wind and react the forces imposed by the rotor and by the wind acting on the tower itself. Fatigue strength of the tower must be great enough to withstand the rotor-induced vibratory loads, including the effects of startup and shutdown cycles, gust variations, tower shadow, and gravity for a 50-year service life. The stiffness of the tower must be selected so that the resulting tower natural frequencies avoid integral multiples of the operating frequency.

The foundation must provide a firm anchor for the tower structure for all imposed loading conditions and certain earthquake conditions.

The turntable and associated connecting structure, orientation drive mechanism and protective shrouding must transmit loads developed by the rotor and power conversion machinery to the tower and protect these components from rain, snow, hail and lightning.

Many other detailed requirements, specific to each particular WGS concept, size and operating condition, were developed and used to guide the tower concept selection and design. The most important detailed requirements covered the subsystem structural criteria, including static strength, fatigue strength and stiffness.

The static strength requirement was established for three basic loading conditions:

> Blowover - For hurricane winds of 53.6 m/s (120 mph), it was assumed that the rotor is parked with the blades vertical and that the wind direction was such that the wind impinges flatwise on the blades and broadside on the nacelle.
>
> Normal Operating Plus Seismic Loads - The wind velocity for this condition is the rated wind speed of the WGS, which produces maximum rotor thrust. A horizontal load factor from the Uniform Building Code for a seismic disturbance was applied to produce inertia loads in the same direction as the rotor thrust.
>
> Maximum Operating Load - The normal operating loads at rated wind speed were multiplied by 2.0 (except that rotor torque was multiplied by 2.5) as conservative estimates of the worst transient loads, including dynamic response of the structure. The peak gust amplitudes were derived from the NASA gust model.

Fatigue strength requirements were established for two repeated loading conditions. For the high frequency vibratory hub moments existing in normal operation, infinite life was required. For the repeated loads incurred by startup and shutdown cycles (0 to 1.5 times maximum steady operating loads), a life of 50 years at five cycles per day was required. In order that structural natural frequencies avoid resonance with the rotor, it was judged to be necessary that the first mode bending and torsional natural frequencies be at least 1.5 and 2.5 times the rotor operating frequency, respectively, and that they should avoid integral multiples of normal operating rotor speed.

Design Approach

To minimize costs, existing commercial quality materials and parts and standard construction techniques were used for all tower concepts. The choice of materials was, therefore, limited to structural steel and concrete and the principal focus of the concept evaluations was on the configuration of the tower and foundation.

Candidate Concepts and Evaluation

Several tower and foundation configurations were considered and evaluated during Phase I, as described earlier. Because large production run costs of both the truss tower and the pre-cast, post-tensioned concrete tower are reasonably close, and each has important advantages, both were carried forward to preliminary design.

A welded structural steel framework of standard sections was postulated for the turntable (Figure 13) as representative of the weight and cost of any feasible alternative.

A detailed study during the preliminary design phase examined the relative merits of foundations of mass concrete, piles, and piles with rock anchors, for both the 500 kW and 1500 kW WGS. To establish strength properties for the foundation, average soil conditions and existence of bedrock at a reasonable depth were assumed. For the high power system, a combination of a truss tower and piles with rock anchor foundation showed a distinct cost advantage. Otherwise, no single foundation concept or tower-foundation combination was significantly advantageous. It was evident from the analysis that local soil conditions should be examined for a particular site to determine the most economical foundation.

Particulars of the various tower-foundation studies are in paragraph 6.4 of the Design Study.

Preliminary Design and Analyses

Since the tower concept studies showed that both the steel truss and pre-cast, post-tensioned concrete tower concepts have advantages, preliminary designs for both concepts were prepared for both the low and high power systems. Design configurations and system costs for all three foundation concepts for both tower types and power levels were also developed, assuming average soil conditions.

The 1500 kW WGS steel truss and concrete shell towers are shown in Figure 18. The 500 kW system towers are similar. The 1500 kW truss tower is a four-sided tower, constructed of standard grade structural steel H-beams and double angles. The width of the top of the tower was dictated by the bearing size required to react the rotor loads. Bending strength is primarily provided by the chords, or corner members, of the tower. The chords are constructed of wide-flange H-beams. Each chord is made up of three different sizes of H-beams, the heaviest at the base and the lightest at the top of the tower. The diagonals provide the shear and torsional strength of the tower. They are constructed of various sizes of H-beams and double angles, again with heavier members used near the base of the tower. The purpose of the horizontal braces is to stabilize the diagonals and reduce their effective column length. The horizontal braces carry no primary loads.

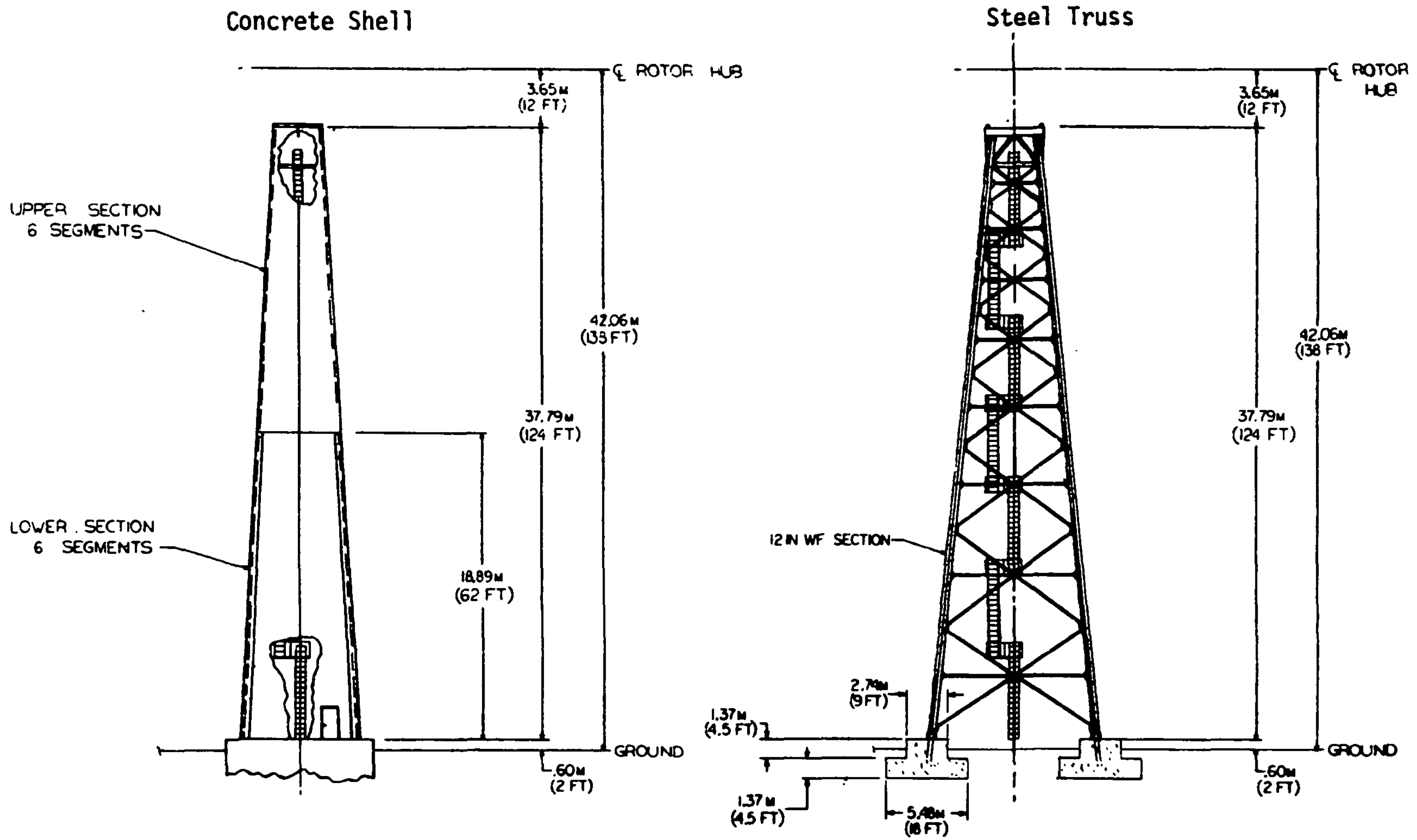


Figure 18. 1500 kW WGS Concrete Shell and Steel Truss Towers

The pre-cast concrete tower for the 1500 kW WGS is a truncated circular cone with a constant cone angle and constant wall thickness, constructed of 12 factory match-cast segments, six upper and six lower, each covering 60 degrees of circumference. The lower six segments are identical, except for a doorway in one, and the upper six are identical. Maximum size of each segment was determined by shipping considerations of weight and dimension. Access to the tower top is provided by caged ladders in the shell interior, protected from the environment. Post-tensioning is accomplished during erection of the tower in two stages; the first post-tensioning is applied after the lower half is erected, while the second post-tensioning is applied after erection of the upper half. Post-tensioning strands are positioned at 12 locations within the shell wall which is thickened locally to provide protection to the strands. These steel strands, running through the shell wall from the foundation toward the top of the tower, are anchored to the foundation and are tightened during the post-tensioning process so that they compress the concrete. The amount of compression is sufficient to keep the concrete in compression for the maximum design loads. Shear ties between the segments are required along vertical joints to provide structural continuity.

For each tower design, the applied loads, member stresses, and natural vibration frequencies were analyzed in detail. Each structure was designed to satisfy the structural criteria described above. Of the three static loading conditions, the storm wind blowover condition was found to be most critical. Either this condition or the stiffness requirements governed the tower designs. The fatigue requirements were not found to be critical.

The relatively small difference in high production rate cost between the steel truss and post-tensioned concrete towers, shown in Table 12, leads to the conclusion that both tower types should be considered for production applications. The truss, however, is very clearly the most economical choice for demonstration and development programs.

(NOTE: As discussed earlier, due to the considerable importance of the excessive shadow effect produced by shell type towers, it now seems unlikely that shell towers will prove feasible.)

TABLE 12. 1500 kW TOWER COST ANALYSIS - DOLLARS

	PRODUCTION QUANTITY			
	1	100	1000	10000
Truss	63,000	63,000	55,000	49,000
Pre-cast, Post-Tensioned Concrete Shell	324,000	63,000	60,600	60,300

DRIVE

The drive subsystem, Figure 13, is comprised of the mechanical components which support the rotor and transmit its torque to the electrical generator. In this study the control system power supply, the mechanical rotor controls, and the turntable orientation mechanism are defined as part of the drive subsystem.

Requirements

Table 13 lists the functional requirements of the drive subsystem.

TABLE 13. FUNCTIONAL REQUIREMENTS OF DRIVE SUBSYSTEM COMPONENTS

COMPONENT	FUNCTION
Rotor Spindle or Shaft	Supports the rotor, allows its rotation
Input Drive	Transmits rotor torque to the gearbox
Gearbox	Provides rotor to generator speed conversion. Drives auxiliary equipment
Parking Brake	Stops the rotor from low rpm and locks it
Inching Drive	Repositions the parked rotor
Pitch Control	Controls pitch setting of the rotor blades
Turntable Control	Orients the rotor normal to the wind
Turntable Bearing	Provides pivot between the turntable and tower
Hydraulic System	Provides power to pitch and orientation controls

Design Approach

In order to minimize cost, maximize reliability and provide long drive train component life, an approach emphasizing simplicity and design ruggedness was used. All drive subsystem concepts considered only off-the-shelf components operating well within their strength and performance capacities. Safe failure modes were designed into the drive subsystem where possible; e.g., feathering the blades and locking the turntable in the case of servo system failure.

Simple field assembly tasks were assured by assigning critical fitting tasks to shop fabrication steps and by allowing latitude for misalignment between field-assembled units. Maintainability was emphasized by the simple design approach, by designing good accessibility provisions and by including strategically placed diagnostic sensors.

The entire design approach to the drive subsystem was geared to achieve low initial and operating costs through the use of rugged components and straightforward, proven component integration techniques.

Candidate Concepts and Evaluation

A number of power transmission configurations were evaluated, including chain and belt drives, hydrostatic transmissions and fixed ratio gearboxes. Only fixed ratio gearboxes were found to be commercially available in sizes capable of handling rated rotor torque. Other candidate components would have to be combined, or staged, to meet the torque requirements. Since fixed ratio gearboxes also offer the best efficiency and highest reliability, they were the clear choice for the power transmission system.

The rotor support/drive shaft must take the form of either an overhung drive shaft supported on pillow blocks, or a static spindle with live bearings for rotor hub support and a quill shaft for torque drive. While simpler in concept, the pillow block shaft was not selected because of the higher weight of the shaft and bearings needed to handle the overhung rotating loads. The static spindle offers a much more efficient structure, not subject to large vibratory bending moments from the rotor.

Auxiliary drive system components, such as shafting, flexible couplings, bearings and clutches were found to be readily available as catalog items. Overall system cost and weight were generally not greatly influenced by these component choices, and most of the effort devoted to the evaluation of these devices concentrated on the selection of low cost designs.

One auxiliary function which received heavy emphasis was the provision for emergency shutdown. A primary brake, capable of stopping the rotor from an overspeed condition due to extreme gusts or network disconnect, was found to be impractical for the WGS. Brake size becomes unreasonably large when installed directly on the low speed rotor shaft, while gearbox strength and brake energy dissipation capability come into question with the brake installed on the generator high speed shaft. This problem was circumvented by providing a direct, fail-safe mechanical method for slowing the rotor by blade feathering, actuated by rotor inertia when overspeed exceeds safe limits. After slowing, the stop is completed with a small parking brake.

Two turntable support configurations were studied. In one, a system of three bearings was arranged on a pintle projecting from the bottom of the turntable. An alternative design used a single, large crossed roller bearing. Advantages leading to the choice of the second scheme were simpler assembly and lower cost, and a large clear center passageway from tower to turntable for personnel and power lines, an important design consideration.

Preliminary Design and Analysis

The preliminary design of the 1500 kW high power WGS drive subsystem is shown in Figure 13. The drive subsystem for the 500 kW unit is similar. Both of these designs are described below, by major component.

Rotor Spindle - The rotor is supported on a tubular spindle which is fitted to a socket in the turntable structure shown in Figure 13. Attachment of the spindle to structure is by means of shear bolts. Stress levels in the spindle are sufficiently low to permit its designation as permanent structure with a life of 50 years. The spindle provides mounting for a pair of tapered roller bearings which support the rotor hub.

Quill Shaft - The driving connection between the hub and gearbox is a quill shaft which transmits torque only, since all other rotor loads are carried by the stationary spindle. In the 500 kW WGS, this tubular steel shaft is .2 m (8 in) in diameter and, in the 1500 kW system, the shaft diameter is .406 m (16 in). A flexible coupling connects the quill shaft to the gearbox, allowing for installation misalignment.

Gearbox - Rotor-to-generator speed conversion is by means of a triple mesh, parallel shaft gearbox. Candidate gearboxes are Philadelphia Gear models for both the 500 kW and 1500 kW WGS. These gearboxes are equipped with anti-friction bearings throughout, and use case-hardened shaved, or ground, gears.

Pitch Control - The rotor pitch control system utilizes a central push-pull control column which is keyed to the rotating quill shaft (Figure 16). A rigid cross beam on the end of this column is linked directly to each of the two blade grip fittings by pitch links so that the push-pull motion is transformed into rotation of the blades about their pitch axes.

The pitch column can be actuated by two independent means. Normal actuation is by means of a single, large hydraulic cylinder which is linked to a yoke on the inboard end of the column. A thrust bearing in the yoke allows transfer of the linear motion from the cylinder linkage to the rotating column. Motion of the hydraulic cylinder is controlled by an electro-hydraulic servo valve, and cylinder position is fed back by a linear displacement transducer.

Emergency actuation of the pitch column is accomplished when cam follower plungers drop into engagement with a helical cam slot in the column. Rotor shaft rotation will then move the column, very forcibly, in the feather direction. A deeper annular slot at the end of travel prevents motion beyond full feather, even if the shaft continues to rotate, and also prevents inadvertent reversing. The cam follower plungers are spring-loaded to the engaged position, and hydraulically disengaged. In the absence of hydraulic pressure, either through malfunction or actuation of a selector valve, the followers will engage and feathering will take place.

Orientation Control - Turntable orientation is accomplished by means of a hydraulic motor and gear train. The motor is mounted on, and drives through, a single stage vertical shaft worm gearbox of 60:1 ratio. Output of this gearbox drives a pinion gear which meshes with a large diameter internal gear. This large gear is integral with the inner race of the turntable bearing, which is secured to the tower. Ratio of the pinion-ring gear is 10:1. The worm gearbox is irreversible, so that the turntable will be rigidly held against the wind load, unless the wind load is assisting the hydraulic motor. Speed of the motor will be regulated by hydraulic flow control valves, so that turntable rotation will be held to 1/3 rpm, even with assisting wind. This is required to limit rotor gyroscopic forces.

Turntable Bearing - The turntable bearing is a single, large-diameter crossed roller bearing. This type of bearing can withstand radial thrust and overturning moment loads, separately or simultaneously. Balance of the complete turntable assembly with all equipment and nacelle is slightly offset, with the rotor on the light side. With the wind thrust, there is a constant moment tending to pitch the rotor down. The bearing is sized to handle all loads, including those generated by the maximum wind blowing broadside on the nacelle and feathered blades.

Parking Brake/Inching Drive - A parking brake/inching drive has been designed as a single unit. For this arrangement, the brake connects the generator shaft to a motor-driven worm gear, which is the inching drive.

The purpose of this arrangement is to eliminate the need for a secondary clutch and actuator, and to bypass a hazardous sequencing step where the brake must be released when the inching drive is engaged. When the parking brake is engaged, it locks the generator shaft to the worm drive, which is irreversible to torque applied to the gear. The worm is driven by a gear motor so that the shaft can be slowly rotated to a selected parking position for stowing or maintenance. At no time is the brake released, until it is desired to start the WGS.

ELECTRICAL

Several types of electrical generation approaches were studied during the concept selection process, including variable rotor shaft speed and fixed rotor shaft speed configurations. Two fixed speed concepts, using either an induction or synchronous generator, were selected for the WGS preliminary design, since these concepts provide the highest system efficiency with the lowest system cost and complexity.

Requirements

The basic requirements of the electrical subsystem are to produce electric power at a voltage and frequency compatible with standard electric utility requirements and practices. The electrical generating equipment must produce this power using minimum-cost equipment to achieve competitive energy costs.

The equipment must operate at a remote, unattended site. Therefore, automatic fault protection and synchronization of the WGS with the utility network must be provided. The equipment must operate over the required range of wind speed, temperature and other environmental effects, and maintain a stable interface with the utility network under expected wind gusts. This represents an additional requirement beyond those usually imposed on conventional utility generating equipment, since the power source, the wind, is a random variable. The WGS must, therefore, include provisions to limit the adverse effects of wind gusts on the WGS and the utility network. This is accomplished primarily through control of blade pitch and by control of generator field excitation.

Design Approach

In selecting the electrical subsystem concept and developing the preliminary design, primary emphasis was placed on minimizing the cost per kilowatt hour of energy delivered to the utility. Since the WGS spends a large percentage of its time operating below rated power, good partial power efficiency was an important consideration in the selection of the generating and interface equipment. Emphasis was also placed on the selection of equipment commercially available and conforming to standard utility practices. Other decision criteria included equipment cost, total weight of the electrical subsystem which affects tower cost, electrical subsystem reliability and maintainability, and utility equipment preferences and control considerations.

Candidate Concepts and Evaluations

Generators - There are two fundamentally different approaches for generating electric power with the WGS. One approach is to use an electrical subsystem which can accept variable shaft rpm, allowing the rotor to operate at a speed proportional to the wind. The second approach operates the electrical equipment at a fixed rpm and requires a fixed rpm shaft drive from the gearbox to the generator. These are described in more detail in Phase I, Evaluation of Candidate Systems.

Both approaches must provide constant frequency output. Although operation at variable rpm complicates the electrical equipment, it does permit the rotor to operate at its most efficient speed over a range of wind speeds. For variable speed systems, a means must be provided to convert the variable shaft rpm into the constant frequency required by the utility network.

In the study, three basic concepts were considered for generating DC power from the variable shaft rpm and then converting to AC power at constant frequency for delivery to the utility network. These three concepts were:

1. A DC motor driving an induction generator.
2. A DC motor driving a synchronous generator.
3. A three-phase solid state inverter.

Two concepts were considered for fixed rpm electrical systems. One using an induction motor operated as a generator, and the second using a synchronous generator of the type normally used by electric utilities. These approaches are straightforward concepts using standard equipment, and very similar to small conventional utility generation installations.

The evaluation of these alternatives determined that the variable rpm electrical system configurations were in all cases considerably more complex, more costly, and less efficient than the fixed rpm schemes. This is shown in Table 14, which gives the results of a study for a 1000 kW WGS in terms of system efficiency and total equipment cost. As might be expected, the slightly higher efficiency of the rotor when operated at variable rpm is overwhelmed by the poor efficiency and high cost of the variable rpm electrical systems.

TABLE 14. ELECTRICAL SUBSYSTEM EFFICIENCY AND COST

1000 kW High Power WGS

		LOAD NET EFFICIENCY, %				
	TYPE	FULL	3/4	1/2	1/4	TOTAL COST, $
1.	Constant RPM/ Induction Generator	94.3	94.0	92.2	87.0	59,305
2.	Constant RPM/ Synchronous Generator	95.0	94.4	92.2	87.5	86,815
3.	Variable RPM/MG Set (Induction Generator)	82.6	81.3	79.4	70.7	208,350
4.	Variable RPM/MG Set (Synchronous Gen.)	83.2	81.6	79.4	71.7	235,860
5.	Variable RPM/Inverter	78.3	77.0	75.5	44.4	364,325

Because of the small cost difference between them, either the induction or the synchronous generator can be used with the fixed rpm system, depending on the preference of the using utility. To provide this option, protective equipment and switch gear specifications were developed to be compatible with either type of generator. Both were carried forward to preliminary design.

Protective and Relay Equipment - Although there are several new developments in the field of generator protective and relaying equipment which hold promise for the future, they were not adopted for the WGS. Included in this category is the microprocessor which was suggested to replace the standard electromechanical and solid state devices commonly used by utilities. The microprocessor was not selected for this role because of the limited experience utilities have with it. However, as discussed in the Controls section, it was selected for non-critical sequencing, monitoring and housekeeping.

(NOTE: The results of a failure modes and effects analysis, carried out after the wind generator study was completed, are included in the Design Study.)

The failure modes and effects analysis provided further evidence that a microprocessor is suitable for use in the sequencing and supervisory control functions of a wind generator system. The microprocessor can detect and take the necessary corrective action in the event of failures in the remainder of the system that could lead to hazardous conditions. In most cases, the microprocessor can even detect its own failures, or at least their effects that might create hazardous conditions, and then initiate proper corrective action.

In one respect, the microprocessor-based control system is quite different from a control system using conventional techniques. This is in the interface with the operator or maintainer. A control system, using conventional techniques, generally has a number of indicator lamps, annunciators, or other directly observable devices that indicate the conditions within the control system at all times. The microprocessor-based system, on the other hand, carries out its logical decision making within the microprocessor circuits themselves, where it is invisible to the operator or maintainer. Diagnostic aids should, therefore, be a part of the microprocessor-based sequencing and supervisory control system. This not only provides the maintainer with a starting point for his maintenance procedures, but also provides a higher degree of confidence that the trouble he finds and fixes is, in fact, the one which caused the system to shut down.

Interface Equipment - Options for the interface equipment to tie the WGS into the utility network are limited. The required transformers may be either air- or oil-cooled, but the oil-cooled unit was selected because of its lower cost and suitability to outdoor operation.

Circuit Interrupts - Standard circuit breakers and recloser breakers were considered. Since the recloser was at first thought to be cheaper, it was evaluated. It was found, however, that the standard recloser lacks repeatable closing times needed to assure accurate synchronization between the WGS and the power grid. Therefore, standard breakers were selected.

Emergency Power Supply - In the event station service power to the WGS is interrupted, emergency power must be available to shut down and secure the system without damage. The two alternatives considered were a gasoline- or diesel-powered auxiliary generator, or batteries with a charger, constantly floating on line. The higher reliability of the batteries and the preference of the utilities for them were the governing factors in their selection. However, the small amount of power available from batteries dictated that all emergency sequences be designed for low power consumption. This requirement influenced the control system design significantly.

Connections from Tower to Ground - Two methods were considered for getting the electrical power and control wiring from the tower to the ground. The first was slip rings and the second was cable. The cable would be allowed to twist up some predetermined amount before it was untwisted by turning the tower head.

Allowing the cable to twist up is a technique that has been used on other large systems with success. Usually, the net twist accumulated over a period of time does not amount to more than a turn or two. This approach has lower cost and higher reliability than slip rings and is more suitable for the large numbers of wires that might be required for the control and signal cables. It does require a long length of cable to absorb the twist and a sensor for the yaw servo during the shutdown sequence to remove the twist.

The major disadvantage of this approach with respect to the power cables is lower reliability; manufacturers of these cables recommend against twisting or flexural motions. It was, therefore, decided to run the power wiring through slip rings and to use direct connections only for the control and signal wiring, with the yaw servo being used to untwist the cable as necessary during each shutdown of the system.

Preliminary Design and Analysis

After selection of the electrical subsystem and component concepts, the system preliminary design process evolved the detailed electrical subsystem configuration and supporting analyses. Descriptions of the major system components are given below and apply to both the 500 kW and 1500 kW units.

Generator - The generator is a high speed induction or synchronous machine operated at 1800 rpm. Voltage is either 2400 or 4160 volts, selected to minimize cable weight and cost, and the cost of the slip ring used to bring the power cables around the rotating joint at the tower head. Cooling is provided by forced ambient air.

Protective and Control Equipment - The protective and control equipment performs the following functions:

1. Protects the WGS against damage from electrical faults.

2. Protects the utility network against failures in the WGS.

3. Differentiates between faults internal to the WGS and faults in the utility system.

The protective equipment is designed so that electrical faults within the WGS equipment initiate shutdown and lockout of the WGS until repaired. External faults, on the other hand, trip the main breaker and the WGS is then allowed to re-synchronize with the network after the fault has been cleared.

Lightning protection for both systems is accomplished by providing good paths to ground for direct strikes along the outside surfaces of the WGS, so that the equipment is inside an effective shield. Lightning arrestors are provided at critical locations to protect against lightning transients.

Utility Interface - The WGS is equipped with an oil-filled step-up transformer to match the generator to the voltage of the distribution system, and to limit fault currents. The breaker is located on the high side of the distribution transformer so that, when the breaker is open, the system is completely isolated from the utility network, except for the station service supply which bypasses the breaker. Large currents can be generated by the grid feeding back into faults within the WGS, therefore, the breaker has been sized to interrupt these currents. Reliability considerations require that emergency power at the WGS site be provided by a trickle-charged battery source, rather than a gasoline- or diesel-driven generator. The WGS has been designed to be compatible with this type of emergency power source.

The final design of the electrical subsystem must be tailored to the needs of the particular user utility company. The design will also be influenced by the location within the network system where the WGS is installed. Its location in the system can affect the type of generator, induction or synchronous, the size of the breakers required, and the type and settings of the required relaying and protective equipment. The electrical subsystem design developed for the WGS provides for this tailoring, and is compatible with standard utility requirements.

Transient Analysis - When the synchronous wind generator unit is connected to the electrical distribution system, the interaction must be analyzed to ascertain the effect this unit will have on the operation of the distribution system, and the requirements for protective and control equipment for the electrical system and the wind generator itself. Because of the importance of this issue, a study was conducted to determine the general response of the WGS unit to faults and switching operations on the distribution system and to changes in unit input torque due to wind gusts. The stability analysis was performed by Northeast Utilities for the 1500 kW WGS. The 1500 kW system was studied for the preliminary design analysis, since stability questions on the 500 kW system will be less critical than the 1500 kW unit when connected to the same network.

The modeling of the generator and network was done by use of a transient stability program which is a standard tool used by electric power system engineers in the study of dynamic performance of power systems. The distribution feeder was modeled as a 13 km (8 miles) long feeder with 7 mW of distributed loads along the feeder. The WGS was connected to the feeder through a dedicated 1.6 km (1 mile) line. Modeling of the wind generator portion was based on a quasi-static approximation of the rotor and controls. Although a more comprehensive model should be developed for analyzing the final detailed system design, the current analysis results are representative of a typical WGS/ utility interface.

Results of the study indicate that the wind generator should be disconnected from the distribution feeder for any disturbance which causes the normal supply to the feeder to open. This will prevent the wind generator from attempting to supply the load on the feeder in an isolated mode, and will assure interruption of power on the line to allow clearing time for faults. Voltage variations on the distribution system due to wind gusting conditions are more severe if the synchronous generator is connected to the feeder at a point remote from the source (substation). They are also more severe for decreasing gusts (loss of wind) than for increasing gusts of the same magnitude. With the generator connected to the system at the substation, voltage variations on any feeder supplied from that substation are less than 0.5% for even the most severe wind gust studied. With the generator connected near the end of the feeder, the same wind gust causes distribution voltage to vary 2.2%. The acceptability of these more severe voltage variations depends upon their frequency of occurrence and upon the standard established by the particular utility company to which the generator is connected. Ultimately, optimization of the design of the pitch control system and the generator regulator could reduce these variations. However, wind gusts up to the maximum design intensity are not likely to cause the synchronous generator to pull out of synchronism with the sytem, for the typical feeder investigated in this study.

While the results of this study are typical, giving general characteristics of system performance, each specific installation will have to be studied separately to establish the operating conditions and electrical requirements particular to that installation. A detailed transient analysis of the WGS connected to the network should also be performed for each installation to optimize the installation and assure stability of the system under all operating conditions at the selected site. Since this is normal practice for utility generating installations, it does not present any unusual demands on the user utility.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions and recommendations derived from this study are summarized here. Detailed conclusions and recommendations pertaining to each subsystem of the WGS are set out in the pertinent section of the Design Study.

1. The WGS concept selected for preliminary design consisted of a 2-bladed variable pitch rotor downwind of the tower driving an AC synchronous generator at constant rpm through a fixed-ratio gearbox. The dynamic components are mounted on either a steel truss or concrete shell tower. Preliminary design confirmed that this concept offers lowest capital investment and energy cost, highest efficiency and reliability, least maintenance and lowest technical risk. This system is recommended, with steel truss tower, for development, test and demonstration.

2. Two WGSs were designed for sites with median wind speeds of 5.4 m/s (12 mph) and 8 m/s (18 mph), a low power system of 500 kW and a high power system of 1500 kW, respectively. For any site with median wind speed between 3.5 m/s (8 mph) and 6.3 m/s (14 mph), the 500 kW system will yield energy at a cost comparable to a system optimized for that site. Similarly, the 1500 kW WGS can be economically employed for sites with median wind speeds between 6.3 m/s (14 mph) and 9 m/s (20 mph). Therefore, these two designs can be economically used at most feasible wind power plant sites in the United States, and are recommended for development.

3. For rotors of the size required for the WGS, 40 to 60 m (130 - 200 feet) in diameter, technical considerations strongly favor composite construction for the blades to meet the demanding structural and dynamic requirements. It is recommended that automatic filament wound fabrication techniques be used for blade construction.

4. The rigid, non-articulated rotor hub design minimizes cost, complexity and potential dynamic problems and is recommended for the WGS.

5. Rotor torque control by changing blade pitch minimizes blade operating loads and permits operation and control in fluctuating aerodynamic flow regimes. Torque control through pitch variation is recommended. Since the blade pitch control rate is determined by gust requirements, it is further recommended that a design gust spectrum be defined prior to detail design of the control system.

6. Brakes capable of preventing rotor overspeed due to control system failure or extreme gusts are not available commercially. Therefore, a mechanical fail-safe emergency blade feathering mechanism is recommended for incorporation into the rotor design to prevent excessive overspeed.

7. Conventional electro-mechanical control of rotor yaw orientation and blade pitch is the method most acceptable to electric utility companies. The mechanical emergency feathering feature recommended above can be economically integrated into such controls. Electro-mechanical control for rotor yaw orientation and blade pitch is recommended.

8. Digital microprocessors offer significant advantages for normal operations, such as sequencing and supervising control of startup, shutdown, operations monitoring, failure detection, and data transmission and recording. Microprocessors for control of these operations are recommended.

9. Standard off-the-shelf electrical generating equipment such as generators, transformers and switchgear can meet all technical requirements of the WGS and is recommended. Either synchronous or induction generators are suitable for the WGS. Proper design of protective devices and electrical interface equipment will make both compatible with the WGS. Therefore, it is recommended that the detail design include provisions for either generator, with the choice left to the utility company.

10. On a typical utility network, analysis shows that the WGS remains stable and synchronized under most operational fault and wind gust conditions. It is recommended, however, that the physical and operational characteristics of the utility distribution network be defined to permit selection of breaker and relay ratings, and generator and regulator characteristics for the WGS detail designs. These network characteristics should be defined to minimize adjustments for a specific installation.

11. The steel truss tower is recommended. Although the pre-cast, post-tensioned concrete shell tower is competitive in large production runs and is considered preferable aesthetically, wind shadow effects, emphasized by NASA's experimental findings subsequent to completion of this study, will probably preclude use of shell towers.

12. Analyses made during this study show that a WGS can be competitive with other energy sources. It is recommended that more detailed analyses be performed during the detail design of the WGS to determine specific applications and utility interface requirements.

13. Capital costs for the 500 kW and 1500 kW systems were derived during this study as \$901/kW and \$481/kW, respectively, for quantity production. Energy cost of 7.1¢/kWhr and 2.7¢/kWhr for the 500 kW and 1500 kW systems were derived. Yearly rotor maintenance costs, which were a major influence on the energy cost figures, were conservatively estimated due to the lack of actual operating experience for such rotors.

14. Operational and institutional issues, including utility attitude, public acceptance, environmental impact, licensing, and safety appear to present no insuperable barriers to the introduction of WGS. However, it is recommended that the question of visual acceptability of large numbers of units be explored to guide tower design and siting.

APPENDIX A

PROTOTYPE WIND GENERATOR SYSTEM COSTS

INTRODUCTION

The purpose of this Appendix is to examine and derive realistic costs for the first prototype WGS systems of the size range developed in the Design Study (NAS3-19404). The Design Study addressed future production costs for such machines. Subsequent evaluations carried out by Kaman during the proposal phase for an actual first unit of a similar WGS (Mod-1 proposal), and in connection with other studies noted below, give an indication of the probable cost of the first pre-production systems. Although these cost levels appear excessively high when compared with the low cost of future machines projected in the Design Study, there is, in fact, no real conflict.

The costs of a present day prototype system are higher than those of a full production first unit due to a number of factors which are discussed and evaluated herein. The cost influence of each of these factors is estimated.

The several factors to be examined in this study include:

- Inflation
- Size changes
- Contractor capability and subcontracting
- Competitive procurement environment
- Production design improvements
- R & D non-recurring activities
- Learning curves

The effects of these factors on system costs are used to bring the Mod-1 Study cost estimate for the 1000th production unit (180 ft diameter system in constant 1975 dollars and an established and growing market) to the expected cost of a near term, prototype first unit Mod-1 system (200 ft diameter in 1977 dollars). The expected end result prototype system costs are not affected by the order in which these effects are estimated and applied; for illustration purposes, the effects are applied in the order presented. Figure A-1 summarizes these costs at the several levels considered. In addition, Tables A-1 and A-2 are given showing subsystem costs for both the Mod-1 1500 kW system and for a 500 kW system.

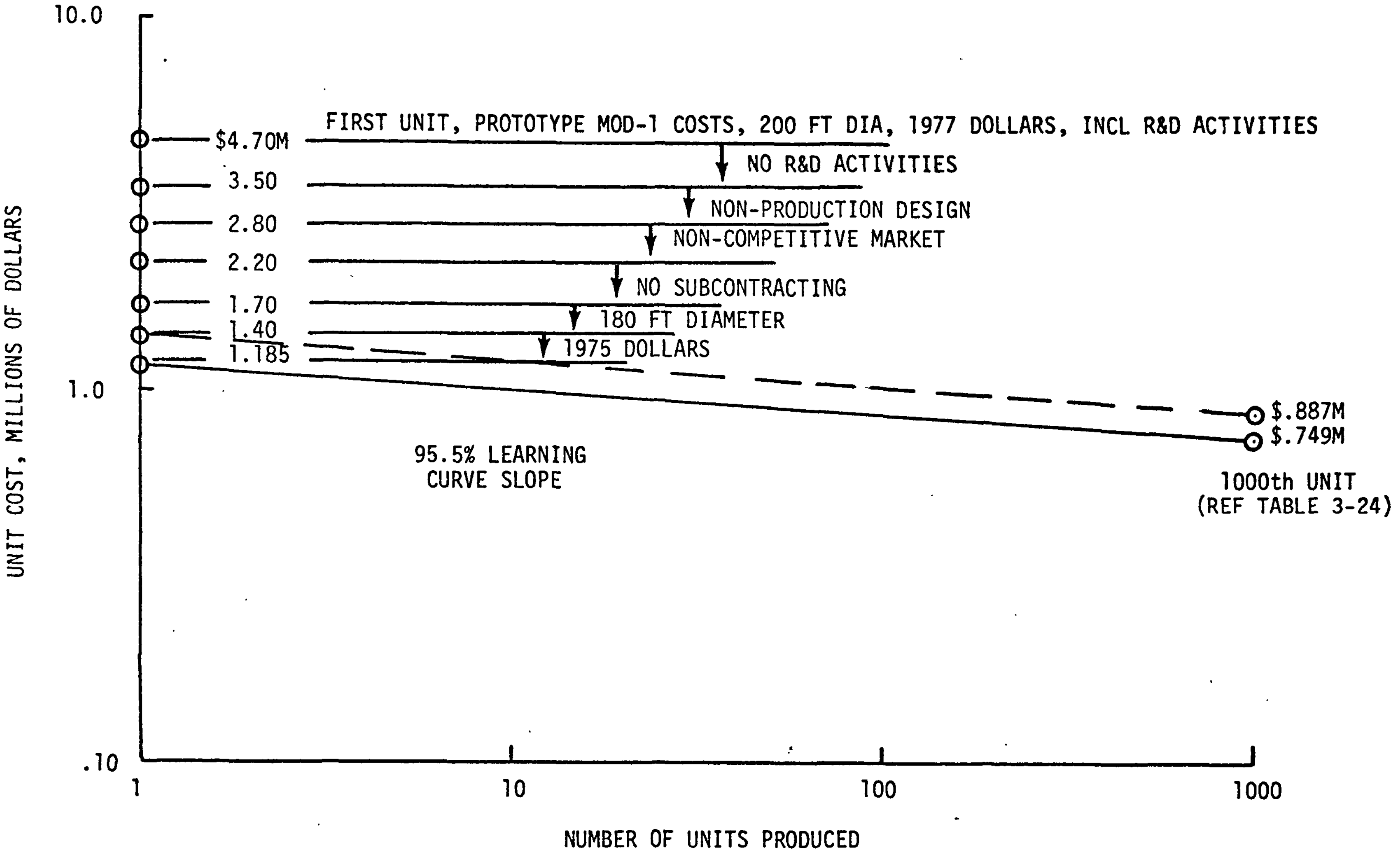


Figure A-1. Estimated 1500 kW Mod-1 System Costs.

TABLE A-1. ESTIMATED 1500 kW SYSTEM PROTOTYPE COSTS (THOUSANDS OF DOLLARS)

		PRIME CONTRACTOR				SUBCONTRACTORS					PRIME CONTRACTOR BURDEN ⑤	TOTALS
		LABOR ①		PURCHASED PARTS ②	OTHER ③	LABOR ①		PURCHASED PARTS ②	OTHER ③	BURDEN ④		
		(HOURS)	($1000)	($1000)	($1000)	(HOURS)	($1000)	($1000)	($1000)	($1000)	($1000)	($1000)
PROGRAM MANAGEMENT & SYSTEMS INTEGRATION		1000	22	---	6	---	---	---	--	---	10	38
EQUIPMENT	ROTOR	9000	174	124	16	3000	64	83	7	39	190	697
	NACELLE	---	---	---	--	5000	100	335	--	95	198	728
	ELECTRICAL	---	---	---	--	600	13	145	--	30	70	258
	CONTROLS	---	---	---	--	5000	99	50	--	39	70	258
	STRUCTURE	---	---	---	--	6000	120	86	--	43	93	342
ASSEMBLY & INSTALLATION	NACELLE	---	---	---	--	3000	60	12	--	20	34	126
	TOWER & FOUNDATION	---	---	---	--	29000	582	54	13	126	290	1065
	ERECTION	---	---	---	--	7000	144	49	--	39	87	319
	CHECKOUT	---	---	---	--	20000	414	7	53	98	213	785
SITE COSTS	LAND PREPARATION	---	---	---	--	2000	39	---	--	5	16	60
	CONTROL BUILDING	---	---	---	--	500	10	4	--	2	6	22
TOTALS		---	196	124	22	---	1645	825	73	536	1277	4698

NOTES:

① Labor costs based on typical aerospace industry composite rates of $9.00 per hour and 125% overhead

② Purchased parts include materials and catalog & off-the-shelf components, as purchased

③ Other costs include computer time, publications, travel, etc., as appropriate

④ Subcontractor burden rates based on typical component and subassembly industry burdens and profits

⑤ Prime contractor burden rates based on typical aerospace industry rates of 25% General and Administrative and 10% profit

TABLE A-2. ESTIMATED 500 kW SYSTEM PROTOTYPE COSTS (THOUSANDS OF DOLLARS)

		PRIME CONTRACTOR				SUBCONTRACTORS					PRIME CONTRACTOR BURDEN ⑤	TOTALS
		LABOR ①		PURCHASED PARTS ②	OTHER ③	LABOR ①		PURCHASED PARTS ②	OTHER ③	BURDEN ④		
		(HOURS)	($1000)	($1000)	($1000)	(HOURS)	($1000)	($1000)	($1000)	($1000)	($1000)	($1000)
PROGRAM MANAGEMENT & SYSTEMS INTEGRATION		1000	22	--	6	---	---	---	--	---	10	38
EQUIPMENT	ROTOR	7000	140	85	10	2000	39	47	3	22	129	475
	NACELLE	---	---	--	--	4000	83	211	--	65	134	493
	ELECTRICAL	---	---	--	--	400	9	97	--	21	47	174
	CONTROLS	---	---	--	--	3000	67	33	--	26	47	173
	STRUCTURE	---	---	--	--	4000	82	58	--	29	63	232
ASSEMBLY & INSTALLATION	NACELLE	---	---	--	--	2000	41	8	--	13	23	85
	TOWER & FOUNDATION	---	---	--	--	20000	395	37	8	86	196	722
	ERECTION	---	---	--	--	4000	81	50	--	27	59	217
	CHECKOUT	---	---	--	--	14000	282	5	36	67	145	535
SITE COSTS	LAND PREPARATION	---	---	--	--	1000	22	---	--	3	9	34
	CONTROL BUILDING	---	---	--	--	500	10	4	--	2	6	22
TOTALS		---	162	85	16	---	1111	550	47	361	868	3200

NOTES:

① Labor costs based on typical aerospace industry composite rates of $9.00 per hour and 125% overhead

② Purchased parts include materials and catalog & off-the-shelf components, as purchased

③ Other costs include computer time, publications, travel, etc., as appropriate

④ Subcontractor burden rates based on typical component and subassembly industry burdens and profits

⑤ Prime contractor burden rates based on typical aerospace industry rates of 25% General and Administrative and 10% profit

DISCUSSION

Table 10 of the Design Study Executive Summary presented estimated WGS costs, including a subsystem breakout, for the 1000th unit (500 kW and 1500 kW systems). The cost level for this 1000th unit was projected by the parametric model in the Design Study final report as approximately $749,000. The cost/performance model that generated this cost level utilized a 95.5% unit learning curve to reflect costs at different production points. On the basis of the production price given above and the learning curve slope, the cost of the first production unit would back-figure to approximately $1,185,000. In actual fact, however, the cost of early engineering prototype units may be expected to be considerably higher than this figure.

Based on work done by Kaman subsequent to the Design Study, specifically the Mod-1 proposal effort, the WECS Off-Shore Study for ERDA, and other proprietary Kaman work, it is possible to estimate the cost of a representative initial prototype unit which reflects the realistic factors for market situation, development stage, and procurement scenario. Accordingly, these factors will be examined in the following paragraphs as they influence the $1,185,000 first-unit production cost figure given above. Note that for reference purposes, the configuration which will be utilized is the 1500 kW, 200 ft rotor diameter system which has been established by NASA as the Mod-1 system.

Inflation. The $1,185,000 first production unit cost, derived in the subject study, is based on 1975 dollars. Using an average inflation rate of 7% per year, this is equivalent to a $1,400,000 first-unit price in the mid-1977 mid-point of the actual Mod-1 development program. Inflation also brings the 1000th unit cost up to $887,000.

Size Changes. Cost sensitivity analyses indicate that total system costs in this size category will increase approximately $15,000 per foot of rotor diameter, increasing the first-unit price to approximately $1,700,000 for the 200 ft diameter final Mod-1 configuration noted above.

Contractor Capability and Subcontracting. The Mod-1 Study cost analysis assumed a wind turbine manufacturer with a breadth of capability to fabricate and erect a complete system without major subcontracting. For near term prototype wind turbines, however, such a corporate structure does not yet exist and some subcontracting will be necessary, the actual amount depending on the specific prime-subcontractor arrangement made.

The typical procurement arrangement used in this analysis assumes that a specialized manufacturer carries out the rotor system development and fabrication and another contractor is responsible for the remainder of the system (nacelle, drive train, tower and site preparation). It is also assumed that the rotor manufacturer is the prime contractor for the total WGS system who subcontracts the remainder of the system.

For this program, the additional burdening effect resulting from the above procurement arrangement is estimated to be $500,000, raising the expected first-unit production cost to approximately $2,200,000.

Competitive Procurement Environment. At the present time, a competitive market in wind turbine components still does not exist. Requests for vendor quotes and cost estimates are complied with on only a routine basis. Given a future market where manufacturers of generators, gearboxes, towers, etc., are aware of the potential for future contracts, lower and more competitive subsystem prices are likely. However, during the more limited market environment situation which exists at present, it is expected that costs will remain higher by an estimated 25%, resulting in approximately $2,800,000 for the first prototype in a non-competitive market.

Production Design Improvements. The first prototype system cost in a non-competitive market is also based on the assumption that a production design has been evolved. At the present time, such a production design does not truly exist and the first prototype unit design will not have had the advantage of experience that will only come with operating time. It is believed that this present lack of experience leads to conservative design loads and heavier and more costly components.

The prototype status of the Mod-1 system also results in the adoption of components which are available, but not necessarily ideally sized or configured for full production use. The gearbox, generator, bearings, electrical system components, etc., are selected for prototype use based on their availability and general suitability for such use.

Additionally, again because of the prototype aspects of the Mod-1 system, some of the components designed and/or selected will not be ideally suited, from a produceability standpoint, for full production use. Given a production status with sufficient units to amortize non-recurring costs, it is strongly believed that more cost effective components could be utilized.

It is believed that all of the non-production aspects of the prototype system just discussed would add an additional 25% to the costs, leading to an estimated pre-production, first-unit prototype cost of $3,500,000. This represents the cost of a wind turbine designed and built to today's state-of-the-art and in today's competitive market. It is a 200 ft diameter, 1500 kW system. The cost is expressed in 1977 dollars, and covers recurring costs primarily, with a level of program management commensurate with the fabrication and erection of a pre-production prototype.

R & D Non-recurring Activities. The above cost, however, does not yet reflect the special costs for a design and development program as procured by a Government agency, such as is the case for Mod-1. Non-recurring program elements such as the presence of the Engineering Data System, the incorporation of test instrumentation and planning, developmental testing, full technical and financial reporting and the R & D program management costs for the above work, are expected to add an estimated $1,200,000 to the Mod-1 program costs. It may be expected, then, that a Mod-1-sized, Government-procured system would cost approximately $4,700,000.

Learning Curves. The learning that will occur as the production progresses to hundreds of units is difficult to estimate with precision. Actual learning will occur only on those components such as blades and other rotor elements which are of new design and where production is just beginning. On the other hand, such items as gearboxes and generators are now in production and little "learning" is likely to occur. Additionally, vendors are likely to pass on the cost reductions resulting from learning only when competition from other suppliers forces them to. Ordering quantities, tooling concepts and line breaks all affect the learning to be expected. Analysis of component statuses and pricing concepts for components and subsystems during the Mod-1 Study derived a conservative 95.5% composite learning curve for the system. There is no evidence to date leading to a change in that conclusion.

CONCLUSION/SUMMARY

The first-unit 1500 kW prototype cost has been estimated at $4,700,000, of which $3,500,000 represents the cost of a pre-production first-unit. Figure A-1 summarizes the foregoing steps leading to this value. Table A-1 shows a breakout of estimated costs by major subsystem and by prime and major subcontractor. The costs include the prime contractor's burden of subcontractor work. Typical component industry average hourly, overhead, general, and administrative and profit rates are used throughout.

Table A-2 shows a similar breakout of estimated costs for the 500 kW prototype first-unit system, including R & D non-recurring costs.

In summary, this cost analysis has discussed the differences between prototype development program costs and full production first unit costs and has estimated the various cost elements therein. A breakout of prototype Mod-1 1500 kw and of 500 kW system estimated costs has been presented, utilizing typical industry rates and fees. The learning that may be expected as production proceeds and the conditions that affect learning have also been discussed; the 95.5% learning curve of the Design Study has been retained as the most likely slope for learning projection which is foreseen at this time.

1. Report No NASA CR-134936	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

DESIGN STUDY OF WIND TURBINES, 50 kW TO 3000 kW, FOR ELECTRIC UTILITY APPLICATIONS - EXECUTIVE SUMMARY

5. Report Date
July 1977

6. Performing Organization Code

7. Author(s)

8. Performing Organization Report No
R-1382

9. Performing Organization Name and Address
Kaman Aerospace Corporation
Old Windsor Road
Bloomfield, Connecticut 06002

10. Work Unit No.

11. Contract or Grant No.
NAS 3-19404

12. Sponsoring Agency Name and Address
U.S. Department of Energy
Division of Solar Energy
Washington, D.C. 20545

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency ~~Code~~ Report no.
DOE/NASA/9404-76/1

15. Supplementary Notes
Final Report. Prepared under Interagency Agreement E(49-26)-1010. Project Manager, John E. Sholes, Wind Energy Project Office, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract This report presents a summary of the results of a program to develop preliminary designs of low power (50-500 kW) and high power (500-3000 kW) wind generator systems (WGS) for electric utility applications. These designs provide the bases for detail design, fabrication, and experimental demonstration testing of these units at selected utility sites. The program included four tasks: a conceptual design task; an optimization task; a preliminary design task; and a utility requirements evaluation task. In the conceptual design task, several feasible WGS configurations were evaluated, and the concept offering the lowest energy cost potential and minimum technical risk for utility applications was selected. In the optimization task, the selected concept was optimized utilizing a parametric computer program prepared for this purpose. In the preliminary design task, the optimized selected concept was designed and analyzed in detail. The utility requirements evaluation task examined the economic, operational and institutional factors affecting the WGS in a utility environment, and provided additional guidance for the preliminary design effort. Results of the conceptual design task indicated that a rotor operating at constant speed, driving an AC generator through a gear transmission is the most cost effective WGS configuration. The optimization task results led to the selection of a 500 kW rating for the low power WGS and a 1500 kW rating for the high power WGS. It was also determined that these two machine designs could be installed at utility sites with yearly median wind speeds from 8 to 20 mph, and provide energy at costs which approach those of machines optimized for each specific site. The preliminary design task produced a detailed refinement of the optimized selected concept, which utilizes a rotor with two variable pitch, filament would composite blades, mounted on a rigid hub, driving a standard AC synchronous generator through a commercial gearbox. The system designs were prepared for both a conventional steel truss tower and a precast, post-tensioned concrete shell tower. The utility requirements analyses indicate that conventional electric utilities can operate and maintain WGS units with no substantial change in normal operating and maintenance procedures. Complete details of the work are available in NASA CR-134937, "Design Study of Wind Turbines, 50 kW to 3000 kW, for Electric Utility Applications, Analysis and Design," February 1976.

17. Key Words (Suggested by Author(s)) Wind energy conversion systems Wind turbine technology	18. Distribution Statement Unclassified - unlimited STAR Category 44 DOE Category UC-60

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	94	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

11 SEP 78 C ~~H. T. Clark 337/32²/23356~~ 11 SEP 1978

14 SEP 78 C ~~J. W. Anderson 342/32²/279~~ 13 MAY 81 MA

9/4/858 J E Mitchell E454/101A²/234 8536