

ERDA/NASA/9403-76/1
NASA CR-134934
GE-SD 76SDS4287
ERDA Category UC-60

DESIGN STUDY OF WIND TURBINES
50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS
VOLUME I - SUMMARY REPORT

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September 1976

Prepared for the
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Contract NAS 3-19403



As a part of the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy
Federal Wind Energy Program

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| (NASA-CR-134934) DESIGN STUDY OF WIND TURBINES 50 kW TO 3000 kW FOR ELECTRIC UTILITY APPLICATIONS. VOLUME 1: SUMMARY REPORT Final Report (General Electric Co.) 65 p EC A04/MF A01 | N78-12529 Unclas CSCI 10B G3/44 53875 |
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|---|--|---|--|---|--|
| 1 Report No NASA CR-134934 | | 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 VOLUME I - SUMMARY REPORT | | | | 5 Report Date September 1976 | |
| | | | | 6 Performing Organization Code GE-SD 76SDS4287 | |
| 7. Author(s) | | | | 8 Performing Organization Report No | |
| | | | | 10 Work Unit No | |
| 9 Performing Organization Name and Address General Electric Company Valley Forge Space Center King of Prussia Park P.O. Box 8661 Philadelphia, Pennsylvania 19101 | | | | 11 Contract or Grant No NAS 3-19403 | |
| | | | | 13 Type of Report and Period Covered Contractor Report | |
| 12 Sponsoring Agency Name and Address Energy Research and Development Administration Division of Solar Energy Washington, D.C. 20545 | | | | 14 Sponsoring Agency Code Report No. ERDA/NASA/9403-76/1 | |
| | | | | | |
| 15 Supplementary Notes Final report. Prepared under Interagency Agreement E(49-26)-1010. Project Manager, W. R. Johnson, Wind Power Office, NASA Lewis Research Center, Cleveland, Ohio 44135. | | | | | |
| 16 Abstract This study was one of two parallel efforts conducted to define the wind turbine configuration that would lead to generation of electrical power in a cost effective manner. All possible overall system configurations, operating modes, and subsystem concepts were evaluated for both technical feasibility and compatibility with utility networks, as well as for economic attractiveness. A design optimization computer code was developed to determine the cost sensitivity of the various design features, and thus establish the configuration and design conditions that would minimize the generated energy costs. The preliminary designs of both a 500 kW unit and a 1500 kW unit operating in a 12 mph and 18 mph median wind speed respectively, were developed. This report summarizes both the rationale employed in this study and the key findings of this study, but does not present an in-depth detail discussion of all design considerations. | | | | | |
| 17 Key Words (Suggested by Author(s)) Wind Generator Solar Turbine Energy Windmill | | | | 18 Distribution Statement Unclassified - unlimited STAR Category 44 ERDA Category UC-60 | |
| 19 Security Classif (of this report) Unclassified | | 20 Security Classif (of this page) Unclassified | | 21 No of Pages | |
| | | | | 22 Price* | |

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SECTION 1.0

INTRODUCTION AND SUMMARY

This study was performed by General Electric's Advanced Energy Systems in fulfillment of contract NAS 3-19403, "Program for Conceptual Design, Parametric Analysis and Preliminary Designs for Low Power (50-250 kW) and High Power (500-3000 kW) Wind Generator Systems". The program was directed by the NASA Lewis Research Center's Wind Power Office, Power Systems Division, for the Energy Research and Development Administration and is an integral part of the Federal Wind Energy Program. This effort was one of two parallel studies directed by NASA to evaluate the use of wind turbines to generate electrical power in a cost effective manner. General Electric was supported in this study by the Hamilton Standard Division of the United Technologies Corporation.

This volume presents the major study conclusions and characteristics of the Wind Turbine Generator (WTG) designs. Volume II (NASA CR 134935) presents a more detailed review of the study trade-offs and results.

Two WTG systems were studied in detail:

a 500 kW unit, assumed to operate at a 12 mph median wind site, and a 1500 kW unit, assumed to operate at an 18 mph median wind site. The capital costs of these units (based on 1975 dollars) were estimated to be \$935/kW and \$430/kW for the 500 kW and 1500 kW systems, respectively. These capital costs assume that 100 units are being procured and that all development has been completed such that the WTG is a "mature commercial product". The capital costs associated with the initial developmental units are substantially higher as indicated in Section 3.1.2.2 under First Unit Costs. The capital costs include:

- Program management of a 3-1/2 year, 100 unit, fabrication and installation program
- Cost of interfacing with the utility
- Equipment and subsystem assembly costs
- Site preparation costs
- System contractor overhead and profit

The capital costs plus anticipated maintenance costs were used in conjunction with an economic model to estimate a typical utility's energy generation cost using WTG's. Using the scenario diagrammed in Figure 3-3, the cost of generating energy was calculated to be 4.04 ¢/kWh and 1.57 ¢/kWh for the 500 kW unit in the 12 mph site and the 1500 kW unit in the 18 mph site, respectively. While these energy generation costs include the utility's cost of financing the purchase and maintaining the WTG's, it does not include power distribution or utility overhead costs. Section 3.1.2.2 presents a detailed explanation of the capital costs and economic model.

1.1 PROGRAM OBJECTIVES

The overall objective of this study was to establish the preliminary designs of cost effective wind turbines that are compatible with utility company requirements. Specifically, the program's activities were directed at:

- Establishing the design and operation requirements for a WTG which is linked to an electrical utility network
- Defining the WTG design and operational concept most suitable for this application
- Determining the most cost effective operating conditions as a function of sites having median winds between 9 and 21 MPH.
- Generating two Preliminary Designs and cost data - one system at a 12 mph median wind site and one at an 18 mph mean wind site.

Assuming that the results support continued investigation of WTG's for this application, it is intended to use the product of the study (and the parallel effort being directed by NASA) as the basis for the final design and construction of prototype systems.

1.2 APPROACH

In order to achieve the program objectives an 8 month technical effort was planned; the major tasks involved in the study are shown in Figure 1-1. The first step in the program was to characterize the WTG in terms of its configuration, operating mode and subsystem concepts. This task was supported by the Hamilton Standard team in the rotor design area and also by Professor Dr. Ulrich Hutter of the University of Stuttgart who is a world renowned expert in large Wind Turbine design. In a parallel effort, the GE Electric Utility Systems Engineering Department (EUSED) evaluated the applicability of WTG's for use in an electric utility network. Results of the Conceptual Design effort served as the basis for developing a design optimization computer code. The purpose of this task was to model the WTG performance for various design conditions. This code was then used in the Parametric Analysis task to determine the sensitivity of the WTG cost to the major design variables. The optimized values of these design variables were used as the design conditions for the Preliminary Designs generated in the final task. Two Preliminary Designs were generated in this portion of the study: a 500kW unit and a 1500kW unit operating in 12 and 18 mph median wind sites, respectively. These designs are discussed at length in Section 3.1.2.

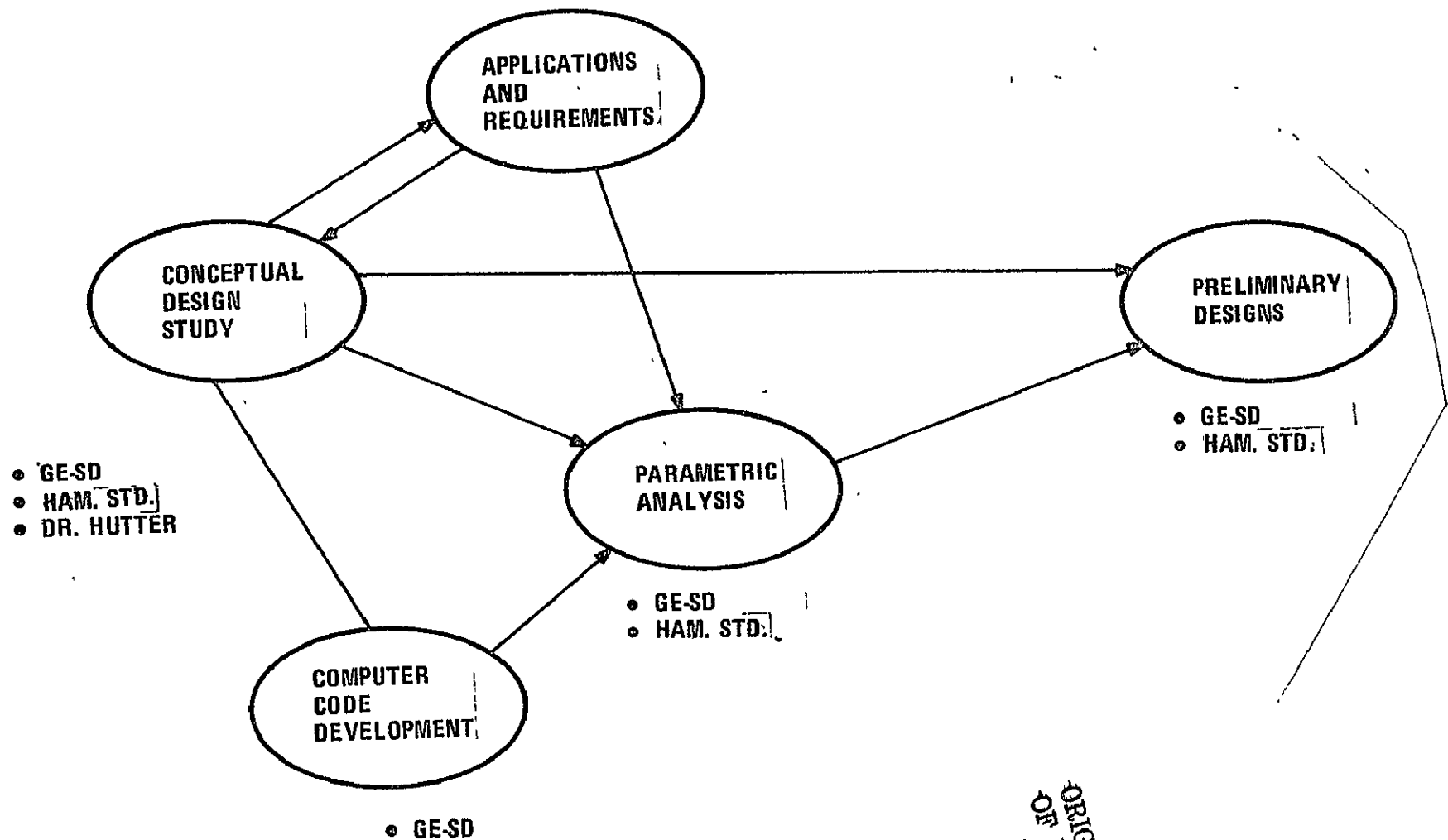


FIGURE 1-1 STUDY APPROACH

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1.3 STUDY CONCLUSIONS

The principal objective of this study was to evaluate the economic incentive for utilizing WTG's in broad scale electrical power generation applications. During the program, conclusions were drawn concerning this question as well as more specific design, operating approach and fabrication alternatives. The purpose of this section is to present both the overall study conclusions and the more specific results pertaining to the individual tasks.

1.3.1 OVERALL RESULTS

The principal results of this study included the following:

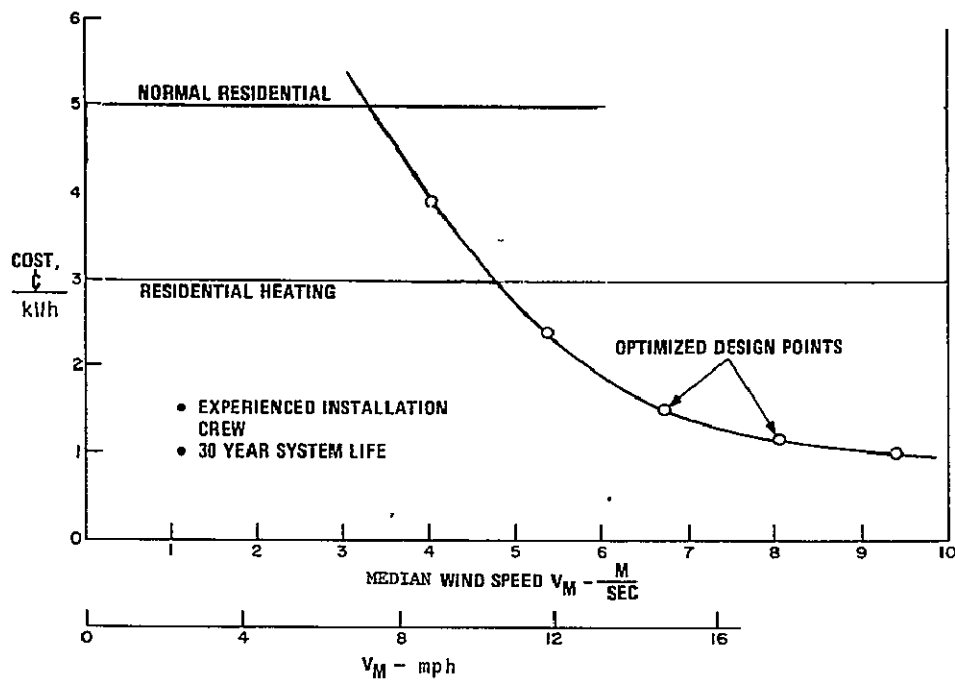
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| Site Selection | • The median wind speed of the site had an overwhelming effect upon the WTG economics |
| Power Level | • Dramatic cost reductions were available by designing systems at power levels at or greater than 500 kW; significant cost reductions continued to accrue up to the 1500-2000 kW range. |
| Cost | • The cost of generating energy with a 1500 kW unit at an 18 mph site and a 500 kW unit at a 12 mph site are estimated to be 1.57 and 4.04 ¢/kWh respectively, based on 100 production units. Capital costs were estimated to be \$430/kW for the 1500 kW unit and \$935/kW for the 500 kW unit. The rotor assembly was determined to be the largest single contributor to the overall system cost. |
| Electrical Utility Integration | • No major technical difficulties were uncovered in terms of linking the WTG in an electrical utility network. The WTG can provide electrical stability under steady state as well as gusting wind conditions and provide operational plant* factors in the 40-50 percent range. |

The importance of site selection is clearly demonstrated by the data shown in Figure 1-2 where the cost of generating energy is plotted against median wind speed. The data shown in this figure was generated by optimizing the WTG for each wind site on the basis of cost: then the locus of minimum cost systems for each wind site was selected to create Figure 1-2.

Note that the cost data shown in this illustration is parametric in nature and is presented to indicate cost trends rather than absolute cost levels. The intent is to clearly illustrate the large decrease in costs at the higher median wind speed sites.

The second conclusion presented above is supported by the results shown in Figure 1-3; this data shows the cost trend as a function of power level for various median wind speeds. At power levels up to 500 kW a sharp reduction in cost occurs due mainly to the economies of size. Above 500 kW further decreases in energy costs are apparent; however, at a slower rate.

* Plant factor is the ratio of the annual energy produced to that which would have been produced if the plant operated continuously at rated power. Also called capacity factor.



*ENERGY DISTRIBUTION COSTS NOT INCLUDED

FIGURE 1-2 EFFECT OF MEDIAN WIND VELOCITY ON ELECTRICAL ENERGY COSTS*

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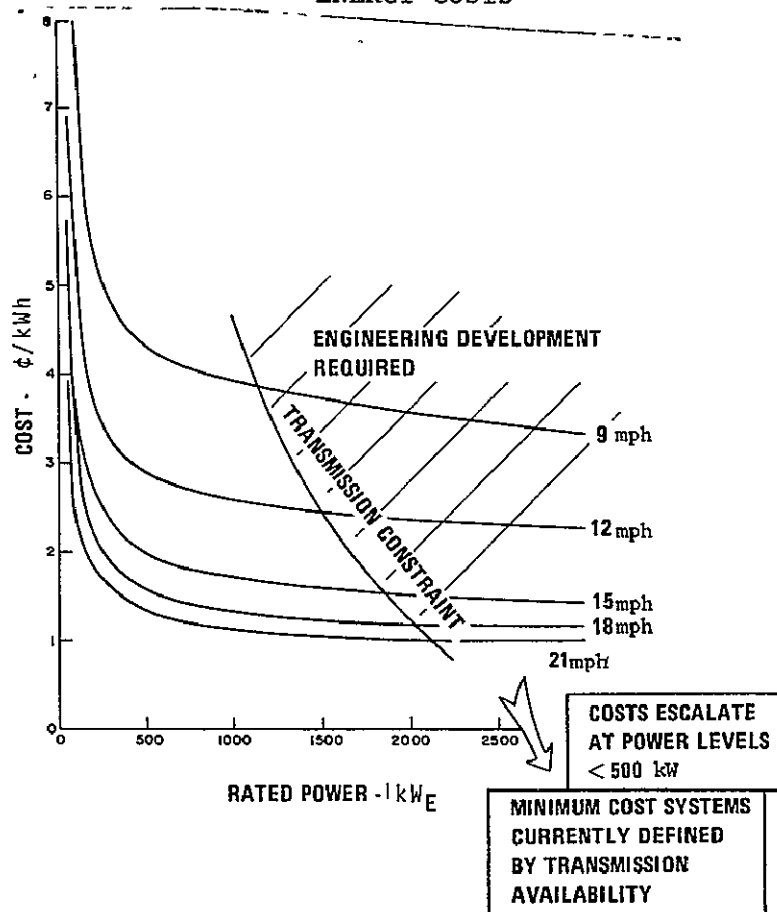


FIGURE 1-3 EFFECT OF MEDIAN WIND SPEED AND RATED POWER ON COST - ¢/kWh

This is true due to the increasing expense of the transmission as a percentage of the total system cost; in fact, current limitations in going to higher power levels are dictated by the availability* of larger transmissions. This constraint is also shown in Figure 1-3. Again the reader is urged to note that the data shown in Figure 1-3 is parametric only and should be used as a means of gauging trends.

The ability to design economically for power levels higher than that permitted by the transmission constraint line is also hampered by unknowns concerning the rotor subsystem design. Figure 1-4 illustrates the optimum blade diameters consistent with the cost/power level data shown in Figure 1-3. This data, which is again parametric, was done for a blade clearance height from the ground of 6.1 meters (20 feet). The major point to be made from Figure 1-4 is the fact that large blade diameters are required to achieve high power level/low cost systems.

This study determined that large blade diameters could best be achieved using propeller as opposed to helicopter technology. This design approach results in a simpler fabrication procedure, a lighter and more reliable blade, and has the least impact on the overall system design. Also apparent in Figure 1-4 is the desirability of sites having high median wind speeds.

The data presented in Figure 1-4 was generated using a cost expression in which the rotor subsystem cost was proportional to: $D^{2.22}$. An obvious concern arises as to the sensitivity of our large blade diameter/low cost conclusion with respect to the validity of our cost expression. Therefore, parametric data was generated to determine the effect of any rotor subsystem cost uncertainties upon our basic conclusion. This analysis showed that low costs continued to be achieved at higher power levels in the range where the rotor subsystem related to diameter between $D^{2.22}$ and $D^{3.0}$. Later, a detailed cost analysis performed during the Preliminary Design task showed the rotor subsystem cost to be proportional to: $D^{2.33}$. Therefore, the conclusion that lowest cost can be achieved by going to higher power systems having large blade diameters has been verified by a detailed analysis of rotor diameters in the 61 meter (200 foot) range.

As a result of the work performed during the Preliminary Design, it has been possible to estimate the cost of WTC's in a commercial product environment. The two designs cited above (1500 kW/18 mph and 500 kW/12 mph units) are presented in detail in Section 3.0. The cost estimate quoted above for the 1500 kW system is particularly attractive in terms of its cost due to the high median wind speed assumed, 18 mph. The 500 kW system was determined to be 2.5 times more expensive than the 1500 kW system on a ¢/kW basis.

The rotor subsystem was found to constitute about 40 percent of the total system cost. Therefore, the system design philosophy must be consistent with reducing the cost of this element. A major reason for the high cost of the rotor subsystem is that it must be designed for any unusual wind conditions that may occur over the lifetime of the unit. During the study, it was determined that the use of an intelligent control system which could avoid situations of destructive winds upon the blades would result in appreciable rotor subsystem cost reductions. Further efforts in this area may reduce the rotor subsystem to a smaller fraction of the system cost.

* in commercial, off-the-shelf, form.

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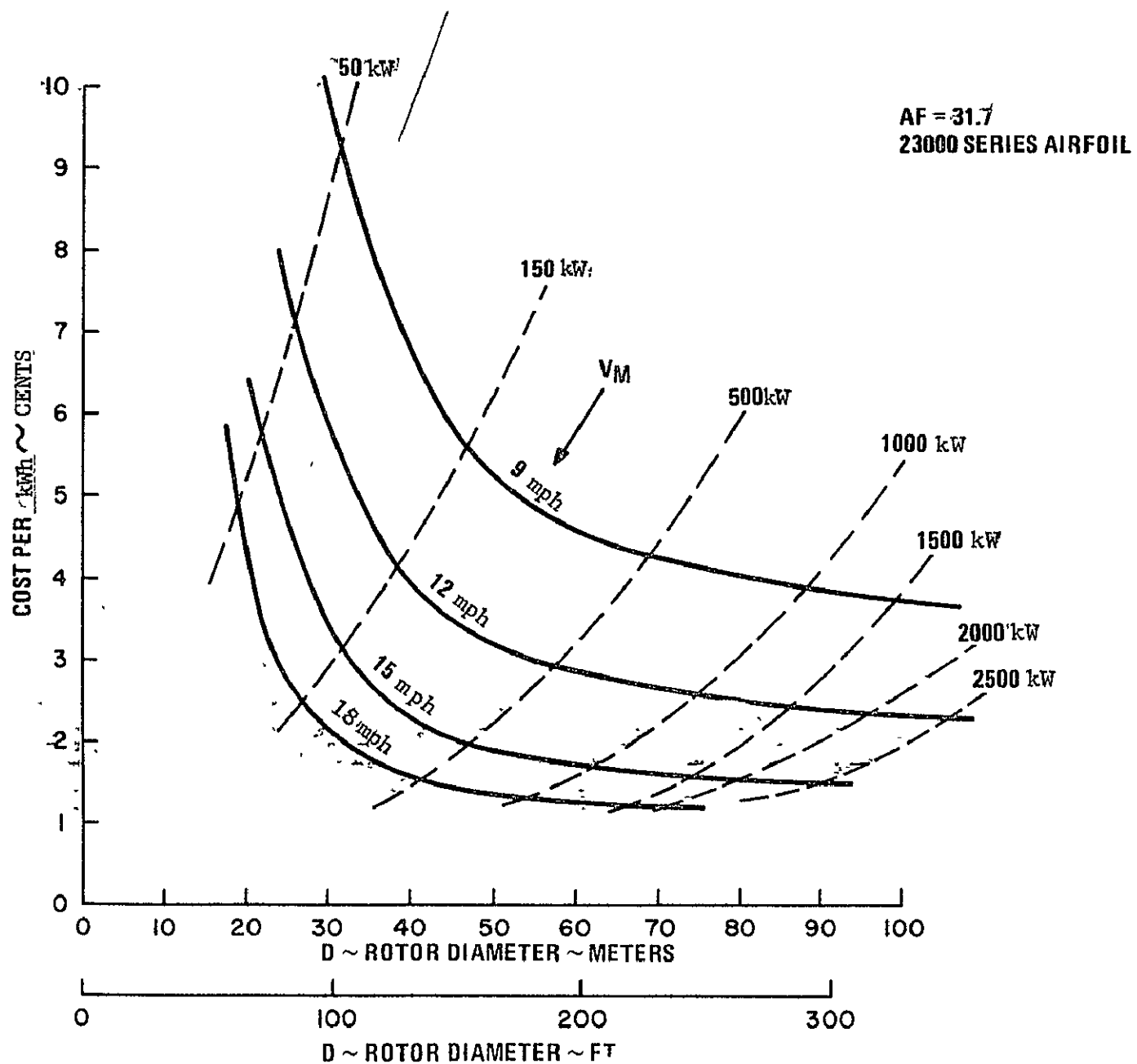


FIGURE 1-4 COST SENSITIVITY TO ROTOR DIAMETER

The fourth major conclusion resulting from this study is the fact that WTG's can be successfully integrated within an electric utility network. The WTG would be linked to the utility by means of a 4160 V line to a transformer which would provide the interface with the network. Voltage fluctuations of less than 3-5 percent can be maintained by the WTG under both steady state and severe gusting wind conditions. Synchronization of the WTG System with the network under a variety of environmental conditions has been investigated in detail and can be performed routinely by modulation of the blade pitch angle. Although both synchronous and induction generators can be utilized in the WTC, the use of a synchronous generator is favored due to the higher power factor offered by this approach. In addition, the transient performance of the synchronous generator is better characterized making the entire system more amenable to a detailed analysis.

The paragraphs above summarize the overall results obtained in this study; the following subsection reviews those conclusions which resulted from the Conceptual Design portion of the study.

1.3.2 CONCEPTUAL DESIGN RESULTS

This portion of the study focused on defining the WTG in terms of its overall configuration, operational mode and subsystem concepts. The principal conclusions found are listed below.

- WTG CONFIGURATION

- The optimum configuration consisted of placing the power transmission/generator equipment atop of the tower. Efforts to place this equipment on the ground were precluded by the unavailability of commercial hydraulic transmissions or of right angle drives in the required size range. The potential cost benefits associated with equipment on the ground are lower maintenance, assembly and tower costs.
- Placing the rotor downwind from the tower is favored due to the inherent stability of this configuration to changes in wind direction. Also of importance is that this configuration minimizes the rotor overhang required to accommodate rotor blade deflections. On the basis of the work performed, cyclic stresses on the rotor due to wind shear were judged to be significantly larger than those due to tower shadow.
- The use of multiple rotors per tower was also considered during the Conceptual Design Phase. In comparing a 100kW system having one rotor to a 100kW system having 3 rotors atop a single tower it was estimated that the cost of the 3 rotor system would be 1.5 times that of the single rotor system. This conclusion can be extrapolated to higher power levels since the rotor cost as a fraction of total system cost remains nearly constant over the 100-1500kW power range; however, the mechanical power transmission cost constitutes a larger fraction of total system cost at higher power levels.

OPERATING MODE

- Systems operating at constant rpm and at constant velocity ratio (see section 1.3.3) were considered. The constant rpm system was preferred because it resulted in lower tower and blade loads as well as a lower cost transmission and generator. The single advantage of a constant velocity ratio system is the potential for higher energy capture (3%);

however, in the investigations performed the increase in energy capture did not offset the higher system capital costs.

- Both variable pitch and fixed pitch systems were considered. Variable pitch system using blade rotation was selected due to its excellent response characteristics under changing wind conditions.

ROTOR SUBSYSTEM

- A two bladed system was selected, as opposed to three, on the basis of lower cost. The technical acceptability of this decision was verified later in the program when studies of rotor/tower dynamic interactions and load magnifications were made.
- A rigid as opposed to a teetered hub was also selected on a tentative basis at this point in the study. Later, a dynamic analysis of rotor/tower interactions confirmed the technical acceptability of a rigid hub in conjunction with 2 blades; this analysis was performed during the Preliminary Design portion of the study.
- Filament wound blades were selected as the lowest cost approach. This concept is amenable to an efficient fabrication technique, provides a lightweight structure and requires minimum maintenance when formed in a propeller type structure. The use of a helicopter type blade, balanced at the quarter chord point, was unattractive due primarily to the following reasons:
 - higher fabrication costs
 - heavier weight
 - higher maintenance costs

In addition, the propeller concept had been successfully demonstrated in Europe by Professor Dr. Hutter and was judged to have less development risk.

TOWER

- Many tower concepts including truss, concrete, tube shell and pole designs were evaluated. The truss and concrete approaches appeared to be least cost with the truss having the advantage of better cost predictability while the concrete offers a more aesthetic design.

TRANSMISSION SUBSYSTEM

- Mechanical, hydraulic and electrical type transmissions were considered. The mechanical concepts such as: gearbox, belts, chains and combinations of these were judged to be the most cost effective. Of these the gearbox was preferred when maintenance aspects were addressed.

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GENERATOR

- Either synchronous or induction generators can be accommodated in the WTG; however, the synchronous generator is preferred due to its higher power factor and the fact that it is better characterized.

CONTROL SUBSYSTEM

- A microcomputer was selected as the main control element in the system. The microcomputer offers an inexpensive approach to handle the many operating situations which can occur. Design emphasis on the control system permits a relaxation of the design requirements on other system components.

1.3.3 PARAMETRIC ANALYSIS RESULTS

Results from the Conceptual Design Task were modeled in a design optimization computer code to evaluate the effect of specific design variables on system cost and to select the design conditions for the Preliminary Designs. The major design variables investigated are listed below.

Median Wind Speed, V_M - is the wind speed, characteristic of the site, for which actual wind speeds exceed that value for one-half of the year and are less than that value for one-half of the year. (NOTE: Statistically and meteorologically defined as the median wind speed.)

Rated Power, P_R - is the power level rating of the system and is governed by the capabilities of the generator. It also represents the power level that is maintained by power regulation at wind speeds above the rated wind speed.

System Life, L - is the time duration over which the machine is assumed to be operable and the capital investment depreciated.

Rotor Speed, N - rpm of rotor blades.

Rotor Blade Diameter, D - effective aerodynamic rotor blade diameter.

Rated-Velocity Ratio, λ_R - is the velocity ratio at which a given rotor design achieves rated power output, where velocity ratio is the ratio of the rotor blade tip speed to the wind speed and represents a performance parameter which relates the rotor speed (rpm), the rotor diameter and the wind velocity to rotor blade performance.

Cut-In Wind Speed, V_{CI} - is the minimum wind speed at which the generator may be cut-in and produce power. It also represents the lower limit of the wind speed spectrum for generator cut-out.

Cut-Out Wind Speed, V_{CO} - is the maximum wind speed at which the generator power output can be adequately regulated.

Blade Activity Factor, AF - is a non-dimensional performance parameter, which characterizes blade planform area and area distribution in terms of both aerodynamic and structural performance. Activity factor incorporates the effects of taper as well as blade solidity (area ratio of blade planform to rotor disc)

Blade Airfoil - is the aerodynamic contour of the blade cross-section, which provides the blade performance characteristics in terms of lift and drag. (Lift and drag forces acting on the blades are resolved into the resultant torque and thrust absorbed by the rotor when integrated over the blade length.)

Blade Ground Clearance, h_g - distance between the ground and the rotor blade tip in the 6 o'clock position.

The parametric analyses were conducted for sites having median wind speeds between 9 and 21 mph (at a 9 mph median wind site the wind is assumed to be above this level for one-half of the year).

The economic assumptions made in calculating energy costs are believed to be representative for an electrical utility company in today's environment. The assumptions made are:

- Depreciation Method - straight line
- Capitalization Method - 50% bonds, 50% stock
- Interest Rate - 9%
- Return on Equity - 11.5%
- Federal Tax Rate - 48%
- Maintenance costs included

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Effect of Power on Cost

Figure 1-3 previously discussed in Section 1.3.1 illustrates parametric system costs (¢/kWh) versus system power level (kW) for wind sites having median speeds between 9 and 21 mph.

Figure 1-5 describes the trend of capital costs, $\text{\$/kW}$, as a function of power levels. The results shown support the previously mentioned conclusion that higher power levels provide greater cost effectiveness.

Effect of Median Wind Speed on Cost

The fundamental importance of the wind speed at the site is evident from Figures 1-2 through 1-5. At higher wind velocities smaller diameter rotor blades are required for the same power level, thereby, reducing rotor subsystems and tower costs. Higher wind speeds also result in a higher design rpm, consequently, reducing transmission costs as well.

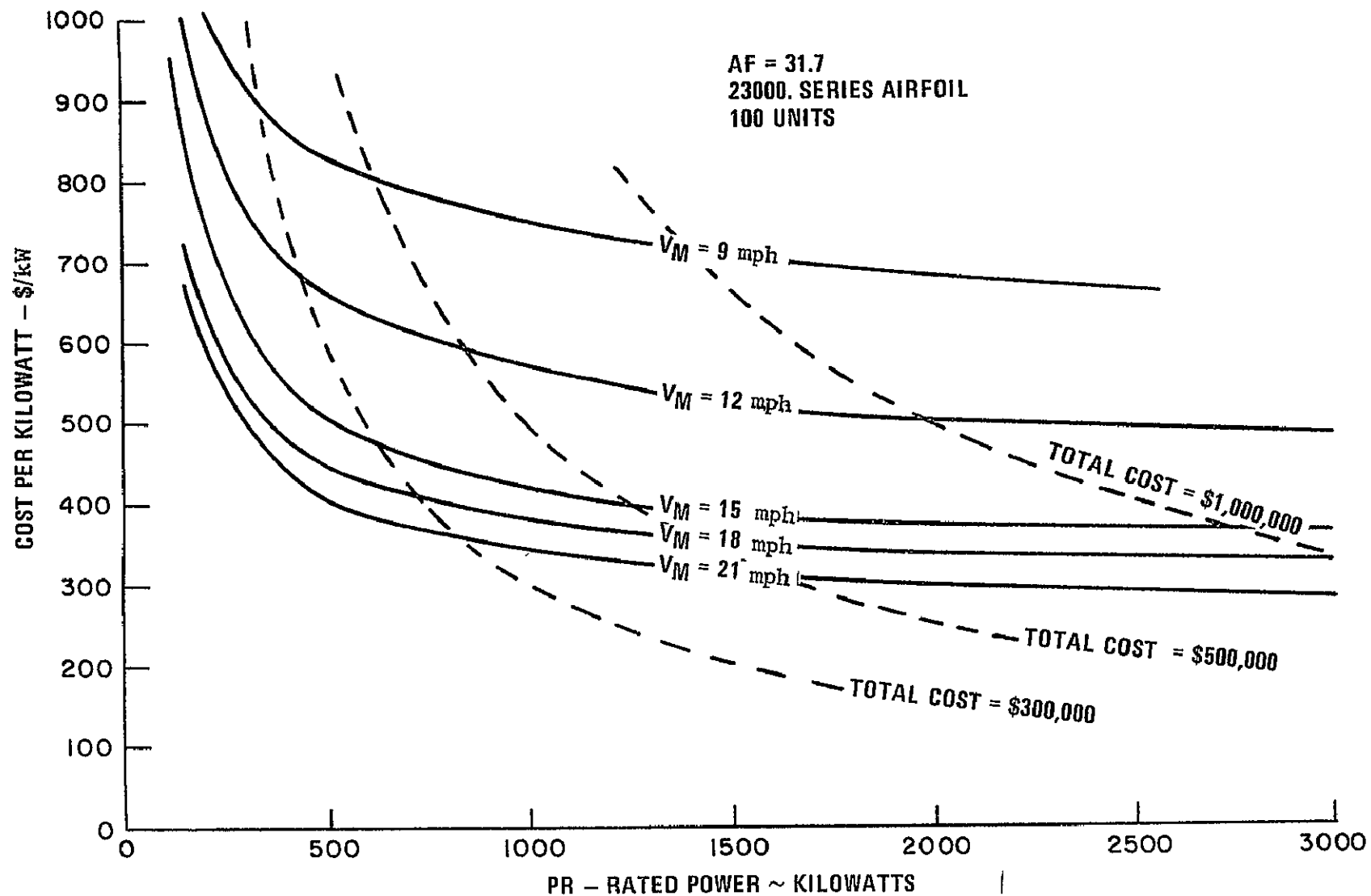


FIGURE 1-5 CAPITAL COST PER KILOWATT VS. RATED POWER

WTG Annual Operating Times

A major concern regarding the use of WTG's in electrical utility applications is the amount of time during the year when power is available. Using the velocity duration curves provided by NASA (see Figure 2-2), data was generated for the optimized systems to assess the annual expected operating time. Figure 1-6 illustrates the number of hours per year a WTG can be expected to deliver power as a function of median wind speed.

In terms of total hours of operation, 5300 to 7200 hours can be expected for 9 and 21 mph median wind speed sites, respectively.

Operation at rated power is predicted to occur for 1300 and 3700 hours, annually for the 9 and 21 mph sites, respectively.

Terrain Factors and Altitude

An important element involved in the design of a WTG is the velocity gradient of the wind with height. This velocity gradient or "wind shear" affects the design of the WTG in several ways; one concern is the effect on the system performance and resulting power generating cost. Figure 1-7 illustrates the effect of the terrain factor, k_o , on system cost where k_o is defined by the following expression: $V = V_o (h/h_o)^{k_o}$,

and

V = wind velocity at some height

V_o = wind velocity at reference height

h = height

h_o = reference height

Terrain factors of 0.15 are characteristic of open, flat land while values of 0.20 are typical for rougher topography with obstructions such as brush and trees. Also shown in Figure 1-7 is the effect on cost of the blade ground clearance height. Some benefit is apparent in increasing the ground clearance to 15.2 meters (50 feet); this is discussed further in Section 3.0.

The effect of altitude (between sea level and 1 mile) on system performance and cost was also investigated. The results, shown in Figure 1-8, indicate that decreasing air density at higher altitudes has a minor impact on overall system cost.

Effects of Lifetime on Cost

A system lifetime of 30 years was used in all economic calculations; the effect of this assumption on system cost was investigated and the results are shown in Figure 1-9. For system lifetimes of 18-50 years the cost per kwh is relatively insensitive to the system lifetime. A major reason for this is that substantial capital expenditures related to the maintenance of the mechanical power transmission are assumed to occur every 5 years. In the lifetime range of 14-18 years the tax deductible expenses were equal to the annual income of the corporation and it is questionable whether this mode of operation would be permitted by the Internal Revenue Service.

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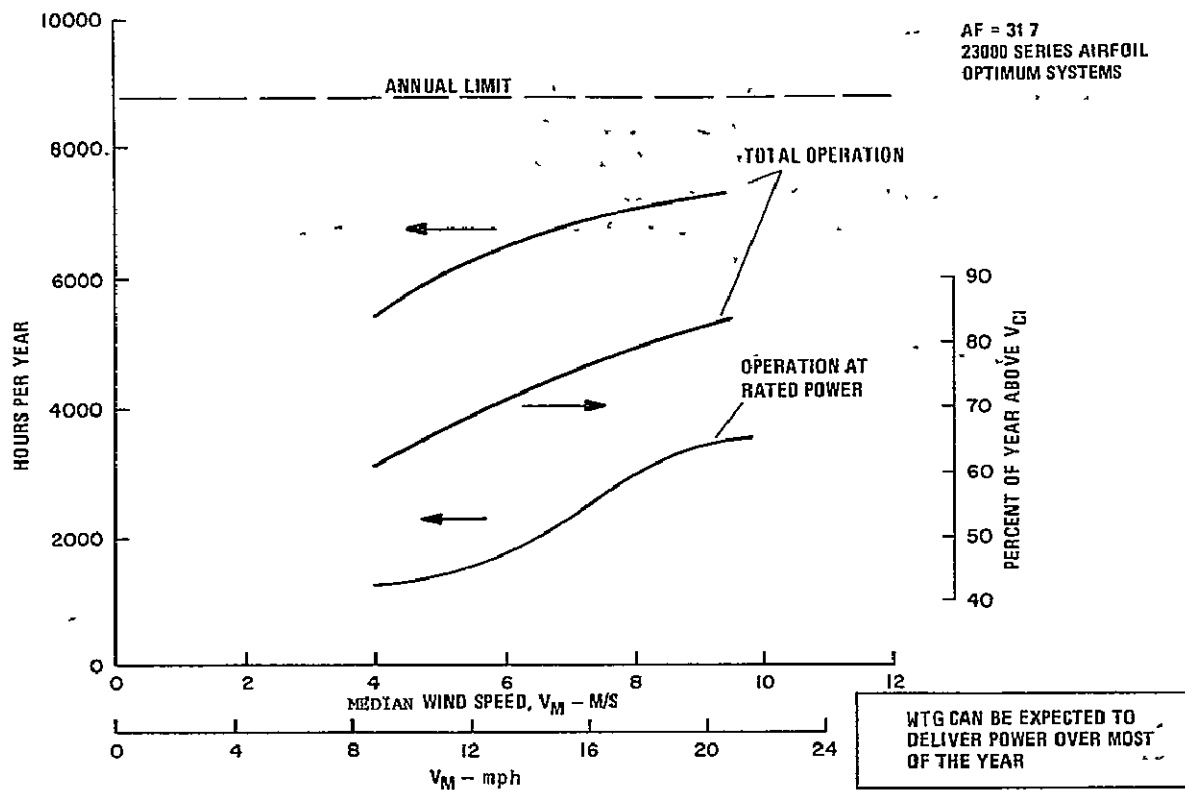


FIGURE 1-6 ANNUAL OPERATING TIME VS. MEDIAN WIND SPEED

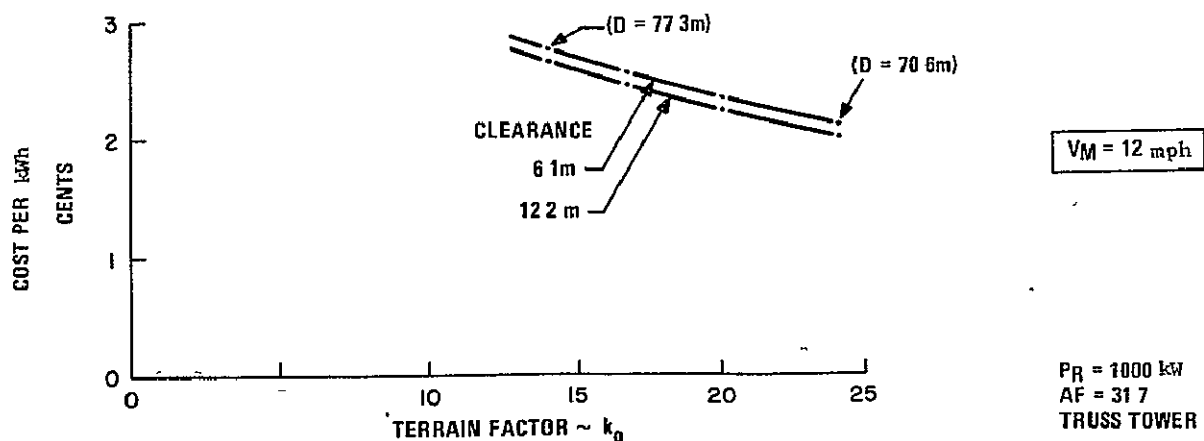


FIGURE 1-7 COST SENSITIVITY OF TOWER HEIGHT
(AS FUNCTION OF WIND SHEAR AND ROTOR GROUND CLEARANCE)

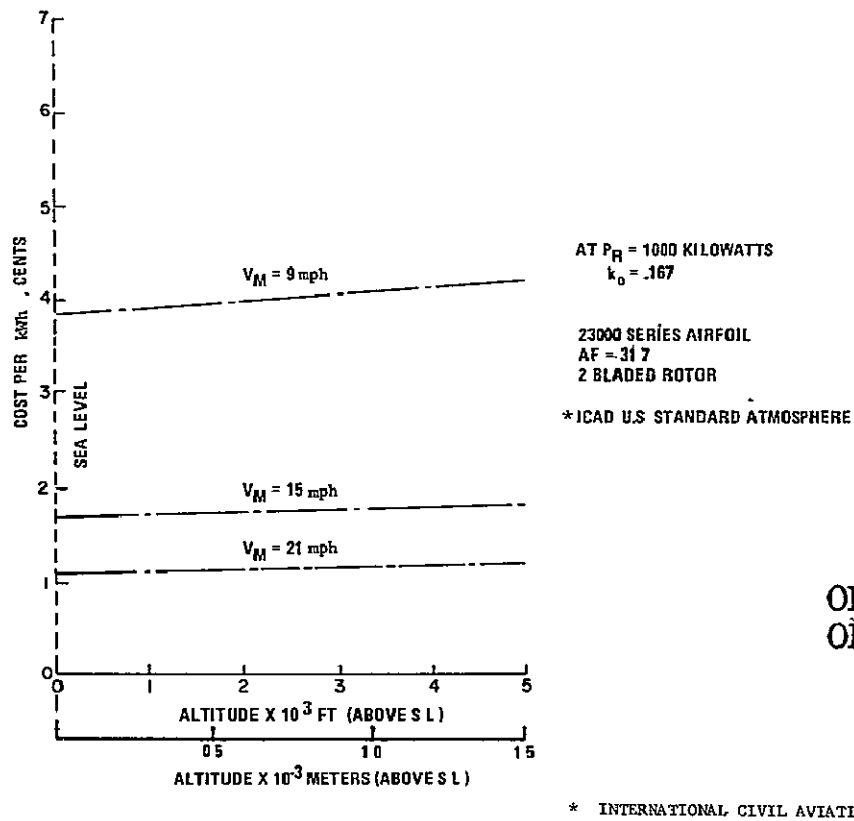


FIGURE 1-8 COST SENSITIVITY TO ALTITUDE

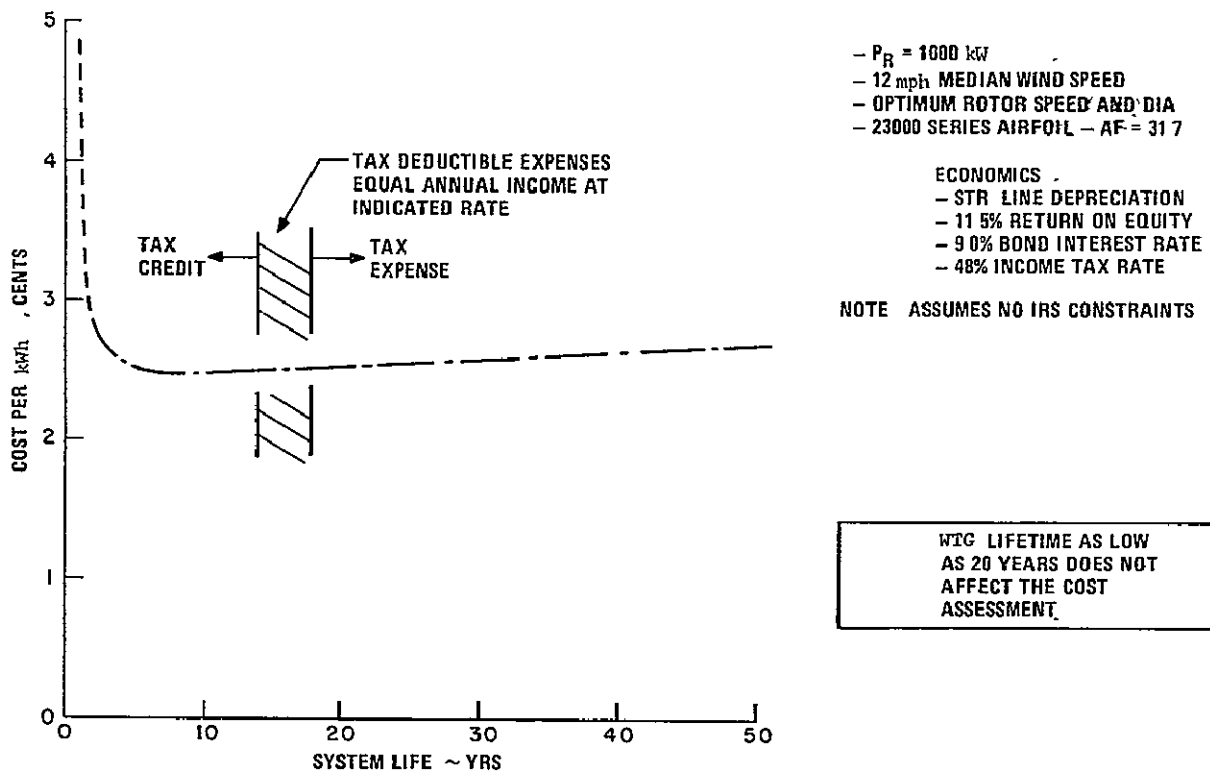


FIGURE 1-9 EFFECT OF LIFETIME VARIATION ON ENERGY COST

Further reductions in the assumed system lifetime resulted in a tax credit situation which would not be permitted by the IRS.

Therefore, the 30 year system lifetime was concluded to be reasonable from an economic as well as a technical (fatigue life) viewpoint based on the assumptions listed on Figure 1-9.

Comparison with Current Utility Costs

Two general methods of evaluation were used to compare WTG's with conventional power generating costs. In the first approach, the WTG was compared on the same basis with conventional methods of power generation where it is assumed that the WTG can be regarded as a basic part of the plant capacity. The second approach considered the WTG strictly on its potential to save fuel since its availability is governed by the unpredictability of the wind and therefore the utility does not regard it as a portion of its plant capacity.

Figure 1-10 presents "screening curves" for various conventional generating plants in terms of cost (\$/yr per rated kW) versus plant factor. Also plotted in this figure are the points for optimized WTG's in 12, 18 and 21 mph median wind sites. This data is parametric and does not reflect the cost iteration conducted in the Preliminary Design. In considering WTG's on a capacity cost basis two major conclusions can be drawn from Figure 1-10:

- The potential for cost competitiveness with conventional plants resides in building a large system (>500 kW) in windy sites (> 12 mph).
- Plant factors of .4 to .6 will be attainable.

Since alternate generating capacity would be required for a utility employing WTG's (assuming no energy storage) a second approach was considered in which the WTG is used as a fuel saver whenever it is available. The results of this analysis are shown in Figure 1-11. Figure 1-11 plots the system value in \$/kW versus the cost of fuel in mils/kWh. Referring to the 12 mph median wind speed line it is apparent that fuel costs must rise to about 19 mils/kWh before there is any advantage to using a WTG. At the higher wind speed sites, however, the WTG's become competitive in the region where fuel costs are approximately 8-14 mils/kWh. The conclusions drawn from the parametric data shown in Figure 1-11 support the results of Figure 1-10. There are strong economic incentives for building larger units in the highest wind velocity sites available.

1.3.4 PRELIMINARY DESIGN RESULTS

Using the component concepts previously identified and the quantitative results of the parametric analyses, 500 kW and 1500 kW units were designed to operate in 12 and 18 mph median wind sites, respectively. The specific results of the Preliminary Design Task are outlined below.

Cost

Costs to generate power were estimated on the basis of 100 production units and include the system contractors overhead and fee. The costs for the 500 and 1500 kW units are \$466,670 and \$643,655 respectively, or 935 ¢/kW and 430 ¢/kW. The corresponding energy generation costs are 4.04 and 1.57 ¢/kWh.

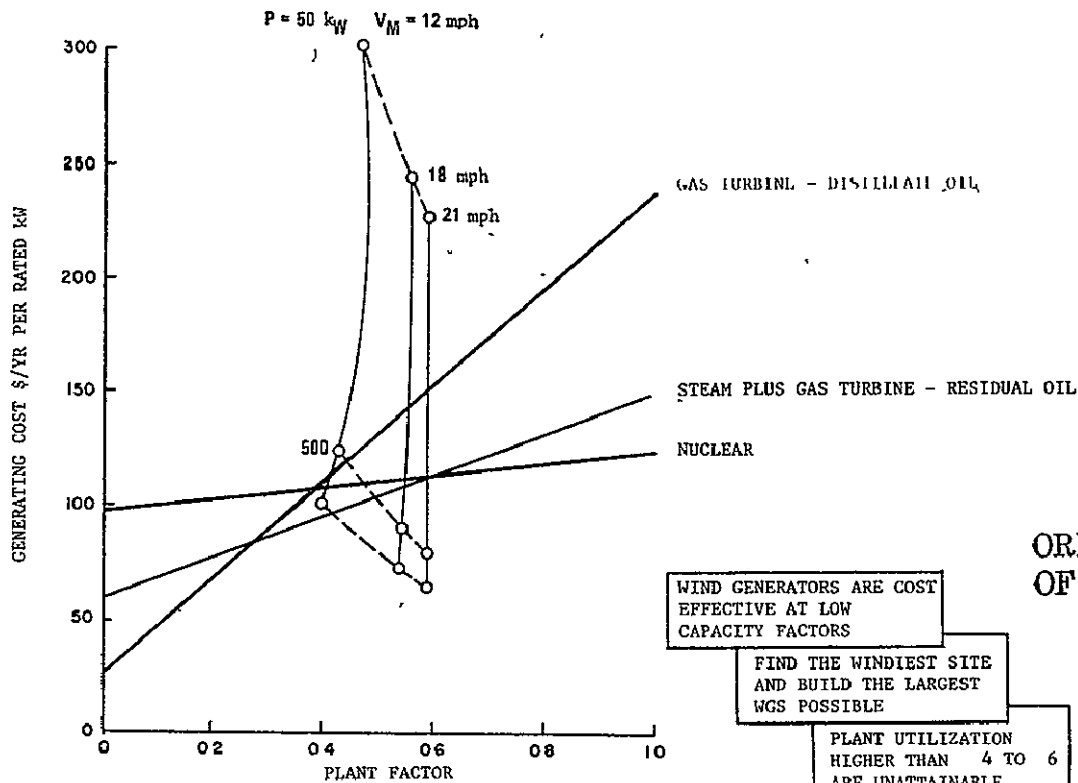


FIGURE 1-10 COMPARISON OF CONVENTIONAL GENERATING PLANTS AND WIND GENERATORS ON BASIS OF CAPACITY COST

FIGURE 1-10 COMPARISON OF CONVENTIONAL GENERATING PLANTS AND WIND GENERATORS ON BASIS OF CAPACITY COST

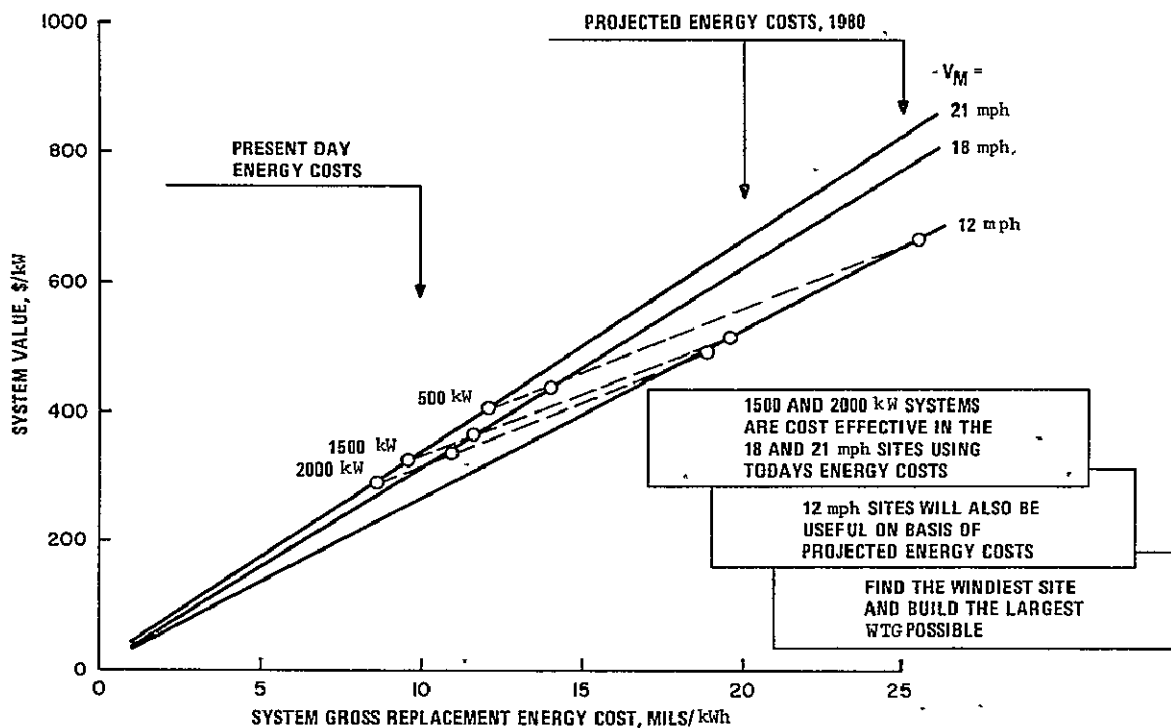


FIGURE 1-11 ASSESSMENT OF WIND GENERATORS ON BASIS OF ENERGY VALUE - ANOTHER APPROACH

If the Preliminary Design costs quoted above are coupled with the parametric trends shown in earlier curves it is possible to estimate costs for power levels and mean wind sites other than the two Preliminary Design conditions.

Final Design and Fabrication Schedule

Figure 1-12 illustrates the estimated schedule to perform a final design, fabrication and assembly, and check-out of the 1500 kW WTG; the schedule for the 500 kw unit would be similar.

Fabrication Approach

The approach used in erecting and checking-out the WTG could have a significant impact on overall system cost. The logistics outlined during the Preliminary Design for these procedures included the following:

- delivery of the rotor subsystem directly to the site
- erection of the tower by a local contractor
- assembly and checkout of the nacelle at the factory
- delivery and installation of the nacelle and installation of the rotor.

Variations in these procedures are possible depending upon the size of the WTG and the site location and condition.

Rotor/Tower Dynamic Interactions

Tower and rotor costs can be minimized by analyzing these two major subsystems simultaneously. Proper selection of operating speed and natural frequencies of the rotor and tower can result in less cost yet higher reliability by reducing system weight and strength requirements. Therefore, the rotor/tower system should be dynamically "tuned" so as to provide the most cost effective design. Failure to assess the dynamic load factors could result in excessive cyclic stresses and fatigue of critical subsystems.

Rotor Subsystem Design

Two rotor blades mounted on a rigid hub were found to offer the least cost rotor subsystem. Both 2 and 3 bladed systems and teetered as well as rigid hubs were evaluated. The increased cost and sophistication of the teetered hub was found to be unnecessary if large overturning moments due to wind directional changes can be avoided by the control system.

Tower

Analyses of both truss and concrete towers for the Preliminary Design indicates that for sites with good soil conditions, the concrete tower is lower in cost. Also of importance is the fact that concrete towers appear to be more aesthetically pleasing to the majority of people.

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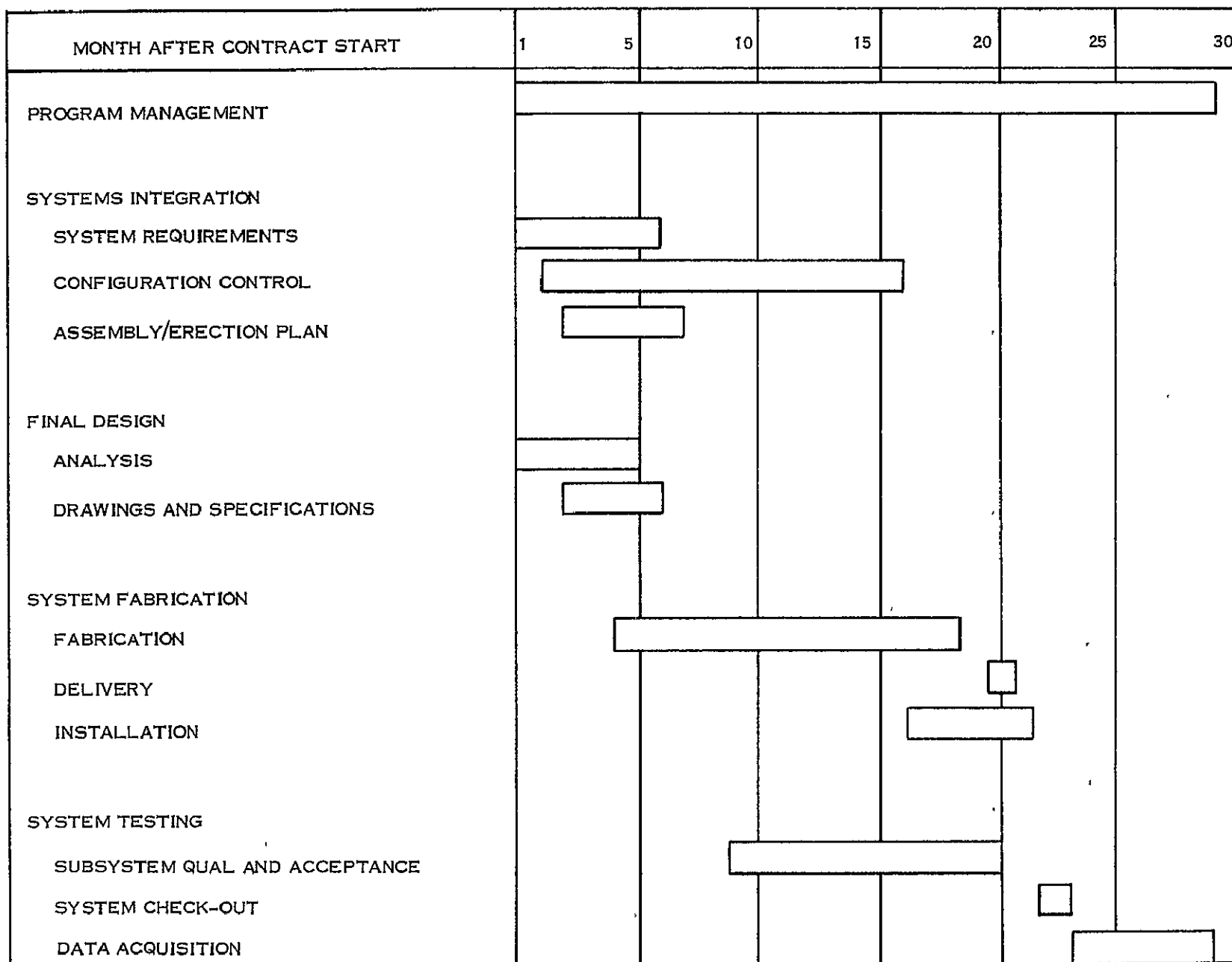


FIGURE 1-12 SCHEDULE FOR DESIGN, FABRICATION, INSTALLATION AND TESTING OF PROTOTYPE UNIT

A comparison between concrete and truss towers is shown in Table 1-1 for 2 power levels. These costs include the system contractors' purchasing cost and profit.

TABLE 1-1 TOWER COSTS

| | | 500 kW | 1500 kW |
|---------------------|-----------------------|----------|-----------|
| Reinforced Concrete | Small Qty. | \$45,200 | \$64,000 |
| | Production Attainable | \$39,300 | \$55,900 |
| Steel Truss | Small Qty. | \$90,700 | \$122,400 |
| | Production Attainable | \$73,800 | \$98,100 |

System Stability

Both the electrical and mechanical stability of WTG's were investigated under a variety of conditions. Electrical stability can be maintained by generator field control under most wind gusting conditions. In situations where there is a high impedance line to the network, blade pitch control may be required in addition to field control, for low frequency wind gusts.

Mechanical stability must be provided in order to synchronize the WTG. Gain factor and speed loop stability analyses indicate that synchronization can be achieved under steady state and gusting situations by varying the blade pitch angle.

2.0 SYSTEM REQUIREMENTS

This section describes the requirements to which the WTG's were designed. These requirements were either provided by NASA-Lewis at the beginning of the study or resulted from the knowledge acquired as the study progressed. The subsections below present these requirements relating to:

- Electrical Utility Interfaces
- Operational Requirements
- Cost Requirements
- Reliability/Availability Requirements
- Development Risk

2.1 ELECTRICAL UTILITY INTERFACES

The WTG's are designed to connect with typical electrical utility network lines. In general, it is expected that these lines will be of the "distribution" or lower "sub-transmission" voltage class. The specific technical considerations involved in connecting the WTG to distribution or subtransmission circuits concern:

- voltage fluctuations
- power factor
- circuit relaying and line reclosing
- telephone interference
- stability

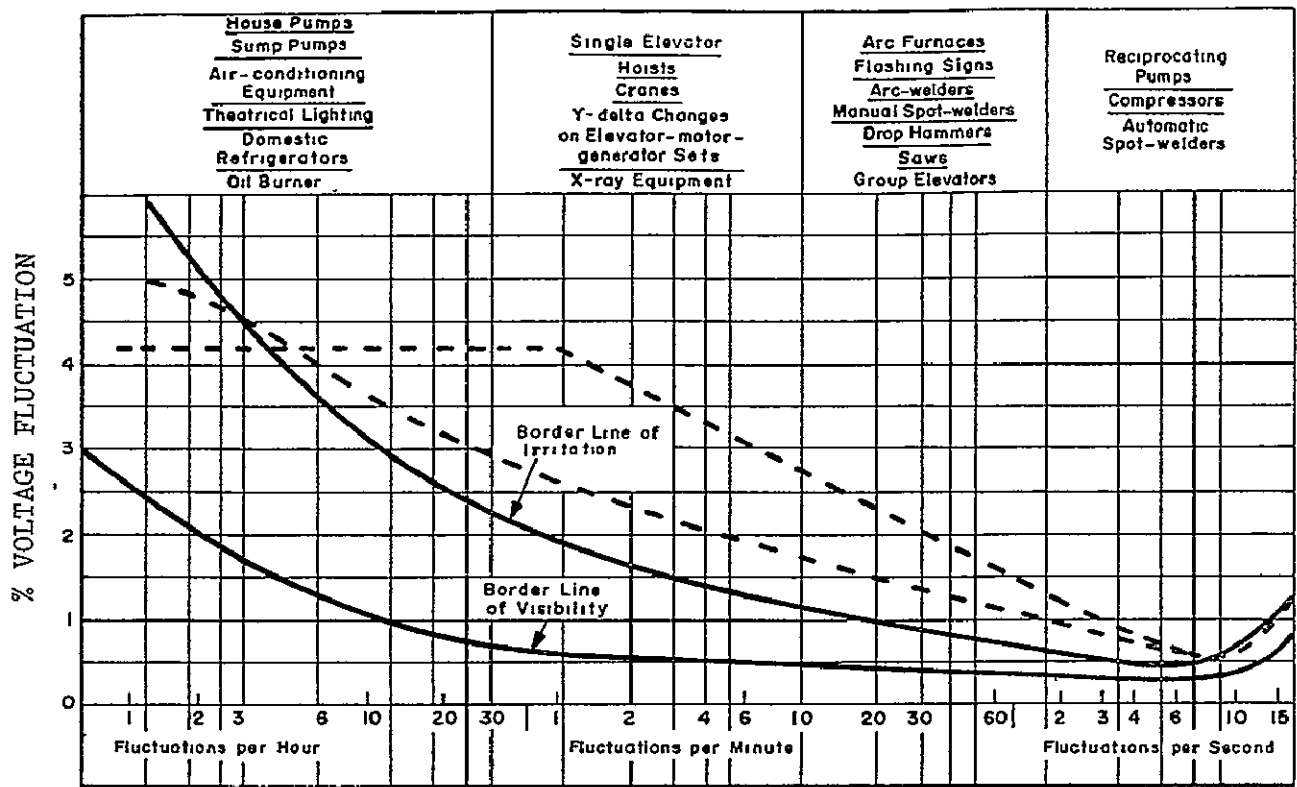
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Each of these areas are discussed below.

2.1.1 VOLTAGE FLUCTUATIONS

Voltage dips associated with the wind turbine generators may occur during starting and stopping of the units and from the output variation resulting from wind velocity changes. For WTG's using synchronous generators, voltage dips resulting from starting could be completely eliminated by automatic synchronizing which is common practice in utility power generation. With regard to induction generators, switching of associated capacitors (used for power factor correction), will also cause voltage dips.

Frequent and/or excessive voltage fluctuations would be annoying to utility customers and must be avoided. Infrequent voltage dips of a larger magnitude may be tolerated; a general criterion which has been used for many years by utilities is shown in Figure 2-1. As shown in the figure larger voltage fluctuations (due to the WTG operation) may be tolerated if they occur infrequently, however, more frequent fluctuations will become an irritation to users of electrical equipment unless their amplitude is reduced as indicated.



Solid Lines composite curves of voltage flicker studies by General Electric Company, *General Electric Review* August 1925, Kansas City Power & Light Company, *Electrical World*, May 19, 1934, T. & D. Committee, EEl, October 24, 1934, Chicago, Detroit Edison Company, West Pennsylvania Power Company, Public Service Company of Northern Illinois

Dotted Lines voltage flicker allowed by two utilities, references *Electrical World* November 3, 1958 and June 26, 1961

FIGURE 2-1 ALLOWABLE VOLTAGE FLUCTUATIONS

2.1.2 POWER FACTOR

A power factor approaching 1.0 is normally preferred by electrical utilities since it maximizes net energy transfer efficiency. Power factors of less than 1.0 result in reactive power which increases the utility equipment requirements. Reactive power is measured in vol-amperes reactive (1000 var = 1 reactive kilovolt-ampere, abbreviated kvar).

Since kilovars cannot be economically transmitted over long distances due to excessive I^2R losses), utilities will use substantial amounts of fixed and switched shunt capacities to supply the kvar near the points where they are consumed. The result is that distribution system power factors approach unity, typically 0.98. In considering induction generators, which have power factors of about 0.8, the kvar requirements should be supplied at the WTG location so as to raise the power factor as close to unity as possible.

2.1.3 CIRCUIT RELAYING AND LINE RECLOSING

A typical distribution circuit will generally have automatic reclosing of the feeder circuit breaker to quickly restore service in the event of temporary faults such as those caused by lightning flashovers. In addition, particularly at the lower voltage levels, such as 24.9 kV and below, there will typically be one or more automatic reclosers spaced along the circuit performing the same task for faults beyond their location. The line reclosers and feeder circuit breaker have carefully coordinated overcurrent trips based on the assumption of radial feed from the substation. Reclosing may be done automatically, but only in the proper sequence, i.e., after the generator is tripped the circuit may be reclosed and, if successful, the wind generators put back on the line.

2.1.4 TELEPHONE INTERFERENCE

Since all generators produce a small amount of harmonics in the voltage wave, there is the potential for harmonic current flow which could cause interference in closely coupled telephone circuits. This has rarely been a problem and has been solved in most cases where it occurred by ungrounding some capacitor banks which acted as a "sink" for certain harmonics, or in some cases relocating the capacitor bank.

2.1.5 STABILITY

Electrical instability in a WTG is most likely to arise from wind gusting conditions. Loss of stability, or synchronism, in a synchronous generator results in high pulsating current flows in the connected circuits and attendant voltage fluctuations. Pull-out of an induction generator, i.e. operation beyond the peak of its slip-torque curve, result in abnormally high reactive current flow (approaching locked rotor values) with similar detrimental results. These conditions generally will require tripping and "re-starting" of the unit with some accompanying outage time to the unit.

2.2 OPERATIONAL REQUIREMENTS

The principal operational requirement is for the WTG to produce electrical energy at a cost which is competitive with conventionally produced energy. The specific operational requirements addressed in this study are presented below.

2.2.1 DESIGN LIFE

All static components including the tower were designed for a minimum service life of 50 years. Dynamic components were designed for a minimum service life of 30 years, but, may include periodic maintenance and replacement.

During normal operation the units will be designed for unattended, fail-safe automatic operation as well as manual control. The units will be designed for a minimum availability of 90 percent over the service life with special consideration given to servicing and maintenance of critical areas.

2.2.2 ENVIRONMENTAL REQUIREMENTS

The units will be designed to withstand the range of atmospheric environments experienced from New England to Alaska or the Caribbean area to hot desert climates. The unit must therefore be capable of operation in snow, rain, lightning, hail, icing conditions, salt water vapors, wind-blown sand and dust and in temperature extremes of -51°C (-60°F) to 49°C (120°F). If cost effective, designs adaptable to local severe conditions with minimum change will be acceptable.

2.2.3 WIND SPEED AND GUST MODEL

In order to calculate annual WTG energy production, velocity duration curves were supplied to GE by NASA-Lewis. The wind profiles used are shown in Figure 2-2 for sites having median winds between 8 and 24 mph.

The WTG is required to operate during normal wind gusting conditions and survive gusts which exceed cut-out velocity. In addition, the WTG must be designed to withstand a maximum steady wind speed of 53.6 m/s (120 mph) at 9.1 meters (30 feet) above the ground.

Velocity versus time relationships for the assumed wind gusts are shown in Figure 2-3. As shown in the Figure the maximum amplitude of an individual gust is nearly twice the steady state level of the wind; the maximum value of the gust occurs at one-half the gust period. Also of importance is the fact that gusts of shorter duration reach lower amplitudes, but the rate of increase in the wind speed is higher.

2.3 COST REQUIREMENTS

An objective of the study was to develop two preliminary designs which represent minimum cost systems in the 12 and 18 mph median wind sites. Minimum cost was to be based upon ¢/kWh and include capital, operational and maintenance costs. Within the framework of minimum cost, consideration was given to architectural aesthetics and public acceptance.

2.4 RELIABILITY/AVAILABILITY REQUIREMENTS

The WTG was designed for a minimum availability of 90 percent over the service life with special consideration given to servicing and maintenance of critical areas.

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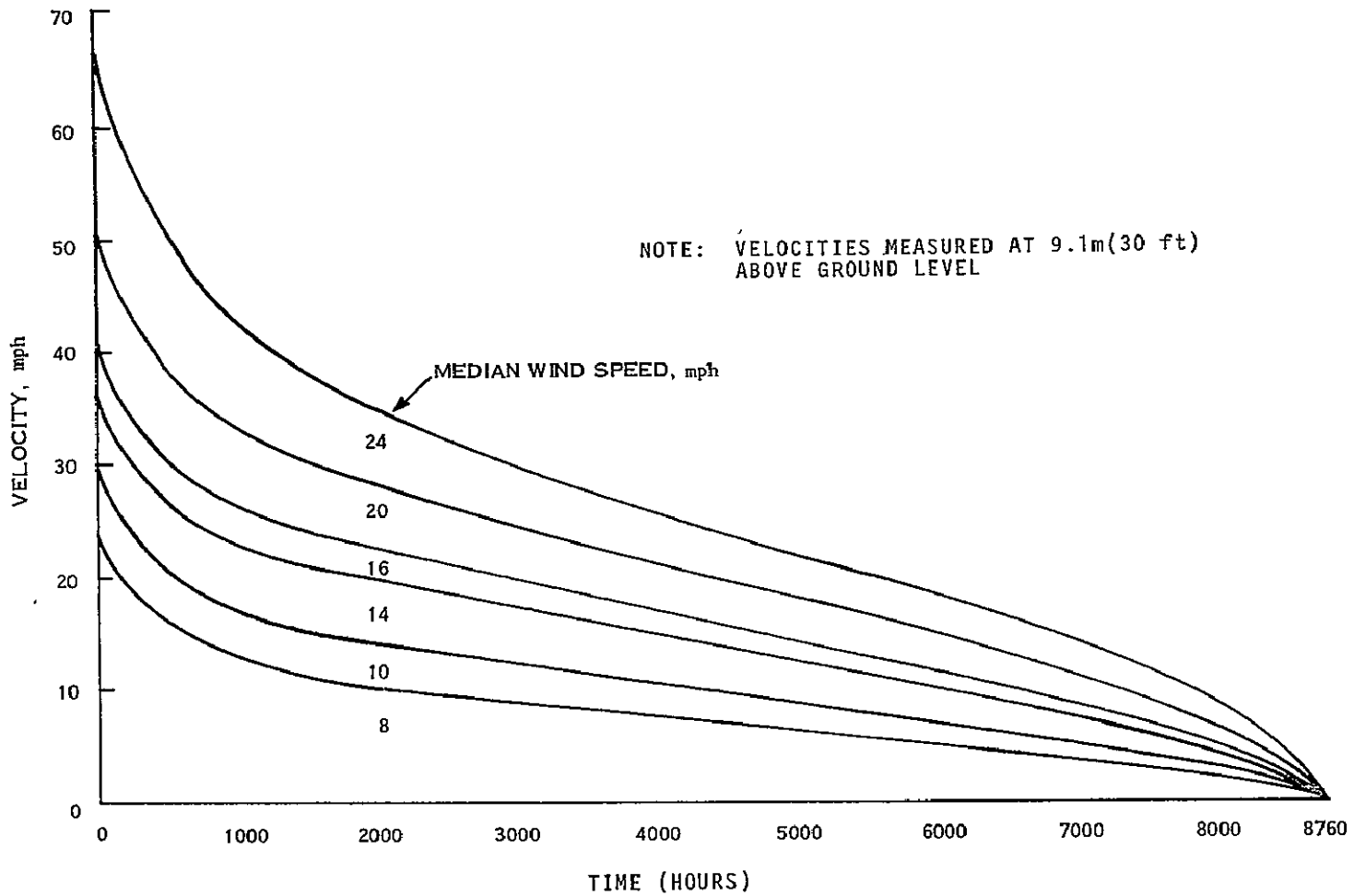


FIGURE 2-2 VELOCITY DURATION CURVES

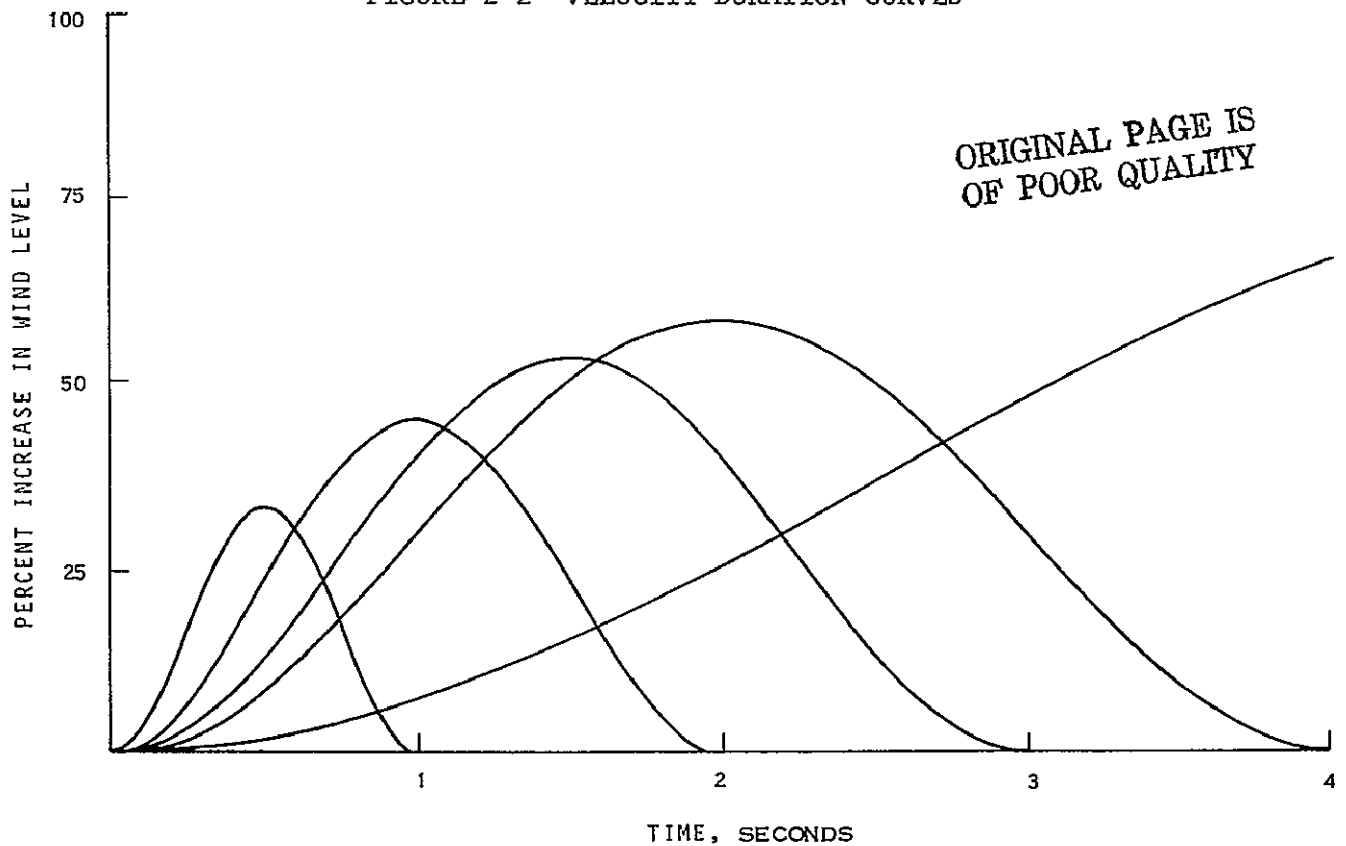


FIGURE 2-3 WIND GUST MODEL

2.5 DEVELOPMENT RISK

It was the intention of this study that the WTG preliminary designs could lead to final design and construction within 2 years. Therefore, the designs must utilize the latest proven design, material and fabrication technology insofar as its use minimizes electric power generation costs. Whenever possible, the technology will have a base of proven experience.

3.0 PRELIMINARY DESIGN

This section describes the two preliminary designs which were generated in the Preliminary Design Task of the study: a 500 kW unit and a 1500 kW unit which operated in 12 mph and 18 mph median wind sites, respectively. Section 3.1 covers the design of the system, 3.2, the operational aspects and 3.3, the design for individual components.

3.1 SYSTEM DESIGN

3.1.1 APPROACH

The basis for the preliminary designs was formulated from the results of the Conceptual Design and Parametric Analyses Tasks. In light of the Conceptual Design Task conclusions, the preliminary designs had the following features incorporated:

- Constant rotor speed
- Variable pitch control
- Single rotor per tower, placed downwind
- Propeller type blades
- 2 blades per rotor
- Fixed ratio gearbox transmission
- Synchronous generator
- Truss or concrete tower
- Microcomputer based control system

Based on the results of the Parametric Analysis Task it was recommended to NASA that the Preliminary Design focus on a 500 kW system for the 12 mph median wind site and a 1000-2000 kW system for the 18 mph median wind site. NASA elected to proceed with a 500 kW unit in a 12 mph site and a 1500 kW unit in an 18 mph site. In addition, the blade clearance height from the ground was directed to be 15.2 m (50 feet) instead of the previously used 6.1 m (20 feet); this change was prompted by data from the parametric analyses which suggested a cost advantage in raising the clearance height. In addition, a larger ground clearance results in a flatter wind velocity profile across the rotor disc, thereby offering the potential for lower cyclic stresses.

The first step in the Preliminary Design was to use an updated version of the design optimization code to obtain the operating conditions for the minimum cost systems at the aforementioned power levels and wind sites. Results from the optimization code are shown in Table 3-1; these conditions formed the basis for the ensuing design work.

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TABLE 3-1 SYSTEM CHARACTERISTICS

| | | |
|---|--------------------|--------------------|
| Power rating, kW _e | 500 | 1500 |
| Annual energy, kWh | 1.88×10^6 | 6.62×10^6 |
| Capacity factor | 0.42 | 0.51 |
| Rotor diameter, m (ft) | 55.8 (183) | 57.9 (190) |
| Rotor Speed rpm | 29 | 40 |
| Rated velocity, m/s (mph) | 7.27 (16.3) | 10.1 (22.5) |
| λ_{Rated} ($\lambda_{\text{Design}} = 10$) | 9.0 | 9.5 |
| Tip speed, m/s (ft/sec) | 84.7 (278) | 121 (398) |
| Cut-in velocity, m/s (mph) | 3.54 (7.92) | 5.11 (11.4) |
| $\lambda_{\text{Cut-in}}$ | 18.5 | 18.4 |
| Cut-out velocity, m/s (mph) | 17.9 (40) | 22.3 (50) |
| $\lambda_{\text{Cut-out}}$ | 3.67 | 4.18 |
| Hours above V_{ci} | 6257 | 6568 |
| Hours at rated | 2067 | 2718 |

The operating conditions identified by the computer code were then used in the aerodynamic and structural design of the blade and hub. This work was also supported by a dynamic analysis of the rotor/tower interactions. Following the design of the rotor subsystem, the main shaft, pintle and tower design was initiated. Design of the generator and gearbox transmission proceeded directly from the results of the computer code. The design of the control system was a continuing process which involved design trade-offs with each of the major subsystems.

Primary emphasis was placed upon minimizing the WTG energy generation cost. Reduction of energy generation costs involves two aspects:

- minimization of capital expenditures and maintenance costs
- maximization of the annual energy produced

Initial design efforts had shown that the most effective way to minimize capital costs was to reduce the structure and overall weight in the system. The relationship between weight and cost is evident in many industrial products which do not contain high technology components requiring exotic manufacturing techniques or materials. In order to reduce weight it is necessary to lower the structural loads on the system such that the system reliability is not compromised.

Therefore, cost effective design requires an approach which avoids high wind loading conditions which can result from rapid changes in wind direction or high wind velocities. This can be accomplished by means of a properly designed control system which maintains the WTG in the least vulnerable condition under adverse environments such as rapidly shifting winds or wind gusting situations exceeding the WTG cut-out velocity.

Maximization of the energy production is achieved by rating the system at the most favorable power level and optimizing the design operating conditions, velocity ratio (λ) and rpm. In addition, it is necessary to ensure that the system operates under the broadest range of wind conditions possible. This requires a control system which:

- Provides for synchronization with the network at the lowest wind speed possible
- Allows continuous operation under varied wind gusting conditions
- Provides system control up to the maximum practical cut-out velocity
- Allows for synchronization under intermediate and high wind conditions to allow restart from a maintenance or high wind cut-out condition

3.1.2 SYSTEM DESIGN DESCRIPTION

This section describes the preliminary designs which were developed. Section 3.1.2.1 addresses the principal features incorporated in the WTG Systems while sections 3.1.2.2 and 3.1.2.3 describe the system costs and weights respectively.

3.1.2.1 KEY DESIGN FEATURES

An exterior view of the upper portion of the 1500 kW preliminary design is shown in Figure 3-1. In the illustration the rotor subsystem can be seen at the left. The hub portion is about 7.6m (25 feet) in diameter while the blade chord and blade root thickness are 3.6m (12 feet) and 1.5m (5 feet), respectively. The mechanical power transmission and generator are housed within the nacelle; at the right of the nacelle is an instrumentation boom which points into the wind. The entire nacelle is mounted atop the pintle which contains the azimuth drive mechanism. As seen in the illustration, the main shaft is inclined 6 degrees to the horizontal in order to reduce the rotor overhand distance required for tower clearance. Also important, is the fact that the blades are coned at 3 degrees, which lowers the steady state shank bending stresses and assists in maintaining the desired blade/tower clearance.

The angle of inclination and the cone angle have been selected so as to achieve the objectives stated without seriously compromising the effective blade diameter.

A view of the 1500 kW WTG with the nacelle cover removed is provided in Figure 3-2. In this illustration the main shaft, supported by two bearings, is shown. Separating the main shaft from the gearbox transmission is a flexible coupling. The coupling will compensate for small misalignments between the main shaft and the gear box which are present at assembly or developed over the life of the unit.

The transmission is oriented such that the high speed shaft is on top where it is accessible for maintenance. Attached to the high speed shaft, at the left of the transmission, is a hydraulic brake which is capable of bringing the system to an emergency stop in 20 seconds.

Another flexible coupling joins the transmission high speed shaft to the generator shaft; located on the generator shaft is a torque sensor. The role of the torque sensor is to measure the torque input to the generator; therefore its effectiveness is not compromised by the presence of flexible couplings elsewhere in the drive train.

Vertical orientation of the transmission results in a favorable position for the generator. In the design shown, the generator and associated electrical leads and auxiliaries are easily accessible.

The pitch change design is a mechanical mechanism utilizing proven commercially available hardware (jack screw actuators, angle gearboxes, universal joints, a T gearbox and a pitch change input shaft). The design relies on electric power for start-up only. During normal operation this design utilizes the kinetic energy of the main shaft to effect changes in pitch, thereby, eliminating any dependency on electrical or hydraulic systems during critical situations.

The control system is comprised of a microcomputer, sensors and actuators; the microcomputer and the isolated sensors are powered by an uninterrupted power supply (UPS). The UPS system, which consists of a battery coupled to a trickle charger (to maintain a full charge at all times), and the use of a redundant microcomputer provide the necessary reliability to the control system. The principal functions of the control system are to provide for system start-up, shut-down, nacelle turning, power regulation, mutual protection of the network and the WTG, data computation and control of the system during maintenance and emergency modes. A description of each of the subsystems is provided in section 3.3.

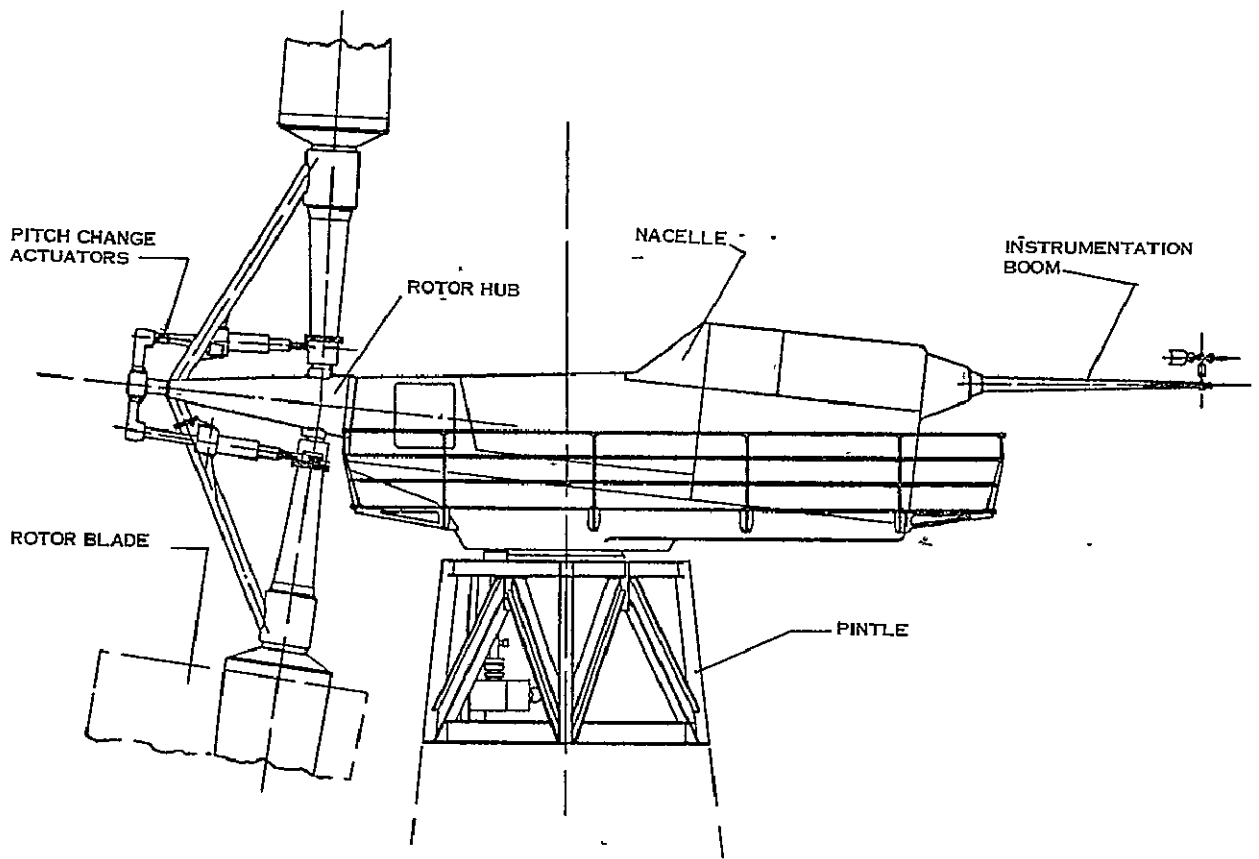


FIGURE 3-1 EXTERIOR VIEW OF 1500 kW WTG NACELLE AREA

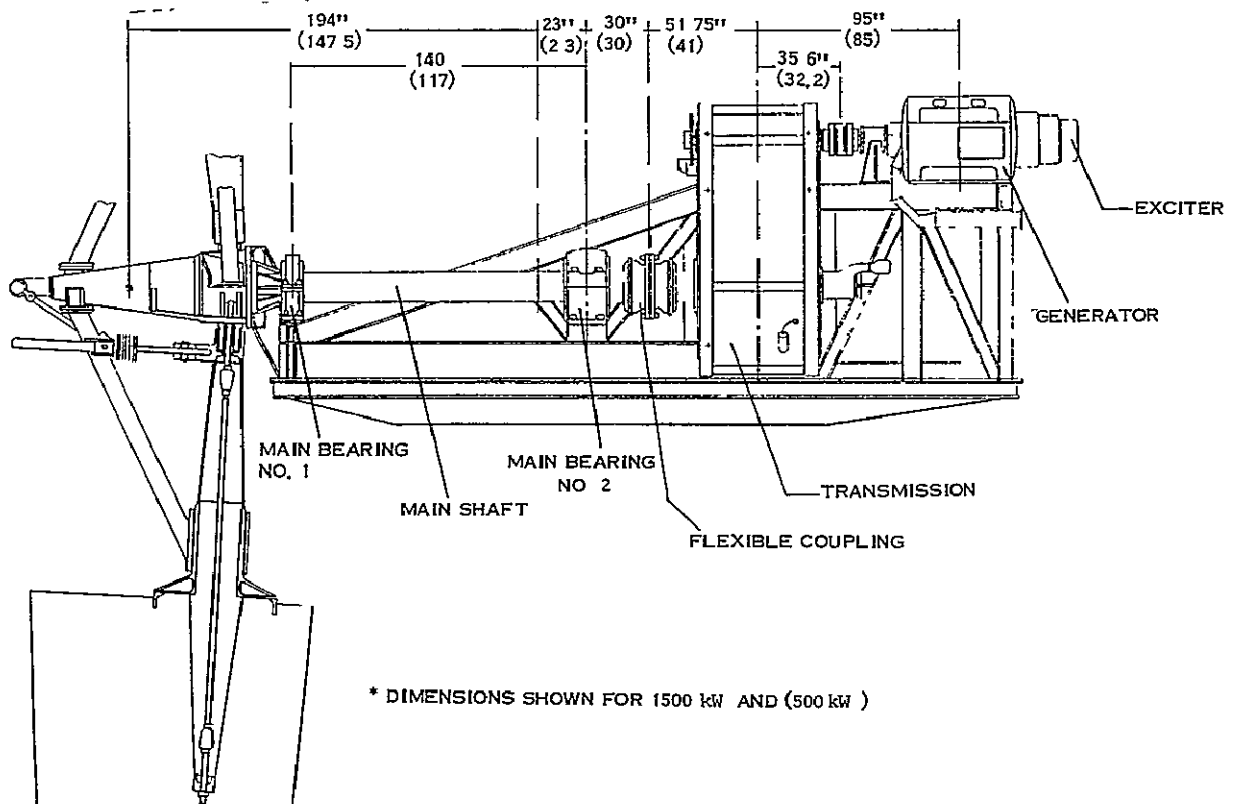


FIGURE 3-2 PRELIMINARY DESIGN LAYOUT*

3.1.2.2 SYSTEM COST SUMMARY

This section describes the anticipated cost of commercial WTG's based upon the designs developed during the Preliminary Design Task. In making this projection, it was assumed that the development of WTG's had been completed and that considerable operational experience had been gained with prototype WTG's operating in the electrical utility application. With this assumption the role of the system contractor becomes:

- identifying the specific requirements of the utility
- performing site planning
- purchasing and/or manufacturing all subsystems
- assembly and installation of the units
- operational check-out of all units

Specifically, it was assumed that 100 production units would be fabricated and installed within 3½ year period and that the facilities for producing these units were available. A summary of the capital costs (1975 dollars) on a per unit basis is shown in Table 3-2. Due to the fact that these costs are being estimated from a limited experience base with this technology, some of the figures are subjective. Therefore, an explanation of these costs is provided below.

Program Management

The total system contractor program management cost was estimated to be \$200,000, or \$2,000 per unit, through labor and overhead. Program management tasks would include program scheduling, purchasing, financial control and any technical direction required. Over the 3½ years it was assumed that the program management manpower level would scale down from three to one-half a man.

Final Design

A total of \$150,000, or \$1500 per unit, was included in the first 6 months of the program to account for a limited amount of redesign from previous units. This is approximately a 6 to 8 man level, and includes labor and overhead.

Systems Integration

During the initial stages of the program, system requirements and interfaces must be identified, a specific site erection plan must be generated, and a configuration control procedure established. A total of \$250,000, or \$2500 per unit, was allocated for these functions which represents a manpower level of four (4) scaling down to one half (0.5) from program start to finish.

Equipment Costs

Equipment costs represent vendor quotations for established commercial products except for the rotor. Quantity order discounts of 15% were included on the

transmission and electrical equipment; systems contractors overhead expense are included, estimated to be 15 percent. The rotor (blades, hub and pitch change unit) cost is the least certain of the equipment costs. An initial cost figure, based on present day knowledge and experience was developed by United Technologies Hamilton Standard Division and resulted, in part, from their discussions with Hercules, a fabricator of filament wound products. Subsequently, downward revisions were made to this estimate to reflect the anticipated experience afforded by the development cycle prior to obtaining a 100 unit order. The final cost of \$185,000 for the 1500 kW rotor reduces to a figure of \$5.3/15, where approximately $\frac{1}{2}$ of the weight is in the hub - a structural steel weldment.

Assembly Costs

The assembly costs of \$35,100 and \$31,400 for the 1500 kW and 500 kW units, respectively, include the Nacelle assembly, site delivery, and system erection and check-out tasks. These functions are assumed to be conducted by a trained crew who would develop considerable expertise and efficiency over the course of the program. The tower erection cost is not included here, but, is covered under the tower equipment cost.

The Nacelle assembly cost assumes assembly of the transmission, generating equipment and pintle to the machine bedplate at the system contractor's plant. Approximately 12 man weeks of technician effort, through labor and overhead was assumed.

Site delivery costs were calculated from standard industry quotations based on weight for a 1000 mile delivery radius. The cost of erecting the system, \$14,700, includes the cost of crane rental as well as labor required to perform mechanical and electrical connections. The erection procedure is described in Section 3.1.3. A separate cost of \$2500 per unit was included for an operational system check-out.

Site Costs

The site costs assume that \$1500 per unit is required to perform soil bearing tests and to accomplish any clearing of brush and trees. Foundation costs are included in the tower equipment cost.

A cost of \$3500 per unit was allocated for a control building located under the tower base. The control building, which housed much of the electrical equipment and controls, is assumed to be a pre-fabricated enclosure. A system contractor fee of 15 percent was added to all costs and represents the gross operating profit margin of the business. Total capital costs of \$466,670 and \$643,655 were calculated for the 500 kW and 1500 kW units, respectively.

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TABLE 3-2 SYSTEM COST SUMMARY

| SYSTEM TASK | 500 kW,WTG 12 MPH MEDIAN WIND | 1500 kW,WTG 18 MPH MEDIAN WIND |
|-------------------------------|----------------------------------|-----------------------------------|
| PROGRAM MANAGEMENT | 2,000 | 2,000 |
| FINAL DESIGN | 1,500 | 1,500 |
| SYSTEMS INTEGRATION | 2,500 | 2,500 |
| EQUIPMENT COSTS | | |
| ROTOR | 154,000 | 185,000 |
| TRANSMISSION | 100,000 | 162,000 |
| ELECTRICAL | 37,400 | 60,700 |
| CONTROLS | 13,600 | 13,600 |
| TOWER (concrete) | 39,300 | 55,900 |
| BEDPLATE/PINTLE | 19,100 | 36,400 |
| SUBTOTAL | 363,400 | 513,600 |
| ASSEMBLY COSTS | | |
| NACELLE | 8,600 | 8,600 |
| SITE DELIVERY | 5,600 | 9,300 |
| ERECTION | 14,700 | 14,700 |
| SYSTEM CHECK-OUT | 2,500 | 2,500 |
| SUBTOTAL | 31,400 | 35,100 |
| SITE COSTS | | |
| LAND | 1,500 | 1,500 |
| CONTROL BUILDING | 3,500 | 3,500 |
| TOTAL DIRECT LABOR & MATERIAL | 405,800 | 559,700 |
| GROSS OPERATING MARGIN | 60,870 | 83,955 |
| TOTAL COST | 466,670 | 643,655 |

First Unit Costs

The costs of Table 3-2 reflect estimates for a "mature commercial product" environment. Costs of early units will be substantially higher due to many factors. Recently, General Electric contracted with NASA-Lewis to construct and install two 1500 kW WTG power systems (Mod-1). The engineering time and purchased parts quotations of the second unit, devoid of recurring costs, was employed to generate Table 3-2a which is a representative first unit cost summary for the 1500 kW WTG system. Note that aircraft industry average hourly, overhead, general and administrative and fee rates were used in Table 3-2a rather than those particular to the specific contractors.

The total cost of Table 3-2 (for the 1500 kW unit) can be related to the \$2.633 million first unit cost by means of the learning curve to establish the cumulative quantity of units necessary to achieve the lower cost. A 90 percent learning curve is quite conservative when compared with historical data on items with similar technological complexity. This means that for each doubling of cumulative production the average unit cost (for all units) will be reduced to 90 percent of the previous value. Thus if the first unit costs one hundred dollars, the first two will average ninety dollars, the first four will average 81 dollars, etc.

Solving for the average cost of 100 unit production runs for a first unit cost of \$2.633 million and 90 percent learning yields:

| Units | 1500 kW WTG Average Cost |
|-------------|-----------------------------|
| 1 - 100 | \$1308 K |
| 101 - 200 | 1046 |
| 201 - 300 | 966 |
| ↓ | ↓ |
| 3401 - 3500 | 650 |
| 3501 - 3600 | 647 |
| 3601 - 3700 | 644 |

Thus, if a 90 percent learning rate is achieved the total cost of Table 3-2 will be reached when cumulative 1500 kW unit production is approximately 3600 to 3700 units. This is consistent with the mature commercial product assumption and well within potential WTG implementation possibilities.

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TABLE 3-2a TYPICAL PROTOTYPE PRODUCTION UNIT COST (\$K) BREAKDOWN - 1500 kW WTG

| SYSTEM TASK | Prime Contractor | | | Subcontractors | | | | Prime Contractor Burden (4) | Total |
|--------------------------------------|------------------|--------------|--------------|----------------|--------------|--------------|---------------|-----------------------------|-------|
| | (1) LABOR | (2) PARTS | (3) OTHER | (1) LABOR | (2) PARTS | (3) OTHER | (4) BURDEN | | |
| Program Management | 22 | | 2 | | | | | 9 | 33 |
| Final Design/ Engineering Support | 22 | | 4 | | | | | 10 | 36 |
| Systems Integration | 67 | | 18 | | | | | 32 | 117 |
| Equipment Costs | | | | | | | | | |
| Rotor/Blade | | | | 237 | 223 | 23 | 181 | 249 | 913 |
| Transmission | | 170 | | | | | | 64 | 234 |
| Electrical/ Controls | | 217 | | | | | | 81 | 298 |
| Tower (Steel) | | 99 | | | | | | 37 | 136 |
| Pintle | | 15 | | | | | | 6 | 21 |
| Assembly Costs | | | | | | | | | |
| Nacelle | | 53 | | | 24 | | 9 | 32 | 118 |
| Site Delivery | | 13 | | | | | | 5 | 18 |
| Erection | | | | 140 | | 21 | 61 | 83 | 305 |
| System Check-Out | 49 | | | | | 8 | 3 | 22 | 82 |
| Site Costs | | | | | | | | | |
| Land Preparation | 45 | | | 101 | 33 | | 50 | 86 | 315 |
| Control Building | | 5 | | | | | | 2 | 7 |
| Total | 205 | 572 | 24 | 338 | 420 | 52 | 304 | 718 | 2633 |

NOTES

- (1) Based on average Aircraft Industry labor rate of \$10.80/hr., OH rate of 107% used for all prime contractor labor costs.
- (2) Includes catalog/off-the-shelf type items/raw materials -- suppliers OH, G&A, margin burdens included, but not definable.
- (3) Includes travel and living, publications, computer, etc. -- direct cost.
- (4) Based on average Aircraft Industry G&A/Matl. Hdlg. rate of 25% and assumed margin of 10%.

A detailed economic model, shown in Figure 3-3 was used to calculate the energy generation costs for these 2 systems. The following assumptions were made in this model:

- straight line depreciation over the system life (50 years)
- capitalization method - 50 percent bonds, 50 percent equity
- cost of capital - 9 percent interest, 11.5 percent return on equity
- 48 percent tax rate on profits
- use of a sinking fund to repay bondholders at end of 50 years
- additional capital costs for rotating parts and maintenance costs included over the system life

Based on these groundrules the energy generation costs are 4.04 and 1.57 ¢/kWh for the 12 and 18 mph systems, respectively. A breakdown of the energy generation cost is provided in Table 3-2b. As shown in the table maintenance (labor and materials) costs were calculated to be 16 percent of the total energy cost or \$12,400 for the 500 kW/12mph system and \$16,100 for 1500kW/18mph system annually.

TABLE 3-2b. BREAKDOWN OF ENERGY GENERATION COSTS

| System | Start Up Costs | Capital Fund | Return on Equity | Debt Interest | Federal Taxes | Maintenance | Total ¢/kWh |
|---------------------------------------|----------------|--------------|------------------|---------------|---------------|-------------|-------------|
| 500 kW 12 mph Median Wind Site | 0.0921 | 0.1071 | 1.419 | 1.110 | 0.6492 | 0.6626 | 4.04 |
| 1500 kW 18 mph Median Wind Site | 0.0535 | 0.0414 | 0.5498 | 0.4303 | 0.2517 | 0.2432 | 1.57 |

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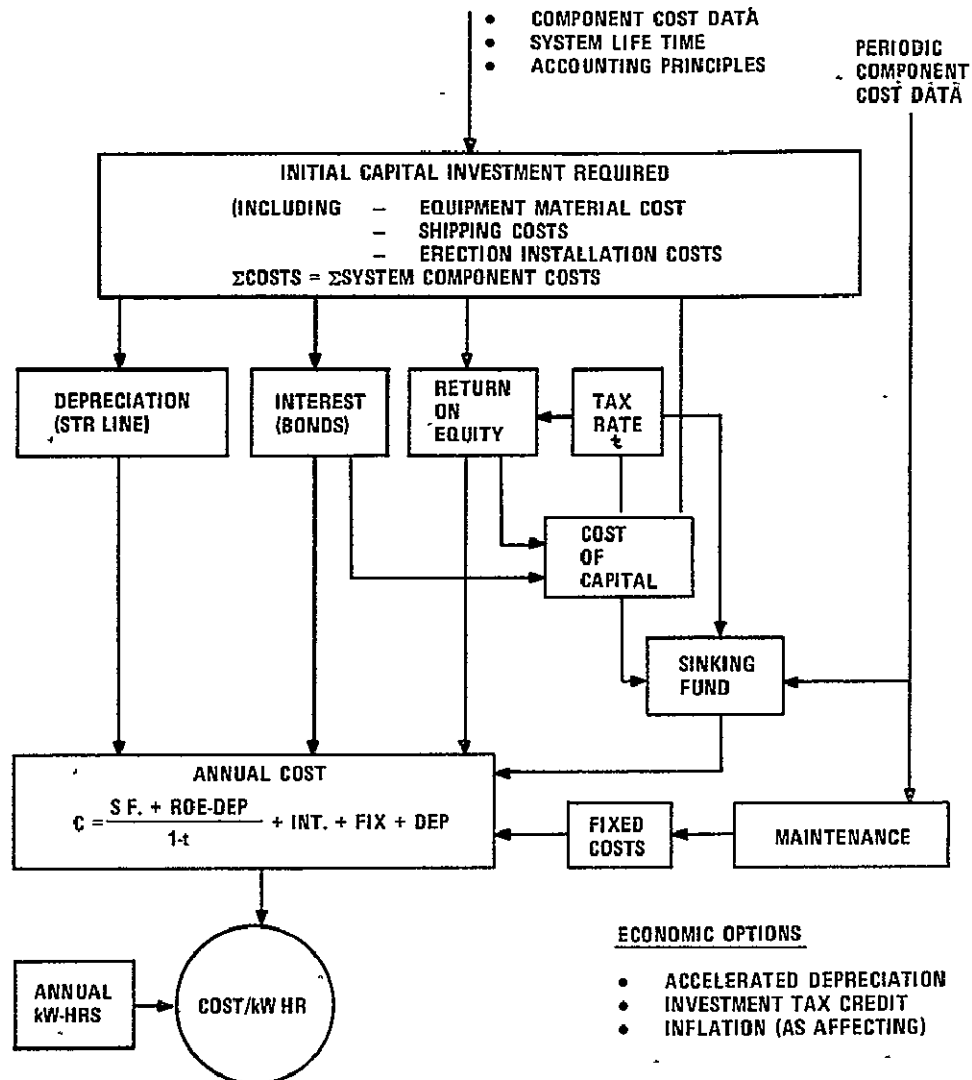


FIGURE 3-3 ECONOMIC ANALYTICAL MODEL

3.1.2.3 SYSTEM WEIGHT SUMMARY

The weight of the system is important since, as for most industrial products, it will relate directly to cost. For a system such as the WTG, the weight of individual subsystems is particularly important since undesirable dynamic interactions (related to weight) can occur between subsystems. Specifically, the rotor/tower dynamic analysis performed showed that it was advantageous to reduce the nacelle weight since higher nacelle weights caused a reduction in the tower natural frequency. Also, higher blade weights result in a necessarily stronger, heavier and more costly mechanical power transmission to accommodate the increased load, as well as decreasing the tower natural frequency.

Table 3-3 provides a weight summary for both the 500 kW and 1500 kW WTG systems. Total weight aloft for the 500 kW and 1500 kW systems is approximately 36,060kg (40 tons) and 58,920kg (65 tons), respectively. The rotor/nacelle configuration was designed such that the static loading provided a zero moment about the azimuth bearing.

The rotor subsystem weights include the hub, blades and pitch change mechanism. The higher weight of the 1500 kW rotor subsystem is directly attributable to the larger loads upon the blades of this unit. Further refinements of the blade design could result in some weight reduction.

Some conservatism may also be present in the weight of the bedplate/pintle sub-assembly, since weights for these structures were calculated on a preliminary basis. During a Final Design effort, a detailed computer analysis might allow some relaxation in the safety factors assumed, which were generally on the order of 1.5.

3.1.3 SYSTEM FABRICATION AND ASSEMBLY

Various approaches were evaluated to determine the minimum cost fabrication and assembly procedure for the WTG. The preferred approach is to maximize the amount of assembly performed at the plant and to minimize the number of site operations.

The pacing items in the WTG fabrication cycle under production conditions are the rotor, transmission and generator. Normal lead times for these subsystems are expected to be 26 to 30 weeks.

The WTG fabrication process can be divided into 5 main areas as follows:

- Assembly of the nacelle at the plant
- Fabrication of the rotor at the plant
- Site preparation and erection of the tower
- Mounting of the nacelle and rotor with the tower
- Completion of system electrical connections and system check-out

Figure 3-4 illustrates the equipment contained within the nacelle. Based upon a preliminary assessment it is estimated that 16 man-weeks would be required to perform the nacelle assembly. Basically, this process would begin with attachment of the pintle and the main shaft subassemblies to the bedplate, attachment of the

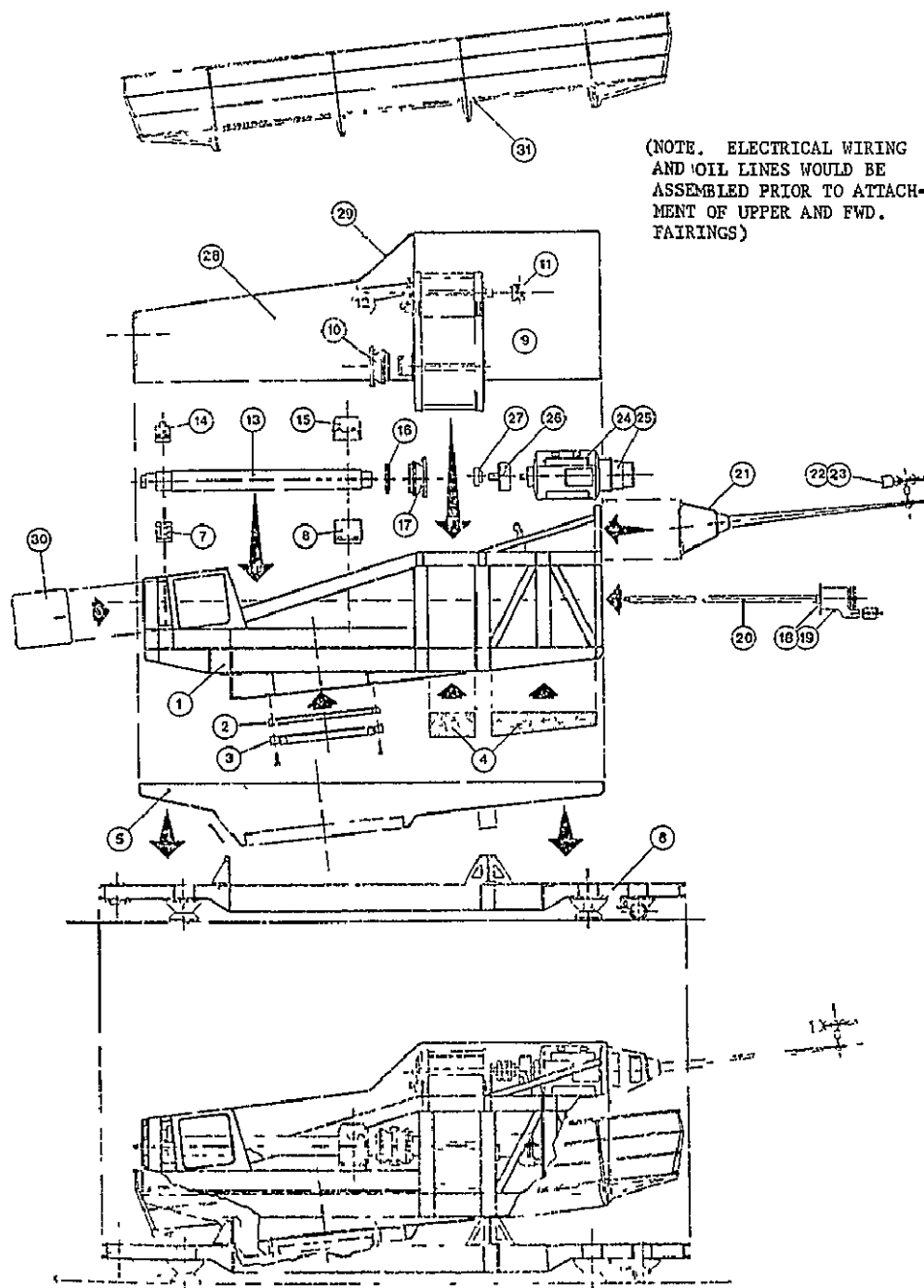
TABLE 3-3. WEIGHT SUMMARY

| Power Level | 500 kW | | 1500 kW | |
|--------------------------|---------|---------|---------|---------|
| | lbs. | kgs. | lbs. | kgs. |
| Rotor | 27,000 | 12,247 | 35,000 | 15,875 |
| Gear Box | 24,000 | 10,886 | 46,000 | 20,875 |
| Generator | 4,500 | 2,041 | 11,200 | 5,080 |
| Main Shaft | 4,000 | 1,814 | 5,000 | 2,268 |
| M.S. Bearings | 2,300 | 1,043 | 3,500 | 1,588 |
| Couplings | 2,700 | 1,225 | 5,200 | 2,359 |
| Bedplate/Pintle | 15,000 | 6,803 | 24,000 | 10,886 |
| Sub-Total | 79,500 | 36,060 | 129,900 | 58,920 |
| Tower | | | | |
| Concrete | 450,000 | 204,000 | 650,000 | 295,000 |
| Steel truss | 86,000 | 39,000 | 118,000 | 53,500 |
| Total | | | | |
| (with concrete tower) | 530,000 | 240,000 | 780,000 | 354,000 |
| (with steel truss tower) | 165,000 | 75,000 | 248,000 | 112,000 |

transmission gearbox, insertion of the variable pitch input actuators, attachment of the generator, installation and connection of instrumentation and electrical leads and attachment of the nacelle housing. The nacelle could be transported to the site by means of a flatbed truck. The rotor would be shipped directly from the factory to the site in a minimum of 3 subassemblies - two blades and the hub. An alternative, which may result in lower transportation as well as tooling costs, is to have a bolted joint in the blades. In either approach, complete assembly of the rotor subsystem would be performed on the ground at the site.

Re: Item description for Fig. 3-4

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1. MAIN STRUCTURAL SUPPORT FRAME
2. MOUNTING PLATE FOR AZIMUTH BEARING
3. AZIMUTH BEARING ASSEMBLY
4. BALLAST BLOCK
5. LOWER HALF FIBERGLASS FAIRING
6. ASSEMBLY AND HANDLING JIG
7. ROTOR HUB BEARING (LOWER ASSEMBLY)
8. MAIN SHAFT THRUST BEARING (LOWER ASSEMBLY)
9. TRANSMISSION ASSEMBLY
10. FLEXIBLE COUPLING (TRANSMISSION SIDE) (LOW SPEED)
11. FLEXIBLE COUPLING (TRANSMISSION SIDE) (HIGH SPEED)
12. BRAKE ASSEMBLY
13. MAIN SHAFT (ROTOR/TRANSMISSION)
14. ROTOR HUB BEARING (UPPER ASSEMBLY)
15. MAIN SHAFT THRUST BEARING (UPPER ASSEMBLY)
16. THRUST COLLAR
17. FLEXIBLE COUPLING (MAIN SHAFT SIDE) (LOW SPEED)
18. PITCH CONTROL MECHANISM
19. DRIVE MOTOR FOR PITCH CONTROL MECHANISM ("0" RPM)
20. PITCH CONTROL DRIVE SHAFT
21. FORWARD FAIRING AND INSTRUMENTATION BOOM
22. WIND DIRECTION INDICATOR
23. WIND SPEED INDICATOR
24. GENERATOR
25. EXCITER
26. TORQUE - RPM SENSING DEVICE
27. FLEXIBLE COUPLING (GENERATOR SIDE) (HIGH SPEED)
28. UPPER FAIRING ASSEMBLY
29. FAIRING ACCESS PANELS
30. MAINTENANCE CREW ACCESS HATCH
31. SERVICING PLATFORM

FIGURE 3-4 ASSEMBLY SEQUENCE AND ITEM DESCRIPTION

Prior to shipment to the site, the entire rotor subsystem would be checked out. However, the extent of the required inspection for a mass production effort has not yet been determined. It is anticipated that blade deflection, hub deflection and variable pitch change functional tests would be made on a sampling basis as a minimum.

Erection times averaging 6 to 8 weeks are reasonable expectations for truss towers. Since the weight of these towers is only about 40 to 60 tons, the foundation requirements are not as extensive as for a concrete tower. In addition, a full cure of 28 days would not be required for the foundation before the steel sections could be erected. The steel beams used in this type of construction can be easily transported by truck.

In constructing a concrete tower, the precast sections can be trucked directly to the site from a central location to the raw materials supplier/tower subcontractor, or, the raw materials can be trucked directly to the site where the precast sections could be made.

The weight of the concrete towers is estimated to be 225 to 325 tons for the 500 kW and 1500 kW systems, respectively. Therefore, larger foundations will be required for these structures. The heavier weight of the concrete tower may also require that a full cure period of 28 days be observed for the foundation before the tower is erected. Consequently, total erection time for the concrete tower is expected to be 8 to 12 weeks.

The equipment can be hoisted atop the tower in 1 or 2 steps. Preferably, the rotor subsystem will be attached to the nacelle on the ground and the entire unit hoisted atop the tower. Alternatively, the nacelle would be put in place first and the rotor hoisted to be mated with the nacelle. The deciding factor as to which approach is used will be the weight of the nacelle and rotor as well as the available crane weight and height capacity.

Following installation of the WTG major subsystems, final electrical connections will be made within the nacelle. In addition, a control building will be erected at the tower base which will house the microcomputer, various electrical equipment and electrical connections to the utility.

The final step in the assembly process will be to check out the system. This procedure will consist of establishing the continuity of all control and electrical circuitry, allowing the system to break away under low wind/no load conditions and then operation under load. The time required for the check out of production units will be dependent upon the experience gained at the time.

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3.2 SYSTEM OPERATION

The WTG must be designed to be controlled in a predictable manner under various conditions ranging from start-up to emergency shutdown situations. Operation of the system can best be explained from the power ratio versus velocity ratio curve shown in Figure 3-5 for the 230XX airfoil series. Power ratio is defined as the power derived from the wind to that which is available (0.593 is theoretical maximum for horizontal axis machine), and velocity ratio (λ) is the blade tip speed divided by wind speed.

Also shown in Figure 3-5 are lines of constant pitch angle; (B); as shown, the optimum performance is achieved at a λ of 10 and a pitch angle of -0.5° . At rated wind conditions the 500 kW and 1500 kW designs operate at λ 's of 9.0 and 9.5, respectively. Lower wind speed conditions result in a higher λ condition; therefore, the tendency is to move along the crown of the $B = -0.5^\circ$ curve for most of the operating time. At wind conditions greater than rated, power regulation is achieved by pitching to higher blade angles until cut-out wind velocities are achieved.

3.2.1 SYSTEM START-UP

Start-up can occur from low, intermediate or high wind conditions; it is expected that start-up from low wind conditions which is discussed here, will be the most common start-up occurrence. When the wind sensor indicates that the wind speed is equal to or greater than the cut-in velocity (V_{CI}) for approximately 5 minutes the control system will sense, via the azimuth position indicator, any misalignment between the rotor axis and the prevailing wind direction and command the azimuth drive motor to align the rotor axis with the wind. Simultaneously, the Bendix type pitch change drive motor will be engaged to cause a change in the blade pitch from $B \ 3/4R = 90^\circ$ to the maximum rotor breakaway torque position of $B \ 3/4R = 72^\circ$. The blade pitch angle is determined from the output of a linear voltage differential transformer (LVDT) attached to the pitch change actuation shaft located in the pitch change power supply. Having the proper blade pitch and cut-in velocity, the rotor will breakaway autonomously as the rotor axis is aligned with the wind. When the shaft speed sensor indicates a main rotor shaft speed of 0.5 rpm, the control system will command the pitch change mechanism to change $B \ 3/4R$ from 72° to 2° and the rotor will then accelerate to near synchronous rpm in approximately 7 minutes provided the wind is maintained. At 10% under synchronous speed the control system will take over speed regulation and by modulating the blade pitch and monitoring the utility voltage, phase, and frequency, utilizing the potential transformers, synchronize the generator to the utility network. Power in the rotor at this time will be sufficient to provide for generator friction and windage core losses, and power train running torque.

3.2.2 SYSTEM CUT-IN

When the WTG approaches synchronous speed conditions the system will be brought to synchronous speed by changing the blade pitch angle. Figure 3-6 illustrates the blade pitch angle movement required and associated speed error as a function of time, before mechanical stability is achieved under steady state wind conditions. Synchronization requirements include: matching phase (rotation and polarity), voltage amplitude and achieving constant rpm at 1800 (frequency of 60 Hz).

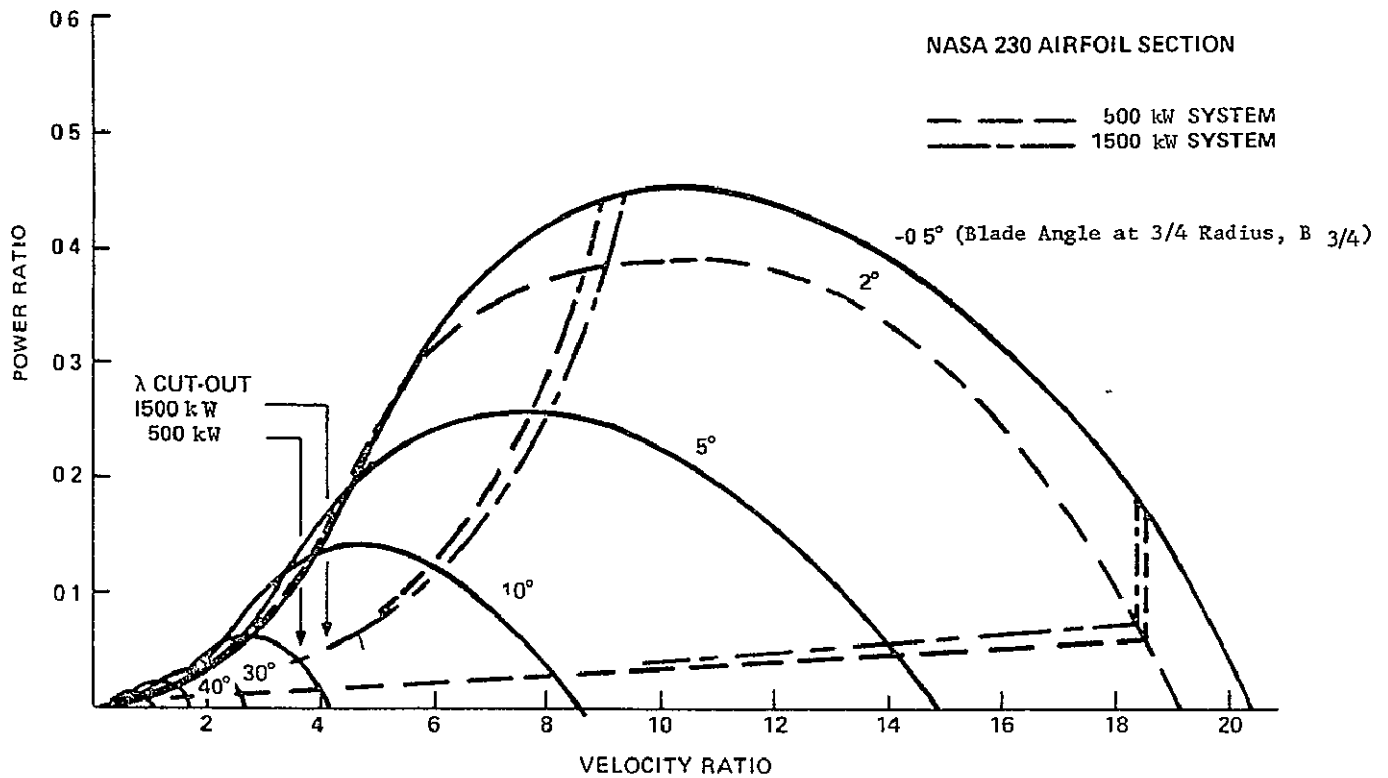


FIGURE 3-5 SYSTEM OPERATION

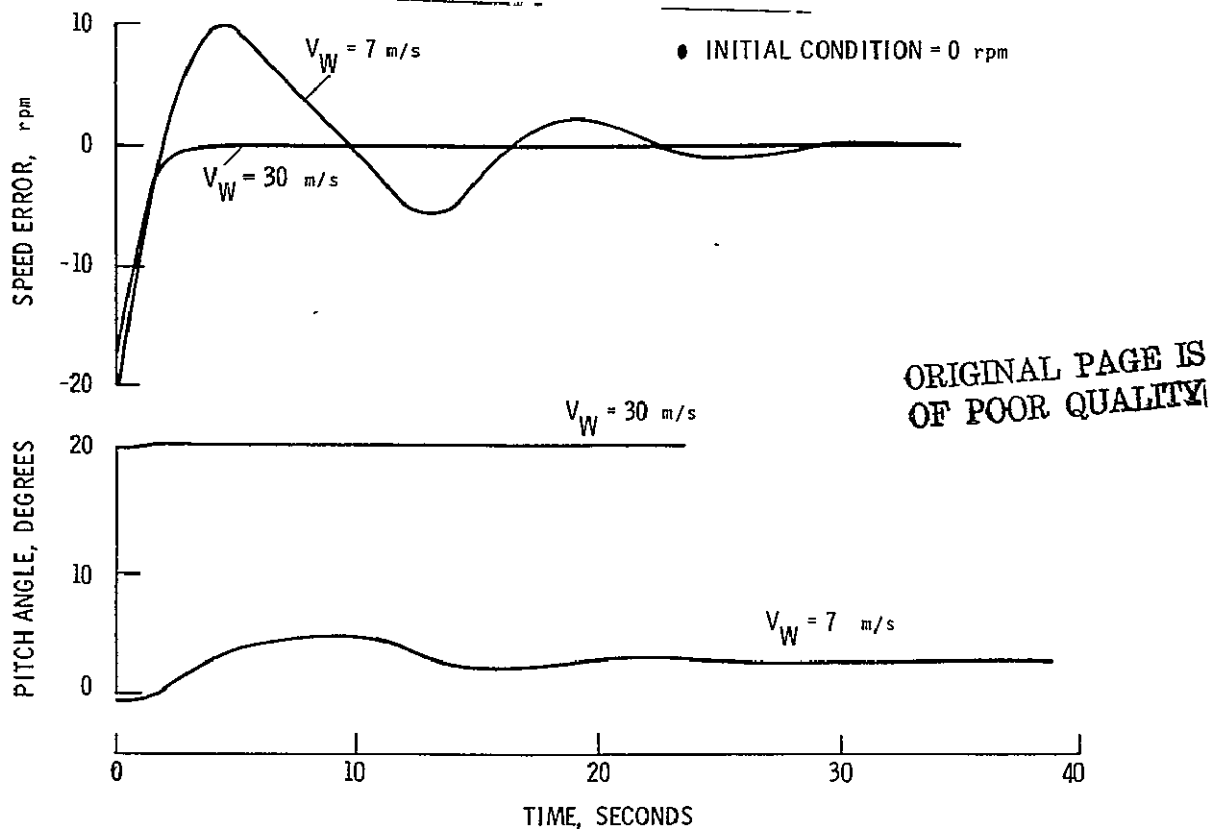


FIGURE 3-6 GENERATOR SPEED RESPONSE UNDER CONSTANT WIND CONDITIONS

Having satisfied the utility requirements for synchronization, the control system will simultaneously command the main circuit breaker to close, thus connecting the WTG to the network. Next, the blade pitch will be changed from $B \frac{3}{4}R = 2^\circ$ to $B \frac{3}{4}R = -.50^\circ$ at which time the electrical power output will be approximately 5kW as determined by the current transformer and potential transformer data.

The control of torque transients due to wind gusts subsequent to cut-in will be controlled by increases in the generator field strength in response to increases in torque as indicated by the torque sensor on the generator input shaft. The control system will house this field-torque feedback loop to maintain on-line stability.

3.2.3 CUT-IN TO RATED POWER

Under these wind conditions the system will operate along the $B = -0.5^\circ$ line. For wind velocities greater than cut-in and less than or equal to rated velocity, the regulation of power is controlled solely by changes in generator field strength in response to changes in the torque sensed by the generator shaft torque sensor. The control system will therefore issue no blade pitch change commands for wind speed less than rated for the purpose of maintaining power. Primary power control is based on torque instead of wind speed.

For wind direction changes $\leq 15^\circ$ for wind velocities less than rated there will be no change in rotor axis azimuth unless this azimuth variation is sensed for a period greater than 6 minutes. If a wind direction change occurs greater than $\pm 15^\circ$ a slip clutch on the azimuth drive will allow the rotor axis to slip in the direction of the rapid change. The slip clutch is located on the output shaft of the azimuth drive speed reducer. The value of the slip torque would be preset and controlled during slip.

To control gusts, blade pitch change and field modulation will be used in response to the torque sensed on the generator input shaft. The control system will initiate command signals to either or both pitch change and field strength depending upon the magnitude and response rate of the gust.

3.2.4 RATED TO CUT-OUT CONDITIONS

For wind velocities above rated velocity, the control system will maintain constant rated power output based on data from the current and potential transformers located on the output of the synchronous generator. As power increases above rated, the control system will sense the current increase and increase pitch to maintain rated conditions. Should the power decrease, the control system will automatically try to reset blade pitch to 0.5° , thereby increasing the power output. The equilibrium blade pitch angle will always be that angle which results in rated power output for wind speed between rated and cut-out.

Gust control will be effected by proper application of either generator field modulation or blade pitch change in response to variations in sensed torque.

3.2.5 HIGH WIND CUT-OUT

Wind speed cut-out velocities of 40 and 50 mph were selected for the 500 and 1500 kW systems, respectively. Above these wind velocities, only a small fraction of the site annual wind energy exists.

When measured wind velocities are greater than cut-out speed for periods greater than 6 minutes the control system will increase blade pitch to bring the generator output current to 25% of the rated value in approximately 10 seconds. When this value is achieved the tie-in circuit breaker will be opened and blade pitch increased to prevent excessive overspeed and maintain turbine rpm to some value below synchronous value as long as the wind velocity is greater than cut-out.

3.2.6 LOW WIND CUT-OUT

When the measured wind velocity falls below cut-in the generator will motor since the wind turbine will not have sufficient power output to supply the parasitic electrical and mechanical losses. This motoring mode will be sensed by the current and potential transformers and after a period of 6 minutes of monitoring, the control system will command the circuit breaker to open and thereby disconnect the Wind Turbine Generator from the network. The control system will set the blade pitch angle to 2° to start the resynchronizing process. If, however, the wind does not return to cut-in speed after 6 minutes the blade pitch will be set to 90° or full feather, minimum drag configuration. The wind turbine will lose rpm slowly and the primary brake (located to the high speed through shaft on the speed increaser) will be proportionally applied to stop the turbine blades in the horizontal position.

3.2.7 EMERGENCY SHUTDOWN

Emergency shutdown may be required in various circumstances; therefore, the WTG has been designed to achieve shutdown as expeditiously as possible. In general, when a condition requiring shutdown is recognized the primary brake will be applied, the blade pitched to full feather and the circuit breaker opened.

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3.3 SUBSYSTEM DESIGN

The major WTG subsystems are the rotor, tower, transmission, generator and controls. Each of these is discussed briefly to illustrate the level of technology identified in this study for cost effective WTG's.

The transmission and generator are essentially commercially available items. Therefore, neither technology or fabrication development is involved with these subsystems.

Concrete or steel truss type towers on the order of 150 feet high are also state-of-the art. The unique design aspect for this application is the ability to define the structural requirements resulting from the dynamic and static loads on a minimal cost basis.

The use of a microcomputer in the control system represents a technology which is not being-used in many commercial applications. The use of a microcomputer will not require any technology development and represents an important asset to the widespread use of WTG's.

The rotor design is based upon state-of-the art propeller technology. Consequently, the tools to analyze the rotor subsystem from a structural and aerodynamic standpoint are sophisticated and their accuracy has been verified from the large hardware data base available. Filament winding fabrication is also well developed. Therefore, the development aspect of the rotor subsystem is in scaling previously developed units to the diameters required for economical WTG's.

While the challenges should not be minimized, only a modest development risk appears to be present due to the well developed supporting technologies involved in the design.

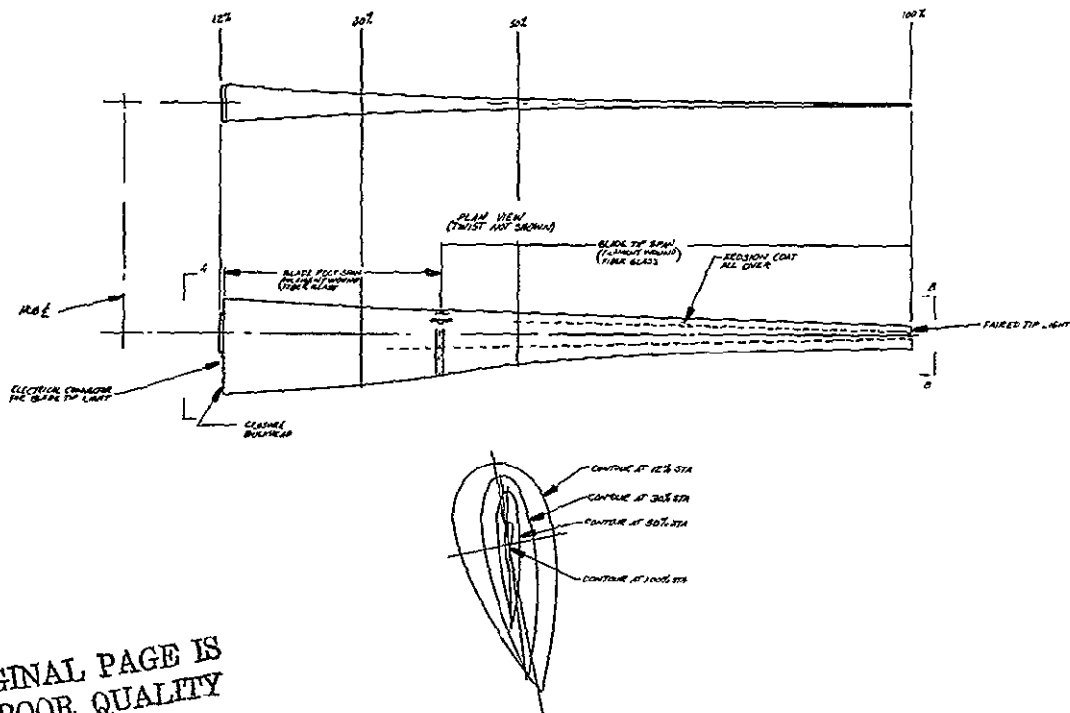
3.3.1 ROTOR

An overall view of the rotor blade design is shown in Figure 3-7. The effective aerodynamic blade diameter is 55.8m (183 feet) and 57.9 (190 feet) for the 500 kW and 1500 kW units, respectively. In order to compensate for blade deflection the mechanical lengths are 56.4m (185 feet) and 58.7m (192.5 feet). Also shown in the figure is an end view of the blade which illustrates the amount of twist in the design. The aspect ratio (blade length/average chord width) is identical for both blade sets.

The rotor blades are made of a filament wound material having a spar/shell construction. This approach was found to provide the necessary stiffness for the least cost.

The blade design presented has a bolted section at the blade midplane region. Use of a bolted section is believed to offer low transportation and tooling costs for the same reliability. This approach may be more thoroughly investigated during the Final Design portion of the program.

A critical feature of the rotor subsystem design is the hub/blade attachment. Obviously a rigid and reliable hub design is needed to achieve the predicted aerodynamic performance. Figure 3-8 illustrates hub assembly selected during the preliminary design which consists of 2 in-plane supports and 1 out-of-plane support per blade.



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FIGURE 3-7 ROTOR BLADE DESIGN

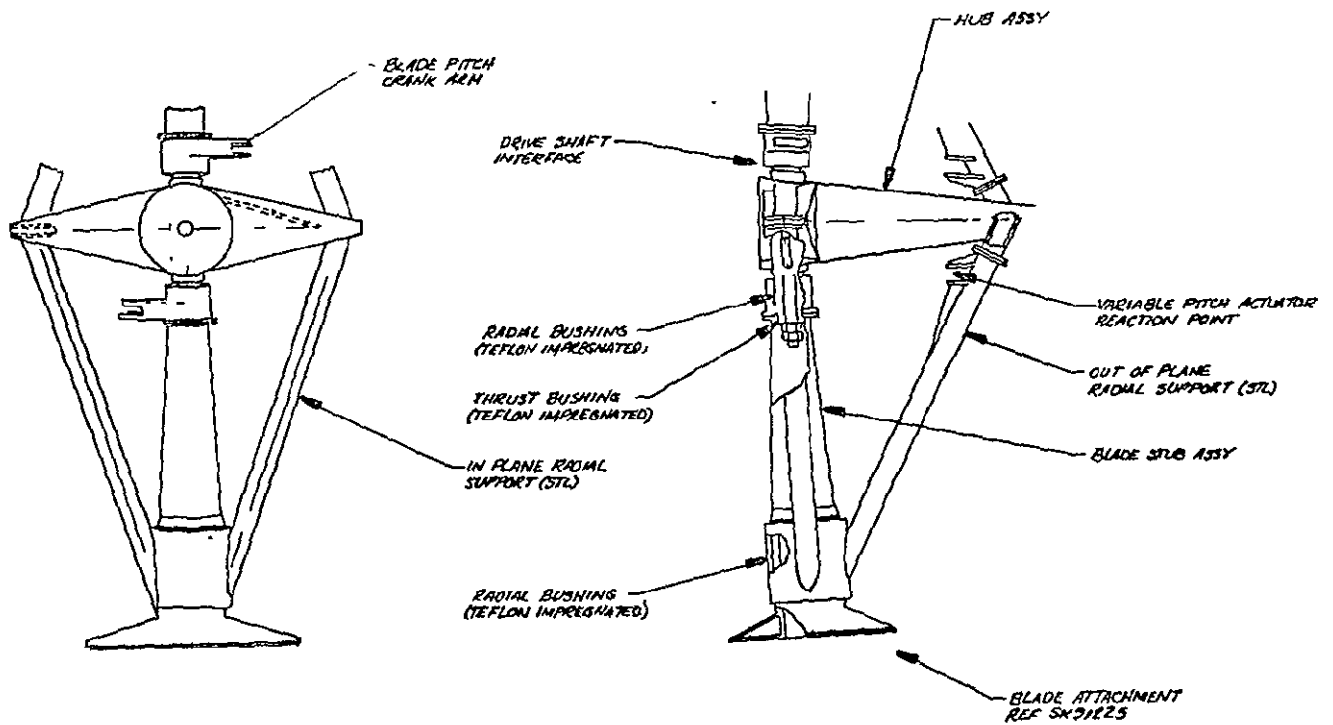


FIGURE 3-8 HUB ASSEMBLY

The third major component of the rotor subsystem is the variable pitch change mechanism which is critical to the overall operation and reliability of the WTG. Under normal operation conditions pitch change capability is required for start-up, synchronization and cut-out situations. Failure to change pitch under operation conditions above rated wind speed could result in blade overload and/or overspeed conditions.

The pitch change mechanism shown in Figure 3-9 was designed to provide high system reliability, minimal or no power requirements and lost cost. The principal features of the pitch change mechanism are listed below:

- No power is required to maintain a fixed blade angle
- Excess load capability is available to clear jams such as icing in the blade bearing areas
- A spring loaded brake to increase blade pitch will automatically feather the blades in the event of loss of the control system input signal.
- A feedback signal to identify blade angle position is incorporated.
- The actuators located at the hub assembly end of the pitch change are industrial catalog items. The power train which runs through the main shaft also uses industrial components and an automotive type disc brake. Therefore, the unit cost and availability are consistent with the overall system objectives.

3.3.2 TOWER

Both truss and concrete tower designs were generated for the Preliminary Design WTG Systems. While the concrete design offers lower cost and aesthetic appeal, the truss tower approach has the advantages of being adaptable, at reasonable cost, to sites having poor soil conditions and presents less of a tower shadow to the rotor.

The load criteria used for the towers assumes:

- continuous cyclic loading at rated wind conditions
- intermittent loads due to an instantaneous doubling of the rated wind velocity
- a 120 mph storm condition

One aspect of the tower design which was investigated in considerable detail was the effect of dynamic interactions occurring between the rotor and tower upon the tower design. The analytical investigations pursued in this regard showed that definite economic advantages could be realized by "tuning" the rotor/tower subsystems so as to minimize rotor/tower dynamic load factors. The effect of tower shadowing was also included in dynamic interactions investigations. In general, tower shadowing exerts an appreciable impact on tower designs, especially from a dynamic viewpoint, because it is the shape of the towers which determine the nature of the forcing functions.

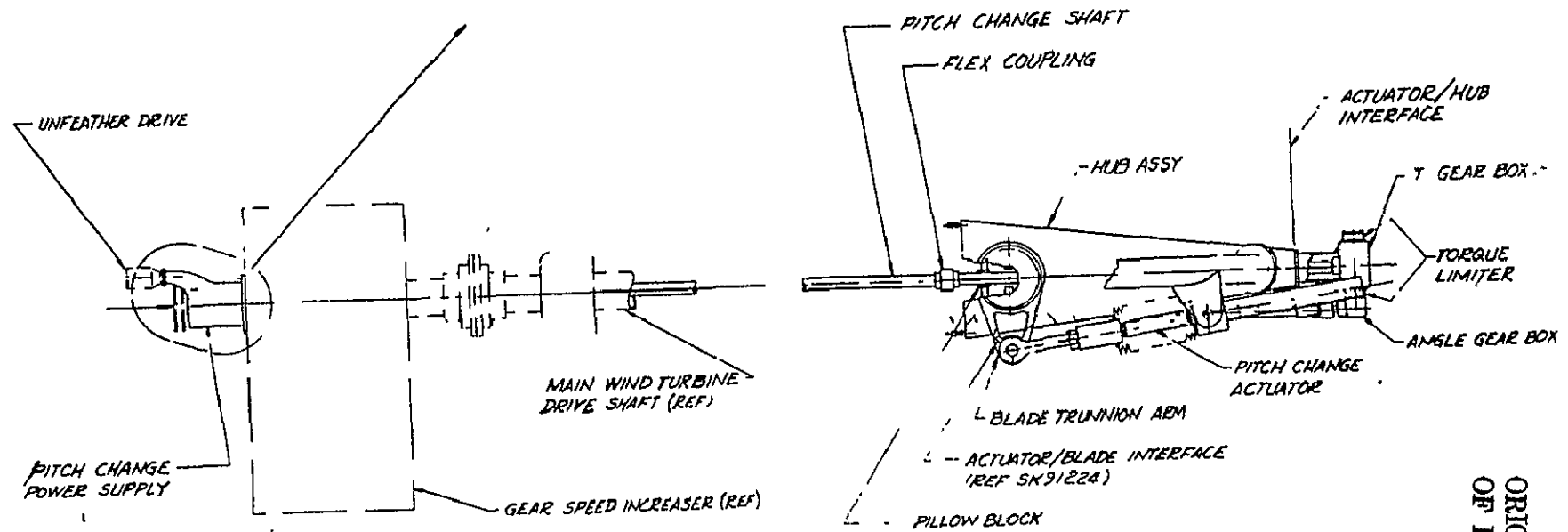
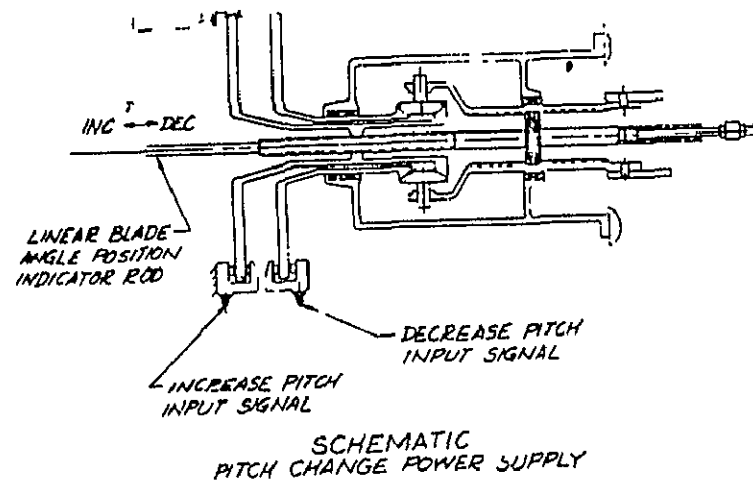


FIGURE 3-9 PITCH CHANGE MECHANISM

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The concrete towers presented in the Preliminary Design were based upon a reinforced concrete, annulus geometry approach which offers a low cost design.

Schematic diagrams of the concrete tower designs are shown in Figure 3-10; due to the small difference in blade diameters, both towers were assumed to be 42.7m (140 feet) in height. The thin wall design approach used results in an economic use of material and good dimensional control during the fabrication process.

The concrete towers were designed in ten 4.27m (14 feet) sections in order to remain within the limits of conventional truck transportation capability. A precasting fabrication technique was selected over a slip forming approach on the basis of preliminary cost estimates. Fabrication of the sections could be done at the factory, at the site or some intermediate location depending on the site location, accessibility, materials availability and local labor rates.

Also shown in Figure 3-10 is a schematic of the truss tower designs.

All members specified for the 500 kW and 1500 kW truss towers are commercially available structural sections. Main supports and lower bays are comprised primarily of higher strength steels while the upper bays and most cross members are lower strength steels. In utilizing bolted construction and minimizing welds the intent has been to duplicate electric transmission line tower technology which is in a mature state of development. Since WTG towers experience greater loadings, however, it has not always been possible to choose convenient member shapes; I-beams were required for their load capability for some of the members. Since those type sections and a symmetrical tower are not convenient for easily bolted joints, some welding will be required.

It should also be noted that galvanized steel is proposed for the towers, with a three to five thousand dollar repaint being required every seven to ten years.

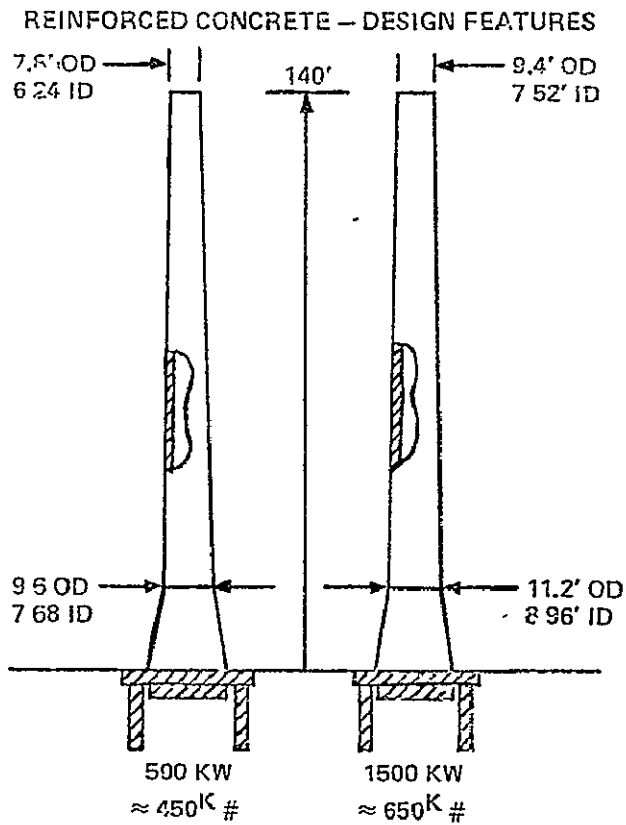
As in transmission line tower technology, the most efficient construction approach appears to be to prepare the members at a central location, transport, and then erect bays at ground level and hoist the bays aloft with a crane. The advantage, as with pre-cast concrete, is to minimize aloft construction. Secondary design refinements could also perturb the 6.10m (20 ft.) bay height presently defined. The truss towers both have the same envelope sizes, a distinct feature that should be maintained. The idea is to maintain as much commonality as possible with the advantage being that for a large number of towers, the same point on a learning curve can be achieved more quickly. As in power towers, deep rooted foundations will be utilized.

3.3.3 MECHANICAL POWER TRANSMISSION

A schematic diagram of the mechanical power transmission is shown in Figure 3-11.

The principal features of the transmission design are:

- all of the components are commercially available
- a shock factor of 1.4 has been incorporated in all of the transmission components



TRUSS – DESIGN FEATURES

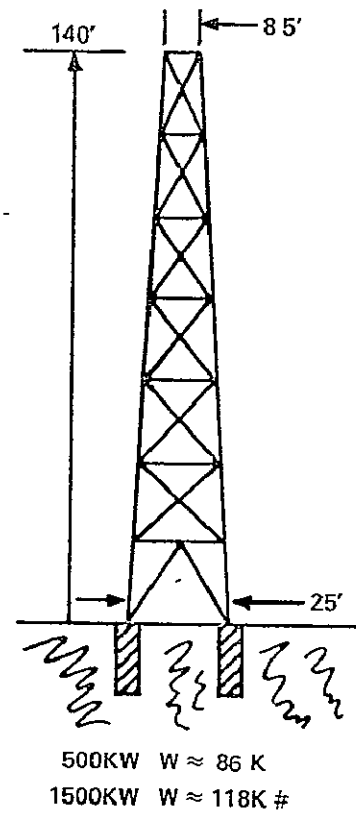


FIGURE 3-10 TOWER DESIGN DEFINITION

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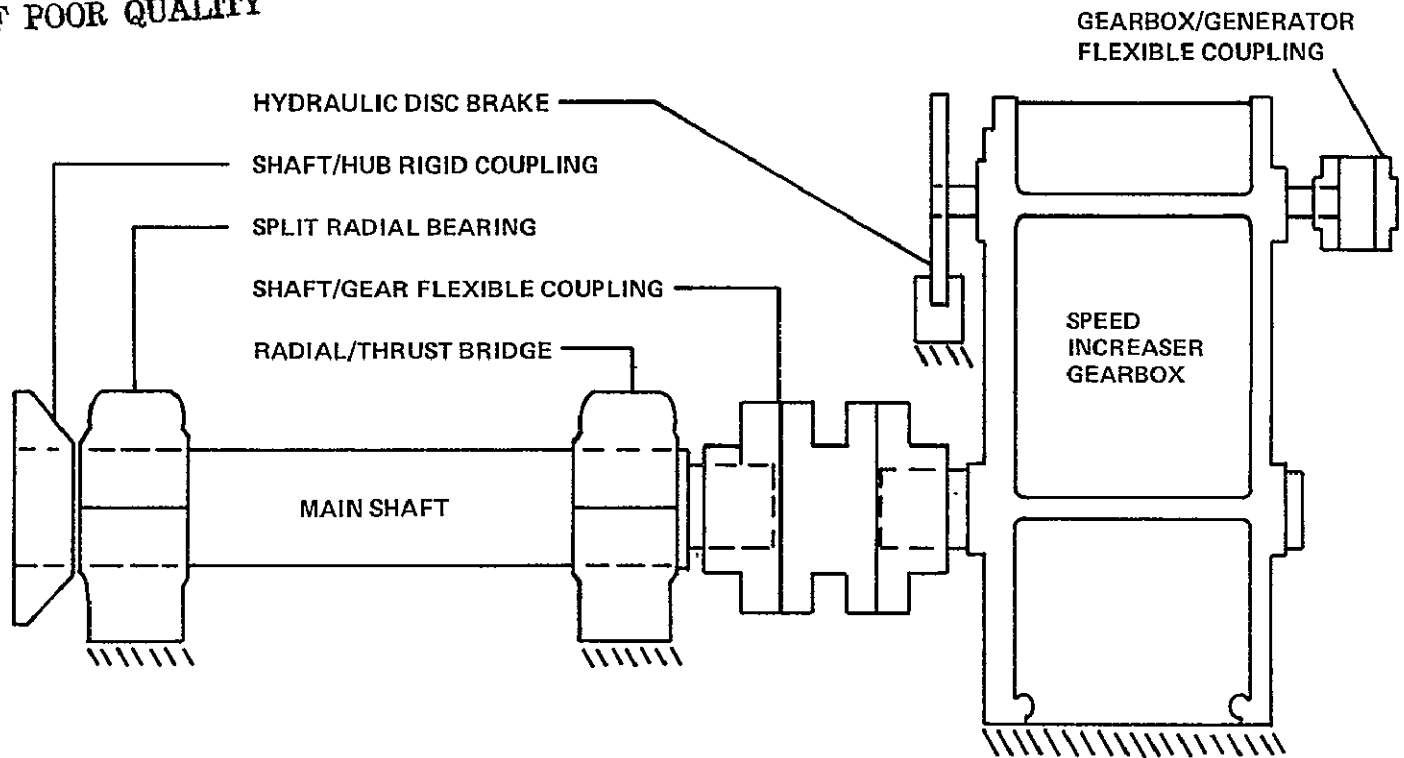


FIGURE 3-11 MECHANICAL POWER TRANSMISSION SUBSYSTEM

- ease of maintenance
- allows for small shaft misalignments
- incorporates system braking capacity

As shown in the Figure the torque is transmitted from the hub to the gearbox by means of the main shaft. The 1500 kW system main shaft has an ID of 22.9cm (9") and an OD of 38.1cm (15") and is made of 4340 steel. Respective dimensions for the 500 kW system are 20.3cm (8") and 34.3cm (13.5").

The main shaft is supported by a radial bearing at the rotor end and a radial/thrust bearing at the transmission end of the system. A flexible coupling connects the main shaft to the low speed transmission shaft. This arrangement, plus the fact that the rotor can be alternately supported by the bedplate, allows for complete teardown and maintenance of the shaft, bearings and coupling if necessary, without disturbing the rotor assembly or other subsystems.

The gearbox is segmented in 3 sections and is oriented with the high speed pinion at the top. Since this is the area in which the most severe wear will occur, it has been made most accessible. The high speed shaft is connected to the generator shaft by means of another flexible coupling in order to compensate for potential misalignments.

A hydraulic brake, located on the rotor side of the high speed shaft provides emergency stopping capability in the event of a network outage or pitch change subsystem failure.

3.3.4 ELECTRICAL EQUIPMENT

The Electrical Subsystem consists of the electrical generating equipment and the equipment necessary to control and protect the generator. For the WTG this includes: auxiliary power (drawn from the utility network) to supply the controls with electricity when the WTG is not producing power, and emergency power for the controls when all connection to the utility network has been interrupted for any reason. In addition, the electrical subsystem includes equipment necessary to control the temperature of components in the nacelle and equipment necessary to maintain the control building in a benign environment. The control building protects the control equipment from severe weather conditions and other natural environments which are likely to be encountered. All electric subsystems equipment except the generator, exciter, and lightning protection units are housed in the control building at the base of the WTG tower. All electrical equipment which is aloft (including drive motors for blade pitch change, azimuth gears and hydraulics) are enclosed in contiguous metal such that lightning striking any part of the WTG aloft will be directed to ground through the tower.

The major elements of the electrical subsystem are: the generator, main circuit breaker, an engine - alternator emergency power source, an automatic transfer switch, a pair of control power transformers (auxiliary and emergency power), a grounding resistor, heating and ventilating air-conditioning equipment, lightning protection equipment, voltage and current instrument transformers, an assortment of small contactors and relays, and cabling for the power and control signals.

The approach is to provide electrical power for pitch and azimuth control and protective functions even when the wind is insufficient for generating purposes or too strong for stable power generation. In the event that electrical power for control is interrupted, the emergency alternator-generator source is automatically

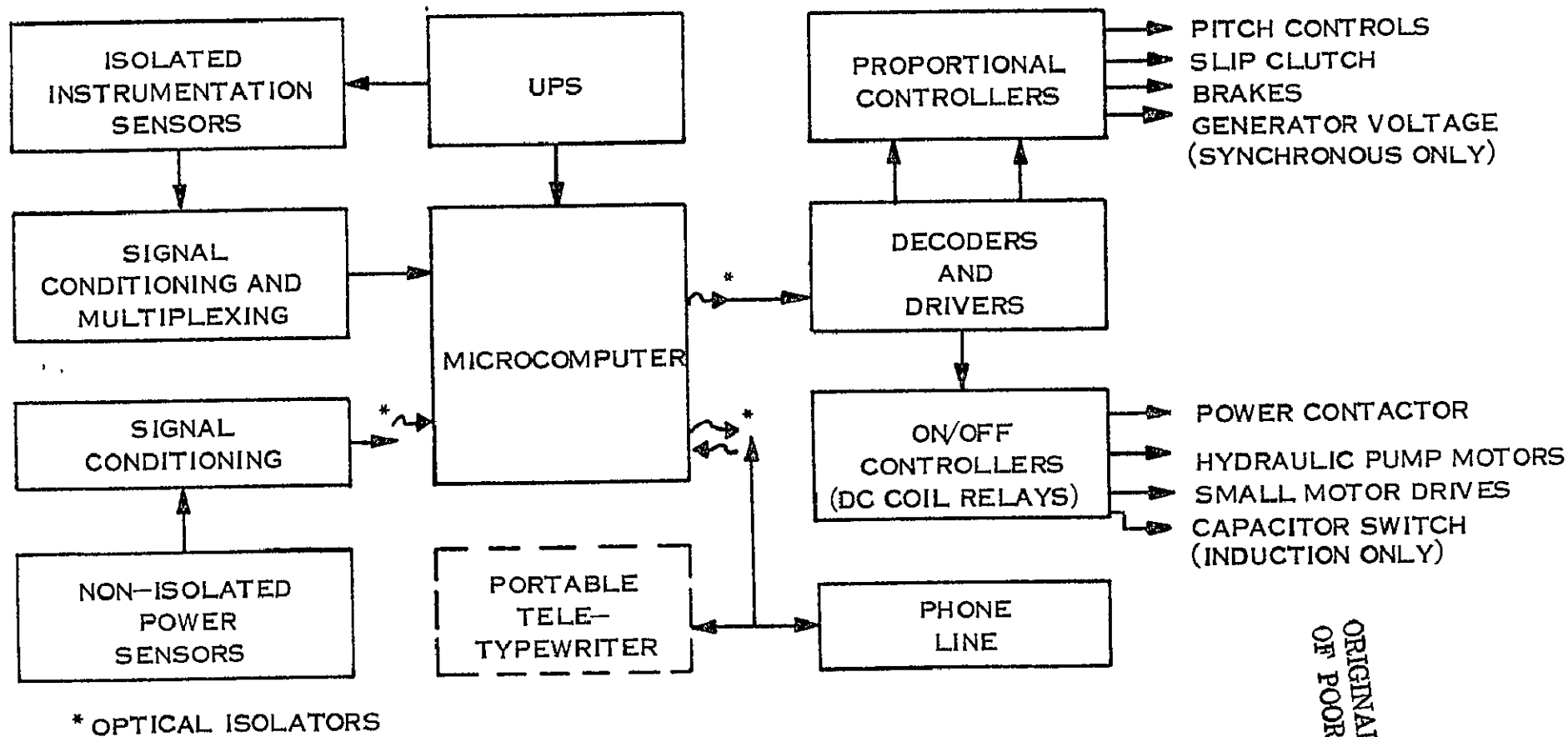


Figure 3-12 Control Subsystem Block Diagram

started and the control power lead is transferred to the emergency set. As long as control power is available the system operation for all modes is autonomous, for abnormal condition the system will protect itself. Should service be required, the WTG will automatically alert a remote location and respond to queries of its condition. The master logic for this scheme is contained in a microcomputer. The data acquisition and data transmission scheme associated with this microcomputer are described in the section on the control subsystem. An uninterrupted power supply (UPS) is provided to insure that the logic process is possible when control power has been lost. A separate battery has been provided for starting the emergency set without control power.

All major electrical loads of the WTG are protected by circuit breakers and all circuit breakers have an operating time which is inverse to the overcurrent condition. The characteristics of the breakers are selected such that the circuit breakers closest to the load operate first under overload condition. A neutral grounding resistor is provided so that generator fault conditions will not be propagated beyond the WTG main contactor and the outage will be confined to the WTG.

For small generators (between 0.5 and 1.0 MW) the standard protective devices are not cost effective. Usually overcurrent, anti-motoring, thermal overload, and loss of potential transformer protection is provided. By utilizing the microcomputer and instrumentation transformer, it is possible to develop algorithms to perform these functions without adding protective relaying. In addition, synchronizing, ground sensing, and phase imbalance/rotor heating can also be provided with little increase in the instrumentation required for the WTG.

A single circuit breaker capable of interrupting 350 MVA is utilized to connect the WTG to the utility network. Control power is obtained for the auxiliary transformer from this circuit breaker by tapping in to the utility before the out-break contactor. This auxiliary transformer is fused for 350 MVA interruption of a nominal 10 kVA load. When the auxiliary transformer is not supplying the control power, only the magnetizing current of the auxiliary transformer is being supplied by the utility network.

3.3.5 CONTROL SUBSYSTEM

The control subsystem (see Figure 3-12) consists of the equipment necessary to control the pitch of the blade, the azimuth of the wind-rotor axis, and the generator operation. It also consists of the instrumentation necessary to measure wind, torque, temperature, pressure, electrical power and other parameters which are significant to the successful operation of the WTG and to record the transmitted information of significance to locations remote from the WTG. The control subsystem also consists of the equipment necessary for operation of the WTG in the maintenance mode.

The control subsystem includes all the components necessary to the above functions except for those components which are included as an integral part of major WTG elements. For example: the pitch control mechanism is a part of the wind rotor; the azimuth drive motor is a part of the pintle section of the tower; and the wind rotor brake and transmission oil heater are part of the transmission gear box.

All instrumentation and electronics that are not required to be aloft are protected in a control house at the base of the WTG tower. The master control for the logic of operation is provided by a microcomputer in conjunction with data acquisition electronics. For on-off control functions, output signals from the microcomputer

are buffered and amplified to drive relays and contactors which apply power to drive at full power as long as the signal is present. For proportional control codes, outputs are decoded to time function for time-ratio-control of silicon-controlled-rectifier circuitry that meter the AC power for the proportional control drives.

The computed data and status data output from the microcomputer is suitable for transmission over a leased phone line. The computer also constructs a coded signal as an input to a telephone call unit which will automatically dial a predetermined telephone number when conditions warrant outside attention to the WTG. Conversely, data can be obtained from the WTG by dialing the modem at the WTG site and upon achieving proper contact can acoustically couple his phone set to a teletypewriter. Once the hook-up is completed the agent may, from his remote headquarters site, command and interrogate the WTG to determine the status of the WTG and the nature of maintenance, if any, required. A maintenance crew arriving at the WTG site may acoustically couple a portable teletypewriter to the microcomputer and in this manner exercise the WTG and determine additional information on the condition of the WTG.

The various inputs and outputs of the microcomputer are isolated by optical coupling, high impedances and other techniques common to data acquisition technology so as to protect the electronics from damage which might otherwise be caused by large-power switching transients and lightning. In addition, a measure of redundancy is provided by using two microcomputers, either of which is programmed to control the critical functions of the WTG. Non-critical functions are divided between the microcomputers. In the unlikely event that one microcomputer fails to function properly only half of the non-critical functions will be temporarily lost.

An uninterrupted power supply insures that power sufficient to supply the data acquisition electronics and microcomputer is available even when the auxiliary power from the utility network is temporarily interrupted. In this circumstance, the microcomputer logic will initiate the operation of a standby engine generator set as a temporary measure, so that WTG control is maintained and the condition can be transmitted to the remote headquarters.

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