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CONCEPTUAL DESIGN OF THE 7 MEGAWATT MOD-5B WIND TURBINE GENERATOR

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ABSTRACT

Similar to MOD-2, the MOD-5B wind turbine generator system is designed for the sole purpose of providing electrical power for distribution by a major utility network. The objectives of the MOD-2 and MOD-5B programs are essentially identical with one important exception; the cost-of-electricity (COE) target is reduced from 4¢/Kwhr on MOD-2 to 3¢/Kwhr on MOD-5B, based on mid 1977 dollars and large quantity production.

The MOD-5B concept studies and eventual concept selection confirmed that the program COE targets could not only be achieved but substantially bettered. Starting from the established MOD-2 technology as a base, this achievement resulted from a combination of concept changes, size changes, and design refinements. The result of this effort is a wind turbine system that can compete with conventional power generation over significant geographical areas, increasing commercial market potential by an order of magnitude.

INTRODUCTION

MOD-5B is under the overall management of the U. S. Department of Energy, with direct management assigned to NASA-Lewis Research Center. Like MOD-2, it is being developed for the sole purpose of generating electricity that can be economically fed into a utility grid. While it is generally considered a third generation large horizontal axis wind turbine, it is more realistically a second generation (to MOD-2) machine with respect to turbines that have been optimized for commercial power production.

A little over two years ago a similar paper [1] was presented by the author at the April 24-26, 1979, workshop in Cleveland describing status of the MOD-2 wind turbine system development. At that time, the major message was that MOD-2 incorporated most of the concepts that showed promise for major reduction in the cost-of-electricity (COE) but that significant gains in the future were still achievable by additional concept changes coupled with component-by-component improvement, using experience from MOD-2 fabrication, test, and operation. Nothing that has occurred since that time has changed this premise. We have been very pleased with the concepts selected for MOD-2. Even so, MOD-5B does show a substantial gain in operating economics with respect to MOD-2. It is the intent of this paper to explain how and where these gains occurred. Frequent comparisons will be made to MOD-2, which represents the technical base from which MOD-5B evolved.

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PRIMARY SPECIFICATIONS AND REQUIREMENTS

The major MOD-5 requirements imposed on the contractors are as follows:

- Shall be designed for electrical utility use.
- Shall generate no less than 1 megawatt of three phase, 60Hz, power into the grid.
- Shall achieve a COE of 3¢/Kwhr or less in mid 1977 dollars. (This compares to a 4¢/Kwhr requirement on MOD-2.)
- Shall attain a 30 year life.
- Shall operate at unattended remote sites.
- Shall be a horizontal axis propellor type configuration.
- Shall be designed for 6.3 m/s (14 mph) yearly mean wind speed and a maximum wind velocity of 53.6 m/s (120 mph), both at 10 m (30') above grade.

Numerous other requirements were imposed with respect to safety, network protection, gusts, lightning strike, seismic disturbance, availability, controllability, instrumentation, analytical methods, environmental conditions, etc. For the complete requirements and specifications, refer to the MOD-5B Statement of Work [2].

CONCEPTUAL DESIGN DEVELOPMENT

The MOD-5B concept development effort was conducted over an approximate seven month period. During this phase, twenty two major trade studies (see Table I) were conducted and reported on in significant detail. In the interest of brevity, only those studies that most impacted the selected configuration or went beyond the scope of the MOD-2 studies will be reported in detail.

Rotor

One concept that has always appeared attractive is the fixed pitch rotor system. Though seemingly simple, in large machine sizes it is a more technically challenging and risky concept than the apparently more complex variable pitch systems. This results from the need to safely stop the machine in an emergency and the necessity of developing a rotor that is efficient, stalls gently, is economical to build, and limits both dynamic and static loads. The loads problem is, in the final analysis, the decisive factor. Figure 1 illustrates that the peak power of the fixed pitch rotor system is over 50% greater than that of the variable pitch system, resulting in comparable rotor and drive train load increases. These loads are further amplified by the inability to attenuate dynamic torque overshoots to the degree possible with a variable pitch system. The result is a very substantial increase in rotor, drive train, and generator weights and costs, offset by an increase of 5% in annual energy produced as illustrated in Figure 2. During the concept studies a competitive fixed pitch rotor system was developed, including wind tunnel testing to assure satisfactory stall characteristics. Despite giving the system every benefit of the doubt, the fixed pitch system could not be shown quite as cost effective as variable pitch, even though it could meet the MOD-5 COE target. Therefore, a partial span variable pitch system was selected. It is probable that a fixed pitch system would prove cost effective on smaller machines where the costs involved in variable pitch control are relatively large.

Another interesting concept that could very well prove cost effective on smaller machines is a rotor center disk to accelerate the velocity of the wind outboard of the disk. This concept (see Figure 3) was evaluated, including wind tunnel testing that showed annual energy production was increased by about 5%, normally a gain that would appear extremely attractive. Unfortunately, the cost of the disk itself, combined with the increased tower and foundation costs resulting from high wind loads, showed the concept to be non cost effective for the MOD-5B.

Numerous minor geometry changes from the MOD-2 developed shapes were incorporated into the MOD-5B rotor, with the biggest gain from solidity ratio, taper ratio, and t/c changes that resulted in a relatively lightweight and efficient rotor. Although, wood and fiberglass were evaluated in detail, steel construction was again found superior in overall cost effectiveness except for the tip, where wood's smoothness and ability to be fabricated to complex shapes offset the performance losses resulting from the additional deflection.

Generator System

The study to select the optimum generator system for MOD-5B was perhaps the most comprehensive of the concept phase studies. Conducted with the assistance of the Westinghouse Corporation, the matrix of potential generator systems illustrated in Figure 4 was first reduced to three; the best single speed system, the best multi-speed system, and the best variable speed system. These three systems were evaluated in detail, including the cost and performance impact of not only the generator system itself but of all other wind turbine system components. Probably the most decisive factor in making the final selection was the dynamic simulation of the competitive systems as illustrated in Figure 5. Even without the quill shaft, the means used to attenuate the large "two per revolution" torque oscillations in the single and two speed systems, the variable speed generator reduced the torque overshoots from approximately 20% to 2%. This permitted not only deletion of the quill shaft but also a reduction in size of all drive train components. These savings, coupled with an increase in annual energy production as illustrated in Figure 6, more than compensate for the very sizeable additional cost of the variable speed system.

An interesting example of the operational flexibility of this system is shown in Table 2, indicating that useful power can be produced a much larger percent of the time during periods of relatively low winds. The impact of this additional operating time on the ability of wind systems to be given "capacity credit" by the utilities may prove to be one of the most valuable, though intangible at this time, system advantages.

Miscellaneous Component Refinement

During the final design, fabrication, test, and operational phases of the MOD-2 program, a number of areas were recognized where additional refinement could reduce component cost or improve performance. These potential improvements fall in three general classifications, all of which were incorporated into the MOD-5B design.

The first classification results from operational data that indicates growth is available because overstrength or oversizing was introduced into some components as a result of conservative loads and analysis. The drive train, particularly the gearbox, is the outstanding example. The active pitch control system, coupled with the quill shaft, attenuated torque oscillations in the drive train far more than predicted. As a result, the gearbox was substantially oversized on MOD-2. The reduced sizing on MOD-5B accounts for a very substantial system saving.

The second classification of component improvements results from recognition during MOD-2 fabrication and assembly that specific hardware component designs, though functionally adequate, could benefit from producibility improvements to reduce production costs. Examples applied to MOD-5B include an all new plate girder type nacelle structure, new rotor tip spindle designs, revised rotor teeter bearing geometry, and revised foundation geometry.

The third classification of component improvement results from recognition that more refined analytical techniques could decrease costs or increase performance. Examples applied to MOD-5B include a sophisticated rotor parameter analysis program that permitted evaluation of literally thousands of variations, resulting in both increased performance and reduced weight and a tower optimization program that solves for the lightest weight tower that precisely satisfies the strength, stiffness, and fatigue requirements.

Machine Size Optimization

The development of weight and cost trend data for use in the machine size optimization studies was in itself a major project. The MOD-5B wind turbine system was broken down into over fifty separate packages for which parametric cost estimating relationships were established, using experience from MOD-2, supplier data, and Boeing estimating techniques applicable to quantity production of large complex systems.

The resulting sizing programs were checked by designing four point design systems; 101.9 m (228'), 135.9 m (304'), 169.9 m (380'), and 187.7 m (420') diameter. The confirmed trending curve is shown in Figure 7, indicating that lowest cost-of-electricity occurs at approximately a 187.7 m (420') rotor and 7200 KW power rating.

The rather obvious question arises as to why the MOD-2 optimized at 134.1 m (300') and the MOD-5B at 187.7 m (420'). Although the cumulative effect of many small changes in the cost estimating relationships played a part, three major changes were primarily responsible:

- Smaller gearbox sizing as a result of reduced torque overshoots found possible with the MOD-2 type active control system and with the use of the variable speed generator.
- On MOD-2, supplier inputs indicated that gearbox costs increased as a function of low speed torque to an exponent of 1. Using experience from the gearbox that was actually developed for MOD-2, it was found this growth exponent could be substantially reduced.
- New crane designs that have been recently developed substantially reduce the erection cost increase with size that prevailed at the time of the MOD-2 studies. The dedication of these cranes to both original erection and subsequent maintenance of large wind farms further reduces both erection and maintenance cost increase with size.

Cost of Electricity (COE)

Although the predicted COE at the start of the MOD-5B concept phase was slightly under the program target (3¢/Kwhr in 1977 $), it was generally anticipated that achievement of that goal during the hardware definition program phases would prove a formidable task. Surprisingly enough, as a result of the concept studies discussed above, the COE actually trended downward as the program progressed. At this point in the program (early in the Preliminary Design Phase) it would take a tremendous and unexpected technical setback if the COE target were not achieved. This is true in spite of the fact that the MOD-5 formula for computing COE is considerably more stringent than on the MOD-2 program, as follows:

$$\text{COE (cents/kwh)} = \frac{\text{(Installed equipment costs, \$) (18)}}{\text{Annual kwh}} + \frac{\text{(Intra cluster costs, \$) (18)}}{\text{Annual kwh}} + \frac{\text{(Land costs, \$) (15)}}{\text{Annual kwh}}$$

$$+ \frac{(\text{Periodic replacement costs, \$})\ (\text{Periodic levelizing factor})\ (100)}{\text{Annual kwh}}$$

$$+ \frac{(\text{Annual O\&M costs, \$})\ (200)}{\text{Annual kwh}}$$

The scenario used on the MOD-5B program for determining COE is based on the following:

- Cost of 100th unit of a 1000 unit production run.
- A dedicated manufacturing facility designed and tooled to accommodate production of approximately 20 units per month.
- Installation in wind farms of at least 25 units. (Preferably as many as 60 units.)

SELECTED CONCEPT DESIGN

The essential elements and features of the MOD-5B wind turbine system that evolved from the concept phase studies are illustrated in Figures 8 through 11. While there is an almost daily change in detail costs and weights, no major size or concept changes are anticipated during the preliminary and final design phases of the program.

CONCLUSIONS AND PROBLEMS

If produced under the program scenario of large quantity production in an optimum facility, MOD-5B can compete with conventional power generation over much larger geographical areas than was possible with previous systems. However, large scale commercialization of large wind turbines suffers from the chicken and egg syndrome. That is, costs of units are so high when produced one or two at a time on prototype tooling that the utilities can scarcely afford to buy them. On the other hand, industry cannot possibly afford to invest the huge capital required for an automated high rate production capability without an established order base. To break this log jam will require a great deal of cooperation between government, industry, and the utilities. We intend to do our part to achieve this end.

REFERENCES

1. Douglas, R. R., "The Boeing MOD-2 Wind Turbine System Rated at 2.5 MW", presented at the Large Wind Turbine Design Characteristics and R&D Requirements workshop, Cleveland, Ohio, April 24-26, 1979, NASA Conference Publication 2106.

2. NASA Contract DEN3-200 Statement of Work - Exhibit B - Requirements and Specifications, Aug. 1, 1980.

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TABLE 1. CONCEPT TRADE STUDIES.

System Configuration Studies

SC-1	MOD-5B baseline compared to modified MOD-2
SC-2	Free yaw
SC-3	Variable pitch versus fixed pitch
SC-4	Optimum machine size

Rotor Studies

R-1	Blade aerodynamics
R-2	Material selection
R-3	Center disk
R-4	Rotor control (braking, etc.)

Drive Train Studies

DT-1	Soft drive configuration
DT-2	Gearbox configuration
DT-3	Gearbox mounted rotor
DT-4	Generation variations

Nacelle Studies

N-1	Unitized steel shell versus truss
N-2	Configuration optimization

Tower Studies

T-1	Tower frequency and diameter
T-2	Tower height

Miscellaneous Studies

M-1	Erection method
M-2	Cluster optimization
M-3	Production optimization
M-4	Component producibility
M-5	Foundation

TABLE 2. EXAMPLE OF LOW WIND ENERGY CAPTURE, SINGLE SPEED VERSUS VARIABLE SPEED GENERATORS.

Ground rules

- Data based on Goldendale MOD-2 site winds 12/8/80 thru 2/8/81 (Hourly averages of continous strip-chart data).
- Assumes a MOD-5B type variable speed generator installed on MOD-2 with 2,500 kW peak power.

Total winds 12/8/80 thru 2/8/81

• Single speed generator	Energy generation potential	= 469 MWH
	Hours operation	= 352 hours
• Variable speed generator	Energy generation potential	= 536 MWH (+14%)
	Hours operation	= 642 hours (+82%)

Low winds [below 8.9m/s (20mph)] 12/8/80 thru 2/8/81

• Single speed generator	Energy generation potential	= 102 MWH
	Hours operation	= 143 hours
• Variable speed generator	Energy generation potential	= 150 MWH (+47%)
	Hours operation	= 433 hours (+203%)

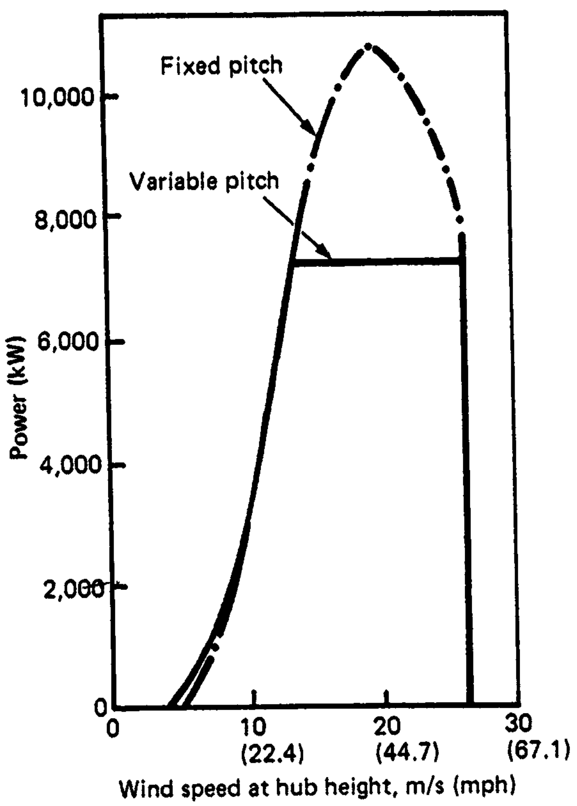

FIGURE 1. VARIABLE PITCH VERSUS FIXED PITCH POWER COMPARISON

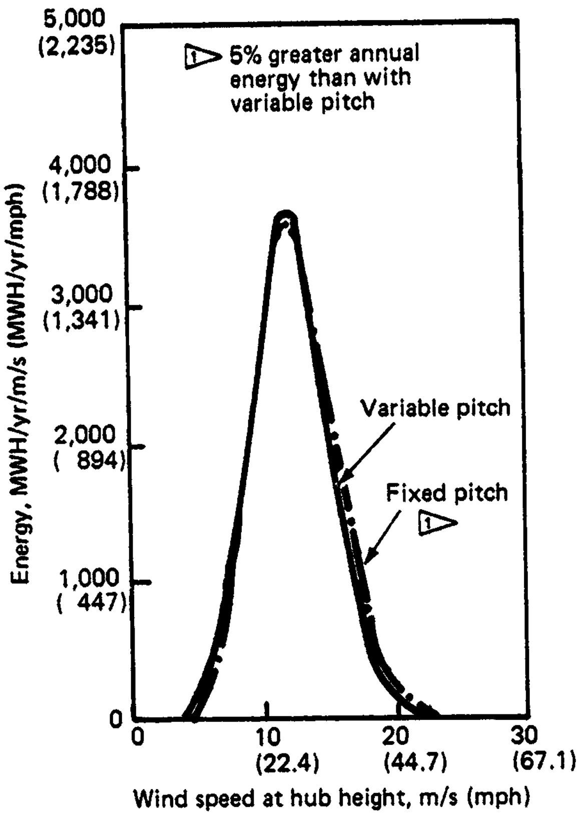

FIGURE 2. VARIABLE PITCH VERSUS FIXED PITCH ENERGY COMPARISON

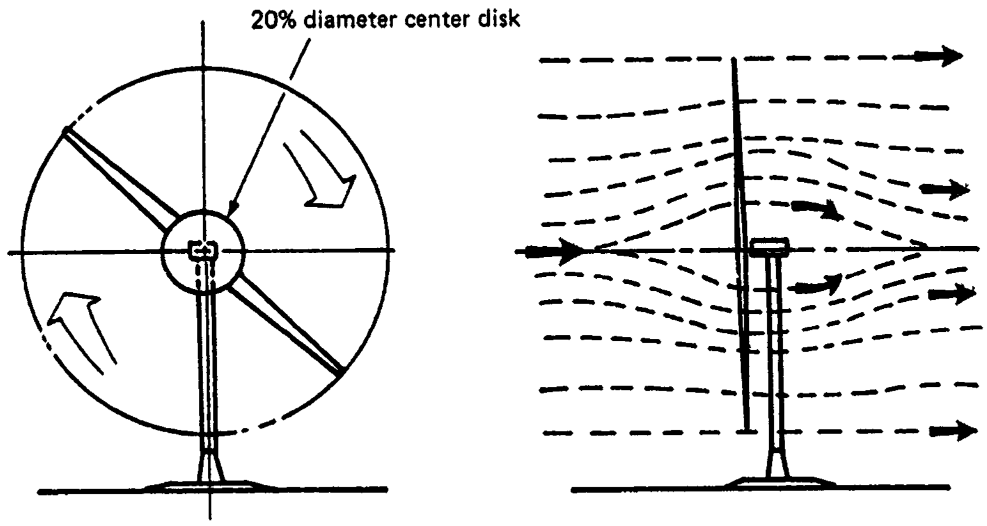

FIGURE 3. CENTER DISK TEST CONFIGURATION

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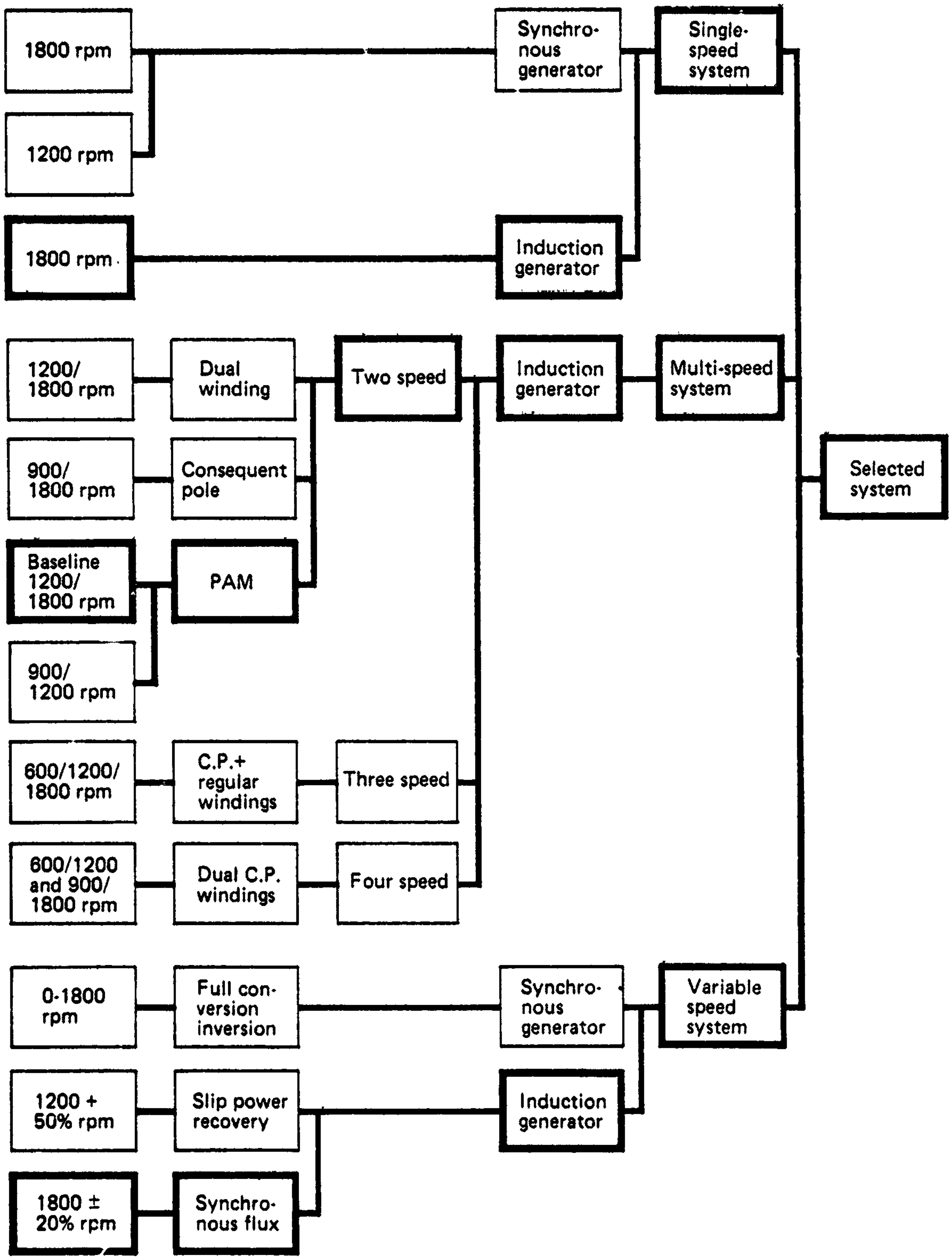

FIGURE 4. GENERATOR SYSTEM STUDY MATRIX

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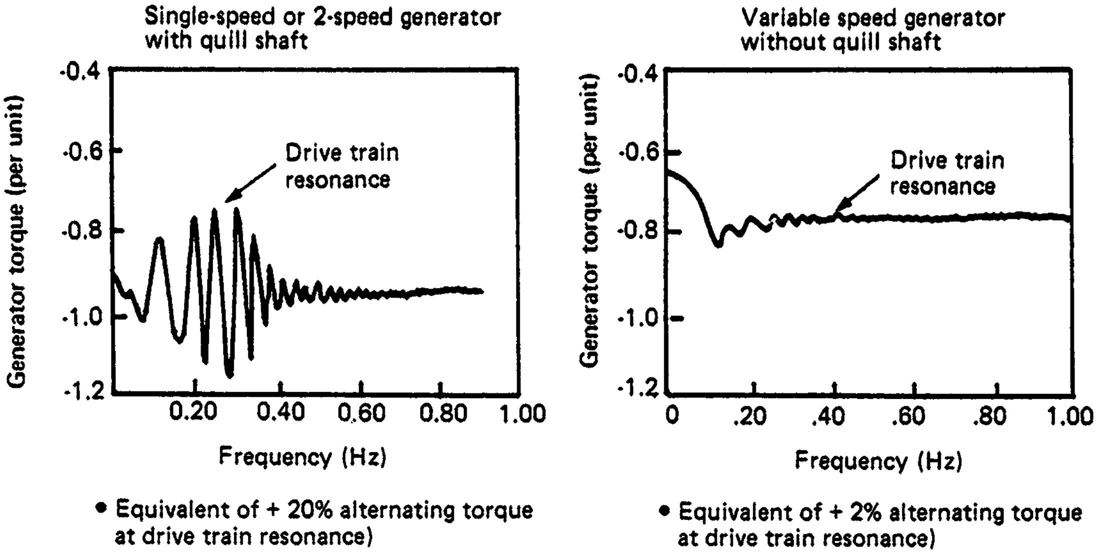


- Equivalent of + 20% alternating torque at drive train resonance)
- Equivalent of + 2% alternating torque at drive train resonance)

FIGURE 5. ALTERNATING TORQUES AT DRIVE TRAIN NATURAL FREQUENCY — DYNAMIC SIMULATION

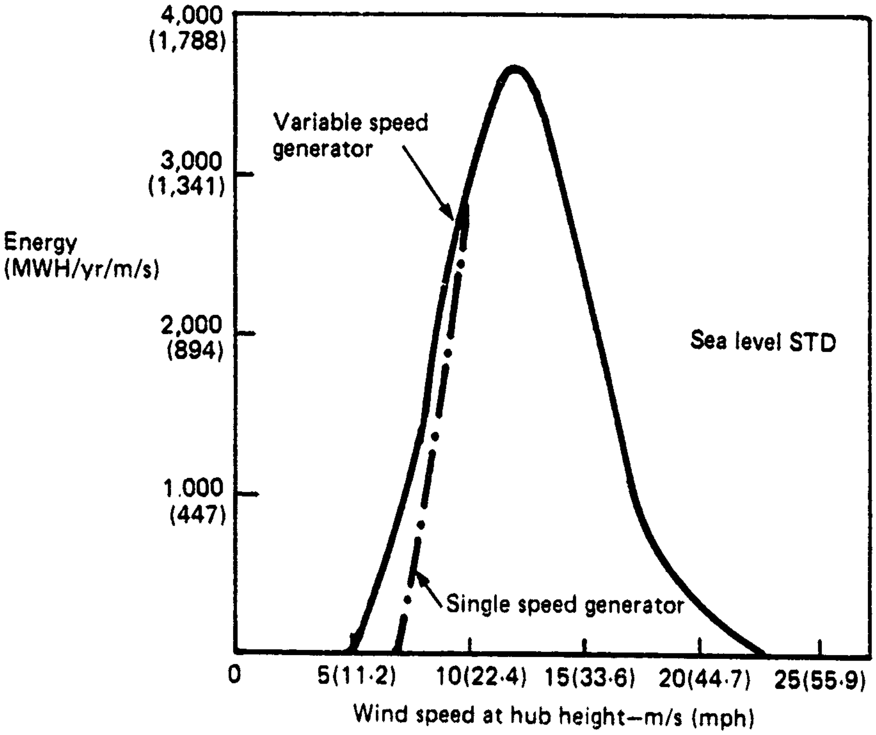


FIGURE 6. VARIABLE VERSUS SINGLE SPEED GENERATOR ENERGY CAPTURE

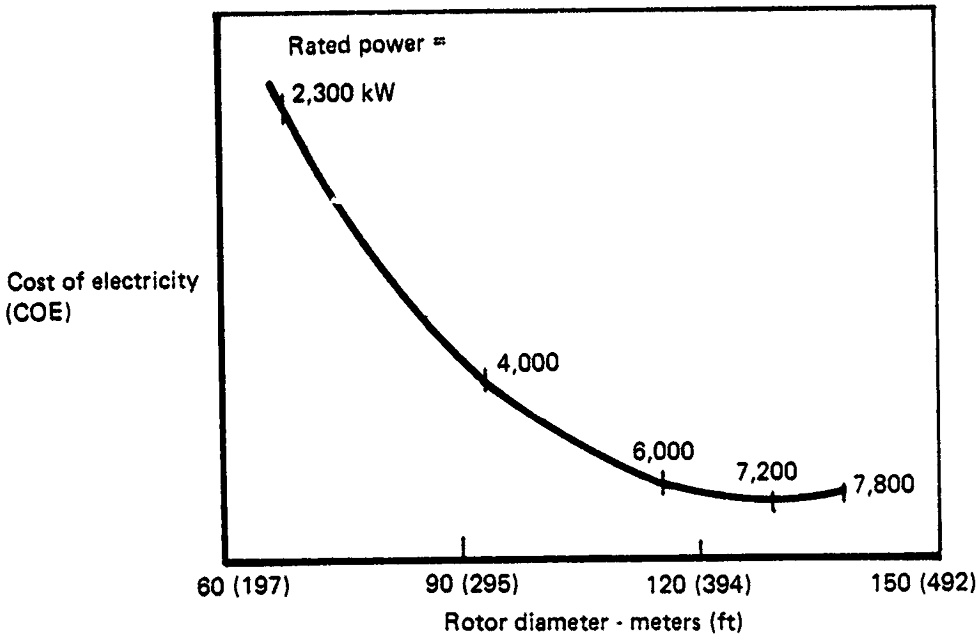
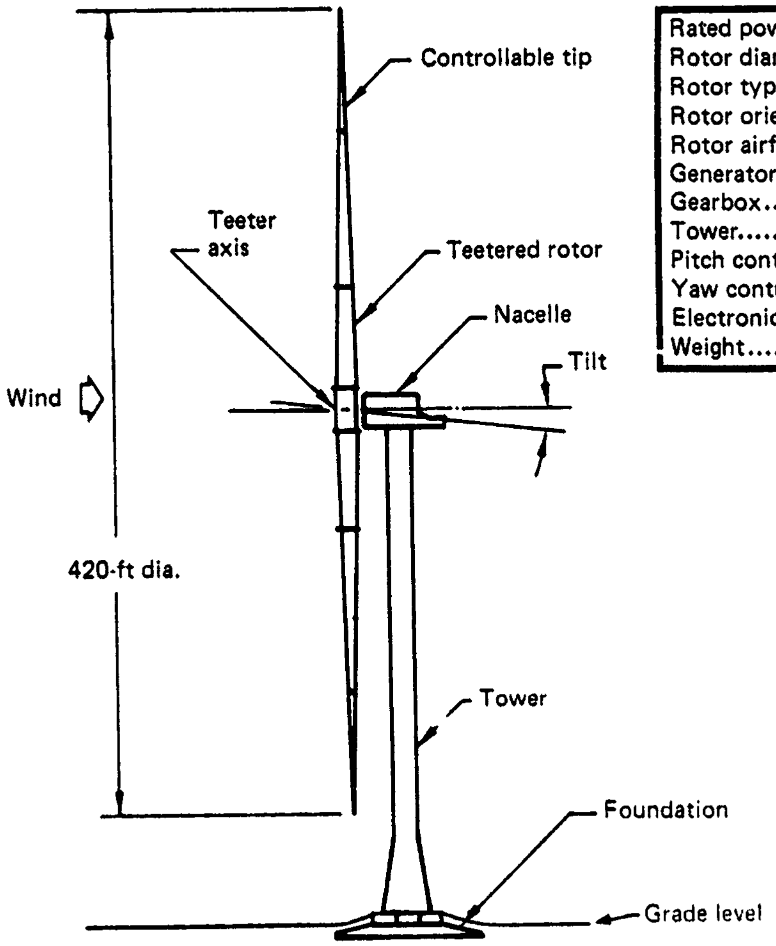


FIGURE 7. COE VERSUS MACHINE SIZE TRENDS



Rated power	7.2 MW
Rotor diamete	420-ft.
Rotor type	Teetered - tip control
Rotor orientation	Upwind
Rotor airfoil	NACA 430XX
Generator type	Variable speed
Gearbox	Compact planetary gear
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
Weight	1,300,000 lbs

FIGURE 8. MOD-5B GENERAL ARRANGEMENT AND FEATURES

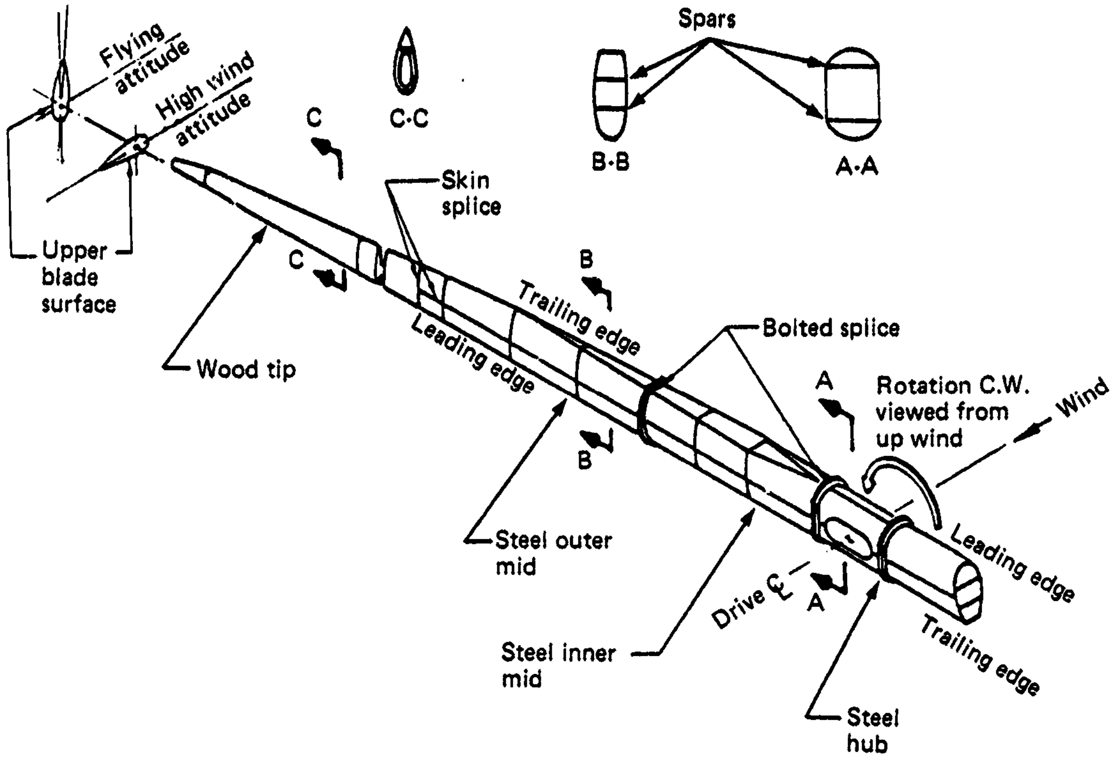


FIGURE 9. ROTOR BLADE CONFIGURATION

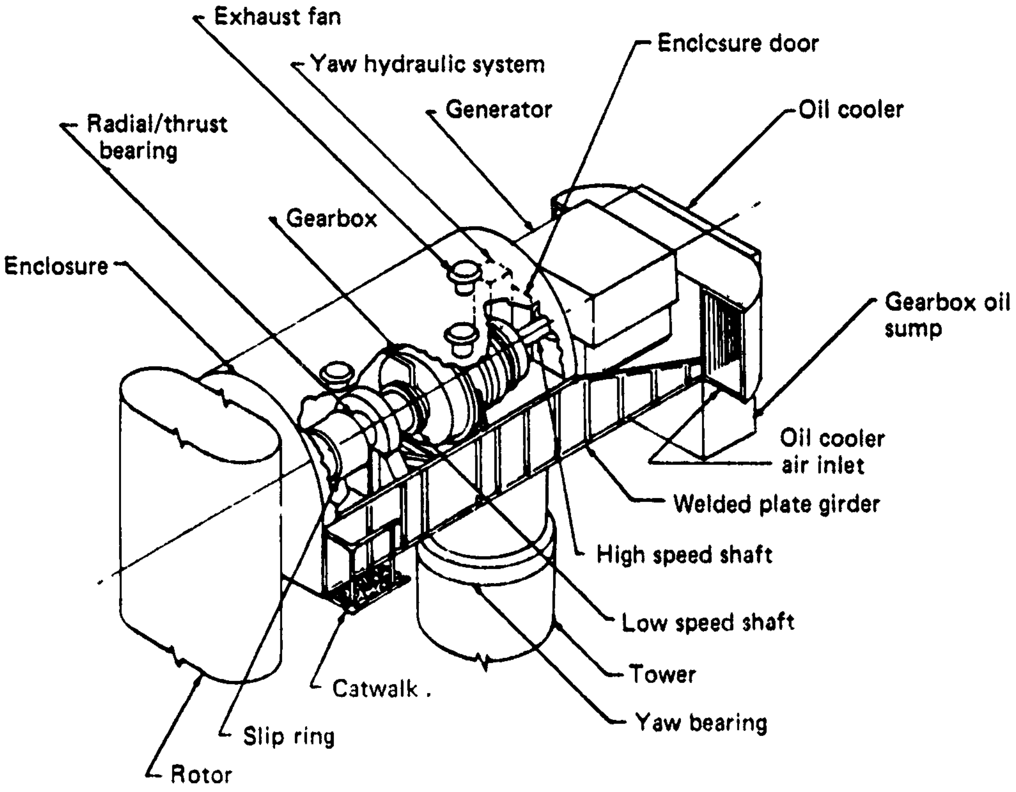


FIGURE 10. NACELLE ARRANGEMENT

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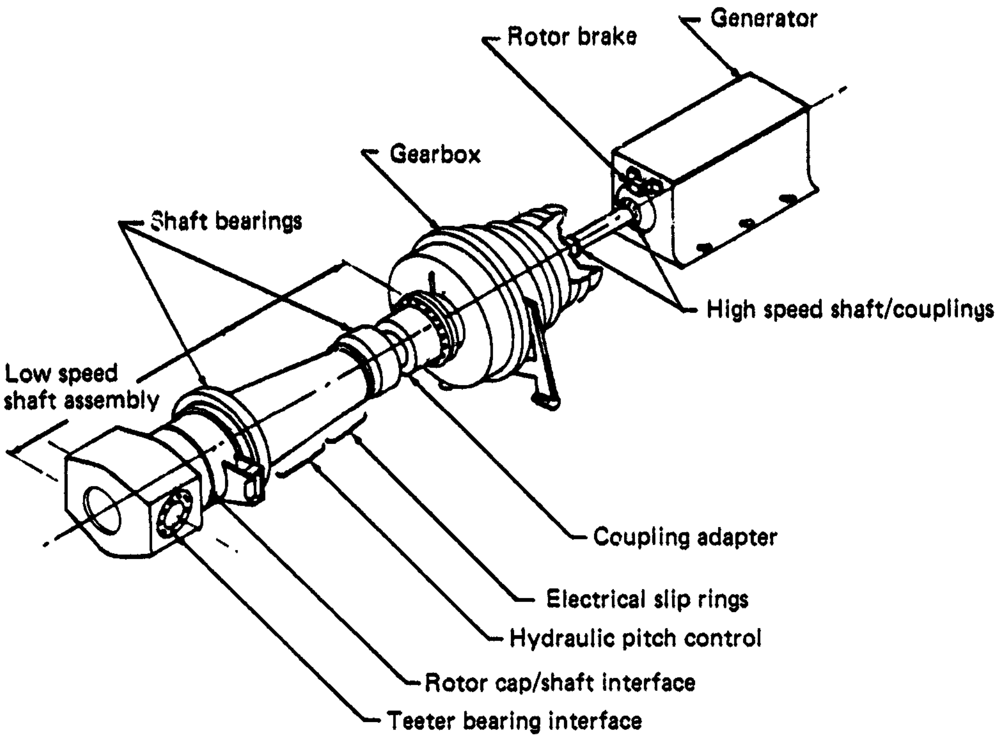

FIGURE 11. DRIVE TRAIN ARRANGEMENT