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CONCEPTUAL DESIGN OF THE 6 MW MOD-5A WIND TURBINE GENERATOR

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ABSTRACT

The General Electric Company, Advanced Energy Programs Department, is designing under DOE/NASA sponsorship the MOD-5A wind turbine system which must generate electricity for 3.75 ¢/KWH (1980) or less. During the Conceptual Design Phase, completed in March, 1981, the MOD-5A WTG system size and features were established as a result of tradeoff and optimization studies driven by minimizing the system cost of energy (COE). This led to a 400' rotor diameter size.

The MOD-5A system which resulted is defined in this paper along with the operational and environmental factors that drive various portions of the design. Development of weight and cost estimating relationships (WCER's) and their use in optimizing the MOD-5A are discussed. The results of major tradeoff studies are also presented. Subsystem COE contributions for the 100th unit are shown along with the method of computation.

Detailed descriptions of the major subsystems are given, in order that the results of the various trade and optimization studies can be more readily visualized.

PROGRAM SCOPE

The MOD-5A Wind Turbine Generator program is a basic element in the overall Federal Wind Program. The goal of the MOD-5A program is to develop a reliable, commercially viable wind energy system, able to produce electricity at a cost of energy (COE) of 3.75 ¢/KWH or less in 1980 dollars, at a site with a 14 MPH annual average wind speed. The program is sponsored by the DOE, with technical management by the NASA Lewis Research Center. General Electric's Advanced Energy Programs Department is the prime contractor. GE's major subcontractors are Gougeon Brothers (GB) for the wood laminate blade, Philadelphia Gear Corporation (PGC) for the gearbox, and the Chicago Bridge and Iron Company (CBI) for the steel shell tower, foundation and erection.

The program began in July of 1980, and is organized into three design phases: Conceptual Design, which was completed in March, 1981; Preliminary Design, which is now underway; and Final Design, scheduled to begin in March, 1982. Each design phase is culminated by a comprehensive design review which has two main objectives: to conduct an

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in-depth review of the design's technical adequacy, and to verify that the program's COE requirement of 3.75 ¢/KWH or less is still being met. (The methodology for estimating and tracking COE is described later.) As the design work progresses through the various phases, subsequent design reviews focus on successively greater levels of detail. Much emphasis is placed on achieving a simple, reliable and maintainable design. In parallel, development and qualification testing is used to verify new elements of the design.

Fabrication of hardware is scheduled to begin late in 1982, with installation and checkout of the first unit completed early in 1984, followed by a two year Operation and Maintenance phase. There is an option in the contract for the manufacture and installation of two additional units. At this point in time, no sites have yet been identified for the MOD-5A.

The purpose of this paper is to describe the results of the Conceptual Design phase, updated by the work accomplished so far in Preliminary Design. We at GE believe that the MOD-5A design meets the program objectives and offers significant advancement in the state-of-the-art. Thus, it is appropriate to review a summary of the major Conceptual Design Objectives as shown in Figure 1.

OBJECTIVE	ACHIEVEMENT
• DEVELOP AN OPTIMIZED LOW COST DESIGN WITH COE LOWER THAN NASA GOAL	• <3.0 ¢/KWH ACHIEVED VS. 3.75¢/KWH GOAL
• VALIDATE THE OPTIMIZATION TECHNIQUE	• POINT DESIGNS VALIDATED WCER'S. SYSTEM OPTIMIZED AT CONCEPTUAL BASELINE DIAMETER 400'
• ADVANCE WIND TURBINE STATE OF THE ART THROUGH INNOVATIVE DESIGN AND OPTIMUM USE OF AVAILABLE OR NEW TECHNOLOGY	• MANY MAJOR INNOVATIONS INCORPORATED IN DESIGN (GEARBOX, BLADE MAT'L ETC)
• VALIDATE THE DESIGN TOOLS	• ANALYTICAL TECHNIQUES AND CODE VALIDATED DURING CONCEPTUAL DESIGN PHASE
• POSITION PROGRAM FOR SMOOTH TRANSITION TO PRELIMINARY DESIGN PHASE	• CONCEPTUAL DESIGN COMPLETED TO POINT WHERE DESIGN SPECS AND PRELIMINARY DESIGN DRAWINGS CAN NOW BE PREPARED

ALL OBJECTIVES ACHIEVED

FIGURE 1. DESIGN OBJECTIVES

SYSTEM REQUIREMENTS

Wind Regime

The MOD-5A system has been developed for a wind regime having a mean wind speed of 14 MPH (at 10 meters). This has influenced the rotor size and rating, Fig. 2. During Preliminary Design, the system is being examined for other wind regimes. The impact of a lower and higher mean wind speed upon the current MOD-5A is discussed later.

GE has selected the cut-in wind speed to assure maximum output and to pre-empt "false starts" in low winds wherein mechanical and electrical losses are likely to exceed the energy to be derived from the wind. A cut-in wind speed of 14 MPH (at the hub or equivalently 9.5 MPH at 10 meters) has been established. A 25% blade tip length was found necessary for satisfactory startup. The cut-out wind speed was first set at 44 MPH because the additional available energy is insignificant at higher wind speeds. Cut-out was not based on structural limitations and the current MOD-5A design high cut-out is higher.

Low cut-out as shown in Figure 2 is at 11.5 MPH and is based on rotor underspeed. Gear shifting for two speed operation occurs near 20 MPH and rating is reached at 29 MPH.

Cost of energy (COE) is the overriding issue to the successful commercialization of wind turbines. Accordingly, NASA has established the competitive figure of 3.75 ¢/KWH (1980) as a bogey for the MOD-5A WTG program. Projections for the MOD-5A indicate less than 3 ¢/KWH (1980) can be achieved at a 14 MPH wind site.

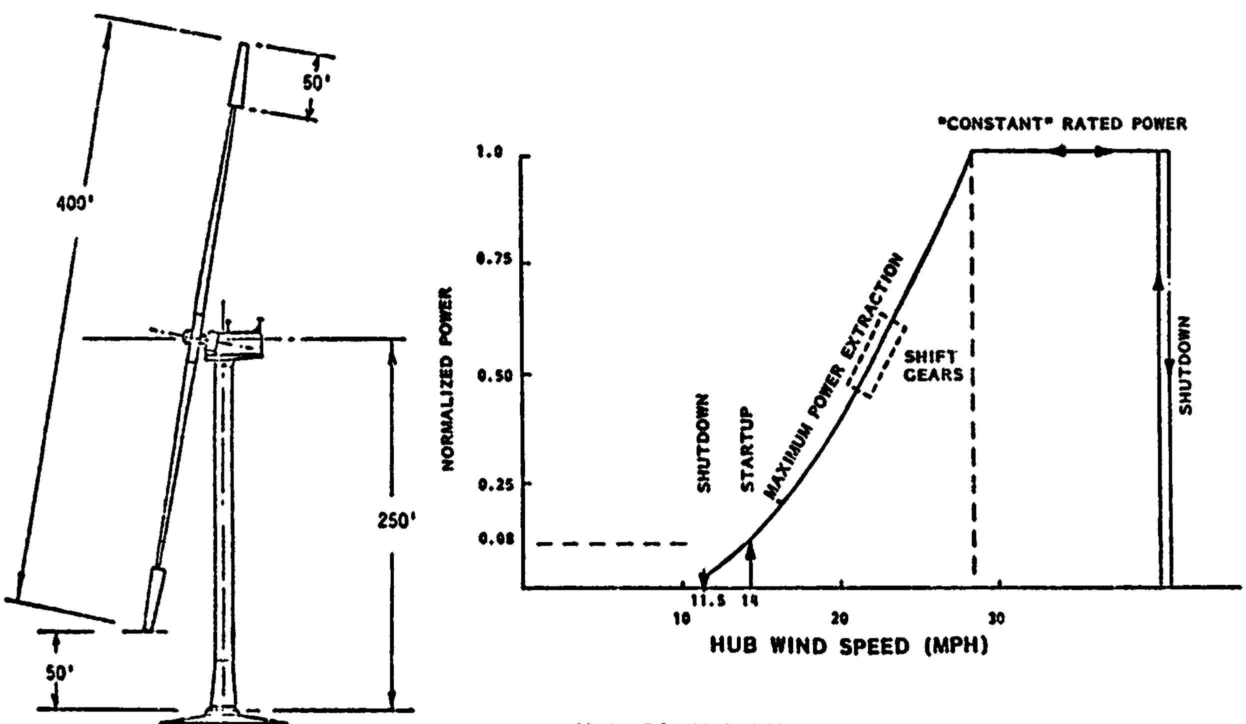

FIGURE 2. MOD-5A SYSTEM

Design Requirements

Major design requirements and their effect on system design are shown in Figure 3. The MOD-5A is based on a comprehensive design driver analysis and definition.

REQUIREMENT	CRITERIA/VALUE	COMMENTS
COST OF ENERGY	• LESS THAN 3.75 ¢/KWH (1980) (SOW) • MINIMIZE	• MAJOR DRIVER IN ALL AREAS
OPERATIONAL WIND REGIME	• 14 MPH MEAN (10 M) (SOW) • CUT-IN AT BELOW 10% OF RATING • CUT-OUT WIND TO MINIMIZE COE	• DRIVER FOR COMBINED TIP SPEED, SPEED RATIO, SOLIDITY TO MINIMIZE COE • DETERMINES TIP LENGTH AND STARTUP 25% TIP, 14 MPH (HUB) ESTABLISHED • DETERMINES SPEED WHERE COE STOPS DECREASING
AVAILABILITY	• 0.92 MINIMUM DESIGN FOR 100TH UNIT BETWEEN CUT-IN AND CUT-OUT (SOW)	• DESIGN GOLAS ESTABLISHED BASED ON RAM ANALYSIS • 0.960+ FOR CLUSTER
EXTREME WIND	• 120 MPH (10 M), 0.1 EXPONENT (SOW)	• DRIVER FOR TOWER AND FOUNDATION • MINIMIZE LOAD BY ORIENTATION
LIMIT THRUST	• 115% SPEED, 1.2 C_L DESIGN POINT WITH 4¢ GUST (GE)	• DRIVING LOAD ON PARTS OF BLADES
EMERGENCY FEATHER	• MAX NEGATIVE C_L ON TIP (-1.5), LOW C_L INBOARD	• NOT AS CRITICAL AS LIMIT THRUST CONDITION
SEISMIC	• ZONE 3-UBC (SOW)	• NOT A DESIGN DRIVER
CYCLIC LOADS	• 30 YEAR LIFE (SOW) • FATIGUE LOAD FACTORS DETERMINED FROM MOD-0A DATA AND GUST MODEL (SOW TURBULENCE)	• 35,000 START, STOP AND GEARSHIFT CYCLES ESTABLISHED FROM HOURLY DATA ANALYSIS • DRIVING LOAD ON PARTS OF BLADES
FREQUENCY PLACEMENT	• AVOID RESONANCES • TOWER BENDING BETWEEN 1.1 AND 1.8P • DRIVETRAIN TORSION BELOW 0.9P and ≥ 25% CRITICAL DAMPING • BLADE CYCLIC MODES AWAY FROM ODD (N ± .2)P (EXCEPT TEETER) • BLADE COLLECTIVE AND FIXED SYSTEM MODES AWAY FROM EVEN (N ± .2)P.	• DRIVES BELL SECTION OF TOWER, HIGH RPM AND RPM RATIO TO INCREASE ENERGY CAPTURE • DRIVER FOR GEARBOX STIFFNESS AND ACTIVE (CONTROL SYSTEM) OR PASSIVE DAMPING • PRELIMINARY DESIGN PHASE REQUIREMENTS FOR SYSTEM

FIGURE 3. DESIGN REQUIREMENTS

Environmental Factors

Sound, TVI (television interference) and other wind regimes were the major environmental factors analyzed.

Wind turbine sound levels are dominated by the effect of change in blade angle of attack and corresponding lift pressures. The potential for complaints is highest with the rotor located downwind of the tower, as on the experimental MOD-1 system, where the tower wake produces sudden large changes in [illegible]. The frequency of blades cutting a wake at twice per revolution is sub-audible, but the complaint potential has been tied to the energy in the range from 20 to 50 hertz by spectral analysis of measurements and computed predictions in the audible range.

The MOD-5A system expected sound spectra was computed, Figure 4, for both the upwind and downwind rotor locations at various distances from the rotor. As shown, the baseline upwind rotor location produces less sound energy at 800 feet (solid line) than a downwind rotor would produce at 3200 feet. The upwind rotor generally produces computed sound pressure levels only a few dB above ambient sound, and no complaints are expected.

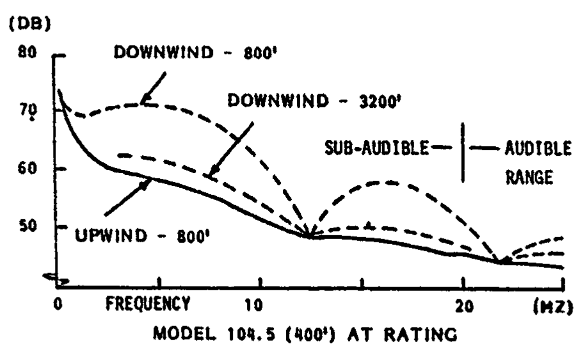

FIGURE 4. SOUND

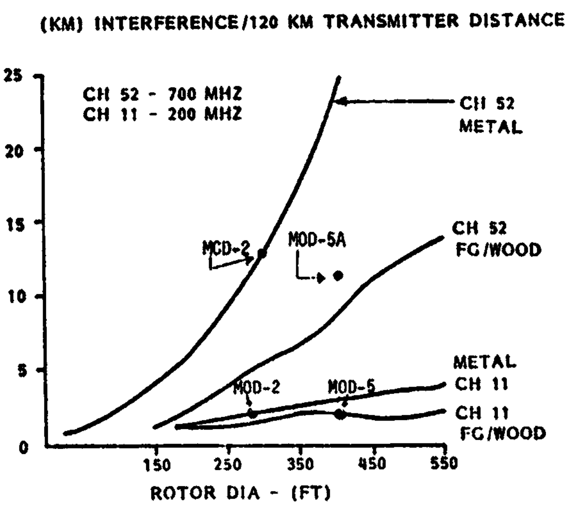

FIGURE 5. TVI

Wind turbine television interference consists mainly of periodic rotor blade blocking or reflecting of a signal between a television transmitter and home receiver. The interference depends on TV channel frequency such that the higher numbered channels are subject to interference at a greater distance from the wind turbine than lower numbered channels. A metallic rotor provides a better reflector than a non-metallic rotor and causes interference at greater distances. The MOD-5A rotor has wood laminate blades, but lightning conductors and the tip control actuator areas are metallic. An effective reflecting area, 25% of the way from non-metallic to metallic, was conservatively selected as representative. (Figure 5)

The MOD-5A system provides close to optimum performance in a variety of wind regimes. Cost of energy was computed for the baseline Model 204 and for a system optimized for the specific wind regime for three Weibull shaped mean wind speeds and for winds at two sites where wind turbines are being located.

The MOD-5A is optimum for 14 and 16 MPH regimes. It is within 1.4% of optimum for 12 MPH where a slightly lower power rating is optimum. Model 204 performance at San Gorgonio and Medicine Bow is within 3% of optimum.

MAJOR TRADE STUDIES

In developing the Conceptual Design of the MOD-5A WTG, eight major trade-off studies were identified which required specific review and approval by the NASA Project Manager before being implemented. In addition to these eight major trade-off studies, a significant number of other design trade-off studies were performed which led to selection of the baseline configuration. Figure 6 defines the eight major trade-off studies, defines the various design alternatives considered, identifies the selected component or subsystem and also establishes the major attributes of the selected component or subsystem which led to its selection. Some of the studies are discussed in more detail in the following.

STUDY	ALTERNATE CONSIDERED	SELECTION	ATTRIBUTES
1. BLADE MATERIAL	• FIBERGLAS (EPOXY & POLYESTER) • STEEL • WOOD EPOXY	• WOOD EPOXY	• LIGHTEST WEIGHT • LOWEST COST
2. BLADE ARTICULATION	• INDEPENDENTLY CONED BLADES • TEETERED ROTOR	• TEETERED ROTOR	• ALLOWS UPWIND • LEAST TECH. RISK • LOWEST COST
3. WIND ORIENTATION	• UPWIND • DOWNWIND	• UPWIND	• LOWEST COST • LOWEST SOUND
4. TORQUE CONTROL	• FLAPS • PARTIAL SPAN CONTROL	• PARTIAL SPAN CONTROL	• LOWEST COST • MOST RELIABLE STARTUP
5. TOWER HEIGHT	• GROUND CLEARANCE 25' TO 125'	• 50' GROUND CLEARANCE	• COST INSENSITIVE 25' TO 75' • CAN MOVE IN EITHER DIRECTION TO ACCOMMO-DATE OTHER DRIVERS
6. SYSTEM RPM	• ONE SPEED • TWO SPEED MECHANISM (UP TO 2:1) • TWO SPEED ELECTRIC (UP TO 2:1)	• TWO SPEED MECHANISM 1.3:1 SPEED RATIO	• GREATER ENERGY CAPTURE • LOWER COE • SYSTEM FLEXIBILITY
7. GEARBOX/NACELLE CONFIGURATION	• SEPARATE GEARBOX • INTEGRAL GEARBC • ROTOR INTEGRATED GEARBOX	• ROTOR INTEGRATED GEARBOX	• MOST EFFICIENT SYSTEM • LOWEST WEIGHT • LOWEST COE
8. ROTOR STOPPING TECHNIQUE	• PARTIAL SPAN CONTROL STOPPING • STOPPING BRAKE	• PARTIAL SPAN CONTROL	• SIGNIFICANT STOPPING TORQUE MARGIN • NO NEW HARDWARE FOR THIS FEATURE

FIGURE 6. MAJOR TRADE STUDIES

Blade Material Study

Cost of energy, shown in Figure 7 as a function of rotor diameter and power density, optimizes at a 400 ft. diameter system with wood laminate blades operating at 350-375 ft/sec. tip speed. The constant power density curves have shifts due to the gearbox exceeding the constraints needed to ship in one piece. Field assembly and test costs due to large size and weight appear as cost jumps.

Performance is based on a NACA 64-6XX airfoil at 1/4 standard rough. Drag characteristics were conservatively calculated by not including the low drag "bucket" that results from the theoretical performance in the laminar flow region. This airfoil has a reverse curvature on the high pressure trailing edge that can be fabricated more readily with the external mold technique used for wood laminates than with the internal mold technique utilized for filament or tape wound structures.

At the system level, with conservative stress levels, the wood rotor system provided lower COE at less risk than either fiberglass or steel bladed rotors. Further optimization during Preliminary Design has made the rotor even lighter and more efficient.

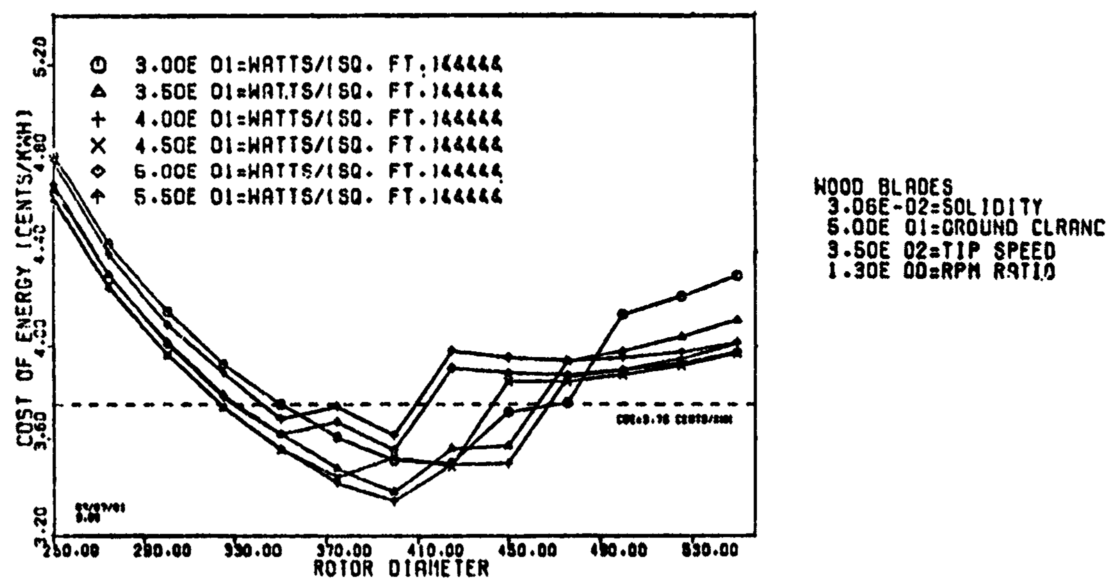

FIGURE 7. BLADE MATERIAL STUDY

Independent Coning Study

Substantially reduced rotor loads on the independently coned configuration resulted in a 30% savings in rotor weight. On the other hand, approximately a 2% loss in energy capture was encountered due to coning. The cost savings were not quite enough to overcome this energy loss, although the final COE was within 1/2% of the baseline. Additional reasons for retaining the baseline are: 1) Sound is significantly higher with the downwind (due to clearance considerations) independently coned system, 2) Lower programmatic technical risk exists with the baseline because it has been extensively analyzed in recent wind turbine programs, and 3) The independently coned hub is considerably more costly due to double hinges, flap restraints, etc.

Flap Study

The flap concept was developed as shown in Figure 8 with 5 actuators mounted externally to the blade surface driving 10 flap sections in pairs. The trade-off was performed on a relatively flexible fiberglass blade and multiple sections were required to provide hinge-line flexibility. A hinge line near the low pressure side of the airfoil provides 60° of up flap and 10° of down flap capability for regulation and camber change. The flap system is more costly and offers no advantages over the baseline partial span control system.

- 25% PSC Baseline
- 50% Span, 30% Chord Flap Provides Equivalent Regulation
- 10 Sections, 5 Actuators Required Due to Blade Motion
- Cannot Rely on Starting Ability Need Motor or Complicated Control
- Supporting Test Data On Partial Span
- No Test Data Available On Flaps
- Small COE Increase Expected On Rotor

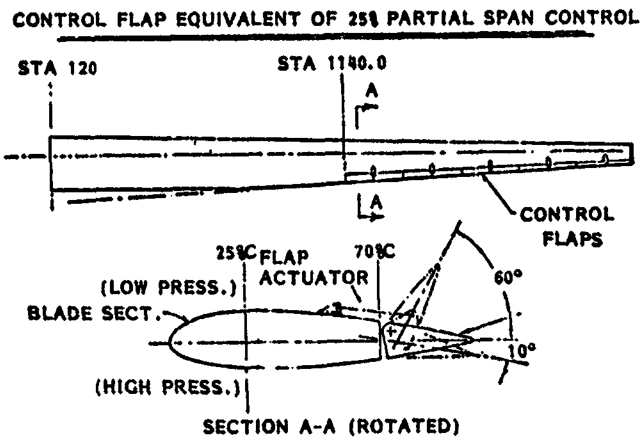

FIGURE 8. FLAP STUDY

Multiple Speed

A comprehensive analysis of multi-speed operation was performed, utilizing the ratio between 2 speeds as the sizing study variable. An optimum shift point was determined by computation of output power at both speeds and shifting when the second speed provides higher power. An analysis with hourly data from Amarillo, Texas for 1978 and 1979 was also made.

Mechanical speed changing systems were examined with shift mechanisms that operated at no load while rotating (warm) and only when not rotating (cold). A reconnectable winding electrical system with warm shift for 2 speed operation, and a full variable speed electrical system were also examined.

Seasonal shifting (twice a year) was examined as an optional cold shift strategy, but energy capture was less than merely operating at a single speed because the torque limited system could not capture substantial high wind energy during the time it was in low speed.

The trade-off was made for three mechanical system operating modes and one electrical shifting mode. A constant torque for the drivetrain and a constant maximum rotor RPM were used.

The single speed system captures 95.5% of the energy that a system operating at maximum power coefficient from cut-in to rating would capture. This leaves only a 4.5% potential for improvement, and the warm shift systems obtain 3.1% of that 4.5% with all shift losses included.

A warm mechanical shift capability is better than cold shift; there is a small cost increase for the mechanism with a substantial increase in energy capture due to more rapid shift times. The electrical shift has more costly hardware than a mechanical shift and provides the same energy capture. Therefore, the lowest COE configuration is with a mechanical two-speed, warm shift.

Nacelle Arrangement

A range of trade-offs were performed to determine the most cost effective method of supporting the rotor. Prior art, as used in the MOD-1 and MOD-2 WTG, employed a rotor support that was independent of the gearbox (stand-alone gearbox). This rotor support structure added size, weight and complexity to the nacelle. Several means of avoiding this were evaluated involving an upgrading of the gearbox input shaft and bearing and gearbox structure. The design that finally evolved incorporates a single rotor bearing in the gearbox structure, that transmits the rotor loads into the gearbox housing. The bedplate is designed to form a unified (but not integral) structure with the gearbox. The advantage of the rotor integrated gearbox design over the stand-alone gearbox can best be appreciated when one considers that the total nacelle weight of the MOD-1 WTG is 100 tons, while the total nacelle weight of the MOD-5A is 180 tons for over three times the power rating, and the nacelle dimensions are approximately equal.

SIZING OPTIMIZATION

Many weight and cost estimating relationships (WCER's) were developed and verified during the course of Conceptual Design. These WCER's permit prediction of system cost and weight as a function of: rotor diameter, blade tip speed (determines main RPM), solidity (determines blade chord dimension and best efficiency vs. RPM), power density (determines power and torque ratings with diameter and tip speed), speed ratio (for two speed operation) and ground clearance.

Figure 9 illustrates the first tier of WCER and cost accumulation. The comment column summarizes what is included in each category and the percent contribution to cost of energy is indicated. At the second tier, the tower structure and the gearbox (part of the drivetrain) are the largest single COE contributors, at about 15% each.

A basic wind turbine, without installation, would be represented by categories 400 through 900, plus part of 1000 which equals about 65%. The other 35% represents installation and O&M related costs.

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1ST TIER CATEGORY	COMMENT	MODEL 204.0 $ COE
100 SITE	FOUNDATION AND GROUND EQUIPMENT	11.03
200 TRANSPORTATION	SHIPPING	3.07
300 ERECTION	INSTALLATION, INTEGRATION, CHECKOUT	6.36
400 ROTOR	BLADES, HUB, SHAFT, PSC SYSTEM	12.63
500 DRIVETRAIN	GEARBOX, SHAFTING, GENERATOR	18.96
600 NACELLE	BEDPLATE, CONTROLS, HYDRAULICS, YAW	7.10
700 TOWER	TOWER, LIFT, CABLING	14.99
800 REMOTE CONTROL	DISPATCHER INTERFACE	.07
900 SPARES	INITIAL SPARES AND SERVICES	.79
1000 SPECIAL	PROFIT, GROWTH, ASM/TEST	14.83
1100 LAND	SITE AND CLUSTER	.14
1200 CLUSTER	SUBSTATION, TRANSMISSION, ROADWAY	4.66
1300 OPERATION & MAINTENANCE	O&M LABOR, CONSUMABLES	6.44

FIGURE 9. WEIGHT AND COST ESTIMATING RELATIONSHIPS

Optimization Procedure

Figure 10 depicts the procedure used to perform the system size optimization. For the set of variables noted above, aerodynamic performance is computed and used in conjunction with wind duration and system availability to determine the yearly energy capture. In parallel, costs (and weights) of the various sytem components and O&M are calculated to determine the annual cost and ultimately the COE. The computations are then repeated until an optimal set of variables is found. The entire procedure is embodied in the GE WINDOPT code, which in effect explores continuous parameter variations over input ranges of the sizing variables.

Optimization Results

The present optimum MOD-5A system, Model 204.2, has a COE below 3 ¢/KWH (1980) as the result of Preliminary Design phase optimization. Figure 11 illustrates the cost and COE trends at Conceptual Design, where a minimum COE slightly above 3.3 ¢/KWH was predicted.

The minimum COE design is at 400 feet. The Statement of Work requirement of 3.75 ¢/KWH COE was met by MOD-5A WTG's with diameters from 325 feet to 450 feet.

The initial cost of the WTG increases dramatically with diameter. Higher cost is balanced by an even greater energy capture, resulting in a lower cost of energy for larger machines until above 400 feet, when capital cost tends to increase faster than energy capture, and cost of energy increases.

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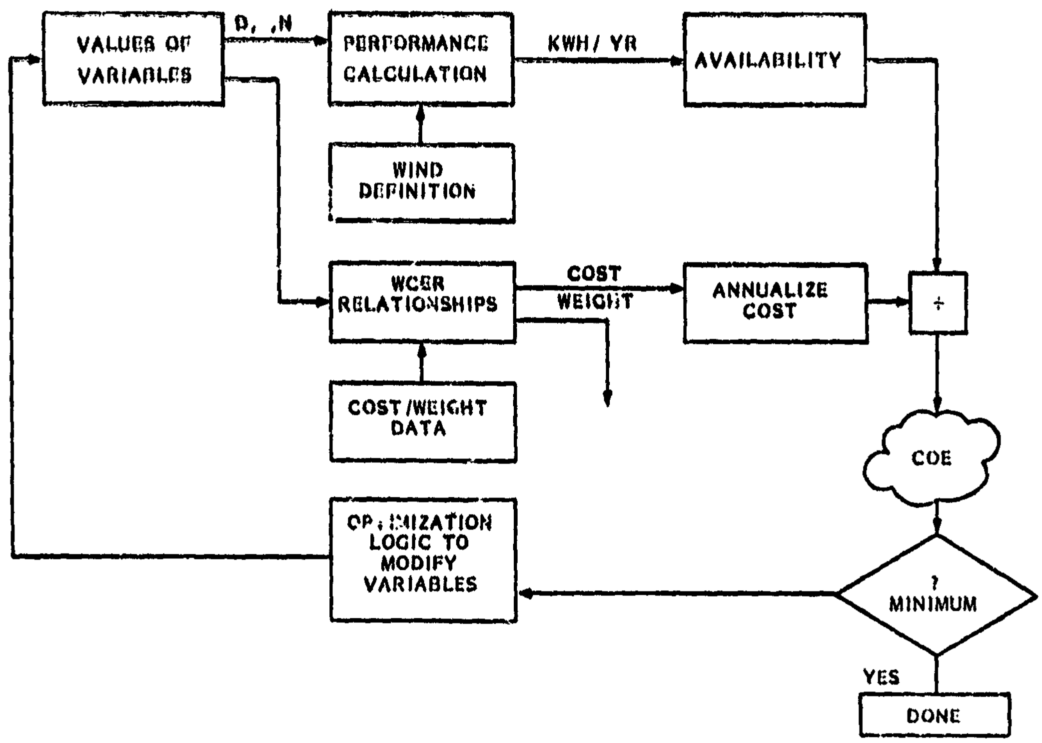

FIGURE 10. SIZING OPTIMIZATION FLOW

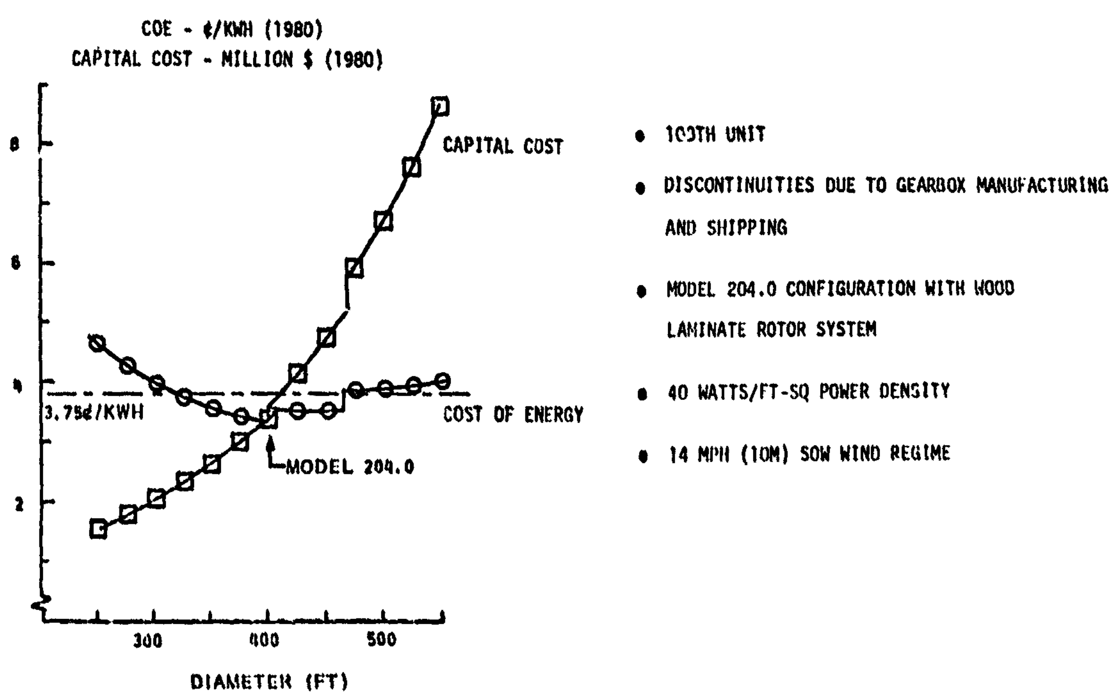

FIGURE 11. COE AND CAPITAL COST

Present Model 204.2 parameters are: Diameter 400 feet; Tip Speed 375 ft/sec. (17.9 RPM); Power Density 50 watts/ft-sq (6.2 MW); Ground Clearance 50 ft (250 ft. hub); Solidity 3.06%; Speed Ratio 1.35.

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Baseline System Definition

The MOD-5A Model 204.2 system features are defined in Figure 12.

ROTOR
- UPWIND
- 375 FT/SEC TIP SPEED DESIGN
- WOOD LAMINATE SPAN AND TIP
- 64-6XX AIRFOIL, 3.06% SOLIDITY
- 25% HYDRAULIC PARTIAL SPAN CONTROL
- 13.25/17.9 (TWO-SPEED)
- TEETERED 30 FT. STEEL HUB
- 9° TILT ±9° TEETER ALLOWANCE
- HYDRAULIC POWER UNIT ON HUB
- 277,800 LB ROTOR WEIGHT

ELECTRICAL
- 6200 KVA OIL-FILLED TRANSFORMER
- WALK-IN AISLE SWITCHGEAR AND CONTROL ENCLOSURE
- 69 KV NOMINAL INTERFACE VOLTAGE
- RADIAL FEEDER-TYPE CLUSTER ARRANGEMENT
- 6.2 MW SYNCHRONOUS GENERATOR

MAINTENANCE
- PERMANENT CLUSTER CREW
- SPARES BUDGET

DRIVETRAIN
- ROTOR INTEGRATED HYBRID GEARBOX
- 2.71 MILLION FOOT POUND TORQUE
- FIRST STAGE PLANETARY, THEN SPLIT PARALLEL SHAFT ON END STAGE, THIRD STAGE AND SHIFTER
- ROTATING SHIFT
- STIFFNESS AND DAMPING CONTROL AT FIRST STAGE
- TWO ROW ROLLER BEARING INTEGRATED INTO CASE FOR ROTOR AND GEAR SUPPORT
- IN-LINE SLIP RING ACCESS
- SHAFT DRIVE LUBE PUMP
- HIGH SPEED SHAFT INCLUDES OVERLOAD RELEASE AND OVERRUNNING COUPLINGS
- ROTOR LOCK AND PARKING BRAKE
- 239,500 LB DRIVETRAIN WEIGHT

NACELLE
- BEDPLATE WITH WIRING, PLUMBING, RUNS UNDER FLOORING
- YAW HYDRAULICS SYSTEM
- GEARBOX AND BEARING LUBRICATING SYSTEM
- CONTROL ELECTRONICS
- PUSH-PULL YAW DRIVE
- YAW BEARING ASSEMBLY ATTACHED TO TOP TOWER SECTION
- YAW SLIP RING
- 116,956 LB WEIGHT

TOWER
- 14.5 FT CYLINDRICAL STEEL
- 250 FT TO HUB
- TAPERED BELL SECTION FOR TUNING
- INTERNAL LIFT
- 490,000 LB WEIGHT

FOUNDATION
- SPREAD FOOTING, REINFORCED CONCRETE

FIGURE 12. MODEL 204.2 DEFINITION

A spread footing tower foundation with triple reinforcing and embedded anchor studs is utilized for most soil densities. The soil flexibility is included in the tower frequency analysis. Rock or very soft soils would require a departure from the basic general purpose foundation after soil analysis.

Electrical protection and interface equipment is located away from the tower base to provide maintenance vehicle access. Factory wiring is provided for the walk-in control enclosure. A window is provided for operator observation of the rotor during manual operations.

The baseline cluster is rated at 150 MW with 25 MOD-5A units. A multiple grid tie is provided with 69 KW cluster distribution. Each WTG has a step-up transformer that limits short circuit duty on the site contactor as well as providing a voltage match. A central spares store and a permanent 4 man cluster maintenance crew are utilized to minimize maintenance costs.

SUB-SYSTEM DESCRIPTIONS

Rotor Blade

The selection of the MOD-5A rotor blade configuration and material was based on the results of an extremely comprehensive system/subsystem trade study. This study defined the 100th unit costs of the three blade materials and explored diameters ranging from 150 to 500 feet.

Initial parametric cost and weight variations were determined for the three materials and iterated based on system performance evaluation. First results indicated that wood laminate had lower cost and weight than fiberglass, with steel a poor third. However, the wood laminate blade required a thicker section due to its relatively lower strength. This thicker blade, when configured as a 230XX airfoil, provided less energy capture than the thinner fiberglass airfoils. An alternate high performance thicker airfoil series 64XXX, which can be readily fabricated in wood laminate but not in fiberglass or steel, allows the thicker wood laminate blade to have performance similar to the thinner 230XX fiberglass blade, and swung the decision to wood laminate.

The blade is constructed of 0.10 inch thick rotary cut douglas fir laminate, which is epoxy bonded at room temperature, using vacuum bags, to form the major load carrying forward portion of the blade. The trailing edge portion of the blade is constructed of plywood faces with a paper honeycomb core sandwiched between them. The upper and lower surfaces are laminated in female molds which assure excellent contour control, and then bonded together, including the shear web, to complete a section assembly. The outer surfaces of the blade are covered with epoxy and fiberglass cloth as part of the molding operation. The blade construction is similar to that successfully used on MOD-0A and hence presents a minimal development risk consistent with the MOD-5A program philosophy. See Figure 13.

Partial Span Control Mechanism

A description of this mechanism is shown on this simplified conceptual drawing (Figure 14). The steel weldments, shown enclosing the spindle shaft, include airfoil shaped skins, longitudinal spars and stiffener ribs at both ends. Not shown is a "thrust tube" which surrounds the inboard end of the spindle shaft between the two bearings. This tube provides the interface with the bearings, and reacts the radial forces into the rib at the inboard bearing location. The tube carries the centrifugal force of the tip from this bearing outboard to the rib at the radial bearing, where it is bolted in and distributes this force into the box structure formed by the two spars and skins immediately surrounding the shaft. The tube, shaft, and bearings form a separate assembly.

Loads from the outboard tip portion of the PSC subassembly are introduced into the shaft by a bolted connection at the outer rib and a bushing joint at the inner rib. The spar arrangement is the same in both sections. The actuator is mounted at the midpoint of the body to minimize the bending moments on the cylinder created by the inertial forces of the actuator under the normal centrifugal acceleration of approximately 20 g's.

Since the drag force provided by one fully feathered tip is sufficient to stop the rotor, dual redundancy has been provided in the hydraulics to ensure that a least one tip will be feathered reliably for a safe shutdown in case of a failure.

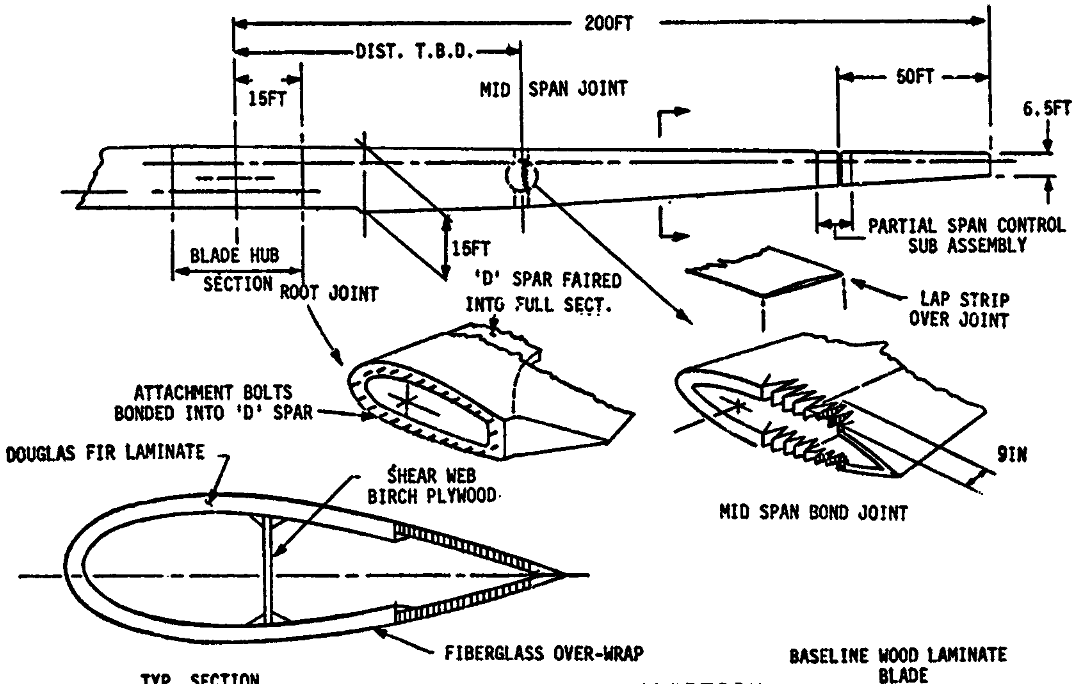

FIGURE 13. BLADE DESCRIPTION

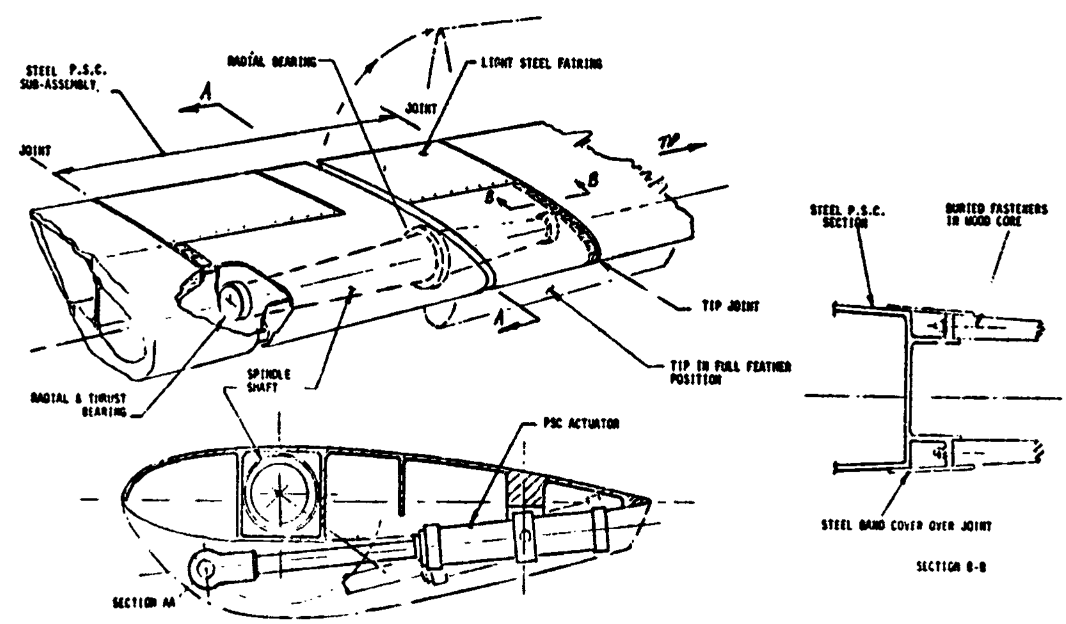

FIGURE 14. PARTIAL SPAN CONTROL MECHANISM

Nacelle Assembly

Wind energy, captured by the rotor at relatively low specific power density over the large area swept by the blades, is "concentrated" by the gearbox and generator located in the nacelle. The large diameter blades result in a massive structure that must be supported safely under all environmental conditions and wind speeds. The nacelle and gearbox provide the means of transmitting the static and dynamic loads safely from the rotor into the tower and hence, into the ground.

It was always known that weight in the nacelle meant a cost penalty. Accordingly, an intense effort was made to reduce as much structure in the nacelle as possible consistent with performance requirements. This led to the selected rotor support method whereby the rotor bearing is integrated into the first stage of the gearbox, assuring a compact gearbox, bedplate and nacelle. The concept is shown in Figure 15.

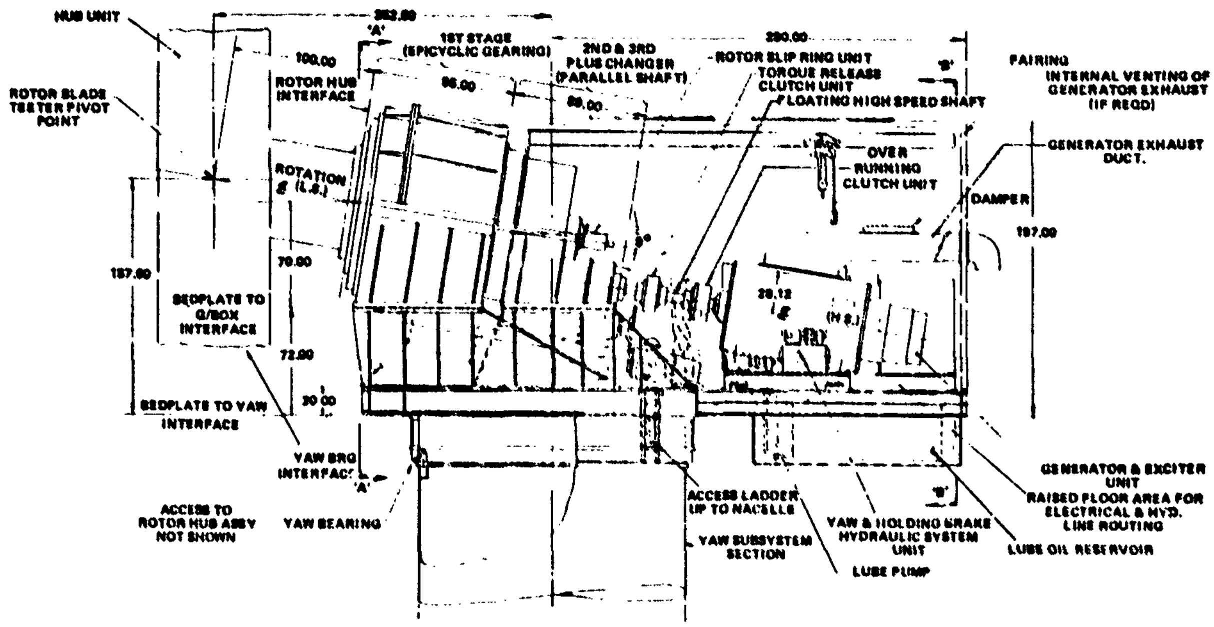

FIGURE 15. NACELLE CROSS SECTION

The gearbox and bedplate were designed as a unified load carrying structure between rotor and tower. A cantilevered section of bedplate suppo.ts the generator and power accessory equipment. A fairing assures a secure and weather-protected work environment during routine maintenance. The function and cost effectiveness of each element was carefully thought out to assure a low COE and maintainability. This is reflected in the compact gearbox and bedplate and an adequate work space. Access to all critical elements is provided by means of roof hatches, removable floor gratings, and ladders.

Rotor Integrated Hybrid Gearbox

The MOD-5A gearbox is advanced gearbox technology applied to wind turbine generators. It incorporates technological innovations in the epicyclic first stage and features borrowed from other applications, such as the torsion bar ring gear suspension used primarily in Basic Oxygen Furnace (BOF) drives, to provide drivetrain compliance. The most rewarding design feature is the integration of the rotor support bearing into the gearbox structure. This alone resulted in a significant savings in size, weight and cost of the overall nacelle by eliminating a separate shaft, and the attendant radial and thrust bearings, gear couplings and bearing pedestals associated with a conventional rotor support, not to mention the extra length of bedplate necessary to accommodate the rotor support assembly. Although the epicyclic implementation of the first stage was found to be most cost effective, succeeding stages were evaluated individually. Accordingly, parallel shaft gearing in the second and third stages was found to offer a significant cost advantage at a small weight penalty. Parallel shaft gearing in the third stage also made it feasible to incorporate a speed changer without increasing the gearbox envelope. See Figure 16. To provide load alleviation and minimize power swings, compliance and damping are required. The drivetrain provides this by hydraulically damping the torsion bar suspension of the epicyclic first stage. The speed changer permits extending energy capture into the lower wind regimes to enhance the COE.

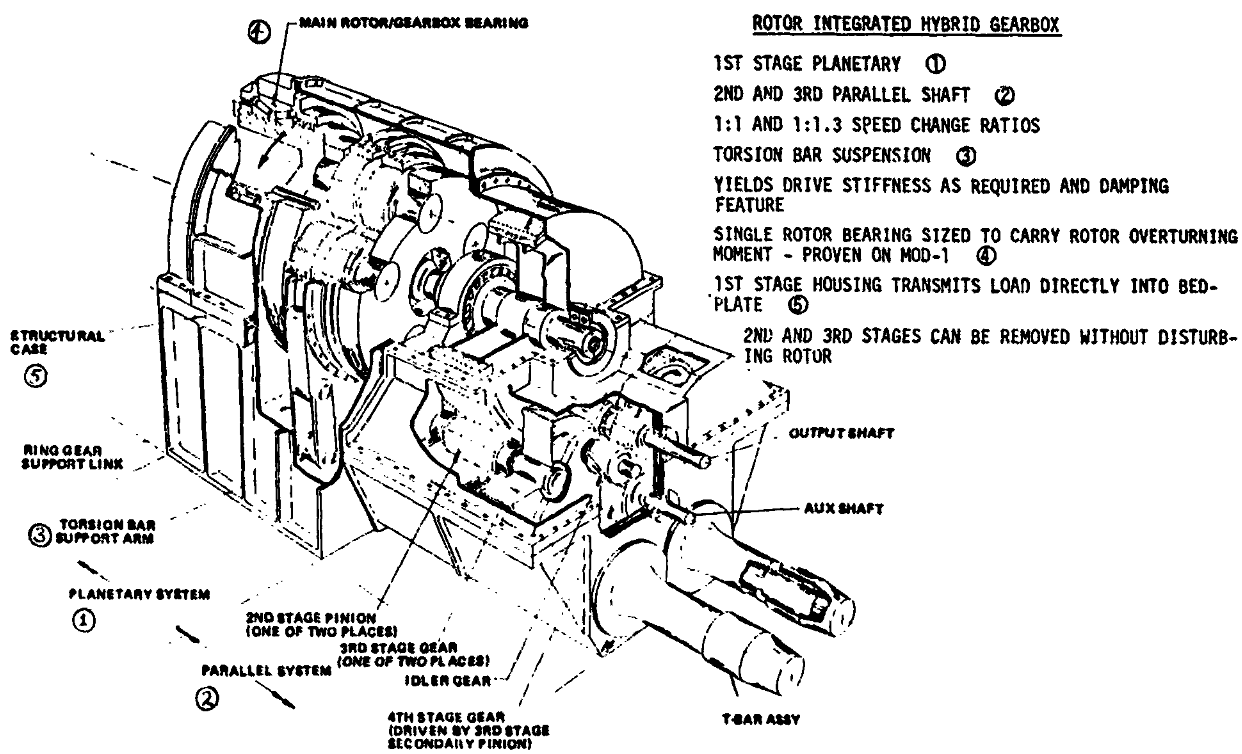

FIGURE 16. ROTOR INTEGRATED HYBRID GEARBOX

High Speed Drivetrain

The high speed drivetrain connects the gearbox output shaft to the generator input shaft. It contains a flexible coupling feature to provide for axial and angular misalignment. Two additional functions are incorporated for operational reasons. One is the torque overload release clutch, which will protect the drivetrain from damage due to excess torque levels (clutch disconnects when the torque level exceeds 1.75 x nominal). The other is an overrunning clutch which will allow the generator to motor when the input speed falls below synchronous speed. The overrunning clutch also assists in providing a smooth transition during speed changing sequence.

Tower and Foundation

The thin tube concept as the basic tower structure has many advantages. It is very efficient in carrying the blade and nacelle bending and torsional loads imposed under normal and abnormal conditions. It provides an all-weather access to the nacelle. But of most importance, it costs less than a comparable truss structure. The tube is not as stiff as a truss structure, but if the system natural frequencies are carefully selected, this can be an advantage also. By placing the first bending frequency between 1P (one per rev. of the blade) and 2P, system dynamic load trade studies have shown rotor, nacelle, and tower loads to be reduced over those of a stiffer truss tower.

The importance of an optimum tower and foundation design is seen from its contribution to the COE figure. The sum is the largest contribution, and the tower design affects foundation costs. During the trade studies conducted by Chicago Bridge and Iron (CBI), several cases were found where the least expensive tower design did not yield the lowest overall cost.

Yaw Drive System

A conceptual layout of the yaw system is shown in Figure 17 along with the main features. The lift terminates at the upper platform. Access to the nacelle is by ladder up through the nacelle floor providing all-weather access. The yaw drive and slip ring assemblies are also easily accessible from inside the tower, as well as the bearing bolts.

To fulfill its design requirements, the yaw drive has to be neither fast acting nor highly precise because of the nature of the wind. The rotation of the nacelle is similar in function to the azimuth drives of cranes, power shovels, rotary derrick, etc. The conventional design uses a single large slewing type bearing with gear teeth integrally cut into either the inner or outer race. A hydraulic motor then drives it with a pinion gear. During conceptual design, methods to reduce the cost centered on elimination of the gearing cost.

The selected concept uses the brake disc (fixed to the tower) which is required in any design, and brakes called grippers mounted on the end of a hydraulic cylinder to push or pull the nacelle around. A similar yaw drive concept is used on the Hawaiian MOD-0A design. Without the gearing there are no backlash problems or precise gear mounting requirements. The stiffness of the yaw drive is dictated essentially by the drive hydraulic cylinders and is only a matter of concern when rotating the nacelle.

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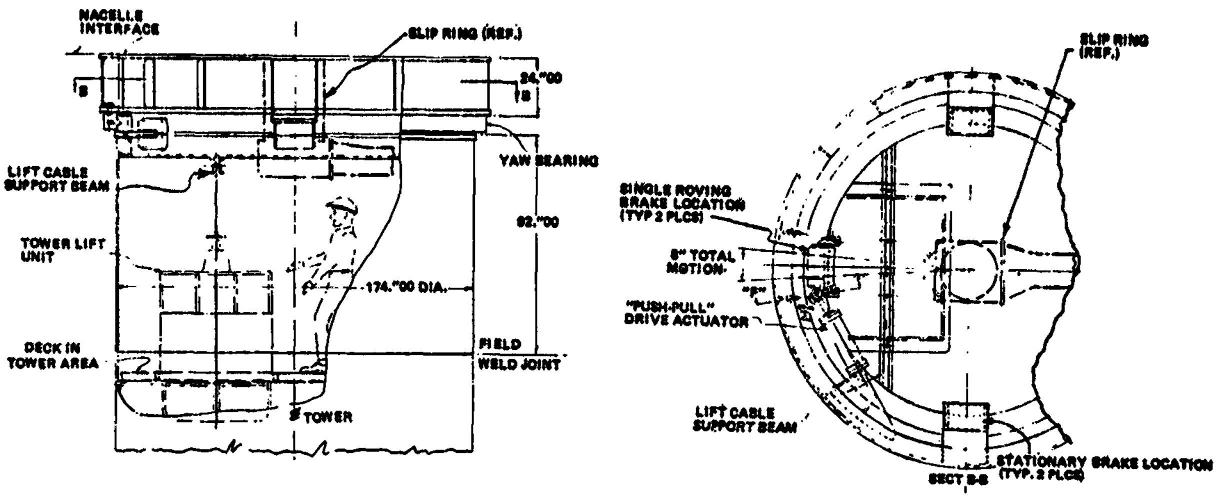

FIGURE 17. YAW DRIVE SYSTEM

Controls Equipment

Several trade-offs made include the type of control, type of processing, location of the central electronics, and the criteria for hardware implementation. The selected design will minimize development by maximum use of proven technology. The conceptual design uses multi-loop control and digital processing, with the control electronics located in the nacelle. The hardware implementation will use proven modular electronics with a minimum of special design and development of the interface circuitry. An operator on site or at a remote location can obtain data and supervise automatic system operation.

Power Generation Equipment

Power generation equipment, with the exception of the yaw slip ring assembly, is standard with optional features. This "off the shelf" approach provides for lower cost and more realistic delivery times. When considering synchronous generators above a rated output of 4000 KVA, 1800 RPM is no longer cost effective; therefore, 1200 RPM was chosen for the baseline 6400 KVA design. By choosing the operating voltage at 5500 instead of the more common 4160 volts, the additional cost for the generator is more than offset by enabling the use of a synchronous motor starter instead of a more costly high current switchgear assembly. Step-up at each wind turbine is provided to minimize interconnection losses.

CONCLUSION

The MOD-5A design concept is an innovative next generation machine, which meets its COE requirement with minimum technical risk.