THE GENERAL ELECTRIC MOD-1 WIND TURBINE GENERATOR PROGRAM

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INTRODUCTION

The MOD-1 WTG is the first megawatt class machine in the national wind program. The MOD-1 Program which started in September of 1976 has as its objectives the design, fabrication, installation and test of a megawatt class wind turbine generator (WTG) which generates utility grade electrical power. The program is nearing the final phase of installation and checkout. The blades are the only components remaining to be installed.

NASA-LeRC is managing the MOD-1 Program for DOE. General Electric's Space Division located in Valley Forge, PA., is the prime contractor, with several GE electrical equipment product departments supplying components ranging from switchgear to the synchronous generator.

WTG SPECIFICATIONS AND REQUIREMENTS

The specifications and design requirements, as originally stated by NASA-LeRC were heavily influenced by the NASA MOD-0 design and operational experience, and as such, the designs have a high degree of similarity. Also, the MOD-1 technical specifications are quite restrictive and allowed virtually no flexibility in design concept except for a trade-off between a rigid and a teetered hub. The general design requirements and program objectives are shown in figure 1. The dominant requirement, which most influenced the design, was the utilization of state-of-the-art technology to minimize technical risk.

A summary of the technical specifications is contained in table I. You will note that the selection of a few of the parameters was optional. Also during the design cycle, a requirements assessment analysis was conducted, which lead to the modification of certain requirements. These items will be reviewed in the discussion on design drivers.

The design wind environment for the MOD-1 WTG is an 18 mph (mean) wind regime with a standard Velocity Duration Curve. The vertical velocity profile is defined by the relationship:

$$V = V_0\left(\frac{H}{H_0}\right)^{0.167} \qquad V_0 = \text{velocity at ref. height } H_0$$

The wind gust model is shown in figure 2.

The blade design load cases are listed in table II. The blade turning requirements were a first flapwise frequency ≥ 2.15 P (P = nominal rotational frequency) and a first chordwise frequency ≥ 4.15 P. The primary requirements of the pitch change mechanism were a maximum pitch rate of 8°/sec and a stiffness of 20×10^6 inch-pound per radian.

The generator specification was 4160 V, 3ϕ, Y-connected, synchronous, 1875 kVa at 60 Hz. Emergency power was to be provided by an auxiliary power unit in the control enclosure. Slip rings or loop cable were indicated for the power connection at the nacelle. Protection items include conventional switchgear as well as lightning protection. Electrical system stability was required for 5 to 1000 MW. The control system functional requirements include startup and synchronization, shutdown, and maintenance of electrical stability. Unattended operation is called for with manual operation from the WTG site. Remote monitoring and control by power dispatcher is also required. Finally, an engineering data acquisition system should be provided.

DESIGN DESCRIPTION

The MOD-1 WTG has a configuration which is depicted in the photo of a scaled model shown in figure 3. It has a 200-foot two-bladed downwind rotor that operates at a constant 35 rpm with its axis at an elevation of 140 feet. An outline drawing (fig. 4) defines the basic WTG dimensions.

The rotor drives a synchronous generator through a speed increaser gearbox. Synchronous speed and power are controlled by varying blade pitch as the wind speed varies. The tower is a 131-foot truss structure with a 48-foot base. A control enclosure and transformer are installed at ground elevation below the WTG within the envelope of the four-tower legs. The major elements of the WTG are briefly described as follows:

a. Rotor. - Two steel blades are attached to the hub barrel via three-row cylindrical roller bearings which permit the pitch angle of the blade to be varied 105 degrees from full feather to maximum power. Blade pitch is controlled by hydraulic actuators which provide a maximum pitch rate of 14 deg/sec. Figure 5 shows the pitch control block diagram.

The hub tailshaft provides the connection to the low-speed shaft and to the dual tapered roller main bearing, which supports the rotor and one end of the low speed shaft.

Each blade is tapered in planform and thickness as shown in figure 6. It utilizes a NACA 44XX series airfoil with thickness ratio varying from 33% at the root to 10% at the tip. The twist of 11° varies linearly from root to tip. The blades are mounted on the hub at a 9° cone angle to optimize stresses due to thrust and centrifugal forces.

The blade in final assembly is shown in figure 7. The major blade load carrying member, a hollow spar, is fabricated from A533 Grade B, class 2 high strength, low carbon steel. The trailing edge is fabricated from urethane foam sections with 301 stainless steel skins.

b. Drive train. - Figure 8 shows the drive train which consists of the low-speed shaft and couplings, a three-stage gearbox and the high speed shaft which drives the generator. The gearbox has parallel shafts. The high speed shaft incorporates a dry disk slip clutch for protection against torque overloads, and a disk brake that stops the rotor and holds it in the parked position. The gearbox lubrication system also provides oil to the rotor bearing and dissipates waste heat by means of a cooler suspended below the nacelle.

c. Power generation/control. - Figure 9 is a block-diagram of the power generation/control system. A GE synchronous AC generator is driven at 1800 rpm by the high-speed shaft. A shaft mounted, brushless exciter, controlled by a solid state regulator and power stabilizer provides voltage control. Generator output at 4160 volts is brought by cables and a slip ring at the yaw bearing down the tower to the control enclosure and then on to the utility interface via a 2000 kVA step-up transformer.

d. Nacelle structure. - A welded steel bedplate is the primary structure, supporting all equipment mounted on top of the tower and providing a load path between the rotor and yaw structure. Other equipment mounted on the bedplate includes the pitch control and yaw drive hydraulic packages, the control electronics and lubrication pumps. A removable aluminum fairing enclosing the nacelle for weather protection has louvers for air cooling and provides mounting for wind sensors.

e. Yaw drive. - Rotation is provided by the yaw drive system, consisting of upper and lower structures, a cross-roller bearing, dual hydraulic motors and hydraulic brakes as shown in figure 10. The yaw brakes control dynamic excitations by maintaining a rigid connection while the nacelle is stationary and also assist in damping yaw motions by maintaining a holding force while the nacelle is being rotated. Power and signal data are transferred to tower mounted cable by slip rings.

f. Tower. - The steel tubular truss tower as shown in figure 11 is made of seven vertical bays. Tubular members were used to reduce "tower shadow" loads on the blades as they pass the tower. Access to the yaw drive and nacelle area is provided by a cable guided, gondola-type lift also shown in figure 11.

g. Ground equipment. - The major ground equipments are the control enclosure, station battery system and the 4.16/12.57 kV stepup transformer. The enclosure, measuring 28 x 10 feet is an air-conditioned steel structure which contains power equipment switchgear and the WTG control and recording unit.

PROGRAM STATUS

During the summer of 1978 the WTG without blades was assembled at the GE Riverside facility in Philadelphia. As shown in figure 12, the yaw drive, nacelle structure, drive train, generator and hub with the blade pitch change mechanism were mounted on the upper section of the tower which served as a test fixture. The control enclosure, control electronics, switchgear, and computer were also assembled. An auxiliary 200 hp motor was mounted on the nacelle structure above the low-speed shaft to rotate the WT drive train and rotor during test. The NASA Portable Instrumentation Van was used to record data from the Engineering Data Acquisition System Sensors.

The factory test program consisted of a checkout of the lube and hydraulic systems and the operation of the yaw drive and pitch change mechanism. The yaw drive rotated 360° and the brake system operation was demonstrated. The pitch change mechanism was operated from the maximum power position to full feather. The rotor was driven at rated rpm, but at a reduced power level, for 20 hours with intermittent yaw maneuvers and pitch change operations. The power generation system was checked out with generated power being dissipated in a load bank.

After test completion in October of 1978 the WTG was disassembled into subassemblies for shipment to the site. Most components were either oversize or overweight for normal road transportation. All subassemblies were shipped by motor vehicle, however, some required special permits. The hub and pitch change mechanism assembly which was shipped by rail due to its weight of 96,000 pounds was the one exception.

Howard's Knob at Boone, NC, is the site selected by DOE for the MOD-1 WTG. The elevation of this site located in northwest NC is 4420 feet above sea level. The Blue Ridge Electric Membership Corporation (BREMC), a rural electric cooperative, will operate and utilize the power generated by the WTG. BREMC is the largest cooperative in North Carolina with annual sales of 555 million kW-hr. BREMC with a peak load of 136 megawatts purchases essentially all of its power for its members from Duke Power.

The Howard's Knob site overlooking the college town of Boone was cleared of trees and graded during the summer of 1978. The concrete tower foundations with the control enclosure, tower lift and transformer pads were poured during August 1978. During October the tower was erected in three sections using a Manitowoc 4100N crane with a boom height of 230 feet and a lift capacity of 55 tons. The WTG installation began in November and consisted of a series of lifts. One lift was considered but was found not to be cost effective and would have had significant schedule risk due to the limited availability of cranes with 200 tone capacity. The installation of the WTG without blades was completed in December and can be seen in figure 13. Figure 14 is a closer view of the WTG with the fairing in place. Shortly after the WTG was assembled aloft, the control enclosure was installed beneath the tower.

Site activity from mid-December to mid-February was curtailed due to extreme cold (wind chill factors of -50° F), high winds (60 mph), icing on the WTG and snow which made the site inaccessible.

Currently the WTG is fully assembled except the blades which are expected to be delivered in April. All cables have been pulled, terminated and checked out. The machine has been mechanically checked out in a similar manner to the Riverside tests, and control/software integration has been in progress since March.

CALCULATED OPERATION CHARACTERISTICS

The steady-state operating characteristics are derived from the MOD-1 performance curve, C_p vs λ (fig. 15). Calculations of the operating characteristics were based on power rating of 2000 kW_e, a rotor diameter of 61 m (200 ft), and a rotor speed of 35 rpm. The MOD-1 design rpm was determined by maximizing annual energy capture (6.5×10^6 kW-hr) at sea level with 100% availability in an 18 mph (mean) wind regime. Using the C_p curve, the electrical power output is calculated as a function of wind speed (fig. 16) which establishes the steady state operating requirements for pitch control and the operating wind speeds for generator cut-in and rated power. The breakaway wind speed is based on calculations of the minimum static blade torque required for starting.

The MOD-1 operating envelope (fig. 17) indicates the operational modes and limits for variations in wind speed and direction. The non-operating mode is shown below the cut-in wind speed of 11 mph. A 5-minute average wind speed and yaw angle above 11 mph and 5° respectively will initiate a yaw maneuver, as shown. Normal operation is obtained when the 5-minute average yaw angle is within the 5° envelope. Normal shutdown is initiated when the 5-minute average wind speed exceeds 35 mph or exceeds the wind speed-yaw angle envelope as shown in figure 17. The emergency shutdown mode is initiated when instantaneous wind speeds and yaw angles exceed 40 mph or 90°, respectively.

Calculations of the system dynamic operating characteristics are based on inherently conservative assumptions of statistical wind dynamics and resulting dynamic interactions with the wind turbine. Resulting operating characteristics in terms of critical operational modes, control functions, and electrical stability are shown in table III.

COST OF ELECTRICITY/COST DRIVERS

As the first of the megawatt class wind turbines, the MOD-1 was designed to insure long life, reliability and safe operation with current state-of-the-art technology. The resulting cost of electricity is expected to be high on the "learning" curve and reflects the inherent design conservatism indicated by subsystem costs and weights. Therefore, the principle cost drivers are the subsystem weights, a lack of maturity in blade design and fabrication, and a lack of experience in assembly, erection, and testing of the system.

A breakdown of the MOD-1 weights and costs of electrical energy by subsystem are shown in table IV to aid in identifying the significant cost drivers. The cost of electricity (COE) is derived for each subsystem, based on an annual FCR of 18%, an annual energy capture with 90% availability in an 18 mph (mean) wind regime, and includes the cost-of-doing-business in the cost of each subsystem. An annual operating maintenance cost of 1% is conservatively assumed as reasonable for the early "prototype" systems.

DESIGN TRADE-OFFS

The MOD-1 Configuration was primarily dictated by the NASA-LeRC design specifications as previously discussed. Some configuration options were left open for design tradeoffs. The procedures used to evaluate these options were generally tradeoffs between performance, structural design requirements, and cost. A brief description of the tradeoff procedure and results for each option is shown below:

Blade airfoil - Performance vs manufacturability/cost. Airfoil selection driven by manufacturability. Selected 44XX series.

Blade twist - Performance vs blade loading. Blade twist driven by structural design requirements. Selected 11 degrees.

Rotor speed - Maximum energy capture vs torque, cost. Rpm driven by maximum energy capture for a given rotor diameter, rated power, wind duration curve. Selected 35 rpm.

Rotor cone angle - Balance blade thrust - centrifugal loads. Cone angle selected to minimize blade root stress. Selected 9°.

Rotor axis inclination - Blade clearance vs yaw moments. Rotor coning more effective. Selected 0° axis inclination.

Hub (rigid vs teetered) - Blade-hub load reductions vs cost. Rigid hub less costly. Selected rigid hub.

FACTORS AFFECTING THE DESIGN

On the MOD-1 Program one of the most significant factors affecting the design was the Technical Specification. During the preliminary design phase a few of the requirements were modified to reduce the WTG costs. The double bearing shaft of the drive shaft/rotor support was replaced by a single bearing with reduced weight and cost. For the yaw drive, a hydraulic motor was used instead of the electric motor-driven worm gear which resulted in less space and weight and better overload protection. Reduced cost was also obtained for the blade inching drive by replacing the independent drive on the high speed shaft with a blade operational control system.

Prior to the establishment of the final design, a rigorous requirements assessment analysis was conducted in an effort to minimize requirements and, hence, reduce WTG costs. At this late stage of the design process the opportunities were limited; however, critical design parameters were modified to reduce WTG costs and the cost of generated electricity. For example, epoxy/glass was replaced with steel as the blade structural material. The rated power was increased from 1500 to 2000 kW as a system limit (present blades have a limit of 1818 kW) in order to increase the rating and energy capture. The cut-out speed was reduced from 50 to 35 mph. This decreased the blade and system loads with only a minor loss (∿5%) in energy capture. Furthermore, the blade tip clearance was reduced from 50 to 35 feet in order to lower the tower height. This reduced cost and system loads with a minor (∿3%) loss in energy capture.

The load requirements were also modified to realistically include the effects of accumulative fatigue over the entire wind regime. In addition, the load cases were simplified to four cases which included continuous, gust, emergency feather and hurricane loads, as shown in table V. To make the gust loading more realistic the wind gust model was modified per figure 18 which replaced the earlier 1-cosine curve.

After the requirements and the design concept were solidifed, the sizing and detail of each component were dictated by certain design parameters. The most significant design drivers for each major component are shown in table VI. As one can observe, fatigue and stiffness have driven the weight of the mechanical configuration. Stiffness has played a prominent role in sizing the pitch change mechanism and the 3.2 P tower, and consequently has affected costs. Limit loads have played a secondary role in dictating system weights.

DESIGN EVALUATION

As mentioned earlier, the MOD-1 WTG is the first of the megawatt size WTG's. With the reservations that we do not have any operating experience at this time, some overall conclusions about the MOD-1 WTG design can be made:

- The design is conservative.
- The weight and cost are high.
- The installation is routine.
- The extensive instrumentation should provide design data for future WTG's.

RECOMMENDATIONS FOR FUTURE DESIGNS

Our current recommendation for a future design is the result of a NASA-directed MOD-1A trade-off study. The objective of the study was to reduce weight and cost of a 2 megawatt WTG with the same operational characteristics as the MOD-1 without restrictions on the design concept. The objectives of the study were to: reduce weight from 655,000 to 400,000 pounds or less; reduce second unit cost from $2,900/kW to $1,000/kw; and reduce the cost of energy from 18¢/kW-hr to 5¢/kW-hr (all costs in 1978 dollars). The design approach was to "wage war on weight" by loads alleviation and simplification. Three candidate concepts, shown in figure 19, were considered for trade-off studies of critical design parameters.

System Number 3 of figure 19 was selected which has as its major characteristics a teetered hub, two downwind blades with partial span control, an integral gearbox structure, an inclined rotor axis and a "soft" tower. Figure 20 is an outline drawing of the MOD-1A. The selected blade has a MOD-1 aerodynamic configuration except that the concept of hydraulic driven partial span torque control is incorporated in the outer 15% of the span. The teetered hub concept resulted in the lowest loads for a two-blade system. The gearbox/bedplate incorporates the rotor and yaw support structure into the gearbox casing, thus eliminating structural weight. The tower is a conical shell with a lateral bending frequency of 1.2 P.

An overall comparison of the MOD-1 and 1A can be seen from the silhoutte of -1 superimposed over the MOD-1A in figure 20. This comparison illustrates the striking reduction in size of the MOD-1A. The most impressive statistic is the magnitude of the weight reduction shown in figure 21. WTG costs, as a consequence, are reduced dramatically, and it follows that the cost of generated electricity is reduced accordingly. The projected installed cost in 1978 dollars of the MOD-1A is in the neighborhood of $1050/kW. As a result, the cost of energy has been reduced to 6¢/kW-hr which is a significant improvement when compared to earlier WTG's, as shown in figure 22. In summary, the MOD-1 will serve the purpose of supplying valuable WTG operating data for the national wind program and the concepts of the MOD-1A will lead us to commercially viable WTG's.

DISCUSSION

Q. Have you investigated designing a machine with a soft tower? What technical risks, if any, are associated with a soft design?

A. This was considered in the slides on our recommendations for the future that were not presented. A conceptual design study, directed by NASA, was conducted in 1977 after the MOD-1 design was finished. In essence, we evolved some concepts that we thought could reduce cost. The soft tower was one of them. We also considered the concept of using an integral gearbox, where the gearbox provides the basic structural member on the tower. We also recommended partial span control to reduce pitch change mechanism costs.

Q. Your normal operation was shown as a ±5°. Do you feel this is a very close angle?

A. That value was a 5-minute average, not an instantantous value. I think the variation was up to 15°. That is the way the system is now programmed to opeate, and we will find out from actual experience if that is the effective way to operate the system. Based upon all of the loads that we can measure and the flexibility of using a computer-based control system, we can then make changes in the software and alter that operation.

TABLE I. SUMMARY OF TECHNICAL SPECIFICATIONS

ITEM	REQUIREMENT
RATED POWER	1500 kW_e @ 22 MPH
CUT-IN WIND SPEED	11 MPH
CUT-OUT WIND SPEED	35 MPH
MAXIMUM DESIGN WIND SPEED	150 MPH (AT ROTOR CENTER LINE - NO WIND SHEAR)
ROTORS/TOWER	1
LOCATION OF ROTOR	DOWNWIND
DIRECTION OF ROTATION	CC (LOOKING UPWIND)
BLADES PER ROTOR	2
CONE ANGLE	OPTIONAL
INCLINATION OF AXIS ROTATION	$\leq 15^{\circ}$
ROTOR SPEED CONTROL	VARIABLE BLADE PITCH
ROTOR SPEED	OPTIONAL/CONSTANT
BLADE DIAMETER	200 FT. (NOMINAL)
AIRFOIL	OPTIONAL
BLADE TWIST	OPTIONAL
TOWER	STEEL TRUSS
BLADE TIP TO GROUND CLEARANCE	>50 FT.
HUB (RIGID VS. TEETERED)	OPTIONAL
TRANSMISSION	FIXED RATIO GEAR, 96% EFFICIENCY
GENERATOR	60 Hz/SYNCHRONOUS
YAW RATE	$\leq 2^{\circ}$/SEC
CONTROL SYSTEM	ELECTRO MECHANICAL/ MICROPROCESSOR

TABLE II. BLADE DESIGN LOADS

CASE NUMBER	DESCRIPTION	FREQUENCY OF OCCURRENCE
1	RATED POWER, RATED WIND SPEED	10^8
2	INITIALLY AT RATED POWER, WIND SPEED INCREASE FROM RATED TO 60 MPH IN 1/4 SEC, NO PITCH CHANGE, ROTOR OVERSPEED 25%.	10^5
3	INITIALLY AT RATED POWER, CHANGE PITCH ANGLE TO FEATHER IN 11 SECONDS.	OCCASIONAL (PROPORTIONAL LIMIT)
4	INITIALLY AT RATED POWER, WIND SPEED DECREASED FROM RATED TO ZERO IN 1/4 SECOND.	10^5
5	BLADES IN HORIZONTAL FEATHERED POSITION: WIND SPEED 120 MPH FROM ANY DIRECTION.	OCCASIONAL (PROPORTIONAL LIMIT)
6	ROTOR OPERATING AT DESIGN RPM, WIND SPEED 50 MPH AT 20° YAW ANGLE, CHANGE YAW ANGLE @ 2°/SEC.	10^5
7	ROTOR OPERATING AT DESIGN RPM, NO POWER, VELOCITY RETARDATION OF 50% DUE TO "TOWER SHADOW"	10^5

TABLE III. - DYNAMIC OPERATING CHARACTERISTICS

Item	Characteristic
CRITICAL OPERATING MODES:	
1. WIND VARIABILITY:	• GUSTING - MAGNITUDE/DURATION (RANDOM) • DIRECTIONAL (RANDOM INFLOW)
2. CYCLIC BLADE LOADING:	• TOWER • WIND SHEAR • WIND INFLOW
3. NON-OPERATING:	• CUT-OUT • LOSS OF LOAD • FEATHERING
CONTROLS AND RESPONSE	
1. PITCH CONTROL:	• 2.1 °/SEC OPERATING/0.2 SEC RESPONSE • 14 °/SEC (MAX. EMERGENCY FEATHER)
2. YAW CONTROL:	• 15 °/MIN.
3. SLIP CLUTCH:	• @ 15,400 FT-LBS (188% RATED TORQUE)
ELECTRICAL STABILITY	
1. CALCULATED TORQUE/SPEED VARIATIONS:	• 420,000 FT-LBS (± 100%) • 35 RPM (± 2%)
2. CALCULATED ELEC. POWER VARIATIONS:	• ± 6% (CYCLIC) • ± 30% (MODERATE GUSTS) • ± 100% (MAX. GUSTS)
3. CALCULATED VOLTAGE VARIATIONS:	• MODERATE GUSTS (<5% @ GEN. TERMINALS) • MAXIMUM GUSTS (<10% @ GEN. TERMINALS)

TABLE IV. - COST OF ELECTRICITY
(MOD-1 2ND UNIT RECURRING COSTS)

SUBSYSTEM	WT, LBS	COE, ¢/kW-HR	% TOTAL COE
BLADES	41,000	4.6	25%
HUB	44,000	1.3	7
TORQUE CONTROL	23,000	0.6	3
NACELLE/STRUCT. & DRIVE TRAIN	153,000	2.4	13
POWER GEN. EQUIP.	17,000	1.1	6
CONTROLS	1,000	0.7	4
YAW DRIVE	56,000	1.0	5
TOWER	320,000	1.3	7
ASSEMBLY/TEST	-	2.3	12
SITE PREP/ERECT. & CHECKOUT	-	2.4	13
TOTALS	655,000	17.8	95%
ANNUAL O&M	-	0.8	5%
TOTAL COE		18.6	100%

TABLE V. - MODIFIED BLADE DESIGN LOADS

CASE	REQUIREMENT	FREQUENCY OF OCCURRENCE
A	ACCUMULATIVE FATIGUE ENTIRE WIND REGIME 20° INFLOW ANGLE INCLUDED	4×10^8 CYCLES
B	35 - 50 MPH GUST 35 - 20 MPH GUST BLADE DISC FULLY IMMERSED MODIFIED WIND GUST MODEL NO PITCH CHANGE	10^5 CYCLES
C	EMERGENCY FEATHER RPM — PITCH RATE $N_O < n < 1.4\ N_O$ — 14° SEC $n < N_O$ — 3° SEC	10^5 CYCLES
D	HURRICANE BLADE FEATHERED IN HORIZONTAL POSITION 120 MPH FROM ANY DIRECTION	OCCASIONAL (PROPORTIONAL LIMIT)

TABLE VI. - DESIGN DRIVERS

SUBSYSTEM	DESIGN DRIVER
BLADES	CUMULATIVE FATIGUE, EMERGENCY FEATHER LOADS AND BLADE STIFFNESS.
HUB	FATIGUE; BLADE WEIGHT AND TORQUE CONTROL MOMENTS.
TORQUE CONTROL	GUST LOADS, MAX. FORCE EMERGENCY SHUTDOWN AND STIFFNESS.
BEARING & DRIVE TRAIN	MAX. AND CYCLIC TORQUE ROTOR LOADS ON BEARING, POWER LEVEL.
NACELLE STRUCTURE	CUMULATIVE FATIGUE IN WELDS.
POWER GENERATION EQUIPMENT	POWER LEVEL, POWER QUALITY WTG/UTILITY PROTECTION.
CONTROLS	UNATTENDED OPERATIONS, POWER QUALITY.
YAW DRIVE SYSTEM	TORQUE (MAX. WINDSPEED & INFLOW ANGLE) OVERHANG MOMENT.
TOWER	LATERAL STIFFNESS AND FATIGUE.
ASS'Y. & TEST	NO. OF PARTS, JOINTS AND CONNECTIONS CRITICAL ALIGNMENTS AND WEIGHTS.
SITE PREPARATION, ERECTION AND CHECKOUT	SITE CHARACTERISTICS, LOCATION, WTG WEIGHT AND NO. OF SUBASSEMBLIES.

- <u>DESIGN, FABRICATION, INSTALLATION AND TEST OF A 1500 kW WIND TURBINE GENERATOR</u>:
    - STATE-OF-THE-ART TECHNOLOGY FOR MINIMUM TECHNICAL RISK.
    - COMPATIBLE WITH LARGE AND SMALL UTILITIES.
    - CAPABLE OF UNATTENDED OPERATION -- I.E. AUTOMATIC AND REMOTE CONTROL FROM UTILITY DISPATCH CENTER.
    - CAPABLE OF 30 YEAR LIFE, WITH "ROUTINE" MAINTENANCE.
    - MINIMUM AVAILABILITY OF 90%.
    - SAFE RELIABLE OPERATION.
    - SAFE AND EASY MAINTENANCE.
    - MINIMUM FIELD ASSEMBLY.
    - TRANSPORTATION VIA EXISTING SURFACE VEHICLES.
    - SNOW, RAIN, LIGHTNING, HAIL, ICING, SALT VAPOR, -31°F TO 120°F.
    - ACCEPTABLE APPEARANCE.
    - COSTS COMPETITIVE WITH ALTERNATE ENERGY SOURCES.
- DEVELOPMENT OF A WTG DESIGN WHICH CAN BE ITERATED INTO A SECOND-GENERATION VERSION SUITABLE FOR HIGH-VOLUME, LOW-COST PRODUCTION.
- ACQUISITION OF DATA AND OPERATING EXPERIENCE WHICH WILL LEAD TO MORE COST-EFFECTIVE, SECOND-GENERATION MACHINES.

Figure 1. - Program design requirements and objectives.

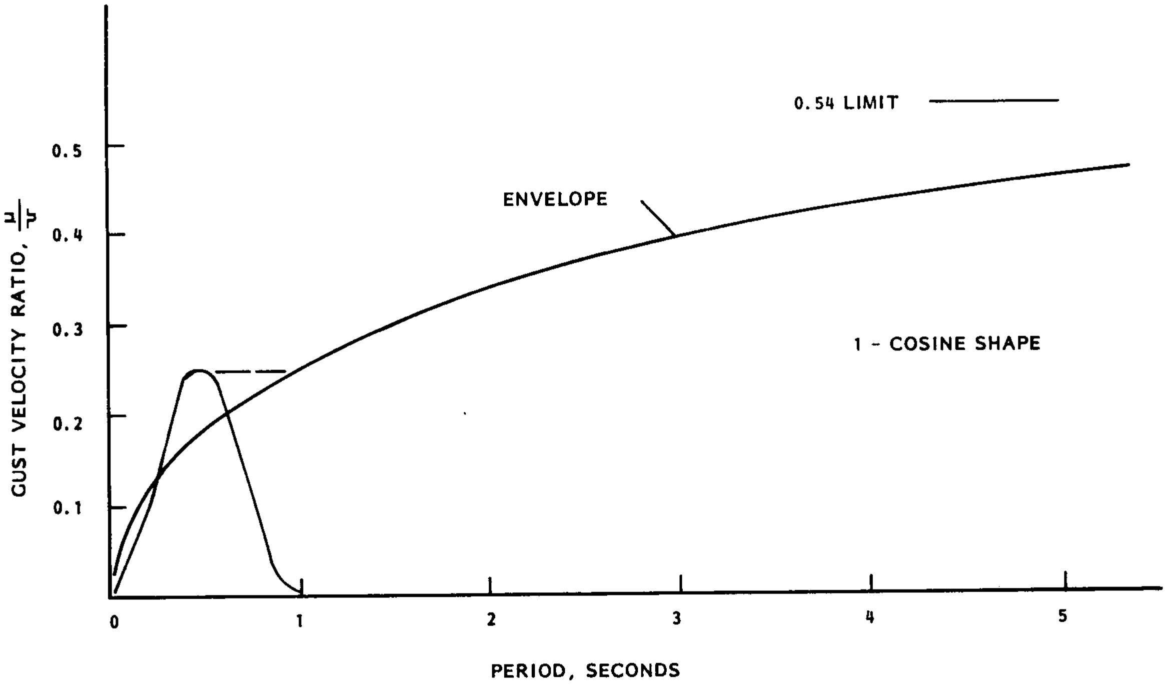


Figure 2. - 1-Cosine wind gust model.

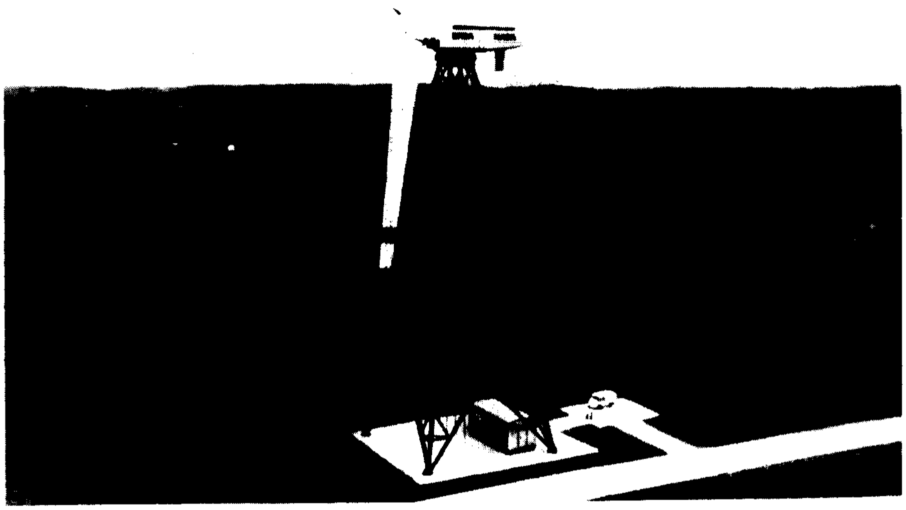


Figure 3. - Scaled model of MOD-1 WTG.

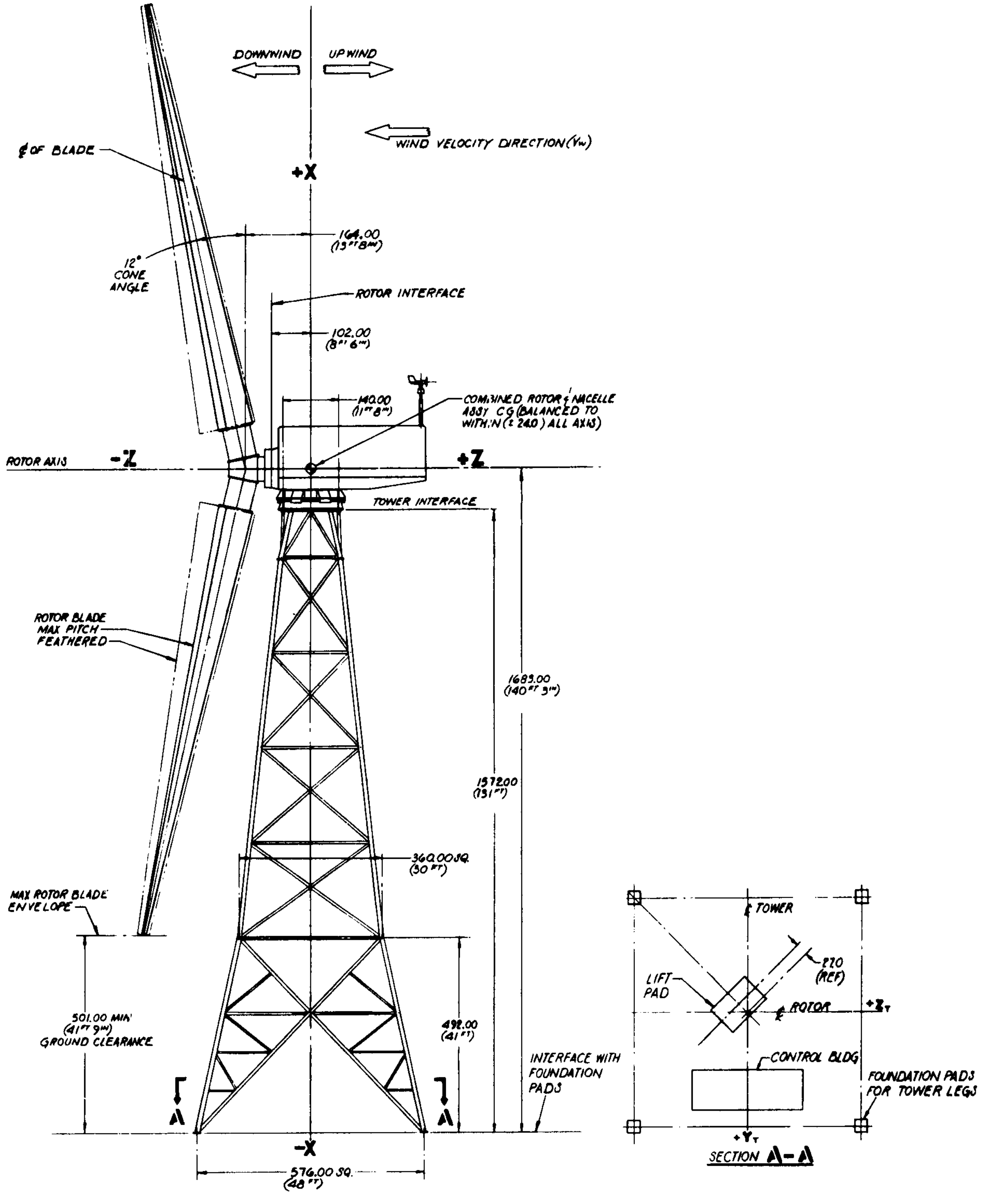


Figure 4. - MOD-1 WTG dimensions.

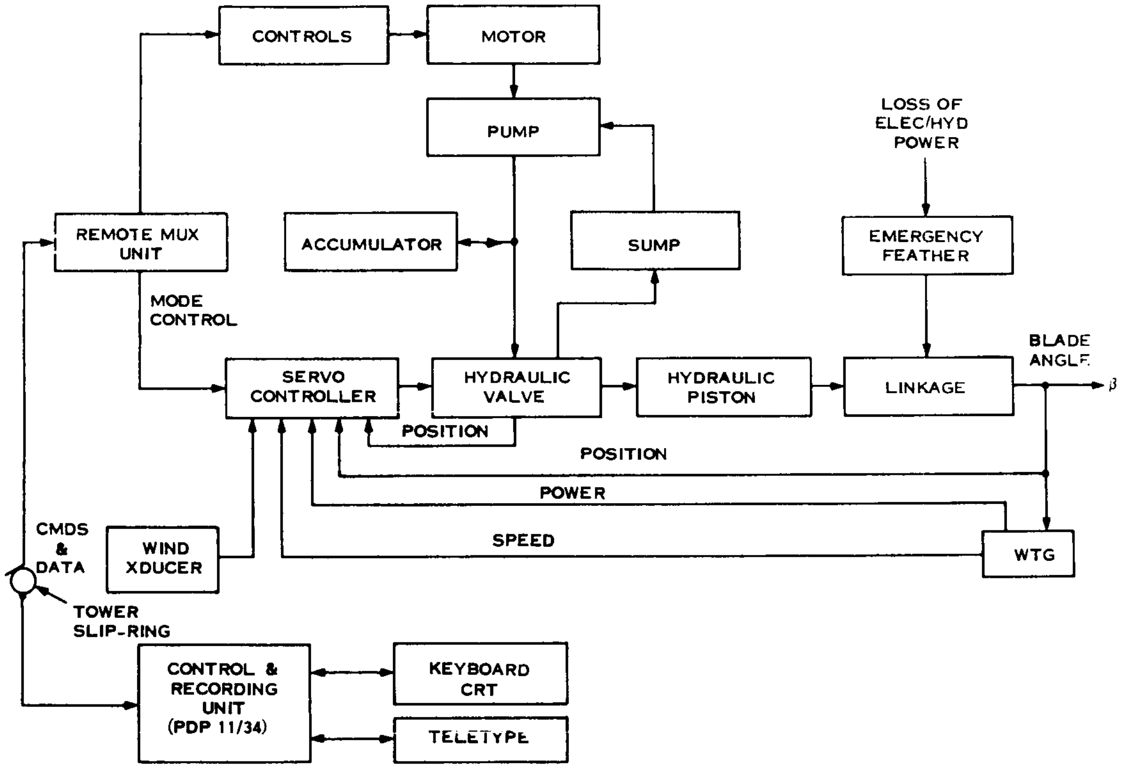


Figure 5. - Blade pitch control diagram.

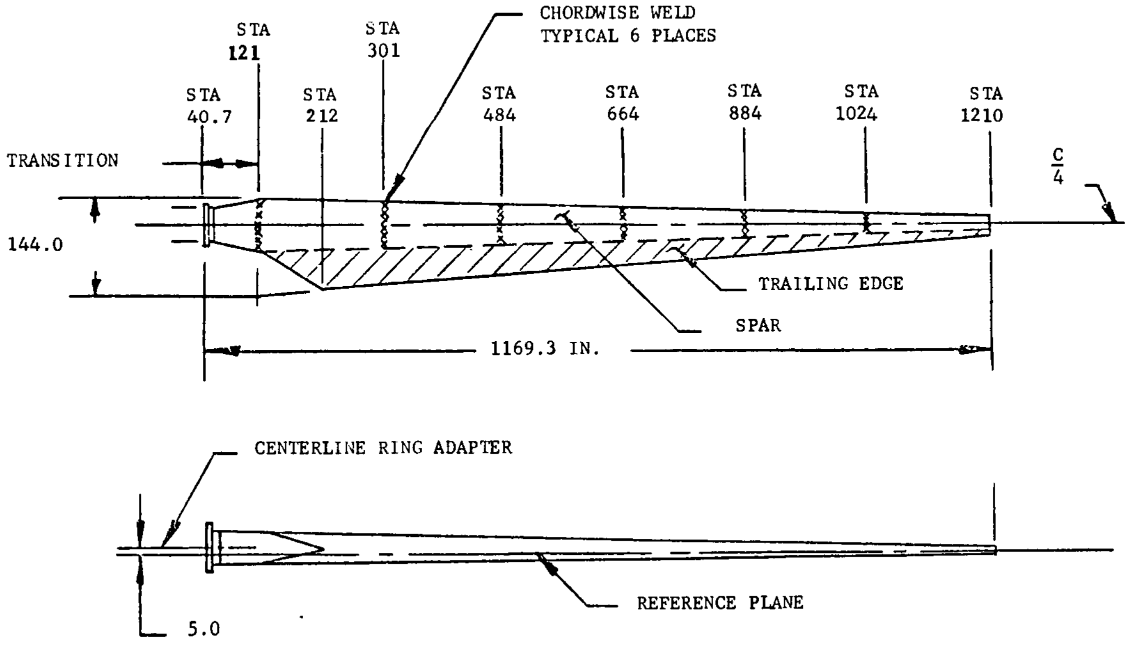


Figure 6. - Blade geometry.

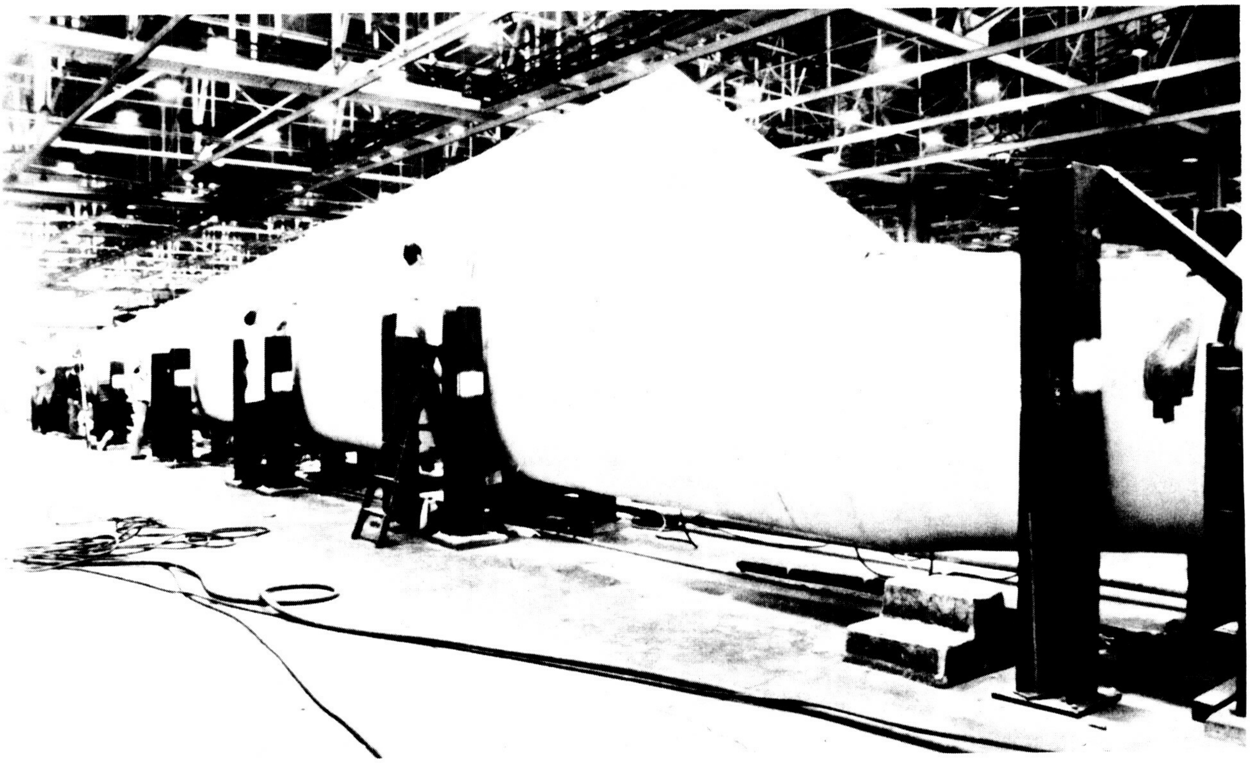


Figure 7. - Blade.

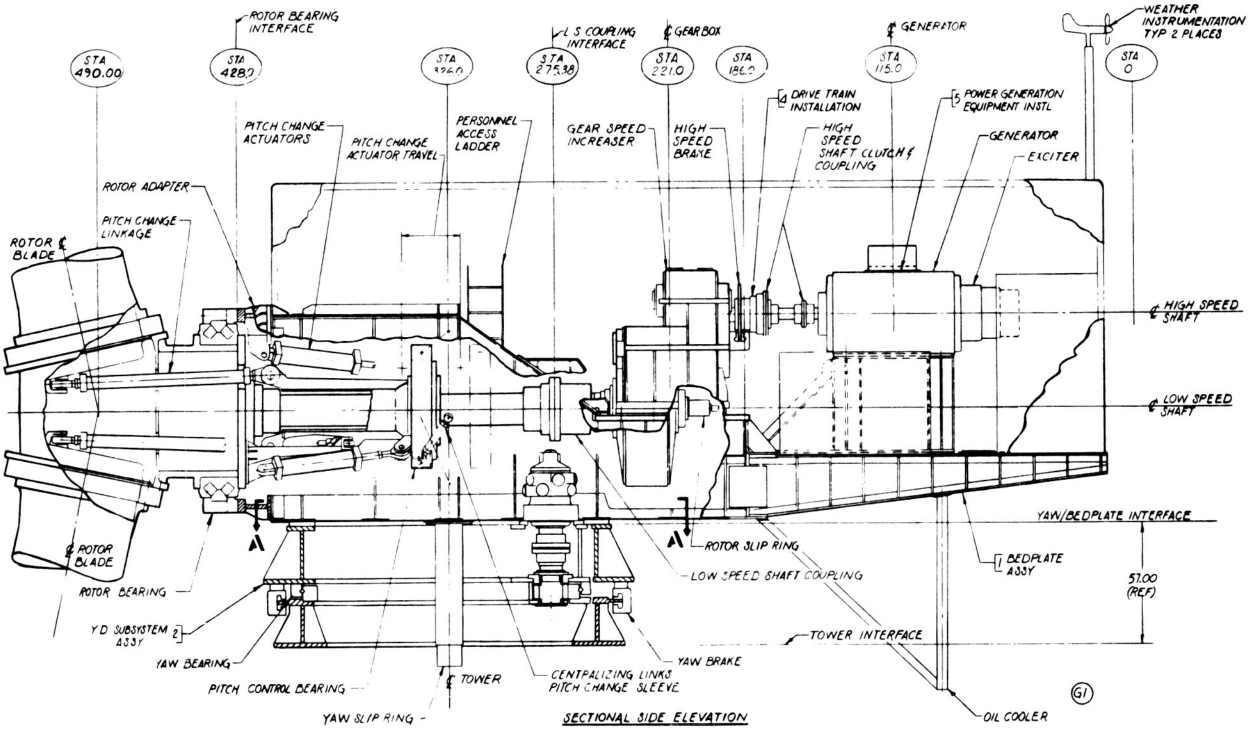


Figure 8. - Nacelle installations.

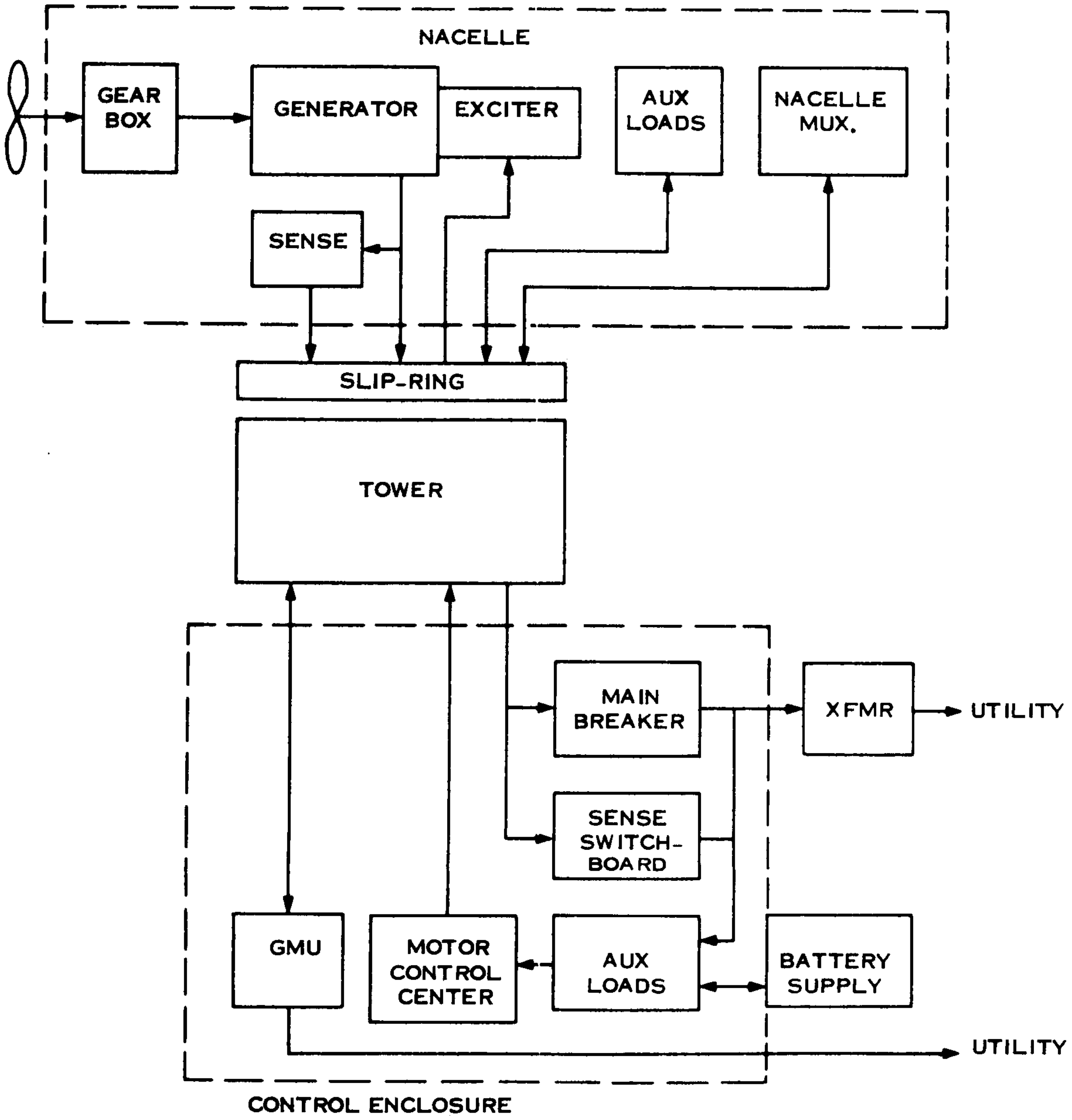


Figure 9. - Power generator/control block diagram.

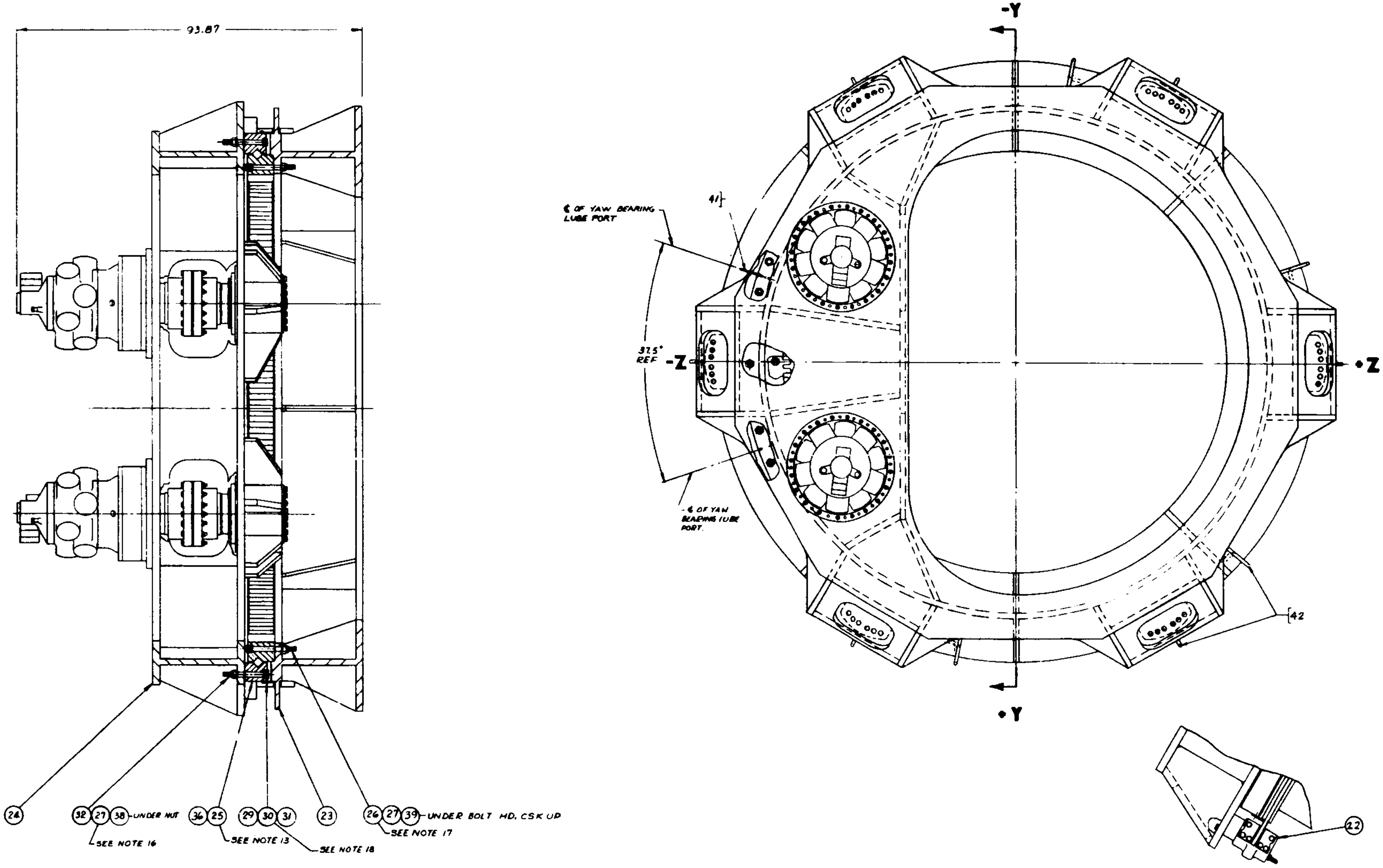


Figure 10. - Yaw drive installation.

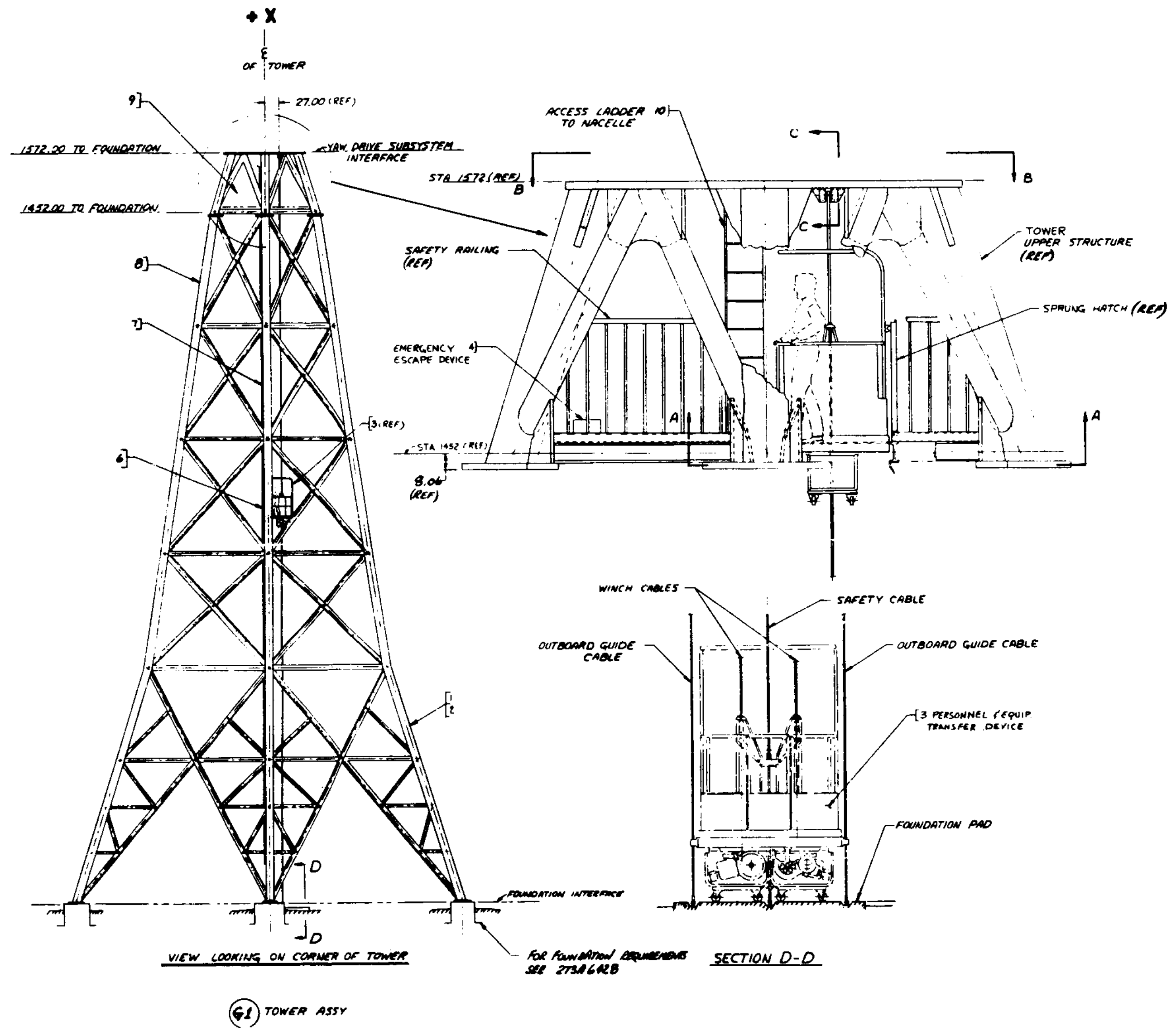


Figure 11. - Tower and lift.

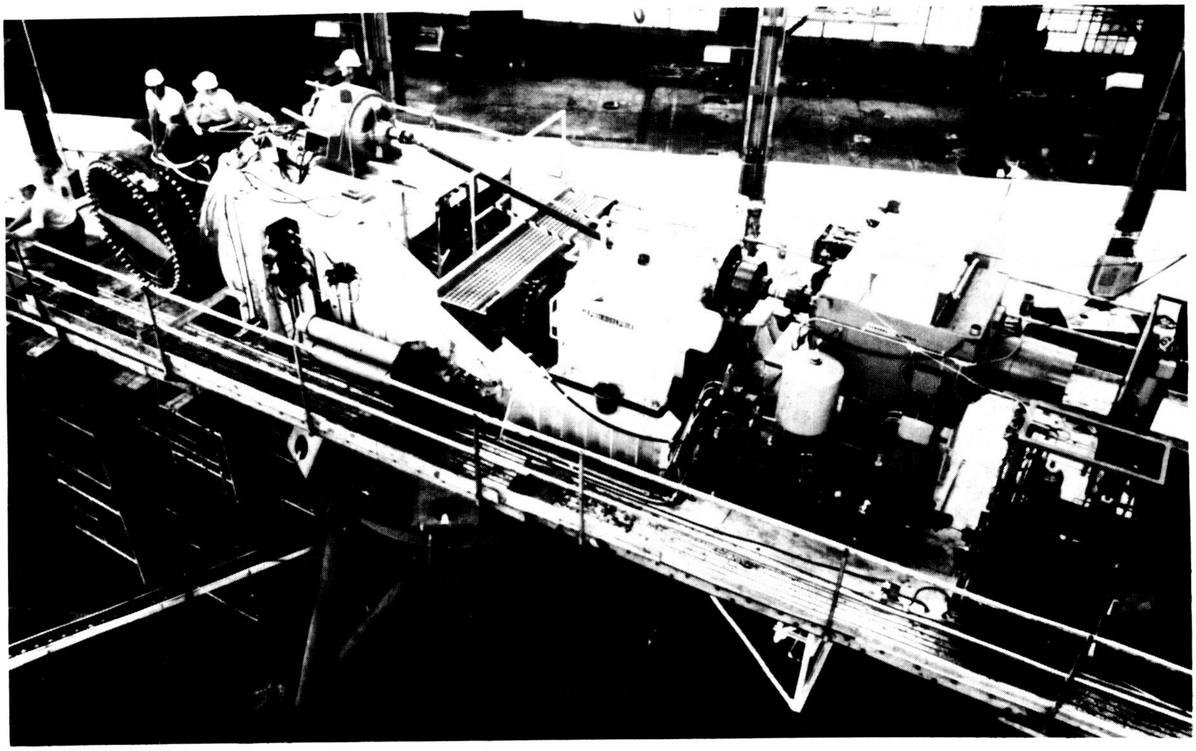


Figure 12. - Test of WTG without blades at Riverside.

Figure 13. - WTG assembly and crane.

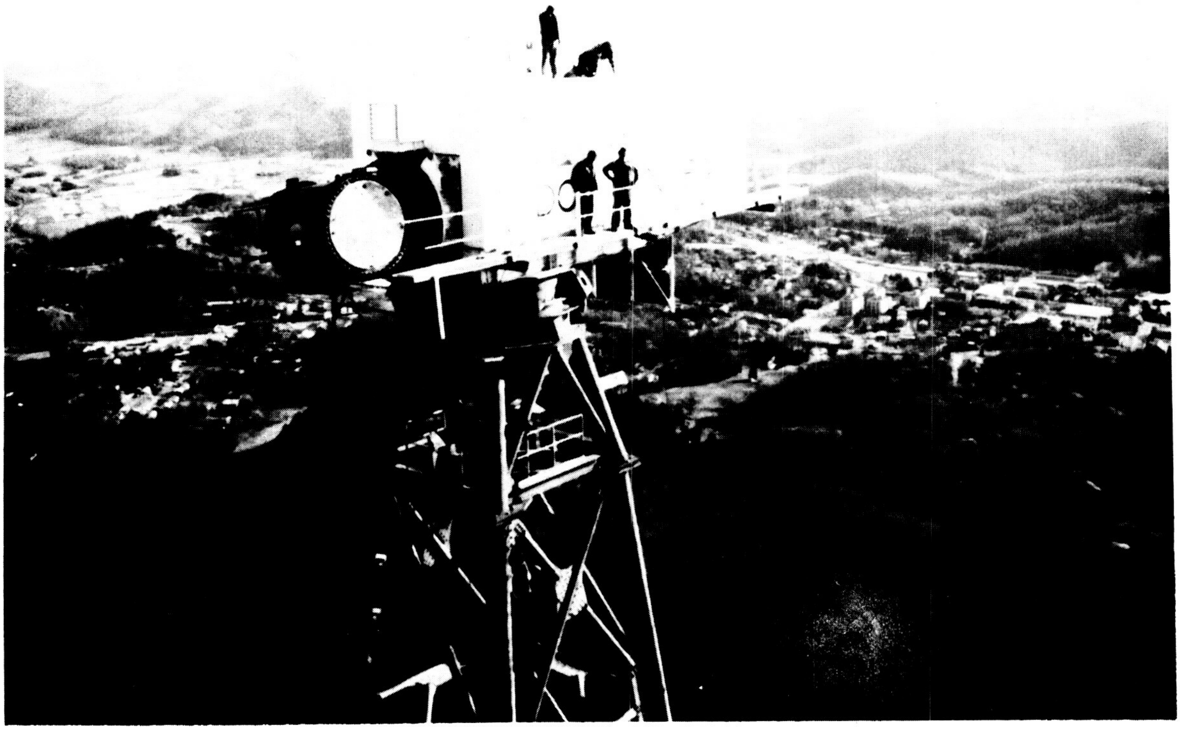


Figure 14. - WTG assembled.

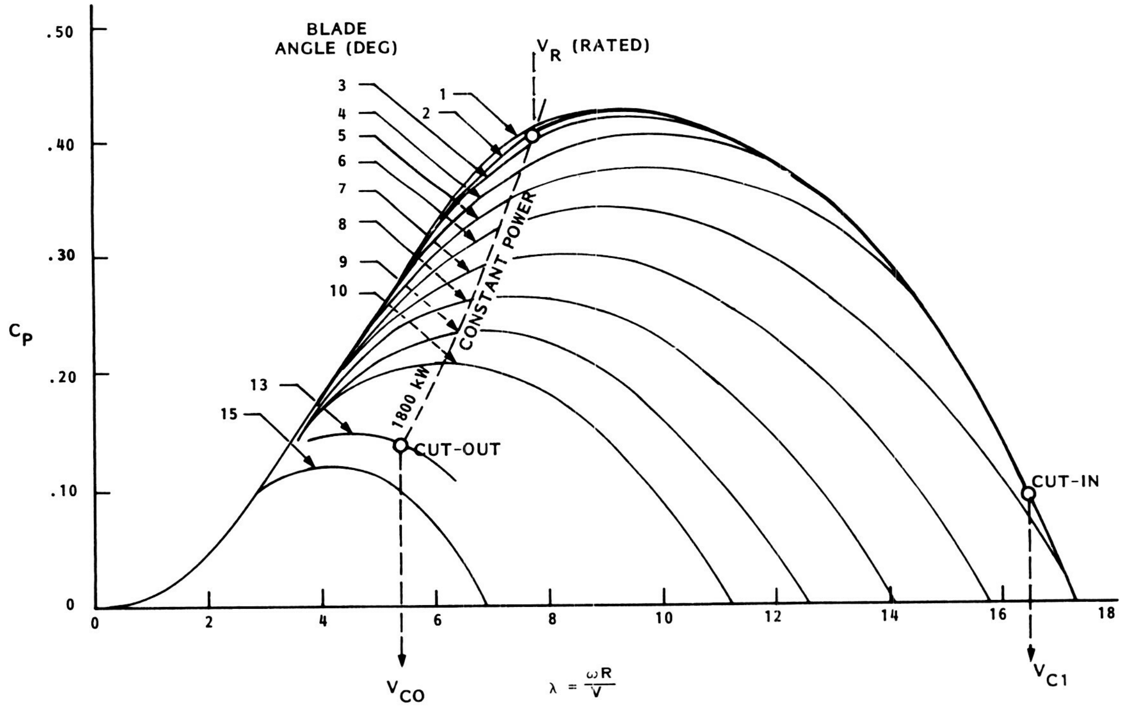


Figure 15. - MOD-1 performance curves.

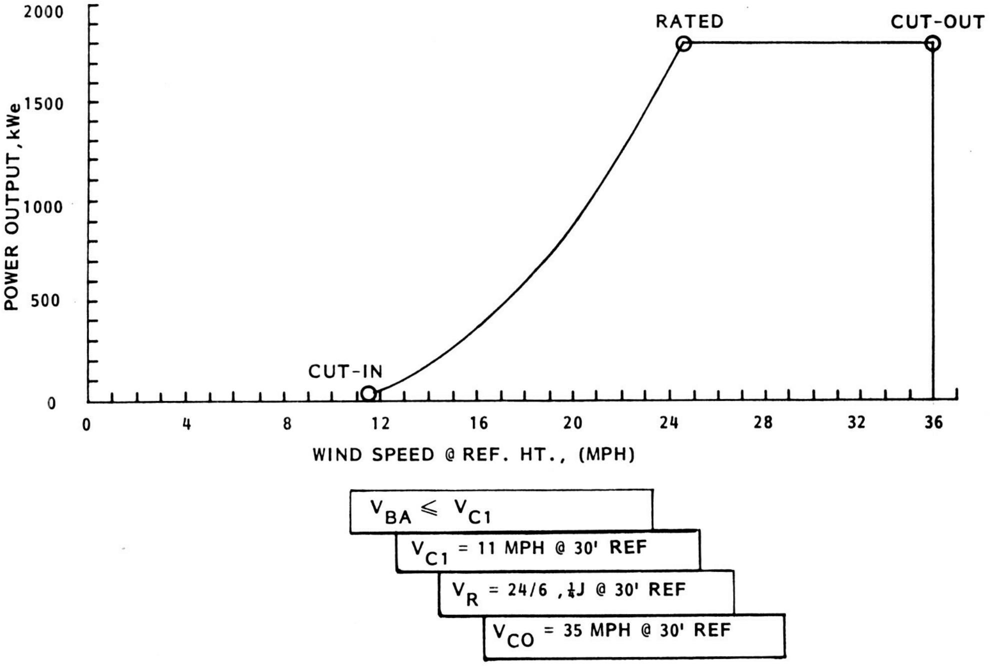


Figure 16. - Steady-state operating characteristics.

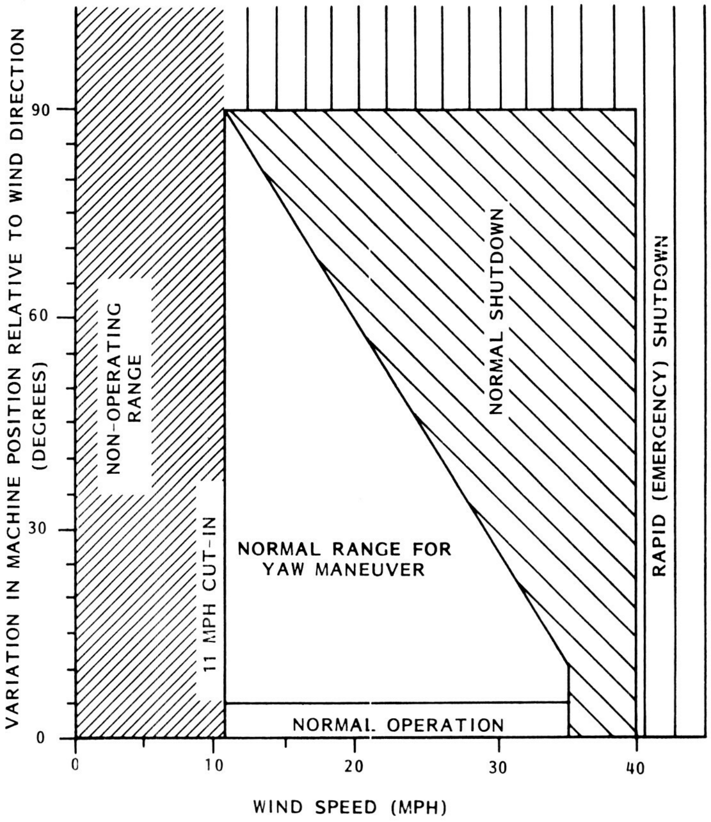


Figure 17. - MOD-1 operating envelope.

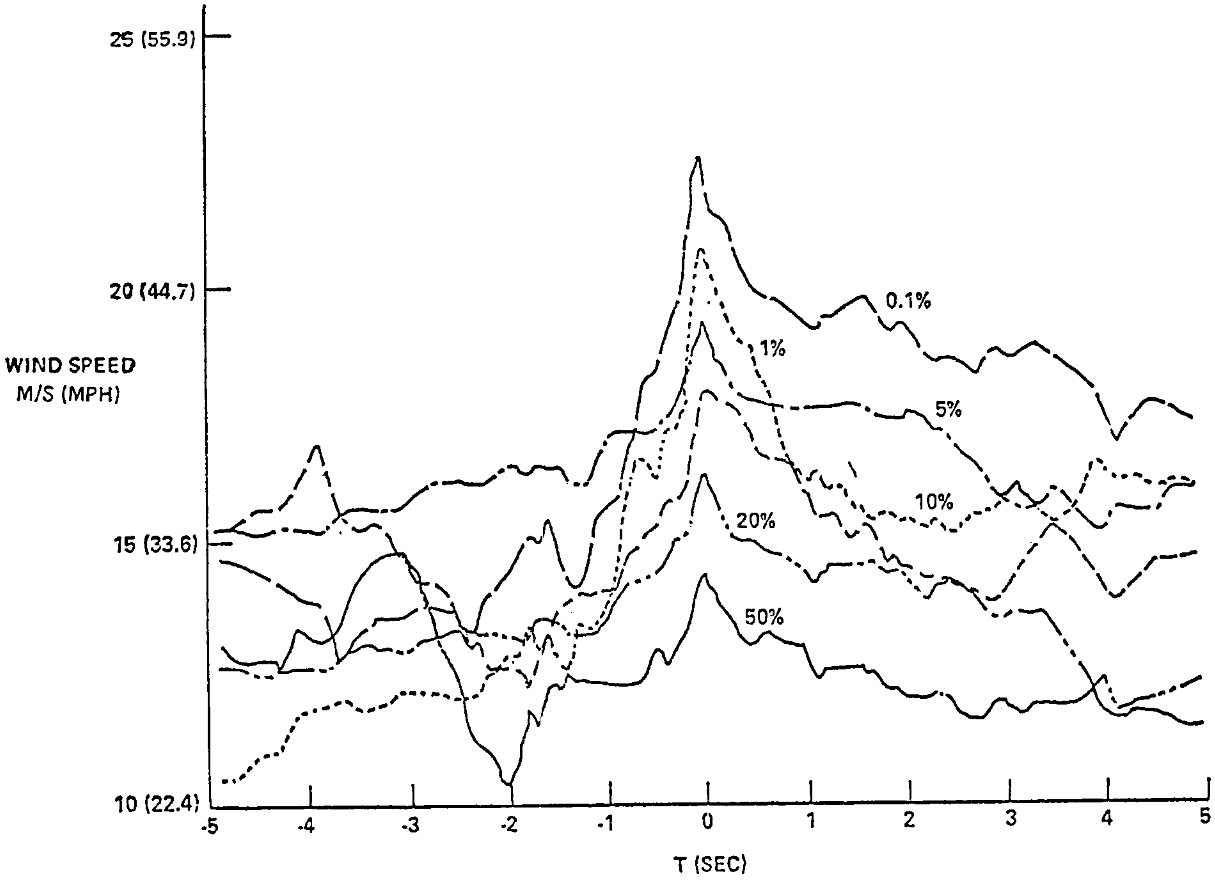
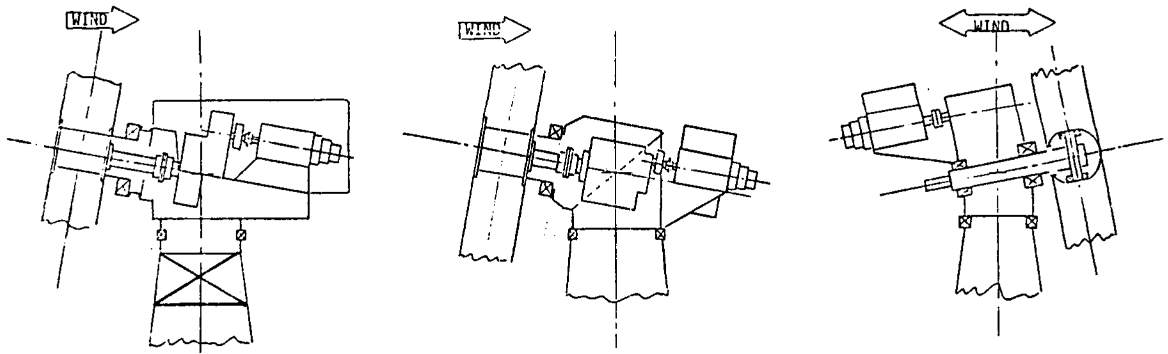


Figure 18. - Modified wind gust model with probability of occurrence.



DESIGN CONCEPT #1
(REDUCED MOD - 1)

- FIXED HUB
- 2 BLADES
- UPWIND ROTOR
- PARTIAL SPAN CONTROL
- MOD-1 GEARBOX
- MOD-1 ELEC. GEN.
- TRUSS TOWER (SOFT)

TOTAL WEIGHT
340,000 LBS

DESIGN CONCEPT #2
(EPICYCLIC GEAR)

- FIXED HUB
- 3 BLADES
- UPWIND ROTOR
- PARTIAL SPAN CONTROL
- EPICYCLIC GEARBOX
- MOD-1 ELEC. GEN.
- SHELL TOWER (SOFT)

TOTAL WEIGHT
355,000 LBS

DESIGN CONCEPT #3
(INTEGRAL GEARBOX)

- TEETERED HUB
- 2 BLADES
- DOWNWIND OR UPWIND
- PARTIAL SPAN CONTROL
- MOD-1 GEAR DRIVE
- MOD-1 ELEC. GEN.
- SHELL TOWER (SOFT)

TOTAL WEIGHT
320,000 LBS

Figure 19. - Three candidate systems.

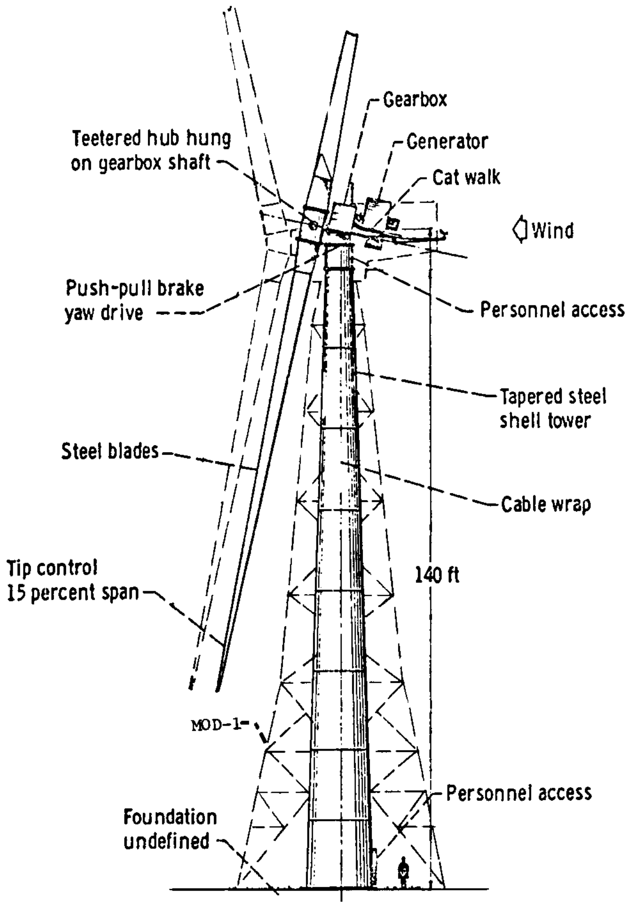


Figure 20. - MOD-1A outline and comparison with MOD-1.

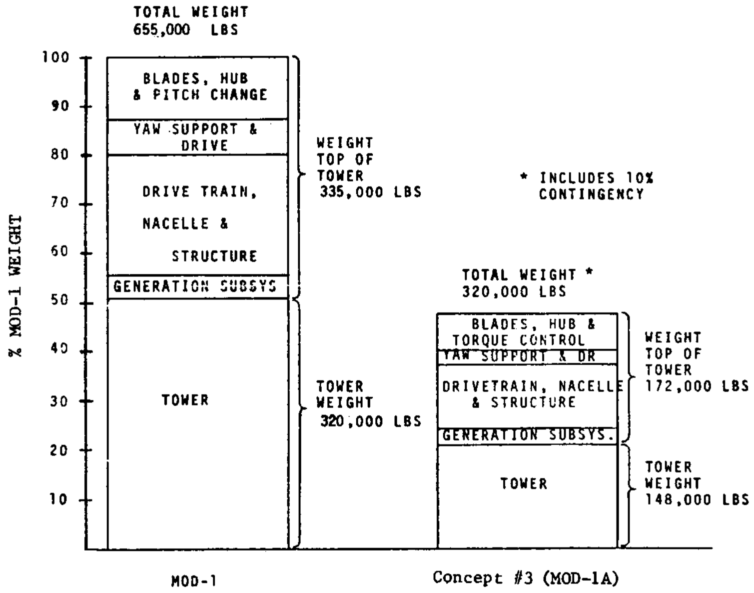


Figure 21. - Weight comparison for MOD-1 and concept #3.

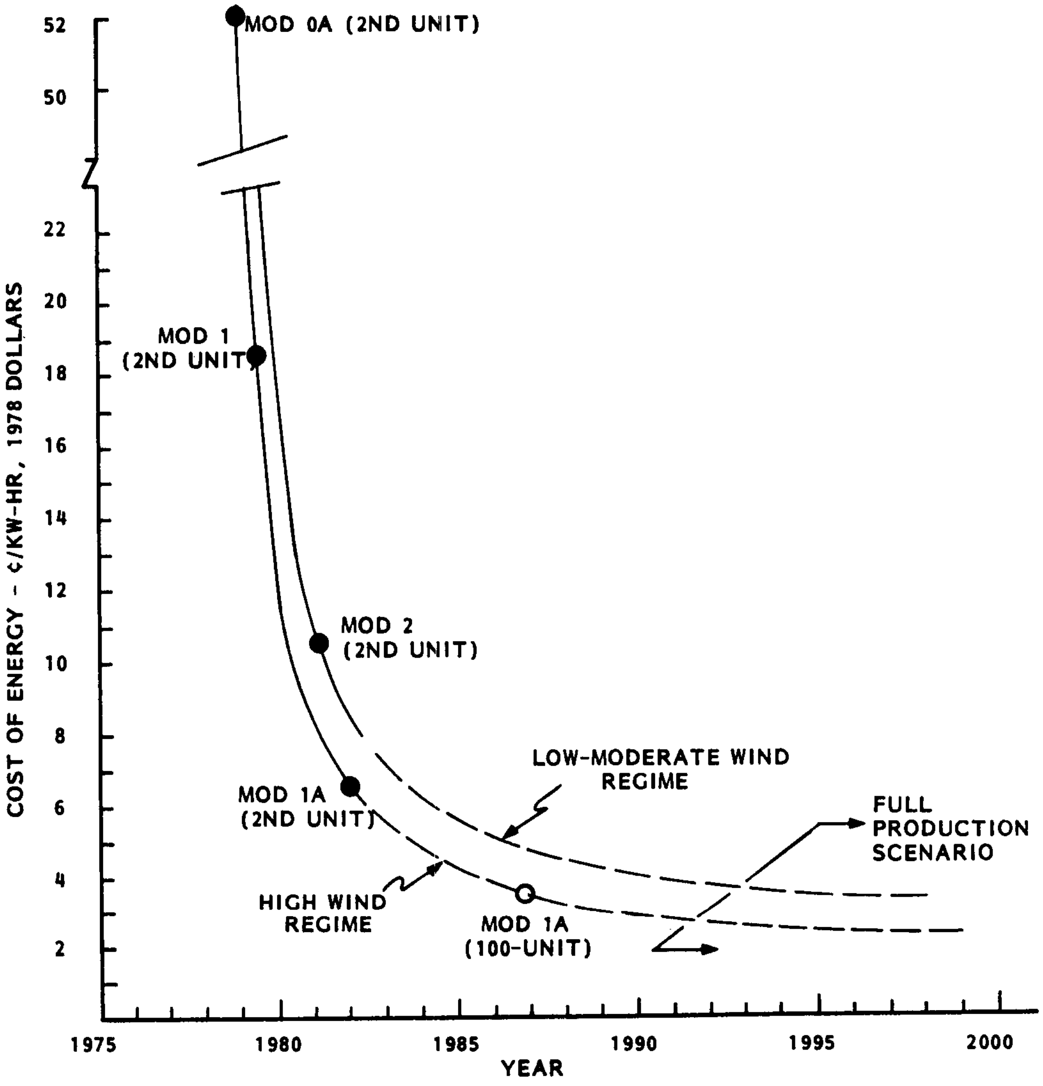


Figure 22. - Cost of energy projections.