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Conceptual Design of a Fixed-Pitch Wind Turbine Generator System Rated at 400 Kilowatts

Adam Pintz, R Kasuba,
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Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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1.0 SUMMARY

This report covers the salient design features and costs of a fixed-pitch, 400 kw Wind Turbine Generator (WTG) concept. The goal of the study was to achieve improvements in reliability and cost reductions with fixed-pitch operation and by incorporating recent advances in WTG technology. The WTG concept reaches its maximum power capacity of 400 kw at 40 mph wind speed.

The work was performed by Cleveland State University (CSU) under a cooperative agreement with the NASA Lewis Research Center (LeRC). The specifications for this WTG concept as supplied by NASA LeRC for the design of the low cost, high reliability WTG were:

a. A fixed-pitch, continuous wooden rotor was to be provided by the Gougeon Bros. Co. under NASA contract.
b. An 8-leg hyperboloid tower which showed promise as a low cost support structure was to be used.
c. Only commercially available components and parts which could be easily purchased or fabricated were to be considered.
d. Design features deemed desirable based on recent NASA research efforts, and field experience with the MOD-OA, MOD-1 and MOD-2 wind turbines were to be incorporated. Among these are the use of a teetered hub, upwind rotor position and high-slip induction generator.

The WTG concept described in this report meets the above specifications and guidelines in all respects. Additional design features include the use of two pillow block bearings to support the rotor and removable couplings for maintenance and replacement purposes. A parallel shaft gearbox is mounted on-end for efficient use of the nacelle space and ease of access from the tower. The auxiliary shafts of the gearbox include a spring-actuated disk brake on the low speed shaft and a hydraulic motor start system on the high speed shaft. A central hydraulic system supplies the rotor and yaw brakes, hydraulic rotor starter and yaw drive.

In addition to the concept layouts, detailed cost and weight estimates were prepared for the second machine and a wind farm arrangement of twelve WTGs. The unit price per maximum power capability of a production WTG is approximately 1000 dollars/kw. The calculated cost of energy (COE) for the fixed-pitch, twelve-unit windfarm arrangement is 11.5 cents/kw-hr not including the cost of land and access roads.

This study has shown the feasibility of fixed pitch, intermediate power WTG operation. Further studies of the concept, to increase energy production as well as reduce costs, will be needed to achieve a competitive COE.

2.0 INTRODUCTION

There are many manufacturers of small WTGs in the U.S. that wish to increase their power generation capability into the range of 100-500 kw. To assess the feasibility of intermediate size WTGs, Cleveland State University in cooperation with the NASA Lewis Research Center, conducted a conceptual design and cost analysis of an intermediate size wind turbine generator for utility grid applications.

The objectives of this joint effort were:

a. Develop a conceptual design for a low cost 400 kw WTG that would be inherently reliable and durable, using as much as possible off-the-shelf commercial components, and incorporating features identified as desirable in recent NASA research studies.

b. Develop estimates for the cost of the second unit and of a farm of 12 units as well as the cost of energy (COE).

c. Identify components and subsystems that provide potential for significant cost reductions.

A measure for assessing economic feasibility is how close the COE of a windfarm comes to the 8 cents/kw-hr paid by California utilities for renewable energy. The results of this study, if promising, were then to be used to prepare a proposal to DOE for the prototype phase.

The initial task consisted of collecting information on the desirable attributes for a WTG based on experience with actual hardware. At LeRC this experience derives directly from operating the 100 kw MOD-0 test bed at Sandusky, Ohio, and four U.S. locations of the 200 kw MOD-OA. Additional information is obtained from managing the large WTG projects like the MOD-1, MOD-2 and MOD-5. Discussions with LeRC personnel and review of literature on WTG technology resulted in a number of desirable features for the candidate WTG concept. Section 3.1 lists these features and summarizes their benefit to the concept.

The equipment of a horizontal WTG which is located on top of the supporting tower represents the major cost contribution. Preliminary investigations were directed towards efficient layout of that part of the WTG (nacelle). Aside from following the objectives listed earlier in this section and paying attention to the individual component selection, care was taken in their arrangement on the bedplate. This was considered important because the arrangement affected the amount of overhang from the tower, the size of the bedplate, clearance between the blades and tower, access to the nacelle, etc. Section 3.2 is devoted to this aspect of the concept development.

Section 3.3 treats the system and component requirements of this effort as well as contributions by other organizations. The detailed requirements are defined in Appendices A and B.

These requirements were then used to select off-the-shelf items as provided by interested vendors, develop drawings and guide design activities of contributing organizations.

The design of the subsystems is covered in Section 3.4. The tower concept represents a novel design idea which was considered worthy of incorporation by LeRC because of its ease of fabrication and assembly. The concept is based on work done by Sizemore, et al at LeRC[1](*). Both the adaptation of this hyperboloid tower concept and the calculations for the nacelle structure were performed by a consultant to LeRC, Dr. G.R. Frederick of Toledo University. Another important subsystem was the continuous wooden rotor developed by the Gougeon Bros. Co. for LeRC[2]. The remaining subsystems consist of conventional components.

The final system configuration is described in Section 4.0, the subsections of which cover the WTG nacelle arrangement, the tower, the control room and the electrical subsystems. Also included in this section are cost and weight estimates, along with suggestions for future cost reduction potential. The design, analyses and cost studies were carried far enough to establish size, weight and cost of the components of the WTG and windfarm. Evaluation of this accumulated information on fixed pitch operation at the intermediate power level is presented in Sections 5.0 and 6.0.

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* Superscripts refer to entries in references.

3.0 SYSTEM DEVELOPMENT

3.1 DESIRABLE FEATURES TAKEN FROM RECENT NASA RESEARCH DISCOVERIES

The MOD-0 has been used as a test bed by LeRC for carrying out various research and technology development projects. The results of these projects, the NASA experiences with operating WTGs in utility environs as well as the experience with contractor-developed WTGs indicated that certain features will lead to a more reliable and less expensive machine. Table I lists the various features considered desirable in such a design concept along with a rationale for the selection.

TABLE I

LIST OF DESIRABLE DESIGN FEATURES FOR LOW COST SIMPLE AND RELIABLE WTGs

Concepts	Beneficial Features
a. Hyperboloid tower structure.	Studies show potential for a low cost tower.
b. Fixed pitch, continuous wood rotor.	Simplifies design of blade, rotor and control systems; Distributes bending moments over larger cross-section in highly loaded hub area; Low cost effective material.
c. Teetered hub.	Reduces bending moment on low speed shaft due to wind shear, gyroscopic forces, etc.
d. Upwind rotor position.	Improves performance and lowers noise; No tower shadow effect on flatwise bending moments.
e. Hydraulic yaw drive with continuously applied friction brake.	Minimizes cost of yaw drive and reduces adverse effects of backlash in gears.

f. High-slip induction generator.	Provides dynamic damping of drive train; Simplifies control and reduces cost.
g. Overrunning coupling betwen gearbox and generator.	Allows continuous running of the WTG even in low wind speeds; Reduces start up and shutdown loads; Reduces energy losses due to startup and shutdown cycles.
h. Hydraulic motor starting of WTG at auxiliary shaft of the gearbox.	Allows use of wooden rotor with no twist, thereby reducing cost of rotor fabrication.
i. Access to nacelle through center of tower.	Good human engineering practice.
j. Protection of components from environment.	Increases life and reduces maintenance.
k. Personnel safety and emergency provisions.	Required human engineering standards.
l. Shared components for different functions.	Reduces cost and saves space.
m. Low maintenance.	Results from design philosophy.

3.2 SELECTION OF NACELLE-DRIVE TRAIN CONFIGURATION

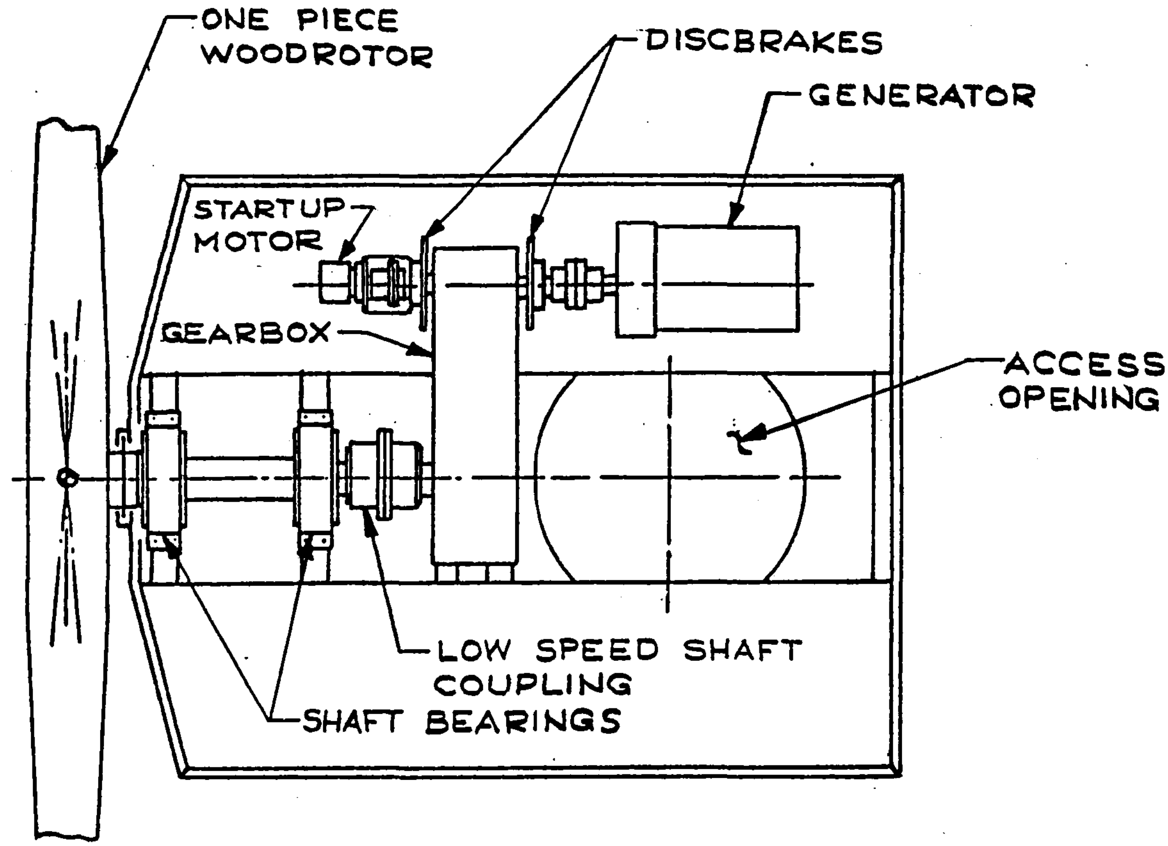
The drive train, supporting bedplate, and the nacelle together represent a sizable fraction of the total weight and cost of a WTG. In addition, the selection and arrangement of the drive train components, i.e. the rotor support, speed increaser and generator as well as the associated shafts and equipment, have a significant effect on the height, size and cost of the bedplate and nacelle. In an effort to identify a potentially cost effective drive train/bedplate/nacelle configuration, a study was initially made of eight configurations that appeared to meet the basic criterion of low cost and weight, and simplicity of design.

The component selection was started with the definition of the power and load capacities required. These two parameters largely determine component size and weight. For concept 1 a parallel shaft speed increaser was selected on the basis of availability as compared to a planetary gearbox. This concept was successfully used on the 100 kw MOD-0 and the 200 kw MOD-0A. Figure 1 shows the top and side view of concept 1 where the rotor is supported by two pillow block bearings as in the MOD-0 configuration. Because of the offset of the two gearbox shafts there is ready access to the nacelle from the tower opening. However, this offset requires a wider bedplate with unused areas to preserve symmetry. This offset could be eliminated because it adds to the bedplate weight and cost, and because the lack of the symmetry would be largely unnoticed. Also, this concept results in a large overhung position of the rotor from the center of the tower.

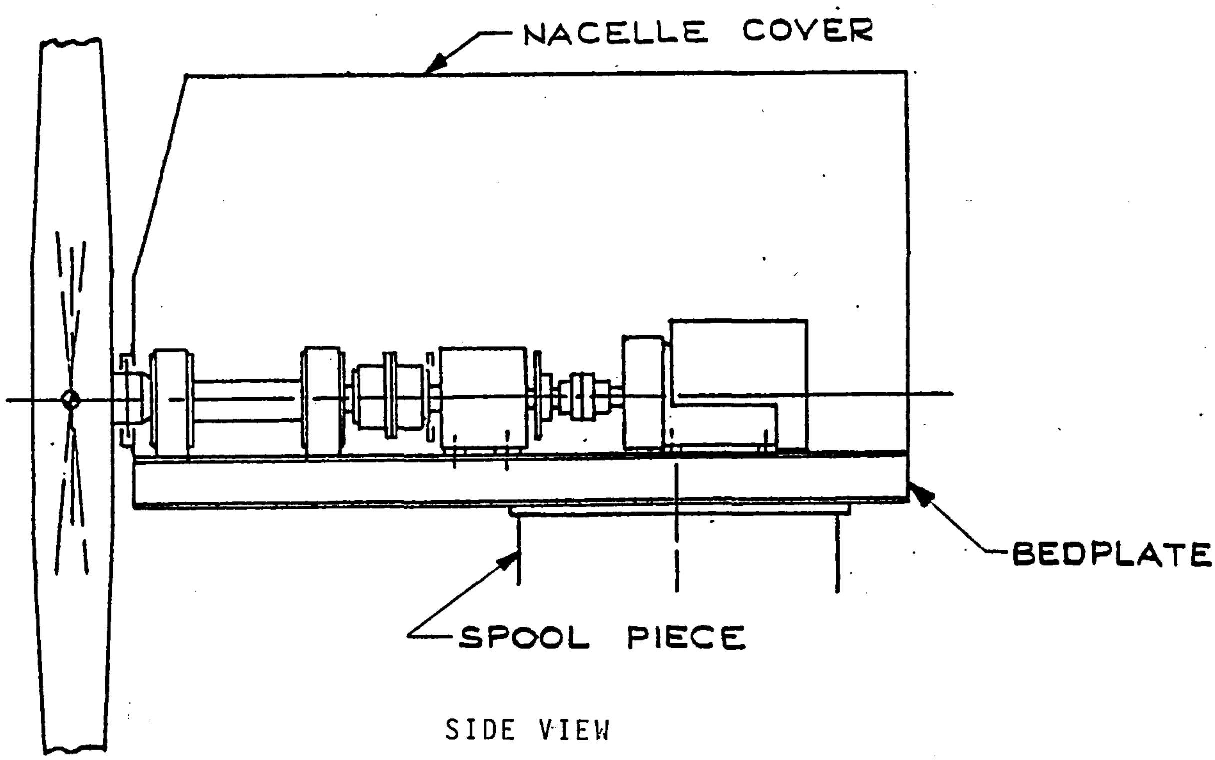
Concept 2 shown in Figure 2 attempts to overcome this shortcoming and reduce the number of drive train components by turning the gearbox on end and mounting the rotor directly to the bearing of the reinforced gearbox. This arrangement greatly shortens the bedplate length and the overhang to the point where the bedplate has to be tilted up so that it clears the tower. This concept had the disadvantages that the gearbox modifications are considered too expensive and shaft alignment between bearing and gearbox would be difficult to achieve and maintain. In Figure 3, the rotor is directly mounted to the low speed shaft of the gearbox. This concept is similar to the previous one except the low speed shaft is on top. The disadvantages of this configuration are found in large overturning moments on the gearbox and bedplate.

Concepts 4 and 5 of Figures 4 and 5 use a single bearing to support the rotor to avoid the high cost of the special gearbox in Concepts 2 and 3. The single bearing might be on the order of three feet in diameter and thus would require a substantial bearing support, bracing of that support and reinforcement of the bedplate. Also, the low speed shaft coupling would be required to react to moments. Couplings which can do this are not readily available. Concept 4 poses a blade-to-tower interference potential. This potential is avoided in concept 5 in the form of a partial tilt of the bedplate but makes alignment more difficult.

Concepts 6, 7, and 8 shown in Figures 6, 7, and 8 were examined in an effort to reduce the bedplate length. They are very much alike except for the placement of the gearbox on the bedplate. Of the three concepts, 6 and 7 result in well centered bedplates on the tower, but they require a long heavy shaft connection between the rear low speed shaft pillow block bearing and gearbox. Because this shaft interferes with the placement of the slip ring and partially blocks access to the nacelle, concepts 6 and 7 were not considered to be suitable. Concept 8 was chosen for final evaluation because it promises to minimize the bedplate size, weight and cost, a saving which benefits the tower as well.



TOP VIEW



SIDE VIEW

Figure 1 Concept 1: Teetered rotor supported by two pillow-block bearings with a parallel shaft gear box positioned with the high speed shaft offset to one side of the rotor center line

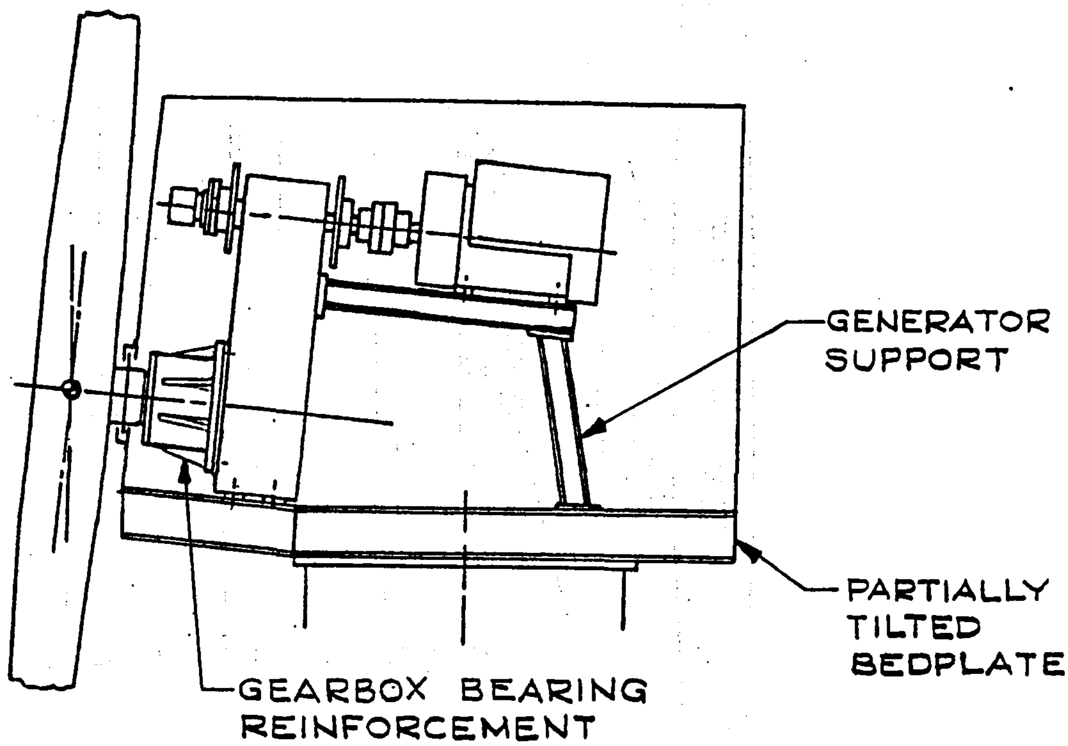


Figure 2 Concept 2: Gearbox on-end with the front of the low speed shaft reinforced to support the rotor

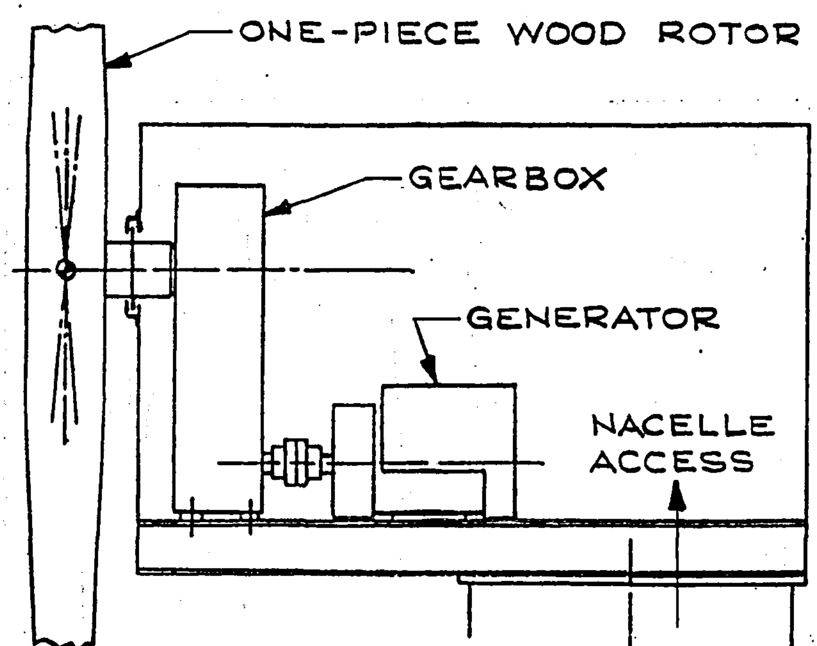


Figure 3 Concept 3: Gearbox on-end with the low speed shaft on top, and the rotor support on an extension of the low speed shaft

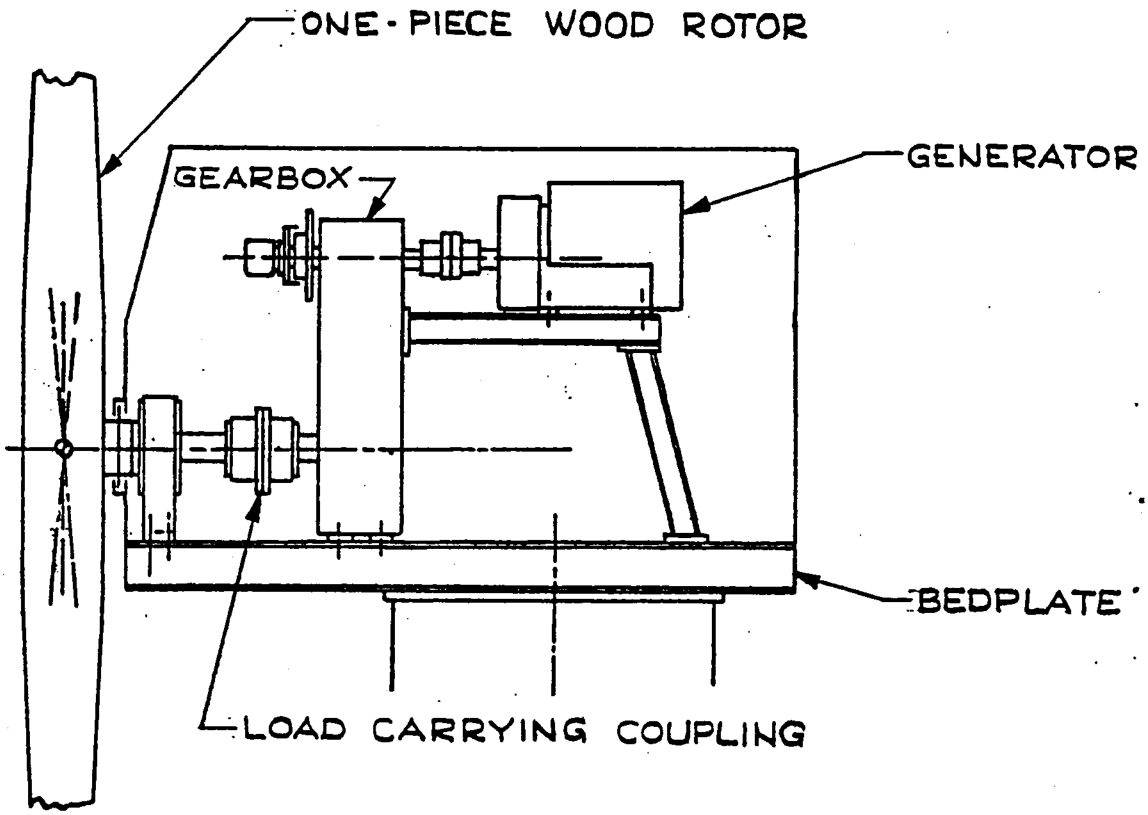


Figure 4 Concept 4: Single bearing support for rotor

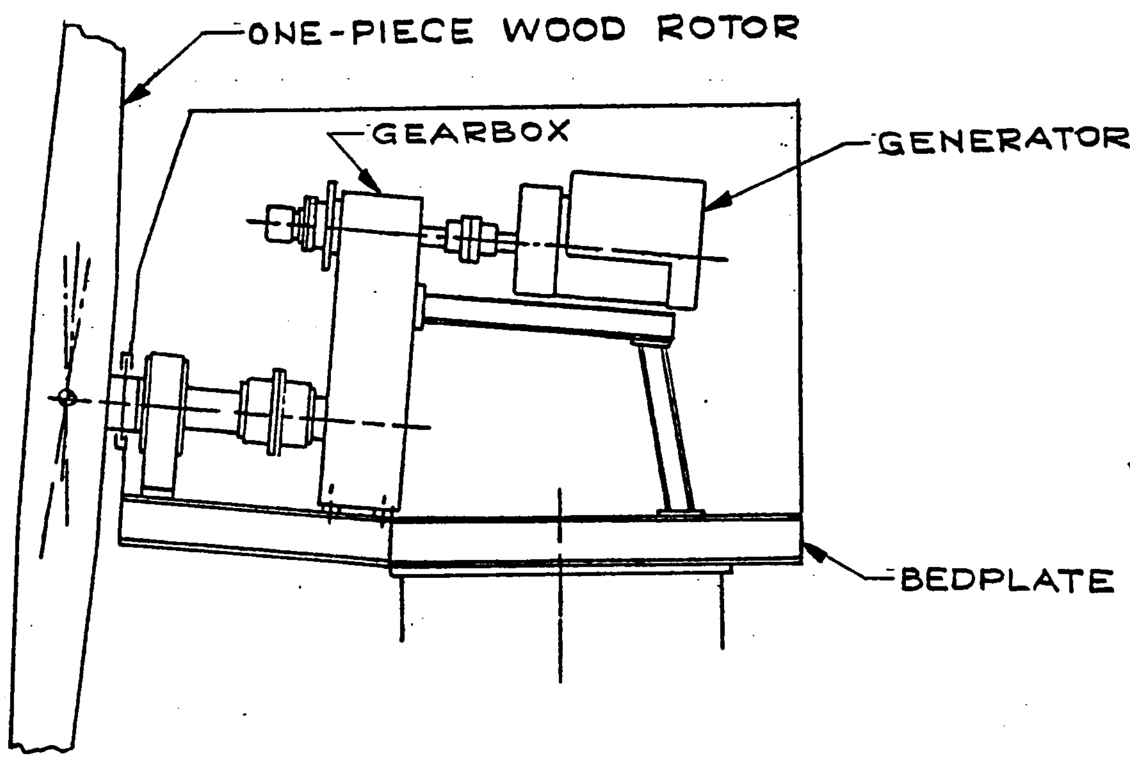


Figure 5 Concept 5: Single bearing support for rotor with partially tilted bedplate to reduce rotor over hang and bedplate length

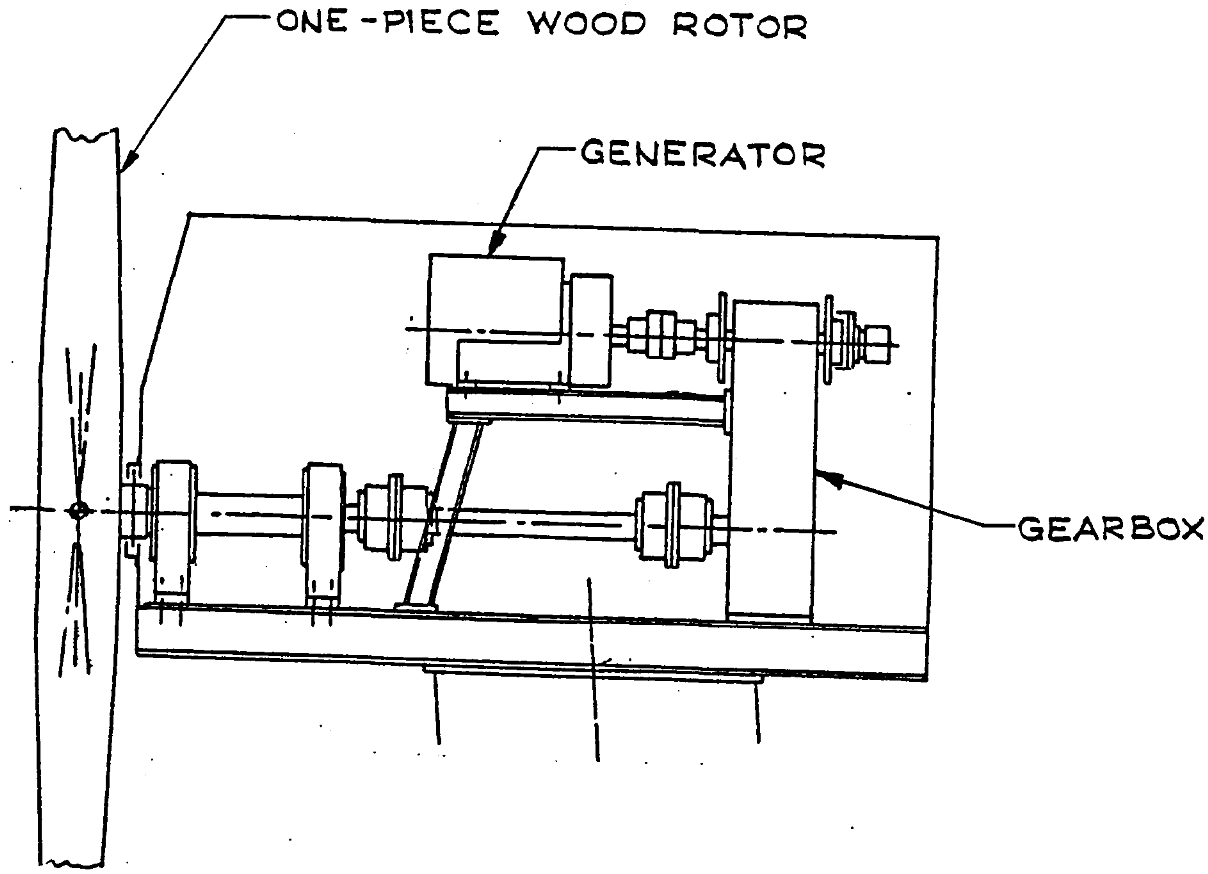


Figure 6 Concept 6: Gearbox mounted on far side of tilted bedplate

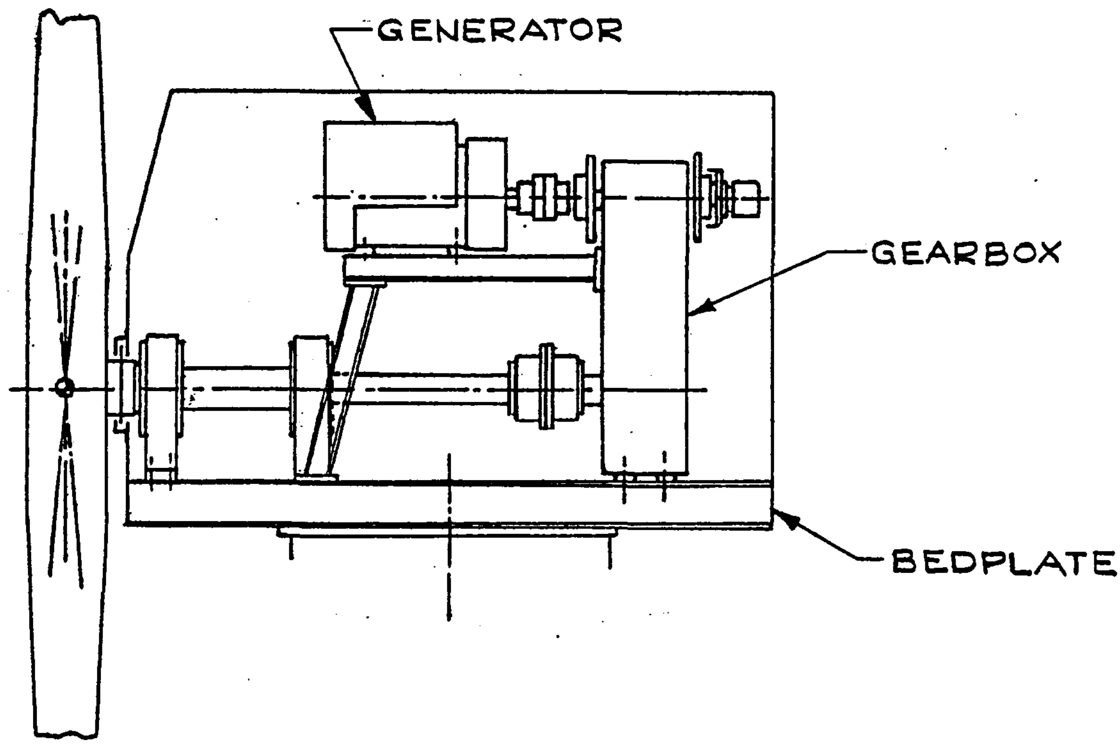


Figure 7 Concept 7: Gearbox mounted on far side of rotor and no tilt in the bedplate

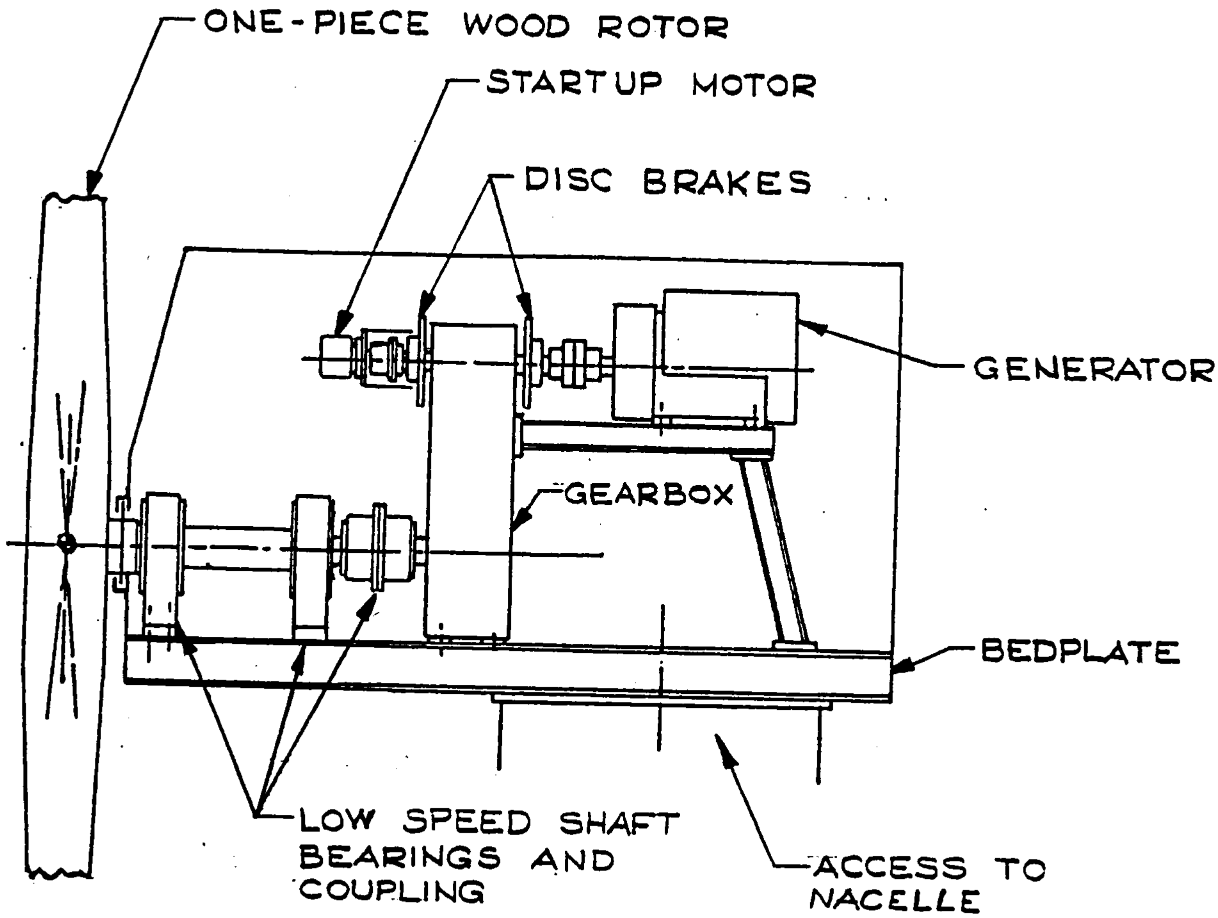


Figure 8 Concept 8: Well-balanced arrangement of components in the nacelle

3.3 REQUIREMENTS

LeRC drafted detailed requirements for the system and the major components. These requirements are listed in Appendices A and B.

3.4 SUBSYSTEM DESIGN

3.4.1 TOWER

At present, cylindrical towers are used on the MOD-0 and MOD-2 configurations in lieu of truss type towers. These were selected because they allowed placement of their natural frequencies to avoid the periodic disturbing effect of the blades as they were passing the tower. Also, they have reduced the width of the tower shadow. Disadvantages to this tower concept consist of the expense of rolling, welding and transporting the large-diameter items. Generally, extensive labor and large hoisting equipment are required in the field.

A search for a new tower concept was undertaken by LeRC. As a goal, this new concept would have to maintain the desirable attributes of the cylindrical tower and eliminate the undesirable features. As mentioned previously, one such concept was investigated by Sizemore for the MOD-0 test bed. The tower concept, shown in Figure 18, uses eight main members arranged to lie on the surface of a hyperboloid of revolution. These members are straight and will intersect where they are joined to reinforce the tower. Intermediate ring girders, composed of straight elements, serve to brace the main members. Sizemore configured the concept for the MOD-0 test bed. Subjecting the concept to the same constraints as the truss tower, he was able to compare the construction costs of the tower designs. The comparisons showed the hyperboloid tower design to be lighter and more easily fabricated and assembled than the truss tower. Accordingly, the estimated cost for fabrication and erection was lower.

Based on this favorable comparison LeRC decided to use this new tower concept for this investigation. The actual design was performed by Dr. G.R. Frederick of the University of Toledo, consultant to NASA. He also provided the final design calculations for the structural aspects of the nacelle. Because of the conceptual nature of this effort, sizing of components and structural elements was based on limit loading due to extreme wind (120 mph) and loads created by weights. Appendix C depicts the various loading cases which were investigated and the load values which were considered critical for the design.

Dr. Frederick supplied to CSU the size of the members and dimensions of the assembled tower. From that he determined weights and cost on the basis of one dollar per pound of finished steel structures as suggested by fabricators. CSU finalized the tower design by making the concept drawings, and by adding electrical equipment and a safety ladder. The tower parts can be fabricated in a factory, shipped on a conventional truck to the site and assembled into its final form by using bolted joints which are piloted together. In this manner it represents a low cost alternative to doing the work on the site.

3.4.2 ROTOR

The fixed pitch rotor was developed by the Gougeon Bros. Co. (GB). This company had successfully applied its experience with wooden boats to the development of reliable, low cost horizontal axis WTG rotors. Encouraged by this success LeRC contracted with GB to investigate the feasibility of fabricating a continuous wooden rotor as in the MOD-2 WTG, and determine its cost in quantity production. If successful, the current large steel hubs for attaching individual blades could be eliminated. Another feature was the load reducing method of supporting the rotor with a teeter bearing in the hub section. The result of the investigation showed that the approach was feasible, and the rotor was incorporated into the WTG design. The final configuration chosen is shown in Figures 9 and 10 and has the following characteristics:

a. Airfoil shapes NACA 64_3-618 and 0027 are used at stations 540 and 180 respectively.
b. Airfoil shapes between stations 180 and 540 are obtained from a straight line development between the two sections in item a.

c. The rotor between stations 180 and 43 is the blade-to-hub shape transition zone. The shape of this section is shown in the cross-sectional view of Figure 10.

d. Twist is zero degrees.

e. Finger joints at station 43.

f. Weight equals 4522 lbs. without teeter hardware.

g. Cost of rotor produced at rates of 2, 10 and 120 units per year were estimated to be $38785, $36222 and $25452 in 1983 dollars respectively.

h. Planform sized to nominal rating of 175 kw at 55 rpm in 25 mph wind. Power at 50 mph wind is 400 kw.

This rotor configuration was then subjected to additional performance analyses by CSU in order to obtain the potential annual energy capture for this rotor using the two power points in (h) above. The well known PROPCODE performance analysis program was used for that purpose.

The input to the analysis consisted of the performance conditions stated in Appendix A, the airfoil geometry, empirically derived aerodynamic data[3], and invocation of the thickness/chord correction feature in the PROPCODE. The resulting analyses matched the two power points. Additional analyses were made to determine the sensitivity of this rotor to changes in twist, length and rotor speed. Figure 11 shows the power versus wind speed of the straight Gougeon rotor and two twisted rotors of the same diameter. On the

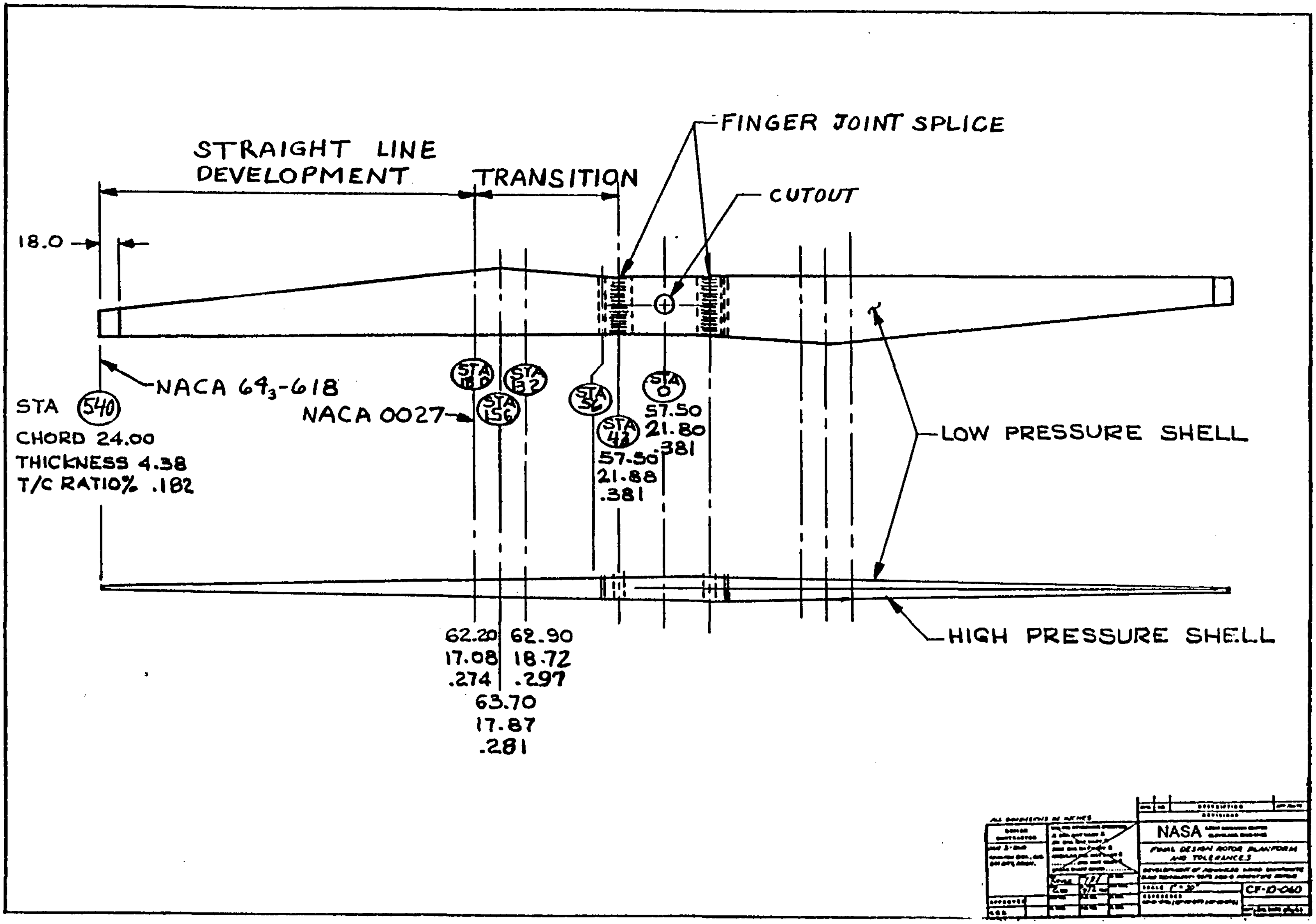


FIGURE 9 BLADE GEOMETRY

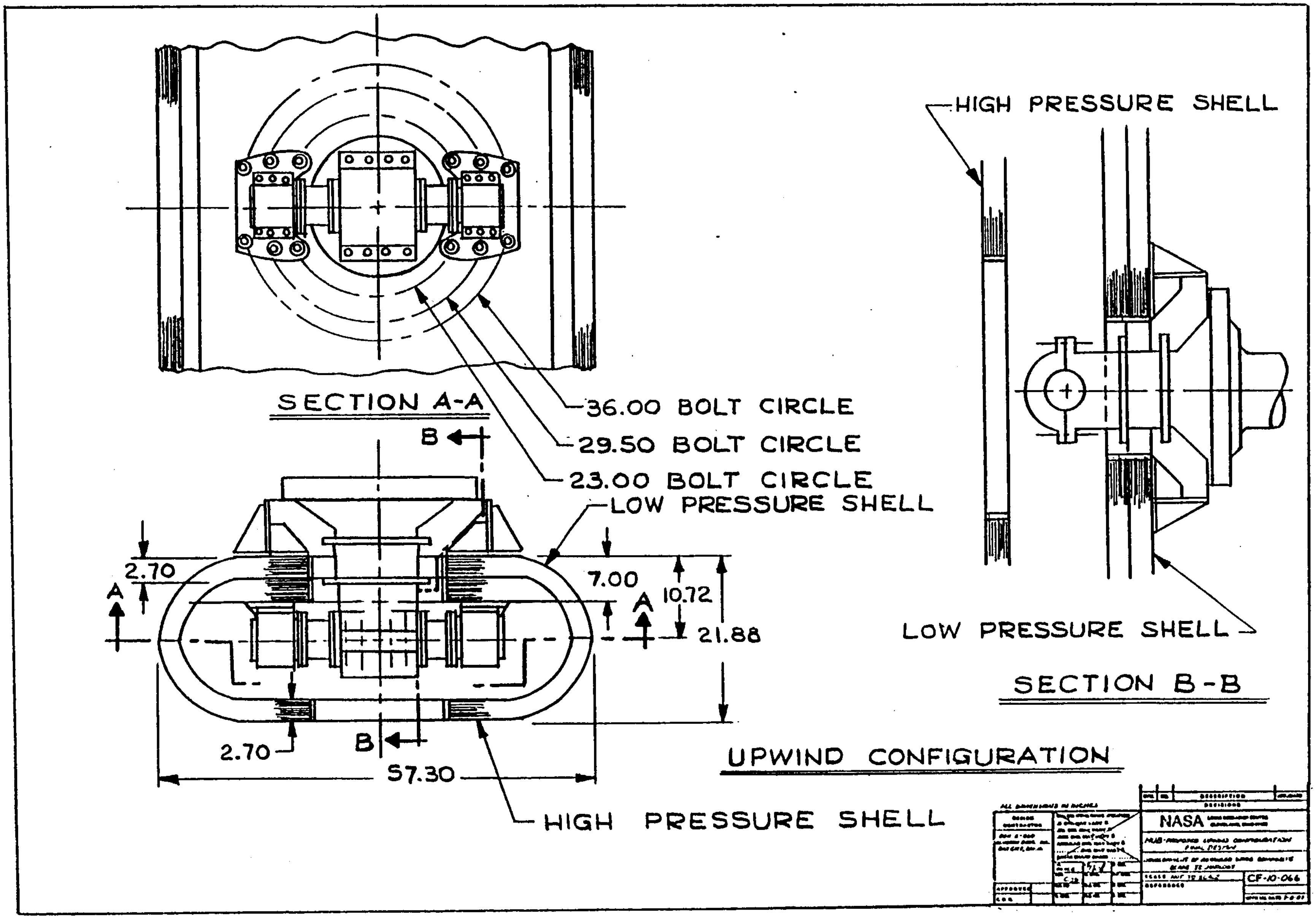


FIGURE 10 TEETER MECHANISM

first rotor the twist starts at 65% radius and linearly progresses to -2° at the tip. This twist represents a compromise between the desired and actual twist achievable with the choice of wood as the material for this rotor. (Note: At the time of this investigation, the techniques needed to fabricate wood rotors with high twist had not been developed. Since then Gougeon Bros. Co. has produced a 3-bladed wooden rotor with 14° twist for a 300 kw WTG[4]. However, no cost data are available about this rotor configuration.)

The second rotor with twist approaches an optimum design by using a non-linear twist starting with 14° at the hub radius and ending at -2° at the tip. However, this latter design would require the use of materials other than wood because of the high twist. It was selected as a comparison of a near optimum blade geometry with the straight Gougeon blade only. For further comparison, the energy capture per year for the three rotors is shown in Table II below.

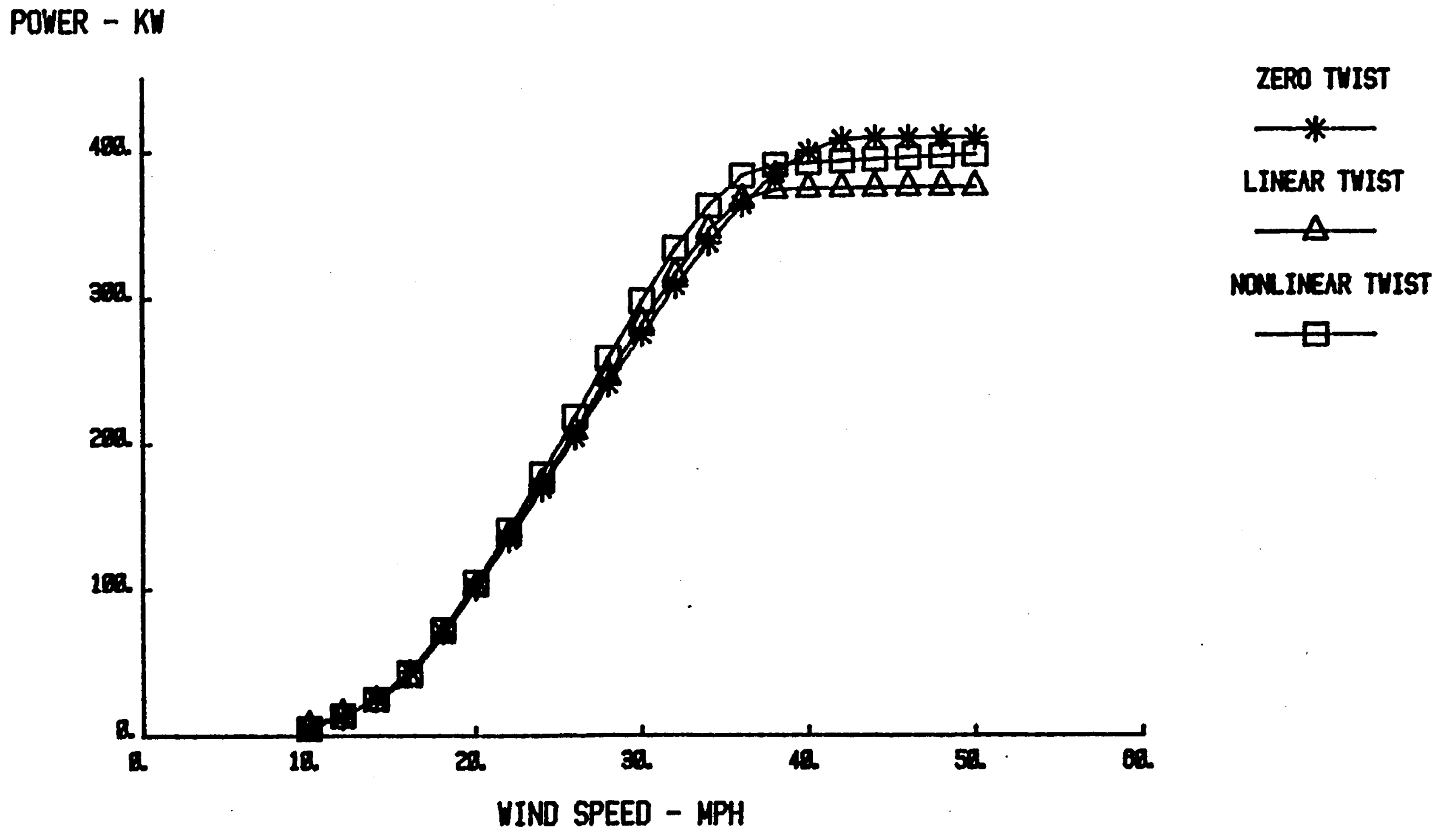
TABLE II

ENERGY CAPTURE OF THREE ROTOR GEOMETRIES

(kw-hrs / year)

AVERAGE WIND SPEED	ROTOR GEOMETRIES		
(mph)	Straight	Linear twist	Non-linear twist
12	493,435	495,424	516,659
14	722,083	726,263	758,940
15	846,118	851,280	890,176
18	1,226,693	1,223,515	1,281,325

FIG. 11 CONTINUOUS ROTOR
POWER VS WIND SPEED
AT 55 RPM



WOODEN BLADE
RADIUS - 540 INCHES

Review of Figure 11 and Table II show that improvements in performance for the twisted rotors are less than 10%, and therefore do not warrant the additional fabrication cost incurred by the twist. Further review of Figure 11 also shows that for the straight blade, the power reaches its peak at the highest wind speed shown. This conservative approach was used in order to minimize the braking requirement in case of electric load loss. Additional energy capture improvements are possible by increasing the rotor diameter so that the maximum power requirement is reached significantly before the maximum wind speed is reached. For example, a 7% increase in rotor diameter yielded a 13% increase in energy capture for a 14 mph wind site. The additional power potential of such a rotor beyond the maximum power requirement can be controlled by maintaining a yaw angle between the rotor and the wind. This larger rotor diameter has not been incorporated into the final concept because it would have affected the size of the components, notably the tower height and overhang position of the rotor to avoid striking of the tower.

The drive train with the Gougeon blade was then subjected to a shutdown analysis using a NASA supplied computer code. This code takes into consideration the torque producing capability of the rotor, the retardation due to the brake and drive train power loss, and the inertia of the power train.

The worst case shutdown results were obtained for the following conditions:

a. Electric load loss at maximum power production.

b. Rotor speed of 55 rpm.

c. Ratio of brake torque to aerodynamic torque equals 110%.

d. Disk brake on low speed shaft comprised of four calipers acting on 42 inch diameter disk (see Figure 13).

e. Brake actuation delay of 1 second after electric load loss.

For these conditions, shutdown occurred in 16.2 seconds reaching a maximum speed of 64.2 rpm at 1 second. These results were not affected significantly by considering yaw rates up to 2 degrees/sec when the WTG had no initial yaw angle. This conclusion is based on the assumption that performance is reduced by a factor of $\cos^3$(yaw angle). Power reduction by yawing would be significant if the initial yaw angle was greater than 20 degrees.

Figure 10 shows a concept of the teeter mechanism. The selection of the two teeter bearings has been of concern because of their exposure to the atmosphere, difficult access and small amount of rotation. The concern was the difficulty in maintaining adequate lubrication and fretting of metallic bearings due to continuous loading in a small sector of the bearing. This was the reason for selecting an elastomeric bearing on the Boeing MOD-2. This approach was investigated for this concept also, but could not be used in the design because of lack of response on the part of prospective vendors and the perceived high cost. Of the other non-metallic sleeve-type bearings which were considered, Rulon has demonstrated superior performance in similar applications.

3.4.3 OTHER SUBSYSTEMS

The course of action taken on the first three "desirable features in a WTG" of Table I have already been discussed in this section under Tower and Rotor. Items d through h of Table I will be discussed in detail below. The last five items are adequately explained within the table or are covered in Section 4.0.

a. Yaw Drive

WTG operation with upwind rotor position necessitates the use of a Yaw Drive and Braking system. The power for this drive may be extracted from the wind or supplied from the electrical grid. Engineering judgment indicated that extraction of power from the wind for auxiliary systems like the yaw drive would not be cost effective. Also, electrical power was required for control, instrumentation and lighting. Consequently, the mechanical power requirements for the yaw drive, rotor startup and brakes were obtained from an electrically driven central hydraulic system in the nacelle. A rotary drive was chosen for the yaw system in preference to a push-pull drive because of the favorable experience on the MOD-0 test bed and the MOD-2, and availability of components. In this rotary drive, backlash is required in the gears for assembly purposes. The presence of this backlash can cause excessive shock loading in the rotor, drive train and yaw systems, even with a teetered rotor. The effects of backlash may be eliminated by preloading of the gears or by a continuously applied yaw brake. Preloading has been tried with limited success on the MOD-0A WTGs. It also added additional components. The final solution was obtained by means of a continuously applied yaw brake. This approach eliminates the complexity of a dual brake system through selection of a drive large enough to overcome the required braking and yaw torques.

b. High Slip Induction Generator

Two generator configurations are presently available for use in WTG applications. Synchronous generators were selected first because of their widespread use in utility applications. Since they operate near synchronous speed, they represent a rigid link in the overall drive train dynamics. Thus, any neccesary damping against aerodynamic disturbances must be provided by mechanical means. One successful approach by NASA was the use of a fluid coupling with 3% slip. The second approach to controlling the drive train dynamics consists of a "soft" shaft and manipulation of the control surfaces as used on the MOD-2 WTG. While both of these approaches were successful, a third alternative is the use of an induction generator. It appears to be preferable for intermediate applications because it simplifies the overall system while damping power fluctuations. Essentially, the simplifications consist of elimination of three subsystems that provide damping, speed control and electrical synchronization. Overall system efficiency is expected to be about the same as for the system with a fluid coupling.

For the prototype of this concept, a wound rotor induction generator with external resistance for control of slip was chosen so that the optimum slip could be determined. The final concept would then incorporate a squirrel cage induction generator with the appropriate slip. For this application, recovery of the circulating power did not prove cost effective.

c. Startup of Drive Train

Startup of a WTG with fixed and straight blades cannot be accomplished by aerodynamic means. Electric motor startup with current limiters did not prove as attractive as a hydraulic motor startup from the auxiliary high speed shaft of the gear box.

Frequent startups and shutdowns of rigid WTG drive trains because of low wind conditions are a significant operating problem which has been greatly reduced by NASA on the MOD-0 test bed by incorporating an over-running coupling in the high speed shaft. This feature is used in the hydraulic starter also.

4.0 SYSTEM DESCRIPTION

The material in this section provides the following information:

a. Explanation of the final 400 kw WTG concept.

b. Cost and weight for the second WTG unit.

c. Cost of energy based on a 12 unit wind farm.

The design evolved from Concept 8 to the detailed layouts in Figures 12 through 20. This stage of the design was reached through trade-offs among the requirements of cost, reliability and performance subsequent to the system development process. The resulting system is an assembly of available components and producible parts. This system, then, can be used as the basis for design of the second generation 400kw WTG which would incorporate advanced concepts and improvements indicated by this detailed design concept.

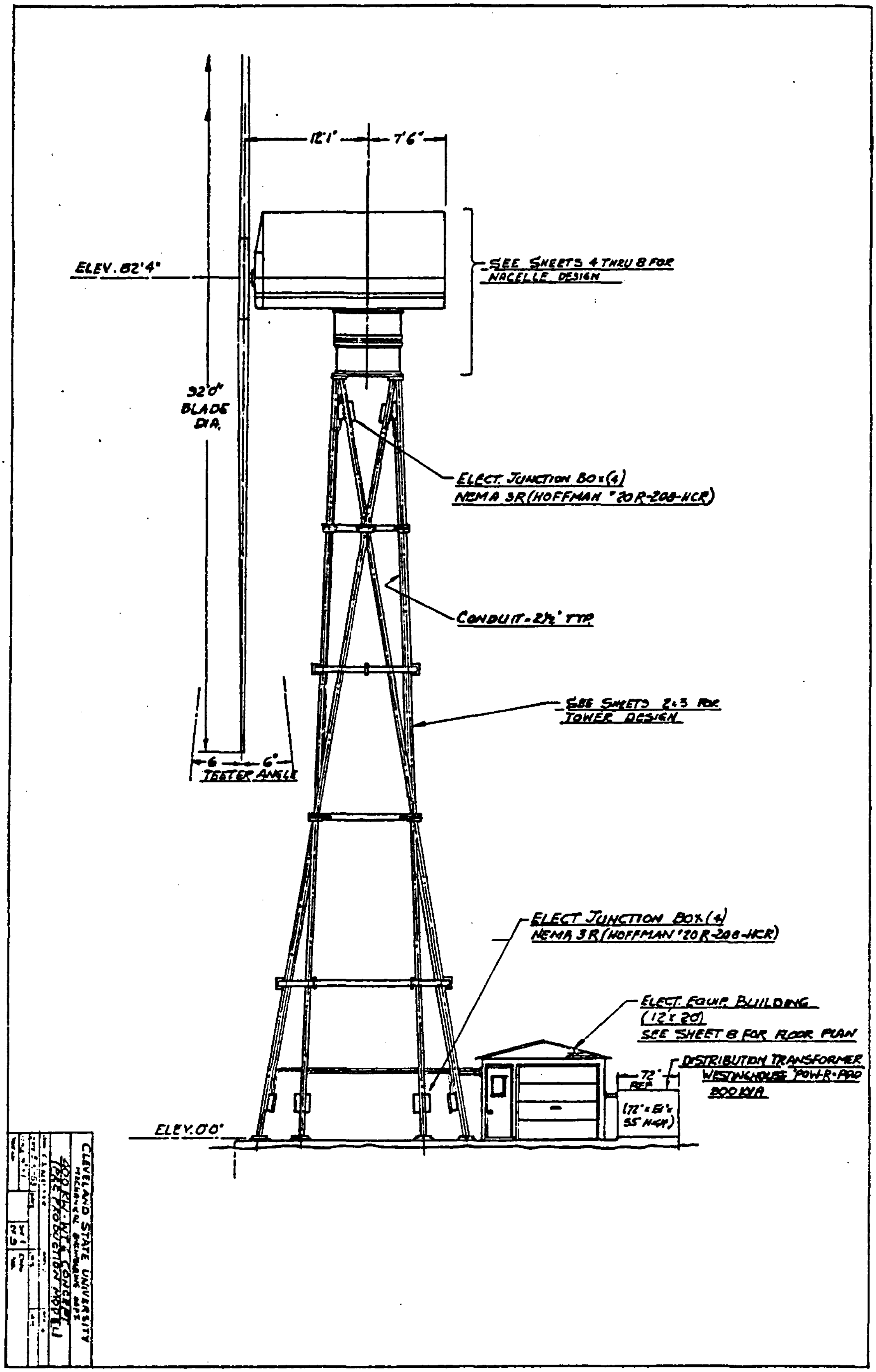


FIGURE 12 SIDE VIEW OF WTG

4.1 ARRANGEMENT OF NACELLE

Figure 13 shows a vertical view of the nacelle arrangement. In line with the low cost, high reliability guidelines, an all wood, two-bladed, fixed pitch, fixed speed rotor is used to avoid the costly pitch change mechanisms and variable speed generator. The rotor, as seen in outline form on the left of Figure 14, is attached to a teetered hub to minimize bending moments on the low speed shaft, yaw bearing and support tower. The low speed shaft, hub and rotor are supported by pillow block bearings as in the MOD-0 and MOD-0A configurations. The gear box is mounted "on-end" to minimize the width of the nacelle. The low speed coupling is of the gear-type with a spool piece between its hubs for ease of disassembly/assembly in the nacelle. This feature of the coupling replacement affords ready maintenance. Additional benefits are possible replacement of other drive train components such as the gear box without the need for removal of the complete nacelle assembly. The penalty consisted of an additional 1 foot length of the nacelle and an oversized low speed shaft coupling. The net benefit will have to be evaluated in a future more detailed design phase.

Fixed pitch operation demands proper design and selection of an adequate rotor braking system. Since this is the primary means of stopping the rotor under normal, parking and emergency conditions, heavy emphasis was placed on reliability and fail-safe operation. Studies of the braking system have shown that a spring actuated, four caliper, disk brake system mounted on the auxiliary low speed shaft of the gear box will meet this requirement. In this location, the brake will eliminate undesirable loading of the gears when the rotor is not in operation. The brake is armed and controlled from the central hydraulic system in the nacelle. This hydraulic system supplies also the yaw drive, yaw brake and rotor starting system.

The gear box is located on the front edge of the nacelle access hole and the generator is supported directly over the hole. This arrangement represents the necessary compromise between desired minimum rotor overhang, adequate tower clearance of the rotating blades, central placement of the nacelle weight, and ready access to the nacelle from the inside of the tower. Vertical mounting of the gear box placed the generator in-line with the low speed shaft but at a higher elevation. A high-slip wound rotor induction generator with external rotor resistance control has been selected for the prototype WTG. Once the neccesary slip for optimum dynamic damping is determined, then a lower cost squirrel cage induction generator with fixed slip would replace the wound rotor generator and external resistance in the second unit. Either combination is capable of ready synchronization to the electrical grid and provides inherent generator damping to the rotor-drive train dynamic system.

The connection between the gear box and the generator consists of an assembly of a gear coupling, an overrunning coupling and a shaft. The overrunning coupling disconnects the generator and rotor below the synchronous speed of 1800 rpm. Thus, the rotor can drive the generator but not vice versa. Decoupling is desirable during start-up and short periods of wind speed below cut-in operation.

A separate rotor starting system is needed since the continuous 2-bladed wooden rotor is not self starting. For this purpose a hydraulic starter motor is mounted on the auxiliary high speed shaft of the gear box to bring the rotor speed to 10 rpm. Beyond that speed the wind accelerates the rotor to synchronous speed. The hydraulic start motor is stopped when the rotor turns at 10 rpm but prevented from interfering with the revolving rotor by virtue of an additional overrunning coupling.

The nacelle interfaces with the tower at the bottom of the lower spool piece. The inner race of a large diameter ball bearing support with an internal ring gear at the inside diameter is bolted to the top of the lower spool piece, as shown in Figure 13. The upper spool piece is bolted to the outer race of the yaw bearing. The yaw drive is attached to the upper spool piece. Its external spur gear pinion engages the stationary internal spur gear of the yaw bearing inner race. Thus rotation of the nacelle is achieved by the pinion gear "walking" around the internal gear. For optimum power performance, the yaw drive maintains the rotor in the upwind position. Yawing motion is provided by a hydraulic motor, a planetary gear box and a pinion drive which engages the ring gear (see Figure 13). The yaw drive also features a passive disk brake, approximately the same diameter as the yaw bearing, which holds the nacelle stationary when the yaw system is not operating (see Figure 15). During operation it provides Coulomb, or frictional, damping against sudden wind gust and shock loading when the rotor hits the teeter stops.

Transfer of electric power to and from the nacelle is effected by means of a slip ring assembly which is mounted to the generator support stand at the center of the tower.

The primary components in the nacelle are directly mounted to the structural steel frame of the bedplate (see Figure 16). Wide flange beams with identical depth provide level top and bottom surfaces. The bedplate frame is closed off with 1/4 inch thick checkered plate which is welded on its underside to the beams. The same plate material covers the top of the bedplate along the side rails. Thus, the center portion of the bedplate affords a low level floor for maintenance of the drive train members. The bedplate interfaces with the upper yaw spool piece by means of a reinforced mating ring. A kickplate made of three inch channels serves as a protective side rail when the top cover is removed, and also simplifies the split labyrinth-type, nacelle-to-low speed shaft seal. The remainder of the protective cover is provided by a corrugated sheet metal enclosure which is reinforced by braces also made of three inch channels.

Additional features in the nacelle consist of an emergency hatch in the rear bedplate, ventilation, heating, windows, lighting on the ceiling, electrical switches, distribution panels, instrument racks and a capacitor bank. The top of the enclosure has removable access covers for replacement of the generator and gear box, and access to the wind direction and speed sensors as well as the aircraft warning light (see Figure 17). These same openings will be used to attach the lifting cables to the bedplate during erection/removal of the nacelle.

The upper spool piece which is attached to the bed plate and the lower spool piece are fabricated from 3/8 in. rolled plates that are reinforced by vertical stiffener plates. The lower spool piece has a circular platform with a trap door for maintenance purposes and as an access point to the nacelle via a steel ladder which is mounted to the top spool piece and rotates with it. The yaw drive and brake calipers are mounted to the upper spool piece. Two electrical conduits are required for the power, control and instrumentation cables. The conduits are attached to the lower spool piece and thus provide the stationary connection for the electrical slip rings.

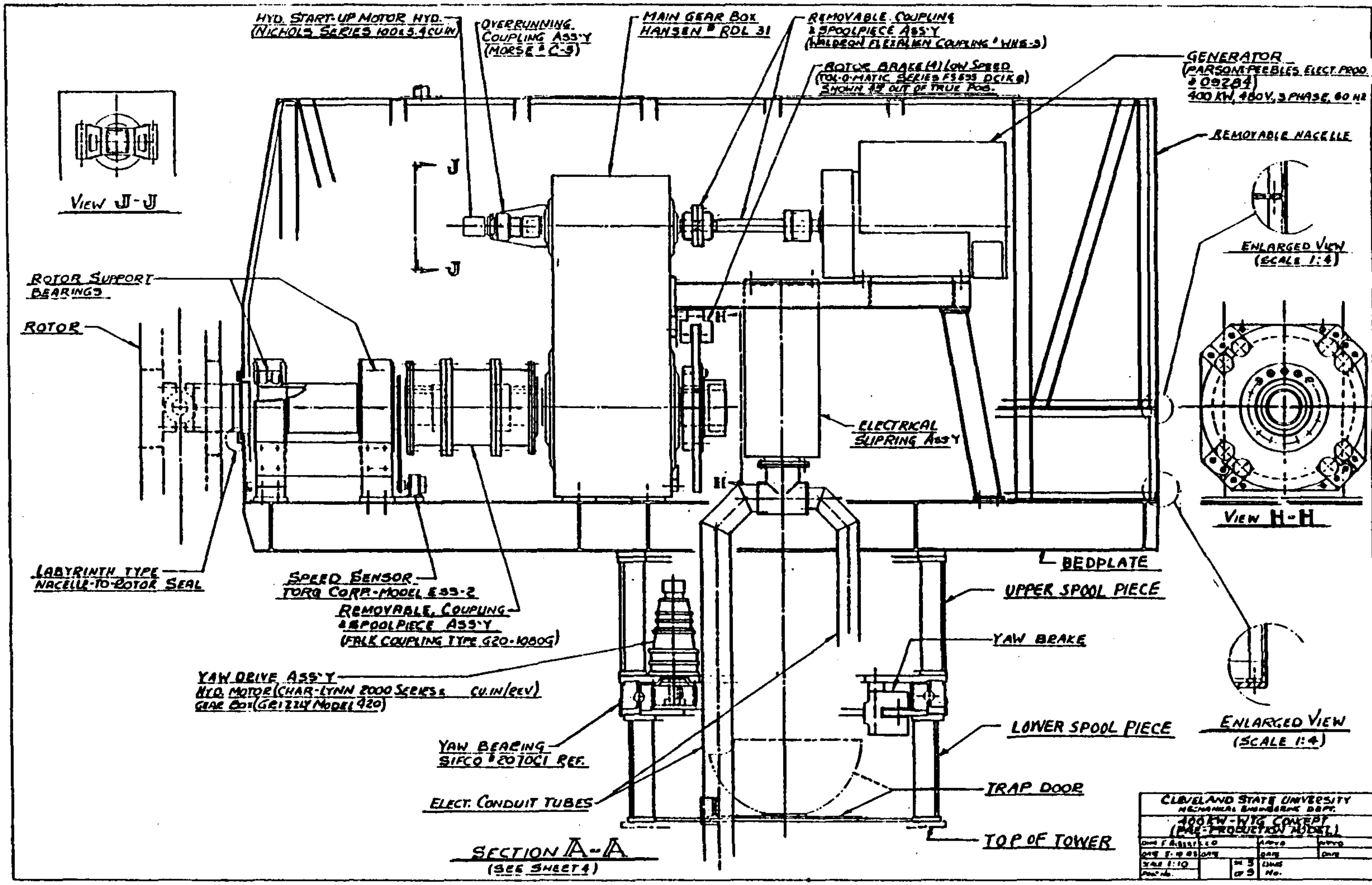


FIGURE 13 NACELLE LAYOUT OF WTG-VERTICAL CROSS-SECTION

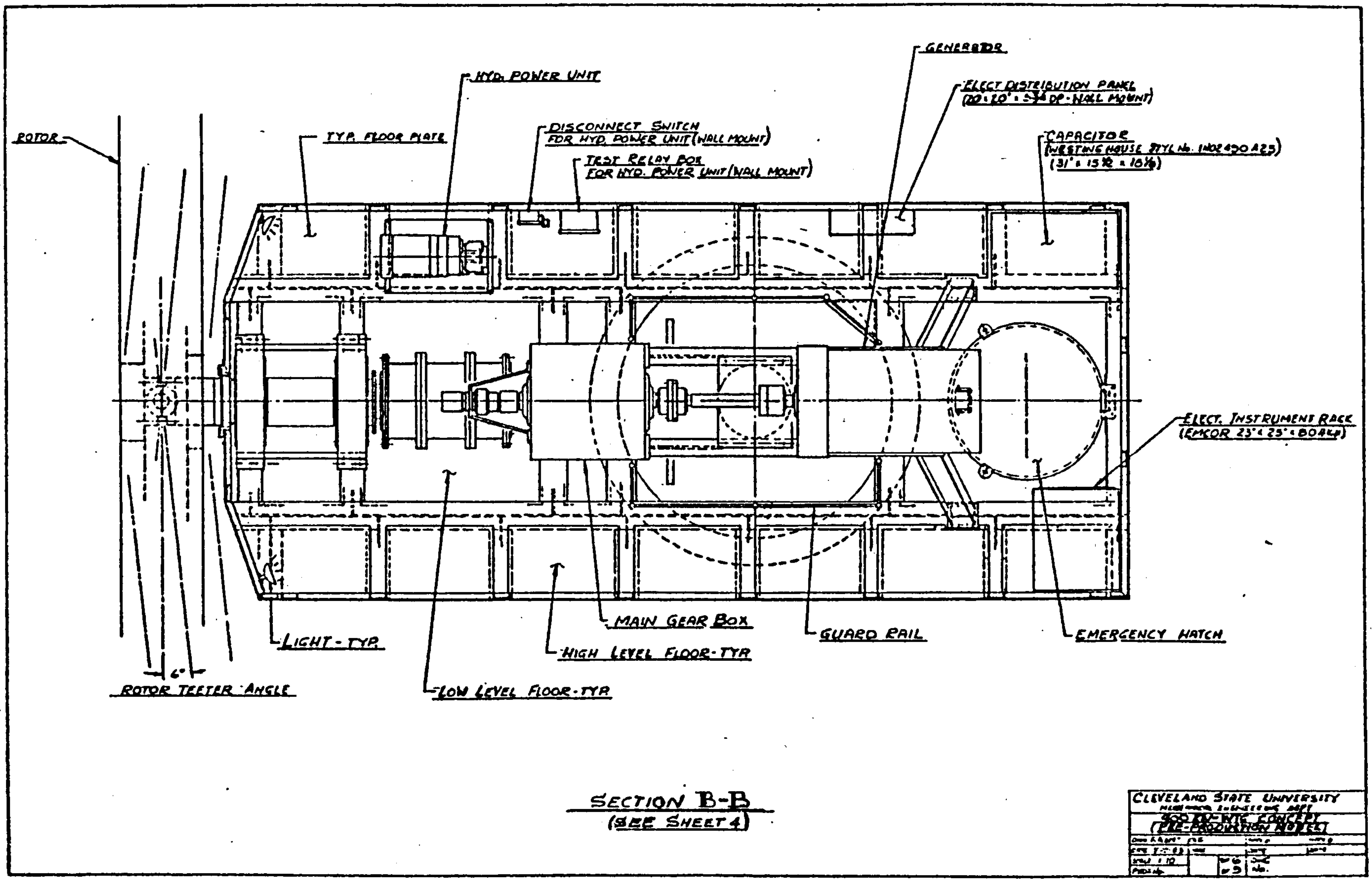


FIGURE 14 NACELLE LAYOUT OF WTG-HORIZONTAL CROSS-SECTION

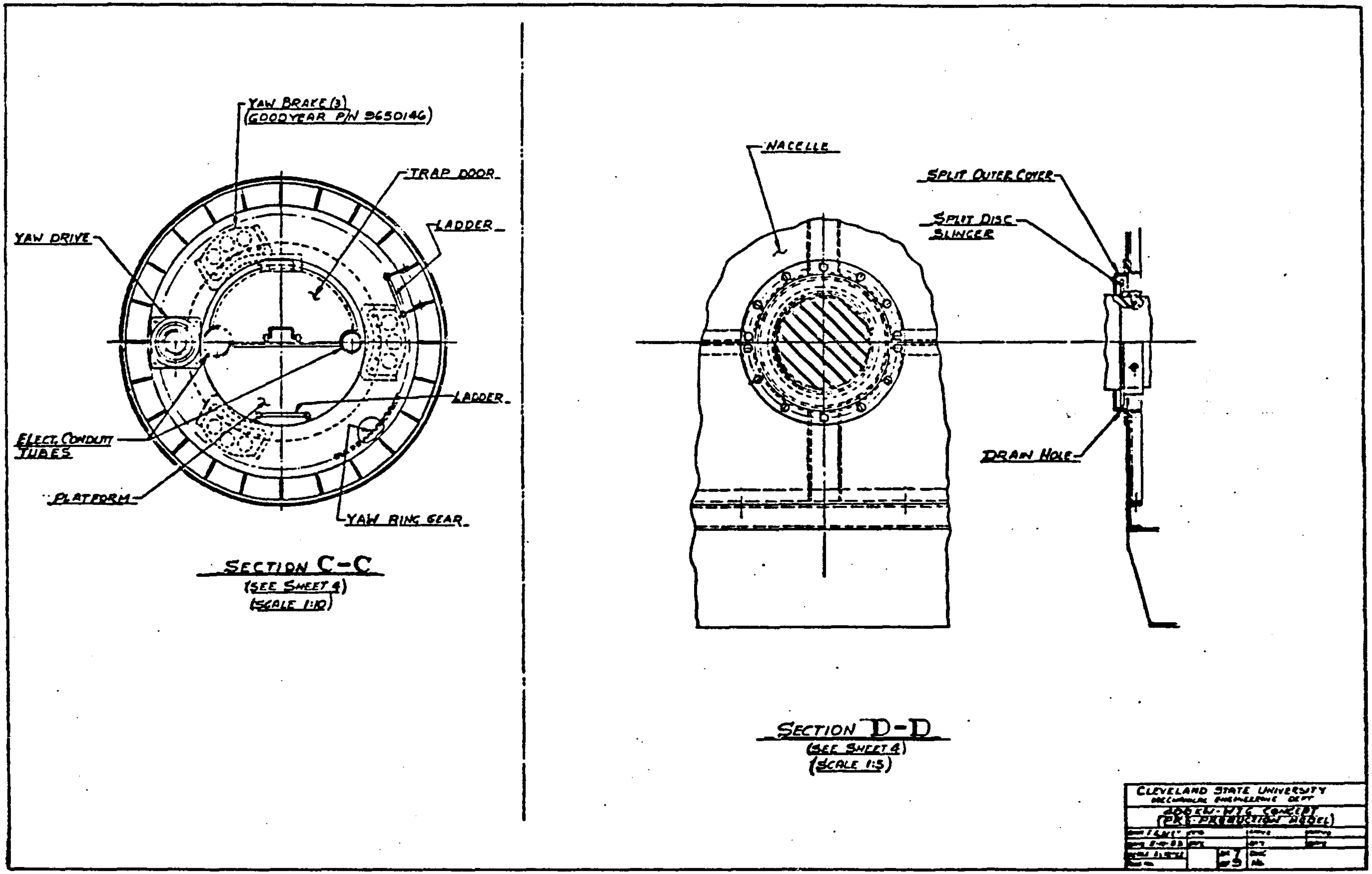


FIGURE 15 NACELLE LAYOUT OF WTG-SECTION VIEWS

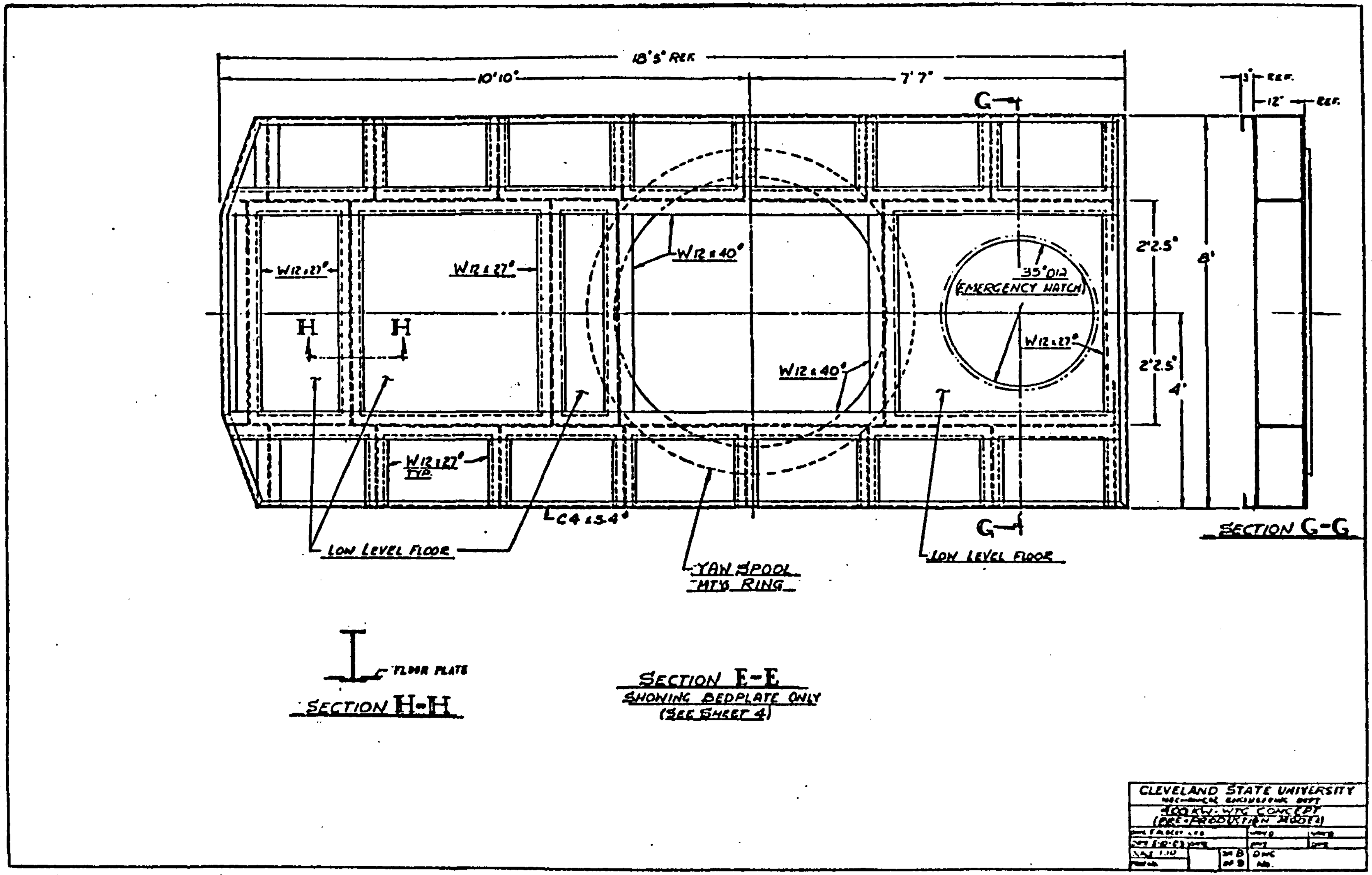


FIGURE 16 BEDPLATE LAYOUT

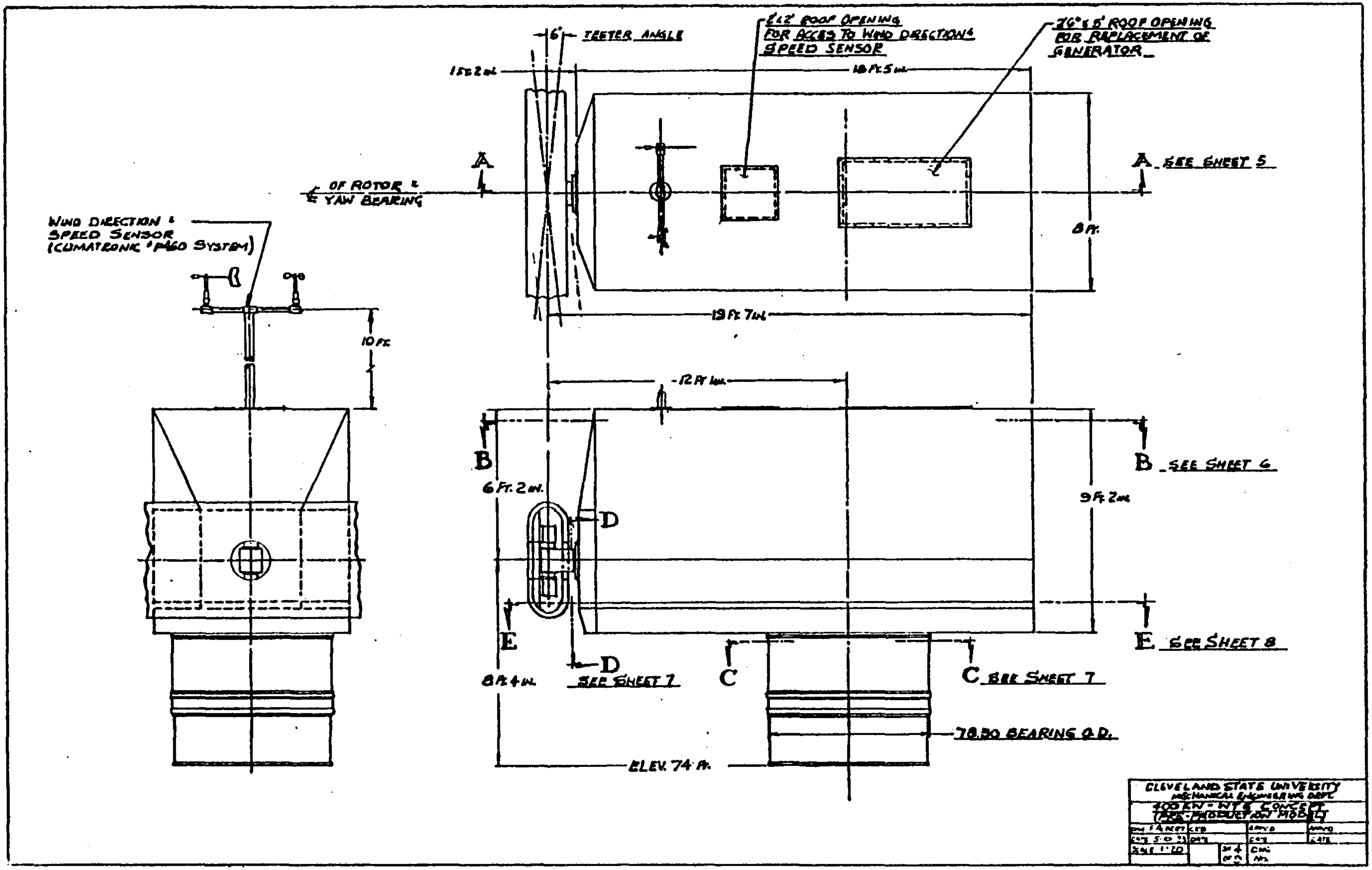


FIGURE 17 NACELLE LAYOUT OF WTG-OUTSIDE VIEWS

4.2 TOWER CONFIGURATION

The tower is constructed of eight (8) straight pipe sections which are rotated about the vertical centroidal axis. In this manner, the structure approximates a hyperboloid of revolution. Each straight member is made of 6 inch pipe and tied to the other members at the top, bottom and at 4 elevations by means of circumferential braces.

The main attraction of this tower construction is its ease of fabrication and assembly. For transportation purposes, the tower is divided into three different frame sections. The lower two sections can further be broken down into pairs of straight sections. The top frame section, the various paired straight sections and circumferential braces can be prefabricated in a shop and easily erected in the field.

For ease of assembly, each straight section and the top frame section has welded-on flanges at its ends. The connecting braces are then sandwiched between the flange of the mating sections (see details in Figures 18 and 19). The tower provides for emergency access to the nacelle by means of a step ladder with protective cage.

Also, the top frame section has a work platform for the purpose of servicing four electrical junction boxes. Four junction boxes are attached at the bottom of the tower also. Connection to the electrical equipment in the control room is directly from these lower junction boxes.

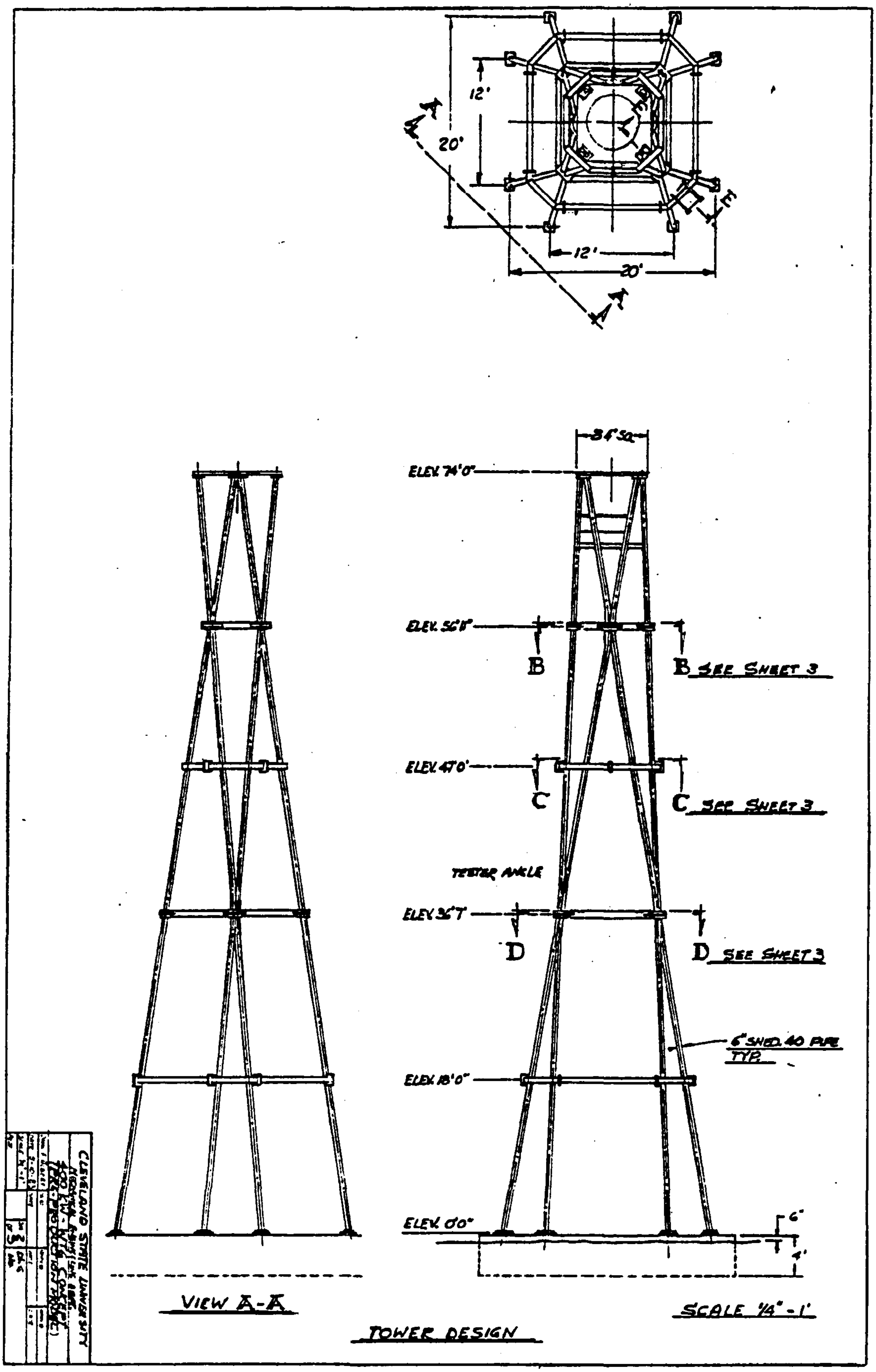


FIGURE 18 TOWER DESIGN

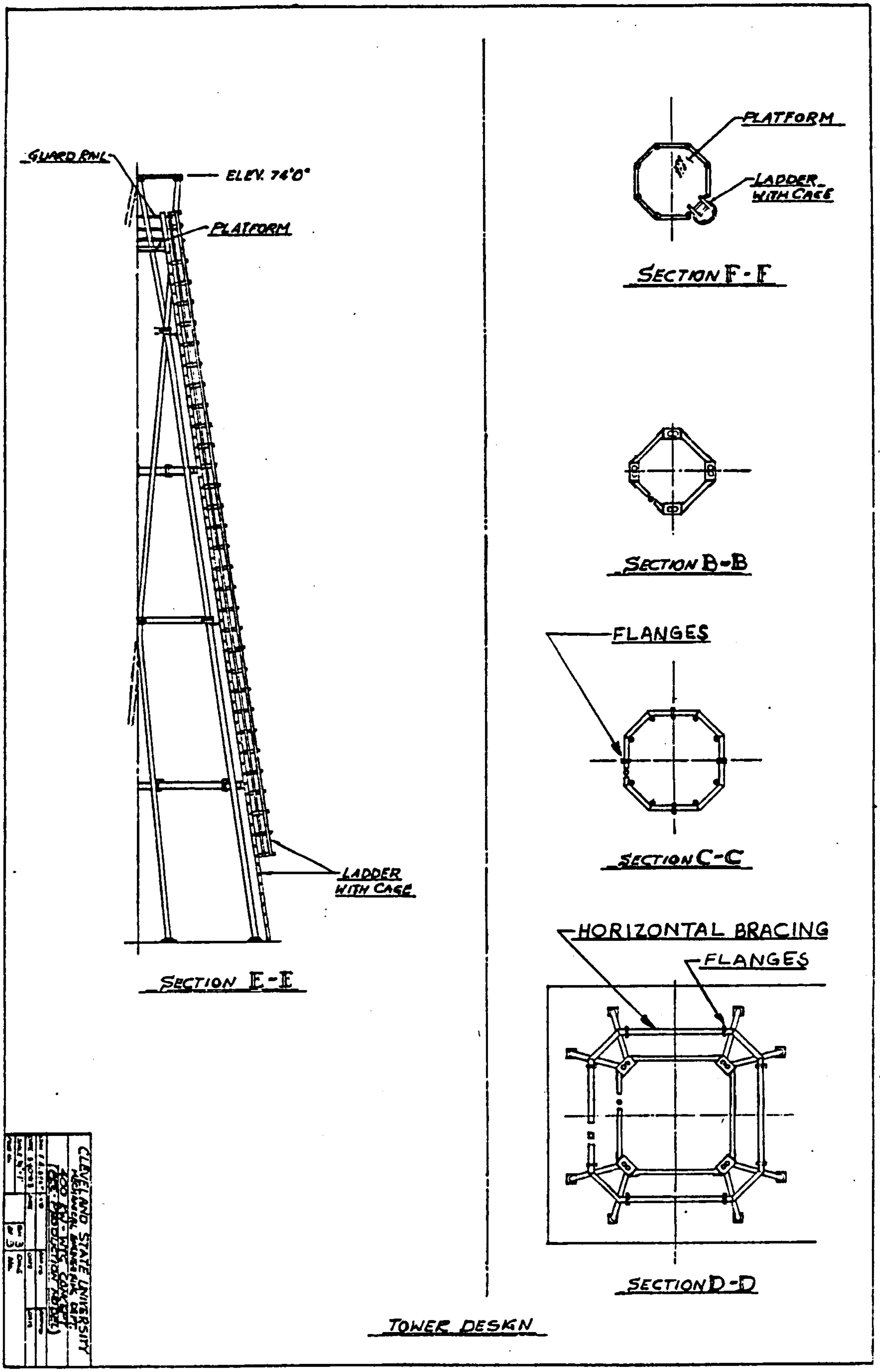


FIGURE 19 TOWER DESIGN-SECTION VIEWS

4.3 CONTROL ROOM AND POWER TRANSFORMER

Because of the great expense of electrical transmission lines, the control room is located next to the tower. Figure 12 shows an outline of the control room structure and the electrical power transformer. Figure 20 shows the layout of the control room including electrical equipment needed for operation of the WTG. A detailed explanation of the electrical design is included in the next section.

4.4 ELECTRICAL SYSTEMS

The controls for the electrical equipment of the WTG are greatly simplified by the selection of a fixed pitch rotor and the use of an induction generator. The former eliminates the need for speed control and the latter eliminates frequency control.

Figure 21 is a schematic of the equipment used to generate, control and safeguard the electric power (power one-line diagram). The diagram shows secondary resistors in the control room for slip control of the 480 V, 400 kw wound rotor generator. Resistor banks have been selected for 1,3,5 and 10% slip control with respective resistor tap settings of 0, 0.013, 0.025 and 0.056 ohms. This equipment will not be needed in the second unit when a squirrel cage generator will be used. Capacitors with ratings from 75-100 kvar for improvement of generator power factor to 96% are placed in the nacelle. The switch-gear which is also in the control room contains the main circuit breaker rated for 800 amps frame, 800 amps trip, and the necessary transformers, meters and relays for protection and indication in one unit. An oil-filled, pad mounted, 500 kva outdoor transformer is used to raise the primary voltage from 480 to 13,800 volts. The transformer also contains the primary disconnect switch.

Figure 22 depicts the WTG and control room one-line diagram with provisions for auxiliary power operation from 480 and 120 volts. The motor control center, lighting panels and instrument and control equipment cabinet are located in the control room. It is planned to use either a microprocessor based system or programmable controller for control of the WTG.

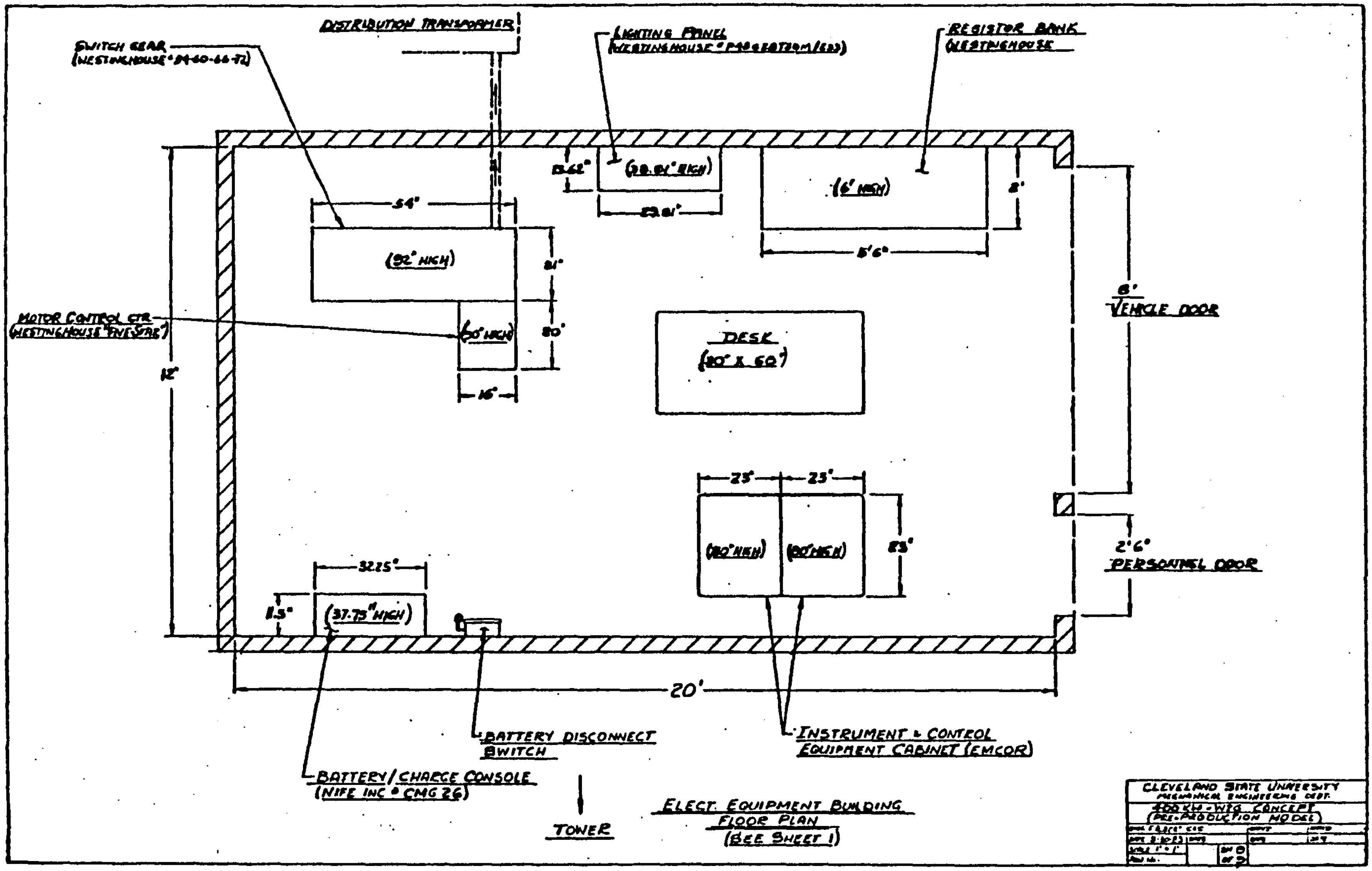


FIGURE 20 CONTROL ROOM LAYOUT

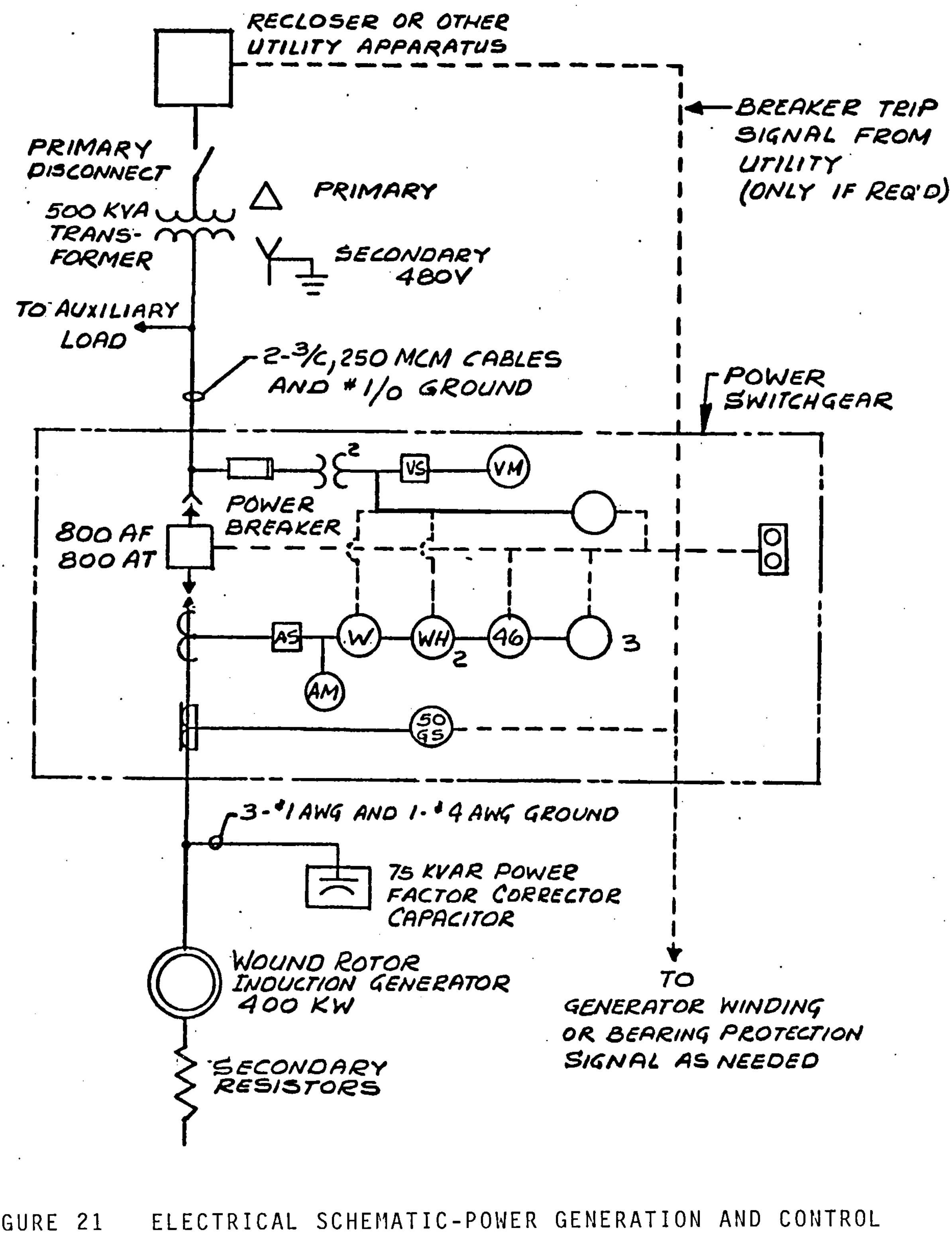


FIGURE 21 ELECTRICAL SCHEMATIC-POWER GENERATION AND CONTROL

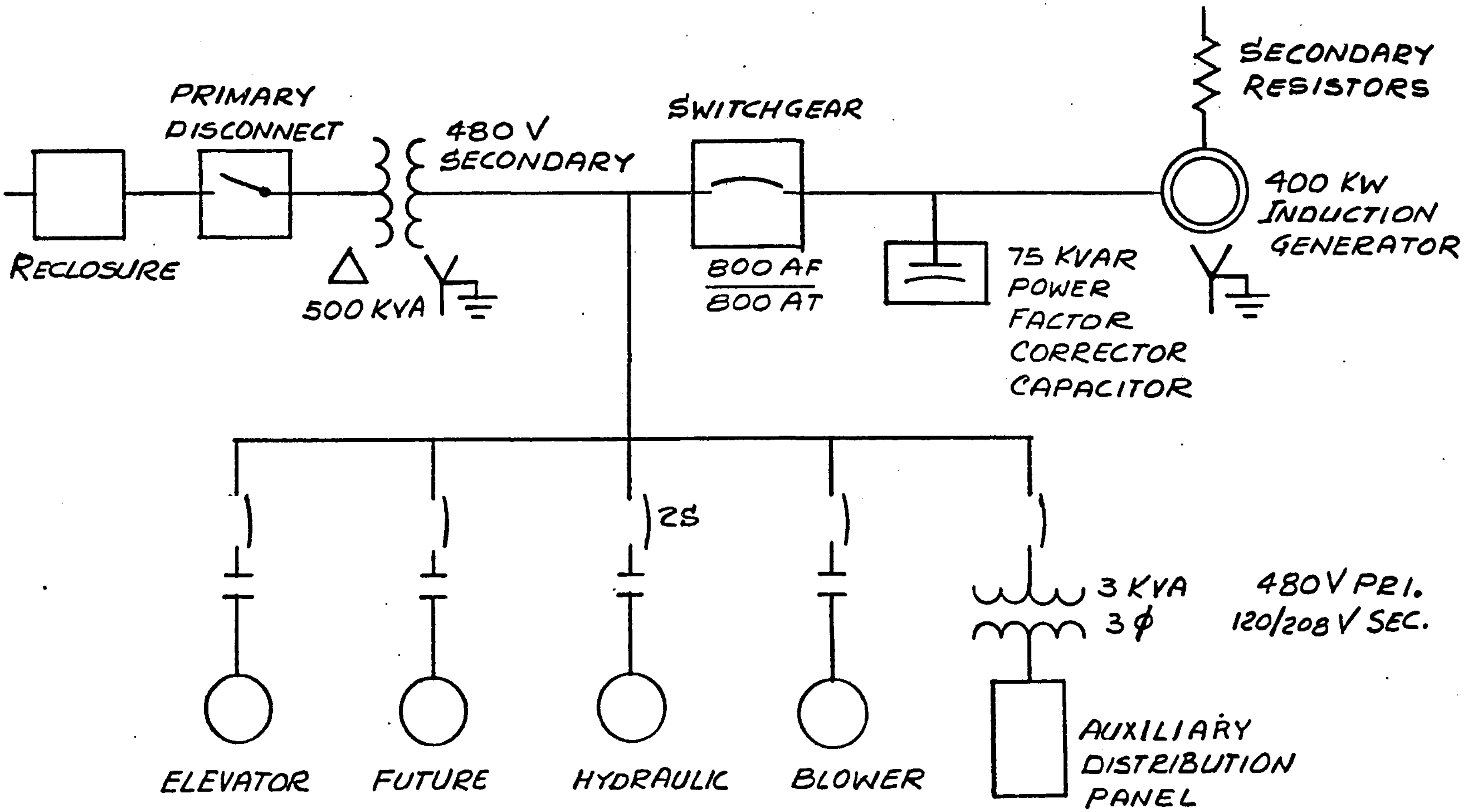


FIGURE 22 ELECTRICAL SCHEMATIC-POWER AND AUXILIARY SYSTEMS

4.5 SECOND UNIT WTG COST

This section contains cost estimates of the second production unit. The cost estimate of a single unit was determined by using prices quoted by prospective vendors, by making construction and fabrication cost estimates as practiced by LeRC, and by making an allowance for those items that did not have cost figures based on either of the other two methods. The cost of labor to install the electrical equipment of the WTG and windfarm was based on the prevailing average wage rate in Cleveland, Ohio during 1983. Specifically, this cost of labor was based on $22.00 per hour plus allowance for 15% overhead and 10% profit.

Table III summarizes the cost estimates for the complete WTG, including installation. No allowance was made for the cost of land or access roads. Detailed cost estimates by functional grouping are in Appendix D. The cost of a WTG with a transmission line of 2 miles and using a fixed slip generator is $596,870. On the basis of cost per maximum power output, this second unit cost is 1492 dollars/kw.

TABLE III

COST ESTIMATE OF SECOND PRODUCTION UNIT

Nacelle..........................	$291000
Tower............................	63180
Control Room.....................	74390
Site Related	
- Foundation...................	18000
- Yard Work....................	8000
- Transportation...............	12500
- Erection.....................	25000
Spares...........................	3000
Misc.............................	5000
WTG INSTALLED-TOTAL	$500070

Transmission Line (2 Miles)	$96800

4.6 COST OF ENERGY FOR WIND FARM

Figure 23 shows the layout of a windfarm containing 12 WTGs. The WTGs are separated from each other by a minimum length of ten rotor diameters (900 feet). Also, the WTGs are grouped so that the electric power is collected into one transmission line and routed to the main substation. Additional land equivalent to 5 rotor diameters is included around the border of the farm to allow for access of undisturbed wind. A typical electrical schematic of a group of four WTGs is shown in Figure 24.

Table IV summarizes the cost of a 12 unit WTG cluster (wind farm). The cost of the 12 WTGs was derived by assuming a 30% reduction in cost through volume production. The reduction was demonstrated by the detailed cost study of the Gougeon Bros. Company for the wooden rotor (see Section 3.4.2). No allowance was made for the cost of land, access roads, etc.

The calculated cost of energy as derived in Table V of 11.7 cents/kw-hr for the chosen fixed pitch WTG concept is based on the following assumptions:

a. 14 mph average wind site

b. WTG spacing 10 rotor diameters

c. 100 units per year produced

d. Land and improvement costs are not included

The COE of 11.7 cents/kw-hr compares favorably with the 8.0 cents/kw-hr paid in California considering that it was obtained from a conceptual design effort. The potential for cost reductions to the concept will be presented in the next section.

TABLE IV

COST OF 12-PRODUCTION UNIT CLUSTER (WINDFARM)

13.2 KV Main Substation..................	$50000
Modem For Remote Control (At Each WTG)....	12000
Modems At Central Control................	12000
Remote Control In Central Control Station.	20000
15 KV Insulated Cable On Poles, Terminations, Conduits, Links............	23330
Transmission Lines (4.8 Miles)...........	230000
Cost Of 12 Wind Turbine Generator Units & One Microprocessor Development System ($353350* + 11 x $342350)................	4119200
	$4,466,530
Unit Price/Windfarm.....	$372,210

* Includes $11000 for Microprocessor Development System

TABLE V

COST OF ELECTRICITY

For this 90 ft. blade, the calculated (PROPCODE) theoretical annual energy production in kw-hrs is at 55 RPM.

12 MPH Average Wind Site...........	493,435
14 MPH Average Wind Site...........	722,083
15 MPH Average Wind Site...........	846,118
18 MPH Average Wind Site...........	1,226,693

ASSUMPTIONS:

Availability of WTG................	.90
Annual Operation and Maintenance Costs	5000
Energy Due To 14 MPH Wind Speed....	722,083 Kw-Hrs

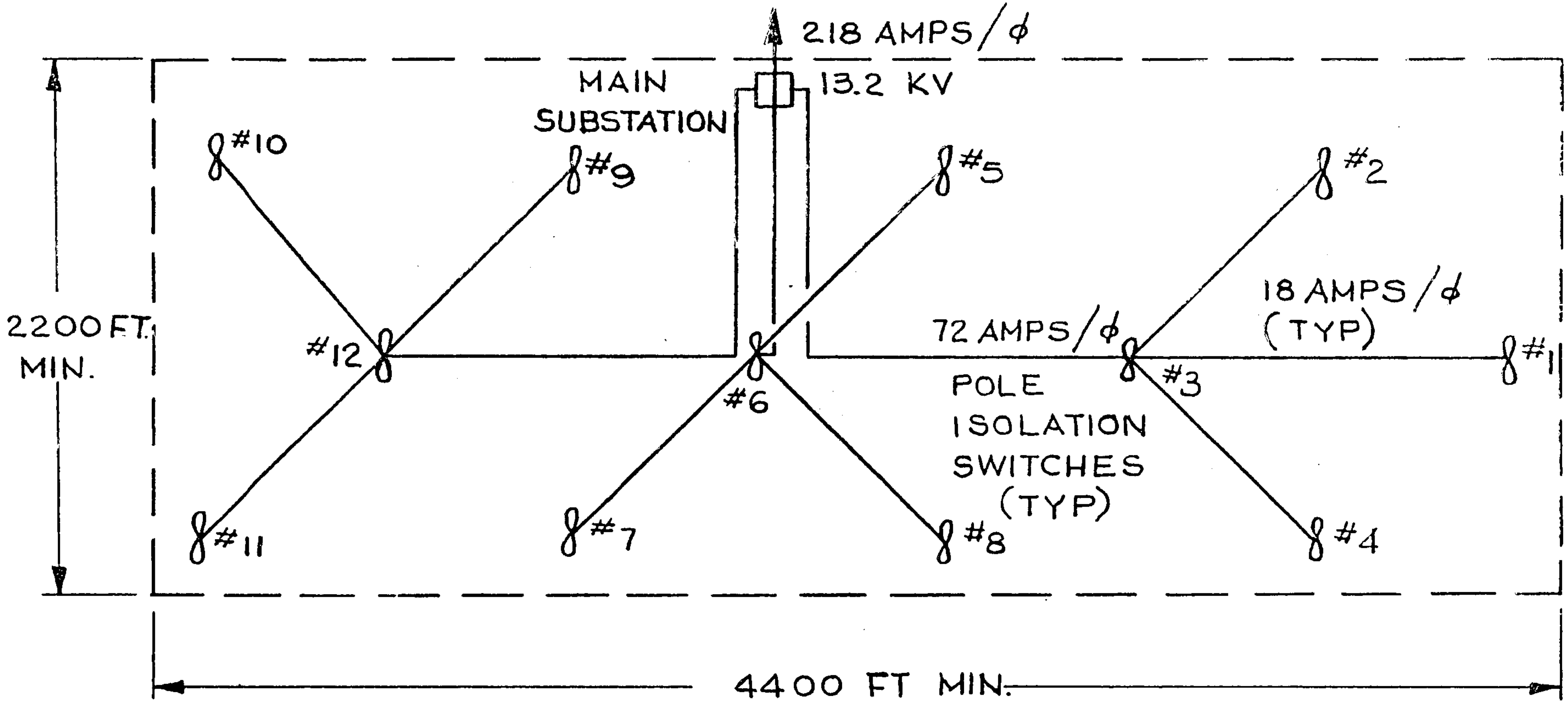
$$\text{Cost of Energy} = \frac{372210 \times L.F. + 5000 \times P.L.F.}{722083 \times .90} \times 100$$

$$= 11.5 \text{ cents/kw-hr}$$

WHERE:

L.F. = Levelizing Factor or Capital Recovery Factor.
At 12% interest rate and 10 year recovery time,
= .177

P.L.F. = Periodic Levelizing Factor
= 2.0



TOTAL LAND AREA ~ .35 MILE^2
MIN. SPACING BETWEEN WTG'S ~ 900 FT (10 x DIA OF ROTOR)

FIGURE 23   ARRANGEMENT OF WINDFARM

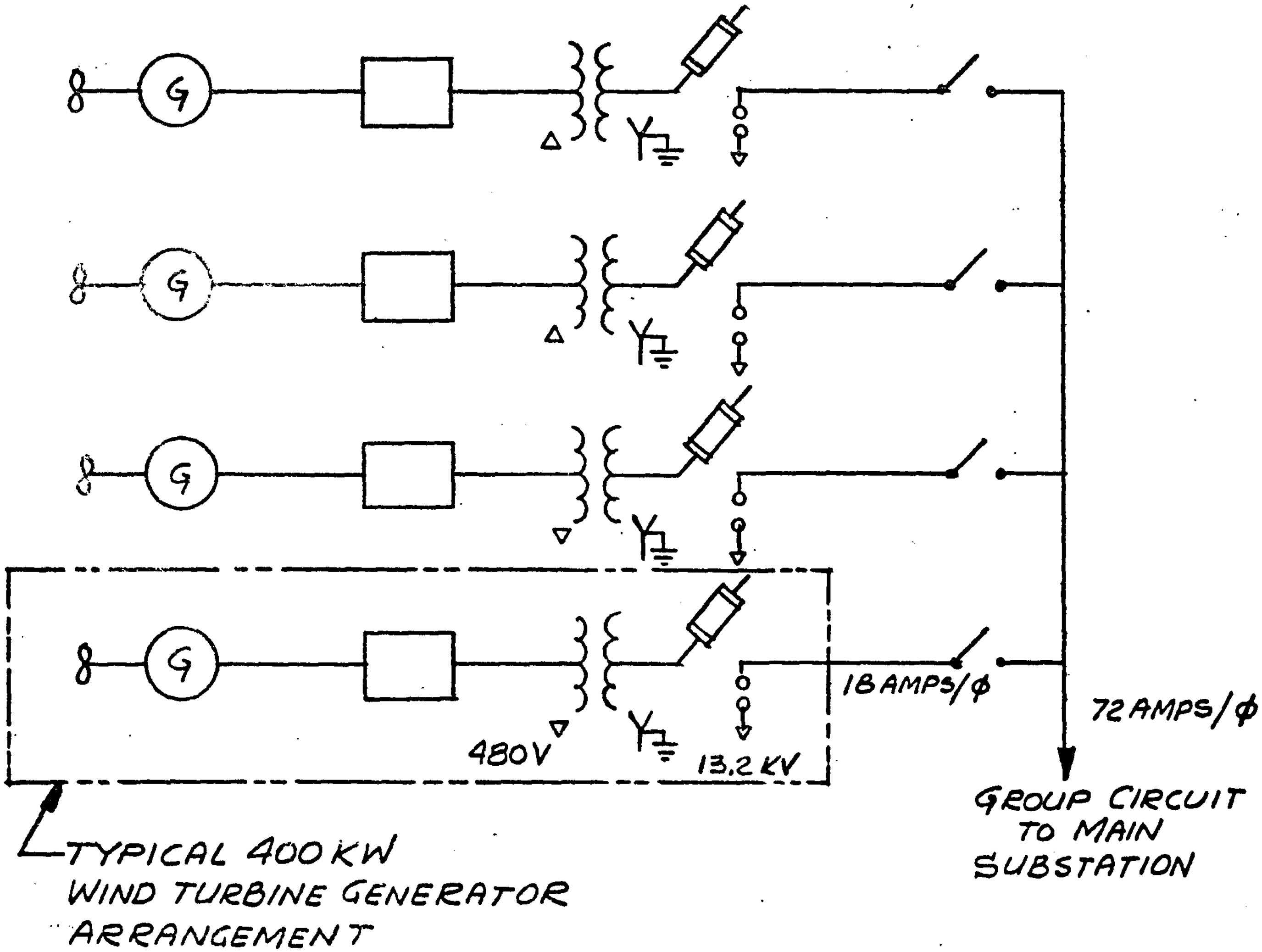


FIGURE 24 ELECTRICAL SCHEMATIC-WTG GROUPING

4.7 COST REDUCTION POTENTIAL

Fixed pitch operation, careful arrangement of components and incorporation of the latest research results, inherently lead to a low cost WTG.

All of the components except the coupling and spool pieces appear reasonably priced for their respective functions. The cost of the rotor, the generator and the tower appear to be at a minimum value already. Therefore, any cost reductions must be obtained from the remaining components and subsystems. This may be achieved through careful purchasing from world wide sources, integration of the functions of several components into one and incorporation of WTG research results obtained subsequent to this design. Cost reduction potentials identified so far include:

- A planetary gear transmission that incorporates the two pillow block bearings for the rotor support is available from Flender Corporation at a cost substantially below the combined cost of the present items. This transmission would place the generator at the same level and in-line with the transmission. Some of this cost reduction may be offset by modification to the bedplate to achieve access to the nacelle.

- The Gougeon Bros. Co. has recently developed a highly twisted wood blade for a 300 kw WTG. This blade has the potential for a 10% increase in energy capture. Also, a twisted rotor eliminates the need for a start-up system. Cost data of this twisted blade for the 400 kw concept is not available at this time.

- The slip rings for the power transfer from the nacelle to the tower have been eliminated in a recent modification to the MOD-0 test bed by limiting yaw rotation to less than 360°. The signal transfer slip rings could be similarly eliminated. Besides the obvious cost reduction this improves access to the nacelle. Most attractive wind sites have a predominant wind direction, thus precluding frequent large angle yaw rotations.

Cost reductions for the windfarm of 12 units included a 30% reduction in WTG cost based on yearly production of 100 units. Higher production rates would certainly result in additional cost reductions both in volume discounts and assembly efficiency.

4.8 WEIGHT

Weight estimates of the nacelle (52,685 lbs), tower (26,550 lbs), and control room (8150 lbs) for the second unit WTG are shown in Tables E-1, E-2, and E-3 of Appendix E. The weight of the outdoor transformer is 5300 lbs.

A breakdown of the weight of the major functional groupings of the WTG is as follows:

Rotor and Hub	7000 lbs
Drive Train	22760 lbs
Yaw Drive and Support Bearing	5825 lbs
Bedplate, Nacelle, Spool Pieces and Component Supports	17100 lbs
Tower - Structure	22000 lbs
Electrical	4550 lbs
Total Weight Above Ground..........	79235 lbs

The associated ratio of cost/weight ($354180 / 79235 lbs) equals $4.47 per pound.

5.0 KEY FINDINGS

Based on the information generated in sections 3.0 and 4.0 the following pertinent findings regarding fixed pitch rotor WTG operation were obtained:

a. Operation with untwisted, tapered rotor blades produces nearly constant power at high wind speeds (Figure 11).

b. Differences in energy capture between untwisted and twisted blades do not warrant the additional cost of twisting (Table II).

c. Operation requires a grid powerful enough to maintain frequency control.

d. Emergency shutdown must be obtained with brakes because use of yaw control alone results in excessive overspeed.

e. Normal shutdown may be obtained with yaw control in combination with brakes.

f. Braking of rotor with a disk brake on the low speed shaft is feasible and improves overall reliability of drive train.

g. Use of over-running coupling in drive train reduces the need for frequent startups and shutdowns in low wind conditions.

h. Parallel shaft gear box is attractive for intermediate power WTG use because it provides convenient locations for attaching auxiliary components such as the brake and startup systems. Mounting the gearbox on end allows ready access to the nacelle from the center of the tower.

i. Inclusion of design features such as teetering of rotor, upwind rotor position, high slip induction generator, hydraulic starting and passive yaw control suggested by recent NASA research efforts greatly contributed to reliability and cost improvements.

j. Analysis and design show that the continuous wooden rotor and hyperboloid tower show promise for low cost components.

k. No components for control of the rotor are located outside the nacelle or control room.

l. The cost of energy when 12 units are clustered into a windfarm was 11.5 cents/kw-hr not including land.

6.0 CONCLUSIONS AND RECOMMENDATIONS

NASA developed the MOD-0 100 kw and MOD-0A 200 kw WTGs as research machines. Both provided valuable operating information in the medium power range. Because they were designed for research purposes, they are not suitable for commercial applications. This study represents the conceptual design phase for a low cost 400 kw fixed-pitch rotor WTG based on the information gained from the MOD-0 and MOD-0A designs. This power capacity was selected as a natural progression of power from the two previous NASA WTG investigations in the medium power range of 100-500 kw. The goals of this study were to design a reliable, low cost WTG using components that are readily available and incorporating recent NASA WTG research results. Along with the conceptual design, cost estimates for the second WTG and a windfarm of 12 units were to be obtained. Finally, areas of investigations for the next phase which point towards further performance, cost and reliability improvements were to be identified.

The conclusions that can be drawn are as follows:

- The study showed that the costs of a WTG can be reduced significantly through the use of fixed pitch operation.
- Additional cost reductions are needed, and possible through integration of components and world wide purchasing.

- o Reliability and safety improvements have been achieved by eliminating all external controls through the use of an induction generator for damping and a disk brake on the low speed shaft for shutdown.
- o The completed design demonstrates an efficient layout of the components, and provides protection from the elements and ready access for maintenance.

The findings and conclusions of this study point toward fixed pitch operation as an attractive concept for intermediate power WTGs. Therefore, this concept should be carried forward to the prototype stage and tested.

7.0 REFERENCES

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2. Stroebel, T. et al; Design of an Advanced Wood Composite Rotor and Development of Wood Composite Blade Technology, DOE/NASA/0260-1, NASA CR-174713, December, 1984.

3. Viterna, L.; An Improved Aerodynamic Model for Wind Turbines, NASA LeRC PIR. No. 144, March, 1980

4. Jamieson, P. and McLeish, D.; The HWP-300 Wind Turbine, IEE Proceedings, Vol. 130, Pt. A, No. 9, December, 1983.

APPENDIX A - GENERAL DESIGN REQUIREMENTS

1. ROTOR

   a. Swept area diameter: 27 meters = 90 ft.

   b. Maximum rotor power output: 440 kw.

   c. Rated power density: 650 watts/sq. meter.

   d. Rotor support: Mounted on the low speed shaft which is supported by two pillow block bearings.

   e. Operating rotational speed: Fixed speed-optimized between 40 and 60 rpm.

   f. Direction of rotation: Clockwise when viewed from upstream.

   g. Blades: Continuous wood blade made by Gougeon Bros.

   h. Rotor location: Must be able to operate upwind of the tower.

   i. Rotors with coned blades and tilted axis are prohibited.

   j. Maximum allowable rotor weight: 10,000 pounds.

2. GEARBOX

   a. Parallel shaft type.

   b. Ratio: Fixed ratio to be optimized for 40 to 60 rpm rotor operation.

   c. Maximum power input to the low speed shaft: 440 kw.

   d. Low speed shaft connected to replaceable coupling and hub.

   e. Low speed shaft to contain a fail-safe emergency overspeed protection brake as per Item 10.0, below.

f. Low speed shaft to be hollow.
   Inside Diameter = 3.0 inches.

g. High speed shaft to drive a 400 kw generator.

h. Splash lubrication or pumped lubrication.

i. Must be operable in both directions.

j. Must provide auxiliary high speed shaft for hydraulic motor starting of rotor.

3. GENERATOR

   a. Type: Induction with wound rotor.

   b. Rated power: 400 kw, 60 Hertz, 1800 rpm synchronous speed.

   c. Output voltage: 480 volts or higher if economical.

   d. Slip: Variable 1% to 10% in discrete steps.

   e. Shaft must have extension to connect to overrunning coupling.

4. YAW DRIVE AND BEARING

   a. Bearing minimum inside diameter = 6 ft.

   b. Bearing to be located between the bedplate and the top legs of the tower.

   c. Bearing shall be grease lubricated.

   d. Yaw drive is to be gear type, operable in both directions, and with zero backlash.

   e. Yaw drive to be supported on a spool type structure that is between the yaw bearing and the bedplate structure.

   f. A friction type brake shall be included to provide yaw damping to secure the machine against yaw motion.

g. Yaw rate: Variable from 1/4 to 5° per second.

5. BEDPLATE STRUCTURE

a. The purpose of the bedplate is to support the power train (which supports the rotor), auxiliary equipment, and the nacelle.

b. The bedplate shall rest on and be fastened to a spool piece which in turn rests on and is fastened to the yaw bearing.

c. The spool piece may be removable for ease of assembly and transportation.

d. A goal is to have the bedplate fabricated of simple structural elements with a minimum of rolling or bending of the elements.

6. NACELLE

a. The purpose of the nacelle is to provide the technicians protection from the weather, and prevent corrosion of components.

b. All electrical lines that run from the bedplate to the nacelle shall have connectors.

c. A removable door on the ceiling shall be provided to permit removal of the generator and gear box.

d. General lighting, electrical space heaters and weatherproof electrical service outlets (120 and 480 volts) shall be provided inside the nacelle.

e. The inside walls and ceiling shall be painted white to improve general illumination.

f. The outside of the nacelle shall be painted and marked. Specific colors and marks TBD.

g. Ventilation louvers, which can be closed, shall be provided on the wall close to the gearbox and on the opposite wall.

h. Personnel access to the roof of the nacelle shall be provided.

i. Appropriate aircraft warning lights shall be mounted on the nacelle roof.

j. Flooring shall be non-skid.

k. Windows and skylights shall be provided for natural illumination.

7. SAFETY SYSTEMS

a. The primary emergency shutdown shall be by a disk brake located on the auxiliary low speed shaft of the gearbox.

b. Backup and emergency shutdown and normal shutdown will be by yawing of the machine.

c. An FMEA shall be performed to identify potential failure modes and define the required sensors.

d. The nacelle shall contain safety features such as fire extinguishers, air packs, guards on rotating elements, provisions for removing an injured person, emergency exit, and emergency lighting inside the nacelle.

8. CONTROL SYSTEM

a. Automatic control shall be primary mode of control.

b. Must not start when wind is blowing from the downwind side of the rotor.

c. Must be capable of automatic and manual operations.

d. Rotor shall be started by hydraulic motor on high speed auxiliary shaft of gearbox.

9. GENERAL OPERATING REQUIREMENTS

a. Hydraulic motor to start rotor at wind speed above cut-in (5 mps).

b. Cutout wind speed = 23 mps.

c. Normal shutdown to be achieved by yawing out of the wind.

d. Wind turbine operating range is in winds between 5 mps and 23 mps.

10. ROTOR BRAKE

a. The brake must stop the rotor in the event of any failure that can result in a rotor overspeed condition in less than 30 seconds.

b. The brake shall be a failsafe system.

c. The brake shall also function as a parking brake.

d. The brake shall be normally on when the rotor is not turning.

e. Drive train must be protected against sudden overtorque.

11. ELECTRICAL SYSTEM

a. The electrical system shall interface between the power grid and the wind turbine generator.

b. The electrical system shall provide all control room and wind turbine auxiliary power requirements.

c. All components shall be sized for 400 kw, 0.8 min. Power Factor generator.

d. Provisions shall be included for power factor correction.

12. INSTRUMENTATION

a. A sensor list shall be developed and implemented to assess performance and safety status of the wind turbine.

13. TOWER

a. The tower on which the pre-production WTG shall be mounted is the hyperboloid type.

APPENDIX B - COMPONENT REQUIREMENTS

1. GEAR BOX

   a. Parallel Shaft: 3" hole through center of low speed shaft (LSS)

   b. Speed ratio: Fixed between 30 and 45

   c. Rated Power: 450 kw

   d. Lubrication: As required

   e. Loads: Load Spectrum TBD

2. GENERATOR

   a. Type: Induction generator with wound rotor

   b. Rated power: 400 kw, 60 Hertz, 1800 rpm synchronous speed, 480 V or higher output, 3 phase.

   c. Slip: Variable 1% to 10% in discrete steps.

   d. Drip proof enclosure

   e. Conform to Nema Standard MGI

   f. Insulation: Class B with 40°C ambient temperature and 80°F temperature rise.

   g. Stator to be WYE connected

   h. Rotor overspeed limit: 125% of rated speed.

   i. Windings: Formed type.

3. YAW BEARING

a. Life Expectancy: 30 years

b. Operating time: 6000 hrs.

c. Rotational speed: .25° per second to 5° per second

d. Lubrication: Self lubricated

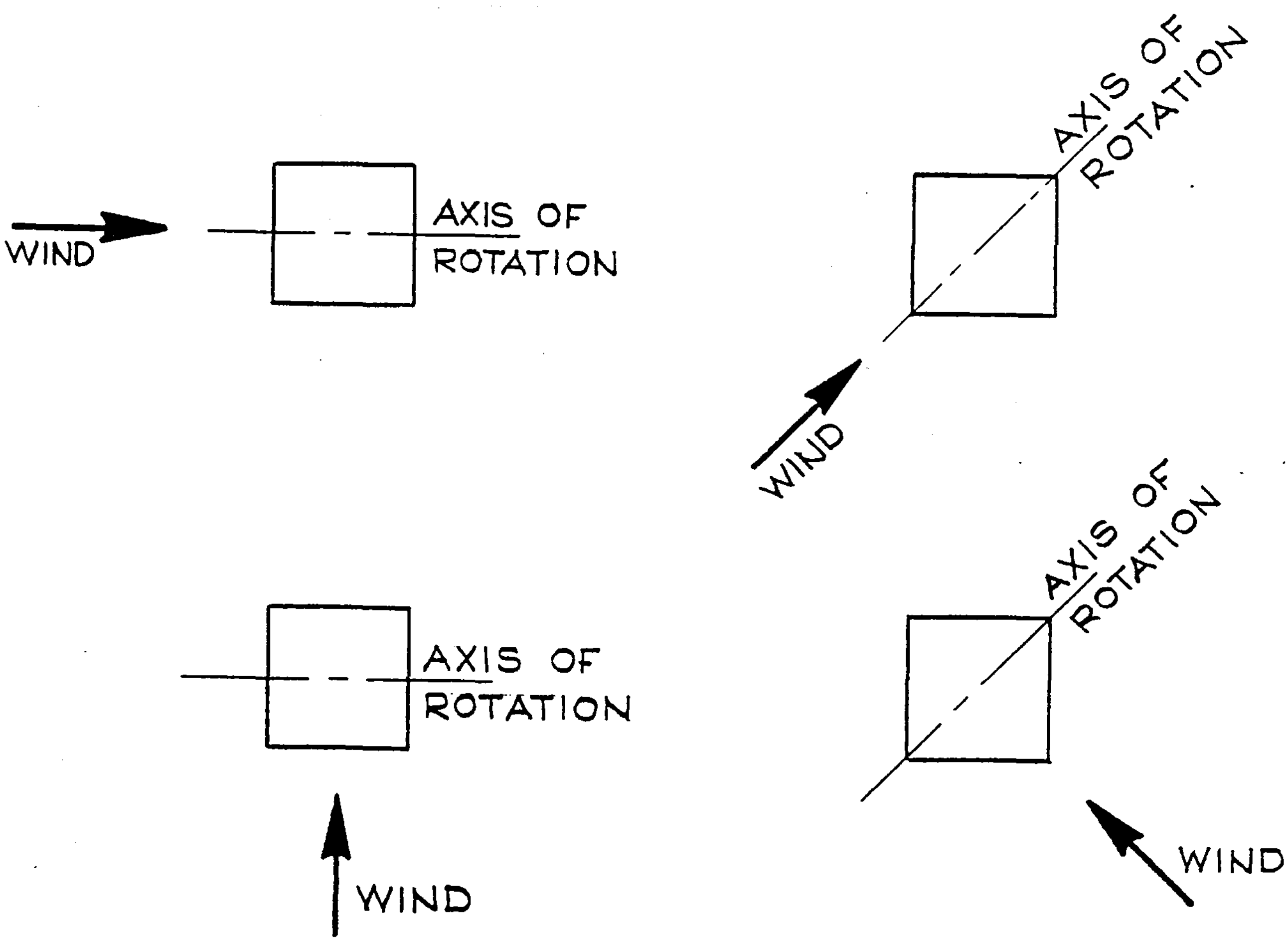
e. Min. Inside Dia.: 6.0 feet

f. Inner race: Internal gear diametral pitch of 2.5

APPENDIX C - LOADING CASES

For each of the cases shown below, two wind conditions were applied:

1. Wind parallel to axis of rotation
2. Wind normal to axis of rotation



The forces due to 120 mph wind loading of the blade, component weights, and live and wind loads on the nacelle are shown in Figure 25. The tower, bedplate and nacelle cover were sized on the basis of the forces in Figure 25 to meet the requirements of the AISC standard.

NACELLE WEIGHT = 2.6^{K}
BEDPLATE WEIGHT = 6.4^{K}

LIVE LOAD ON BEDPLATE = 75 psF
SNOW LOAD OR WIND LOAD = 35 psF

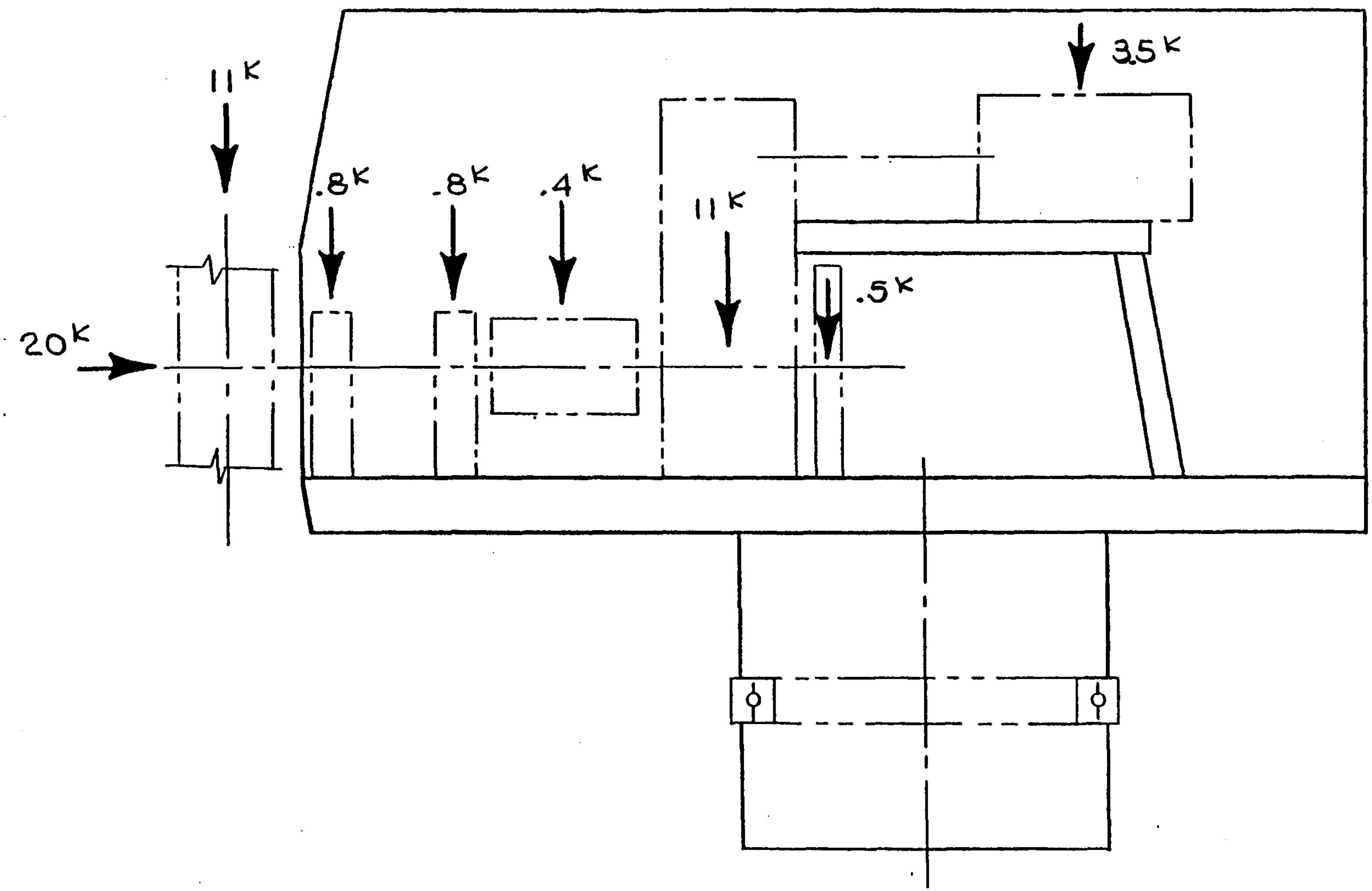


FIGURE 25 LOADING DIAGRAM OF NACELLE

APPENDIX D - COST ESTIMATE OF MAJOR FUNCTION GROUPS FOR SECOND PRODUCTION UNIT

TABLE D-1

COST ESTIMATE OF SECOND PRODUCTION UNIT

	Purchased	Fabrication	
	Items	Material	Labor
NACELLE:			
Mechanical (Total- $184095):			
Rotor....................	$38785		
Hub......................		$7500	$2500
Low Speed Shaft..........		5000	5000
Pillow Block Brg's & Sup't	5090	500	1500
Low Speed Shaft Coupling..	11220		
Gear Box.................	42000		
Rotor Brake & Bracket.....	6500		
Hydraulic Start Motor.....	500		
High Speed Shaft & Coup'g.	500	500	1500
Hydraulic System..........	10000		
Slip Rings................	12000		
Yaw Bearing...............	11000		
Yaw Drive			
- Hydraulic Motor.....	500		
- Planetary Gear Box..	4000		
- Disc Brakes.........	4500		
Assembly..................		2500	10000
	$146595	$16000	$21500

TABLE D-1 (Continued)

COST ESTIMATE OF SECOND PRODUCTION UNIT

	Purchased Items	Fabrication Material	Fabrication Labor
NACELLE:			
Structural (Total- $67205):			
Bedplate..................		$4795	$13700
Protective Covering.......		1405	9250
Generator Support.........		565	1250
Upper & Lower Spool Piece.		2760	25760
Trap Door.................		420	1000
Yaw Brake Disc............		500	1500
Yaw Drive Support.........		200	600
Misc......................		1000	2500
		$11645	$55560
Electrical (Total- $39700):			
Generator.................	$16800		
Cables, Connections, Lights, Beacons, Weather Vane, Panels		16800	4070
Power Factor Capacitor....	1900		130
	$18700	$16800	$4200

GRAND TOTAL NACELLE: $291000

TABLE D-2

COST ESTIMATE OF SECOND PRODUCTION UNIT

	Purchased Items	Fabrication Material	Fabrication Labor
TOWER:			
Structural (Total- $39950):			
Hyperboloid Tower.........		$9750	$18200
Ladders..................		500	500
Platform.................		500	500
Elevator.................	$10000		
	$10000	$10750	$19200
Electrical (Total- $23229):			
Cables, Boxes, Lightning Protection, Grounding.....		$13755	$9475
		$13755	$9475

GRAND TOTAL TOWER: $63180

TABLE D-3

COST ESTIMATE OF SECOND PRODUCTION UNIT

	Purchased Items	Fabrication Material	Fabrication Labor
CONTROL ROOM:			
Mechanical (Total- $ 5000):	$1500	$1500	$2000
Structural (Total- $10000):		5000	5000
Electrical (Total- $59388):			
Power Transformer.........	10500		924
Switch Gear...............	12900		352
Motor Controls............	3750		88
Batteries.................	2035		210
Programmable Controller...	3000		550
Lighting Transformer......	1915		220
Instrument Racks, Relay Panel, Etc.		1790	550
Control Panel, Meters, Switches, Etc.		1070	1034
Micro Processor System			
- Processor...........	7500		
- Development System..	11000		
	$52600	$2860	$3928

GRAND TOTAL CONTROL ROOM: $74388

APPENDIX E - SUMMARY OF WEIGHTS OF MAJOR FUNCTIONAL GROUPS

TABLE E-1

SUMMARY OF NACELLE WEIGHTS

MECHANICAL	Wt.-lbs
Rotor	4000
Hub	3000
Low Speed Shaft	1400
Pillow Block Bearing and support	2700
Low Speed Shaft Coupling	1550
Gear Box	10000
Rotor Brake and Bracket	800
Hydraulic Start Motor and Support	150
High Speed Shaft and Coupling	500
Hydraulic System	500
Yaw Bearing	4150
- Hydraulic Motor	25
- Planetary Gear Box	400
- Disc Brakes	750
Misc	1000
SUB-TOTAL	30925 lbs

STRUCTURAL	Wt.-lbs
Bedplate	3700
Protective Covering	2600
Generator Support	800
Upper and Lower Spool Pieces	5600
Trap Door	100
Yaw Brake Disc	1000
Yaw Drive Support	1200
Misc	1000
SUB-TOTAL	16000 lbs

ELECTRICAL	Wt.-lbs
Generator	4500
Power Factor Capacitor	160
Cables, Lights Beacon	1100
SUB-TOTAL	5760 lbs

TOTAL WEIGHT OF NACELLE: 52,685 lbs

TABLE E-2

SUMMARY OF TOWER WEIGHTS

STRUCTURAL	Wt.-lbs	ELECTRICAL	Wt.-lbs
Hyberboloid Tower	19500	Conduit	2500
Ladders	750	Junction Boxes	420
Platform	1000	Slip Rings	200
Elevator	750	Cable Power	1080
	------	Aux. Power	175
SUB-TOTAL	22000 lbs	Control & Instrument	175

		SUB-TOTAL	4550 lbs

TOTAL WEIGHT OF TOWER: 26,550 lbs

TABLE E-3

SUMMARY OF CONTROL ROOM WEIGHTS

MECHANICAL	ELECTRICAL	Wt.-lbs
1000 lbs	Switch Gear	1475
	Motor Control Center	1200
	Batteries & Charger	200
STRUCTURAL	Lighting Transformer	
	& Distrib. Panel ...	625
2000 lbs	(2) Instrument Racks	1200
	Cables and Conduit .	450
	SUB-TOTAL	5150 lbs

TOTAL WEIGHT OF CONTROL ROOM: 8150 lbs

WEIGHT OF POWER TRANSFORMER: 5300 lbs

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16. Abstract
This report covers the design and cost aspects of a fixed-pitch, 400-kW Wind Turbine Generator (WTG) concept. The goal of the study was to achieve improvements in reliability and cost reductions with fixed-pitch operation and by incorporating recent advances in WTG technology. The work was performed by Cleveland State University for NASA Lewis Research Center (LeRC). The specifications for this WTG concept as supplied by Lewis were as follows:

(1) A fixed-pitch, continuous wooden rotor was to be provided by the Gougeon Bros. Co. under NASA contract.
(2) An 8-leg hyperboloid tower that showed promise as a low cost structure was to be used.
(3) Only commercially available components and parts that could be easily fabricated were to be considered.
(4) Design features deemed desirable based on recent NASA research efforts were to be incorporated.

Detailed costs and weight estimates were prepared for the second machine and a wind farm of 12 WTG's. The calculated cost of energy (COE) for the fixed-pitch, twelve-unit windfarm is 11.5 cents/kW-hr not including the cost of land and access roads. The study has shown feasibility of fixed-pitch, intermediate power WTG operation. To achieve a competitive COE, further reductions in cost and increases in energy production are needed and possible.

17. Key Words (Suggested by Author(s))
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