NASA TM- 79032

DOE/NASA/1028-79/1
NASA TM-79032

NASA-TM-79032 19790009162

200-kW WIND TURBINE GENERATOR CONCEPTUAL DESIGN STUDY

National Aeronautics and Space Administration
Lewis Research Center

January 1979

Prepared for

U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology

NOTICE

1 Report No
NASA TM-79032

2 Government Accession No

3 Recipient s Catalog No

4 Title and Subtitle
200-kW WIND TURBINE GENERATOR
CONCEPTUAL DESIGN STUDY

5 Report Date
January 1979

6 Performing Organization Code

7 Author(s)

8 Performing Organization Report No
E-9825

9 Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

10 Work Unit No

11 Contract or Grant No

12 Sponsoring Agency Name and Address
U S Department of Energy
Division of Distributed Solar Technology
Washington, D C 20545

13 Type of Report and Period Covered
Technical Memorandum

14 Sponsoring Agency ~~Code~~ Report No
DOE/NASA/1028-79/1

15 Supplementary Notes
Final report Prepared under Interagency Agreement E(49-26)-1028

16 Abstract
A conceptual design study was conducted to define a 200-kW wind turbine power system configuration for remote applications The goal was to attain an energy cost of 1 to 2 cents per kilowatt-hour at a 14-mph site (mean average wind velocity at an altitude of 30 ft) The costs of the Clayton, New Mexico, Mod-0A (200-kW) were used to identify the components, subsystems, and other factors that were high in cost and thus candidates for cost reduction Efforts devoted to developing component and subsystem concepts and ideas resulted in a machine concept that is considerably simpler, lighter in weight, and lower in cost than the present Mod-0A wind turbines. In this report are described the various innovations that contributed to the lower cost and lighter weight design as well as the method used to calculate the cost of energy.

17 Key Words (Suggested by Author(s))
Wind turbine

18 Distribution Statement
Unclassified - unlimited
STAR Category 44
DOE Category UC-60

19 Security Classif (of this report)
Unclassified

20 Security Classif (of this page)
Unclassified

21 No of Pages

22 Price*

---

* For sale by the National Technical Information Service Springfield Virginia 22161

DOE/NASA/1028-79/1
NASA TM-79032

200-kW WIND TURBINE
GENERATOR CONCEPTUAL
DESIGN STUDY

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

January 1979

Prepared for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology
Washington, D.C. 20545
Under Interagency Agreement E(49-26)-1028

N79-17333#

This Page Intentionally Left Blank

CONTENTS

APPENDIXES

ABBREVIATIONS AND ACRONYMS

ALT	Alternator
COE	Cost of Energy
C_P	Rotor Efficiency
CT	Current Transformer
CYL	Cylindrical
D, DIA, DIAM	Diameter
ELEV	Elevation
EPRI	Electric Power Research Institute
FCR	Fixed charge rate
G&A	General and Administrative costs
GEN	Generator
HYD	Hydraulic
IND	Induction
K	Thousands
K	Spring constant, lb/in.
K	Proportionality constant used in COE calculations
K$	Thousands of dollars
LEV	Levelized
LVDT	Linear voltage differential transformer
M. H.	Manhours
O&M	Operations and Maintenance
P	Period of rotor revolution
PCM	Pitch change mechanism
PF	Power factor
PID	Proportional plus integral plus derivative
P_R	Power rating, kW
S. C. I.	Structural Composites Industries

SYN	Synchronous generator
SYS	System
TFT	Transverse fiberglass tape
TYP	Typical
V	Wind velocity at hub
$\overline{V}$	Site mean wind velocity
W	Wind velocity at 30' altitude
WTG	Wind Turbine Generator
η	System efficiency

1.0 INTRODUCTION

The NASA/Lewis Research Center (LeRC) has been involved in the development of large horizontal axis wind turbine generators (WTG's) since 1973. Machines designated Mod-0 and Mod-0A are currently operational in test-bed and utility network applications, respectively. Additional Mod-0A, Mod-1, and Mod-2 machines are in various stages of construction, design and development. Major features of each of these designs are presented in appendix A. An ongoing supporting research and technology program is also underway. The knowledge and experience acquired in these programs has been applied to the conceptual design of a new 200 kW WTG, designated Mod-X, and described in this report.

The LeRC in-house Mod-X conceptual design study was initiated in March, 1978. The stated goal was to design a 200 kW WTG which would produce electricity at a 14 mph site (mean average wind velocity at an altitude of 30 ft) at the lowest possible cost, hopefully 1 to 2 cents per kWh.

The study plan is presented in Section 2.0. System requirements and overall study goals are given in Section 3.0. The selected baseline configuration for the Mod-X WTG is described in Section 4.0. Details of the selected individual components and subsystems, as well as the considerations leading to those choices are presented in Section 5.0. Section 6.0 deals with the on-site installation concept, a major cost driver. Energy costs and the economic competitiveness of Mod-X are discussed in Section 7.0 Remaining open issues and conclusions are given in Sections 8.0 and 9.0, respectively. Appendix A includes a brief summary of the Mod-0, -0A, -1, -1A, and Hutter WTG's and Appendix B describes the factors which influence the fixed charge rate calculations.

2.0 CONCEPTUAL DESIGN STUDY PLAN

2.1 Objective

The objective of this study was to develop a conceptual design of a 200 kW wind turbine that had a potential for producing electrical energy at the lowest possible cost at a 14 mph site if the machine was mass produced. This machine was to have a 125 foot diameter rotor and a hub height of 100 feet. It was to be usable both in utility networks and as a stand alone power source in remote applications.

2.2 Approach

A team of NASA Lewis Research Center engineers and specialists who have considerable knowledge and experience on the Mod-0 and the Mod-0A projects was formed to develop a conceptual definition of the Mod-X wind turbine.

3.0 SYSTEM REQUIREMENTS AND GOALS

3.1 Cost and Weight Goals

An analysis was made using the cost methodology described in Section 7.0 to determine what the capital cost and the operation and maintenance (O&M) costs must be to meet an energy cost goal of 1 to 2 ¢/kWh. The results show, figure 3-1, that the capital cost of the machine must fall between $8 000 and $65 000, and the O&M costs must be no more than $4 000 per year if this goal is to be met. In figure 3-2 is shown how the O&M cost was derived. Clearly, to achieve such low annual O&M costs will require that the Mod-X's be very reliable and durable machines The capital cost goal is somewhat optimistic based on the costs of various commercially available components for the Mod-0, Mod-0A, and Mod-1 as well as other types of machinery. Hence, for this study, revised cost goals were selected for each major subsystem.

Weight goals were also selected using the weights of the major components for the Mod-0A and Hutter machines. Weight and cost goals used in the study are summarized in figure 3-3. The Mod-0A weighs 90 000 pounds excluding the foundation. The 100 kW Hutter wind turbine weighs about 29 000 pounds (ref. 1) The Hutter machine is obviously a lightweight design for its size. The selection of a total weight goal of 35 000 pounds was influenced by the low weight actually realized in the Hutter machine. A study of the Hutter wind turbine indicates that the low weight was achieved by a combination of design simplification, compactness, and load alleviation achieved through use of a teetered hub. Precisely the same desirable features were identified in the Mod-1A and Mod-2 studies.

Having established the weight goals for the major Mod-X subsystems and components, the cost goals were determined using a dollars per pound figure chosen from available data for mature mass produced commercial products. These are also shown in figure 3-3 where it is seen that significant reductions must be achieved in the costs of the rotor, drive train, yaw drive, tower, and installation.

3.2 Technical Requirements

The choice of technical requirements was guided by the experience that has been acquired to date in the other projects, namely the Mod-0, Mod-0A, Mod-1, Mod-1A, and Mod-2. These requirements are

1. The machine rated power is to be 200 kW.

2. The site annual average wind speed is 14 mph at 30 ft. This wind speed is typical of many midwest, coastal, and small off-shore island sites.

3. The machine must survive (a) 120 mph winds with blades feathered (assuming that the blades are pitchable over some or all of the span); and (b) 60 mph winds at hub height with the blades not feathered.

4. The Mod-X must withstand earthquake loads of Zone 2 seismic intensity. Most of the U. S. is classified as Zone 2 or less.

5. The Mod-X must operate reliably, safely, and unattended in either utility network or isolated applications.

6. The machine shall be designed to operate in the range of ambient air temperatures from -40° to 120° F

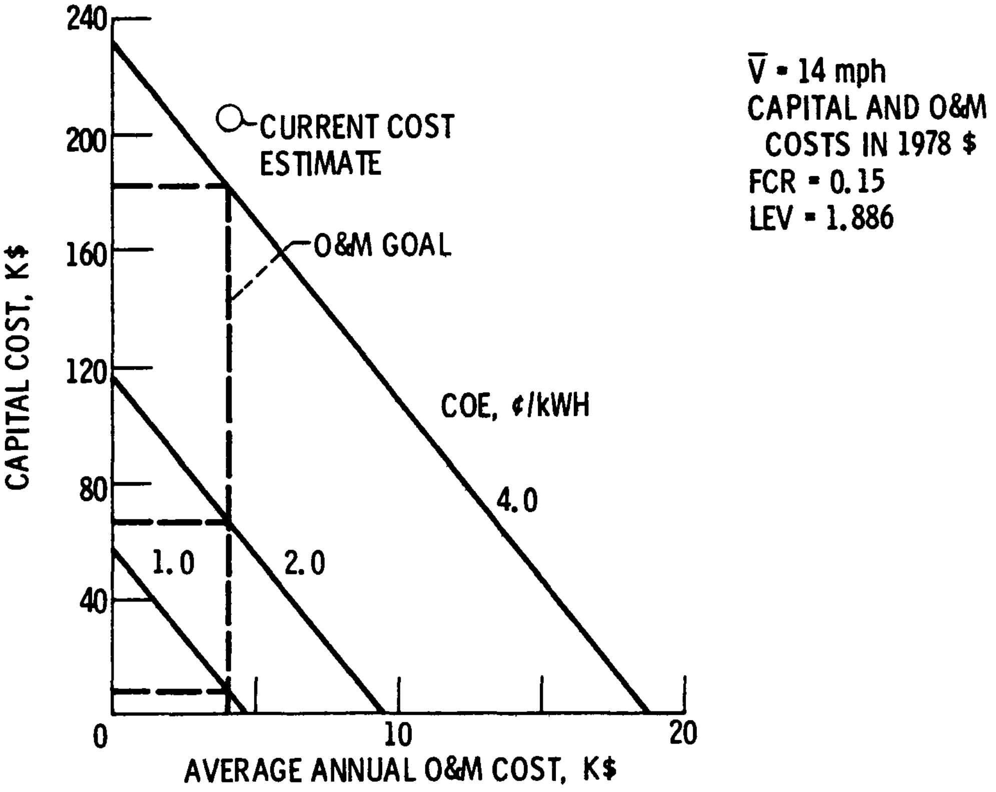


Figure 3-1. - Cost goals for Mod-X.

ITEM	RATIONALE	ANNUAL M.H. REQM'T	COST AT 28 $/M.H.
ROUTINE OPERATION	DAILY LOGGING OF MACHINE PERFORMANCE AND OPERATIONAL MONITORING AT DISPATCHER STATION (0.1 M.H./DAY)	36 M.H.	$1008
ROUTINE MAINTENANCE	ONE SITE VISIT PER MONTH TO PERFORM VISUAL INSPECTION AND ROUTINE LUBRICATION (2 M.H./MONTH)	24 M.H.	$ 672
EMERGENCY MAINTENANCE	ASSUMED TO BE EQUAL TO ROUTINE MAINTENANCE	24 M.H.	$ 672
ANNUAL MAINTENANCE	REPLACE FILTERS, CHANGE GEARBOX OIL, CALIBRATE SENSORS, VERIFY ALL SYSTEMS FUNCTIONING (2 MEN, 1 DAY)	16 M.H.	$ 448
10-year MAINTENANCE	ROTOR INSPECTION, PITCH ACTUATOR OVERHAUL, GEARBOX INSPECTION, REPAINT SYSTEM (2 MEN, 2 WEEKS)	16 M.H.	$ 448
REPLACEMENT PARTS	0.5 percent OF CAPITAL COST/YR		$ 750
	TOTAL	116 M.H.	$3998

Figure 3-2. - O&M cost goal calculation.

	MOD-0A			MOD-X		
	Wt, lb	COST,* $	$/lb	Wt, lb	COST,* $	$/lb
ROTOR - BLADES & HUB & PITCH CONTROL SYSTEM	13 800	593 K	43	7 500	37.5 K	5
GEARBOX - GENERATOR - HUB SUPPORT	26 800	190 K	7	10 000	25 K	2.5
YAW BEARING; DRIVE & BRAKE SYSTEM	3 900	56 K	14	1 500	3.75 K	2.5
TOWER	45 000	66 K	1.5	15 000	11.25 K	.75
PERSONNEL ACCESS SYSTEM	500	-------	----	1 000	750	.75
FOUNDATION		44 K			15 K	
ELECTRONIC CONTROL SYSTEM		51 K			10 K	
SAFETY SYSTEM		15 K			2 K	
ELECTRICAL SYSTEM		51 K			12 K	
SHIPPING		13 K			3 K	
INSTALLATION		188 K			29.75 K	
	90 000	1 267 K	14.1	35 000	150 K	4.30

*ALL COSTS ARE IN 1978 DOLLARS AND DO NOT INCLUDE PRIME CONTRACTOR FEES.

Figure 3-3. - Mod-X cost and weight goals.

4.0 SELECTED BASELINE MOD-X CONFIGURATION

The selected baseline Mod-X configuration was the result of an intensive evaluation and trade off study of major components and subsystems. The selection of the baseline configuration was guided by the philosophy that those features of a wind turbine that were shown to be potentially cost effective and to be technically feasible in earlier work were to be incorporated into the baseline configuration and changed only if shown to be too costly or impractical during the design. This philosophy led to an efficient approach in the development of a baseline design.

Efforts to reduce weights and costs were made on all components and subsystems, with special emphasis on the four major subsystems which on the Mod-0A account for 82 percent of the total costs (fig. 3-3). The high costs of the rotor, drive train, yaw drive, tower, and installation prompted an intensive effort to develop innovative methods and designs to reduce costs

4.1 General Features

A sketch of the Mod-X baseline configuration is shown in figure 4-1. This chapter will discuss only the general features of the Mod-X. A detailed discussion of the various components and subsystems design is given in Section 5.0.

The following is a list of the Mod-X features

Rated power - 200 kW
Rotor
    Two blades, 125 ft diameter downwind
    Teetered hub
    Hub height - 100 ft
    Rpm and power control - pitchable blades (either partial or full span)
    Mount on low speed shaft of gearbox
Gearbox - 3 stage, parallel shaft
Alternator
    200 kW, 1800 rpm
Yaw drive - passive
Control/safety system - microprocessor based system capable of handling all control and safety functions for unattended automatic operation
Tower - cantilever rotating cylinder
Foundation - factory precast concrete vaults - dirt filled

Wind regime

14 mph annual average at 30 ft

Maximum wind 120 mph

Climate - suitable for anywhere in U S.

Applications

Isolated

Utility grids

4. 2 Pod Assembly Atop the Tower

The Mod-X pod assembly atop the tower uses the gearbox as the main load bearing component with the rotor and the hydraulic pitch change actuator supported on the low speed input shaft (see figs 4-1 and 4-2). The gearbox rests on a very simple bedplate which, as will be explained later, is also used during the field assembly. The rotor has two blades and a teetered hub which is mounted directly on the low speed shaft of the gearbox. The blades can be either full span or partial span pitchable.

The key features of the machinery are its relative simplicity, compactness and lightweight The gearbox serves as a main support structure as well as a speed increaser and a power transmitter. All pod assembly components are weatherproof to eliminate the need for a nacelle to protect the equipment from the environment. The bedplate is a simple structure fabricated from standard structural members and is attached to the tower by a pair of hinge pins. These hinges allow the bedplate to tilt up in a clockwise direction during field installation (or removal) of the pod on the tower. The bedplate is tilted 3^{o} from the horizontal, and the blades are coned 2^{o}. These features were chosen to provide adequate blade tip clearance while maximizing the yearly energy production and maintaining a simple, compact, and low cost design

The pod assembly, by virtue of its simplicity and the ruggedness of the components, will require very little routine maintenance. The generator, gearbox, teetered hub bearing, pitch link joints, and pitch change mechanism will require only occasional visual inspection and lubrication. Hence, the need for service personnel to climb to the top of the tower will be greatly reduced which will in turn reduce the maintenance costs.

In this conceptual definition, the question of whether to use rotor blades that are full span pitchable or partial span pitchable is an open one and is in large part dependent on how the pitch span length impacts other components such as the tower, the pitch change mechanism and the blade design. Each of these will now be discussed.

In figure 4-3 is a plot of the thrust force on the rotor for various lengths of feathered tips, and on the tower in winds of different speeds. This figure shows the large effect the feathered tip length has on the overturning thrust force on the rotor. To limit the total thrust loads on the wind turbine to those of a Zone 2 earthquake load would require that the full blades be pitchable because the thrust on the tower at 120 mph is about equal to the earthquake load and the blades must be fully feathered to achieve near-zero rotor loads. If a partial span pitchable blade is used, then the tower would have to be heavier. The tower in this concept was sized by a rotor thrust force of 8 000 pounds. Obviously, if the tower has to withstand a higher thrust, then it will be heavier and more expensive.

A second issue related to the length of the pitchable portion of the blade concerns the mandatory overspeed protection of the rotor by an emergency feathering procedure. Figure 4-4 shows how the rotor rpm changes with time following a loss of electrical load for full pitchable and 10 foot tip control Mod-0A blades. The feathering rate for the 10 foot tip span must be twice that of a full-span pitchable blade (-8°/sec versus -4°/sec) for the same rotor overspeed limit. Higher pitch rates increase the size and cost of the control system and also produce higher control loads on the blades.

A blade with pitchable partial span is going to be more complicated structurally than a fully pitchable blade. The complication will arise from two factors· (1) the need to incorporate a structure that will support the moveable tip and that will allow it to rotate up to 90°, and (2) the need to incorporate the pitch change mechanism. It is believed that the more complex structure will result in a blade that is heavier and more expensive than a one piece blade; thereby offsetting the reduced cost of the smaller lighter weight pitch change system associated with partial pitchable span blades. To resolve the question of whether to use partial or full span pitchable blades for the Mod-X machine will require the development of more detailed designs and cost estimates of the blades, pitch change mechanisms, tower, and control system than has been done here.

The Mod-X hydraulic pitch change mechanism, figure 4-5, is very similar to the one that was successfully used in the Hutter 100 kW wind turbine. Both systems use a hydraulic linear actuator to vary the pitch of the blade during normal startup, shutdown, and operation. Also in both systems a large coil spring is used to drive the blade into emergency feather to prevent rotor overspeed in the event of a hydraulic failure. In the Hutter system the hydraulic actuator rotates with the low speed shaft, requiring a rotating hydraulic seal. In the Mod-X, this seal and its maintenace requirements are eliminated by fixing the hydraulic actuator to the pod. A transfer bearing is used between the stationary hydraulic actuator and the rotating pushrod inside the low speed main shaft to eliminate the need for a rotating hydraulic interface. The pushrod motion is converted to blade rotation by the blade pitch links as in the Hutter system. These links would be connected to the blade root for a full span pitchable blade or to a torque tube for partial span control.

4.3 Tower and Foundation

The tower and foundation concept development was the result of an intensive analysis and trade-off effort. The Mod-0A installations at Clayton, New Mexico and Culebra, Puerto Rico showed that the site preparation and installation cost are high and need to be lowered significantly. The Mod-0A experience indicated that (1) elevator access to the top of the tower is very expensive, (2) use of an on-site crane for assembly of the nacelle and rotor is costly, and (3) factory assembled structural steel components are relatively inexpensive. Accordingly, considerable attention was given to concepts that minimized tower top access and mobile crane requirements and that utilized factory assembly and structural steel usage wherever practical.

The tower and foundation designs are shown in figure 4-1. The main section of the tower is a cantilevered cylinder that enclosed an access ladder and all the electrical and hydraulic conduits Also, the pod assembly is rigidly attached to the tower. This tower design is unique' in that it is supported on bearings and can rotate about its vertical centerline, and because the base of the tower is used to house the control and hydraulic equipment. This tower design was chosen because (1) it is the lowest cost, (2) all equipment in the base can be preassembled at the factory and shipped to the site ready for use, (3) it can be quickly and inexpensively assembled, (4) most of the equipment needing routine servicing is located at ground level for ready access, thereby reducing maintenace costs, and (5) a slipring assembly will be needed only for the output power, which will make it less expensive, more reliable, and easier to service. The yawing control moments are to be provided by the drag of the wind on the rotor blades. This passive system was selected on the basis of Mod-0 passive yaw tests that showed that an active yaw may not be needed, thereby simplifying the control system, eliminating components, and reducing costs. If subsequent detailed design activity indicates that an active yaw drive or brake system is needed, it can be installed at the tower base where it will be easy to service. The fact that the tower and the control room rotate with the pod assembly will increase the polar mass moment of inertia during yawing maneuvers. This will serve to dampen the response to sudden changes in the wind direction.

A tripod base was chosen to support the tower bearings and to resist the overturning forces. The reasons for this choice are given in the Section 5.0. Basically the tripod arrangement leads to a more stable, lighter weight tower design, and a lower cost foundation. The bearing system atop the tripod carries the weight of the cylindrical tower, the control room, and all the machinery on top. This bearing and the one at the base of the control room also resist the overturning moment.

The Mod-X foundation concept consists of three earth filled factory precast concrete vaults. These are shipped to the site, set in place, and filled with earth for added stability. The fill material could be the same material that was removed for placement of the vaults. This concept makes the design of the foundation largely site independent except for sites that have very soft soil or solid rock One important advantage of this type of foundation is that it eliminates the need for pouring concrete on site which is weather dependent and very expensive at remote sites. A second important advantage is that, since foundations are required to support vertical loads primarily, if bearing loads are sufficiently low, no soil exploration is required prior to installation. Factory precasting of vaults is a well developed technology. Shipment is no problem. Placing the vaults into excavated holes and backfilling is a fast and straightforward operation. The use of dirt filled concrete vaults is a most cost effective foundation design.

4.4 Summary of Weights and Costs

The estimated weights and costs for the Mod-X concept are summarized in table 4-1. The costs are given for the second unit and the one hundredth unit. The figures for the one hundredth unit (without G&A and profit) are very close to the cost goals.

In table 4-2 is a comparison of the weight and cost of the second unit Mod-X with a Mod-0A These costs include 15 percent G&A and 15 percent profit. The figures show that significant weight and cost reductions were achieved in all the major subsystems, and in particular in the five highest cost items of the Mod-0A

The data in both tables show that there is a large potential for lighter weight and lower cost wind turbines in the 200 kW and 125 foot diameter size. Using a total cost for the hundredth unit of $202 810 and an energy output of 875 megawatt-hours at a 14 mph site, the energy cost is 4.34 cents per kWh.

TABLE 4-1. - COST & WEIGHT SUMMARY

(1978 dollars)

	Weight, lb	2nd unit cost, $	Production quantity cost, $
Rotor			
Hub	2 800	19 600	8 120
Blades	4 700	70 000	30 000
Pitch change	1 700	12 000	8 700
Gear box	15 000	36 000	25 300
Electrical			
Generator	2 500	6 500	5 000
Switchgear & wiring	1 600	7 600	5 400
Capacitors	1 300	500	500
Sliprings	100	900	810
Structure			
Tower	41 500	62 250	31 540
Bedplate	1 500	2 250	1 140
Bearings	------	6 000	5 400
Foundations	------	4 000	4 000
Installation	------	8 250	8 250
Control	200	9 000	6 700
Safety	20	2 000	1 000
Shop ass'y & test	------	18 000	4 000
Shipping	------	3 000	3 000
Installation & checkout	------	4 500	4 500
Subtotal	------	272 350	153 360
15% G&A	------	40 850	23 000
15% profit	------	46 980	26 450
Total	72 920	360 180	202 810

TABLE 4-2. - MOD-X/MOD-0A WEIGHT AND COST COMPARISON

(1978 dollars)

	Mod-0A			Mod-X		
	Weight, lb	Cost	Percent of total	Weight, lb	Cost	Percent of total
Rotor - blades & hub & pitch control system	13 800	$814K	47	9 200	$134K	38
Gearbox - generator - hub support	26 800	260	15	17 500	56	15
Yaw bearing drive & brake system	3 900	77	4	------	8	2
Tower	45 000	90	5	43 000	85	24
Foundation	------	60	4	------	5	1
Electronic control system	------	70	4	200	12	3
Safety system	------	21	1	20	3	1
Electrical system	------	70	4	3 000	12	3
Shipping	------	18	1	------	4	1
Installation	------	258	15	------	41	12
	90 000	$1738K	100%	72 920	$360K	100%

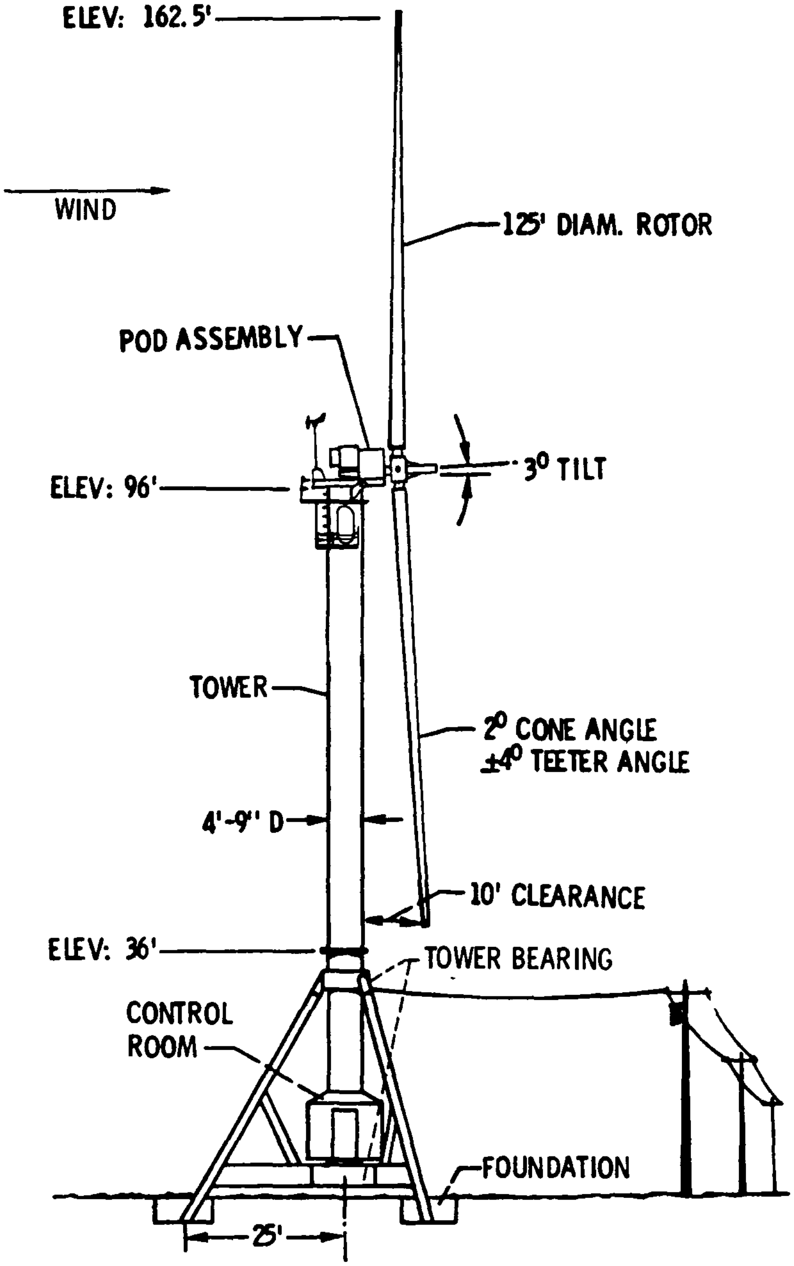


Figure 4-1. - Selected Mod-X baseline configuration.

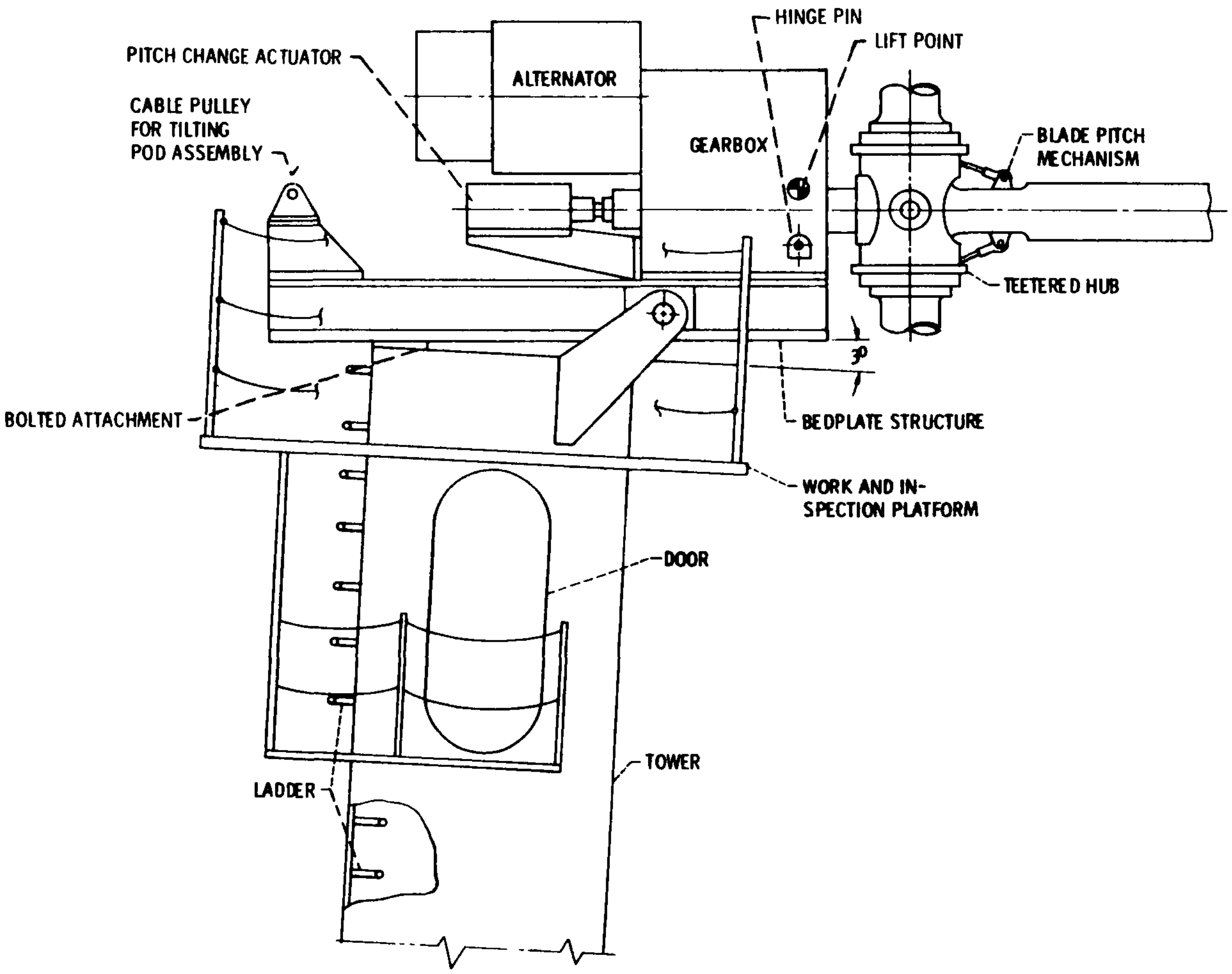


Figure 4-2 - Mod-X pod assembly

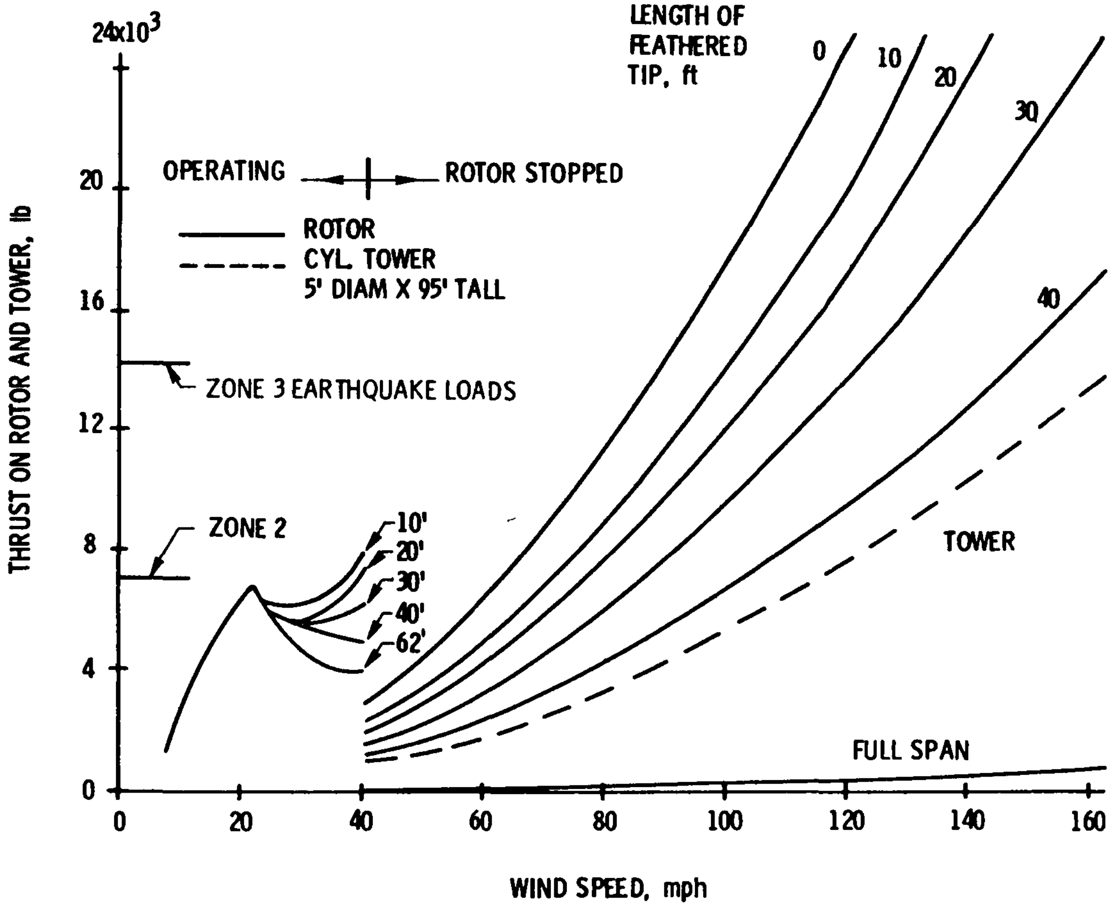


Figure 4-3. - Rotor and tower thrust force variation with wind speed.

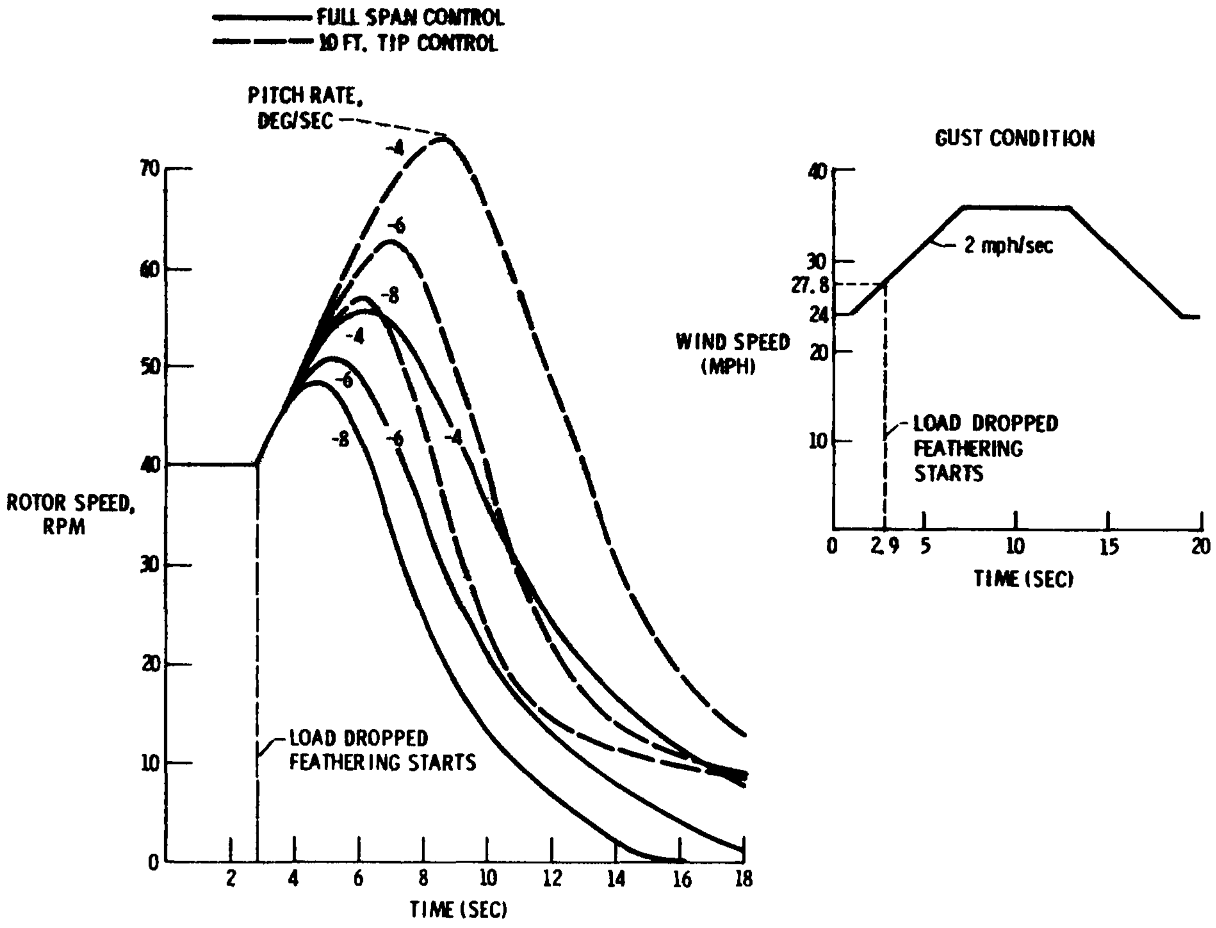


Figure 4-4. - Rotor overspeed characteristics in gust conditions.

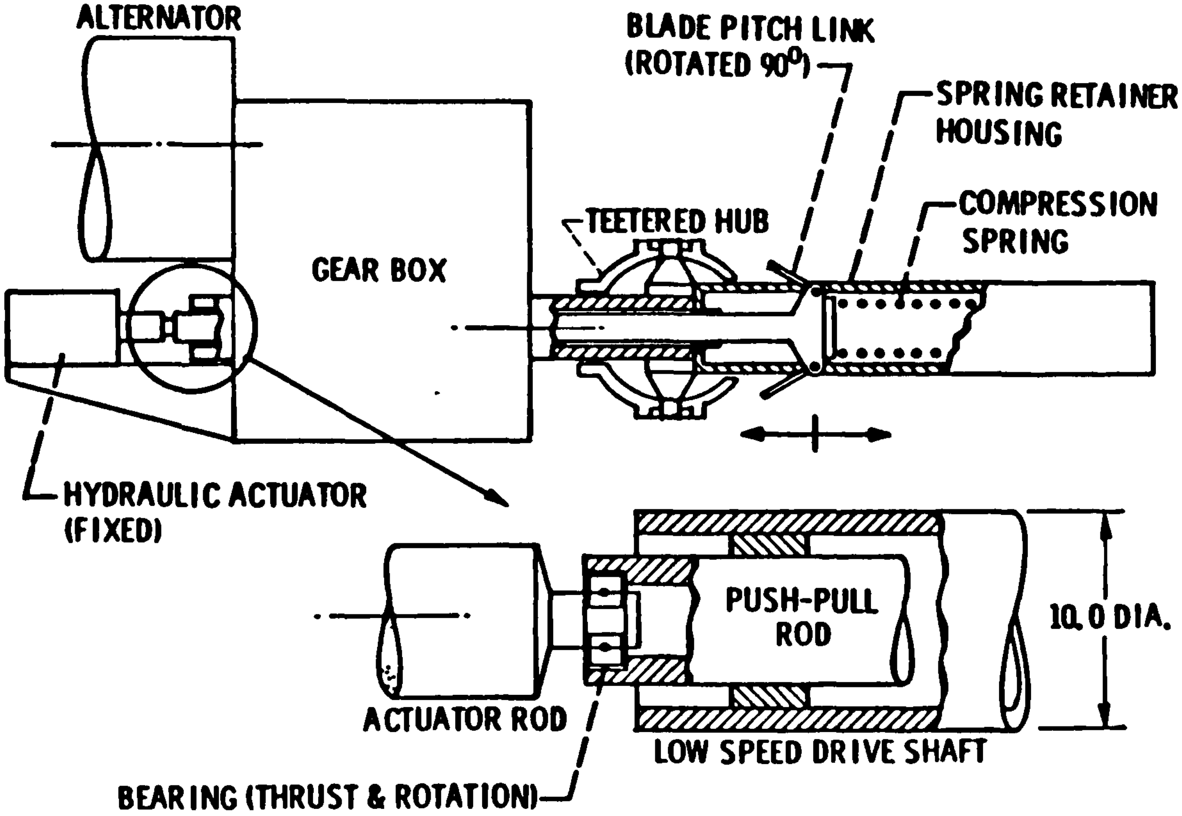


Figure 4-5. - Blade pitch change mechanism schematic.

5.0 COMPONENT & SUBSYSTEM CONCEPT SELECTION

Each subsection of this section is devoted to a particular component or subsystem of the Mod-X machine. Included are the design goals and requirements, a discussion of the alternate designs considered, and the rationale for the particular baseline design selected for the Mod-X The selected concept is discussed in detail. Included are the technical characteristics of the system, the weight and the costs.

5.1 Pod Assembly Configuration Design

The pod assembly as defined in this report consists of the equipment atop the tower (rotor, gearbox, alternator, pitch change mechanism, bedplate, etc) In the Mod-0, Mod-0A, and Mod-1 designs, the pod assembly was heavy and expensive. The Mod-1A pod assembly was lighter, simpler, more compact, and less expensive than that of earlier designs. The pod assembly of the Hutter 100 kW wind turbine was only 18 000 pounds compared to the 40 000 pounds of the Mod-0 pod assembly. Thus it appears from both the Mod-1A study and the Hutter experience that lightweight, compact, and inexpensive pods are achievable.

5.1.1 Design Considerations

The design of the pod assembly configuration was affected by the following requirements and considerations

1. Yearly energy output should be maximized.
2. Adequate clearance between the blade tip and tower must be provided.
3. The pod assembly atop the tower should be simple, compact, lightweight, and low cost.
4. The pod should be factory assembled for low cost
5. The number of items needing scheduled maintenance should be minimized.
6. Installation of the pod atop the tower should be easy, quick and inexpensive.

5.1.2 Configurations Considered

The first concept considered is one in which a strong bedplate serves as the main support for the entire drivetrain, including the rotor. Two large bearings support the rotor shaft which is connected to the gearbox by a coupling. The gearbox rests on the bedplate and transmits the rotor power to the generator (which is also supported by the bedplate) at a much higher rpm. In production models of this concept, the generator shaft is connected to the gearbox high speed shaft by a coupling. This concept is essentially the one used in the Mod-0, Mod-0A, and the Mod-1. The main disadvantage of this concept is its high weight.

A variation of this concept is one in which the rotor shaft is supported by a single large bearing close to the hub and by the gearbox. One large rotor shaft bearing is eliminated. Hutter's machine utilized this concept.

A third concept considered is one in which the gearbox is used to support the rotor and the generator The rotor is mounted directly on the low speed shaft of the gearbox and the generator is bolted onto the gearbox casing at the high speed shaft. This arrangement results in a simple, compact, lightweight, and lower cost pod assembly, and was developed in the Mod-1A study. The compactness and cost savings are achievable because gearbox manufacturers routinely build combinations of gearboxes and generators for a variety of large industrial applications. Several gearbox suppliers indicate that it would be a straightforward matter to design and mass produce systems that would include a gearbox, a generator, a yaw bearing, and other needed auxiliary equipment at costs less than those of the individual components. With the gearbox functioning as the main supporting structure for the generator pitch change mechanism and rotor, the bedplate is either eliminated or greatly reduced in size and weight. Combining the generator, gearbox, yaw bearing, rotor hub and other components into a single factory assembled package also reduces both fabrication costs and field assembly costs.

The advantages of the third pod configuration were considered sufficiently great to warrant an effort to use it in the Mod-X design. The chief design features incorporated were to reduce the rotor tilt and coning angles and to locate the pitch change actuator on the low speed shaft (fig. 4-2) and the hydraulic supply system inside the tower base This arrangement has the advantage of minimizing the maintenance costs. The only service needed atop the tower is to inspect and grease the joints at each end of the pitch links and the transfer bearing between the actuator rod and the push-pull rod. Clearly the most difficult part to service and inspect will be the pitch links.

Reduction of the tilt and coning angles to 3° and 2°, respectively, was accomplished by positioning the pod equipment out from the tower. This design results in near maximum yearly energy production but requires a heavier bedplate structure. By incorporating hinge pins and a rotatable bedplate, the need for a large crane during field installation is eliminated. As can be seen in figure 4-2, the bedplate is rigidly attached to the tower with the hinge pins and a bolted attachment rather than through a yaw bearing. The absence of a yaw bearing at the top of the tower reduces maintenance costs because it eliminates the need for service personnel to climb to the top of the tower to service the yaw drive system, and other equipment which is located at the base of the tower, and also eliminates any need for sliprings between the tower and nacelle.

The major penalty for placing the pod away from the tower is the added weight and cost of the bedplate. However, because the bedplate is made from standard steel structural members, its cost will still be low. The advantages of reducing the tilt and cone angles more than offset the additional bedplate cost.

The weight and cost estimates for the pod assembly include the bedplate, gearbox, generator, pitch change actuator system, and the rotor. These figures are shown below for the second unit and for the 100th production unit

Subsystem	Weight	2nd unit cost, $	100th unit cost, $
Blades	4 700	70 000	30 000
Hub	2 800	19 600	8 120
Pitch change mechanism	1 700	12 000	8 700
Gearbox	15 000	36 000	25 300
Generator	2 500	6 500	5 000
Bedplate	1 500	2 250	1 140
Total	28 200	146 350	78 260

5.2 Blades and Hub

The blades and hub are two components of a wind turbine that are not commercially available. They must be fabricated as few-of-a-kind products. The Mod-0 and Mod-0A blades were manufactured by the Lockheed Aircraft Company. These blades are a semi-monoque structure and are hand crafted from hundreds of parts which include ribs, stringers, curved leading edge plates, and high strength fasteners. Because the fabrication of these blades are labor intensive, they are costly and are not amenable to low cost quantity production. Each blade for the Mod-0 and Mod-0A weighs 2000 and 2300 pounds, respectively. These weights are considered low for metal or fiberglass composite blades is labor inten-

The Mod-0 and Mod-0A fixed hubs are rigidly attached to the rotor shaft and accept all of the blade loads and transmit them to the shaft. A teetered hub is one that attaches the rotor blades to the low speed drive shaft by a hinge pin which allows the blades to rock on the shaft. This type of hub alleviates the flapping bending loads. A careful comparison of the teetered and fixed hub concepts in the Mod-1A and Mod-2 conceptual design studies showed that the teetered hub design is preferable to the fixed hub design on a cost basis. For this reason the Mod-X design incorporates a teetered hub.

5.2.1 Design Goals and Requirements

The hub should be designed for low weight and ease of fabrication. The hub structure must be designed to carry blade loads to the low speed shaft and be designed for adequate fatigue life. It must interface with the blades and the low speed shaft. The hub allows the blades to teeter, and provides for passage and support of the pitch drive mechanism. The hub requires provision for a teeter damper, and extreme teeter angle stops.

The blades must be designed for two loading conditions. First, they must withstand a wide spectrum of relatively low loads during operation that can cause cumulative fatigue damage. Second, they must withstand high loads that occur infrequently, such as a hurricane wind load. Low blade weight is also a desirable feature. An airfoil should be selected to provide good aerodynamic performance, allow ease of fabrication and allow for adequate structural design.

For this study, the structure of the various blade concepts that were considered was sized using wind loads for a steady 150 mph wind at hub height. In addition, the blade structure was chosen so that the natural bending frequencies were above 2 per revolution and were not some integer multiple of the rotor rpm.

5.2.2 Concepts Considered

Two teetered hub concepts were considered the Hutter designed teetered hub, and the Mod-1A teetered hub design.

There is no obvious choice of a blade design that will provide a significant cost reduction and will withstand the rigors of wind turbine operation. Several concepts now under development were considered as candidates for the Mod-X. These include a wood blade, a steel spar and rib blade, a steel blade, and a transverse fiberglass tape (TFT) blade These concepts are shown in figure 5-1 and are discussed in the following paragraphs.

The wood blade concept is shown in figure 5-1(a) as proposed by the Gougeon Brothers, Inc., Bay City, Michigan. The 2.3 inch thick nose section is fabricated by forming and glueing together wood laminates. Two plywood webs form a three cell structure. The center cell is enclosed by a sandwich structure fairing of foam and plywood. The trailing edge cell is enclosed with a plywood fairing and filled with foam.

For a 60 foot long blade having a planform airfoil geometry the same as the Mod-0A blade, Gougeon Bros. estimate the wood blade weight at 1 600 pounds. The Lockheed aluminum blade weight is near optimum for the design loads and fatigue life selected. It is considered unlikely that the wood blade can be designed for the same loads and fatigue life and be lighter than the aluminum blade. As a result, for this study the wood blade weight was increased from 1 600 to 2 000 pounds.

Costs for the 2nd and 100th blade were estimated by the Gougeon Brothers, and are shown in table 5-1.

The steel spar and rib concept is shown in figure 5-1(b). The steel round spar varies in diameter from 18.0 inches at the root end to about 4.0 inches at the blade tip. The spar is formed in two halves and joined by seam welding along the span. Wood ribs form the airfoil shape and are bonded to the tapered steel tube. Polyurethane foam is bonded between ribs and to the spar to provide stiffening of the trailing edge. Foam is also bonded to the spar at the leading edge to provide the necessary aerodynamic contour. The outer surface is covered with fiberglass cloth and bonded to the foam and wood ribs.

For a 60 foot long blade, similar to the Mod-0A blade, it is estimated that this blade will weigh 3 500 pounds. The tapered cylindrical steel tube is not an efficient spar structure, from the standpoint of weight, when compared to the tapered D-spar design. As a result this configuration is considerably heavier than the conventional airplane wing type structures.

The second unit and 100th unit fabrication costs, estimated by NASA LeRC, , are shown in table 5-1. Compared with the other four concepts, this concept appears to be the most economical.

The steel blade concept is shown in figure 5-1(c). This design is identical in concept to the blade design for the Mod-1 wind turbine. The D-spar is formed in two halves and joined by spanwise welding. One spanwise weld is located at the leading edge and the second weld is located at the trailing edge of the D-spar. Thin steel sheets form the trailing edge structure. These sheets are bonded to the D-spar. The sheets are supported by polyurethane foam and bonded to the foam. To maintain the airfoil center of gravity near the 25 percent chord point, low density foam is used near the trailing edge and a higher density foam is used near the D-spar.

For a 60 foot long blade, similar to the Mod-0A blade, the weight is estimated at 2 500 pounds.

The blade costs are shown in table 5-1. These costs were derived from the estimated costs for a third rotor blade for the Mod-1 wind turbine. Estimated costs for the third Mod-1 blade were obtained from Boeing Engineering and Construction, Seattle, Washington through General Electric, Valley Forge.

The TFT concept is shown in figure 5-1(d). This design is identical in concept to the 150 foot long TFT blade being fabricated by Kaman Aerospace Corporation, Bloomfield, Connecticut, and Structural Composites Industries (SCI), Los Angeles, California.

The D-spar is wound on a removable mandrel with transverse fiberglass tape. Trailing edge panels for the upper and lower surface are fabricated as a sandwich of honeycomb and fiberglass cloth impregnated with epoxy. Upon completing the D-spar, the trailing edge panels are bonded to the D-spar and to the trailing edge spline.

For a 60-foot long blade, the weight is estimated at 2 000 pounds. The cost estimates are shown in table 5-1 for the TFT wound blade. The cost estimates are based on cost information received from Kaman.

5.2.3 Concepts Selected

The Mod-X teetered hub design is shown in figure 4-5. Features of this design were taken from the Hutter and Mod-1A designs. The weight of the hub structure used by Hutter was estimated at 2 800 pounds. The Mod-X teetered hub weight was also estimated at 2 800 pounds. The Hutter hub design operated successfully for a considerable length of time. As a result the selected concept appears sound. Second hub unit cost was estimated at $19 600 while the production unit price is estimated at $8 120.

The blade design and material cannot be selected as a result of currently available information. Further blade design effort and associated cost estimates are needed. The final blade design, after further effort is expended, will probably be different than any one of the four concepts considered here.

5.3 Blade Pitch Change Mechanism

The method chosen to control the Mod-X power output and the rotor rotational speed during normal operation, startup, and shutdown is to change the pitch of the movable portion of each blade. The rate at which the pitch is changed depends on the wind conditions and the applied load. For example, when the load and the wind speed changes are slow, the pitch rate is low On the other hand, when the wind is gusting or when a load failure occurs, the pitch rate must be very high to prevent overloading the generator or permitting rotor overspeed and possible destruction of the rotor, respectively. For the Mod-X to operate safely the pitch change mechanism and its control system must be capable of sensing and responding to all the various conditions to which the wind turbine will be exposed.

TABLE 5-1. - MOD-X BLADE WEIGHT AND COST SUMMARY

Material and manufacturer	Blade weight, lb	2nd unit blade cost, $K	100th unit blade cost, $K
TFT Kaman - S. C. I.	2200	31.3	13.5
Wood-Gougeon Bros.	2000	35.0	15.0
Steel-Boeing	2500	40.0	17.0
Steel tube spar-NASA-LeRC	3500	29.0	12.5
Aluminum-Lockheed	2350	225.0	97.0

5.3.1 Operating Modes

When the Mod-X is in the shutdown mode, because the wind speed is below cut-in or above cut-out, the pitchable portion of each blade is feathered (pitch angle is approximately 90° negative). The rotor remains in this condition as long as the wind speed is outside the operating range.

When the wind speed changes from below cut-in or above cut-out to a value between cut-in and cut-out, the blades' pitch is gradually changed to a value that will start the rotor and bring it up to its operating rpm. Then the generator is connected to the network. If the wind speed is between cut-in and rated value, the blade pitch remains at a constant value and the rotor operates as a fixed pitch rotor. The electrical load is varied to maintain rated rpm. When the wind speed is between rated and cut-out, the blade pitch is changed with changes in wind speed to maintain rated power. Under gusty conditions, the blade pitch must be changed quickly to adjust blade efficiency and prevent overloading the generator. Sudden decreases in wind speed are not usually a hazard because the generator then acts as a motor and drives the rotor until the blade pitch is changed back into the power mode. When the wind speed drops below cut-in or increases above cut-out, shutdown procedures are initiated wherein blade pitch is changed toward feather to slow down and stop the rotor at the point where no output power is being produced, and the generator is disconnected from the load. Emergency shutdown procedures are similar except that the pitch change rate must be high enough to prevent overspeeding of the rotor, but low enough to prevent overloading the blades.

5.3.2 Design Goals and Requirements

The prime function of a blade pitch change system is to reliably control the rotor rpm and power under all operating wind conditions and to protect the rotor from overspeed in a failsafe manner These functions are to be performed by a mechanism which is highly reliable but also low cost, simple in design, and very nearly maintenance free.

Because the Mod-X is similar in some ways to the Mod-0A wind turbines, the Mod-0 and Mod-0A blade characteristics and experiences were used to draft the following requirements for the Mod-X pitch change mechanisms

(1) Blade weight	2000 lb each
(2) Max feather torque req'd	14 000 ft lb each blade
(3) Max continuous blade pitch rate	2°/sec
(4) Max instantaneous pitch rate	5°/sec

(5) Max hydraulic pressure (low maintenance)	2 200 psi
(6) Pitch change resolution	2°
(7) Max pitch rate (emergency feather condition)	8°/sec

(8) Provide a backup means to feather blades in event of hydraulic system failure

5 3.3 Concepts Considered

The basic pitch change mechanism (PCM) considered for the Mod-X consists of a linear actuator that is located on the rotor axis with a push rod inside the rotor shaft, and a pair of straight links that connect the end of the rod to a bell crank at the root of each blade (fig. 5-2). This system converts the linear motion and force of the actuator to the rotary motion and torque needed to pitch the blades. Around the actuator rod is a large coil spring whose function is to supply power to quickly feather the blades during an emergency shutdown.

In the design of the entire pitch change mechanism, it was decided to mount the actuator drive system directly on the gearbox, and to eliminate sliprings or rotating hydraulic joints. This was accomplished by installing a transfer bearing at the end of the actuator rod opposite the end to which the pitch links are attached.

Five concepts using this basic mechanism were considered. They differ only in the equipment used to drive the linear actuator. The five concepts are either hydraulic or electrically powered and are described below

Concept	Drive type
A	Hydraulic piston
B	Hydraulic piston
C	Electric motor-worm gear drive
D	Electric motor-parallel axis gear drive
E	Linear induction motor

Concepts A and B are similar in that both use a hydraulic piston to drive the linear actuator rod, but they differ in the way the emergency feathering is achieved, figure 5-3. In the event of a power failure, the hydraulic failsafe servo valve simultaneously vents ports 1 and 2 to the return line (Concept A), thereby releasing the hydraulic pressure in the piston and allowing the coil spring to drive the actuator to the feather position. In Concept B, the servo valve releases the pressure in port 2 into the return line and pressurizes port 1. The force of the hydraulic fluid is added to the spring force to drive the piston to the feather position. With this arrangement the coil spring can be greatly reduced or eliminated completely. The disadvantage of Concept B is the possible reduction in redundancy. Both Concepts A and B compare favorably in price and performance with a small price difference due to the difference in spring size.

Concept C uses an electric motor/gearbox with a clutch between the gearbox and the actuator pinion drive to power the linear actuator (fig. 5-4) This drive system will meet the pitch change performance and stiffness requirments but its major drawback is the high cost ($9 000) of the clutch override. The clutch is a necessary component in this concept because it disengages the drive system from the actuator in the event of a power loss, thereby allowing the spring to drive the blades to feather.

Concept D, figure 5-5, is essentially the same as C except D uses a parallel axis gearbox and a lower torque rated brake at the motor. The brake would be applied whenever a pitch change would not be required On emergency feather, the motor would be de-energized and the brake released. The reliability of the system is decreased because of a possible gear jam or motor freeze-up. All other failures would cause the blades to feather. The stiffness of this system, though adequate, is not as high as that of Concept B. The cost of the brake for Concept D is lower than that of C because of the lower torque required.

Concept E, figure 5-6, is a linear induction motor which is connected directly in line with the actuator rod. Motors with the force capability needed for this application under normal operating conditions are commercially available. But the force needed to cock the emergency feather spring is much higher and motors with this higher rating are not available. Lower spring forces or a large number of units might make the development of this method practical.

5.3.4 Concept Selection and Rationale

Concept A, figure 5-3, was selected for the Mod-X for the following reasons this concept could easily meet or surpass the performance requirements of the Mod-0 and Mod-0A type blades, all components used are commercially available proven items, they require a minimum of field maintenance and replacement parts are readily available, since these items are available in many sizes, changes requiring different forces, speeds, etc. are easily accommodated; and there were no long lead items or component developments required.

Modifications of the blade geometry, changes in performance specifications and/or additional component testing on the Mod-0 system may change the maximum feather torque or system stiffness requirements which in turn could influence the pitch change system concept selection.

For long term maintenance and utility acceptability, Concepts C through E may be more desirable. Even with good hydraulic design, system leaks do occur. In addition, to insure long maintenance-free life with servo valves, the hydraulic system must be clean. The extreme cleanliness required is often difficult to maintain in remote areas and without support equipment.

5.3.5 Description of Selected Concept

The following is a brief description of the operation of the blade pitch change system as shown schematically in figure 5-7. Figure 5-8 shows how Concept A was incorporated in the Mod-X design.

The hydraulic pump (6) supplies hydraulic pressure to the servo valve (2). The pump package is sized to maintain a constant pitch change rate of 2° per second. A 10 gallon accumulator in the pump package will supply enough capacity for one emergency feather at any operating condition. The 480 volt power for the hydraulic pump is the same voltage as generated by the WTG.

The servo valve (2) would be a 10 gpm model similar to that used in Mod-0 and Mod-0A. This would allow a maximum stroking speed of approximately 5°/sec. The 5°/sec is also based on Mod-0 and Mod-0A experience. This capability will allow the WTG to withstand any wind gust experienced to date with minimum utility disruption.

The control signal to the servo valve, would be from the microprocessor, discussed in section 5.7. The microprocessor would sense the operating parameters (wind speed, load, rotor speed, blade angle position, etc.) and would provide the correct voltage to the servo valve. The servo valve is capable of modulating hydraulic fluid to either end of the cylinder (1) or providing a null or zero flow.

The fail safe valve (4) is a bypass between the servo valve and the hydraulic cylinder (1). The fail-safe valve action is caused by a safety system shutdown, electrical system failure, or hydraulic failure. When the fail safe valve is deactivated, both ends of the hydraulic cylinder are ported together and also to the hydraulic return. The feather spring (5) then drives the blades to the feather position.

The hydraulic cylinder (1) provides the necessary force to overcome the feather spring (5) and the torque required to pitch the blades. The cylinder has an 8 inch bore and 13.5 inch stroke. A minimum system pressure of 1000 psi is required. The cylinder is a standard commercial model with a heavy duty service rating.

The spring size and spring constant (K, lb/in.) were selected using Mod-0 and Mod-0A data. The free length is 50 inches and K = 2500 lb/in. If alternate airfoil or pitch lengths are selected, resizing of the PCM will be required The spring would be wound to meet maximum design criteria at the full power position. The force required to feather the blades would be 28 000 pounds. The spring would be sized for 33 000 pounds to overcome starting and operating friction.

The position indicator (3) is a linear voltage differential transformer (LVDT) The output of this LVDT with a demodulator is a linear relationship between voltage and position This provides a method of monitoring blade position for logic decisions in the microprocessor, startup, shutdown and maintenance requirements. The signal from the LVDT would be sent to the microprocessor. Corrections to the blade angle would be made via the servo valve. The correction is sensed by the LVDT voltage, providing closed loop control.

The hydraulic pump package (6) is a commercially available 5 gpm, 3 000 psi rated unit. The package includes a reservoir, 10 gallon hydraulic accumulator, 1 200 rpm motor and over-temperature protection. The system operating pressure is between 1 200 and 1 500 psi.

A thrust transfer bearing is placed between the nonrotating piston rod and the actuator rod. This allows the blade pitch actuator rods to rotate with the rotor while the hydraulic equipment remains stationary.

5 3 5 1 System Operation Description

The overall system will operate as follows. As the microprocessor senses the need for increased pitch for start up or power control, it will send a voltage signal to the servo valve The servo valve will in turn port oil to side two of the hydraulic cylinder, causing the cylinder to extend to the right in figure 5-3. The cylinder will continue to extend until the voltage feedback from the LVDT balances that required by the microprocessor. The reverse process is true for feathering the blades. Any outside disturbance to the actuator is seen as error and the servo valve will respond by correcting the actuator position. Extending the actuator action through the control arms will cause the blades to go to the power position. Retraction of the actuator will cause the blades to go the feather condition. If at any time there is not enough force to overcome the feather spring, the blades revert to the feather condition. Deactivating the fail safe servo valve for any reason will drive the blades to feather.

5.3.5.2 Cost Estimate

The costs obtained were from current product price lists, telephone quotes, and/or experience on Mod-0. The figures were adjusted to cover inflation and options. Most of the items (except the LVDT and fail safe valves) are available from many manufacturers. The LVDT is available only from a single supplier as is the fail safe valve. The spring is a special item but would require no development. There are many manufacturers who build springs to customer specifications.

Cost estimates for the 100th unit were not obtained. From experience on off-the-shelf items on a 100 lot basis, the reduction is 20 to 30 percent.

The data in table 5-2 indicates the weight and costs for commercially available items used in Concept A.

5.4 Gearbox

Existing wind turbine designs utilize a mechanical gearbox to transmit power efficiently from the rotor to the generator and to increase shaft speed. Because the input shaft receives its power from the slowly rotating rotor, the torque is high. Also, frequent over-torques up to 100 percent of the rated torque are experienced by the input shaft due to the gustiness of the wind. When the rotor is rigidly connected to the gearbox and the gearbox is rigidly connected to the generator, torque fluctuations are passed thru the gearbox. For this reason, the gearbox must be robust if it is to run with minimum maintenance for 30 years

Using a gearbox to transmit only torsional loads requires that it, the rotor, and the generator be supported by a bedplate structure. This type of configuration was used in the Mod-0, Mod-0A, and Mod-1 designs and it proved to be heavy and expensive.

In the Mod-1A concept, the gearbox functions were expanded to include supporting the rotor on the input shaft, incorporating the generator as an integral structure on the high speed shaft side and housing the yaw gear. To be able to carry the added loads, the gearbox casing, the input shaft and the bearings have to be heavier The added weight of the gearbox was offset by a greater weight and cost reduction that resulted from elimination of the large bedplate and a separate rotor main shaft and its bearings. Hence, on the basis of the Mod-1A design, it was decided to use a similar gearbox concept for the Mod-X

TABLE 5-2. - BLADE PITCH CHANGE SYSTEM

WEIGHT AND COST ESTIMATE

Item	Weight, lb	Cost, \$*
Cylinder 8 in. bore x 13.5 in. stroke	300	1 000
Servo valve 10 gpm at 3000 psi	10	1 200
Position indicator	2	600
Failsafe valves	20	1 500
Spring	300	750
Hydraulic package	1 000	5 000
Miscellaneous hardware	100	2 000
	1 732	12 050

*Second unit costs.

5.4.1 Design Requirements and Specifications

Requirements and assumptions affecting the gearbox concept selection include the following

1. Rating 250 kW
2. Input shaft speed = 40 rpm
   Output shaft speed = 1 800 rpm
3. Input shaft gravity load = 15 000 pounds
4. Over torque = 100 percent × rated (frequent occurrence)
5. Generator directly connected to the high speed shaft and supported on gearbox.
6. All pod equipment must be weatherproof.
7. The gearbox casing must support the pitch change mechanism.
8. The low speed shaft must be hollow and extend out both sides of the gearbox casing.

Vendors have indicated that a gearbox that meets the above requirements and specifications would be a straight-forward item to design and mass produce. The cost relations for such gearboxes are shown in figures 5-9 and 5-10 for various production runs. Clearly, the weight and cost numbers are reasonable for this stage of the Mod-X design.

5.5 Electrical Generation System

5.5.1 Design Goals

The basic Mod-X goals are that it produce electrical power to commercial specifications and have low initial and maintenance costs. It must interface easily with a large variety of power systems and must be able to synchronize and desynchronize with the system many times a day in an unattended mode with only scheduled maintenance at intervals of many months. It must also have sufficient protective devices to insure that, in the event of a failure, it does not place a burden on the rest of the system, and similarly will not be damaged by faults in the external power grid.

5.5.2 Design Requirements

During the initial stages of the conceptual design several broad assumptions had to be made so that a parallel effort among subsystem designers could begin. The two major assumptions that impacted the electrical design were

1. The Mod-X wind turbine shall have a constant rotor speed.
2. There will be no nacelle covering the pod machinery.

The constant speed constraint has evolved during previous trade studies by the need to avoid resonance in the various structures. The second constraint requires that the generator and any other equipment on top of the tower be weatherproof

5.5.3 Concept Development

The nature of the shaft power of a constant speed wind turbine differs significantly from that of conventional prime movers in only one regard. That difference is the larger random and cyclic power content of the WTG Without some method of energy storage or dissipation this fluctuating input power will show up in the output This in itself is not objectionable when a machine is tied to a large network because the fluctuations of even a large WTG will be small compared to normal load variations.

Power fluctuations are of particular concern, however, from a stability standpoint with a synchronous machine. With a change in power the synchronous generator will "hunt" or change speed at a frequency dependent on machine parameters, drivetrain configuration and utility network variables. Any input excitation at this frequency can cause the oscillations to grow to a point where synchronism is lost. Increased drivetrain inertias help lessen these swings as do heavy damper windings in the synchronous generator. Historically these approaches have not provided enough damping and some additional means had to be added.

The Mod-0 power output initially had large fluctuations which were reduced when a slip coupling was added to the high speed shaft. The slip coupling forms the basis for our concept 1 shown in figures 5-11 and 5-12. General Electric has designed a power system stabilizer to be used on Mod-1 that electrically damps oscillations at the hunting frequency and this system forms the basis for concept 2 An induction generator has less tendency to hunt and is stable without any additional drivetrain damping as demonstrated in the Gedser wind turbine (ref. 2). An induction generator was considered as concept 3. The induction generator cannot stand alone, however. For isolated operation the hunting problem disappears for the synchronous generator since the line frequency (and thus machine speed) can be allowed to change over a large enough range to allow the drivetrain inertias to act as an effective energy storage medium, therefore the additional damping components are dropped from concept 4.

5.5.4 Baseline Concept Selection

Cost estimates were developed for each of the four concepts. Costs for the major items were obtained from two sources and the lower figure used For example, weatherproofed synchronous generators were priced at $16K and $12K by different vendors, weatherproofed induction generators were priced at $7.5K and $6.5K. Costs of $12K and $6.5K were used for synchronous and induction generators, respectively. All prices are for single quantities and since all are standard units large price breaks with quantity are not expected. A summary of the results of this cost analysis is shown in figure 5-13

From strictly a cost standpoint the induction generator was clearly favored. Even when costs are put aside, concept 1 has the disadvantages of not being economically scaleable. Fabrication costs and weight above the tower are higher. Concept 2 has the disadvantage of needing considerable site study and engineering for each installation, due to the effect the utility will have on the placement of the critical frequencies. These costs are not included in our estimate. Concept 3 has the potential for increased reliability due to the minimum number of auxiliary devices required, and to the robust nature of the squirrel cage induction generator. All of these considerations led to the choice of the induction generator (concept 3) for our baseline design for utility application and the synchronous generator setup of concept 4 for isolated operation.

More detailed drawings of the baseline systems including details on the protective devices are given in figures 5-14 through 5-17. In comparison with Mod-0A, another 200 kW machine, one will note that the main circuit breaker (CB2 in 0A) has been replaced with a motor starter contactor. The reason for this change was to increase reliability and minimize maintenance as the contactor is rated at thousands of operations before maintenance whereas the circuit breaker is rated for only hundreds of operations before maintenance and has been a minor source of irritation in Mod-0. One will also note the primary overcurrent sensors are transducers working off the current transformers (CT's) needed for the power transducer, rather than separate relays as in Mod-0A. Redundant overcurrent protection is provided by fuses in the disconnects rather than by the circuit breaker/reclosure (CB2) of Mod-0A. Correction of power factor is accomplished with a small bank of outdoor capacitors which are sized to correct to unity power factor (PF) at no load so that they will not be able to excite the generator to higher voltages if the generator should become separated from the line while running. Over- and under-voltage monitoring is also provided by the microprocessor. No special synchronizer is needed as the micro monitors generator speed and will be able to command the contactor to close within 1 percent of synchronous speed thus minimizing current inrush. There is no need to match phase as with the synchronous machine which also reduces pitch control requirements.

5.6 Tower and Foundation

The primary purpose of the tower is to support the pod assembly and rotor at the required elevation. It must have the strength to survive very severe wind conditions and its stiffness must be such that resonant conditions and dynamic instabilities are avoided. In addition to its structural capabilities the tower can serve other functions. It can serve as a conduit for electrical wires and hydraulic lines running between the ground and the top of the tower. It could serve as a shelter for a ladder or stairway between the ground and the tower top. And, a lower portion of the tower could serve as a housing for personnel and equipment that doesn't have to be in the pod assembly.

The purpose of the foundation is to support the entire wind turbine. Its surface area must be adequate to prevent excessive soil bearing pressure. It must also prevent the wind turbine from overturning.

5.6.1 Design Requirements

The design requirements for the tower and foundation evolved over the period of the conceptual study. The requirements are as follows·

1. The tower design must result in a hub height of 100 feet.
2. The first bending natural frequency of the tower when supporting 28 000 pounds of weight at the top should be approximately 1.5 times the rotor frequency. With a rotor frequency of 40 revolutions per minute, the required system frequency is about 1 hertz.
3. The tower should be capable of withstanding the critical load cases (to be described in a subsequent section) without the stress exceeding code allowable and without overturning.
4. The foundation should be independent of site soil conditions.
5. The design should reduce the tilt and cone angles to a minimum.
6. The tower shadow effect on the blades should be minimized.

In addition to these specific design requirements, the low cost design philosophy dictates a design that provides easy shipment, rapid low cost installation and easy service access.

5.6.2 Concepts Considered

Figure 5-18 shows schematic representations of the six concepts analyzed. In addition to these a soft truss tower was considered. However, the cost per pound for the truss tower was greater than the other cylindrical towers. The difference in cost was sufficient to eliminate it from further consideration.

The first concept considered (fig. 5-18(a)) represents a tower very much like the one being considered for the Mod-2 wind turbine. It was scaled down to meet Mod-X requirements. The central column supported by three legs at the base, is a cylindrical tube with a diameter of 4-3/4 feet and a wall thickness of 3/8 inch.

The second concept considered (fig. 5-18(b)) is a guyed tower based on the design of Hutter. The central column for this tower is a cylindrical tube with a diameter of 2 feet and a wall thickness of 3/8 inch.

These first two tower concepts were eliminated from consideration because their foundation requirements would be costly and not independent of site. However, because of the weight advantage of a guyed tower two designs of this type were investigated that would be independent of site. They are shown in figures 5-18(c) and (d).

The design philosophy here was to support the tower on concrete vaults of sufficient weight to prevent overturning and of sufficient plan area so that the soil bearing pressure was small enough to allow installation on all but the softest soils. It was found that these two designs were nearly identical in the areas of weight and cost. The following comments apply equally to both designs.

The initial guy angle (the angle between the tower main column and the guy bar) was selected to be 10°. However, it was found that use of this angle requred an excessive amount of material to meet the stress and frequency requirements. Use of a guy angle of 15° resulted in a much more efficient design.

When the design requirement to reduce tilt and cone angles to a minimum (so as to maximize the yearly energy output) is introduced, it effectively eliminates any kind of a guyed tower from further consideration.

The fifth tower design considered is shown in figure 5-18(e). With this design the overturning moment could be resisted by the use of concrete vaults or by filling the legs with ballast. It was found that this design offered no weight or cost advantage.

The final concept considered and the one chosen as the Mod-X baseline design is shown in figure 5-18(f). The unique feature of this design is that the tower central column rotates with the pod and rotor. The following section gives a detailed description of this design and the rationale for its selection.

5.6.3 Baseline Design

The baseline tower design is shown in figure 5-19. Vertical loads are transmitted into the three legs by a bearing at the 35 foot elevation level. Horizontal loads are resisted by bearings at the 35 foot elevation and at ground level. The three legs are supported on concrete vaults as shown in figure 5-20. The building for housing the controls, electrical switchgear, hydraulic equipment, etc. is an integral part of the tower central column (fig. 5-21).

The rationale for selection of the baseline tower/foundation was as follows. Cylindrical members are the cheapest to fabricate. Tower sections can be fabricated with all the necessary electrical wiring, hydraulic lines and other equipment preassembled at the factory. Placing the rotating/stationary interface at the tower base, reduces the amount of equipment that must be on top of the tower and, therefore, decreases maintenance costs. The design provides for easy installation and eliminates the need for a large crane. Rotating the tower mass provides greater stability for passive yaw. Access to the top of the tower is protected from the elements.

The concept selected for the baseline foundation was the use of precast concrete vaults backfilled with excavated earth (fig. 5-22). This concept was selected for the baseline design because it is nearly independent of site soil conditions and eliminates the need for pouring concrete on site.

5.6.4 Load Cases

Because the pitchable length of the blade was undetermined during the tower/foundation design studies, the two extreme cases were chosen for design purposes. These were a fully pitchable blade and a blade with a 10-foot tip control. A comparison of these two cases will provide an indication of the penalty that must be paid in tower and foundation cost if less than the full blade is pitchable.

The aerodynamic loads on the rotor and tower as a function of wind speed are given in figure 4-3 for various tip pitch lengths. The aerodynamic loads used for design were based on this chart. These loads were multiplied by 1.25 for determining member size requirements and by 1.50 for determining vault weight requirements. The maximum wind speed used for design purposes was 120 mph.

For the fully pitchable blade, tower member size was dictated by the first bending frequency requirement. Vault weight was determined for a case that combined aerodynamic loads for the machine operating at maximum rotor thrust (22 mph) combined with a 0.25 g (Zone 2) seismic load in the same direction as the thrust load.

For the 10-foot tip control rotor, tower member size was determined by a case that combined aerodynamic loads for a 120 mph wind with the tip feathered with the load from a 14° down gust. Vault weight was determined by a case that combined aerodynamic loads for a 120 mph wind with the tip feathered with the load from a 14° up gust.

5.6.5 Weight and Cost

Weight and cost estimates for the tower based on the critical load cases given in the previous section are presented in table 5-3. Material costs were obtained assuming an average cost of $0.76 per pound.

Erection costs were based on the requirement for a small crane for 4 days at $500 per day, a four man crew for 7 days at $675 per day, and $500 for winching equipment.

The estimated weight of the baseline tower for a fully pitchable rotor is 41 500 pounds. For a rotor with a 10-foot tip control this weight would have to be increased to 50 800 pounds. Thus, use of tip control imposes about a 20 percent penalty in increased tower weight.

Foundation details and cost estimates are given in table 5-4. The table gives the estimated vault size required to prevent overturning for the load cases presented earlier. The cost is based on vendor quotes for delivery within a 200 mile radius. The vaults for the tip control rotor would cost about twice those for the fully pitchable rotor.

Table 5-4 gives the amount of excavation required to place the vaults. Also given is the time estimated to excavate for the vaults and backfill them. Total excavation cost is based on a cost of $500 per day for 2 men and a backhoe.

The total tower/foundation cost is $43 765 for a fully pitchable rotor and $54 935 for a 10-foot tip control rotor or a difference of $11 170. Therefore, the cost benefit for going to a 10-foot tip control rotor must exceed $11 200 in order to provide any overall cost benefit.

5.7 Control System

The basic function of WTG control system is to safely perform three major tasks

(1) Startup and shutdown sequencing

(2) Power and rotor speed control

(3) Yaw control

TABLE 5-3. - TOWER STRUCTURE WEIGHT AND COST

Component	Fully pitchable rotor	10-ft tip control rotor
Main column, lb	22 000	25 000
Legs (3), lb	6 400	6 400
Base, lb	3 000	3 000
Bearing ring, lb	3 000	9 000
Connections (10 percent), lb	3 100	3 400
Control house, lb	4 000	4 000
Total weight, lb	41 500	50 800
Cost ($0.76/lb),* $	31 540	38 610
Erection cost, $	7 225	7 225
Total cost, $	38 765	45 035

*Based on 100th unit.

TABLE 5-4. - FOUNDATION SIZE AND COST

Component	Fully pitchable rotor	10-ft tip control rotor
Vault size		
Side, ft	9	12
Depth, ft	4	5
Wall thickness, in.	8	8
Floor thickness, in.	15	18
Vault cost, $	4 000	8 400
Excavation required, yd^3	34	76
Excavation time, days	2	3
Excavation cost, $	1 000	1 500
Total cost, $	5 000	9 900

These tasks are discussed in more detail in the following paragraphs.

As part of the startup task, the control system must sense that all necessary conditions are proper for successful WTG operation. Normal strategy, successfully employed on earlier WTG machines, is to initiate the startup sequence when the wind velocity remains above the specified cut-in value for a minimum period of time. If a hydraulic system is utilized, the pump must be started and full hydraulic pressure attained before proceeding. If an active yaw system is used to properly align the rotor with the wind direction, appropriate commands must be issued to the yaw motors. When passive yaw is employed on downwind rotor machines, yaw brake drag pressure (if used for damping) must be controlled. The yaw control continues for the duration of WTG operation.

Power and rotor speed control is accomplished by varying the rotor blade pitch and the electrical load. During the startup sequence the pitch control system adjusts the blade pitch to start rotation and increase rotor speed to the nominal operating value. A chief consideration is the restriction on blade pitch angle to prevent stall. The restriction is a function of both wind speed and rotation rate. The tendency to stall is more pronounced at low rotor speeds and for rotor blades having little or no twist. A typical proportional plus integral plus derivative (PID) control system, with gains set for optimum performance at rated wind speed and with the speed command set point set at nominal operating speed at the onset of rotation, will pitch the blades through the stalling point, preventing attainment of rated speed. One expedient solution is to increase the speed command at a rate low enough so that equilibrium conditions are met and large error signals are avoided.

During normal operation the speed and power control strategy differs for machines designed for isolated operations and those operated in synchronism with a utility system. A synchronous generator is utilized for WTG's in isolated applications. When the rotor speed reaches approximately 90 percent of nominal, the generator field coil is energized and at 100 percent the main contactor is closed, connecting the load to the WTG. Since the wind speed and thus power output cannot be controlled, the load must be adjusted to match the available power from the WTG. If the load is too large the WTG will "lug down," that is, rotor speed will decrease. When this condition is sensed by the control system, it must shed some of the load on a predetermined priority basis.

When the Mod-X WTG is synchronized with a system of larger capacity, an induction generator is used. The control system in this application commands the main contactor to close when nominal rated rotor speed is reached. At the same time, the blade pitch control is switched from the speed control mode to the power control mode. The power control transfer function is also proportional plus integral in nature, but the gains are generally different than in the speed control mode. The power command is set to rated power initially and remains at that value. Maximum blade pitch is chosen to prevent a stall condition at all wind speeds.

Shutdown sequencing is independent of the WTG application. The blades are commanded to feather at a fixed rate and the main contactor is commanded open when the power output becomes zero or negative. If the detected wind speed drops below the low wind speed cutout value for a specified period of time, a shutdown is commanded. High-wind shutdowns are actuated when the wind speed exceeds the high wind speed cutout for a specified period of time. Hysteresis is incorporated to preclude repeated cycling at marginal wind speeds.

5.7.1 Design Goals

The goal of this conceptual study was to design a safe and highly reliable WTG that will provide electrical energy at the lowest possible cost. Both initial cost and maintenance cost of the control system contribute directly to the cost of energy generated by the WTG. To reduce these costs, the control system must be as simple as possible because simplicity of design contributes to both low initial cost and high reliability. High reliability reduces maintenance and repair costs. High reliability and low cost are achieved through the use of proven components which are commercially available.

5.7.2 Design Requirements

The Mod-X is to be a mass-produced machine that will be used at a wide variety of sites having greatly different climates and which will be required to interface with a variety of utility networks. As a result, the Mod-X control system must meet the following requirements·

(1) It must withstand all climatic conditions in all 50 states. This will include a wide range of temperature and humidity conditions and salt air environments.

(2) It must be easily modified to adapt to the particular user's applications and specifications.

(3) It must be insensitive to electromagnetic interference that is to be expected from the contactors and motor starters of the WTG as well as from such external sources as electrical storms and communications-related interference.

(4) In order to minimize repair costs it must be designed so that·

(a) When faults do occur, their location can be readily identified.

(b) System checks can be made rapidly and efficiently.

(c) It will require a minimum of routine maintenance.

(5) It must have the capability of starting and stopping the WTG under remote control from the utility control room.

5.7.3 Baseline Mod-X Control System

A schematic of the selected baseline control system is shown in figure 5-23. The heart of the system is a microcomputer similar to the one used with the Mod-0A machine (ref. 3). The overall control system is cost-effective, highly reliable and extremely flexible. The programming capability of the microprocessor will allow software changes during the initial debugging phases of control system operation and will permit the same control system hardware to be used in a wide variety of customer applications from isolated operation with a custom programmed load control to a standardized utility grid application. The hardware commonality will lead to lower production and maintenace costs and higher reliability.

The microcomputer software program will be time-interrupt driven. This is necessary for proper functioning of the integration approximation used in the pitch controller loops. The time constants associated with blade pitch changes are sufficiently long that ample time will be available between integration cycles to process all other control functions. Cycle time in the Mod-0A machine is 6 milliseconds excluding pitch and yaw control functions. An overall cycle time for the Mod-X machine of 10 milliseconds seems possible which is much faster than the servo response time and should allow for precision pitch control. All other control algorithms are straightforward decision-making processes which have been implemented in previous WTG's and present no problems. For these decisions, current values of the inputs are compared to prespecified limits and the appropriate response is initiated. The main program loop is variable and self-modifying depending on the current state of the WTG.

As shown in figure 5-23, wind speed, power, rotor speed and pitch angle are monitored continuously by the microprocessor. As a function of the input values, the microprocessor issues appropriate commands to the WTG controls. The microcomputer also has provisions for interfacing with a diagnostic control panel which will permit manual operation of the WTG so that repair work can be effected. The control/diagnostic panel can also be used to aid in the diagnosis of electrical signal failures. In addition, a remote control and monitoring unit is connected through either a telephone or radio link to an interface with the microprocessor. The remote operator will have the ability to monitor operating conditions and to command start-ups and shutdowns.

Predicted costs for the control system are given in figure 5-24. A total initial cost of $9000 is estimated for the microprocessor and its associated equipment. This excludes the cost of a diagnostic panel and software development.

5.8 Safety System Design Requirements

A safety system is required to protect the machine from catastropic failure. The safety system has no control functions, as the largely independent control system assumes all control functions, including allowable wind conditions. The safety system is a protective system that monitors the WTG operation and commands a shutdown for abnormal operation.

Although the most critical area of protection is overspeed, protection must also be provided for excessive vibration, hydraulic failures, pointing errors, control problems, high temperatures, electrical faults, or failures which would disable the safety system.

5.8.1 Concepts Considered - Mod-0A and Mod-1 Safety Systems

The Mod-0A and Mod-1 designs both include safety systems, but they are entirely different in their implementations. The Mod-0A WTG safety system is a completely separate entity from the rest of the WTG systems. It contains its own independent sensors and shutdown path, and it is backed up by a completely independent, almost totally redundant, shutdown system, using different sensing techniques when possible and independent sensors throughout. Only a few noncritical checks are made from the control system sensors. In contrast the Mod-1 WTG has no independent safety system as such. All critical control sensors are redundant, and their signals are compared against each other to verify the sensors. Besides verifying sensors, the control system computers constantly check all responses to control system commands and sensor redline values to ascertain proper operation.

The shutdown commands are also quite different. The Mod-0A safety system commands emergency feather, desynchronizes the machine, and turns off the field current and the pitch hydraulic system. Shutdown is independent of and overrides the control system. The Mod-1 safety system directly commands emergency feather, but relies on the normal control system for all other functions. Additionally, Mod-0A overspeed shutdowns actuate a brake to stop the machine in case the emergency feather has failed.

Both the Mod-0A and Mod-1 concepts are viable and Mod-0A has been proven through actual operation. But both systems are too expensive to meet the Mod-X cost criteria. Mod-0A requires many additional sensors and much interconnecting wiring. The Mod-1 system requires very little additional hardware, but assumes a more powerful control system computer and redundant sensors, which is incompatible with the Mod-X design.

Both of these systems were judged to be overly complex for this application in that an excessive number of parameters are sensed, and too many functions are controlled during shutdown.

5.8.2 Baseline Safety System

The Mod-X safety system shown in figure 5-25 is a hybrid of the Mod-0A and Mod-1 designs. Independent sensors are used, for monitoring critical functions (i.e., overspeed) and parameters not measured by control system sensors. These independent sensors are detailed below. The control system microprocessor is used for several other shutdown functions using analog control sensors which are checked against redline values to initiate a shutdown. Wind speed, rotor speed, power, and pitch angle values are checked for consistency to assure that the sensors are all functional. Electrical system failures are also checked through the computer.

The shutdown function directly feathers and desynchronizes the WTG. The pump and field are turned off by the control system, as these items are not critical to the machine safety. A rotor brake is not currently designed into the system, but may be required if a Failure Mode and Effects Analysis determines that emergency feather is not sufficient to stop the WTG from an overspeed condition. A parking brake of some sort will be required for maintenace, and would be adapted to a dynamic brake if required.

The safety sensors are listed below, including their design and function.

5.8.3 Discrete Sensors

Overspeed. - The low speed shaft overspeed switch is an optical device with self contained signal conditioning circuitry. It is currently used on Mod-0A machines. In the Mod-X application it is redundant with the control system alternator speed pickup sensor. Redundancy is required since overspeed is the most critical concern in the WTG safety system.

Vibration. - Machine vibration is sensed by a mercury switch, figure 5-26, in which the mercury moves enough to open the circuit whenever the normal vibration levels are exceeded. Vibration sensing is a universal mechanical failure detector, sensing gross unbalances, bearing failures, gearbox roughness, excessive blade loads, etc.

The mercury filled tube is sensitive to low frequency vibrations, and will not respond to high frequency vibrations and minor shock and could therefore be calibrated at a value corresponding to the 1 or 2 P oscillations.

Temperature. - Selected Mod-X temperature sensors are similar to the Mod-0A sensors. They are bimetallic snap action switches. When mounted on the gearbox, alternator bearings or hydraulic system, malfunctions are detected before total failure of a component. The sensors latch when tripped to indicate which component overheated.

Yaw error. - Yaw error is determined by a windvane mounted on the nacelle. With a passive yaw system no control signal is required, and the shutdown command is generated by limit switches indicating a large angle with respect to the wind direction. Using a spring restraint on axial motion makes the shutdown angle a function of wind speed, and damping eliminates wind gust effects. A conceptual sketch is shown in figure 5-27.

Microprocessor failure. - A circuit independent of the microprocessor is used to verify the microprocessor's operation. During the program cycle, a timer is reset. If the program does not progress properly the timer will time out and initiate a shutdown.

Safety system shutdowns effected through control systems sensors. - Several sensors are used in the normal machine control system, through the microprocessor. They are additionally processed in the microprocessor to determine faults. A major portion of the testing is to determine if the sensor calibration is in error by checking the machine performance in terms of wind speed, rotor speed, power and pitch angle against a data base. Significant deviation indicates a sensor failure, and is a shutdown criteria.

Servo response. - Pitch angle and pitch servo command can be compared to verify servo response. The servo valve current also indicates servo response. These checks indicate hydraulic failures, binding in the pitch mechanism, servo instability, pitch transducer failure, and pitch controller failures.

Alternator speed. - This speed signal is a backup to the discrete overspeed pickup mentioned previously. In addition, this speed signal is checked through the WTG operation to verify speed sensor operation and WTG response, and crosscheck other signals, such as wind speed and pitch angle.

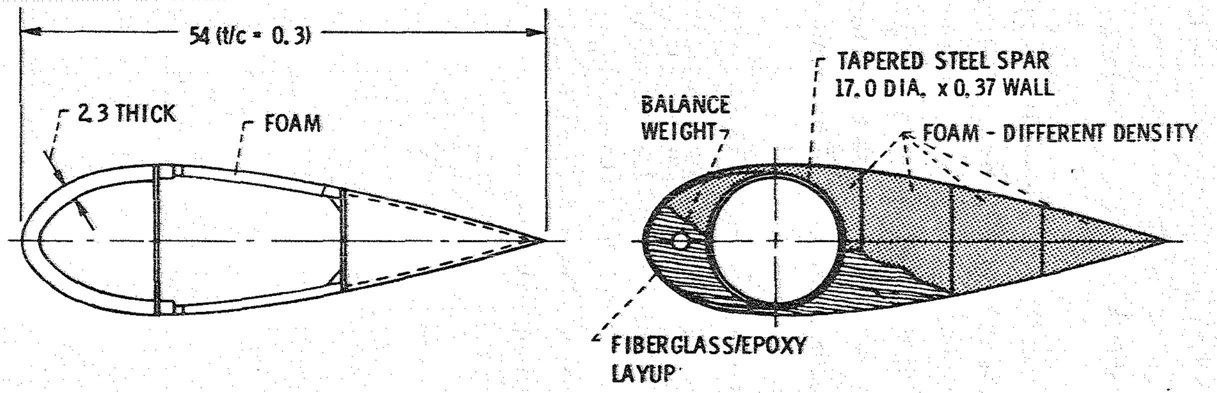
Reverse power/over power. - The alternator power signal is checked to verify that the servo loop is controlling power correctly, and that the machine is shutoff at low wind speeds. The power signal is also checked against pitch angle and wind speed to verify the ammeter and power transducer.

5.8.4 Electrical System Sensors

The electrical system is a self protected system and its sensors do not directly trip the safety system. The interconnection is through a "loss of synchronization" signal, indicating if the synchronizing contactor is open when it shouldn't be, and effecting a shutdown.

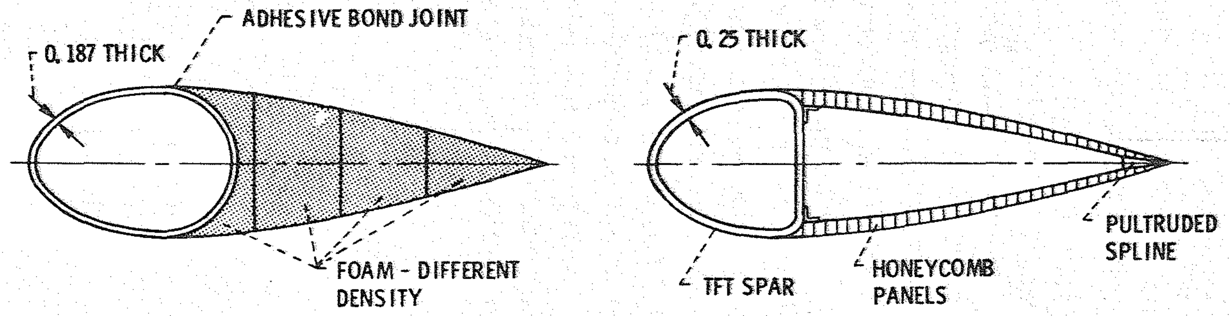
The Mod-X safety system cost is based upon the additional items required to implement a safety system which are not in the existing system. Therefore, the discrete sensors must be included in the cost, but the control system analog sensors are not. The microprocessor is a part of the control system and only the additional memory and input/output capability required for safety system functions is costed in this section. The electrical system protection is inherent in and costed with the electrical system, not in the safety system.

The major expense is in the discrete sensors, primarily in the overspeed sensing, the most critical but redundant function. The cost of the overspeed sensor, with mechanical drive and installation is approximately $750, the machining required for the yaw and vibration sensors adds another $750 and the total safety system cost is $2 000. Large production runs would reduce all these cost radically as they would not be produced as singular hand machined specials, and total system cost would then be on the order of $1000.



(a) WOOD CONSTRUCTION.

(b) STEEL SPAR AND RIB CONSTRUCTION.



(c) STEEL CONSTRUCTION.

(d) TRANSVERSE FIBERGLASS TAPE WOUND CONSTRUCTION.

Figure 5-1. - Blade concepts considered.

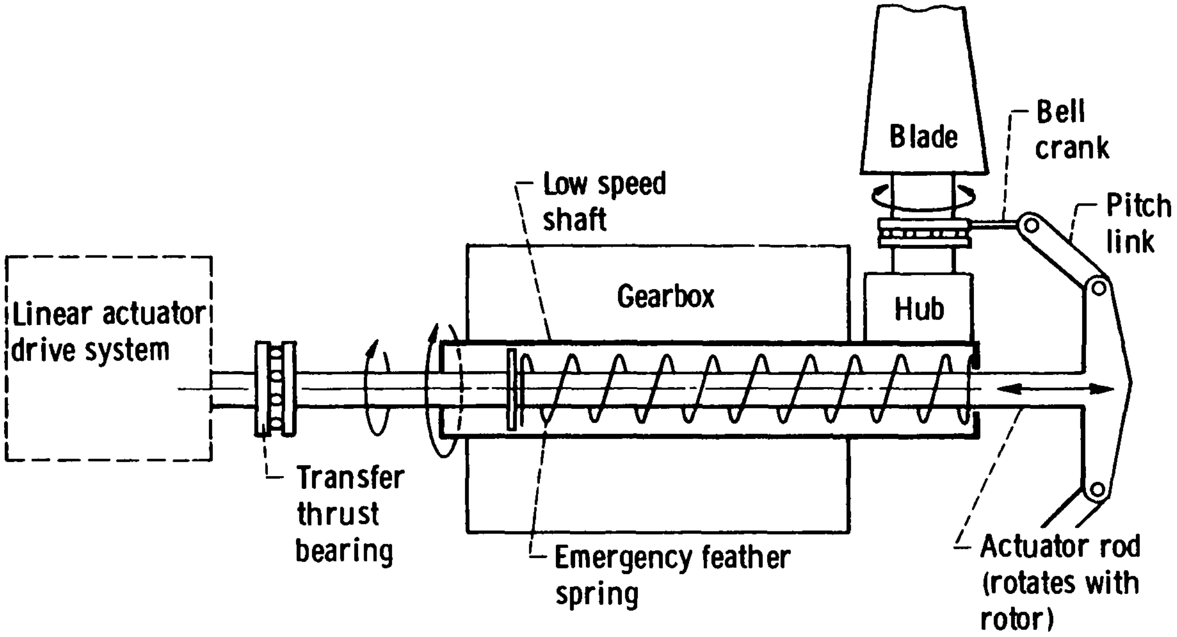
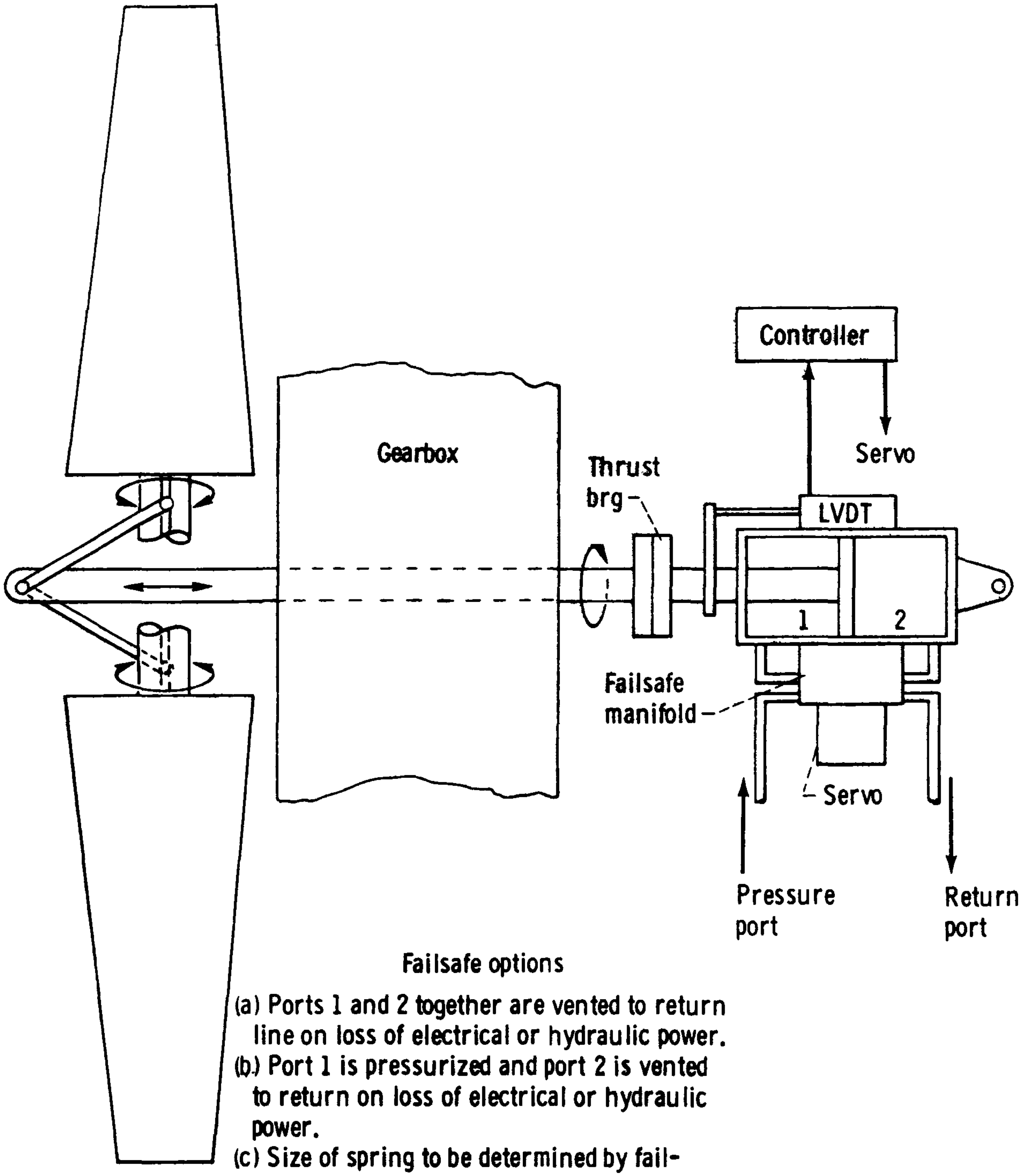


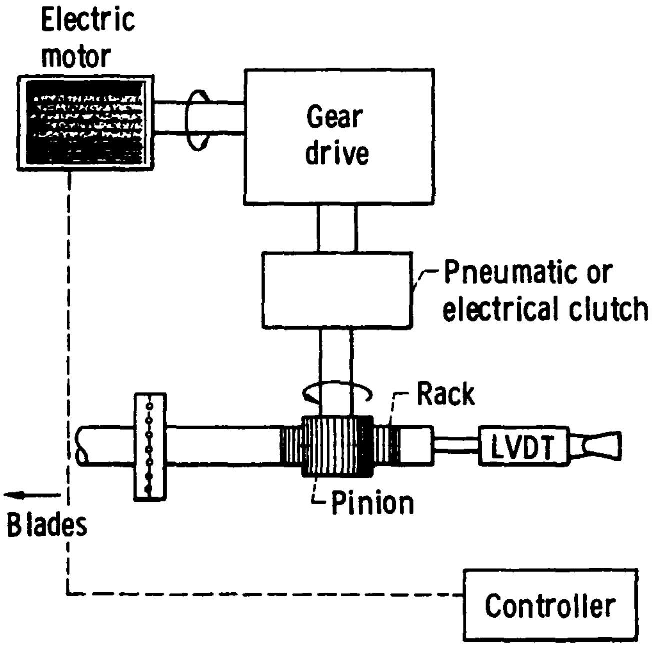
Figure 5-2. - Selected pitch change mechanism.



Failsafe options

(a) Ports 1 and 2 together are vented to return line on loss of electrical or hydraulic power.
(b) Port 1 is pressurized and port 2 is vented to return on loss of electrical or hydraulic power.
(c) Size of spring to be determined by failsafe option.

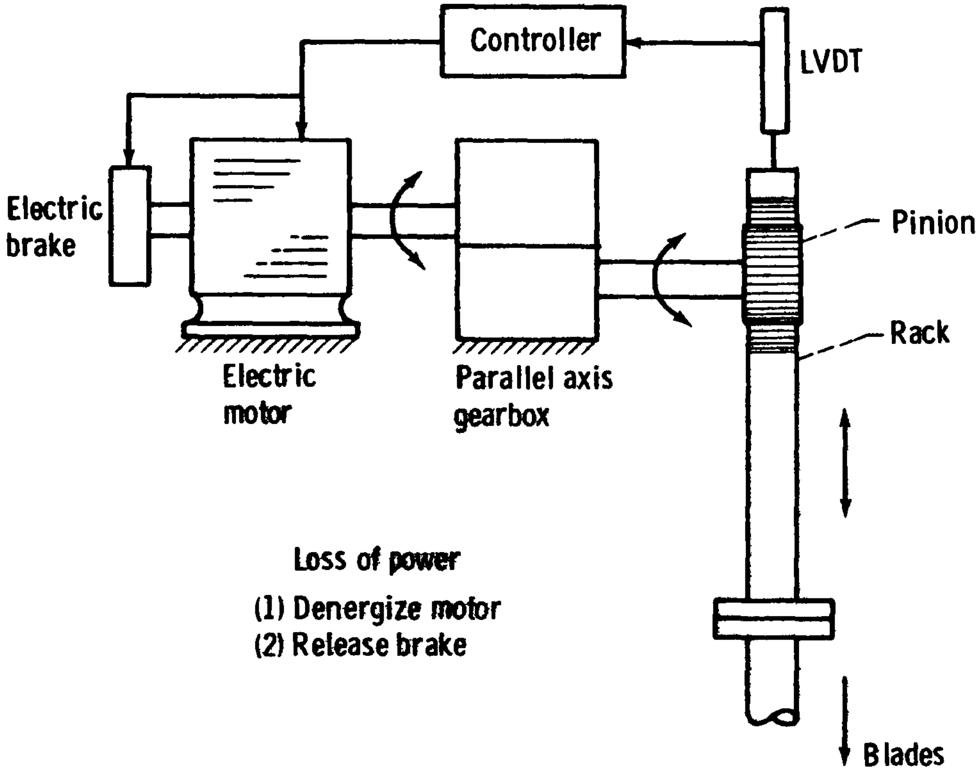
Figure 5-3. - Pitch change concepts A and B.



Failsafe options

(1) Loss of power or pneumatic (low pressure) release clutch.

Figure 5-4. - Pitch change concept C.



Loss of power

(1) Denergize motor
(2) Release brake

Figure 5-5. - Pitch change concept D.

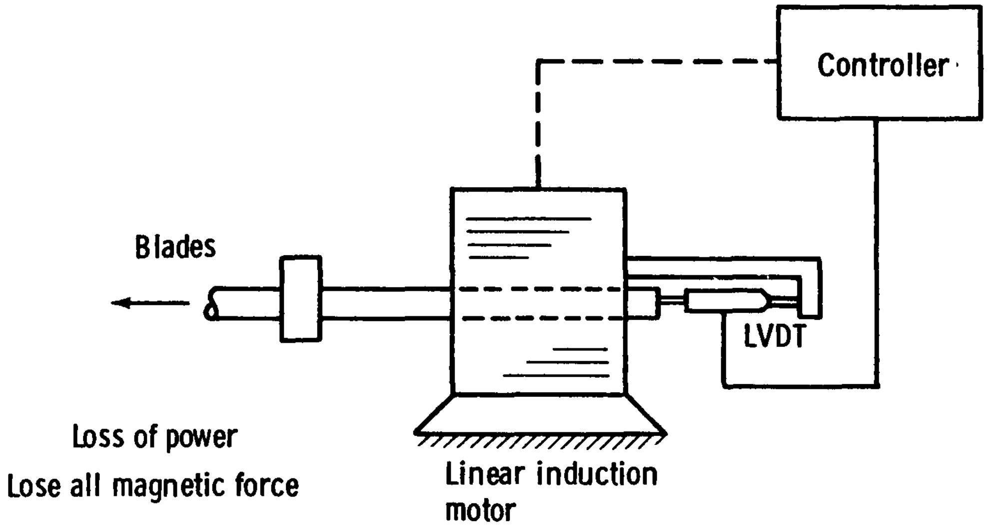
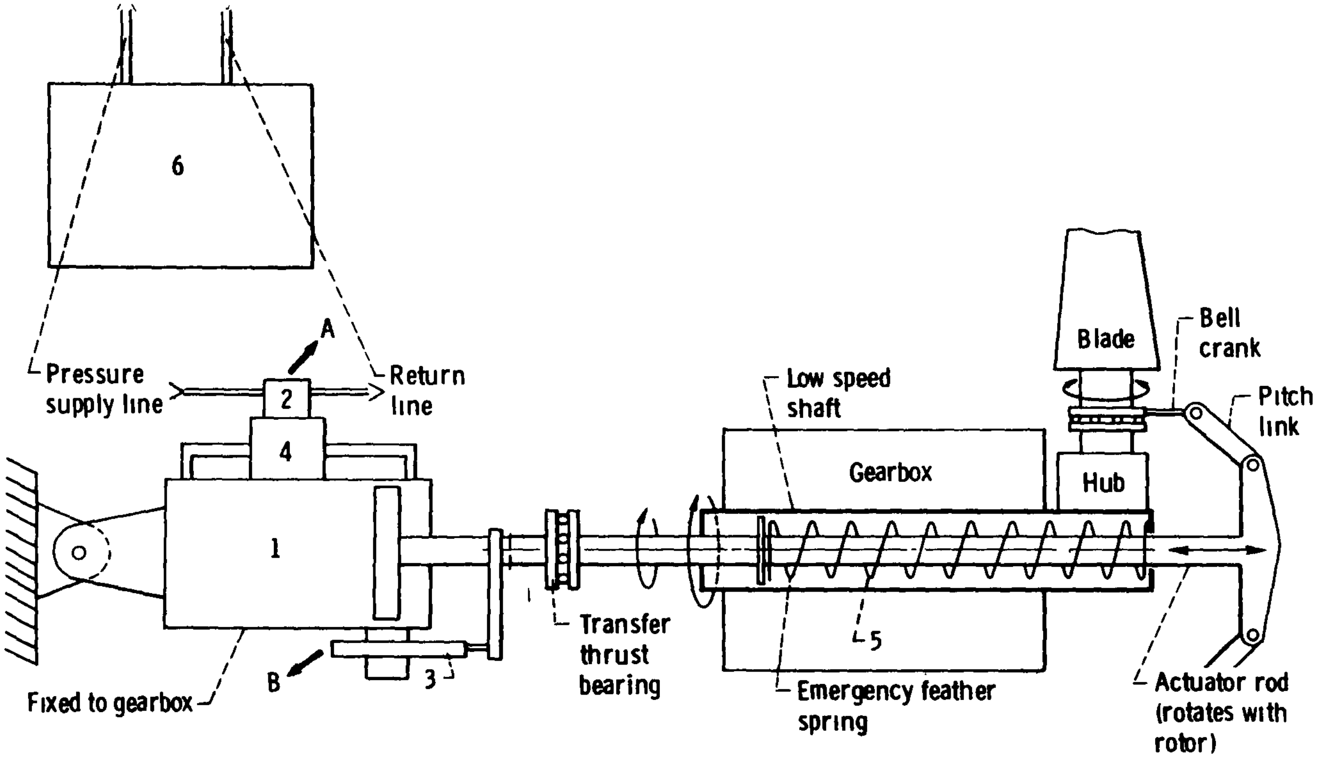


Figure 5-6. - Pitch change concept E.



1 Hydraulic cylinder 8" bore x 13.5" stroke
2 10 gpm servovalve
3 15" position indicator
4 Failsafe valve
5 Spring
6 5 gpm, 3000 psi hydraulic pump package, with reservoir and controls
A, B Signals to microprocessor

Figure 5-7. - Schematic of selected pitch change mechanism.

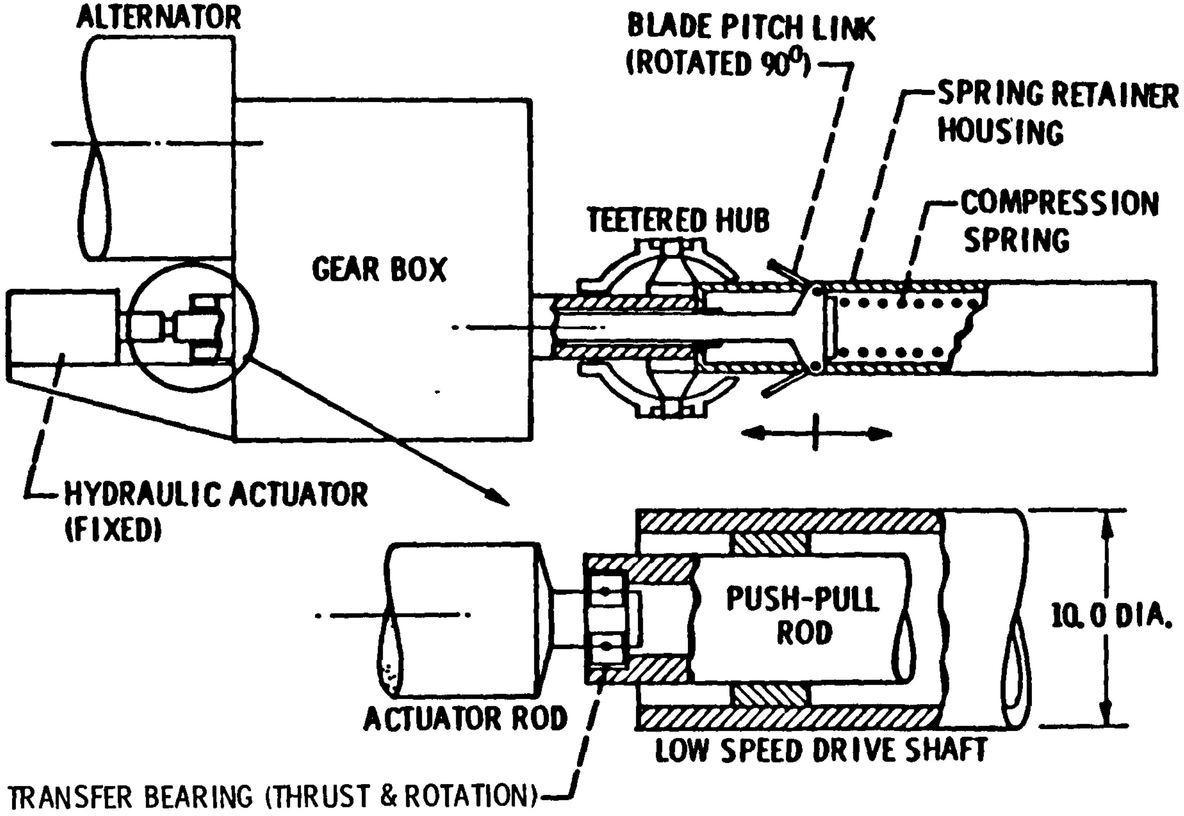


Figure 5-8. - Schematic of pitch change mechanism/hub incorporation.

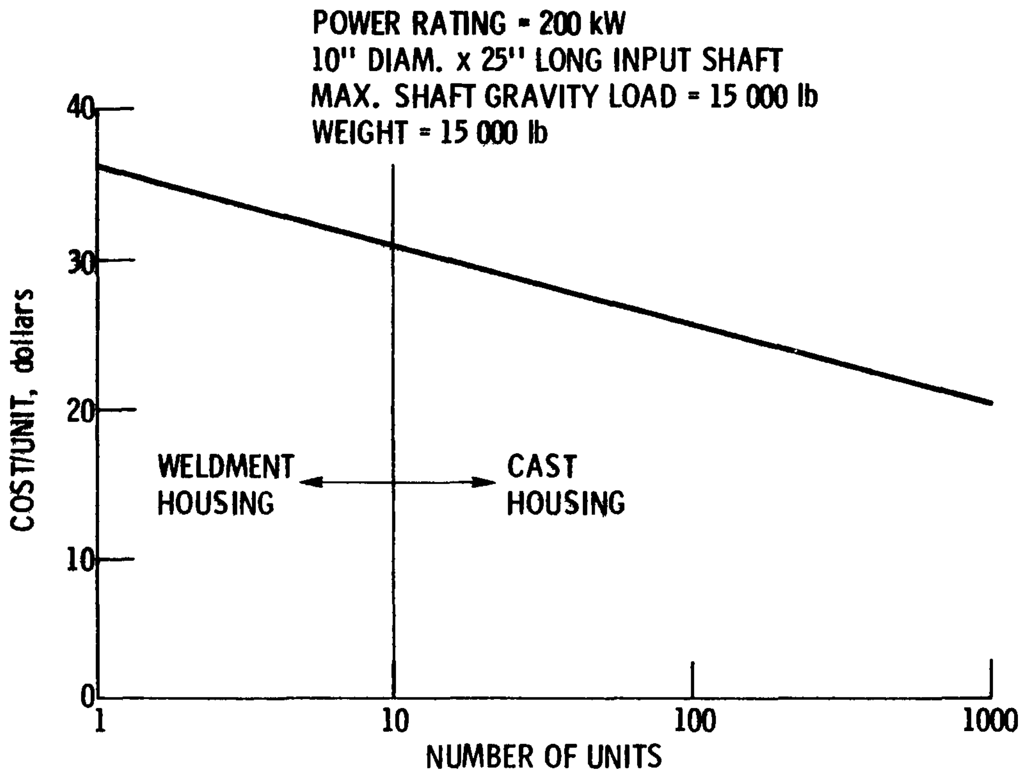


Figure 5-9. - Gearbox costs versus number produced.

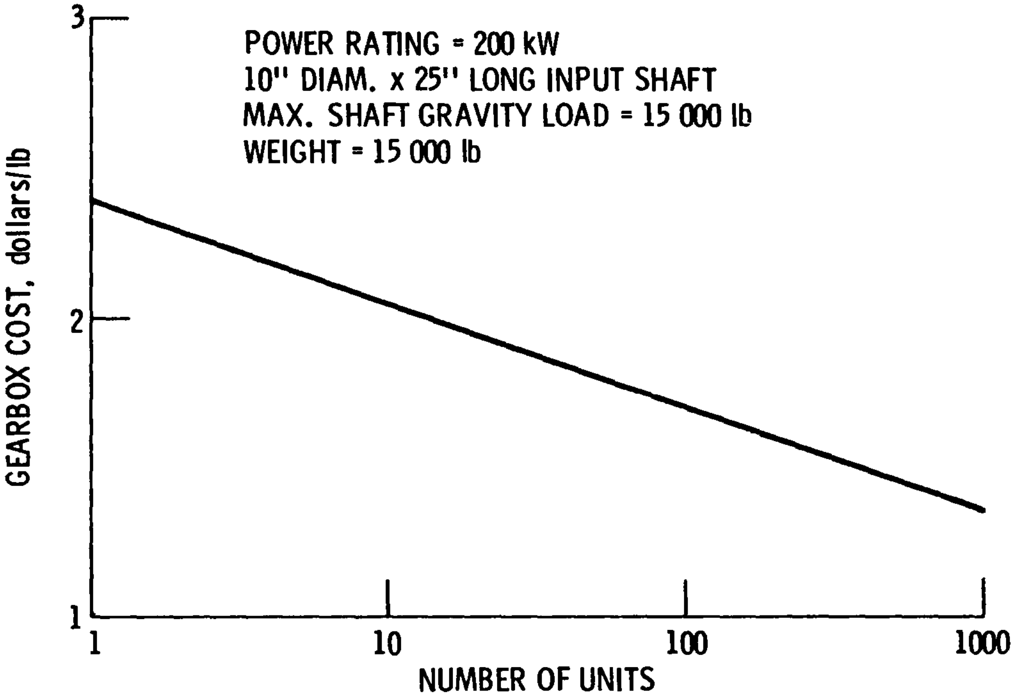


Figure 5-10. - Gearbox costs in dollars/pound.

CONCEPT NO.	ELECTRICAL GENERATION SYSTEM & TORQUE DAMPING	APPLICATION	WIND TURBINE
1	SYNCHRONOUS & FLUID COUPLING	UTILITY & ISOLATED	MOD-0, -0A
2	SYNCHRONOUS & POWER SYS. STAB.	UTILITY & ISOLATED	MOD-1
3	INDUCTION & POWER FACTOR CORRECTION	UTILITY ONLY	GEDSER
4	SYNCHRONOUS	ISOLATED ONLY	MOD-0

Figure 5-11. - Electrical generation system concepts.

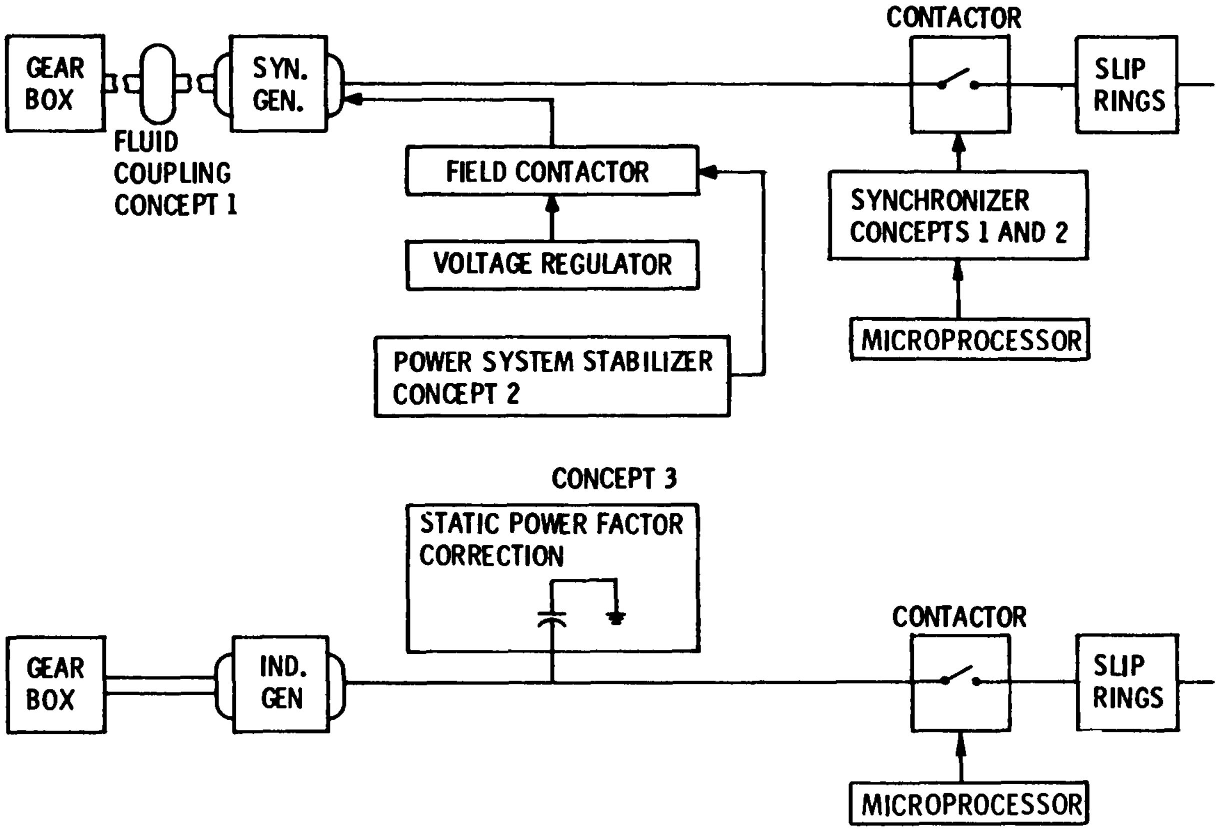


Figure 5-12. - General layout of electrical generation system concepts 1, 2, and 4.

CONCEPT NO.	WEATHERPROOF ALTERNATOR		DRIVE TRAIN DAMPING		EXCITATION & CONTROLS		COSTS,** $K
	TYPE	$K	TYPE	$K	TYPE	$K	
1	SYN.	12.0	FLUID COUPLING	3.0	VOLT REG. FIELD CONTROLLER SYNCHRONIZER	0.5* 1.0*	16.5
2	SYN.	12.0	POWER SYSTEM STABILIZER	4.0*	VOLT REG. FIELD CONTROLLER SYNCHRONIZER	0.5* 1.0*	17.5
3	IND.	6.5	NONE REQ'D	----	STATIC CAPACITORS	0.5	7.0
4	SYN.	12.0	NONE REQ'D	----	VOLT REG. FIELD CONTROLLER	0.5	12.5
OTHER COMMON ITEMS (SLIPRINGS, FUSED DISCONNECTS, MAIN CONTACTOR, PROTECTIVE DEVICES, WIRING, ENCLOSURES, ETC. TRANSFORMER NOT INCLUDED)							8.5

*THESE COSTS ARE INDEPENDENT OF POWER RATING.
**SECOND UNIT COSTS.

Figure 5-13. - Electrical generation system estimated costs.

For utility grid application:
  Rationale
    Lowest cost
    Fewest components

Induction generator (concept 3)

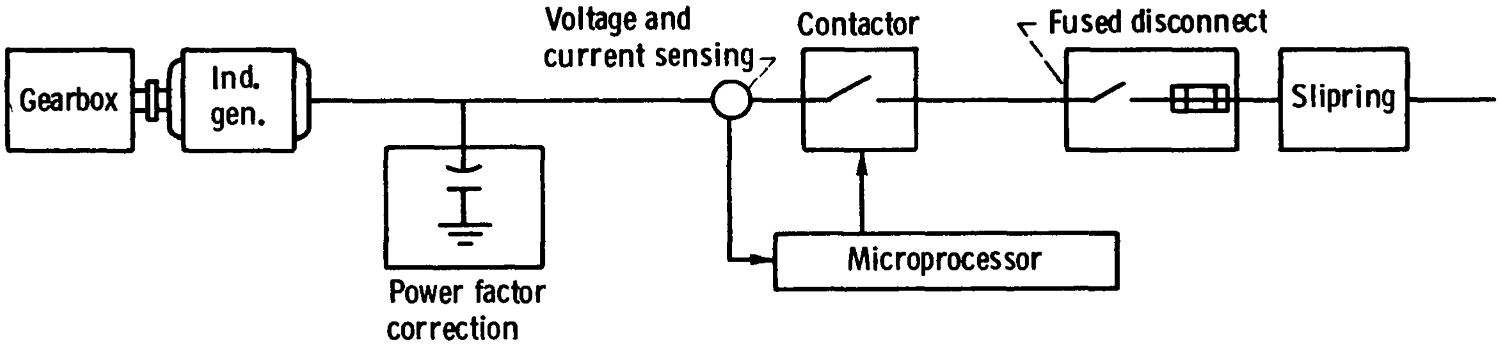


Figure 5-14. - Selected baseline electrical generation system.

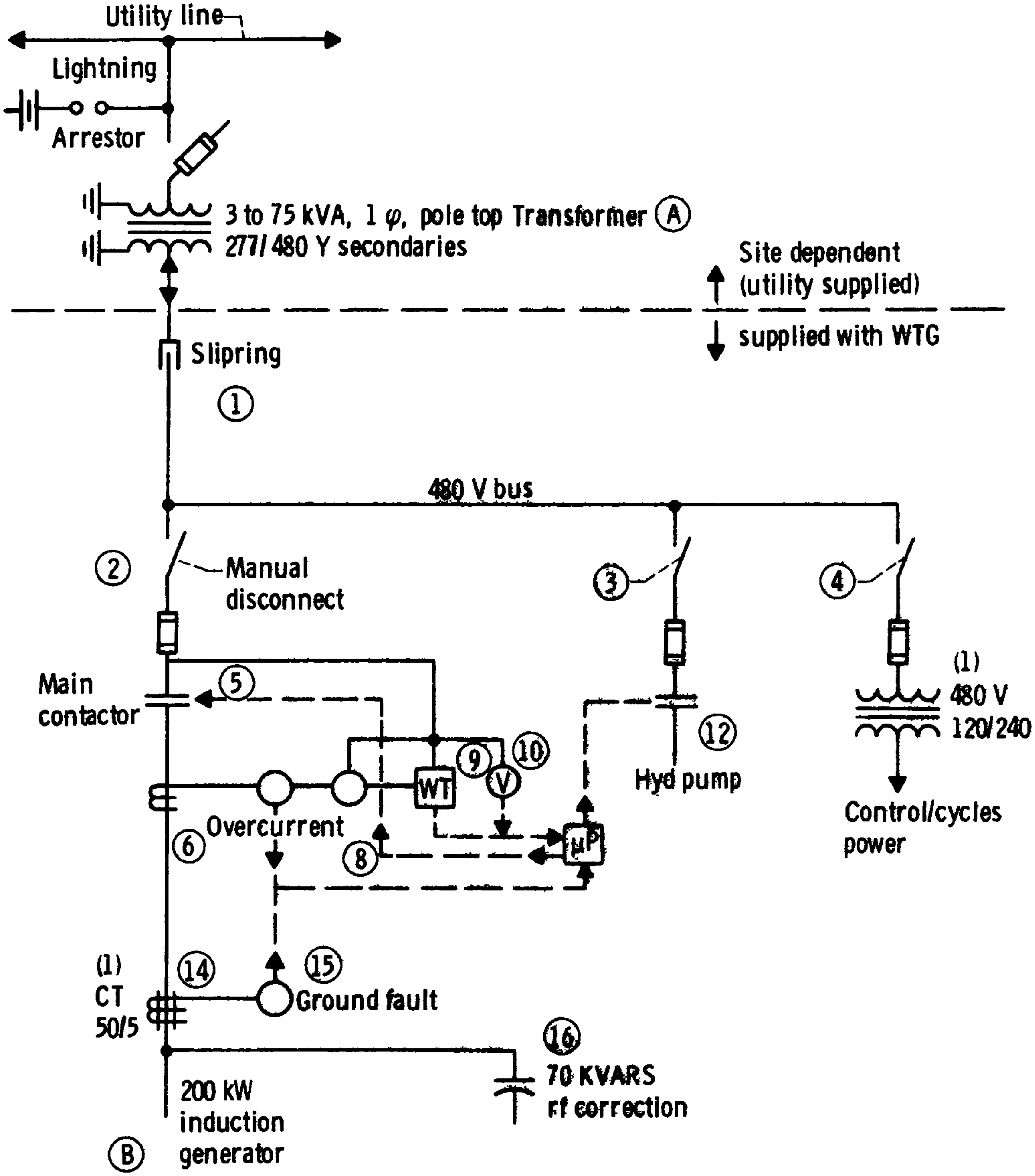


Figure 5-15. - One-line diagram of baseline system.

ONE LINE KEY NO.	DESCRIPTION	PRICE, $ 2nd unit
1	SLIPRING 4 300 A CONTACTS	885
2	FUSED MANUAL DISCONNECT 600 V 400 A/PHASE	450
3	FUSED MANUAL DISCONNECT 600 V 30 A/PHASE	80
4	FUSED MANUAL DISCONNECT 600 V 5 A/PHASE	50
5	MAIN CONTACTOR (300 hp MOTOR STARTER)	2000
6	(3) CURRENT TRANSFORMERS 300:5 480 V	40
7	(3) CURRENT TRANSDUCERS 0 to 5 A 0 to 1 mA OUT	255
8	WATT HOUR METER 480 V 3 PHASE	200
9	WATT TRANSDUCER 480 V 3 ELEMENT	550
10	VOLTAGE TRANSDUCER 480 V	90
11	MICROPROCESSOR INPUT CARDS	750
12	HYDRAULIC PUMP CONTACTOR	50
13	POWER TRANSFORMER 480/120 1 kVA	100
14	CURRENT TRANSFORMER 50:5	12
15	CURRENT TRANSDUCER 0 to 5 A 0 to 1 mA	85
16	CAPACITORS - OUTDOOR 70 KVAR	500
N/A	ENCLOSURES, WIRING	3000
A	UTILITY CONNECTION TRANSFORMERS (3 - 75 KVA 1 φ UNITS) POLE TOP OUTDOOR	3200
B	INDUCTION GENERATOR 250 hp INDUCTION MOTOR FULLY WEATHERPROOF (COSTED WITH GEARBOX)	6500

Figure 5-16. - Component price breakdown for baseline system.

Rationale:
Lowest cost
Fewest components

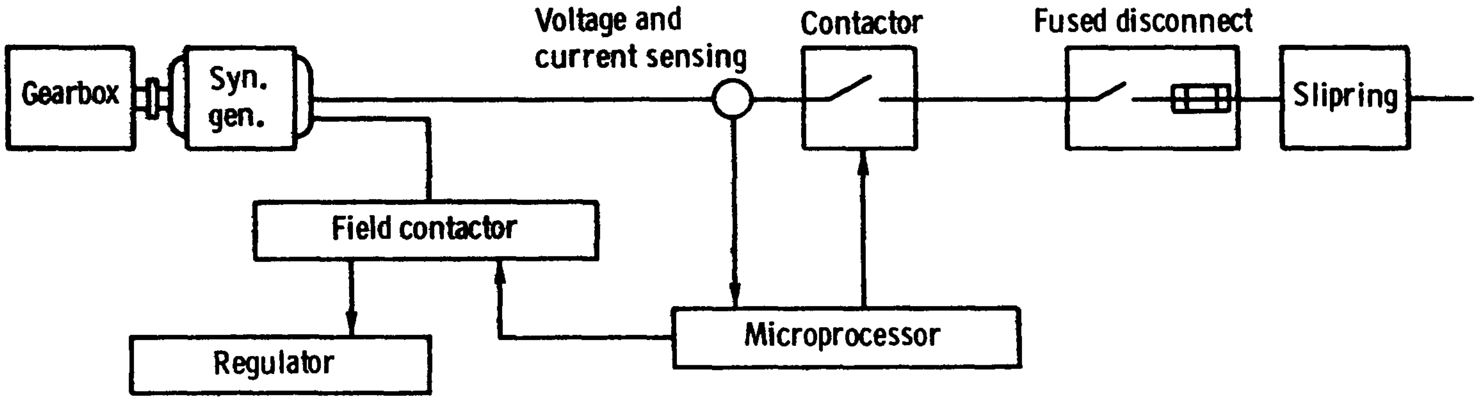
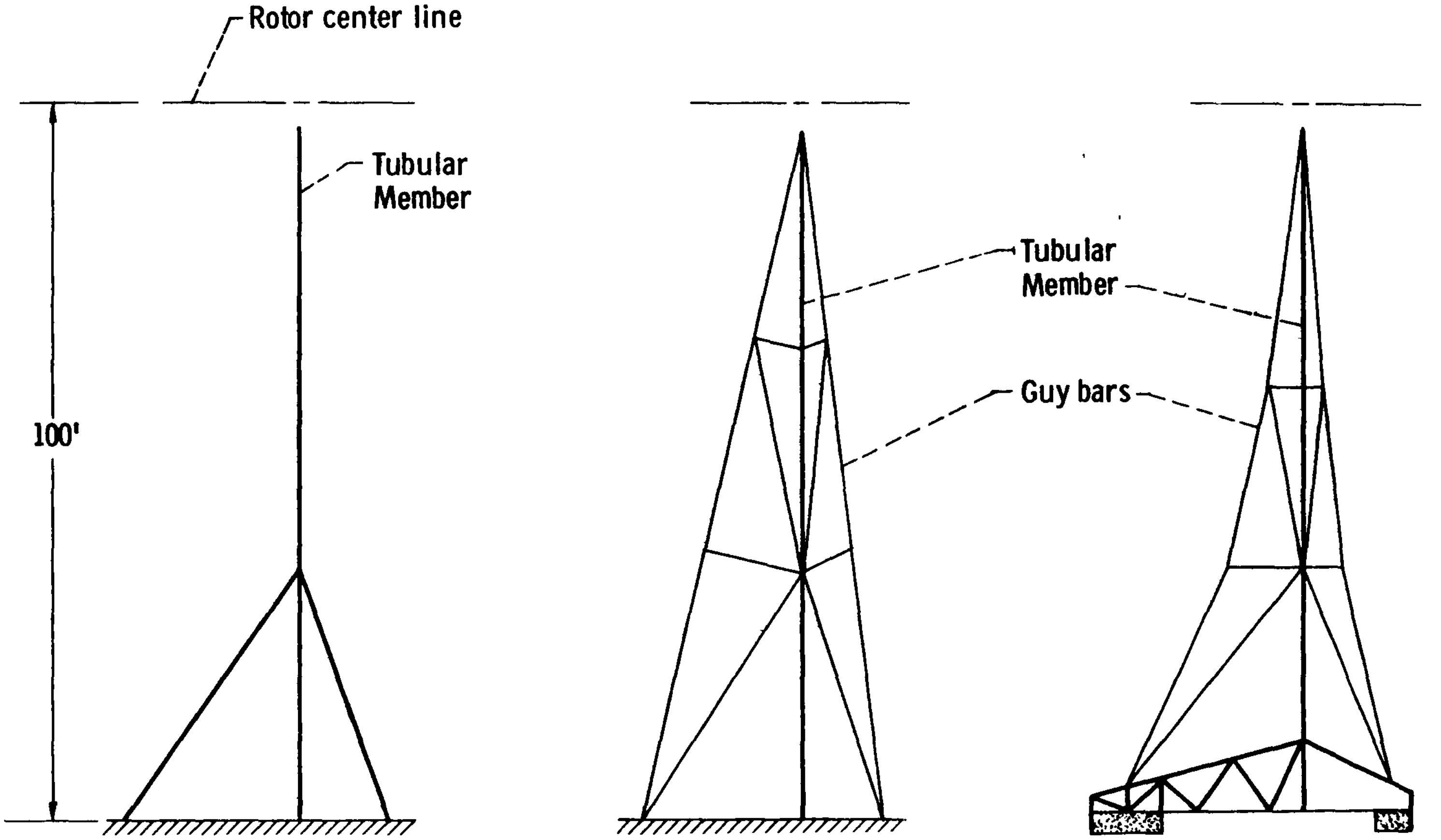


Figure 5-17. - Baseline electrical generation system for isolated applications.

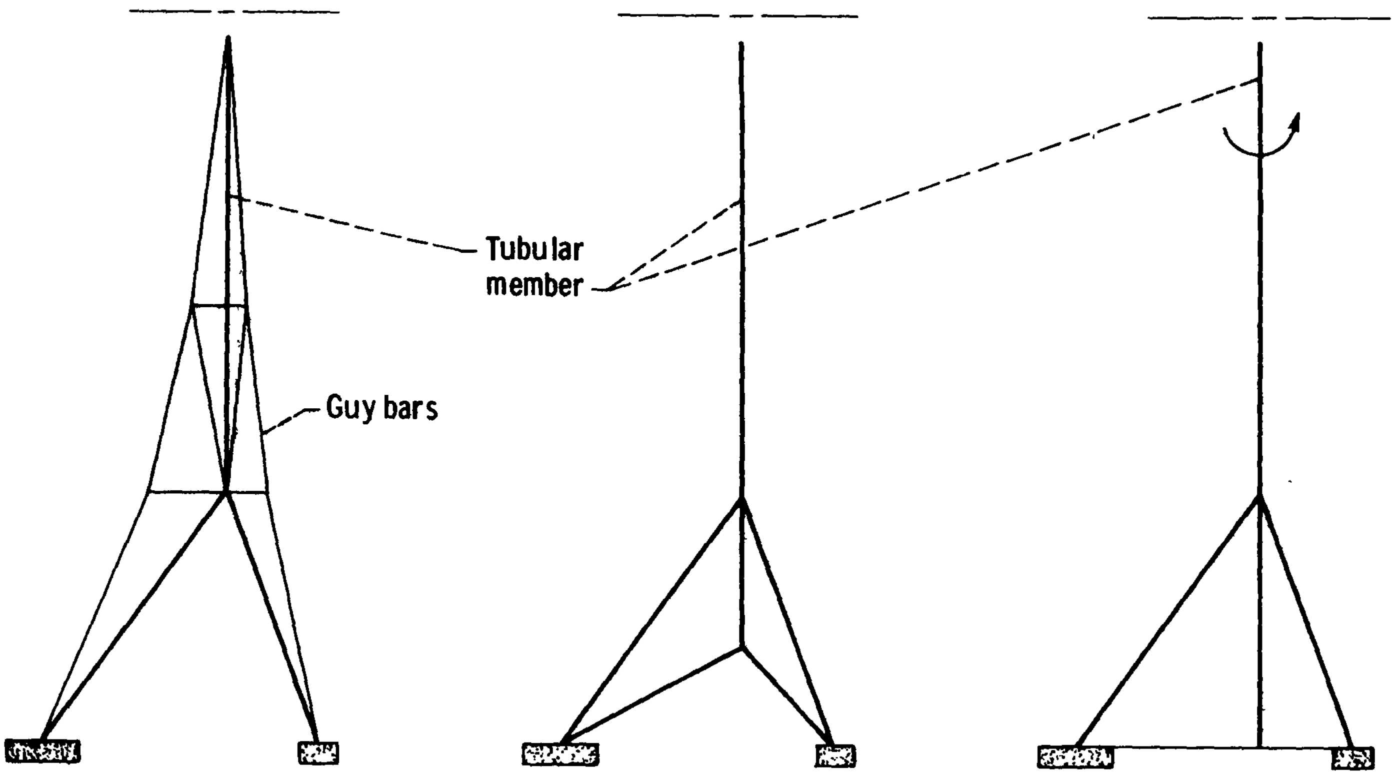


(a) Scaled down Mod-2.

(b) Scaled up Hutter.

(c) Guyed with truss base and vault foundation.

Figure 5-18. - Tower concepts considered.



(d) Guyed with tripod base and vault foundation.

(e) Tripod base with vault foundation.

(f) Rotating tower with vault foundation.

Figure 5-18. - Concluded.

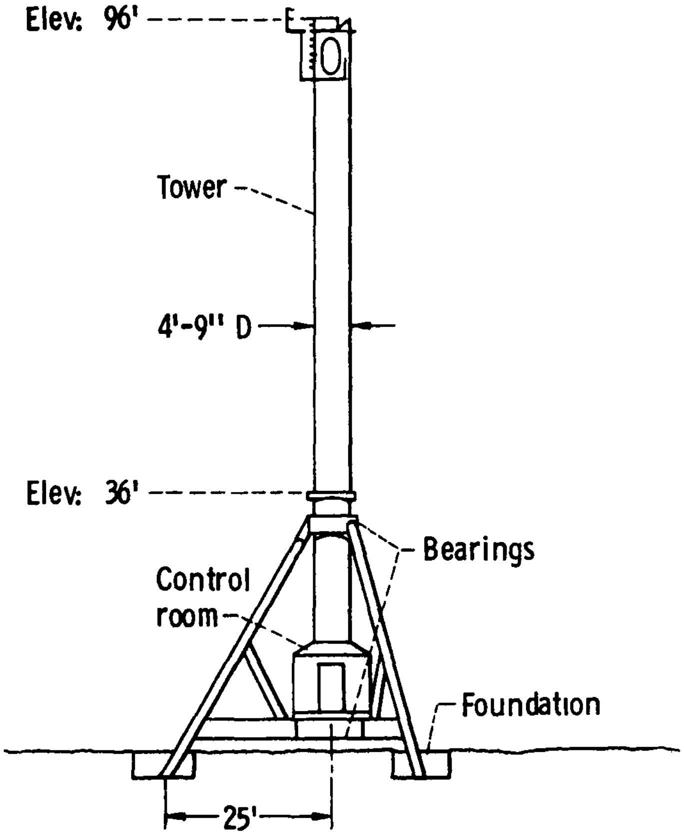


Figure 5-19. - Mod-X baseline tower and foundation.

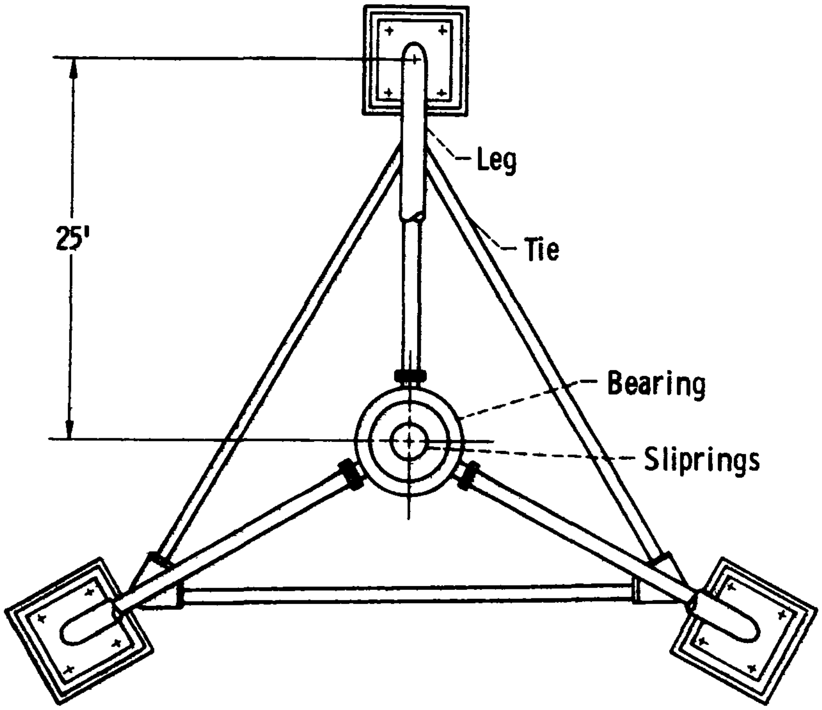


Figure 5-20. - Tower lower support structure.

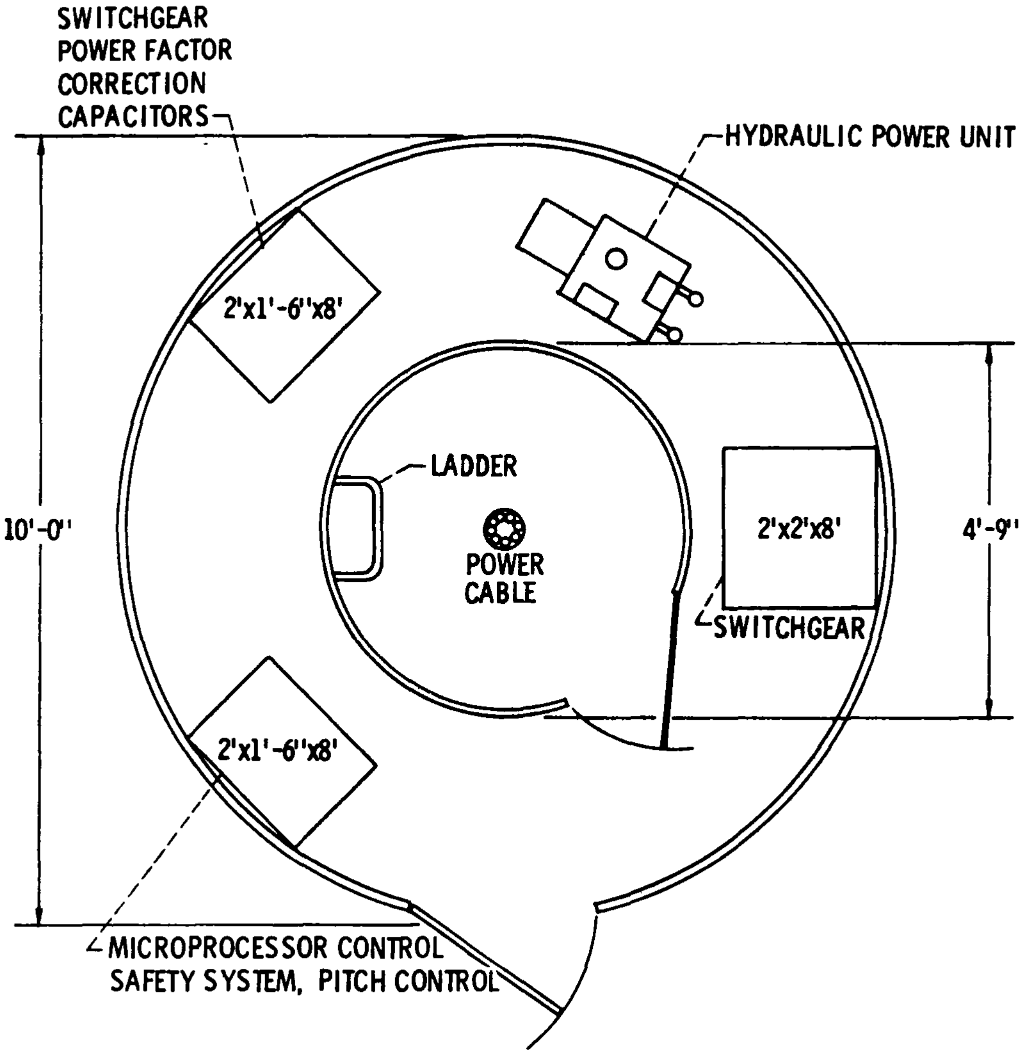


Figure 5-21. - Control room plan view.

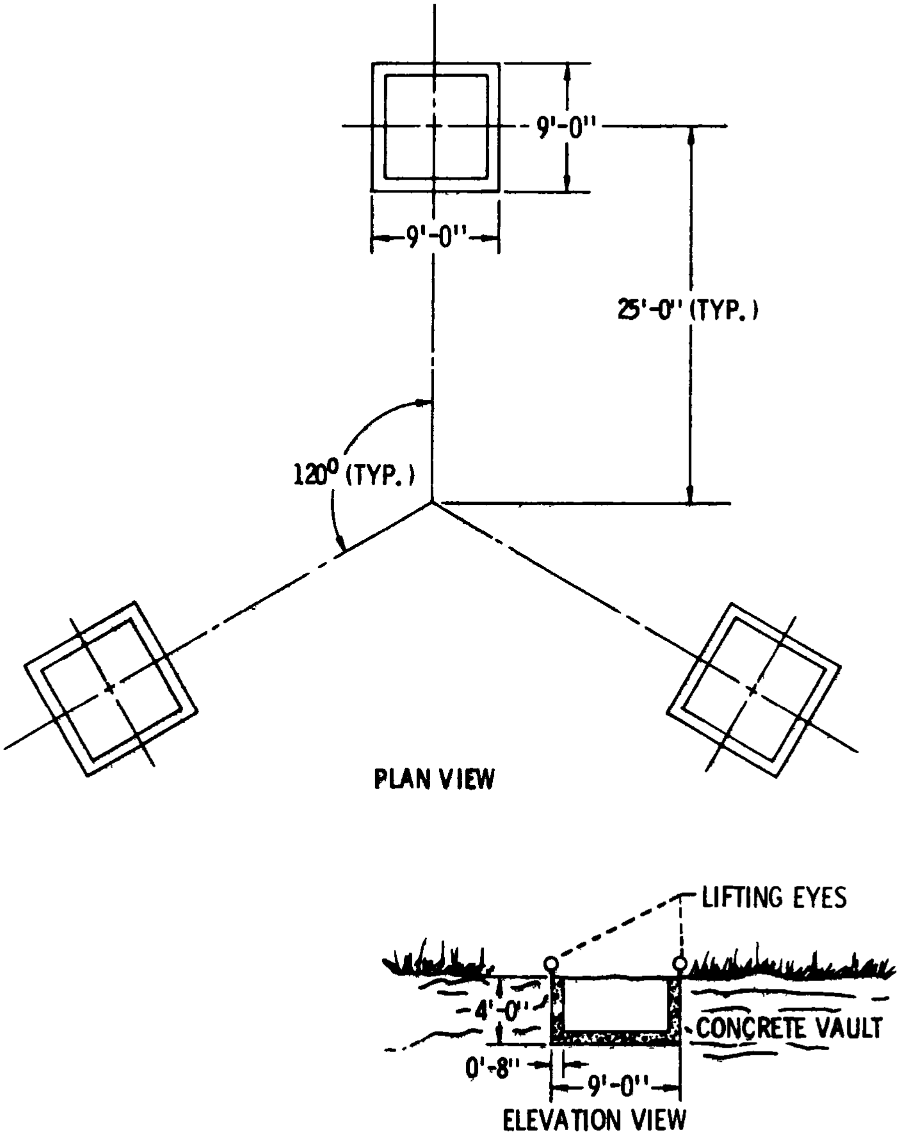


Figure 5-22. - Foundation design.

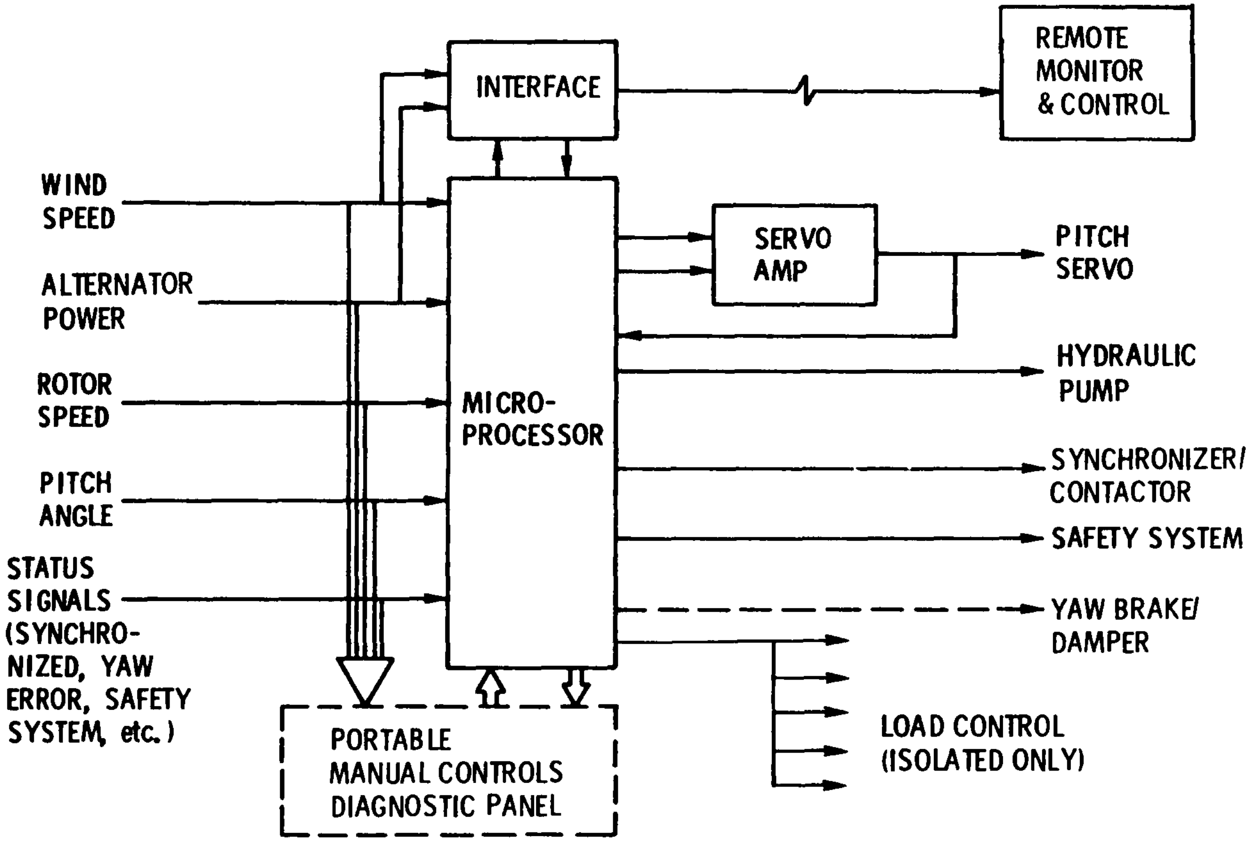


Figure 5-23. - Schematic of selected baseline control system.

	2nd UNIT COST, $
SENSORS	
WIND SPEED	300
rpm	200
POWER	1000
PITCH	1000
ELECTRONICS	
MICROPROCESSOR	5000
SERVO AMPLIFIER	300
POWER SUPPLY	200
REMOTE CONTROL	1000
TOTAL	$9000

Figure 5-24. - Control system cost breakdown.

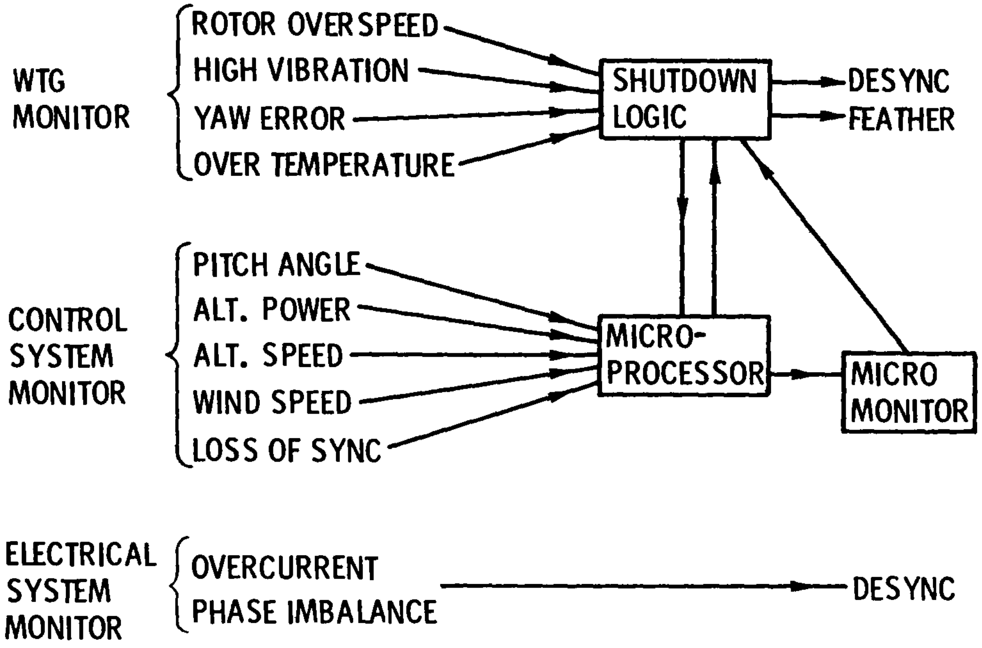


Figure 5-25. - Baseline Mod-X safety system.

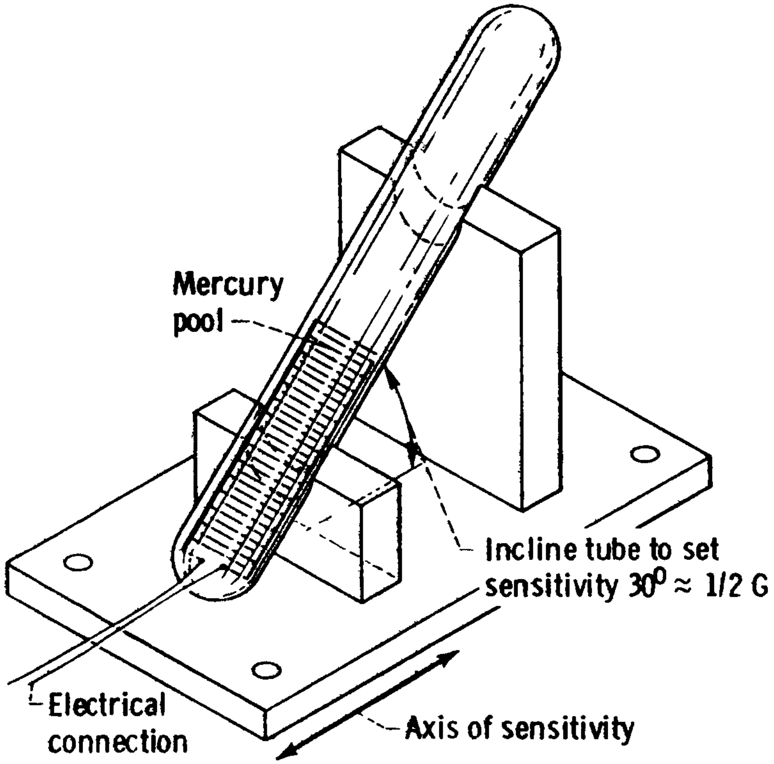


Figure 5-26. · Vibration sensor schematic.

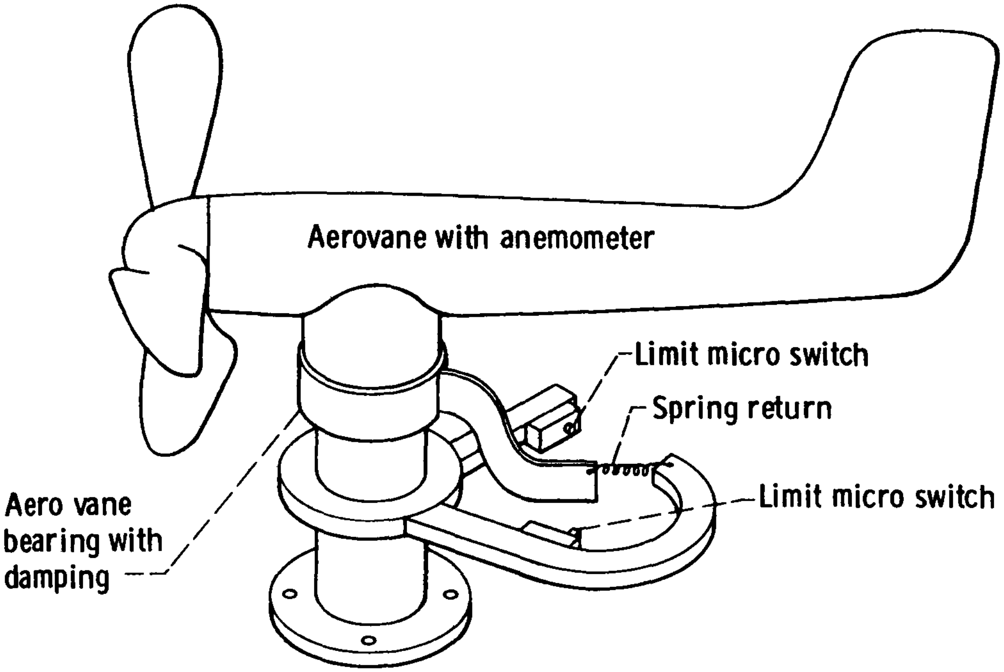


Figure 5-27. - Yaw error sensor schematic.

6.0 ASSEMBLY, TEST, TRANSPORTATION, INSTALLATION & CHECKOUT

Assembly and testing of equipment in the factory is less expensive than the same activity accomplished on site. The Mod-X tower and control room are designed to permit installation of all necessary equipment and completion of all but final checkout testing in the factory. The estimated cost for shop assembly and test of the second unit is $18 000, based on 18 man weeks of effort at $25 per hour. Included in this total are 8 man weeks for pod assembly, 2 man weeks for pod equipment testing, and 4 man weeks each for control room equipment assembly and test. The one hundredth unit cost of $4000 assumes an 85 percent learning curve on assembly operations and 35 man hours to accomplish the pod assembly and control room tests.

Shipping costs are based on Mod-0A experience and assume a factory-to-site distance of 1200 miles.

The on-site installation methods were given in depth study in an effort to simplify the procedures, reduce installation time, and reduce costs.

The installation begins by excavating and leveling the bottom of the holes into which the foundation vaults are to be placed. The exact positions of the holes will be carefully spotted. The shipping truck(s) with the vaults on board will be backed up to each hole and each vault will be lifted off the truck with a small crane and carefully placed into position in the bottom of the hole. Then the vault and the hole around the outside of the vault will be backfilled carefully to insure that the vaults are not shifted from their position.

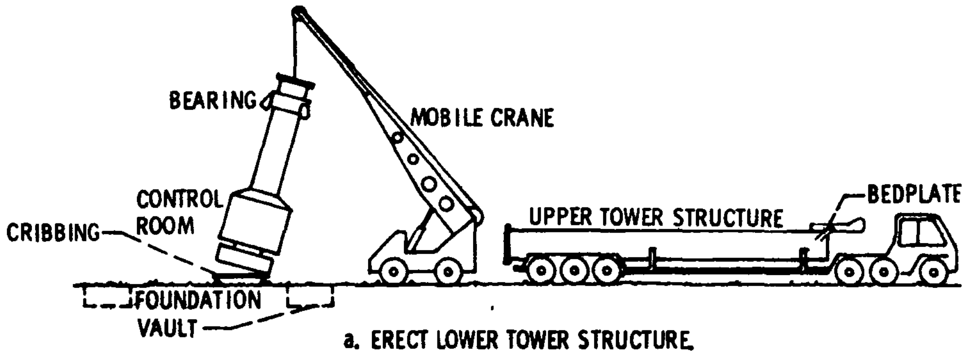
The second stage will be the installation of the lower sections of the tower. This is depicted in figure 6-1(a). Two trucks deliver the tower sections to the site. The lower section is set up on cribbing with a small crane. Each of the tripod legs and the tie members are lifted and bolted into place (figs. 6-1(b) and 6-2). The cribbing is then removed.

The third step is the installation of the upper section of the tower and bedplate. The crane hoists the lower end of the section from the truck to the top of the tripod while the upper end of the section rests on the truck. The raised end of the section is pinned to the top of the tripod. Then gin poles and a winch are set up as shown in figure 6-1(c) and the upper section is slowly raised into place and bolted to the tripod top.

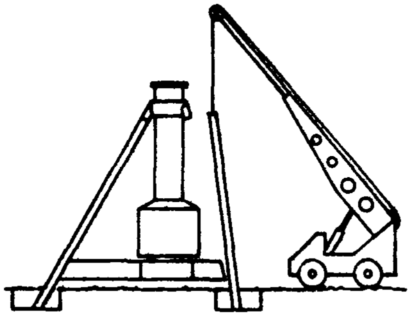
The fourth step is the installation of the pod atop the tower. This is depicted in figure 6-3. The entire pod minus the blades is brought to the site preassembled and checked out. The blades are installed onto the pod while it is still on the truck. The truck is positioned near the tower base. A spreader bar is connected by a pivot joint to the tower on one end and rigidly to the pod on the other. The spreader bar is necessary to keep the blades clear of the tripod legs during the hoisting of the pod. The bedplate on the tower is tipped up 90° and latched in the vertical position. The cable and winch are placed into position, and the cable end is attached to the pod. The pod is hoisted off the truck to a position half-way up the tower (fig. 6-3(a)) and the spreader bar is removed. The pod is then slowly raised to the top of the tower (figs. 6-2(b) and (c)) and secured to the bedplate. The bedplate is then rotated to a horizontal position and fastened to the tower. Finally the cable and winch are removed from the tower.

The final steps of the field installation are the connections of the various electrical, mechanical, and hydraulic interfaces located between the pod assembly and the top of the tower, and between the tripod and the lower end of the main section of the tower; and the final check out prior to startup.

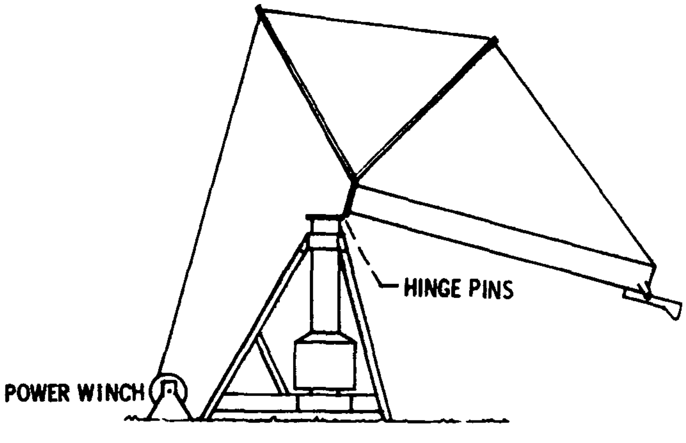
Total installation cost is estimated to be $4500 for both the 2nd and 100th units. This estimate is based on a 4-man crew for 1 day for installation of the blades on the pod and of the pod on the tower ($675); rental of a small crane for 1 day ($500); winch rental ($500); and a 4-man crew for 1 day for final hook-up and checkout of all hydraulic, electrical, and electronic equipment ($675). In addition, the prime contractor will be required to provide a project manager to direct the installation activity and demonstrate operation of the machine to user utility personnel. The project manager's expenses are estimated at $40 per hour for 40 hours plus $50 per day living expenses for 5 days plus a $300 travel allowance. Demonstration of proper machine operation is the only on-site checkout deemed necessary.



a. ERECT LOWER TOWER STRUCTURE.



b. ASSEMBLE TRUSS MEMBERS.



c. ERECT UPPER TOWER STRUCTURE.

Figure 6-1. - Tower assembly schematic.

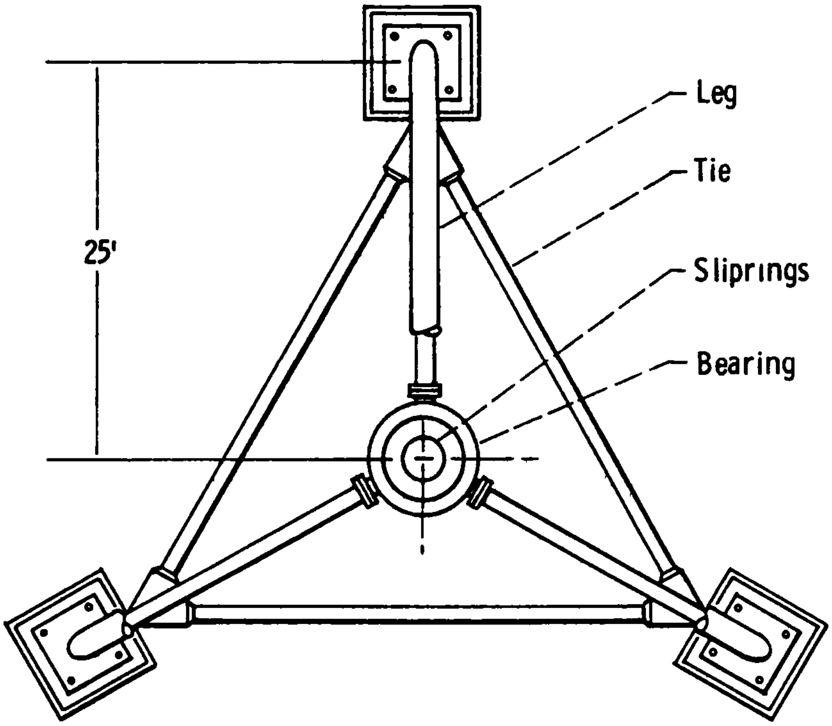
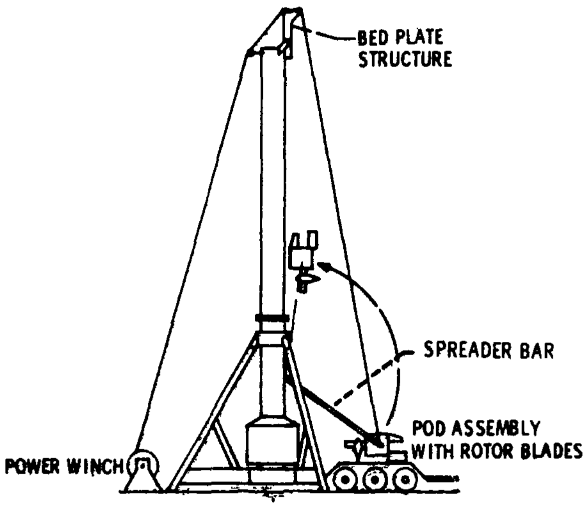
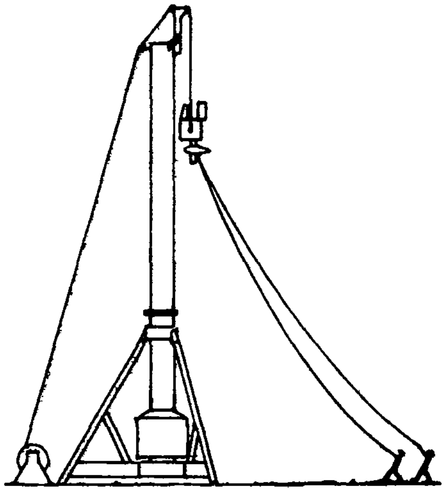


Figure 6-2. - Lower tower support structure.



a. REMOVE FROM TRAILER & HOIST.



b. HOIST & ATTACH POD & BLADES TO BEDPLATE.

c. ROTATE ASSEMBLY AND SECURE TO TOWER.

Figure 6-3. - Pod installation concept.

7.0 MOD-X ENERGY COSTS

Wind turbine generators (WTG) must yield sufficient revenue to meet all of the costs associated with the required capital investment and operating and maintenance expenses. This required revenue may be expressed in terms of the cost of electricity (COE) in cents/kWh generated by the wind turbine. The COE of the WTG must be less than the COE associated with not having the WTG if the WTG is to be economically viable. When the WTG operates it will save fuel, otherwise consumed in the utility system. It may also reduce the amount of required installed capacity of conventional units - depending on the utility generation mix, load profile and wind statistics. The Mod-X is designed with the goal of being competitive with conventionally fueled systems. While the baseline design does not meet the original target of 1 to 2 cents/kWh, it is shown in this chapter that the estimated COE is economical in utility applications where fuel costs exceed 2.30 cents/kWh. It is also shown that a significant portion of this country's utility companies are currently experiencing fuel costs above 2.30 cents/kWh.

In this assessment the WTG will be evaluated only as a fuel saver and the estimated COE of the Mod-X will be compared with the estimated savings of reduced fuel consumption. Some of the factors influencing COE include

1. Wind availability and profile at the site.
2. Machine characteristics such as rated power, efficiency, and machine downtime.
3. The capital cost of the installed WTG. Estimated component and installed system costs were addressed in previous chapters.
4. Annual operation and maintenance expenses. These expenses are estimated at $4000 per year in 1978 dollars.
5. The cost of money to the utility.

7.1 Utility Methodology to Calculate COE

The uniform revenue required per kilowatt-hour of electricity produced by the wind turbine may be expressed as follows.

$$\text{COE (cents/kWh)} = \frac{\text{(Capital cost, \$)(Fixed charge rate, \%)}}{\text{(Annual energy, kWh)}}$$

$$+ \frac{\text{(Annual O\&M costs, \$)(Levelizing factor) 100}}{\text{(Annual energy, kWh)}}$$

The estimates of capital cost and annual O&M cost were discussed in section 3. The other elements of this relationship will be discussed in the following paragraphs.

7.1.1 Annual Energy Production

The annual energy produced by the WTG depends upon the wind characteristics of the site, the power output of the machine at each wind speed and the WTG downtime.

Figure 7-1 illustrates a wind speed duration curve for a site with an annual average wind speed of 14 mph measured at a height of 30 feet above ground level. The curve indicates the hours per year for which the wind speed at 30 feet height is greater than some wind speed, W. The shape of the curve will vary for different sites. This curve is representative, however.

The electric power (kW) available from the WTG is a function of the cube of wind speed (V) at the hub height, generator power rating (P_R), system efficiency (η), rotor efficiency (C_p) and the square of rotor diameter (D). The power is given by a relationship

$$\text{Power} = KV^3\eta C_p D^2$$

The proportionality constant (K) accounts for conversion of units to kW and includes the effect of air density. The WTG power is computed for wind speeds between cut-in and cut-out. The profile of generator output of the Mod-X with wind speed is shown in figure 7-2. Wind speed is shown on the abscissa measured at the reference 30 foot height and at hub height. The power level is computed using the value of wind speed at the hub height (100 ft for the Mod-X) as the representative speed across the rotor disk. The relationship between wind speed at different heights is discussed in reference 4. As seen in figure 7-2 the power increases with wind speed until rated generator power (P_R) is reached. At this point the rotor blades are pitched to reduce rotor torque sufficiently to maintain the rated power. At cut-out wind speed the blades are completely feathered and the machine shutdown.

The annual output is obtained by summing the power (kW indicated in fig. 7-2) at each wind speed and the time spent at that speed. The time can be derived from figure 7-1. An availability factor of 0.90 is multiplied times this sum to account for estimated downtime required for service or repair. The annual energy output of the Mod-X is shown as a function of site mean wind speed in figure 7-3. At the 14 mph site, the annual Mod-X output is 875 000 kWh. The selection of a site with a mean wind speed of 12 or 16 mph would decrease or increase the annual energy output by about 20 percent, respectively.

7.1.2 Fixed Charge Rate

Fixed charges are those revenue requirements associated with the capital investment. They include return to investors, depreciation, taxes, etc. Expenses, on the other hand, are revenue requirements which result from the use of the equipment, such as fuel costs, operations and maintenance costs. Revenue requirements will be different during each year of the life of the investment. For comparative purposes, necessary for weighing alternatives, the varying revenue requirements are "levelized" to a single value, the sum of levelized fixed charge and levelized expenses. This is consistent with the relationship, shown earlier, for COE.

The fixed charge rate used in this assessment is 15 percent. This was chosen as the appropriate rate for private utility planning with near term technologies. Appendix B addresses the parameters affecting this rate and relies on the guidelines of reference 5.

7.1.3 Levelizing Factor and O&M Expenses

Expenses such as operations and maintenance costs are expected to increase at least at the rate of general inflation. Thus, in terms of 1978 dollars, the revenue required for O&M is a variable stream. To determine the COE required for energy generated by the WTG, these O&M costs must be levelized before summing with the levelized fixed charges.

The annual cost associated with an expense which increases only at the inflation rate of 6 percent (no real escalation of cost) is shown over the 30 year plant life in table 7-1. This table also illustrates the concept of levelizing. If the cost at the end of year 0 (or start of year 1) is 1.00 ¢/kWh and payments are made at the end of each year 1 through 30, then the payments of 1.06 ¢/kWh through 5.74 ¢/kWh are the actual required revenues. The levelized cost of 1.886 ¢/kWh represents a stream of revenues which has the same present worth for a discount rate (cost of money) of 10 percent as the nonlevelized stream. The two revenue streams may be viewed as equivalent annuities payable from an initial principle of 17.778 at an interest rate of 10 percent (the discount rate or cost of capital) Additional discussion of this concept from the utility viewpoint is found in reference 5.

7.2 Mod-X Cost of Electricity

For the baseline Mod-X at a 14 mph mean wind speed site, the levelized cost of electricity is computed as 4.34 ¢/kWh using the COE relationship of section 7.1. Values of the elements are as follows

Fixed charge rate	15 percent
Capital cost	\$202 810
Levelizing factor	1.886
Annual O&M cost	\$4 000
Annual energy	875 000 kWh

The competitiveness of this estimated COE to the estimated breakeven cost of a fuel saver is addressed in the following section.

7.3 Economics of the Mod-X WTG in Utility Applications

Wind turbines in utility applications save fuel and may be counted as capacity additions similar to the way in which conventional units are considered. In the present assessment Mod-X competitiveness as a fuel saver is addressed.

The levelized revenue requirement or COE of the Mod-X at a 14 mph mean wind speed site is estimated to be 4.34 ¢/kWh. To break-even as a fuel saver the Mod-X must then displace fuel with a levelized cost of 4.34 ¢/kWh. If the cost of fuel in 1978 is assumed to increase for 30 years only at the general inflation rate, the same levelizing factor of 1.886, used to levelize O&M expenses, must be applied to the 1978 cost to obtain the levelized fuel cost. The breakeven 1978 average cost of fuel for the Mod-X is then 2 30 ¢/kWh (4.34 - 1.886).

The estimated weighted cost of fossil fuel for 310 utilities in 1978 is illustrated in figure 7-4 as a cumulative distribution. These estimates are based on Federal Power Commission data collected from utilities (refs. 6 and 7) for 1976 and 1977. The utilities included account for nearly 98 percent of all U.S. fossil generation. The 1977 fuel prices were increased by 6 percent to provide 1978 dollar estimates.

The use of the average cost of fuels is conservative since no credit is taken for possible reductions in conventional generating capacity. Most utilities use economic dispatch and the wind turbine, when generating power, would tend to displace or save the highest cost fuels. As a utility adds more wind turbines, the subsequent machines would tend to displace cheaper fuels. Assessment of wind turbine generators on the basis of the average cost of fossil fuel is a reasonable assumption in this situation. The assumption that fuel prices increase only at the general inflation rate may also be considered conservative with the suggestion often made that fuel prices are expected to escalate at least 2 percent faster than general inflation, i. e., a real price growth of 2 percent per year.

Figure 7-4 indicates that about one-third of the total number of utilities might find this COE economically attractive as a fuel saver alone without consideration of real fuel price escalation. This, however, would require sites with mean annual wind speeds of 14 mph. These may not be available to all the utilities. Figure 7-4 indicates where the Mod-X COE would fall on the estimated fuel price curve for sites with mean annual wind speeds of 12, 14, and 18 mph.

TABLE 7-1. - LEVELIZATION OF COST

(6 percent inflation, 10 percent cost of money)

End of year	Annual cost, ¢/kWh	Levelized cost, ¢/kWh
0	1.00	1.886
1	1.06	
2	1.12	
3	1.19	
4	1.26	
5	1.34	
6	1.42	
7	1.50	
8	1.59	
9	1.69	
10	1.79	
11	1.90	
12	2.01	
13	2.13	
14	2.26	
15	2.40	
16	2.54	
17	2.69	
18	2.85	
19	3.03	
20	3.21	
21	3.40	
22	3.60	
23	3.82	
24	4.05	
25	4.29	
26	4.55	
27	4.82	
28	5.11	
29	5.42	
30	5.74	

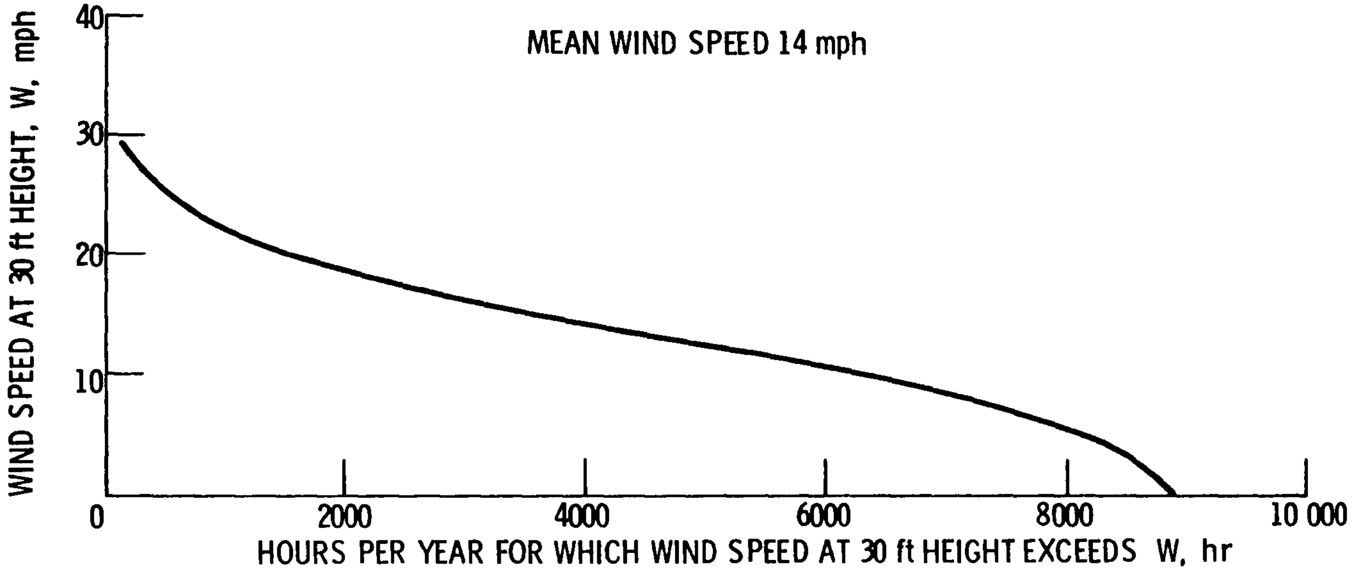


Figure 7-1. - Wind speed duration.

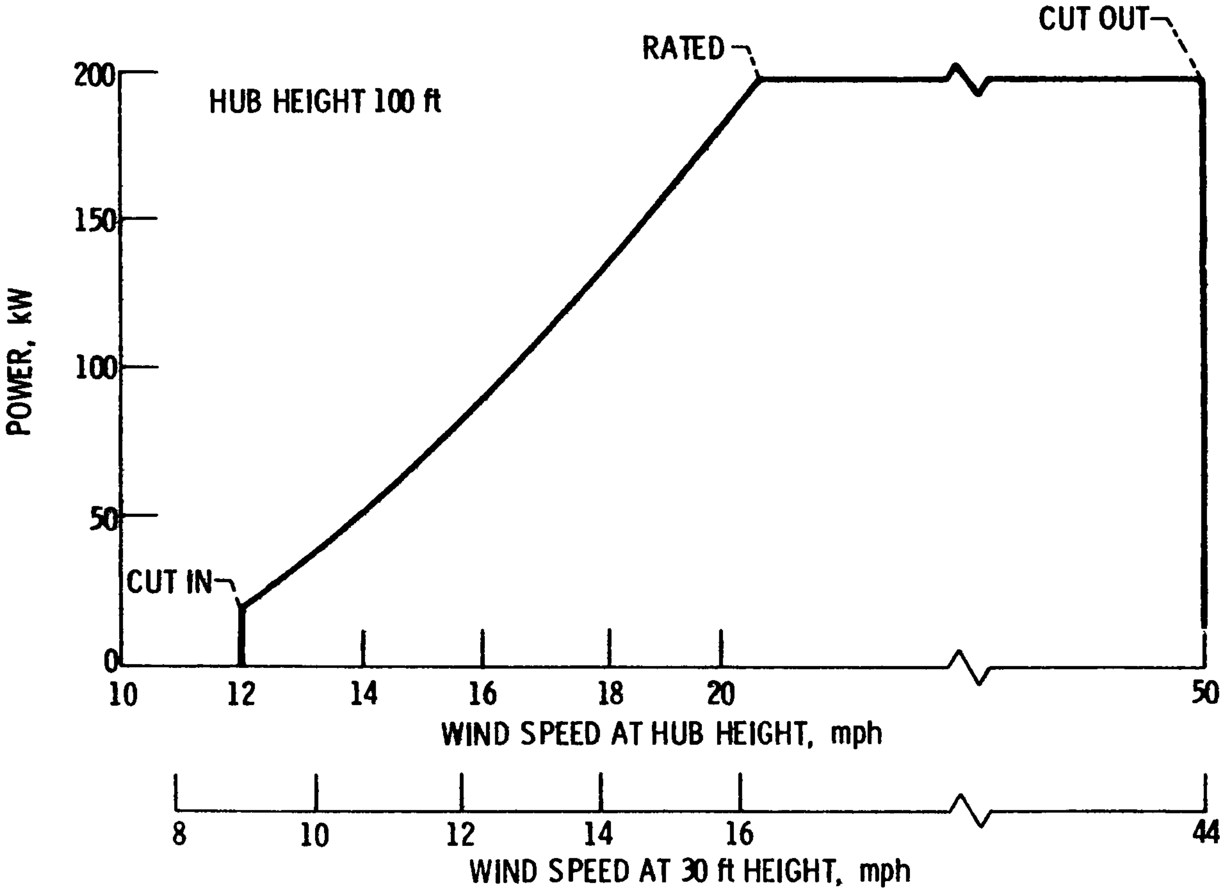


Figure 7-2. - Mod-X power output vs wind speed.

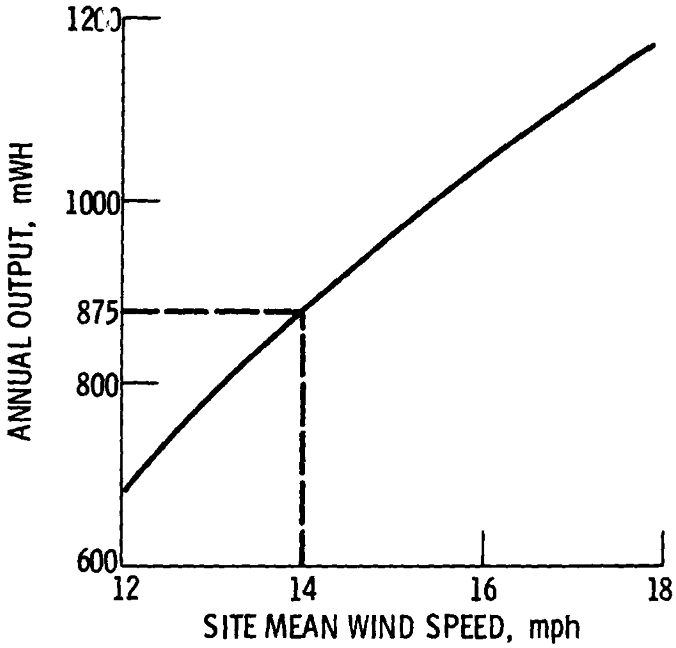


Figure 7-3. - Baseline Mod-X annual energy output.

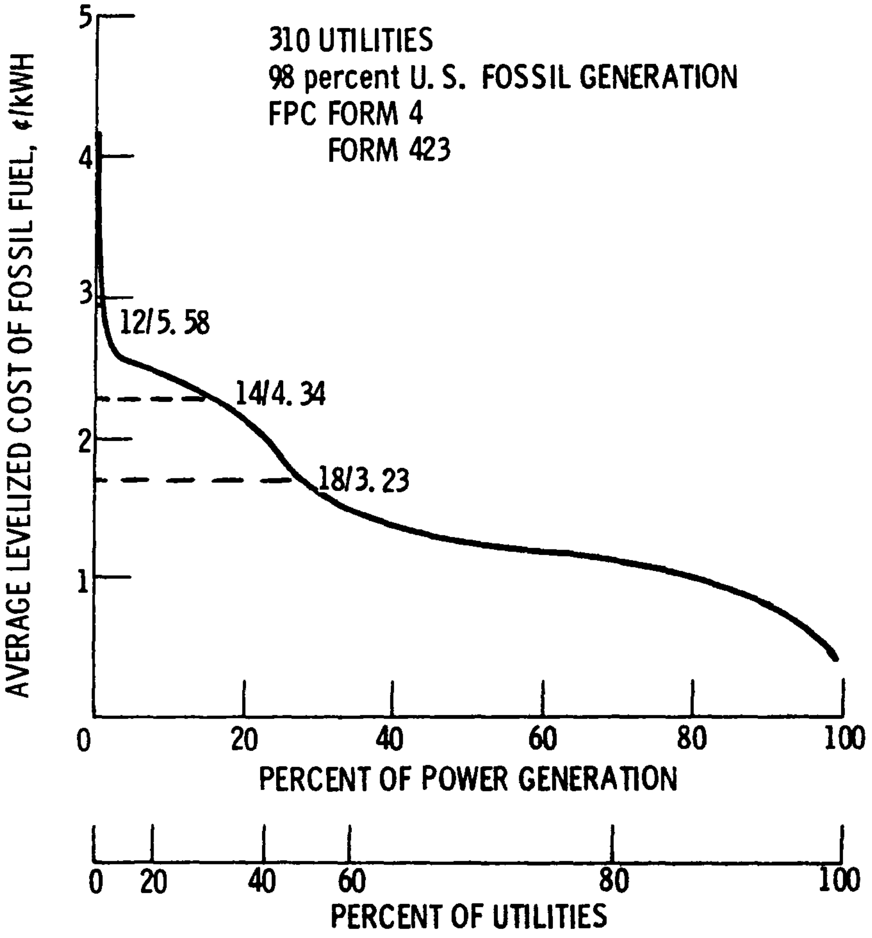


Figure 7-4. - Baseline Mod-X as utility fuel saver.

8.0 OPEN ITEMS WITH DECISION CRITERIA

The Mod-X concept development is somewhat incomplete in that several components and subsystems could not be defined without going into a more detailed design. Each of these will now be discussed.

8.1 Blades

8.1.1 Blade Geometry

The blade geometry, namely the solidity, twist, taper, and airfoil section, has an important effect on the yearly energy production which, as was pointed out earlier, should be maximized. Blade geometry also affects the starting characteristics and the blade fabrication costs. Some methods of blade fabrication can be used to economically build blades with twist and taper, and other methods cannot.

The shape of the most cost effective blades will be determined by their contribution to the energy costs. And until more definitive data becomes available on blade fabrication costs, the blade geometry will be an open question.

8.1.2 Blade Material

The material to be used for blades is very closely tied to the fabrication method to be used. The most important effect of blade weight will be the cost on a dollars per pound basis. Another direct impact of the blade weight will be on the weight and cost of the gearbox because an increase in blade weight will increase the gravity moment on the input low speed shaft. This in turn will increase the weight and cost of the input shaft, shaft bearing, and the gearbox casing. A third effect of blade weight will be on the hub design and weight, and on the polar moment of inertia of the rotor about the vertical axis of the tower which affects the yaw drive if one is used.

Thus, the effect of blade weight is several fold and cannot be assessed simply on the basis of blade cost. The impact on the gearbox, hub and yaw drive must also be determined.

8.1.3 Percent of Pitchable Span

The length of the pitchable blade span to be used is one of the most difficult of the open questions to be settled. This is because the pitchable length has a sizeable impact on the designs of (1) the blade structure, (2) the pitch change system, (3) the tower and foundation, and (4) the cyclic in-plane blade loads which in turn affect the teetering angle. Clearly, the issue of the optimum pitchable blade length can only be settled by a more detailed design and trade study which is relegated to the preliminary design phase.

8. 2 Teetered Hub

The teetered hub design is open at this stage for several reasons. The bearing design is difficult because of the small motions and the high loads involved. Except for the Hutter machine, there is no operating experience to draw from. The teetered hub design will therefore be very nearly an untested one. The hub design will also depend somewhat on the length of pitchable blade section.

8. 3 Yaw Bearing Concept

The Mod-X tower design is innovative in that the main tower and pod assembly rotate together. The rotating structure is supported on a bearing which also carries sizeable transverse load. This bearing is a critical item in that its initial cost and maintenance requirements will have an important impact on the entire basic Mod-X concept of low cost and simplicity of operation. Therefore, the design of this bearing will require considerable attention during the preliminary design phase.

Another unknown item is the need for damping of the yaw motion. The Mod-0 free yaw tests have shown that some damping (in the form of friction from the yaw brakes) is desirable to prevent high yaw rates. This experience suggests that the Mod-X yaw bearing need not be a low friction bearing. Also, the large mass polar moment of inertia of the tower and pod assembly may serve to reduce the cyclic yaw motions sufficiently to eliminate the need for any additional frictional drag. This question of how much yaw damping to include in the yaw bearing design will likewise have to wait until preliminary design.

9.0 SUMMARY AND CONCLUSIONS

A conceptual design of an advanced 200 kW wind turbine has been completed. This design, designated Mod-X, incorporates a number of significant improvements over previous machine designs. The results demonstrate the potential for significant reductions in the cost and weight of large WTG's as a result of innovative design concepts and quantity production techniques.

The estimated levelized cost of energy (COE) for the Mod-X conceptual machine is 4.34 cents per kilowatt hour for a site with an average wind speed of 14 mph. This COE is considerably higher than the cost goal of 1 to 2 cents per kilowatt hour. Additional design innovations or technological breakthroughs will be required if the COE goal is to be achieved or closely approached. It should be recognized, however, that some market potential exists, even at today's fuel prices, for a machine capable of producing electricity at 4 to 5 cents per kilowatt hour.

APPENDIX A

DESCRIPTION OF VARIOUS WTG DESIGNS

Large wind turbine programs currently underway include the Mod-0, Mod-0A, Mod-1, and Mod-2 machines. Major features of each of these designs are presented here for reference. In addition, since some of the concepts investigated in the Mod-X conceptual design study are derived from features of the Mod-1A concept and the German Hutter wind turbine design, these machines are also discussed.

The Mod-0 100 kW wind turbine has been operated as a test bed since 1975. The machine is located at the NASA Plum Brook facility near Sandusky, Ohio. A broad range of tests have been conducted for the purpose of (1) acquiring data on the behavior of large wind turbines under a wide range of wind and climatic conditions, (2) evaluating various subsystem concepts, and (3) validating analysis methods. The Mod-0 tests have contributed greatly to our understanding of the dynamic behavior of wind turbines, and to our ability to accurately analyze these machines. A system schematic of the Mod-0 design is shown in figure A-1.

The first Mod-0A 200 kW wind turbine was installed on the Clayton NM network in 1977 and has demonstrated that large wind turbines can run unattended in parallel with diesel-generators as a supplemental source of power. The Mod-0A design is nearly identical to the Mod-0 and, like the Mod-0, it was conservatively designed. As a result, both are heavy and expensive machines. Additional Mod-0A machines are or will be located in Culebra, Puerto Rico, Block Island, Rhode Island; and Oahu, Hawaii.

The Mod-1 2000 kW wind turbine is the first Federally funded machine that was completely designed by a private company (General Electric Co., Philadelphia, Pa.) This machine, which is presently being fabricated, was also conservatively designed. The Mod-1 configuration is basically the same as the Mod-0 and Mod-0A configuration.

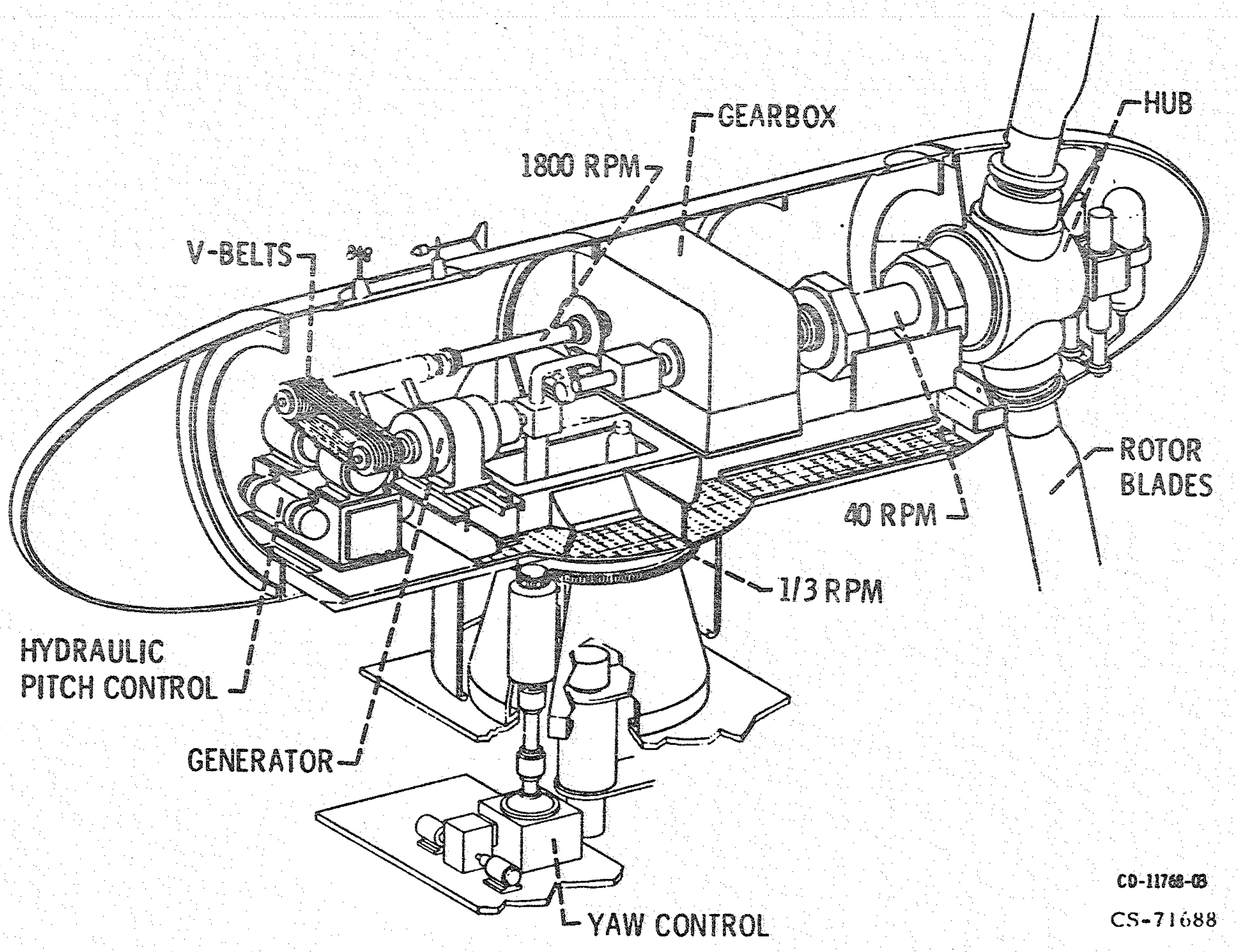
The Mod-2 project was started in Summer of 1977. The objective of this project was to design, and build a wind turbine with a minimum rotor diameter of 300 feet that has the potential for producing 2 to 4 ¢/kWh electrical energy at a 14 mph site. The contractor, Boeing Engineering and Construction Company, Seattle, Washington was requested to evaluate many different subsystems and total system concepts in detail in their effort to identify the configuration with the greatest potential for meeting the energy cost goal. The results of the conceptual design phase point to load alleviation and structural flexibility as a way to reduce the weight and thus the costs of megawatt size machines.

A schematic comparison of the Mod-0, -0A, -1, and -2 machines is shown in figure A-2.

After the Mod-1 design was complete, GE was asked to use the experience and knowledge they had acquired to develop a conceptual design of a lighter weight machine of the same power rating. The result was the Mod-1A wind turbine concept which was at least 50 percent lighter and less expensive than the Mod-1. The important conclusions of this study were that lower costs will be achieved with reduced machine weights, reduced number of components, more compactness of the machinery atop the tower, and load alleviation features such as a teetered hub.

Significant features of the Mod-1A machine are shown in figure A-3. The tower is a tapered steel shell design. The rotor is supported directly on the low speed shaft of the gearbox. The generator is also supported off the gearbox, at the high speed shaft side. The nacelle and bedplate are eliminated. The Mod-1A also incorporates a teetered hub and can operate as either an upwind or downwind machine. The blades are a partial span tip control design. The yaw bearing structure is integral with the gearbox case.

Major features of Hutter 100 kW wind turbine are presented schematically in figure A-4. This machine was designed and built by Dr. U. Hutter in West Germany in the late 1950's. Its significant features include a downwind 112 foot rotor, two fiberglass blades mounted on a teetered hub, a guyed cylindrical tower, and a weatherproof gearbox and generator mounted on a bedplate without a nacelle covering.



CD-11768-03

CS-71688

Figure A-1. - Mod-0 WTG schematic.

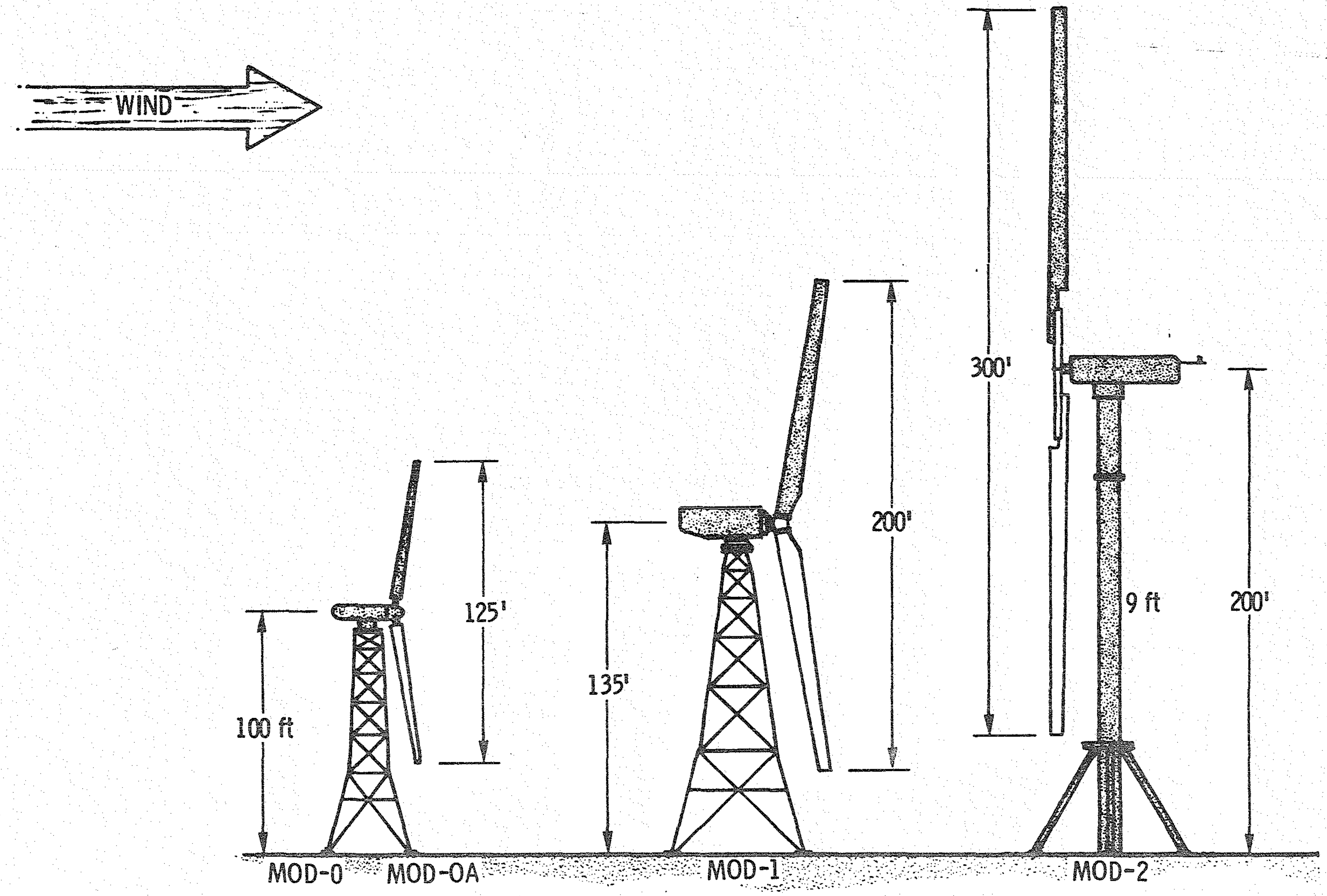


Figure A-2. - Comparison of Mod-0, -0A, -1, and -2 designs.

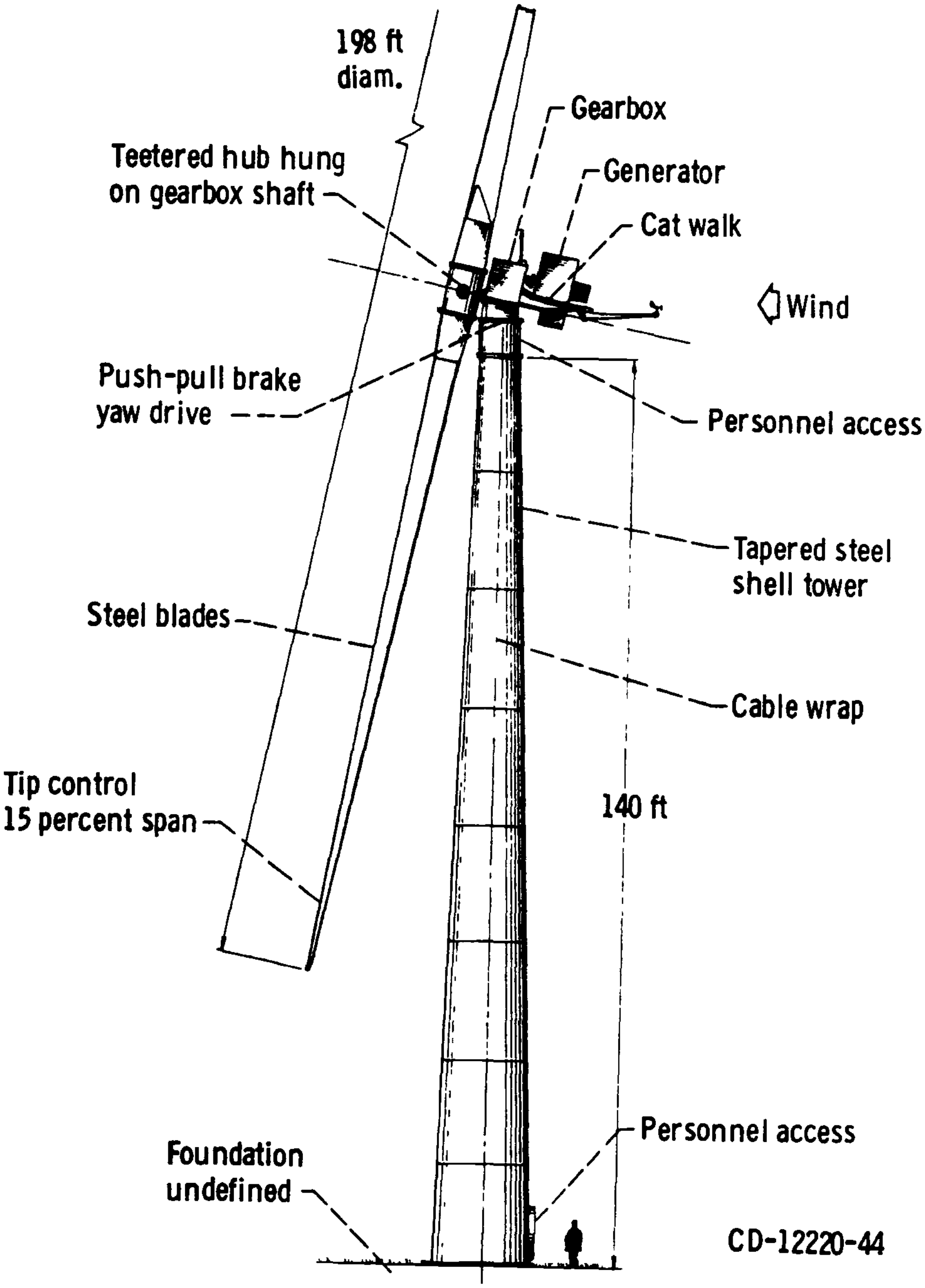


Figure A-3. - Mod-1A 2000 kW wind turbine concept.

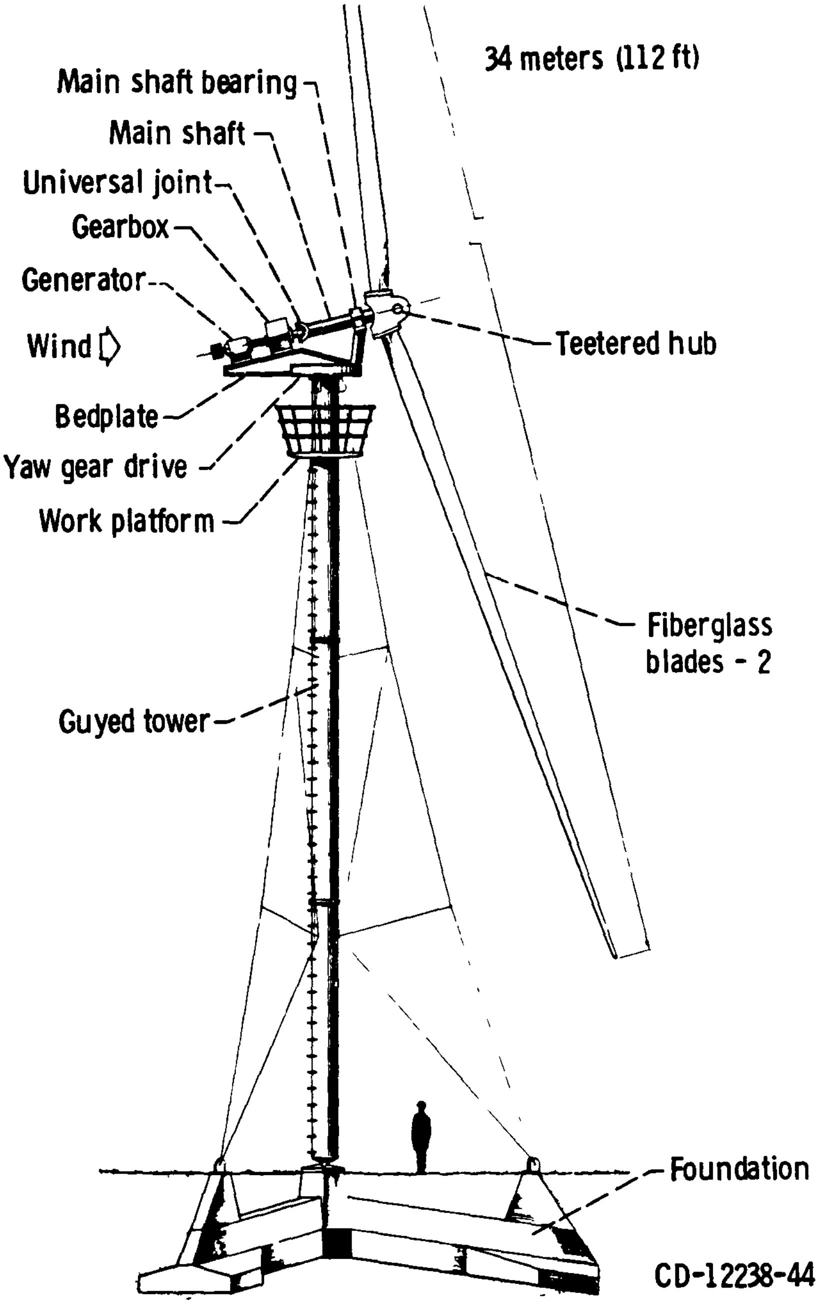


Figure A-4. - Hutter 100 kW wind turbine.

APPENDIX B

FIXED CHARGE RATE CONSIDERATIONS

The ratio of the levelized fixed charges to the initial capital investment is the "fixed charge rate." It is a function of numerous factors including the design life of the unit, the assumed general inflation rate, the debt/equity ratio of the particular utility and other financial parameters. The Electric Power Research Institute (EPRI) recommends (ref. 5) that in considering new technologies that have a 30-year life (the design life of large wind turbines), a fixed charge rate of 15 percent be used where accelerated depreciation and investment tax credit are allowed and 18 percent be used where no allowance for these tax preferences is made. These values are applicable for investor-owned utilities. EPRI points out that although accelerated depreciation and investment tax credit are often neglected in an analysis of investments planned for far in the future because of their history of frequent changes, it is appropriate to include them in studies of near-term technologies. Since our interest is in the near-term cost competitiveness of wind turbines, a 15 percent fixed charge rate on capital has been used. The results of course, can be readily adjusted for other fixed charge rate assumptions.

The following values are recommended by EPRI for the base parameters used in financial calculations. They imply a 6 percent rate of inflation.

Debt ratio	50 percent
Debt cost	8 percent
Preferred stock ratio	15 percent
Preferred stock cost	8.5 percent
Common stock ratio	35 percent
Common stock cost	15.5 percent
Weighted cost of capital	10 percent
Federal and State Income Tax Rate	50 percent
Property taxes and insurance	2 percent
Investment tax credit	0 to 10 percent

EPRI believes these parameters are consistent with each other and reasonably represent current conditions in the utility industry as a whole.

Based on a 30-year book life and a 20-year tax life and using flow-through accounting, EPRI computes the fixed charge rate as follows

Total return (weighted cost of capital)	10.00 percent
Book depreciation (sinking fund)	0.61
Allowance for retirement dispersion	0.56
Basic Income Tax	4.70
Accelerated depreciation factor	(2.47)
Investment tax credit at 4 percent	(0.77)
Property taxes, insurance, etc.	2.00
Fixed charge rate including tax Preference Allowances	14.63 percent

The total return plus book depreciation equals the capital recovery factor for a life of 30 years and 10 percent interest, namely, 10.61 percent.

It should be noted that the weighted cost of capital computed above (10 percent) is a before-tax weighted cost of capital. Some utilities use an after-tax weighted cost of capital when computing fixed charge rate. The after-tax weighted cost of capital corresponding to the financial parameters assumed above is 8 percent and the fixed charge rate would be 14.16 percent instead of 14.63 percent. The difference is small and the assumed 15 percent for fixed charge rate may be taken to apply to either method.

The accelerated depreciation factor assumes the sum-of-the-years-digits method. According to EPRI, both the accelerated depreciation and investment tax credit at 4 percent are allowable under current tax laws. Investment tax credits higher than 4 percent are currently allowable but are only temporary by law (expiring by the early 80's) and EPRI did not include these to be conservative.

It should be noted that an expectation of inflation is included in the assumption of the cost of any form of capital. An assumed value of 10 percent for the before-tax weighted cost of capital is consistent with a 6 percent inflation rate and is typical of values used in current studies.

REFERENCES

1. Huetter, U.: Operating Experience Obtained with a 100-kW Wind Power Plant. NASA-TTF 15,068, 1973.
2. Juul, J.: Design of Wind Power Plants in Denmark. Proc. of United Nations Conference on New Sources of Energy. Vol. 7 - Wind Power. United Nations, 1963-64, pp. 229-240.
3. Whitehead, G T., and Gnecco, A. J Microprocessor Control of a Wind Turbine Generator. NASA TM-79021
4. Justus, C. G.; Hargraves, W. R , and Mikhail, A.. Reference Wind Speed Distributions and Height Profiles for Wind Turbine Design and Performance Evaluation Applications. ORO/5108-76/4, Dept. of Energy, 1976.
5. Technical Assessment Guide. EPRI PS-866-SR, Electric Power Research Institute, 1978.
6. Price of Fossil Fuel delivered to Utilities, 1976. Data filed with the Federal Power Commission on FPC Form 423, Monthly Report of Cost and Quality of Fuels For Electric Plants.
7. Generation and Fuel Consumption of Utility Generation Units. Data filed with the Federal Power Commission on FPC Form 4, Summary of Monthly Power Plant Reports. (Available from Federal Power Comm. on Computerized Tape.)
8. Coty, U. A.: Wind Energy Mission Analysis, SAN/1075-1/1, Dept. of Energy, 1976.
9. Wind Energy Mission Analysis. COO/2578-1/2, Dept. of Energy, 1977.

End of Document