THE BOEING MOD-2 -

WIND TUNNEL SYSTEM RATED AT 2.5 MW

Richard R. Douglas
Boeing Engineering and Construction Company
Seattle, Washington 98124

INTRODUCTION

The MOD-2 project is an approximate 36 month program for the development, design, fabrication, installation, and check-out of a wind turbine system (WTS) optimized for commercial production of power into a utility grid. Similar to the MOD-0 and MOD-1 programs, MOD-2 is managed by NASA-LeRC. Contrary to those programs, the primary objective of the end hardware is for direct and efficient commercial application, rather than for Research and Development. The program has been structured to achieve this desired commercial objective by a substantial concept selection effort, comparatively few firm requirements imposed on the contractor, and encouragement of commercial practice application. This paper provides a summary description of MOD-2 development and of the resulting system hardware.

PRIMARY SPECIFICATIONS & REQUIREMENTS

The major firm requirements imposed on the contractor were as follows:

- 14 mph average wind speed at 30 foot altitude.
- Horizontal axis.
- Minimum rotor diameter of 300 feet.
- 30 year service life.
- Unattended remote site operation.

Essentially all other requirements were subsequently agreed to by NASA and the contractor as a result of requirement sensitivity studies generated during the program concept study phase. A list of the major requirements thus developed are shown in Table I.

PRIMARY DESIGN CHARACTERISTICS

Four significant changes from the MOD-0 and MOD-1 wind turbine system design characteristics were incorporated into the original MOD-2 proposal:

- Use of a soft shell type tower.
- An epicyclic gear box.
- A quill shaft to attenuate 2/rev. torque and power oscillations.
- A rotor designed primarily to commercial steel fabrication standards.

Through the many months of detailed study since the proposal, these four features are still retained and account for a major portion of any cost-of-electricity advantage that MOD-2 may have compared to competitive systems. During the concept study phase, decisions were made to change from a combination welded and bonded rotor to an all-steel rotor, to use a teetered in place of a fixed hub rotor, to use tip control rather than full span control, to orient the rotor upwind rather than downwind, and to change from a ground located computer with nacelle located multiplexer to a microprocessor system located in the nacelle. Each of these changes resulted in a favorable decrease in cost-of-electricity.

The major characteristics and general arrangement of the current MOD-2 WTS configuration are shown in Figure 1. Illustrations of all other major components of the system are provided by Figures 2 through 12. Weight status is shown in Figure 13. MOD-2 is a horizontal axis machine with a 300 foot diameter, tip control, teetered, upwind rotor. The rotor axis is located 200 feet above ground level. The all steel rotor is supported by the low speed shaft through an elastomeric bearing that permits teetering. Torsion from the rotor is transmitted by an attenuating quill shaft to the step up planetary gear box, which in turn drives a 2500 KW synchronous generator at 1800 rpm. Teeter and rotor brakes are used primarily to eliminate motion when the wind turbine is not operating. All of the drive train, the generator, the generator accessory unit, the electronic control system, the pitch and yaw hydraulic system, and other support equipment are housed in the nacelle. The nacelle itself is kept oriented into the wind by a single hydraulic motor driving through a planetary reduction gear. The tower is a shell type with a conical base and contains an elevator, an emergency ladder, and control and electrical system components in the base. The foundation is conventional reinforced concrete but has a unique inverted mushroom configuration that permits use of earth fill to reduce the concrete required.

OPERATING CHARACTERISTICS

The MOD-2 system is designed to operate unattended into a utility grid whose power substantially exceeds the 2.5 megawatt output of MOD-2. The system is designed to cut-in at a wind speed of 14 mph, to cut-out at 45 mph, and to generate full rated power (2.5 megawatts) at 27.5 mph. (See Figure 14) While the MOD-2 system was optimized for a site with an annual mean wind speed of 14 mph at 30 foot altitude, Figure 15 illustrates that it operates with little penalty at sites with a wide band of wind speeds.

Rotor and system efficiencies are best portrayed by the rotor and system coefficient versus wind speed chart shown in Figure 16. The rotor and power coefficients are that portion of the wind's kinetic energy passing through the rotor disk that is converted into torque and electrical energy, respectively. The difference between the two represents the losses in the turbine subsystems.

COST OF ELECTRICITY

Cost-of-electricity assessment for MOD-2 is based on cost of the 100th production unit. Fig. 17 illustrates the cost approach and Fig. 18 presents the cost groundrules and resulting costs. The cost-of-electricity is computed as follows:

$$\text{COE} = \frac{\text{IC} \times \text{FCR} + \text{AOM}}{\text{AEP}}$$

where IC = total WTS cost = \$1,720,000

FCR = annualized fixed charge rate = 18%

AOM = annual operation and maintenance = \$15,000

AEP = annual energy production = 9.75×10^6 kWh

COE = 3.3 ¢/kWh

PROGRAM APPROACH

During the Third Wind Energy Workshop in Sept., 1977, Jim Couch did a fine job of describing the MOD-2 planned design approach. Briefly, this consisted of a substantial conceptual design effort to select the most cost effective system concepts, a preliminary design effort to refine the design and a detail design phase to produce the final drawings. At this time, we are nearing completion of the detail design phase. In fact, numerous releases have already been made for long lead items such as the gear box, low speed shaft bearings, yaw bearings, etc. With the exception of some contract extensions during the concept and preliminary design phases to conduct additional studies desired by NASA-LeRC, the program has proceeded as planned. A summary of program events and future plans is illustrated on the schedule shown in Fig. 19.

MAJOR DESIGN FACTORS

Undoubtedly, the most important of all the design features on MOD-2 is the soft shell type tower concept. Fig. 20 illustrates a comparison between a soft shell type tower and a stiff truss type tower at the time of the original study. The basic difference between the soft tower and stiff tower is shown in Fig. 21, illustrating that the soft tower has a lower frequency than the rotor while a stiff tower has a higher frequency. Fig. 22 illustrates the precise relationship of the tower design. Note that it is designed by a combination of frequency, seismic, fatigue, and high wind factors. Not only does the soft tower weigh much less, the shell type construction is considerably cheaper to fabricate on a cost per pound basis. Direct tower cost savings are substantial. Of perhaps even more importance is the fact that rotor stiffness and weight are not serious restraints when using the soft tower, permitting the use of heavy but economical and reliable rotor designs.

Though time does not permit a detailed review of every MOD-2 feature, the following is a list and brief comment on those other features most responsible for achieving the relatively low MOD-2 cost-of-electricity:

Drive Train Quill Shaft - As illustrated in Figure 23, the on line shaft frequency of approximately .5 per revolution economically attenuates the two per rev. alternating torques that are particularly troublesome with a teetered-tip control rotor configuration.

Tip Control - A feature that substantially reduces rotor weight and cost with only minor compromises in power output, startup and shutdown control, and torque oscillation.

Teetered Hub - First looked at primarily as a means of reducing rotor fatigue, the major payoff of this feature is a reduction in weight and cost of the nacelle, low speed shaft, yaw system, and tower.

Compact Planetary Gear Box - Selection and development of this advanced design gear box has resulted in over 100,000# system weight saving, a much simplified nacelle installation, and direct cost saving.

Upwind Rotor - The upwind rotor configuration slightly reduced rotor fatigue and resulted in a 2 1/2% increase in annual power produced while adding negligible cost to the yaw system. Impact on the yaw system is minimized with the teetered rotor.

Nacelle Located Microprocessor - The change from a ground located computer with a multiplexer in the nacelle to a microprocessor located in the nacelle resulted in both direct cost savings and a substantial reduction in anticipated maintenance cost.

Gin Pole & Hoist Erection & Maintenance - Very large wind turbines can experience severe maintenance costs as well as loss of power produced when held up for the expensive and sometimes unavailable large cranes required for major component replacement or repair. The MOD-2 solution is to provide permanent gin pole, hoist, and guy line foundations at each site, permitting the use of a relatively inexpensive gin pole and hoists. A secondary fallout of this basic maintenance provision is a convenient and economical means of system erection.

MAJOR PROBLEMS

I have been asked to report on major problems. At this writing, I am happy to report that except for the everpresent problems of schedule and budget, we are aware of no serious technical problems. But don't misunderstand; we anticipate problems will arise in subsequent program stages. However, at this point, we would have to call them unk -unks.

CONCLUSIONS & RECOMMENDATIONS

After working on the MOD-2 program for nearly two years, one conclusion is evident: Wind Power has come of age. It not only promises to be more practical than any of the other so-called alternate energy sources, but it is actually competitive with today's energy sources in many geographical areas.

The intent of the MOD-2 program has been to incorporate all concepts that show reasonable promise and, to the extent program scope has permitted, the intent has been implemented. Additional study of such potential advanced features as a fixed pitch rotor can no doubt be justified. However, we see the largest system improvement potential in a component-by-component study effort, applying value engineering disciplines as well as seeking efficiency gains. As has been proven true on our commercial aircraft programs, these improvements can best be made utilizing experience gained from a sizeable number of commercially deployed units.

MOD-2 can and will be improved with time, just as fifty years from now the then current systems can and will be improved. But using today's technology, no concept changes show sufficient promise to warrant any further delay in production deployment of wind power. Let's get on with it!

REFERENCE

1. Couch, J. P., MOD-2 Wind Generator Program, Third Wind Energy Workshop, Sept., 1977.

DISCUSSION

Q. How many planets do you have in the first stage of the gearbox?

A. Actually we are developing two gearboxes for Mod-2. The primary gearbox has eight planets in the first stage; the alternate gearbox has six.

Q. In your discussion of the tower loads, vibrations seemed to be linked to rotor dynamics. Have you determined what effect isotropic turbulence or even micro turbulence might have on tower loads? Also what limiting turbulent conditions did you consider?

A. Oscillations due to both vortex shedding and turbulence have been considered in the Mod-2 tower loads using coupled modes analysis. The resulting response to vortex shedding was small. Tower loads due to the maximum statistical isotropic turbulence acting on both the tower and the rotor was also analyzed. We found that the maximum turbulence induced loads were less critical than steady extreme wind loads.

Q. In your cost of energy equation, how do you handle the effect of inflation over the 30-year life?

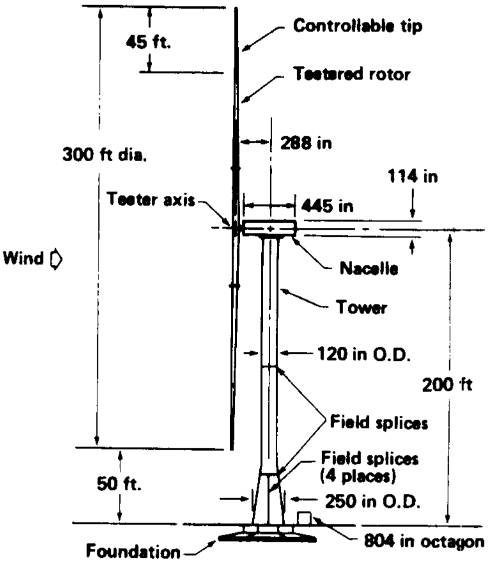
A. The cost-of-energy equation shown in my presentation was given to us by NASA as a Mod-2 program ground rule. However, we have looked at 30-year levelizing using a factor applied to the operation and maintenance term. Since operation and maintenance are a comparatively small part of annual cost, application of this levelizing factor has only minor impact on Mod-2 cost of electricity.

Q. Your design is facing into the wind. How severe is the extreme wind load case, and what extreme wind velocity have you designed to?

A. We had designed to an extreme wind of 120 mph. This case designs a very minor portion of the rotor and a major portion of the tower and foundation.

Table 1. MOD-2 Design Requirements

Requirement	Value
General:	
Service life	30 years
Rotor orientation	Horizontal axis
Rotor diameter	300 feet
Environmental:	
Mean yearly wind speed	14 mph at 30 feet
Wind gradient	Variable power law
Wind speed duration	Weibull distribution
Altitude	0 - 7,000 feet
Lightning	Per NASA model
Seismic - Wind Turbine	Zone 3
Seismic - Foundation	Zone 2
Temperature range	-40°F to 105°F
Rain, hail, snow, etc.	Yes
Max design wind	120 mph at 30 feet
Operation and maintenance:	
Fail safe unattended operation	Yes
Fire and ice detection	Yes
Network and turbine protection	Yes
Obstruction marking and lighting	Yes
Maintenance tools and vehicles	Commercial



Rated power	2,500 KW
Rotor diameter	300 ft
Rotor type	Teetered - tip control
Rotor orientation	Upwind
Rotor airfoil	NACA 230XX
Rated wind @ hub	27.5 mph
Cut-off wind speed @ hub	45 mph
Rotor tip speed	275 ft/sec
Rotor rpm	17.5
Generator rpm	1,800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height	200 ft
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient	0.382

Figure 1. General Configuration & Features

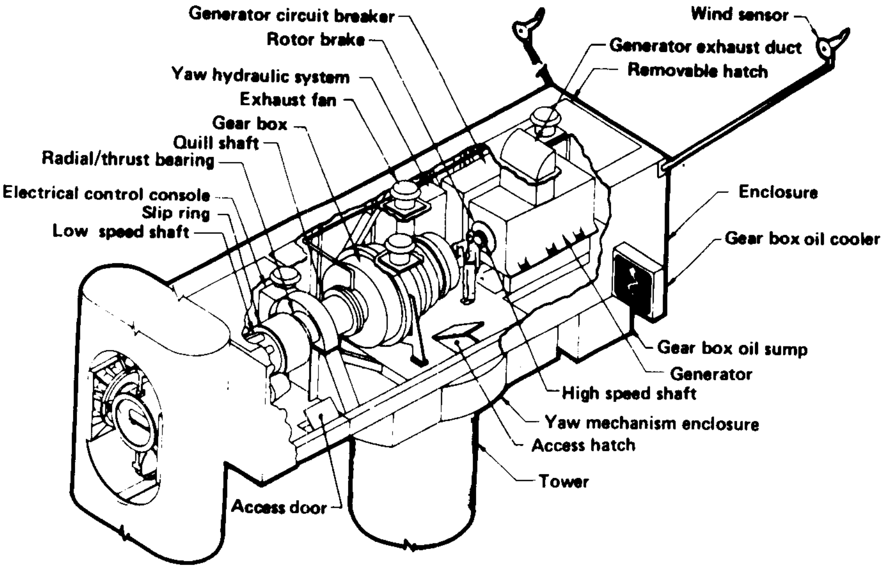


Figure 2. General Nacelle Arrangement MOD-2-107

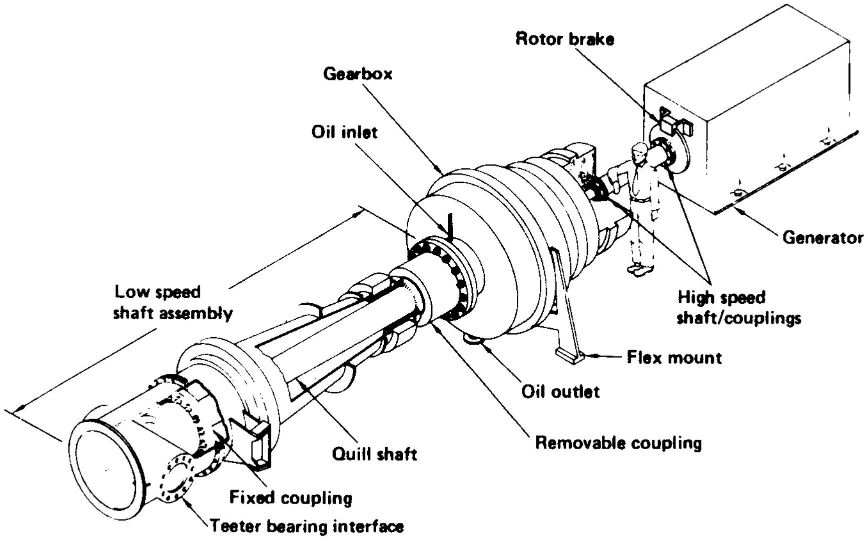


Figure 3. Drive Train

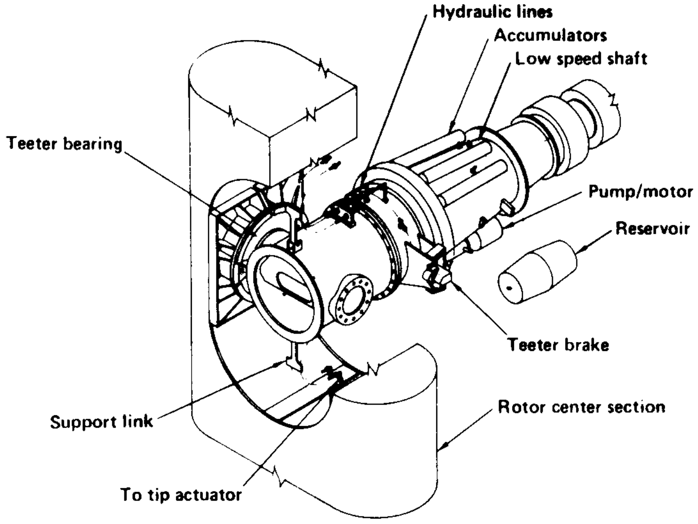


Figure 4. Pitch Hydraulic System Low Speed Shaft

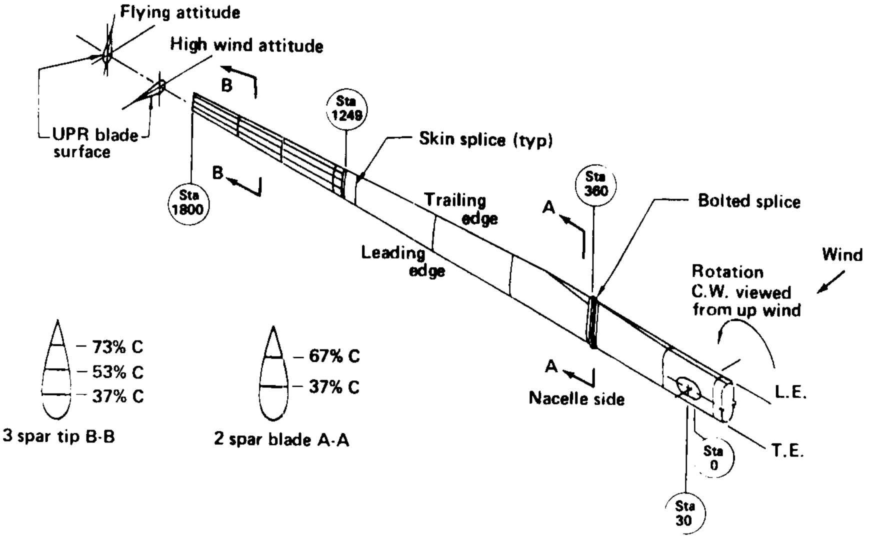


Figure 5. Steel Rotor Blade Configuration MOD-2-107

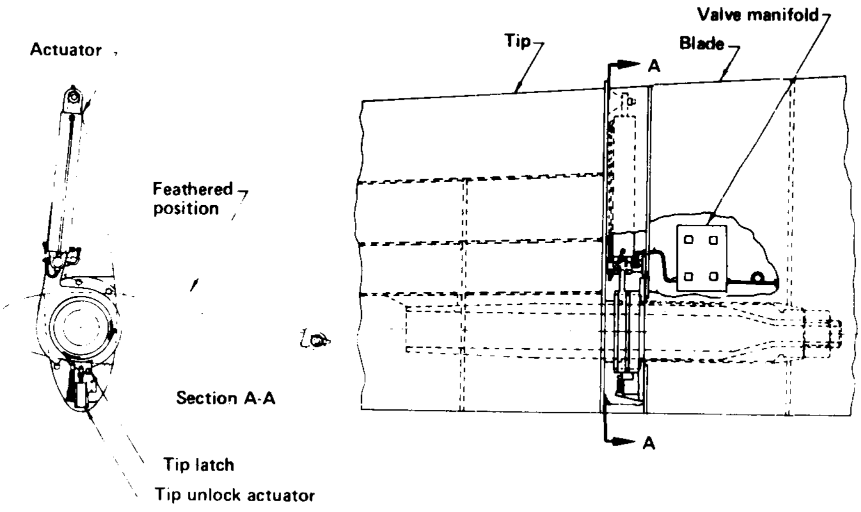


Figure 6. Pitch Control Mechanism MOD-2-107

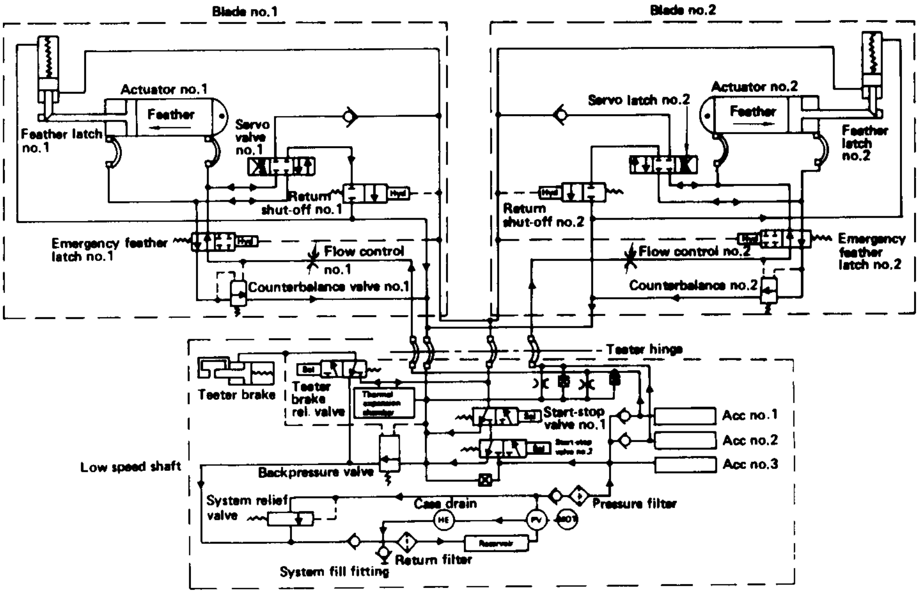


Figure 7. Hydarulic Schematic Pitch Control System MOD-2-107

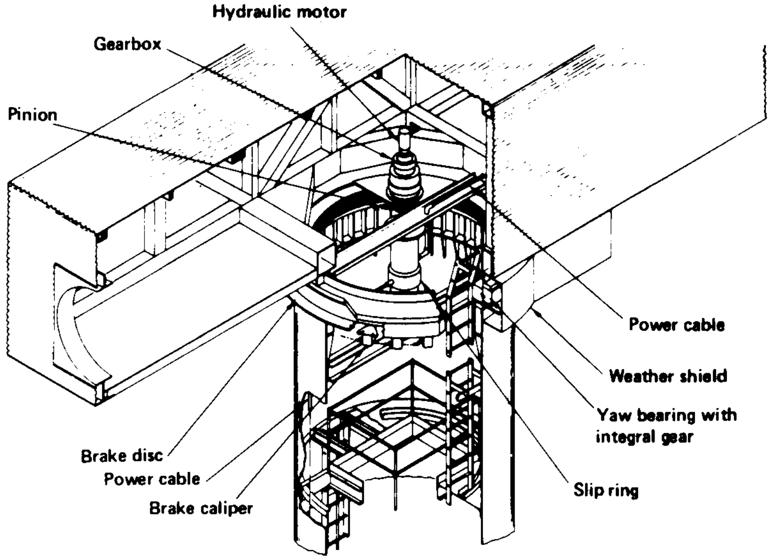


Figure 8. Yaw Drive Installation

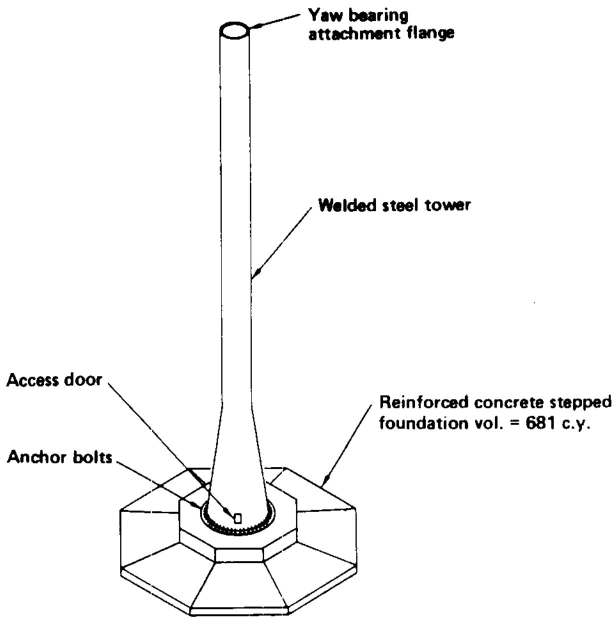


Figure 9. Tower/Foundation MOD-2-107

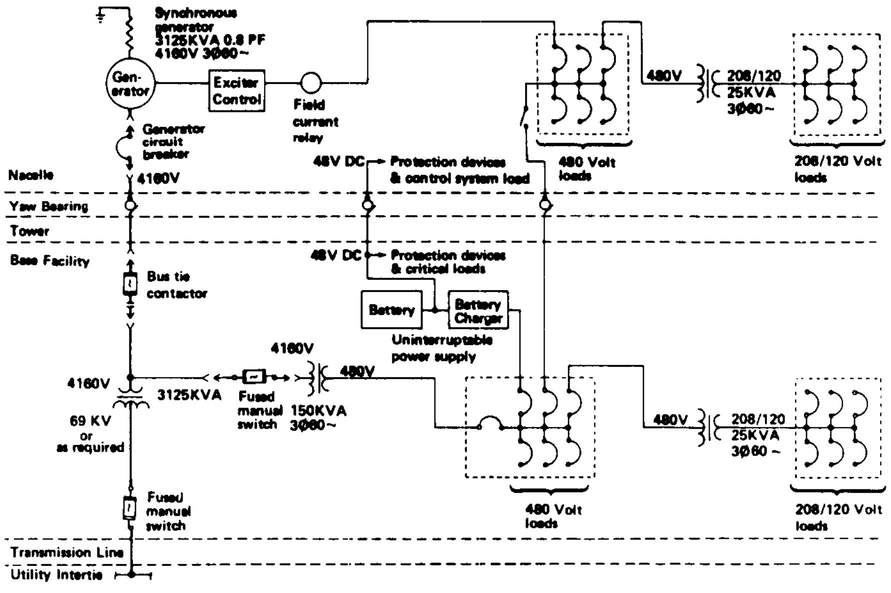


Figure 10. Electrical Power System - Power Network MOD-2-107

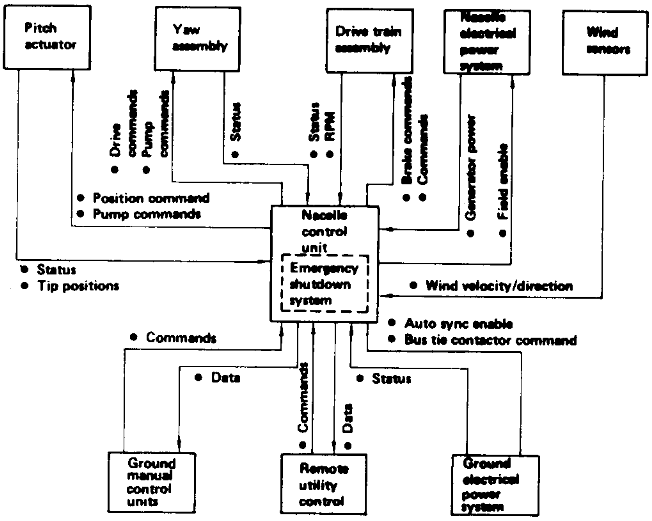


Figure 11. Control System Interface Diagram

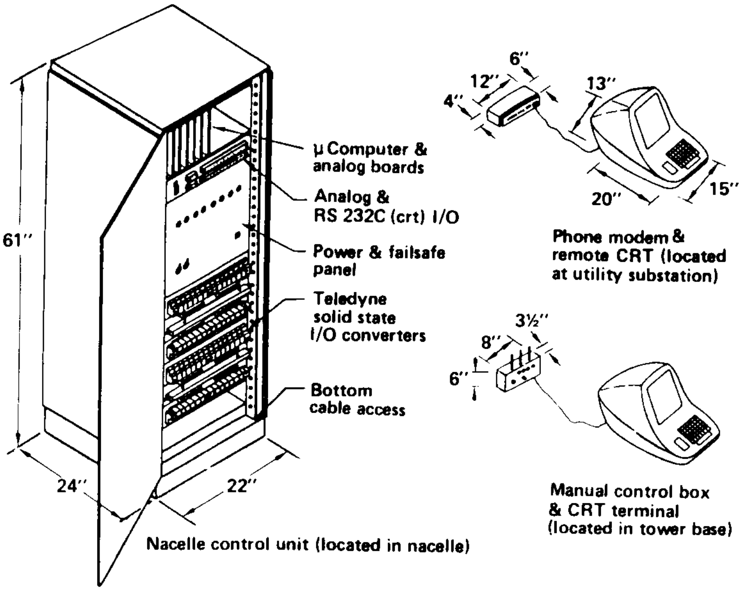


Figure 12. Control System Major Components MOD-2-107

Element	Weight (lbs)
Rotor assembly	169,567
Gearbox	39,000
Generator	17,000
Drive train components	39,892
Nacelle structure	40,832
Yaw drive	17,742
Misc. Nacelle equipment	4,705
Tower assembly	251,466
	580,204

Figure 13. Weight Summary

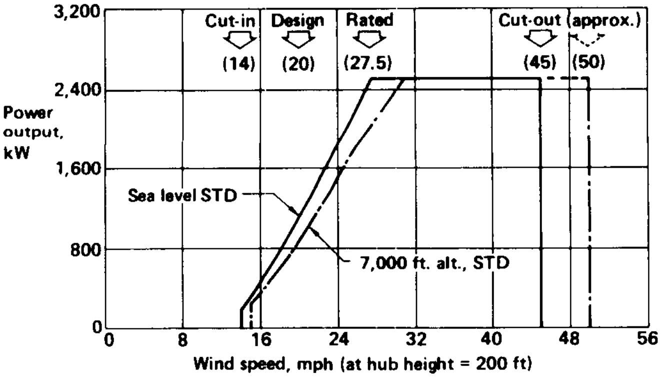


Figure 14. Power Output Vs. Wind Speed

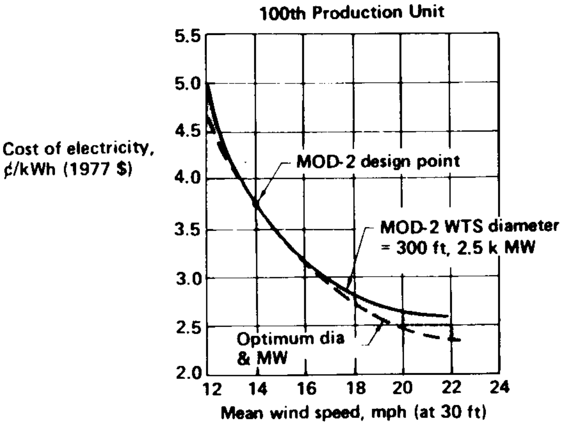


Figure 15. Effect of Mean Wind Speed on Economic Performance

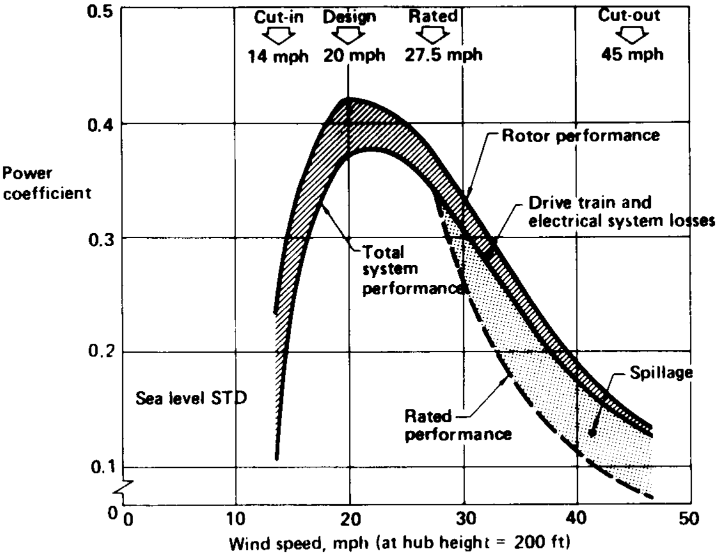


Figure 16. System Performance

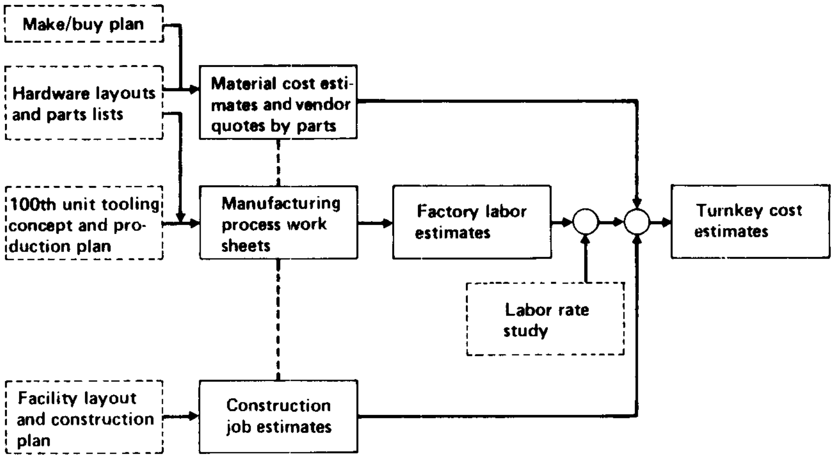


Figure 17. Cost Approach

Turnkey account		Cost
1.0	Site preparation	$162,000
2.0	Transportation	29,000
3.0	Erection	137,000
4.0	Drive train	329,000
5.0	Rotor	379,000
6.0	Nacelle	184,000
7.0	Tower	271,000
8.0	Initial spares	35,000
8.A.	Non-recurring	35,000
9.0	Total initial cost	$1,561,000
	Fee (10%)	156,000
	Total turnkey	$1,717,000
10.0	Annual operations and maintenance	$ 15,000

The cost estimating ground rules are as follows:

- All costs are in mid 1977 dollars
- Costs of installation and operation are based on a 25 unit farm
- Transportation costs are based on rail and truck transport over a distance of 1,000 miles

Figure 18. 100th Unit Production Costs

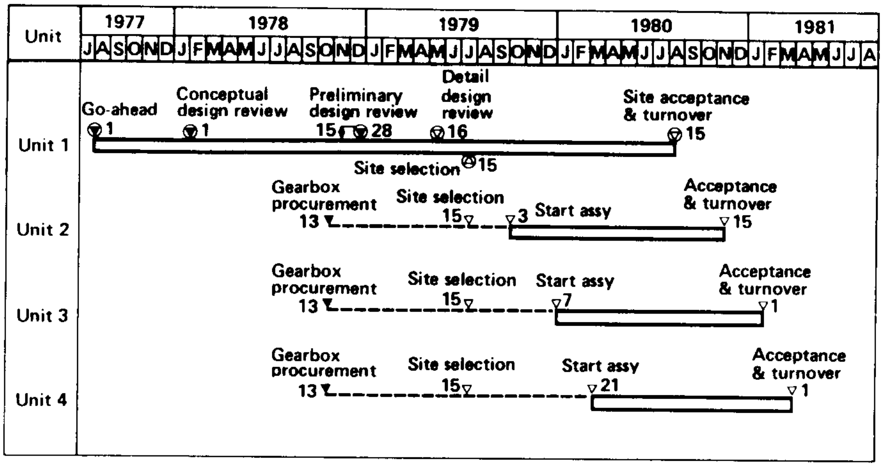


Figure 19. WTS MOD-2 Tier I Master Schedule

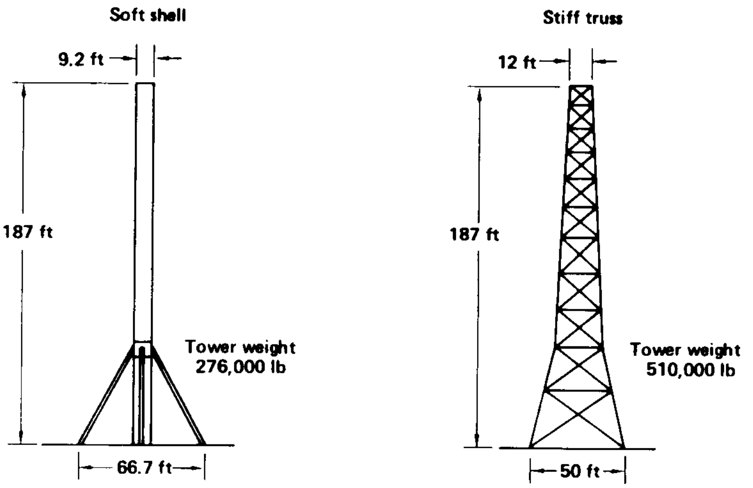


Figure 20. Tower Configurations

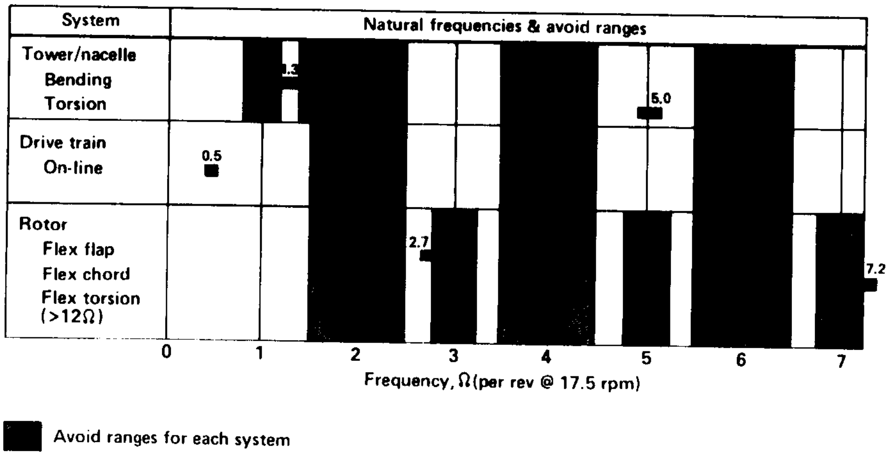


Figure 21. MOD-2 System Frequencies

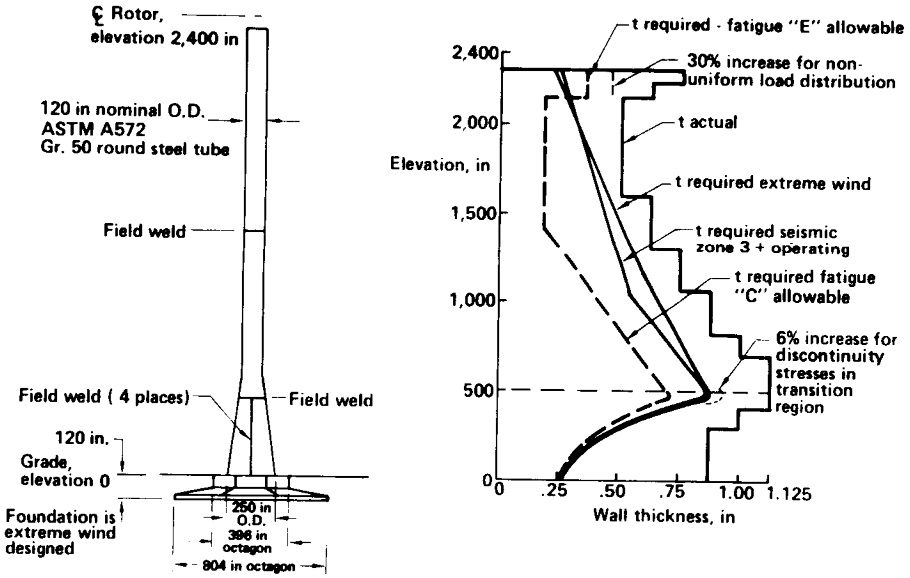


Figure 22. Tower/Foundation MOD-2-107

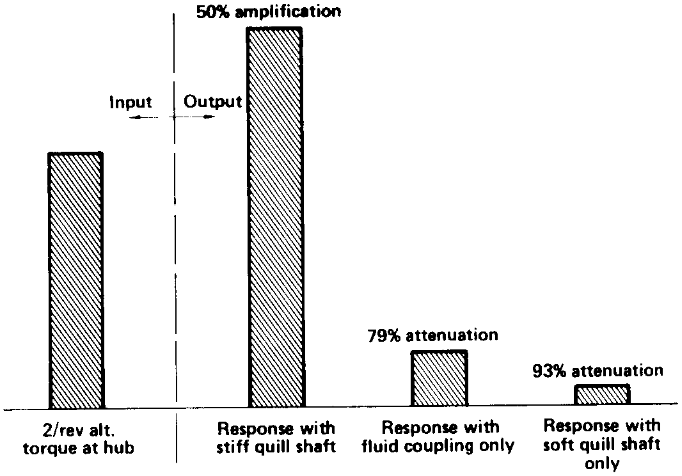


Figure 23. Response to 2/Rev Torsional Forcing Functions