DOE/NASA/20305-5
NASA TM-82681

The Mod-2 Wind Turbine Development Project

(NASA-TM-82681) THE MOD-2 WIND TURBINE DEVELOPMENT PROJECT Final Report (NASA) 24 p HC A02/MF A01 CSCL 10B

N81-27606

Unclas
G3/44 26883

Bradford S. Linscott
National Aeronautics and Space Administration
Lewis Research Center

Joann T. Dennett
Rdd Consultants Inc.

and

Larry H. Gordon
National Aeronautics and Space Administration
Lewis Research Center

July 1981

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Wind Energy Systems

DOE/NASA/20305-5
NASA TM-82681

The Mod-2 Wind Turbine Development Project

Bradford S. Linscott
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Joann T. Dennett
Rdd Consultants Inc.
Boulder, Colorado 80303

and

Larry H. Gordon
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

July 1981

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Wind Energy Systems
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-79ET20305

Introduction

People have used the wind for a millennium to pump water, grind grain, and sail ships. More recently, people have been using wind to produce electricity.

Years ago, interest flourished in developing large wind-driven electric generating systems. However, interest in such systems declined because they were not cost competitive with systems using fossil fuels. Growing energy requirements, increasing fuel costs, declining fuel reserves, and dependence on foreign sources is changing substantially this economic picture.

The primary objective in the development of Mod-2 was to design a wind turbine to produce energy for less than 5¢/kWh based on 1980 cost forecasts. The pricing method used to project the Mod-2 energy costs is the levelized, fixed-charge-rate approach, generally accepted in the electric utility industry as a basis for relative ranking of energy alternatives. This method derives a levelized energy price necessary to recover the utility's purchasing, installing, owning, operating, and maintenance costs.

The Federal Wind Energy Program

The U.S. Department of Energy (DOE) has spent about $200 million on wind turbine research and development. Known as the Federal Wind Energy Program, its purpose is to develop small, intermediate, and large-scale wind turbines to harness the wind in a cost effective way. This wind turbine development effort includes construction of several intermediate and large-scale wind turbines at utility sites and experimental testing of these machines on utility networks.

The Mod-2 wind turbine, a second generation machine, is the latest development in the program conducted jointly by the U.S. Department of Energy (DOE) and the Lewis Research Center of the National Aeronautics and Space Administration (NASA). Mod-2, designed, built, and installed by the Boeing Engineering and Construction Co., is the culmination of a technology effort to attain a machine that has high potential for commercial production. In addition, Mod-2, when produced in quantities of 100 or more, can generate electrical energy at a cost very close to the current cost of fossil-fuel generated electricity. The first cluster of three Mod-2 wind turbines, located near Goodnoe Hills, Washington, is now producing power for the Bonneville Power Administration.

Four significant design features account for Mod-2's major cost-of-electricity advantage over the earlier Mod-0, Mod-0A, and Mod-1 first-generation research machines. First, only the 45-ft-long blade tip, rather than the entire 150-ft-long blade, is pitched to control rotor speed and power. This design feature reduces rotor weight and cost with only minor compromises in power output and startup and shutdown control. Second, a lighter, more flexible tubular tower replaces the heavier truss towers that were used for the first DOE/NASA wind turbines. A lighter, more compact epicyclic gearbox located in the nacelle further reduces costs when compared with the parallel shaft gearboxes used on the earlier DOE/NASA wind turbines. Finally, by allowing the rotor blades to teeter at the hub in response to wind forces, in contrast to rotor blades rigidly attached to the hub, the loads on all components are diminished.

The Bureau of Reclamation within the Department of the Interior has developed a concept for the integration of large clusters of wind-turbine generators with existing hydroelectric power systems. The technical and economic feasibility of this concept will be evaluated by the installation and operation of two different wind turbines. Each wind turbine, called a Systems Verification Unit (SVU), will be installed at the site of a potential cluster of wind turbines. One such site is located approximately 5 miles southwest of Medicine Bow, Wyoming. The SVU wind turbines will be placed about 3000 ft apart and are scheduled to start checkout operations in late 1981. The Bureau of Reclamation awarded a contract to Hamilton Standard to design, fabricate, install, and check out a wind turbine called the WTS-4 SVU machine. The WTS-4 has a 256-ft-diameter rotor, supported on a tubular steel tower that locates the center of the rotor 262 ft above ground. With a wind speed of 36 mph at 262 ft above ground, the WTS-4, produces 4 MW of power. In addition, NASA awarded a contract to the Boeing Engineering and Construction Co. to fabricate a Mod-2 SVU machine and install the Mod-2 near Medicine Bow. The Mod-2 SVU will be identical to the three machines installed by Boeing and now operating near Goodnoe Hills.

First Generation Wind Turbines

The first experimental wind turbine, called Mod-0, started operation in September 1975. Mod-0 has a rotor diameter of 125 ft, generates 100 kW of electricity in an 18 mph wind, and is located at NASA's Plum Brook Station in Sandusky, Ohio. This machine was designed as an experimental test bed. Mod-0 was first used to validate the accuracy of analytical design methods. It is now used to test new wind turbine configurations. For example, the Mod-0 configuration was changed to simulate the teetered rotor and the flexible tower, when Mod-2 was first being designed. Mod-0 was tested to explore the performance of these two design features. Results of these tests were used by the Boeing Engineering and Construction Co. and incorporated into the final Mod-2 design.

Four Mod-0A machines were built to gain early experience with wind turbines connected to and operated by utility companies. Although similar to the Mod-0, the Mod-0A has a larger gearbox and generator, which allows generation of up to 200 kW in a 22-mph wind speed. The first machine began operation in Clayton, New Mexico, in November 1977. In June 1978 a sister machine was started on the island of Culebra, off Puerto Rico. Another island site, Block Island, Rhode Island, received its Mod-0A wind turbine generated power in May 1979. The fourth Mod-0A wind turbine started utility operation on the island of Oahu, Hawaii, in June 1980. The Clayton and Block Island machines provide electricity to relatively small-scale utility networks. The Mod-0A's located at Culebra, Puerto Rico, and Oahu, Hawaii, however, joined larger utility networks. The Westinghouse Electric Corporation installed the Culebra machine and assembled, tested, and installed both the Block Island and Oahu machines. Westinghouse presently performs nonroutine maintenance on all of the DOE/NASA Mod-0A machines. The valuable experience gained during early operation of the Clayton and Culebra Mod-0A machines was factored into the final design of the Mod-2.

In 1979, the first experimental multimegawatt machine, the Mod-1, began operation for the Blue Ridge Electric Membership Corporation at Howard's Knob, near Boone, North Carolina. With a rotor diameter of 200 ft, it was the world's largest experimental wind machine. Mod-1 can produce up to 2 MW of electricity in a 26 mph wind. The Mod-1 wind turbine was designed, fabricated, and installed by the General Electric Co., for DOE/NASA. Near the end of the Mod-1 design effort, General Electric conducted a study to define a wind turbine that was more advanced than Mod-1. The study, which came to be called Mod-1A, identified innovative design features, including the pitchable blade tip rotor and the tubular tower. This study led to the tests conducted on Mod-0 and assisted the Boeing Engineering and Construction Co. during its design of Mod-2. Experimental performance tests were conducted on the Mod-1 wind turbine. Results of these tests are now being used to assist designers in defining wind turbines even more advanced than Mod-2.

U.S. Wind Resources

Environmental, economic, and meteorological research is keeping pace with hardware development in the Federal Wind Energy Program. For example, appropriate site selection is essential for optimal power production. Current studies will more thoroughly quantify U.S. wind resources; however, broad estimates are available (fig. 1) General Electric Space Division surveyed the nation for good wind turbine sites—those with strong, steady winds (averaging 11 to 14 mph). It found many regions with winds averaging more than 14 mph (fig. 2).

Wind turbines require a minimum 10-mph average wind for efficient electricity production. Estimates basing wind power production on average annual wind speeds may be conservative since power production varies with the cube of the wind speed, and since power output increases dramatically with high gusts. Once general areas are established, it will be necessary to detail the wind resources available at specific sites.

Wind Turbine Economics

Table 1 details the cost of energy produced by Mod-2. The cost of wind-generated electricity will decrease as more machines are produced. Figure 3 cites economies of scale for the early machines. Estimates of the 100th production unit costs for the Mod 2 are summarized in table 2. These costs assume

- – Mid-1980 dollars
- A 25-unit wind cluster
- A rate of installation of one machine per month
- Generally flat sites with few natural obstacles
- Soil easily prepared for foundation
- Land cost not included
- Transportation distance of 1000 miles

TABLE 1.—COST OF ELECTRICITY

The cost of electricity is a function of the turnkey cost analysis, annual energy production, and cost of operation and maintenance

COE	$\frac{IC \times FCR + AOM}{AEP}$	4.1¢/kWh
FCR	18% per year	levelized, fixed charge rate including return on capital, income tax, property tax, and insurance FCR is sensitive to the cost of capital, capitalization method, income tax rate, and system lifetime
IC	$2,150,000	initial (turnkey) cost of the energy system including complete cost exposure to the utility for purchasing, installing, and setting up logistics for the energy production system
AOM	$19,000	annual operation and maintenance (O&M) cost including operating budgets and maintenance budgets
AEP	9.75×10^6	anticipated annual energy production of the energy system in kWh AEP takes into account energy production losses attributed to the unavailability of the energy system equipment and the unavailability of the energy source (i.e., wind)

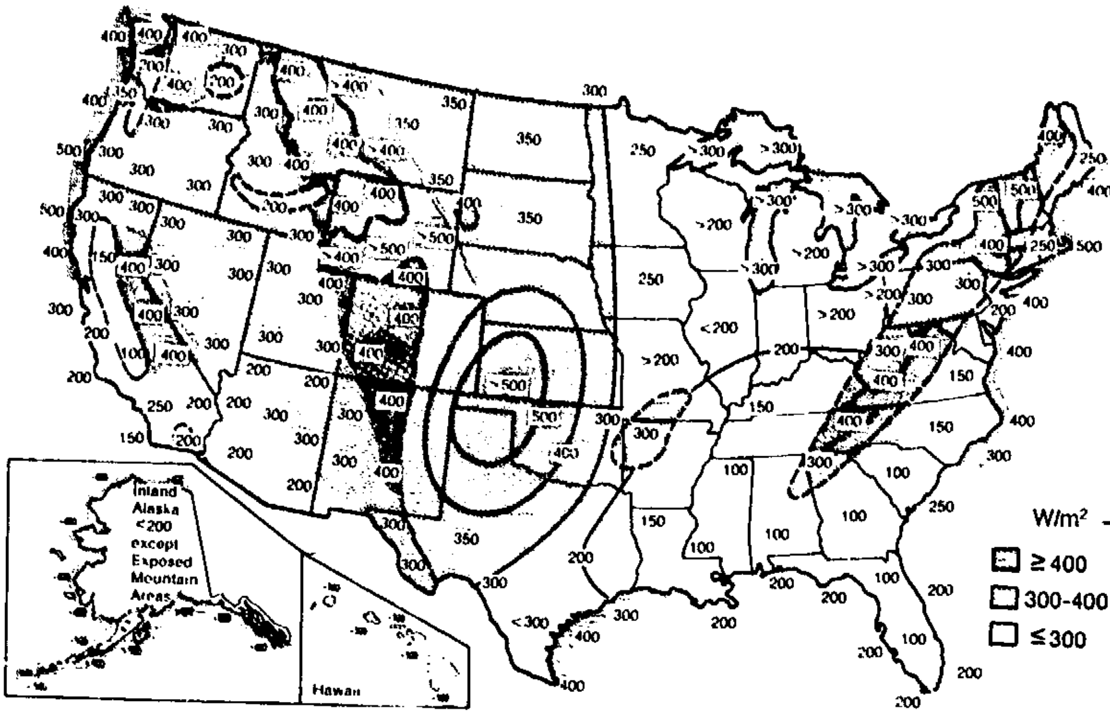


Figure 1. Annual Average Wind Power (W/m²) at 50 m

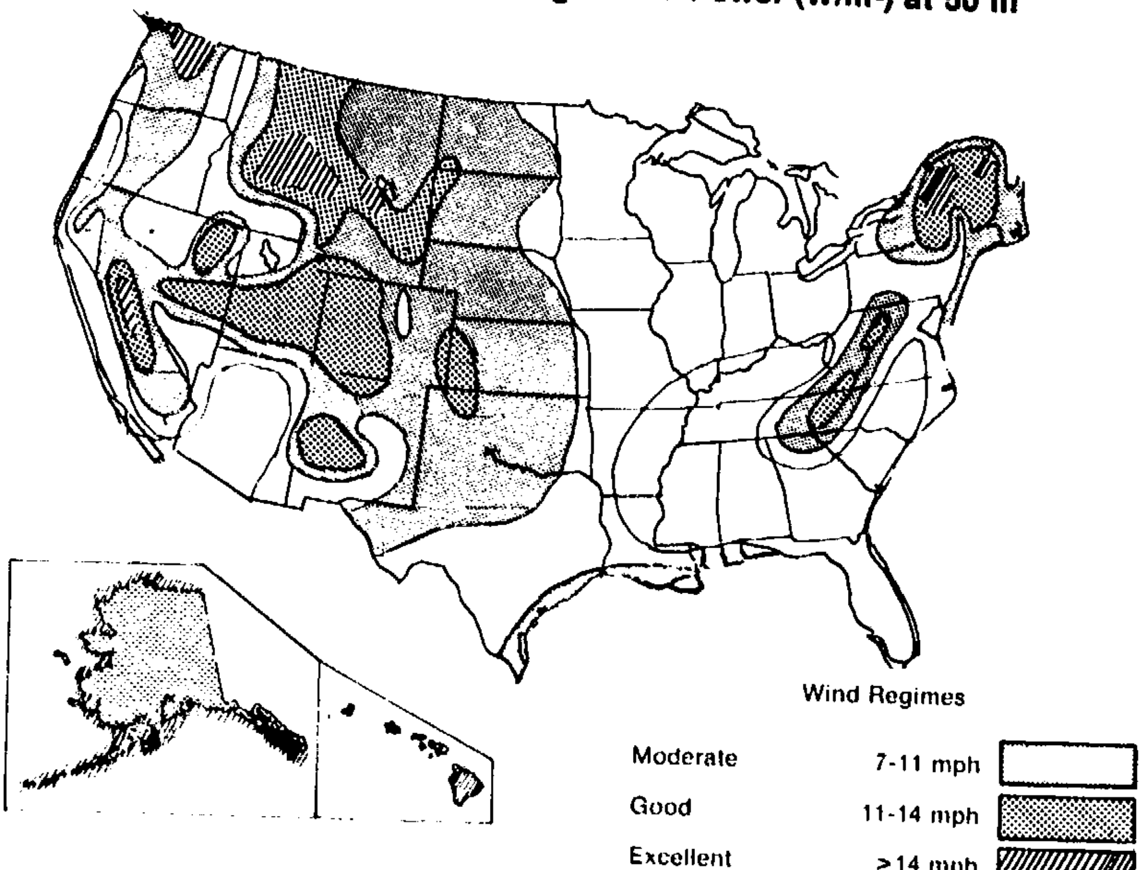


Figure 2. Average Wind Energy in U.S.

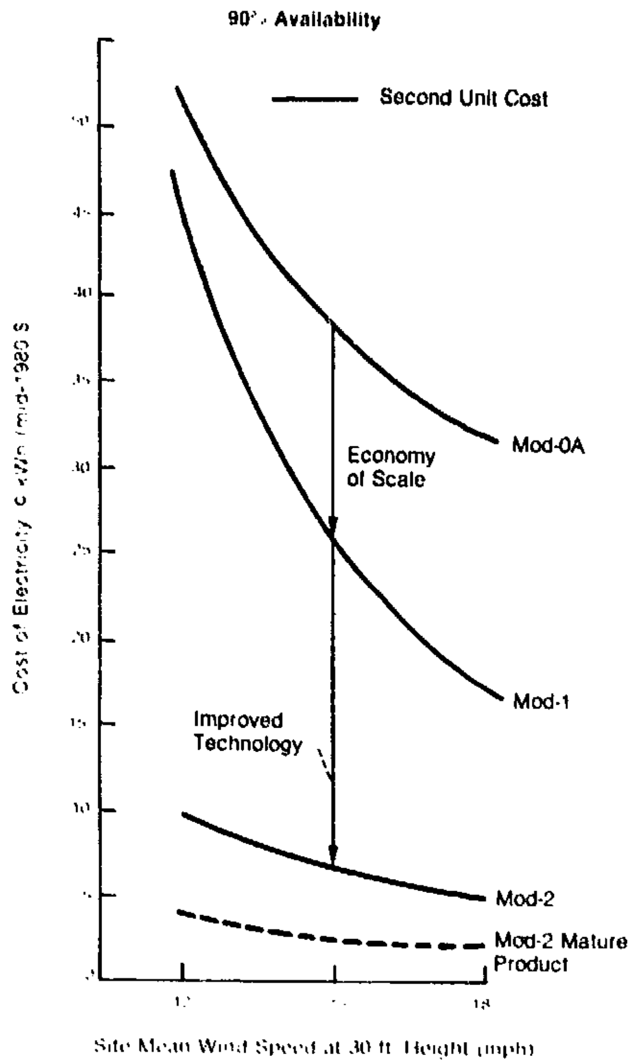


Figure 3. Cost of Electricity

TABLE 2.—COST SUMMARY, FOR 100th PRODUCTION UNIT, MID-1980 DOLLARS

Turnkey account	Cost
Site preparation	203,000
Transportation	36,000
Erection	171,000
Rotor	411,000
Drive train	474,000
Nacelle	230,000
Tower	339,000
Initial spares	44,000
Nonrecurring	44,000
Total initial cost	$1,952,000
Fee (10%)	195,000
Total turnkey	$2,147,000
Annual operations and maintenance	$19,000

Based on the gross national product implicit price deflation, the mid-1980 dollar costs in table 2 were established by applying a 25% increase to the mid-1977 dollar reports in Boeing's system design and concept reports (see bibliography). In mid-1977 dollars the estimated total turnkey cost of the 100th production unit for the Mod-2 would be $1,720,000, the annual operations and maintenance cost would be $19,000.

For these first wind turbines, various sizes of wind energy generators, rotor configurations, generating and control components, towers, and foundations were analyzed. For a given design concept, rotor diameter and system power output are the major factors determining economics. Various components, however, contribute to the cost (fig. 4). The selection of the design values is dependent on the site and wind characteristics as well as the cost, weight, and performance characteristics of the wind turbine design concept (fig. 5).

Mod-2—Second Generation

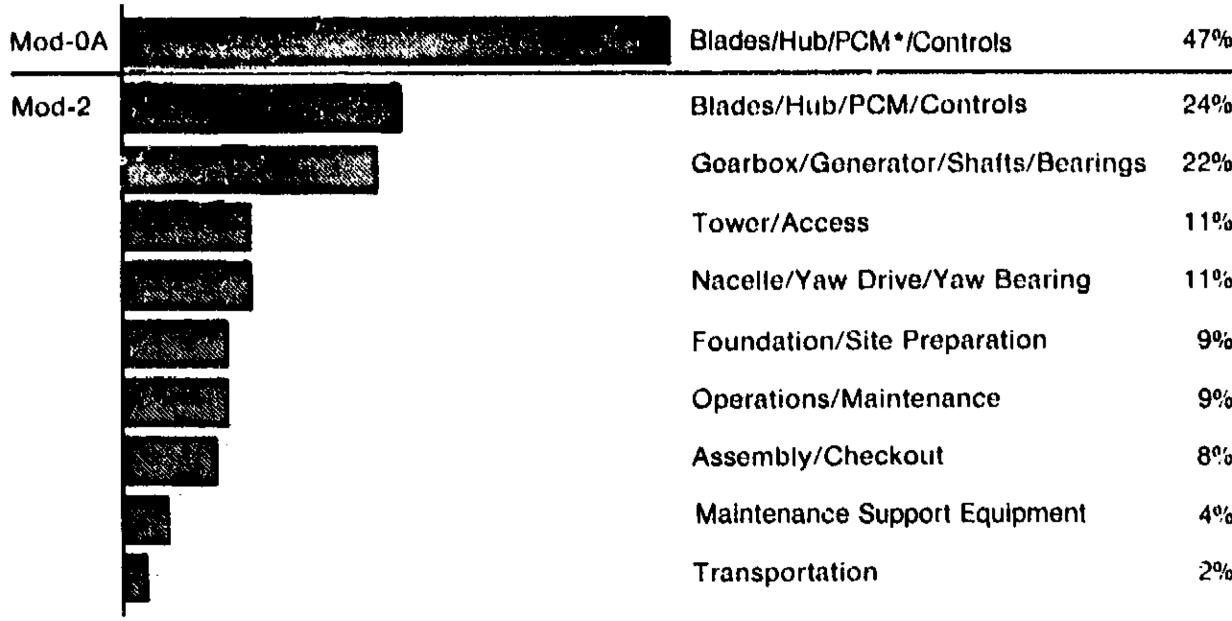
Fabrication of Mod-2 machines began in 1979. A Mod-2 rotor is 300 ft in diameter, the largest ever built for a wind turbine. At 200 ft above the ground, the Mod-2 (fig. 6) is designed to generate 2.5 MW of electricity at a wind speed of 27.5 mph.

Table 3 summarizes the Mod-2 annual electric energy output, in megawatt-hours, for various mean wind speeds. The reference mean wind speeds are measured 30-ft above sea level.

Design improvements gathered from the Mod-0, Mod-0A and the Mod-1 reduced the weight and complexity of Mod-2, thereby increasing its cost effectiveness. Similarly, Mod-2 operating experience is now helping to optimize the design of a third-generation wind turbine, called Mod-5. Studies by the Boeing Engineering and Construction Co. and General Electric show that Mod-5 wind turbines, presently planned larger than Mod-2, may provide electrical energy at a cost even lower than Mod-2 will provide.

The three Mod-2 machines located west of Goodnoe Hills, Washington, and north of the Columbia river (fig. 7) compose the Nation's first cluster of wind turbines (fig. 8). The combined capacity of these machines produces 7.5 MW of electricity into the transmission lines of the Bonneville Power Administration. Mod-2 is designed to be available 96% of the time the wind blows. The availability is compatible with similar requirements for conventional energy sources. The machine weight (table 4) relative to power outputs is 252 lb/kW for Mod-2, a considerable improvement over earlier machines.

The Mod-2 mechanical system consists of two propeller-type rotor blades The rotor is attached to



*Pitch Control Module

Figure 4. Contribution of Design Elements to Cost-of-Electricity

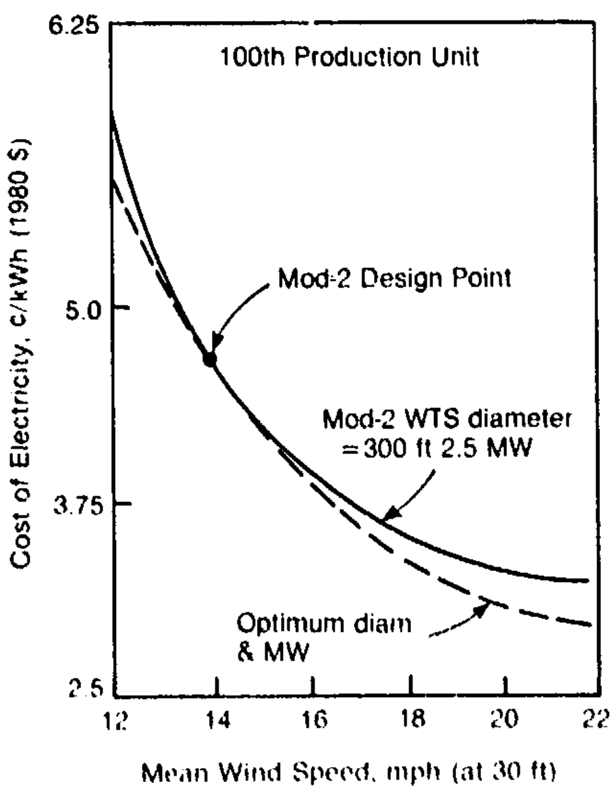


Figure 5. Effect of Mean Wind Speed on Economic Performance

Figure 6.

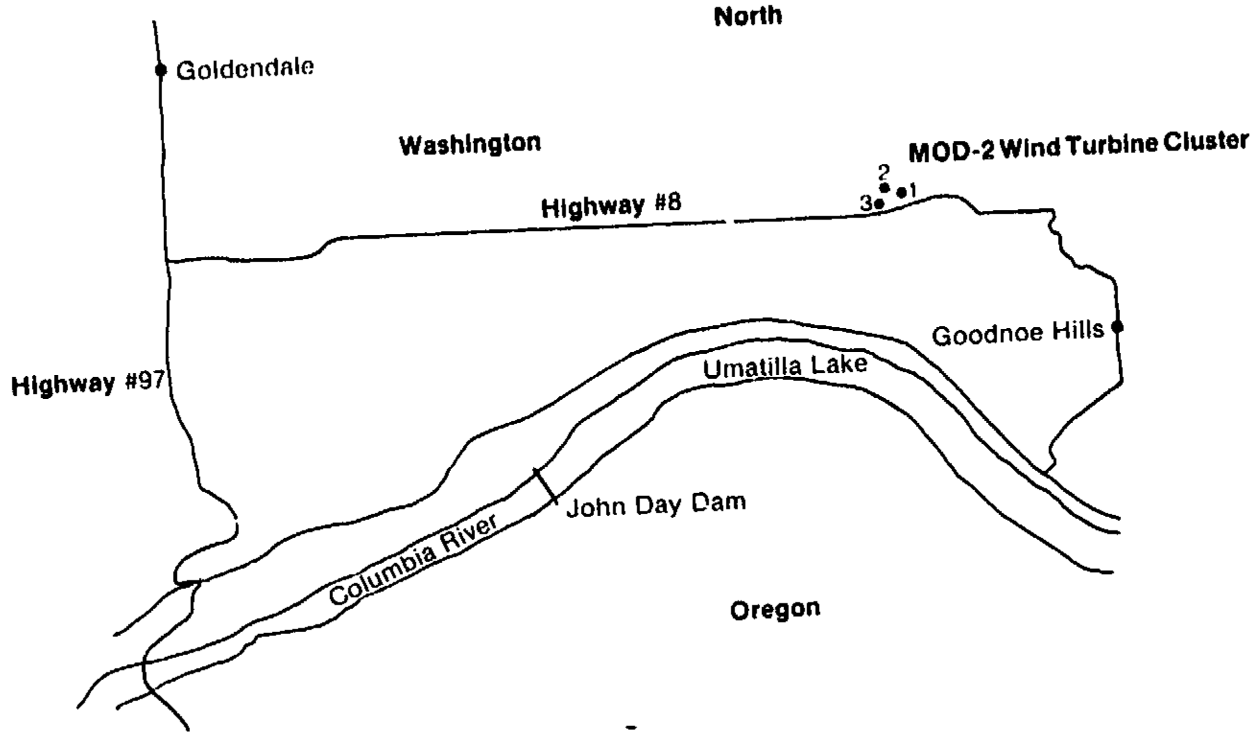


Figure 7

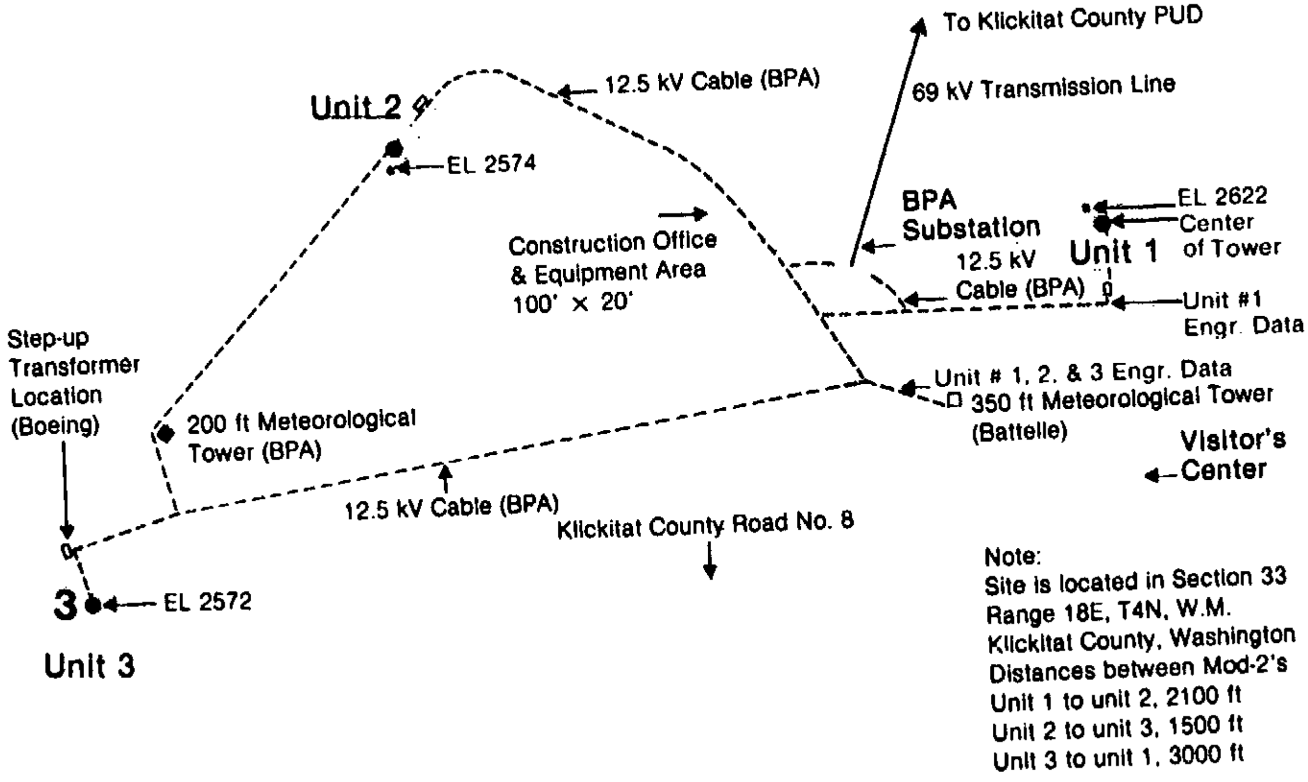


Figure 8. Bonneville Power Administration Mod-2 Wind Turbine Cluster Site Plan, Goodnoe Hills, Washington

TABLE 3.—MOD-2 ANNUAL ENERGY PRODUCTION

Mean wind speed,[a] mph	Energy,[b] MWh
10	4,842
12	7,033
14	9,263
16	11,343
18	13,116
20	14,455

[a]Measured at 30-ft altitude.
[b]90% availability.

TABLE 4.—WEIGHT SUMMARY

Element	Weight (pounds)
Blade	109,800
Hub	80,500
Pitch control	2,200
Rotor subassembly	192,500
Low speed shaft and bearings	24,400
Quill shaft and coupling	7,900
Gearbox	37,000
High speed shaft and coupling	700
Rotor brake system	300
Lubrication system	12,300
Generator	18,500
Drive Train	101,100
Nacelle structure	53,200
Yaw drive	15,800
Rotor support structure	8,100
Environmental control and fire prevention	900
Cabling and electrical facilities	1,400
Instruments & controls	700
Generator accessory unit	2,500
Nacelle	82,600
Tower	251,000
Cable installation	3,600
Cable transition	500
Tower subassembly	255,100
Total	631,300

a low-speed shaft which transmits the torque from the rotor to a gearbox. The gearbox converts the relatively slow rotor speed into the high-speed rotation necessary to drive the generator. The resulting electrical power is channeled into a utility power grid.

The Mod-2 system includes a rotor; a nacelle, which houses the major subsystems such as the drive train, generator, yaw bearing, yaw drive, and associated subsystems for pitch/yaw control and maintenance; safety systems; the tower; and the foundation. The Mod-2 configuration is shown in figure 9.

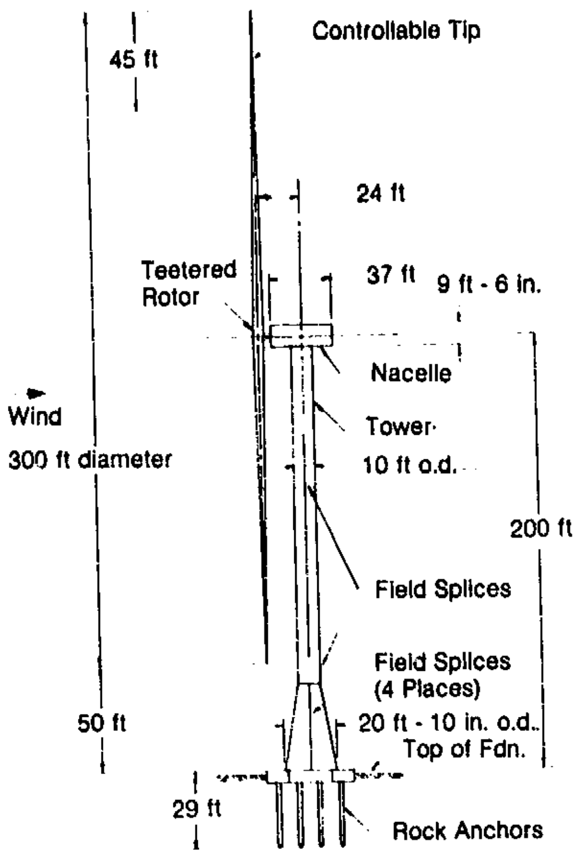


Figure 9

Wind turbine systems will "cut in," or begin generating power, at the wind speed selected as the lowest useful startup speed. The wind turbine will "cut out," or cease operation, when the wind achieves a velocity that would overload certain components.

To some extent, the cut in speed is arbitrary, but sufficient torque must be produced to overcome initial rotor, generator, and ancillary mechanical and electrical system resistances. The torque must also be sufficient to synchronize the wind turbine with the utility grid and produce enough power to justify operation. At 200 ft above ground, the Mod-2, cut-in wind speed is 14 mph. When the average wind velocity exceeds 45 mph for a short length of time, the wind turbine automatically stops (fig. 10).

The most desirable wind regime for Mod-2 operation is between 27.5 and 45 mph. Power produced by the turbine varies from 200 kW at cut-in (14 mph) to 2500 kW, achieved when wind speed reaches 27.5 mph or greater. Wind speed of 27.5 mph is called "rated" wind speed because at that speed the generator operates at its "rated" or maximum power.

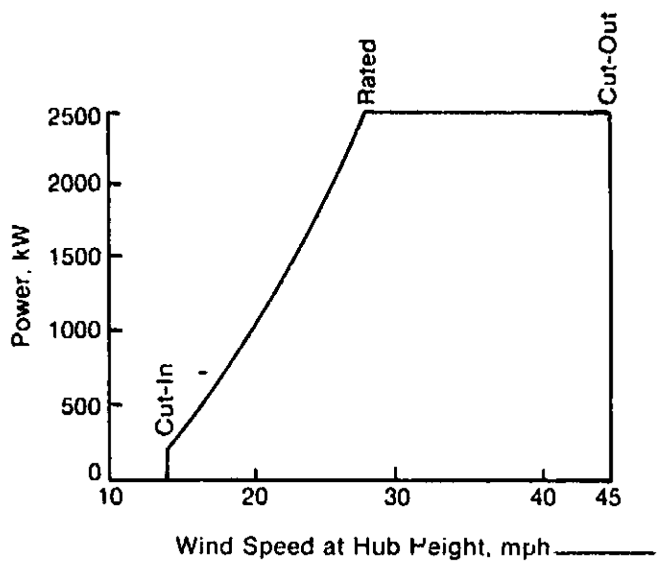


Figure 10

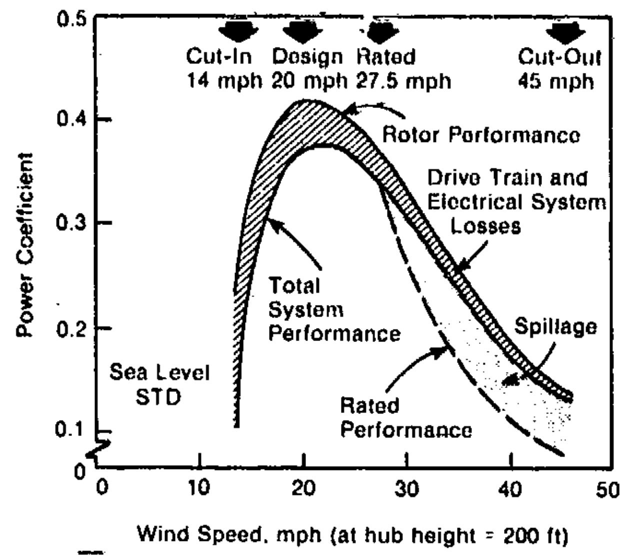


Figure 11. System Performance

The normal mechanical operation of a wind turbine includes a series of possible operating modes. Operation begins with the machine shut down but ready for operation in "standby mode" with the rotor and yaw brakes on. The control system initiates startup whenever the average wind speed at hub height is between 14 and 45 mph. For startup, the yaw brake is released, the nacelle is yawed to align the rotor with the wind, blade pitch is changed from feathered to operating position, the rotor brake is released, and the rotor begins to turn.

When the wind is above cut-in but below rated speed, the blades' pitch angle is selected to deliver maximum power. Above rated wind speed (27.5 mph for Mod-2), the pitch angle is controlled to maintain constant rated power.

When wind speeds become too high (above 45 mph) or too low (below 14 mph), shutdown is initiated. The control system feathers the blades and disconnects the generator from the utility grid whenever the power generated drops below 125 kW. The rotor teeter brake is applied, and when the rotor stops the rotor brake prevents inadvertent turning.

Figure 11 illustrates some of the concepts important in wind turbine optimization and operation. The power coefficient (C_p) is the fraction of energy captured from a stream of wind passing through the rotor disk. The rotor power coefficient represents rotor capability. This accounts for all aerodynamic effects including drag increases due to wear and dirt, and heading losses due to operational tolerances on yaw control. The bell-shaped curve indicates that a peak value occurs at a 20-mph wind speed. This is the designated design wind speed. The peak C_p value could be shifted to any other wind speeds by changing certain operational parameters. However, at the 20 mph design speed, the yearly energy capture is maximized. This optimal design wind speed is primarily a function of rated power and only secondarily related to the actual wind speed.

Power flow through the Mod-2 begins with the wind. This wind stream is met by the rotor disk and ends when 2500 kW of electric power is delivered to the utility grid. The Mod-2 rotor can capture 41.5% of available wind power. This peak value occurs at 20 mph so as to maximize the yearly energy output.

Mod-2 Innovations

On the basis of the technology developed in the Mod-0, Mod-0A, and Mod-1 projects, DOE and NASA provided some basic requirements for the development of the Mod-2 wind turbine. Baseline requirements called for the wind turbine to

- Operate in areas where mean wind speed is 14 mph at 30 ft above ground (This is typical of many midwest, coastal, and off-shore sites.)
- Have a service life of 30 years
- Have a horizontal axis with a minimum rotor diameter of 300 ft
- Operate reliably, safely, and unattended at a remote site.

Four significant innovative changes from the Mod-0 and Mod-1 wind turbine designs were incorporated into the Mod-2. These innovations are the teetering rotor with partial span pitch control, the soft shell tower, the epicyclic gearbox, and the use of a quill shaft in the low-speed drive train. These improvements account for the major cost-of-electricity advantage over competing wind turbine systems.

Upwind Teetering Rotor with Partial Span Pitch Control

The rotor is a two-bladed steel, teetering type with partial span pitch control. Orienting the rotor upwind reduces rotor fatigue slightly and increases annual power production by 2.5%. The rotor converts up to 41.5% of the wind power to rotational electrical generating power. Adverse impacts of the upwind rotor on the yaw system are minimized by the teetering mechanism.

Soft Shell Tower

The tower is fabricated using manufacturing techniques developed for utility cantilever power poles.

A soft shell tower has advantages over the stiff-truss tower previously used. The soft tower weighs much less, the shell type of construction is less expensive to fabricate, and the tower design reduces vibration problems throughout the wind turbine system. A dynamically soft rather than stiff tower also permits the use of heavy but economical and reliable rotor designs.

Dynamically soft towers have a lower natural frequency of vibration than the blade passing frequency while a stiff tower has a higher frequency. The soft tower is therefore less likely to reinforce vibrations established by the rotation of the rotor. Consequently the effects of fatigue and extraneous motion on the drive assembly and other subsystems are reduced.

Three-Stage Epicyclic Gearbox

The wind turbine system is designed so that the rotor, connecting shafts, and generator operate at constant rpm, called the system's "operating" rpm. Vibration can be a problem and designers seek to reduce this as much as possible. The Mod-2 gearbox was designed with this in mind. The three-stage epicyclic gearbox chosen for the Mod-2 wind turbine is smaller, lighter, less expensive, more efficient, and more tolerant of the extraneous twisting and bending moments that occur along with the power-producing rotational motion of the drive shaft. The gearbox is flexibly mounted to the nacelle to further reduce the deleterious effects of these forces, which tend to both decrease the efficiency of power production and increase fatigue. The compactness of the gearbox simplifies installation and maintenance; in fact, it can even be completely overhauled inside the nacelle.

Quill Shaft

This shaft design reduces the two-per-revolution rotor torque oscillations that can be pronounced and troublesome. The quill shaft is flexible and reduces these oscillations, reducing the fatigue effects at the gearbox and the possibility of desynchronization with the utility grid.

Although less significant, two other changes from previous designs were also made. The microprocessor control system is located in the nacelle rather than on the ground in the tower's base. This proved less costly and reduced anticipated maintenance costs. Field assembly costs were also diminished by installing gin pole hoist and guy line foundations at each site. This permits use of less expensive gin poles and hoists rather than a cumbersome crane to erect the turbine. Thus, field installation efficiency was increased.

Components of the Mod-2 Mechanical System

Rotor

The identifying silhouette of the wind turbine, the rotor, has three major parts: the blades, the pitch-change mechanism, and the hub.

Blade.—The blades of the Mod-2 300-ft-diameter rotor are hollow steel shell construction with steel spar members. The blades have continuous construction through the hub, which greatly increases their strength and resistance to fatigue. The steel blades are impervious to dust, rain, and lightning and resist handling damage during transport and erection.

The rotor is oriented upwind to reduce the problems previously encountered with "tower shadow," a pulse induced by the sudden, sharp reduction in wind velocity as downwind rotors pass behind the tower. This cyclic pulsing increases blade fatigue and wear on the other mechanical components. Thus, tower shadow both reduces efficiency and shortens the life of the rotor blades, the gearbox, and generator.

The Mod-2 blades have partial span pitch control (fig. 12) resulting in substantial weight and cost savings. This design feature moves the pitch control mechanism away from the blade root end. Loads on the pitch bearings and pitch actuating devices are less than those at the hub. The outer 30% of the blade, rotatable through 100°, is used for pitch control, which is exerted through a hydraulic system similar to that used in variable pitch airplane propellers. This feature is the major means of control for both rpm and power. The weights of the blade components are rotatable tip section, 12,150 lb each; mid-section, 39,250 lb each; and center section, 70,900 lb (fig. 13).

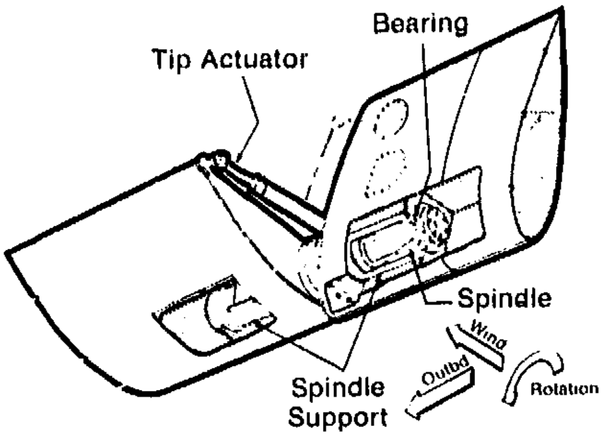


Figure 12. The Spindle

Pitch change assembly.—Sensors monitor wind turbine operating parameters, such as wind speed, rotor speed, and blade angle position. This information is used to provide the correct voltage to an electric-motor-driven pump and control valves of the pitch control hydraulic system (fig. 14). These control valves are part of a feedback system providing corrections to blade angle.

Hub.—The hub of the Mod-2 is "teetered" (fig. 15). Teetering minimizes the effects of induced blade forces which are not strictly rotational. Examples of such forces are the one-per-revolution blade flapwise loads produced by the rotation of the blades, the effects of small, unsymmetric gusts of wind, and the wind gradient effects.

The weight necessary in the nacelle and tower is reduced by a teetered hub, and the hub itself can be lighter because it absorbs less stress than a fixed hub. The teetered hub design concept was successfully tested on the NASA Mod-0 experimental wind turbine.

The Drive Train Assembly

The principal components of the drive train assembly are the low-speed shaft, the gearbox, the high-speed shaft, and the generator (fig. 16). All are mounted in the nacelle.

The rotor force, or torque, is transmitted by the low-speed shaft to the quill shaft, a flexible shaft which reduces the fatigue effects at the gearbox (fig. 17). This shaft improves generator output by reducing any motion extraneous to the rotational motion about the drive shaft's axis.

The rotor's torque is transmitted via the quill shaft to the gearbox, which effects a 103:1 step-up from the constant 17.5 rpm to a constant 1800 rpm delivered to the generator. The gearbox is a three-stage, epicyclic type that is smaller, lighter, less expensive, more efficient, and more tolerant of deflections than a parallel-shaft gearbox with a similar rating.

The generator is a synchronous generator rated at 2500 kW. This type of synchronous generator is widely used in other applications by utilities.

Parking Brake

The parking or rotor brake, located in the nacelle, consists of a disk mounted on the high-

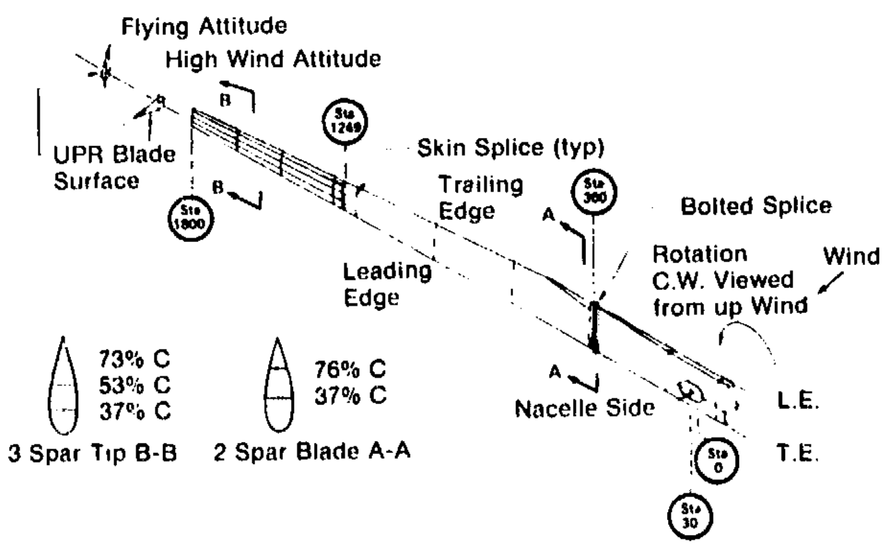


Figure 13. Steel Rotor Blade Configuration Mod-2

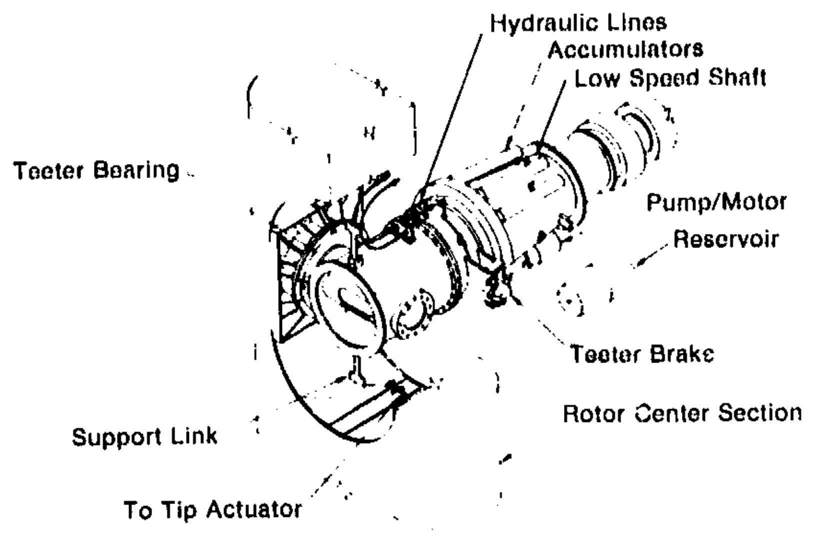


Figure 14-A. Pitch Hydraulic System Low Speed Shaft

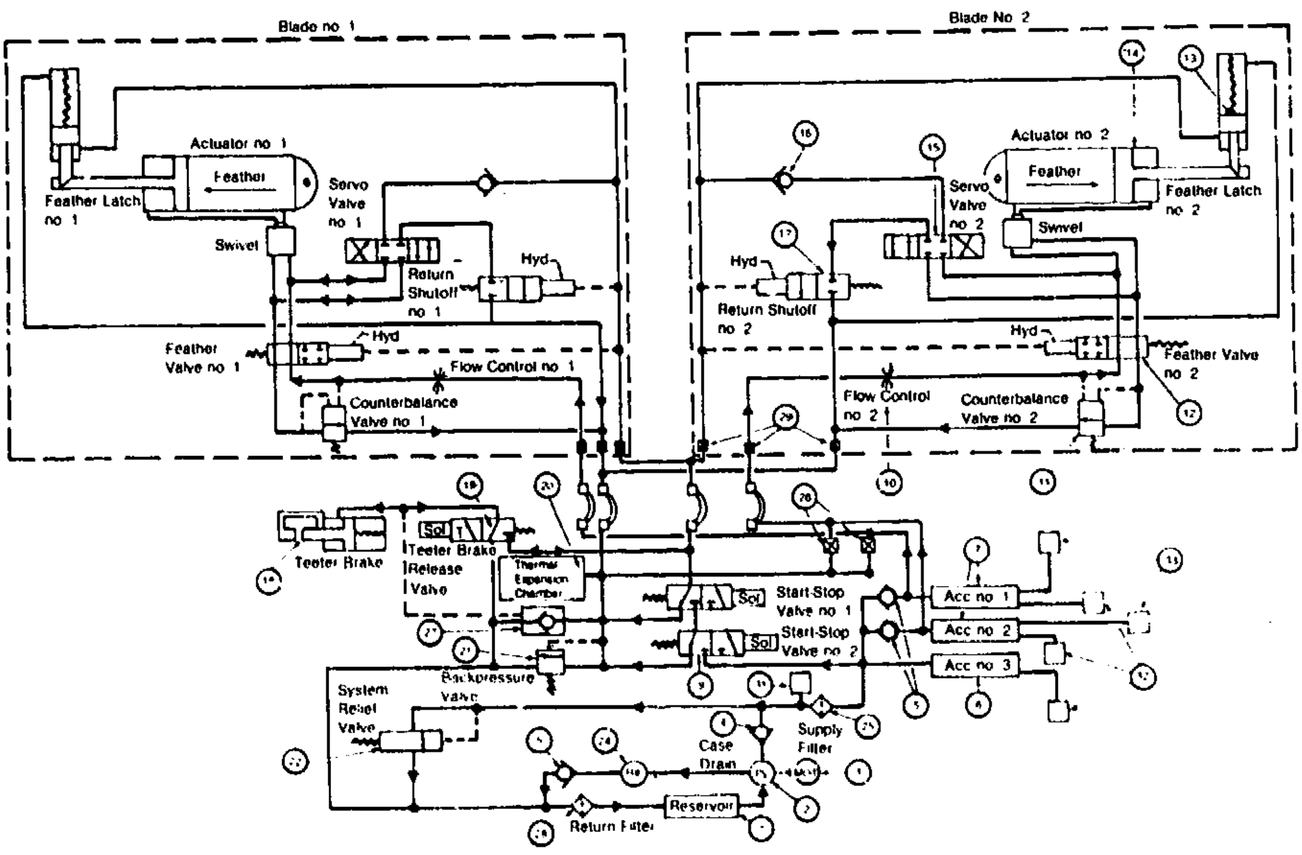


Figure 14-B. Hydraulic Schematic Pitch Control System Mod-2-107

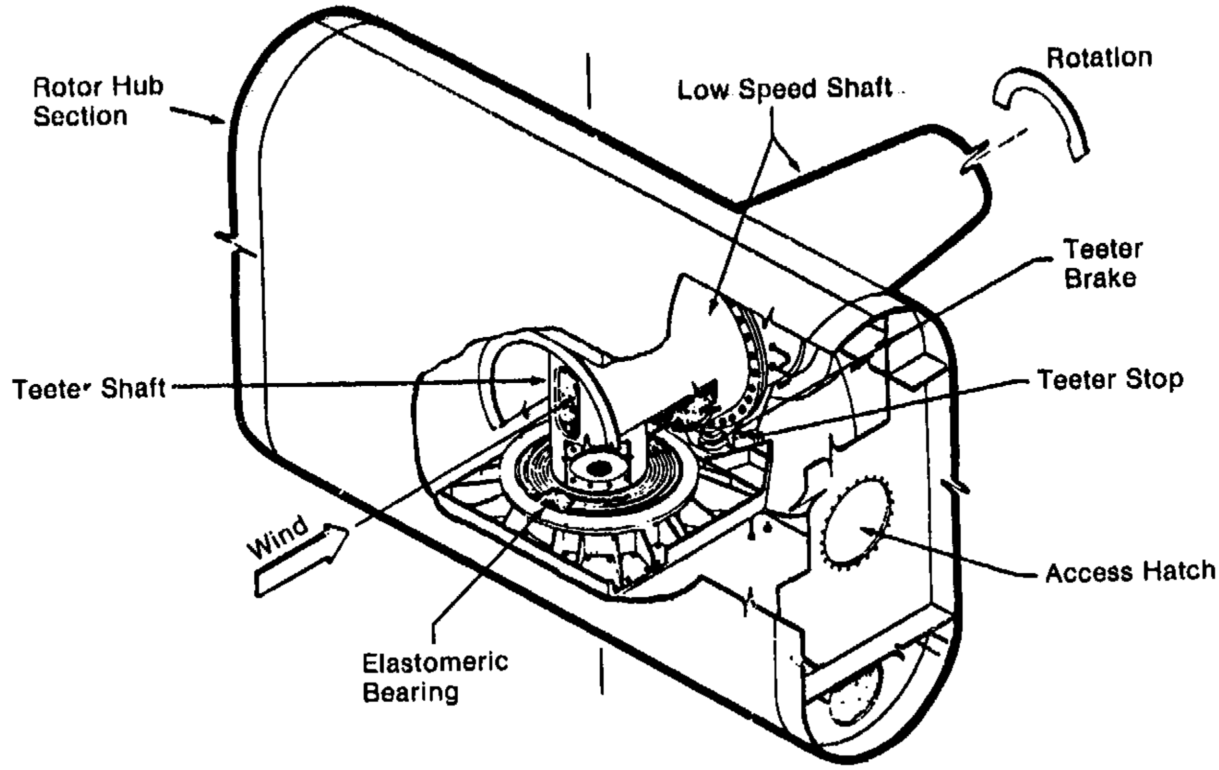


Figure 15. The Hub

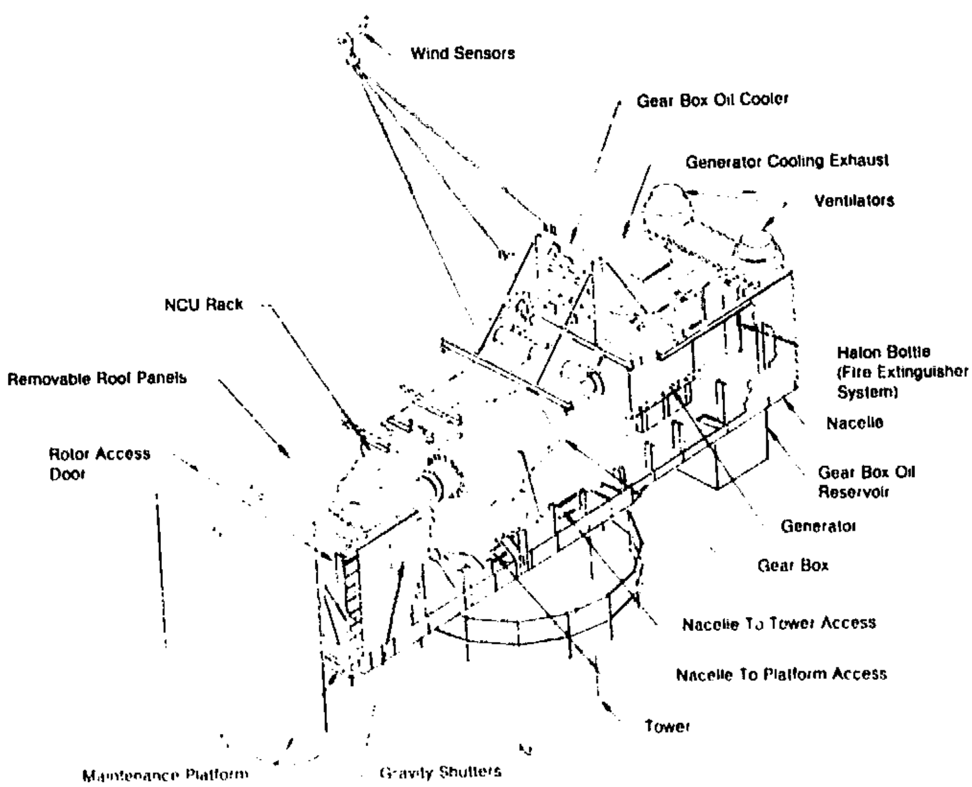


Figure 16. General Nacelle Arrangement Mod-2-107

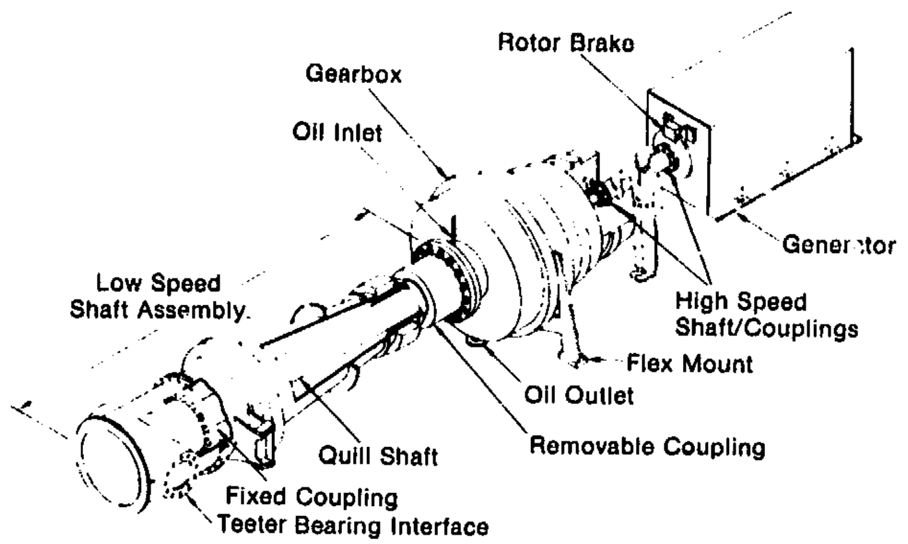


Figure 17. Drive Train

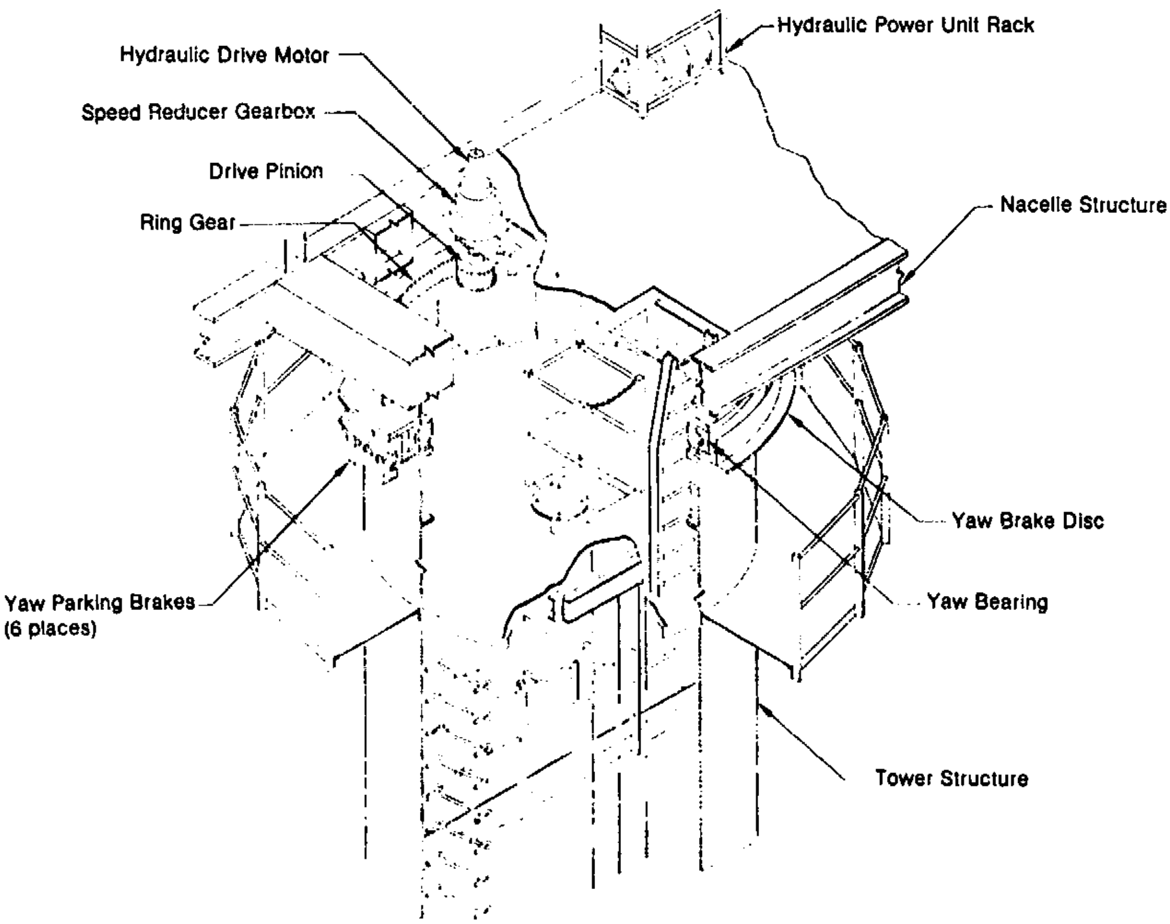


Figure 18. Yaw Drive Installation

speed shaft and a spring-actuated brake attached to the generator frame. The device serves as a parking brake to prevent rotor motion when the system is not in operation.

Yaw Drive System

The yaw system connecting the nacelle to the tower turns the rotor into the wind and holds it in position as commanded by the yaw control system (fig. 18). Wind direction sensors send signals to the yaw control system. The yaw system then holds the heading within a few degrees of the long-term average wind direction. Thirty-second average wind directions are monitored, and the control system changes heading whenever wind direction changes exceed 20°. This feature prevents extreme blade stress and minimizes power losses due to rotor heading error.

A hydraulic brake provides damping during yaw motion. Six additional brakes prevent inadvertent yawing of the nacelle. The power for the yaw drive system and brakes is furnished by a hydraulic system in the nacelle.

The Nacelle

The nacelle houses the major Mod-2 subsystems such as the drive train, generator, yaw bearing, drive subsystem, and the associated hydraulic subsystems for pitch and yaw control. It also contains cooling, fire protection, and maintenance equipment and protects these systems from weather and dust.

Tower, Foundation, and Facility Layout

The 193-foot-high tower supports the nacelle and rotor through the yaw bearing. The tower is composed of a 150-ft-long, 10-ft-diameter cylindrical tube which flares to a 21-ft-diameter base. The tower is mounted on a base of reinforced concrete. Each Mod-2 machine requires a square site, 400 ft on a side. Within this constant, however, the final layout of the machines in any wind-turbine cluster can be designed to take maximum advantage of available wind power. The Goodnoe Hills facility will be gathering data on possible intermachine effects.

Mod-0 Simulation of Mod-2

The concept of a dynamically soft tower, noted earlier to be a Mod-2 design innovation, was tested on the NASA Mod-0 at Plum Brook. It was not easy to make the Mod-0 rigid truss-style tower dynamically soft. To do so, engineers at the NASA Lewis Research Center designed gigantic leaf springs (fig. 19). They then lifted the entire Mod-0 and resettled it on the leaf springs. The Mod-0 then operated with its newly teetered rotor to provide researchers an estimate of the dynamic effects of the proposed Mod-2 design.

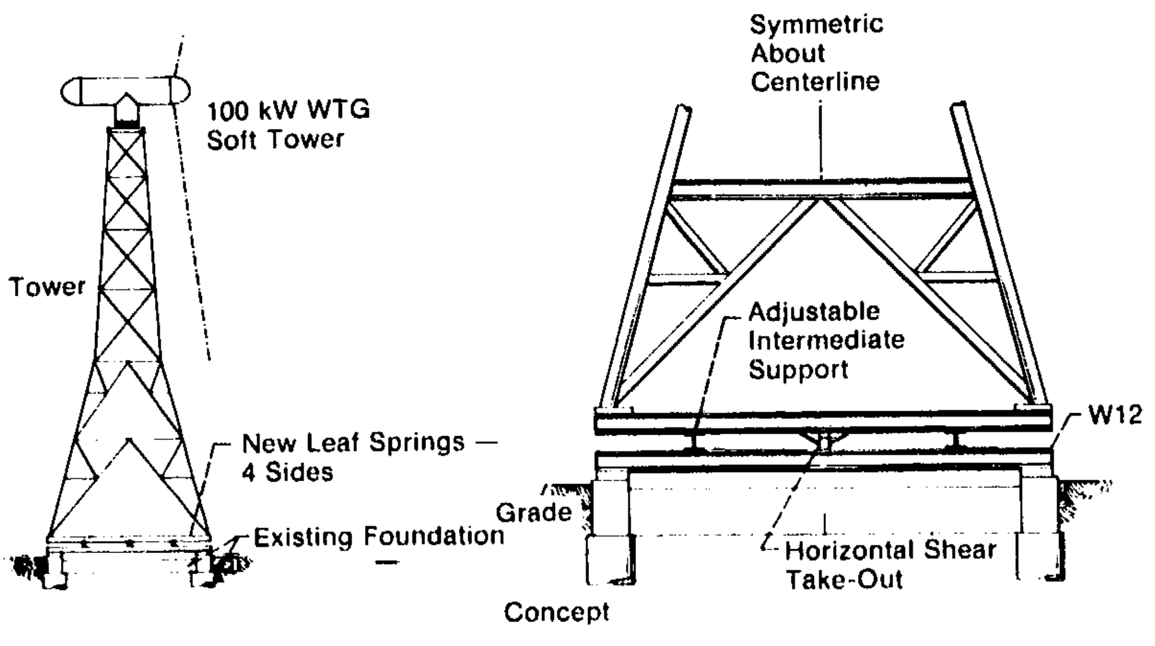


Figure 19. Soft Tower Simulation Fixture

The Mod-2 Electrical Power System

Normal power flows from the generator, mounted inside the nacelle, through the tower to a bus tie contactor at the base, then underground to the transformer and manual disconnect switch and, finally, to the utility's lines.

The electrical power system is designed to deliver power to the utility transmission network. It includes the electrical equipment required for the generation, conditioning, and distribution of electrical power. The generator is powered by synchronous speed torque from the gearbox. Electrical power at appropriate voltage is delivered to a utility interface point on the output side of . fused manual disconnect switch located at the tower's base. Once the wind turbine and the utility lines are electrically connected, the tie results in generator voltage and frequency control and maintains constant generator and rotor rpm.

Excitation control maintains proper voltage prior to synchronization with the utility. Protective relays guard against potential electrical faults, out-of-tolerance performance, or equipment failures by detecting overvoltage, loss of excitation, underfrequency, overcurrent, reverse phase sequence, reverse power, and differential current. These relays protect the system by inhibiting synchronization, directing the control system to shut down the wind turbine or, if required, tripping the generator circuit breaker.

The Mod-2 Control System

For the wind turbine system to provide safe, reliable operation at a remote, unattended site, it must

- Control production of electric power over a wide range of wind velocities, including startup, shutdown, and synchronizing activities
- Align the rotor assembly with the wind direction
- Protect against damage due to abnormal operating conditions and extreme environmental conditions.

The principal controller is a microprocessor which is located outside the nacelle. The microprocessor initiates startup when the wind is within the prescribed operating limits. It also implements fail-safe actions. The microprocessor continuously monitors wind conditions, rpm, power, and equipment status and shuts the system down for out-of-tolerance conditions.

A control panel and a cathode-ray tube (CRT) terminal are located in the tower's base to provide displays of operating and failure data and to allow manual control during maintenance. A remote CRT terminal at the utility substation provides a similar display and limited wind turbine system controls.

The Mod-2 is protected from computer system failure or any unsafe operating condition by an independent fail-safe shutdown system. The electrical system contains relays which guard against electrical faults, overload conditions, and equipment failures by inhibiting synchronization with the utility grid, directing the control system to shut down, or, if necessary, tripping the generator circuit breaker, resulting in high-speed shutdown. The generator is protected by overtemperature sensors. Thus, the Mod-2 wind turbine is fail-safe. If any condition outside the safe operating range is detected, the safety system automatically shuts the wind turbine down. For example, in the event of rotor overspeed, a speed sensor would issue the command to feather the blades, which would stop the rotor (fig. 20).

After startup, the microprocessor computes commands for blade pitch and nacelle yaw to yield maximum power output. This system continuously monitors wind conditions, rpm, power, and equipment status and shuts down the wind turbine system when conditions exceed tolerance levels. The microprocessor monitors the pitch actuator yaw assembly, drive-train assembly, nacelle electrical power system, and wind sensors.

Data on the wind and the generator are fed into the microprocessor, which in turn controls blade pitch. Below cut-in wind speed and above cut-out wind speed, the blades are feathered so as to not react to the wind pressure. Between cut-in wind speed and rated wind speed the blade pitch is set at the most aerodynamically efficient position. To accommodate variations in wind speed and still maintain a constant rotor speed, the aerodynamic efficiency is varied by altering pitch. Thus, the sensors designed to monitor wind direction and speed make appropriate changes in blade pitch and assist the control system.

Mod-2 Engineering Parameters

With each component designed for maximum system performance, Mod-2 operates at its rated wind speed of 27.5 mph with a power coefficient somewhat below theoretical maximum because of friction in the teeter bearings, rotor-shaft bearings, and the high-speed flexible coupling. The epicyclic gearbox design is relatively efficient since its gears are compact and the gear-tooth contact velocities are low. The generator absorbs power due to windage, field excitation, copper resistance, and bearing friction losses. For this generator the efficiency remains nearly constant even when the output power is reduced.

The Mod-2 is the first large wind turbine designed specifically to minimize electricity cost.

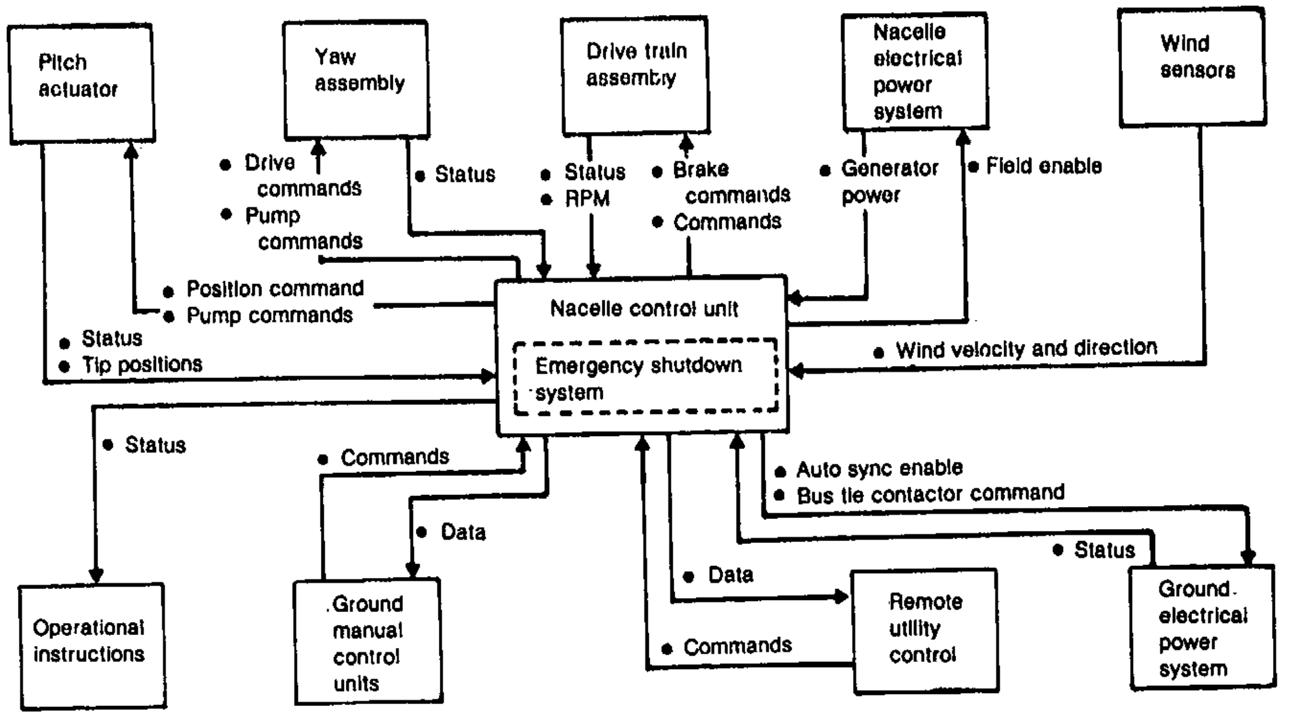


Figure 20. Control System Interface Diagram

In addition to engineering considerations, safety features and procedures were inherent factors in designing for cost. Environmental and operational hazards were significant. Environmental hazards include seismic activity, extreme winds, lightning, temperatures, hail, snow, ice moisture, and windborne objects. Operational hazards include the stresses or "loads" that the wind turbine components will be subjected to over their projected 30-year life.

Although startup and shutdown cycles are few, relative to the total number of rotations, the stress exerted is relatively high and contributes significantly to wind turbine system fatigue. Each turbine component experiences load variations during every startup and shutdown. Over 30 years, the rotor may turn 200 to 400 million times. The startups and shutdowns could number 25,000. To assure safe-life, the machine is designed for 75,000 startups to compensate for partial startups. Other cyclic stresses exist as well. For example, each revolution of the rotor stresses the blade with bending moments caused by gravity. Loads also vary because of decreases in wind speed near the ground due to surface features or wind gusts.

Operating loads or stress, environmental loads, and nonoperating loads were calculated in designing the Mod-2. The major parameters involving operating loads were

- Extreme gustiness during normal operation in which the nacelle is at a yaw angle within 20° of the mean wind
- Overspeed 115% of the normal rotor rpm
- Inadvertent blade feathering caused by failure of the hydraulic or control system
- Inadvertent rotor, yaw, or teeter braking caused by failure of the hydraulic or control system.

The wind turbine was designed for specific environmental loads:

- The turbine must withstand reasonable seismic disturbances
- The blades, nacelle, and tower are designed to withstand the impact of large birds or other objects moving at 35 mph
- Turbine components and shipping containers must be designed to withstand transportation and handling stresses
- The turbine must be able to sustain lightning strikes without damage
- The turbine must withstand the impact of 1-in.-diameter hailstones
- The turbine must operate in temperatures between -40° to +120° F.

The wind turbine must also survive these nonoperating stresses:

- The turbine must withstand a maximum steady wind of 120 mph at 30 ft above ground with the rotor parked and braked in any position
- The turbine must withstand 21 lb/ft^2 of snow on the rotor blade when parked horizontally and 41 lb/ft^2 of snow on the nacelle roof
- The turbine must withstand 2 in. of glaze ice on all exposed surfaces.

Load calculations were the basis of Mod-2 design and safety features (fig. 21). In addition to calculating loads and sizing components accordingly, design details for critical components were verified by structural tests of full-scale hardware.

Three design concepts apply to operation and safety: fail-safe, safe-life, and product assurance. Fail-safe means that a component or structure will fail in one of three safe ways: adequate warning is given so that corrective action can be taken; or the system automatically corrects the problem; or the machine is automatically shut down.

Mechanical and electrical components are designed for safe shutdown upon failure. Where this is not possible, back-up systems keep the machine running until the operator is warned to take action. Structural components are capable of sustaining detectable damage for a reasonable time between inspections without catastrophic failure.

All parts of the Mod-2 structure not fail-safe were designed to meet safe-life criteria. Safe-life requires that the structure sustain no failure during its service life. Expected service lives are established for such hardware, and fatigue tests have verified each estimate of safe hardware lifetime. Mod-2 hardware is designed to the safe-life concept when high cost or weight prevent the fail-safe alternative.

Product assurance or quality control assurance plans are an integral part of the Mod-2 testing and safety programs. Components or processes must meet quality acceptance criteria. Inspections and test data are documented and reviewed for proof of completion at the "readiness" reviews. These reviews precede installation, first rotation, and turning over the wind turbine system to the operating utility.

Where unique or critical components, practices, or procedures are involved, more stringent controls are invoked. For example, critical forgings for blade material can be traced from the original melt or rolling process for quality control purposes.

Failure Analysis

Extensive analyses were conducted to estimate the types of failure possible in all Mod-2 components. For each possible failure the projected effect on the operation of the Mod-2 was established. Corrective measures were incorporated to eliminate adverse or unsafe effects. Typical examples of this type of failure mode and effect analysis are shown in table 5.

Readiness Review

The readiness review occurs after the wind turbine system is completely installed, and all

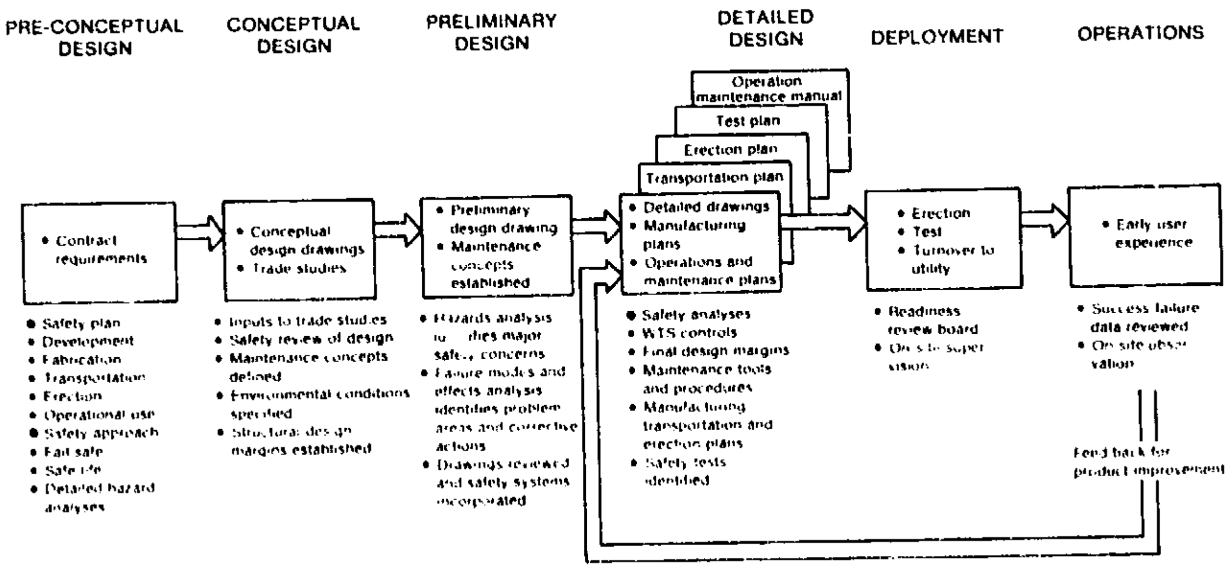


Figure 21. Mod-2 Project Flow Diagram

TABLE 5.—SUMMARY OF POSSIBLE FAILURES AND PROJECTED EFFECTS

Failure	Effect	Corrective action
Tower		
Failure of structure or foundation	Extensive damage	Safe life design
Control System Failures		
Signal to one tip incorrectly drives control surface to zero	Emergency shutdown triggered by differential of tip position	None required, analysis verifies that one tip operative can safely stop rotor
Control system signal to both pitch actuators incorrectly drives control surfaces to zero pitch	Emergency shutdown triggered by generator output power	None required—shutdown occurs before damaging overspeed
Power output sensor fails, calling for power increase when system is already at full power output	Damaging overspeed possible if load drops off before initiating shutdown	System changed to command shutdown before load dropping off. Also, backup power sensor signal sent to controller
Electrical Power Failures		
Synchronizer provides signal to close bus tie contactor too soon or too late	High current transient causing high torque load on the generator that could cause mechanical or drive train damage	Synchronizer is fully redundant and fail safe
Loss of commercial power while WTS is at rated power	Rotor speed increases	None required—shutdown occurs before damaging overspeed

functional and fail-safe tests are complete. Only after this review can the turbine turn under wind power.

The Mod-2 safety system includes:

- Safe-life design of all structural elements
- Constant system monitoring by microprocessor
- Shutdown capability on failure of any primary or monitoring device
- Independent, redundant safety sensors and shutdown system
- Fully protected electrical equipment
- Compliance with Occupational Safety and Health Act (OSHA) and other applicable construction codes.

In complying with all applicable OSHA requirements, Mod-2 designs used MIL-STD-1472, "Human Engineering Design Criteria for Military Systems, Equipment, and Facilities," as a guideline. Sources of safety design criteria are summarized in Table 6. Additional safety features such as backup personnel safety systems, emergency exit doors, and escape devices were also used. Figure 22 summarizes the Mod-2 safety system.

Operations and Maintenance

Operations and maintenance manuals for utility personnel are provided during a four-week training course for utility operators and dispatch and maintenance personnel. The Mod-2 operates without any manual control, and, as such, is compatible with standard utility operations and maintenance practices. However, the utility operator of a wind farm must check the operational status of each unit and dispatch maintenance from a central utility substation. These central substation displays of wind turbine performance parameters are very important for smooth operation (fig. 23).

The Future of Wind Energy

Although further wind turbine development is planned, Mod-2 machines carried into the

TABLE 6.—SAFETY CONSIDERATIONS

General "Design for Safety" Criteria	Mod-2 safety system	
Occupational Safety and Health Act of 1970 (Public Law 91-596) and applicable State Safety Regulations	All structural members "safe life" designed, all controls and electrical systems designed for "fail safe"	Unauthorized entry disables WTS "Buddy" system used for all maintenance
MIL-STD-1472, Human Engineering Design Criteria for Military Systems, Equipment and Facilities. IEEE Standard 142-Grounding of Industrial and Commercial Power Systems	Capability to remove person on stretcher from Nacelle	All hazardous rotating devices guarded
ANSI C2 American National Standard, National Electrical Safety Code, 1977 Edition	Automatic fire detection and extinguishing system	Aircraft warning lights and markings per FAA regulations
	Emergency exit doors and "Rescumatic" device to allow egress from either end of Nacelle in case of uncontrolled fire	Scheduled maintenance plan to ensure integrity of safety systems
	Ability to lock rotor in horizontal and vertical positions (lock on low speed shaft)	

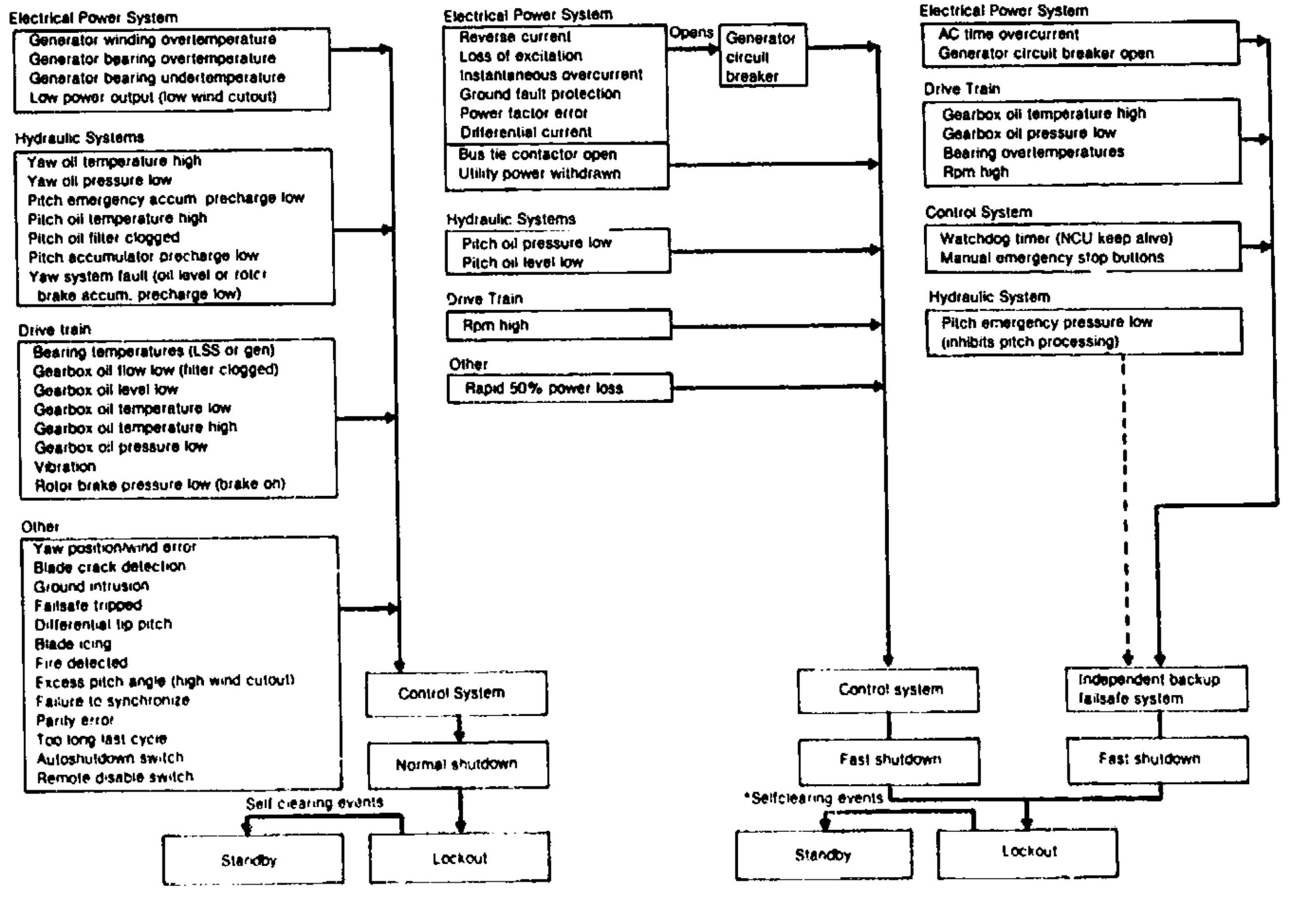
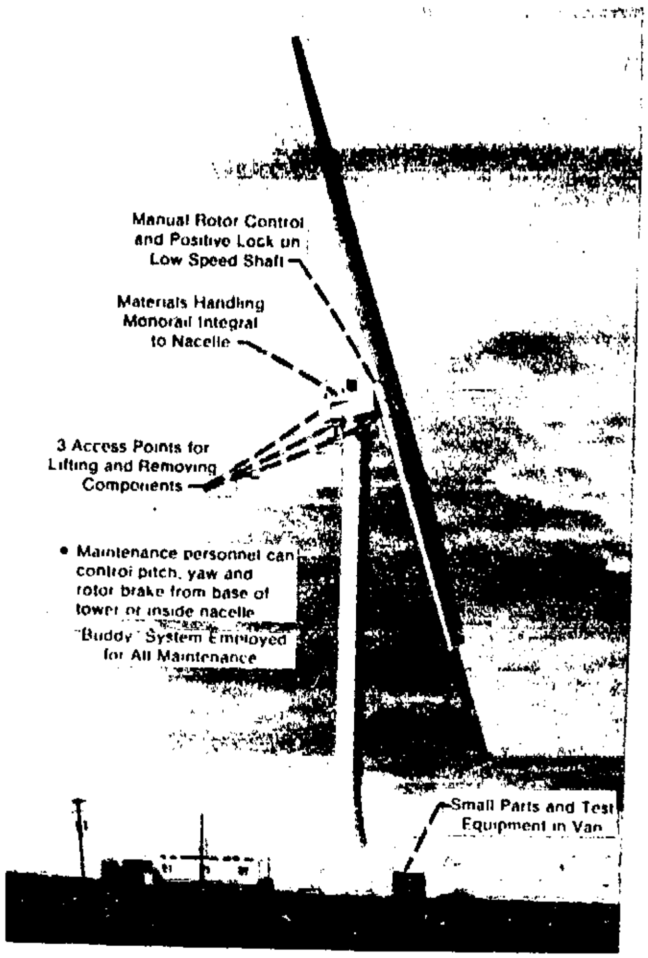


Figure 22. Mod-2 Safety/Shutdown System



Maintenance Concepts and Costs

- 2-shift coverage, 2-man crews, 6 days per week
- Outside services used for shop repairs, special tasks and heavy equipment rentals
- Annual O&M costs for WTS (for 25-unit farm)

• Labor	$3,000
• Materials, parts and outside services	$7,000
Total	$15,000

Figure 23. Maintainability Features

production stage may be the backbone of the nation's first wind clusters. For example, a 25-unit Mod-2 cluster could produce 62.5 MW. The wind turbines would be spaced less than a mile apart in a staggered pattern, combined in groups of four or five units around a substation. Sprinkled across our country, such clusters could readily tap a continuous, nonpolluting, free, and totally renewable energy source—a source which may soon supply a significant portion of our nation's electrical energy needs.

Concluding Remarks

The Mod-2 wind turbine project described is one phase of the Federal Wind Energy Program managed by the NASA Lewis Research Center for DOE. Industry, public utilities, and the government have been working partners in this program designed to produce the technology to supply wind generated electric energy. Industrial involvement in machine development provides the necessary commercial base, while utility operation of the evolving machines in their networks assures a viable end product in this government-supported program.

For further information contact:

NASA Lewis Research Center
Public Information Office
21000 Brookpark Road
Cleveland, Ohio 44135

Bonneville Power Administration
Department of Energy
Bonneville Power Administration
Public Information Office
P.O. Box 3621
Portland, Oregon 97208

Boeing Energineering and Construction Co.
Public Relations Director
P.O. Box 3707, M/S 9A-22
Seattle, Washington 98124

Bibliography

Boeing Engineering and Construction Co.: Mod-2 Wind Turbine System Concept and Preliminary Design Report. Vol. I, Executive Summary and Vol. II, Detailed Report. DOE/NASA/0002-80/2, July 1979.

Glasgow, J. C.; Robbins, W. H.: Utility Operational Experience on the NASA/DOE Mod-0A 200 kW Wind Turbine. DOE/NSA/1004-79/1, NASA, TM-79084. Paper presented at Energy Technology VI Conference; February 26-28, 1979, Washington, D.C.

Linscott, B. S.; Glasgow, J.; Anderson, W. D.; Donham, R. E.: Experimental Data and Theoretical Analysis of an Operating 100-kW Wind Turbine. DOE/NASA/1028-78/15, NASA TM-73883. Paper presented at Twelfth Intersociety Energy Conversion Engineering Conference, August 28, September 2, 1977, Washington, D.C.

Lynette, R.; and Poore, R.: Mod-2 Failure Modes and Effects Analysis. DOE/NASA/0002-79/1, July 1979.

Puthoff, R. L.: Fabrication and Assembly of the ERDA/NASA 100-Kilowatt Experimental Wind Turbine. NASA TM X-3390, 1979.

Robbins, W. H.; Thomas, R. L.: Large, Horizontal-Axis Wind Turbine Development. NASA TM-79174, 1979.

Robbins, W. H., Thomas, R. L., and Baldwin, D. H.: Large Wind Turbines—A Utility Option for the Generation of Electricity. DOE/NASA/023139-1, NASA TM-81502, 1980.

Spera, D. A.: Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines. DOE/NASA/1028-78/16, NASA TM-73773. Paper presented at Third Biennial Conference and Workshop on Wind Energy Conversion Systems, September 19-21, 1977, Washington, D.C.

U.S. Department of Energy: Environmental Assessment, Eighteen Prospective Mod-2 Wind Turbine Sites—The Goodnoe Hills, Washington Installation Site. DOE/EA-0096, 1979.