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Experience and Assessment of the DOE-NASA Mod-1 2000-Kilowatt Wind Turbine Generator at Boone, North Carolina

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SUMMARY

The broad objectives of the Mod-1 program are defined, including the background information leading to the inception of the program. Activities on the Mod-1 program began in 1974, and the turbine was dedicated in July 1979. Rated power generation was accomplished in February 1980. The Mod-1 wind turbine is described in this report. In addition to the steel blade operated on the wind turbine, a composite blade was designed and manufactured. During the early phase of the manufacturing cycle a Mod-1A configuration was designed that identified concepts such as partial span control, a soft tower, and upwind teetered rotors that have been incorporated in second- and third-generation industry designs.

The Mod-1 electrical system performed as designed, with voltage flicker characteristics within acceptable utility limits. Power output versus wind speed has equaled or exceeded design predictions. The wind turbine control system was operated successfully at the site and remotely from the utility dispatcher's office in Lenoir, N.C. During wind turbine operations, television interference was experienced by the local residents. As a consequence, operations were restricted. Although not implemented, two potential solutions were identified. In addition to television interference, a few local residents complained about objectionable sound, particularly the "thump" as the blade passed behind the tower. To eliminate the residents' objections, the sound generation level was reduced by 10 dB by reducing the rotor speed from 35 rpm to 23 rpm. During January 1981, bolts in the drive train fractured. A solution has been identified but not implemented as yet. During the past 2 years the public reaction toward the Mod-1 Wind Turbine program has been overwhelmingly favorable. This includes the vast majority of Boone residents.

INTRODUCTION

The Federal Wind Energy program administered by the Department of Energy (DOE) has as one of its goals the development of the technology for practical, cost-competitive wind turbines that can be used to supply significant amounts of electric energy. As a part of the wind turbine development, the Lewis Research Center of the National Aeronautics and Space Administration (NASA) was given the responsibility to carry out the Mod-1 program. The General Electric Co. (GE), under contract to Lewis, designed, built, and installed the Mod-1 wind turbine at Howard's Knob in Boone, N.C. The Blue Ridge Electric Membership Corp. (BREMC), a rural cooperative with headquarters in Lenoir, N.C., received the power generated by the Mod-1 wind turbine; and BREMC operated the wind turbine remotely from the dispatcher's office in Lenoir.

The overall objective of the 2-MW Mod-1 program was to obtain early operational and performance data that could be used in the design of second-generation cost-competitive wind turbines. The Mod-1 wind turbine was the first megawatt-size machine in the Federal Wind Energy program to produce electric power from wind energy. Specific project objectives were as follows:

(1) To obtain operational and performance data for a megawatt-size wind turbine in a utility-operated application

(2) To demonstrate unattended, fail-safe operation

(3) To involve a utility as user and operator

(4) To identify maintenance requirements for large wind turbines

(5) To involve industry in the design, fabrication, and installation of a wind turbine

(6) To identify component and subsystem modifications that will reduce cost, improve reliability, and increase performance

(7) To assess public reaction to and acceptance of large wind turbines

(8) To demonstrate compatibility with utility requirements

A very significant benefit of the Mod-1 program was the discovery that under some conditions the wind turbine emitted an objectionable sound level to 10 families living near the site. Methods to characterize the sound in order to establish acceptable sound standards and to reduce the sound levels became a significant part of the Mod-1 program.

The chronology of the major events in the Mod-1 program is as follows:

Project begun	1974
Contract placed with General Electric Co.	July 1976
First rotation	May 1979
Turbine dedicated	July 1979
Turbine synchronized with BREMC network	September 1979
Semiregular operation begun	October 1979
Turbine acceptance testing completed	January 1980
Utility training completed	February 1980
Full power (2000 kW) generated	February 1980
Reduced-rotor-rpm modification completed	November 1980
Drive train problem developed	January 1981

There have been many participants involved with the Mod-1 program that have contributed to its success. R. Puthoff, NASA Lewis Research Center, and R. Barchet, General Electric Co., made outstanding contributions to the program. Successful completion of the program would not have been possible without project support from G. Ayers, Jr., and R. Bumgarner of BREMC in North Carolina.

DESCRIPTION OF MOD-1 WIND TURBINE GENERATOR

Current Mod-1 Wind Turbine Generator

The Mod-1 2000-kW wind turbine generator is mounted on top of a truss tower with its horizontal rotor axis 140 ft high. Its two blades are 200 ft in diameter (fig. 1) and located downwind of the tower. The nacelle-bedplate, which supports and encloses all equipment mounted on top of the tower, is driven through a yaw-bearing assembly that rotates about the vertical axis of the tower in response to changes in the wind direction. The tower is 12 ft square at the top and 48 ft square at the bottom and is anchored to reinforced concrete footings at each leg. Figure 2 shows the machine installed on Howard's Knob, in Boone, N.C. The elevation at the site is approximately 4500 ft above sea level. The original design specifications are presented in table I.

The wind turbine assembly consists of the rotor assembly, the drive train - bedplate assembly, the yaw assembly, and the tower (fig. 3). The turbine rotor initially operated at 35 rpm and generated 2000 kW of electric power in a 25.5-mph wind (at 30 ft); it was modified to 23 rpm and 1350 kW in November 1980. The hub and blades are connected to a low-speed shaft that drives a gearbox. In the gearbox the low-speed shaft speed was increased from 35 rpm to 1800 rpm and later from 23 rpm to 1200 rpm. A high-speed shaft connects the gearbox to the alternator. The entire system weighs 655 000 lb, 335 000 lb in machine weight and 320 000 lb in tower weight. Table II presents a weight breakdown of the machine. The major components are described in the following subsections.

<u>Rotor assembly</u>. - The rotor assembly consists of three major subassemblies: the blades, the hub assembly, and the pitch-change mechanism. Each blade is attached to the hub through a three-row, cylindrical roller bearing that permits the full pitch of the blade from the power position (0°) to the feather position (90°). Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades at an average rate of 8 deg/sec.

The blades are constructed of a monocoque, welded-steel leading-edge spar and an aerodynamically contoured, polyurethane foam afterbody with bonded 301 stainless-steel skins (fig. 4). Measuring 100.8 ft long with a tapered planform and thickness, the blade uses an NACA 44XX series airfoil with a thickness ratio varying from 20 percent at the tip to 33 percent at the root. The blades, which weigh approximately 21 500 lb each, are assembled in six main sections. Spar welds are located at five stations, as are the trailing-edge-section splices. A transition piece is welded to the spar to provide the blade continuity to the interface with the hub. A longitudinal stiffner and chordwise webs are welded in the spar to provide buckling strength. Ballast weights are used at each blade tip for static and dynamic balance.

The hub assembly consists of a hub barrel and a hub tailshaft (fig. 5). The hub barrel houses the pitch-change bearing and supports the blades at a 9° cone angle. The tailshaft joins the barrel with a 120° saddle flange and a transition to the circular main-bearing seat and flange. The main rotor bearing is shrink fitted to the hub tailshaft and bolted to the bedplate adapter to form the rotor-bedplate interface.

The pitch-change mechanism positions the blades in response to commands from the control system. It consists of hydraulic actuators, swing links, a thrust ring and bearing, and two blade pitch rods (fig. 6). The stationary hydraulic actuators translate fore and aft motion to the rotating (35 rpm) pitch assembly through a thrust ring. This assembly is supported by both stationary and rotating swing link arms to maintain clearance from the low-speed shaft and thus allow the fore and aft motion to change the pitch of the blade through the pitch rods.

Drive train - bedplate assembly. - The drive train assembly consists of a low-speed shaft and couplings, a three-stage gearbox, and a high-speed shaft that drives the alternator (fig. 7). The high-speed shaft incorporates a dry-disk slip clutch for protection against torque overloads and a disk brake that will stop the rotor in the event of an overspeed condition and also is used to hold the rotor in a parked position. The entire assembly is supported on a bedplate and enclosed in an aluminum nacelle fairing for protection.

Yaw drive assembly. - Yaw rotation of the machine to align with the wind is provided by the yaw drive, which consists of upper and lower structures, a cross roller bearing, dual hydraulic drive motors, and six hydraulic brakes (fig. 8). Each yaw motor drives a pinion meshing with a ring gear on the inner race of the yaw bearing. The yaw brakes dampen dynamic excitations in yaw motions while the nacelle is being driven. These components are housed in a yaw structure that interfaces between the machine and the pintle structure of the tower.

Tower. - The steel tubular truss tower (fig. 1) is made of seven vertical bays with bracing designed for bolted field assembly. Tubular members were used to reduce "tower shadow" loads on the blades as they pass the tower. The tower was designed to provide stiffness in the lateral and torsional modes. The bending frequency is 2.8 times the rotor operating frequency, and the torsion frequency is 6.5 times the rotor operating frequency. The maximum design wind load is 150 mph. All tower members were fabricated from A333 steel, which provides good low-temperature fracture toughness.

The tower is supported by separate foundations for each of its four legs. Because of the deadweight of the wind turbine, relatively small tension loads are developed in the foundation. Each leg is secured by eight 1.5-in.-diameter anchor bolts hooked at a depth of 30 in. into the foundation. Tower baseplate shear loads react through a nonshrink grout to a lip on the foundation that is tied into reinforcing bars in the foundation.

Control system. - The control system for the wind turbine includes a PDP Digital Equipment Corp. 11/34 computer located in the ground enclosure at the base of the tower. The PDP 11/34 interfaces with two PDP 11/04 microcomputers. One PDP 11/04 is located in the control enclosure, and the other in the nacelle. The control system provides unattended safe and reliable operation of the wind turbine plus the features of a data logging system. It will automatically start, operate, and stop the machine, align it with the wind, and provide dispatcher control through a telephone link. In addition, if the control system detects any operation or machine anomaly, it is programmed to safely shut the wind turbine down. Figure 9 presents a simplified control schematic. Reference 1 provides additional Mod-1 information on the actual installation and checkout of the machine. References 2 to 4 provide a detailed description and a summary of the design calculations, including an analysis of failure modes and effects.

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Kaman Composite Blades

Two composite rotor blades, designed and built specifically for operation on the Mod-1 wind turbine by Kaman Aerospace Corp., Bloomfield, Conn., have recently been completed. The design, manufacture, and ground testing of these blades are described completely in reference 5. These blades were developed as the second phase in NASA's on-going evaluation of the applicability of composite construction for very large wind turbine blades. The first phase served to develop the technology for such blades and demonstrated this in a 150-ft test blade, which was completed and static tested in 1978. This was the largest composite rotor blade ever constructed and successfully demonstrated the potential of this material.

The final blades, illustrated in figure 10, are fully compatible with the Mod-1 wind turbine and possess dynamic characteristics equivalent to those of the present steel blades. The blade's main structural member is the D-spar, which reacts all primary loads and comprises over 70 percent of blade weight. The spar was constructed by the transverse filament tape (TFT) process, first used for a rotor blade in the 150-ft-blade program. An epoxy resin is used for its superior fatigue strength, compatible with the 30-year design life of the blades. The afterbody portion of the blade, a lightweight structure that completes the airfoil cross section, comprises upper and lower panel members. These are of sandwich construction, inner and outer fiberglass skins with a honeycomb core of resin-impregnated kraft paper; the panels vary in thickness from 1 in. to 3 in. An adapter fitting of welded steel construction is permanently installed at the inboard spar end by means of a bolt attachment. The blades incorporate lightning protection that is capable of withstanding 200 000-A strokes. The lightning protection is configured to minimize its adverse effect on the inherently low-television-interference characteristics of composites. The new blade also includes an ice detection device, as well as a polyurethane paint system and leading-edge protection to withstand environmental effects.

Mod-1A

Shortly after the Mod-1 wind turbine final design was completed, a trade-off study was begun on a conceptual design that would take advantage of innovative design approaches that were identified during the Mod-1 design experience but that could not be incorporated in the Mod-1 because of schedule and cost constraints. This design concept, which was called Mod-1A, had as its basic objectives the reduction in weight from 327 to 200 tons and in the cost of energy from 18 to 5¢/kW-hr (in 1978 dollars), see table III. In the trade-off study, three candidate systems were identified, as shown in figure 11.

Configuration 3, which has as its major characteristics a teetered hub, two upwind blades with partial span control, an integral, parallel-shaft gearbox structure, an inclined rotor axis, and a "soft" shell tower, was selected. The Mod-1A overall configuration is shown in figure 12. A view of the upper portion of the tower and nacelle is shown in figure 13. Although the Mod-1A was not built, many of the concepts identified in this trade-off study have been incorporated in second- and third-generation designs.

EXPERIENCE AND ASSESSMENT

Effect of Power Generation on Utility Grid

Wind turbine power generation system. - The Mod-1 wind turbine power generation system is shown in figure 14. It consists of a synchronous generator, a contactor, and a stepup transformer, with auxiliary power connections on the line side of the contactor. High-resistance grounding is provided for the generator to limit ground-fault current levels. The contactor is an unfused 5-kV-class motor starter with a latching circuit-breaker mechanism. Its 50-MVA interrupting rating is more than is needed to clear faults fed by either the generator or the utility system. The stepup transformer is delta connected at 4.16 kV with a generator Y-connection. At the 12.47-kV utility side the Y connection is solidly neutral grounded and has lightning arrestors and a fused load-break switch for disconnection and protection of the transformer.

The generator has two controls on its output: real power and excitation. Real power is controlled at the turbine rotor through full-span blade pitch control, and excitation is controlled through a voltage regulator and auxiliary equipment that feeds the generator shaft-mounted brushless exciter. Power control is inactive for wind speeds below rated wind speed, and at these speeds the Mod-1 output will fluctuate with wind speed and deliver as much power as it can extract from the wind. For wind speeds above rated wind speed the controller regulates average power output to the level of the system torque rating with an integral-plus-lag-power-error type of feedback control. The excitation system controls voltage prior to synchronization with the grid. Voltage, power factor, or reactive power control modes may be selected after synchronization. Most operation has been in the reactive power control mode with a 250-kVAR delivery to the grid. A stabilizer circuit is also used to modulate the excitation in response to hub speed fluctuation.

Blue Ridge Electric Membership Corp. system. - The Blue Ridge Electric Membership Corp. (BREMC) 12.47-kV distribution system around Boone, N.C., is shown in figure 15. The Mod-1 wind turbine is connected to the Howard's Knob circuit, one of three radial feeders from the Boone substation. Other connections are possible with manual switching, to feed the Sherwood or Hound Ears substations. The effective impedance seen by the wind turbine generator to an infinite bus equivalent is 0.142 per unit on the originally installed generator base of 2 MVA.

The Boone substation has a 12.47-kV-bus voltage regulator and a recloser on each feeder. A voltage blocking device was added to the Howard's Knob circuit recloser to prevent nonsynchronous reclosing with the wind turbine generator. The substation transformer rating was raised from 6 MVA to 7.5 MVA in October 1980 by BREMC and has had a 45-min peak load of 8.1 MVA recorded in 1981. About 3600 customer accounts are served by the Boone substation, of which 660 are on the Howard's Knob circuit. A residence located 1400 ft from the wind turbine is the closest load. The most voltage-critical load is a water filter plant with 350 total motor horsepower and 67 percent undervoltage dropout on the circuit breaker. The Bamboo circuit, connected to the Boone 12.47-kV bus, has about 1370 accounts, including a hospital and motor loads at a sewage treatment plant.

Utility requirements. - Maintaining constant voltage, providing service, and protecting equipment from faults are the primary operating goals of BREMC. BREMC operation maintains voltage within a 5-percent band by using regulators and other devices and limits the size of customer motors that can be full-voltage started. A standard voltage flicker chart, shown in figure 16, is appropriate for dynamic voltage fluctuations that elicit negligible complaints and therefore are acceptable to most utilities. The utility grid acts as a large source/sink at constant frequency relative to the wind turbine, and large power fluctuations in the connecting line are not objectionable to the utility as long as they do not cause objectionable voltage fluctuations in the line.

General operating experience. - BREMC has received no complaints associated with Mod-1 power or voltage disturbances. To quantify the voltage characteristics on the BREMC system, voltage recorders were temporarily installed by BREMC on the 12.47-kV line at the Boone substation and on a circuit supplying power to the meteorological tower that is about 200 ft from the Mod-1 wind turbine. Typical traces from these recorders are shown in figures 17(a) and (b), respectively. Figure 17(c) shows the line-to-line voltage and phase current at the generator during a transient (breaker closure followed by breaker opening) that occurred during the same period that voltage was recorded at the Boone substation and at the meteorological tower circuit. Although the site voltage fluctuation was almost 7 percent, the voltage variation at the Boone substation was not discernible on the recorder traces. Most of the recorder voltage change is due to voltage regulator action at the substation, rather than to wind-turbine-produced excitation.

A typical site record of operation at 35 rpm is shown in figure 18. There is a time-scale change part way through the record that increases the chart speed by five times for better high-frequency detail. The power set point is 1000 kW during this time and during the first 60 sec, and the pitch angle is off the electronically controlled stop at about 1.5° in order to regulate. For the balance of the record, pitch angle is constant. Power trace oscillation represents wind fluctuations plus drive train natural-frequency intermittent oscillation and the two-per-revolution response due to the tower shadow. The blade flap bending trace shows the impulsive tower shadow response that occurs once per revolution per blade for the Mod-1 downwind configuration. Voltage fluctuation is limited to ±1 percent with frequencies of two per revolution and one per revolution by the power system stabilizer circuit (speed sensor and voltage regulator). The drive train fundamental mode damping is increased by the power system stabilizer action, and the resulting voltage fluctuation is well within acceptable limits. The reactive power trace is similar to the voltage trace and illustrates that an average 65 kVAR (lagging) was being delivered to the BREMC system.

The amplitude of two per revolution (fig. 18) on the real power trace is about 15 percent peak to peak, which is better than the design value based on the system dynamic simulations made during the design phase. The on-line behavior of the Mod-1 electric power system at 35 rpm showed no evidence of instability and exhibited adequate well-damped decay in transient wind-induced oscillations at the drive train fundamental frequency.

A typical site record of power parameters from recent operation at 23 rpm is shown in figure 19. The voltage at the generator bus varies about 4 percent overall because of the generator power angle changes resulting from drive train oscillation with a less-than-optimum power system stabilizer circuit. A generator bus variation of 4 percent corresponds to a critical bus variation of 2.2 percent which is well within the small-gust flicker criterion. Reactive power oscillates about ±50 kVAR around the 250-kVAR nominal set point, also because of drive train oscillations.

The real power and rotor shaft torque traces are in phase, which illustrates that drive train oscillations are at the torsional fundamental frequency. The frequency of the higher amplitude oscillations is 0.42 Hz, which is near the one-per-revolution frequency of 0.383 Hz. Response at two per revolution, 0.77 Hz, is also seen periodically at lower amplitudes. Shifts in average power at lower frequencies are due to wind speed changes or blade pitch changes. Some oscillatory behavior only occurred at 23 rpm with the present control system.

Assessment. - The Mod-1 wind turbine's electrical generation system has performed as expected on the BREMC system. Voltage flicker characteristics are within typical utility limits. Power variation at 35 rpm is about 15 percent peak to peak and is of no concern to the user utility. Power oscillations result primarily from the two-per-revolution response to tower shadow. Electrical performance showed no evidence of instability and exhibited an adequate, well-damped response to transient wind-induced oscillations. Oscillatory behavior at the drive train fundamental frequency is higher at 23 rpm than at 35 rpm.

Controls and Unattended Operation

Modes of operation. - The Mod-1 wind turbine was designed to operate in three control modes: manual operation, automatic operation, and unattended operation with remote control. The first mode, manual operation, enables the on-site wind turbine operator to perform specified maneuvers in order to conduct maintenance and test functions while off line. Included in these maneuvers are (1) orientation of the nacelle at any yaw angle (angle relative to wind turbine vertical axis), (2) orientation of the blades at any angle relative to the hub axis of rotation, (3) orientation of the blade at any pitch angle, and (4) rotation of the wind turbine off line at any speed up to and including rated speed. A complete list of functions is given in table IV.

The second mode of operation, automatic operation, enables the wind turbine operator at the site to start up the wind turbine, to set the output power level, to obtain data, and to shut down the wind turbine. All other control functions are performed automatically without operator intervention. The purpose of this mode is to generate power to the utility grid while the wind turbine is controlled by an operator located at the site. If the wind conditions are within cut-in V_{CI} and cut-out V_{CO} wind velocity, the wind turbine will generate power at the operator-prescribed set point (or less depending on the wind velocity conditions) in a fully automatic manner.

The third and last control mode, unattended operation with remote control, enables the operator located at a remote site to start up the wind turbine, to set the power output level, and to shut down the wind turbine. The purpose of the mode is to operate the wind turbine from the utility dispatcher's office at Lenoir, N.C., 30 miles from the wind turbine site, with no operators at the site.

Control system. - To understand how the wind turbine operates in the manual and automatic modes (controlled at the site or from a remote location), a description of the overall control system is appropriate at this time. The primary control mechanism of the Mod-1 is blade pitch control. Off line the primary control parameter is rotor speed, and on line it is generator power. In general the control system performs all sensing, recording, utility communication, signal conditioning and buffering, and command functions for the wind turbine. A block diagram that illustrates the overall functional arrangement of the equipment to perform the control functions is shown in figure 20. The upper block of equipment is located in the nacelle, and the two lower blocks are located in the control enclosure. The wind turbine system provides precision analog control of blade angle and yaw orientation in response to wind direction, wind speed, power set point, rotor speed, and other operational parameters. The control of most functions depends on multiple inputs and varying "logic" within an operating mode. The control and recording unit (CRU), with its data gathering and processing capability, is the system master controller. CRU logic is used to determine whether to operate on the basis of operator commands and control parameters. As an example, the operational envelope of wind speed versus yaw error (difference between nacelle direction and wind direction) is shown in figure 21. Manual control, with input from a keyboard, is also processed through the CRU to eliminate human control errors and thus provide maximum machine and personnel safety.

Output power level is controlled by commands to the analog pitch control loop in the servocontroller. This permits considerable flexibility in operation. A discrete power level can be maintained, the system can track wind speed and maximize power output continuously, and the CRU logic enables the system to come on line automatically and autonomously when wind conditions permit. Also the control system provides maximum energy capture capability at below rated wind speeds and maintains safe control of rotor speed at above rated wind speeds. Sufficient diagnostic data can be automatically recorded so that the causes of shutdowns or anomalous operation can be readily determined. Operating procedures for the Mod-1 require that diagnostic data always be automatically recorded.

The control system has the following specific functions:

(1) Control the rotor blade pitch angle to startup; supply subrated power at wind speeds between 11 and 25.5 mph and rated power at wind speeds between 25.5 and 35 mph (nominal)

(2) Control the nacelle position through the yaw drive and yaw brake actuators

(3) Condition, buffer, and optionally record sensor signals

(4) Provide operator interface

(5) Provide remote dispatcher control by means of the telephone line

(6) Provide supervisory, alarm, and shutdown control logic

These functions are performed fully automatically without an operator in attendance at the site to accommodate internal system variables as well as external variables such as wind speed and direction. A detailed set of control system functions during startup and generation are shown in table V.

As stated previously, control of blade pitch angle is the predominant dynamic function that directly controls rotor torque. A detailed listing of pitch control modes required to operate the wind turbine, with associated operating conditions, is shown in table VI. The startup sequence to synchronize with the utility grid is shown in figure 22.

The second control function positions and holds the nacelle by actuating the hydraulic yaw motors and the yaw brakes. To be able to collect the maximum wind energy possible, the nacelle must be rotated about its vertical axis and aligned with the wind direction. Control logic for the four wind speed regimes is given in table VII. If the average yaw error has persisted above 5° for 5 min, the yaw hydraulic motors are turned on, in the appropriate direction, until the corrected angle is less than 1°. Because of the slow 1/4-deg/sec yaw rate, a shorter persistence period is selected as the yaw error increases, as shown in figure 23. This change in sensitivity allows higher energy capture during a changing wind direction.

The wind turbine is a complex electromechanical system that must be protected from internal failures and from external forces such as wind, ice, snow, and temperature extremes. For this reason, fail-safe logic has been designed into the controls. The types of shutdowns and the criteria for each shutdown are shown in table VIII. Backup direct-acting sensors are also provided for overspeed control of the emergency feather and brake systems.

Experience. - One of the main objectives of the Mod-1 program was to demonstrate the feasibility of remote wind turbine control by the utility. Communication for remote operation is accomplished at 300 baud by using Southern Bell Co. telephone lines. Initial remote control was attained during acceptance testing in January 1980 and was regularly used thereafter when the wind turbine was not allocated to sound and television interference testing or undergoing major modifications. Remote control operation usually occurred between 11:30 p.m. and 8:00 a.m. After remote control operation procedures were established, phone line communications were found to be acceptable. Several dispatchers at BREMC were trained and operated the wind turbine successfully. As experience was gained, additional machine operational parameters were made available to the remote operator to provide a more thorough understanding of the machine operating state. Typical learning problems were experienced, including remote-terminal hardware failures, occasional switch adjustments, and initial operator unfamiliarity with control procedures. Since the wind turbine control logic was based on a fail-safe philosophy with numerous safety checks, personnel and terminal hardware problems did not result in wind turbine misoperation or malfunction.

Significant and beneficial controls information, data, and experience were acquired during the wind turbine operation phase. The most significant problem in the wind turbine control system was computer-to-computer communications. This problem occurred between the Digital Equipment Corp. (DEC) PDP 11/34 control and recording unit (CRU) and two PDP 11/04's located in the wind turbine nacelle multiplexer unit (NMU) and in the control enclosure ground multiplexer unit (GMU), respectively. The occasional loss of communication between computers resulted in unscheduled wind turbine shutdowns. When communication failures occur, operator error message statements such as nacelle multiplexer link fail, transmit buffer overrun, or connect fail are printed on the operator terminal to aid in diagnostic procedures. Communications are controlled by DEC commercial computer electronics boards (DMC-11's), which contain a microprocessor. The kinds of communication failures can be understood by examining the definitions of operator error message statements. A connect fail occurs when a NMU or GMU fails to return an acknowledgment of an attempt to communicate by the CRU. A nacelle multiplexer link fail occurs when the time for data transfer between either the NMU or the GMU and the CRU is excessive. If a successful data transfer occurs, a buffer is released for reuse. When the data transfer is unsuccessful, a buffer is not available for transfer of additional information and a transmit buffer overrun occurs.

Before active investigation and solution implementation of the "link failure" problem began in March 1980, communication malfunctions were experienced about 8 days per month. As causes were determined and solutions implemented, malfunctions were progressively eliminated by November 1980. The specific steps taken to eliminate computer-to-computer communication malfunctions were numerous. The initial step in March 1980 was to install slower byte-rate DMC-11 microprocessor boards, 50 kilobytes/sec, in place of the existing faster DMC-11 microprocessor boards, 1 million bytes/sec, in the control enclosure - nacelle link. The slower byte-rate boards are more tolerant of brief communication lapses. As a result these new boards reduced link failures but did not eliminate them.

Second, in April 1980 the allowable cycle time for computer communication was increased to 350 msec from 150 msec. This reduced link failures further, particularly in the automatic mode. To improve the manual mode, the cycle time was increased to 600 msec in May 1980. Subsequent to this modification, link failures consisted primarily of transmit buffer overruns, with the preponderance occurring during lightning storms and yaw maneuvers. In spite of several electrical measurements indicating that the yaw slip ring was performing acceptably, an auxiliary cable bypassing the slip ring was installed for diagnostic tests. Since there were no further link failures while the bypass control cable was installed, it was concluded that the last major cause of communication irregularities was a deteriorated slip ring. In May 1981 a slip ring manufacturer's inspection revealed salt deposits on the silver-plated contacts. This was the second such detection of salt deposit on the slip ring contacts even though prescribed cleaning procedures were used about 22 months earlier. Based on the pattern of link failures, it was concluded that the slip rings were being progressively contaminated with a salt deposit. Since the Boone Mod-1 wind turbine is not in a salt air climate, it is speculated that some fluids used in wind turbine operation or maintenance, such as hydraulic fluid, may contain a salt additive and might have inadvertently spilled into the slip ring assembly during the initial assembly period. It is planned to investigate the chemical composition of all Mod-1 fluids to confirm this hypothesis. Since the May cleaning no link failures have occurred with the control system that can be attributed to the yaw slip ring.

Another lesson learned was the need for qualified and readily available expertise for the computer system preventive and corrective maintenance. Mod-1 site operation records indicate that for the period March-December 1980 expert computer technicians were required 13 times. Only during July and August was no preventive and corrective maintenance required. In addition to preventive maintenance every 3 months, computer services were needed for repair of the line printer, replacement of electronic boards, replacement of the disk drive, repair of the tape unit, and repair of the remote terminal. On-call maintenance service was purchased from DEC since they supplied the total computer system including peripherals.

Operation with a minicomputer-based control system proved to be highly flexible in making system changes quickly and inexpensively. As an example, after it was concluded that the system rotor speed had to be slowed to reduce the sound generation to acceptable levels, the central processor logic within the CRU was easily modified to operate the wind turbine at 23 rpm with a 1200-rpm generator. The control system flexibility was further demonstrated when the wind turbine was operated at 23 rpm with the existing 1800-rpm generator (prior to a generator change) while generating power to a temporary load bank without changing control hardware.

Also during routine testing, the CRU data base was temporarily changed numerous times in minutes to suit test requirements. Finally, since the Mod-1 was the first development vehicle planned to demonstrate the feasibility of a megawatt-size wind turbine, a number of unexpected events occurred that required data for analytical investigation. The data archive feature of storing historical operational data on magnetic tape within the CRU proved useful in investigating, analyzing, and evaluating all facets of system operation. This system records on tape all "traffic" between the CRU and each of the remote multiplexer units (RMU's), all "traffic" between the CRU and BREMC, all communications between the CRU and the on-site operator, and all changes in data states. Recorded data are available for troubleshooting through the playback processor when the wind turbne system is not operating. An RKO 5 disk has been allocated to record operational data for analysis if the magnetic tape recorder is not available.

Assessment. - The Mod-1 control system should be more appropriately referred to as an operational control, data acquisition, recording, and display system. Based on the wind turbine system performance during and after the program acceptance test, a general assessment is that the control system performed as designed. The wind turbine was operated successfully in all three modes, including the unattended, remote control mode from the BREMC dispatchers office in Lenoir, N.C., about 30 miles from the Howard's Knob site. Perhaps the greatest advantage of the Mod-1 control system is flexibility, and this was a key requirement of the Nation's first megawatt-size research and development wind turbine generator. With the experience gained from the Mod-1 system, second-generation machines are using a more simplified and durable microprocessor.

Environmental Issues

While conducting the initial checkout of the wind turbine during the winter of 1979-80, complaints were received from residents in the immediate vicinity that the machine was producing interference with television reception and was emitting an annoying sound. Machine operations were restricted to minimize these disturbances to the affected areas while evaluation studies were begun and established experts hired to properly evaluate these environmental issues. It should be noted that only 10 households have complained about noise, and 35 households have noted some television interference out of a community with a population of over 10 000.

The wind turbine is located on top of Howard's Knob (elevation, 4420 ft), a heavily wooded mountain in the Blue Ridge Chain of the Appalachian Mountains. Howard's Knob is located outside the city limits of Boone (elevation, 3266 ft) in Watauga County in northwest North Carolina near the Tennessee border. It is important to realize that the mountainous terrain (see fig. 24, local map of Boone) surrounding the Mod-1 site has a significant influence on how these environmental issues affect the residents in the community.

Television interference. - Throughout 1980, television reception was investigated and evaluated at areas where complaints of interference were received and at other locations in the general area to fully identify the scope of the problem. Communications consultants were used to conduct these test programs and investigations. The geographic orientation of the nine television channels available to the Boone residents are illustrated in figure 25. All of the transmitters are over 46 km from the wind turbine. Table IX lists the nine network channels available in Boone, the station locations, the network affiliation, the effective radiated (visual) powers, the transmitting antenna locations, the distances from the wind turbine, and the compass bearings.

Discussion: The quality of television reception depends on the signal-to-noise ratio of the receiver, the receiving antenna used, and the television signal strength. To determine the quality that is possible in the Boone area, the ambient field strengths were measured at the test sites on all of the available television channels. Since most of the homes are located in the valleys below the tops of the surrounding hills, it was expected that the television signals would be weak as a result of shadowing by the terrain. This proved to be the case; and according to the industry specification of the signals needed for high-quality service (good reception), the reception of most channels at almost all homes would be classified as poor. The severity of wind turbine interference with television reception depends on the ratio of the wind turbine's scattered signal strength to the ambient signal strength at the location in question. The television signal strengths were determined at the base of the wind turbine tower and at the top of the nacelle approximately 150 ft above the ground. The signal strengths at the nacelle and at the base of the wind turbine were similar, and the signals received on all channels were quite strong. Because the signal strengths are so strong at the site of the Mod-1, the reflected signal throughout the interference regions will have a large potential for causing television interference.

The blades of a wind turbine can interfere with television reception by producing video distortion. No audio distortion has been observed. When the wind turbine is operating, the interference is caused by the time-varying amplitude modulation of the received signal produced by the rotating blades. In the neighborhood of a wind turbine, the signals scattered by the blades combine with the primary broadcast signal to create a form of time-varying multipath signal, thereby amplitude modulating the total received signal. The modulation waveforms consist of synchronous pulses, and since each blade of the wind turbine contributes independently, the pulses repeat at twice the rotational frequency of the machine rotor. If sufficiently strong, these extraneous pulses can distort the received picture. When the blades are stationary, the scattered signal may appear on the television screen as a ghost whose position (separation) depends on the difference between the time delays of the primary and scattered signals. A rotation of the blades then causes the ghost to fluctuate, which can result in a more objectionable picture. In such cases, the received picture displays a horizontal jitter in synchronism with the blade rotation. As the interference increases, the entire fuzzy picture shows a pulsed brightening, and still larger interference can disrupt the television receiver's vertical synchronization, causing the picture to roll over (flip) or even break up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering off the broad face of a blade and is called backward-region interference. In the forward interference region, when the wind turbine is almost in line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals (fig. 26). The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases the amount of interference depends on the strength of the scattered signals relative to the primary one, and the interference decreases with increasing distance from the wind turbine. Although interference decreases with increasing distance from the machine, in the worst cases it can still produce objectionable video distortion at distances up to a few kilometers. At a given distance from the wind turbine, the interference increases with increasing frequency; and the interference is worse on the upper VHF channels.

Test results and tentative solutions: As a result of the measured data and the analysis performed by the University of Michigan, Department of Electrical Engineering (refs. 6 and 7), the following observations were made:

(1) In the city of Boone and the surrounding area, the ambient field strengths are low on all of the available television channels. Even with the wind turbine stationary, the quality of reception is poor; and a high-performance antenna is not sufficient to make it good.

(2) With the wind turbine operating, varying amounts of television interference were found at all test areas and on all television channels. One reason for this is the large increase in reflected field strength in the test area due to the Mod-1 wind turbine. With a high-performance antenna, the backward-region interference observed at the test areas was judged to be acceptable; however, interference in the forward region was judged to be unacceptable.

Four tentative solutions to the Mod-1 television interference problem were considered:

(1) Restrict machine operating time to avoid operating during prime television time.

(2) Use special high-performance antennas at the affected residences.

(3) Extend cable television into affected areas.

(4) Rebroadcast television signals via television translators to the affected areas.

Restricted wind turbine operation to avoid operating during prime television time was implemented early in 1980 to minimize the inconvenience to the Boone residents. This was considered only as a temporary solution and for the long term would not be economically advantageous. High-performance antennas would be economically attractive but would not completely solve the problem. They would eliminate interference in the backward interference region but would be totally ineffective in the forward interference region. The city of Boone and the densely populated areas around the city have access to cable television. Cable service has not been extended to all the valleys and mountainous areas surrounding Boone and the Howard's Knob area because it is not attractive from a business viewpoint. These were the areas where the wind turbine caused the television interference problems.

John F. X. Browne and Associates made an in-depth investigation of the use of television translators as a potential solution in the Boone area. A television translator is a rebroadcast station operating with a low-power transmitter, usually 10 to 100 W. The translator converts the conventional

VHF television signals to specific UHF television channels and rebroadcasts the signals to a specific area. The translator approach depends on the interrelationship of many variables, including (1) terrain, (2) power, (3) antenna height and pattern, (4) operating frequency, (5) viewers' reception facilities, and (6) localized objects, such as buildings and trees, that restrict reception. The television signal quality, within the affected area adjacent to the wind turbine site, provided by the translator system would be equivalent to that provided by a high-power television station in a metropolitan area. These broadcast stations are considered to be a "secondary" service by the FCC and are licensed on the basis of noninterference with regular television broadcast stations. Further details of the translator application can be reviewed in reference 8.

Summary: Cable television and rebroadcast via translators both would provide technically adequate solutions to eliminate television interference in the affected areas surrounding the Mod-1 wind turbine on Howard's Knob. Special antennas will not solve the television problem associated with wind turbines. Restricting the operating time for a wind turbine is not considered an acceptable solution to television interference.

Sound. - During the initial checkout operation of the wind turbine in the fall of 1979, a few complaints were received from local residents that the machine was emitting an objectionable sound. In some instances, it was reported that the sound was accompanied by vibration of residential houses. The character of the sound was described by affected residents as an audible "thump" (similar to a large heart beat) at a repetition rate equal to twice the blade rotational speed. The "thump" occurs when a blade passes behind the tower. In addition to the thump, a typical wind turbine "swishing" sound can be heard in the background that is relatively inconspicuous.

Initial complaints were sporadic and as a consequence difficult to correlate. This inconsistent pattern of complaints was partially due to the seasonal nature of the Boone residential community in the vicinity of the wind turbine. To date, 10 specific residences within a 2-mile radius have complained about objectionable sound, with only two residents complaining persistently. The residents complaining about objectionable sound also complained about television interference.

As a result of the sound complaints, a joint NASA-BREMC-GE decision was made to limit operation of the wind turbine to daylight hours with the exception of brief periods during the night for necessary sound measurements. To gain community understanding, BREMC conducted informative meetings with affected residents in March 1980. At that time consideration of a rotor slowdown to 23 rpm later in the year was mentioned as a potential method to reduce sound levels. Also during 1980, BREMC released articles to the local press informing the general public of the status of the sound situation.

Testing program and results: During the early winter of 1979 the Solar Energy Research Institute (SERI) conducted a limited sound survey at the wind turbine site and near a few affected residences. This survey confirmed the existence of random sound levels at the residences that could be considered the basis for complaints. This is especially true for a rural community that has a very low level of background sound. The initial measurements also revealed that additional in-depth tests would be required to obtain a basic understanding of the sound generation and propagation mechanisms. Initial concerns in addition to the basic sound level were low-frequency sound and structural vibration. At this time local atmospheric and terrain characteristics were suspected of intensifying sound at some locations.

The first in a series of three in-depth sound measurement and analysis programs was conducted during February, March, and April 1980. This program, which was implemented by GE and SERI, measured sound pressure level as a function of time and frequency. These measurements were made at the wind turbine and in and near the home of a resident that had registered sound complaints on several occasions. In addition to sound measurements, vibration levels in the home of one resident were measured. To evaluate the meteorological effects on sound propagation, Penn State University and University of Virginia personnel measured atmospheric parameters of temperature and wind velocity as a function of elevation. In reference 11 the authors discuss a theoretical model of refracture focusing and measured sound levels at the Mod-1 site.

The results and basic data from this test program were documented in reference 9. Test data indicated that objectionable sound was basically a sequence of impulses at a blade-passing-the-tower repetition rate, as shown typically in figure 27. A typical sound-pressure-level-versus-frequency curve is shown in figure 28 as measured within 50 ft of the wind turbine when it was generating 1000 kW on February 12, 1980. A comparison of the sound pressure level outside the house of a local resident versus that inside the house can be obtained by comparing figures 29 and 30.

It was concluded from this initial test program that the frequency range of primary interest with regard to complaints was from 5 to 70 Hz. The condition referred to as a "thump" is characterized by an increase in sound, especially in the 20- to 30-Hz range. Any objectionable house vibration is due to low-frequency acoustic energy in the same frequency range (20 to 30 Hz). A mathematical model developed as a sound level predictive tool suggested that appreciable atmospheric focusing of sound energy could be typical of the Howard's Knob area. Finally, it was predicted that a reduction in rotor speed from 35 rpm to 23 rpm would reduce sound; however, the amount of sound reduction might be marginal with respect to complaints because affected families had been sensitized.

The second sound measurement program was conducted with the wind turbine in a temporary configuration operating at 23 rpm and generating power into a portable resistor type of load bank. The results indicated an average 8- to 10-dB reduction in sound power level from the 35-rpm sound power levels (fig. 31). These measurements supplied supporting data to continue with the program plan to reduce the wind turbine rotor speed to 23 rpm by replacing the 1800-rpm synchronous generator with a 1200-rpm generator.

The third sound measurement program was conducted in January 1981 after the 1200-rpm generator had been installed and when the wind turbine was generating power into the utility grid at 23 rpm. Statistical data were recorded in the 31.5-Hz-octave-band near field (approx 240 to 270 ft from the wind turbine center) at three locations and in the far field at two of the local residences. Data were recorded continuously, and statistical distributions were automatically generated for half-hour periods so that sound pressure level data could be plotted as a function of the percentage of the time that a specific level occurred. A typical curve is shown in figure 32 with a 50-percentile-near-field (at the wind turbine) sound pressure level of 71 dB as compared with a minimum ambient level of 54 dB.

The results of this test program have been reported in reference 10 by R. J. Wells of the General Electric Co. At one residential area the average sound pressure level (50 percentile) varied from 64 dB when a complaint was registered to 51 dB when no complaints were received (fig. 33). At the second residential location the average sound level (50 percentile) was 49 dB while the wind turbine was on line (fig. 34).

From the results of this test phase, it can be concluded that the sound level in the 31.5-Hz octave band is a reasonable choice for a convenient measure of wind turbine sound. The sound levels in the near field were essentially constant for a given yaw angle and wind velocity. The sound levels measured in January 1981 correlated closely with the prior 23-rpm-load-bank tests from the summer of 1980. Much of the time the far-field levels in the 31.5-Hz band were about as would be expected if spherical divergence were assumed. No complaints occurred under these conditions. The condition referred to as "thump" seems to be caused by occasional atmospheric focusing due to unusual wind and temperature gradients. At one far-field location, measured levels as much as 25 dB above that expected by spherical divergence occurred, and in such cases the far-field level exceeded the near-field level.

Assessment: Complaints about objectionable sound from the wind turbine were restricted to an area with a radius of 2 miles and to 10 residents. Only two of these residents complained persistently. Because of the concerns of the local Boone residents, wind turbine operation was curtailed during early evening hours with a few exceptions. The character of the sound is repetitive, similar to a heart beat. Reducing the rotor speed to 23 rpm reduced the sound level by about 10 dB near the wind turbine as predicted. Statistical analysis of sound measurements at the wind turbine rotating at 23 rpm indicate that the average sound (50 percentile) was about 70 dB and that 1 percent of the time the sound level was about 77 dB. Near the home of one of the local residents who was more persistently annoyed the average sound level was about 52 dB, and exceeded 60 dB for 1 percent of the time during the test period. At the same location during a 1.5-hour period when a complaint was received, the average sound level was 63 dB and 1 percent of the time the sound exceeded 77 dB. The measured sound levels at local residences, which on rare occasions are equal to or greater than sound levels measured at the wind turbine, substantiate the notion that atmospheric focusing is a significant factor in causing the limited number of complaints at Boone. Another interrelated factor in causing sound complaints is wind-turbine-produced television interference that creates an awareness on the part of a sensitized resident of wind turbine operation through a visual medium.

Wind Turbine Performance

The performance of the Mod-1 wind turbine was originally reported in 1980 in reference 12. The experimental data used in this performance analysis of generator power output versus wind speed at the hub were preliminary at that time, but the machine was operating as predicted. Figure 35 illustrates the same plot as reference 12 except that there are substantially more data samples included in each plotted point. The machine's performance follows the design prediction very well. A few data points from the reference plot and figure 35 are above the design line, an indication that the machine has a higher overall efficiency than was originally predicted.

As expected, losses occur in the drive train and rotor of the machine. The generator, bearings, and gearbox are standard components and their manufacturers have well-documented efficiency curves.

The resulting efficiency increase is attributed to the higher than predicted aerodynamic performance of the blades. The original Mod-1 wind turbine performance calculations may have been conservative because of the lack of blade aerodynamic performance data, particularly with regard to blade surface effects. A more detailed performance analysis of the Mod-1 wind turbine has been reported in reference 13.

Drive Train

Drive train dynamics. - In March 1980, trade-off studies were begun to identify near-term practical methods of reducing the sound level emitted by the wind turbine. Reducing the rotor speed was selected as the option to be implemented. This change could be accomplished by changing synchronous generators (from 1800 rpm to 1200 rpm) and thus reducing the rotor speed from 35 rpm to 23 rpm. This option was selected because it yielded the best set of advantages: (1) minimum changes to the machine, (2) minimum time schedule to complete the machine changes, (3) minimum costs, and (4) high probability of solving the sound problem. A solution had to be selected early so that hardware procurement could be begun for installation during the fall of 1980 for subsequent testing during the winter of 1980. Selecting the reduced-rotor-speed option in March 1980 provided 6 months to procure the hardware and schedule the change.

Discussion: During the analysis and design period for the reduced-rotor-speed option, it was realized that the once-per-revolution excitation frequency (0.383 Hz) is close to the drive train natural frequency of 0.41 Hz when the wind turbine is operating at 23 rpm. This situation presented the possibility that if the blades were not well balanced or aerodynamically trimmed, an undesirable one-per-revolution response might be experienced in the drive train. The wind turbine was operated at 23 and 35 rpm in a manual mode and synchronized to the utility grid at 35 rpm without any indication of an inbalance between blades. Therefore, since there was no positive indication of an impending problem associated with this proposed change, it was decided to proceed with the rotor speed reduction.

During the period of time when the wind turbine was operated at 35 rpm, the machine performed well, was compatible with the utility grid, and was dynamically very stable. When the reduced-rotor-speed option was completed, our concerns during the analysis and design period became a reality. During gusty wind periods the machine experienced power swings of ±40 percent about the control set point during intermittent time periods. Although this did not affect the utility or its customers because of the relative size of the utility and the power generated by the wind turbine, power swings of this magnitude are undesirable. Power swings of this magnitude on the wind turbine would reduce the life of some components, primarily the gearbox, and on commercially produced wind turbines would add unnecessary capital equipment costs to withstand 40-percent-fatigue overload conditions. To avoid potential damage to the wind turbine gearbox, the power set point was temporarily limited to 1000 kW until the power swings could be reduced.

Wind turbine generators have a lightly damped torsional mode, generally below 1 Hz, that is determined by turbine inertia and shaft stiffness. The generator inertia for the change from 35 rpm to 23 rpm increased from 50.5 lb-ft-sec^2 to 69.7 lb-ft-sec^2, which was an insignificant drive train inertia change. The frequency and damping ratio of the first torsional mode are influenced by four factors: drive train, power regulation, power system stabilizer, and hub speed feedback. The first torsional mode of the wind turbine drive train is 0.41 Hz, which primarily represents the movement of the hub and blades against the effective stiffness of the shafting, gearbox, and generator conection to the power system. Since the electrical stiffness between the generator and the utility power system is higher than the mechanical stiffness between the rotor and generator, the displacement of the turbine rotor on the first torsional mode is much greater than the displacement of the generator rotor. The stiffness ratio of the utility power system to the wind turbine drive train system is 8.33 to 1. Electrical damping at the generator is difficult because the generator rotor is a minor part in the displacement caused by the first torsional mode. Shaft damping can be effective but would require extensive structural changes.

Assessment: Damping at the rotor can be achieved by a more active blade angle control. A control system analysis of a Mod-1 system indicated that damping of the first torsional mode could be increased from 5 percent to 25 percent of critical damping by adding a signal in phase with the hub speed deviation to the output of the blade pitch angle controller. This would require a more active pitch hydraulic system, which could increase maintenance on this system at some time in the future since the system was not originally designed for the more active duty cycle associated with the added hub speed control signal.

During January 1981, the wind turbine was operated at the reduced-power set point while sound measurements were made in order to evaluate the machine operating at 23 rpm. The program operating schedule called for completion of the evaluation and demonstration of the 23-rpm control system problem in February 1981. A problem developed in the drive train on January 20, 1981, that terminated operations. The problem is discussed in the next section.

Drive train problem. - On January 20, 1981, the wind turbine experienced a failure of 22 studs in the drive train. Specifically these studs attached the low-speed-shaft gear coupling to the rotor hub. Figure 36 illustrates the general drive train arrangement on the wind turbine and identifies where the bolted joint is located. When the rotor hub separated from the low-speed drive shaft and the remaining portion of the drive train, the safety system initiated feathering of the blades, which stopped the rotor hub and opened the circuit breaker to the utility. This electrically isolated the generator from the grid.

Discussion: The machine was safely secured and sustained relatively minor damage during the safety-system-controlled shutdown. The torque plate, which is mounted on the rotor hub assembly, contained the 22 broken ends of the studs within helicoil inserts. The remaining portions of the broken studs were recovered from the lower portion of the bedplate. The outer sleeve of the gear coupling was damaged during the shutdown and will require replacement. It rapped the pitch-rod adjusting mechanism during the shutdown. These adjusting mechanisms and the "uniball" end fittings must be replaced. The instrumentation and the power wiring bundle and conduit within the low-speed shaft were severed when the coupling and low-speed shaft separated from the rotor hub and must be replaced.

Figure 37 illustrates a section view of the hub-shaft interface and locates the studs that failed. During assembly, personnel access to the back side of the hub torque plate was limited. This necessitated the blind connection. Figure 38 illustrates the stud-helicoil installation in the coupling joint between the rotor hub torque plate and the low-speed shaft. Self-locking stainless-steel helicoil inserts were used to increase the thread strength in the mild steel torque plate. The studs pass through clearance-oversized holes needed for helicoil installation in the torque plate before engaging the helicoil insert.

The rotor-hub-torque-plate-to-coupling interface was designed as a conventional friction joint, with the fastening studs providing the preloading to a joint capacity of 885 000 ft-lb. The drive train has a rated torque capacity of 442 000 ft-lb, which yields a joint safety factor of 1.99. The drive train slip clutch is adjusted to slip at a setting of 829 000 ft-lb, or 93 percent of the joint rating.

Metallurgical analysis of the failed studs revealed that high strain, predominantly low-cycle bending fatigue, was the cause of the stud fractures at the helicoil end. The stud material was found by metallurgical analysis to be of excellent quality and free of any defects. After the failure, examination of engineering log books indicated that the studs were not properly preloaded. It is believed that this would result in a joint torque capacity of 683 000 ft-lb, or only 77 percent of its original design value. The stud geometry and spacing in the oversized torque plate and gear coupling holes would allow a relative rotation of 1° between the torque plate and the gear coupling. Torque loading of the drive train forced relative rotation, which in turn caused the studs to fail by bending fatigue. A second major contributing factor was that the slip clutch malfunctioned on several occasions before it was discovered to be operating improperly. A third contributing factor was occasional torque loadings in excess of the design values, including both peak and cyclic torque overloads. This failure can be attributed principally to improperly installed studs and a malfunctioning slip clutch, which was installed as an overtorque protection device.

Assessment: The failed joint has been fully reviewed and analyzed and a suitable repair method identified. The drive train damage can be repaired for the most part in the nacelle with only the low-speed shaft and pitch-change mechanism being removed. The rotor hub torque plate rework will require precision machining, and several sources that can provide this type of service have been identified.

Specific recommendations: Basic friction-torque joints are desirable in future wind turbine applications because they cost less than other conventional designs. Also, some drive train designs may have no other alternative than to use friction-torque joints. Designers in designing this type of joint should consider providing a friction-torque capability for all specified loads, with a safety factor of 2.5 as a minimum. In addition, the designer should assume that the joint will slip near limit loads and that the fasteners will be carrying the torque load in shear. Clearances around fasteners should be minimized so that the fasteners will be more uniformly loaded. Designers are urged to be conservative in selecting a friction coefficient for this type of joint. Through-joint fasteners that are positively locked are recommended. Lastly, the fastener tensioning technique must be verified by testing and also verified at installation by proper inspection. Using a slip clutch as a overtorque safety device in wind turbines is considered acceptable. Particular attention must be paid to the application installation, and understanding of all facets of its operation and maintenance. Designers must obtain enough detailed information from the slip clutch manufacturers to fully understand the operation and limits especially if the unit is not a shelf item or is a shelf item that has been modified.

Public Reaction and Acceptance

Over the past 2 years, public reaction to the Mod-1 Wind Turbine program has been favorable. This includes most local people who live in and around Boone near the turbine site. In that regional area of North Carolina and over the rest of the country, people were supportive although not as interested in the project as the Boone residents. Nationally, the Mod-1 program was recognized as the first operational megawatt-size wind turbine in the world.

Discussion: There have been many articles in the North Carolina and Boone papers reporting on the various phases of the Mod-1 program over the past 2 years. Occasionally, national publications such as Time Magazine, the Wall Street Journal, and Aviation Week & Space Technology have had articles on the Mod-1. Trade journals including 1980 Generation Planbook and Electrical World have published material describing the Mod-1 wind turbine. Newspapers outside North Carolina such as The New York Times, Washington Post, Cleveland Plain Dealer, and Philadelphia Inquirer and others have published articles about the project. The North Carolina television stations have also reported numerous times on the Mod-1 program.

Various management personnel from the Blue Ridge Electric Membership Corp. have given an average of over 100 talks per year around the state of North Carolina to various civic, religious, and public organizations during the first 2 years of the project. The BREMC management has reported that the groups they have talked to as well as the general Boone residents have been very supportive of wind power as a form of generating electric energy. The academic community from Appalachian State University, a local college, has conducted energy seminars, including wind energy reviews, and are conducting their own wind energy project, which consists of operating a small horizontal-axis wind turbine.

The Mod-1 site is a continual attraction to visitors to the Boone area, many of whom come from the southeastern part of the United States. Approximately 4000 informational brochures on the Mod-1 have been passed out to site visitors per year during the normal working hours by maintenance personnel. During the fall of the year, when the leaves are changing color in the local mountains, 1500 visitors have visited the site on several successive weekends. This caused traffic problems on the access road, and local off-duty police were hired to control the traffic flow. Many foreign visitors from South America, Asia, and Europe as well as members of the United States Government and industry leaders have visited the site. In fact, the large number of foreign and domestic VIP groups has occasionally disrupted the Mod-1 program schedule. School classes, youth groups, professional organizations, etc., are continually scheduling visits through the local BREMC District Manager.

Assessment: The public reaction to the Mod-1 Wind Turbine program has been demonstrated continually by the number of visitors to the site. The people have clearly expressed to BREMC and site personnel their desire for pollution-free electricity that is not dependent on foreign-produced oil. The local people have expressed their desire to see the wind turbine operating more of the time. The wind velocity is highest during the evening and early morning hours; therefore they have not observed the wind turbine during much of the operating time. In addition, configuring for testing causes periods of time when the wind turbine cannot be operated. In the opinion of the personnel involved with the wind turbine from BREMC, NASA, and the General Electric Co., the public who have visited the site and the local Boone residents are definitely in favor of producing electric power by wind turbines generators.

CONTRIBUTIONS TO WIND TURBINE TECHNOLOGY

Since the Mod-1 wind turbine was the first modern megawatt-size machine that had as its purpose research and development, it has made a number of major contributions to wind turbine technology. These contributions resulted both from deliberate investigative efforts as well as from unexpected problems that occur during any "first of a kind" endeavor. The important technology developments that can be attributed to the Mod-1 program include innovative low-cost wind turbine design concepts and metal and composite blade fabrication techniques. The Mod-1 was the first remote, unattended 2-MW wind turbine to synchronize, to generate power to a public utility system, and to be controlled by a utility dispatcher. Computer codes were verified for dynamic and loads analysis, performance prediction, and electrical stability analysis. These will be useful for future generation designs of megawatt-size systems. Environmental impact issues, such as sound generation and television interference, were experienced and evaluated and solutions for wind turbines were identified. And finally, a host of "lessons learned," including the importance of optimizing an installation site to wind turbine characteristics, have been reported in the literature for the benefit of the industry.

Innovative Design Concepts

Just after the completion of the Mod-1 design, a Mod-1A configuration was designed and was reported to the wind turbine industry at a NASA workshop in March 1979. The Mod-1A synthesized the innovative concepts that were a byproduct of the Mod-1 design experience. These low-cost concepts identified on the Mod-1A, which were beyond the scope of the Mod-1 specification, have been incorporated in second- and later-generation wind turbines. These innovations are a soft tower, partial span control, a teetered hub, and an upwind rotor. The use of these concepts, along with others, has resulted in cost-effective wind turbines that are the keystone of the emerging commercial market.

Blade Manufacturing Technology

The manufacturing of the Mod-1 rotor blades, modern industry's initial attempt to construct a 100-ft-long blade, established the fabrication technology for welding and stress relief of steel blades for the wind turbine industry. The Mod-1 blades have performed successfully for over three quarters of a million cycles, and "know how" from these blades has been incorporated in second-generation welded steel blades. Also two composite fiberglass rotor blades designed specifically for the Mod-1 have recently been manufactured, further establishing the transverse filament tape (TFT) manufacturing process. One-hundred-foot blades once regarded as a challenge in the 1970's will be commonplace in the 1980's primarily as a result of the knowledge gained by the Mod-1 design and manufacturing experience.

Power Generation Feasibility

In the area of performance, the Mod-1 demonstrated that a multimegawatt wind turbine could be successfully synchronized with a utility grid and generate stable electric power that meets utility-quality standards. The Mod-1 also demonstrated that an unattended wind turbine could be operated remotely in conjunction with a utility system by a utility dispatcher in a fully automatic mode. Although power level varied significantly with wind speed and direction fluctuations, voltage flicker was well within utility standards. Transients associated with initial synchronization and wind turbine shutdown exhibited a stable, acceptable behavior.

Environmental Impact

Perhaps the most significant contribution to wind turbine technology resulted from the environmental effect of the Mod-1 on the Boone, N.C., community. In the fall of 1979, shortly after dedication, unanticipated complaints from local residents about objectionable sound and television interference caused by the wind turbine were received by BREMC, the local utility. As a result, extensive efforts were conducted to characterize and solve sound and television interference problems at Boone and to establish standards. The specific knowledge developed on the phenomenon was then incorporated into the second-generation wind turbines.

In regard to sound, extensive measurements were made in the immediate vicinity of the wind turbine and at remote residential locations, intermittently and continuously, and during daylight and evening hours at various weather conditions. These measurements were made at various wind turbine rotational speeds, on line and off. The most important favorable effect of the Mod-1 experience at Boone was an acute awareness throughout the industry of the noise generation problem. A solution to the Boone problem was arrived at by reducing the rotor speed. In addition, this unexpected site-specific environmental concern provided the impetus to characterize wind turbine sound generation, to develop predictive computer codes, and to establish sound standards. The body of knowledge that evolved from the Mod-1 experience is being incorporated into future-generation designs and into utility site-selection criteria.

A parallel story about television interference unfolded in much the same manner as that for wind-turbine-generated sound. Although not totally unexpected because of prior experience at Mod-0A sites, television interference caused complaints within a 1.5-mile radius because of the terrain and consequently restricted wind turbine operation. An extensive measurement program was conducted that evaluated basic signal strength and interference characteristics. The results of the test program led to the evaluation of three tentative solutions: high-gain residential antennas, cable television, and VHF-to-UHF rebroadcast translators. In the interim, however, the television interference problem was eliminated by restricting the turbine operation to other than prime television time. Thus far Mod-1 has contributed to the understanding and identification of solutions to this critical environmental problem that will affect future wind turbine siting decisions.

CONCLUSIONS

Power Generation on Utility Grid

The wind turbine has generated electric energy within utility standards in a stable and well-controlled manner. At 35 rpm transient wind conditions have had no adverse effect on the power generated or the machine. At 23 rpm the power generated was still within utility standards, but the drive train was responding to its fundamental frequency.

Controls and Unattended Operation

The control system initially presented a succession of minor problems and they were eventually solved. After the program acceptance tests the control system performed flawlessly as designed. The wind turbine was operated successfully in all modes, including manual operation, automatic operation, unattended operation, and unattended remote control from the Blue Ridge Electric Membership Corp. (BREMC) dispatchers office in Lenoir, N.C. In addition, the versatility of the control system allowed testing in various unconventional machine configurations during the Mod-1 test program.

Television Interference

Cable television and rebroadcast via translators both provide excellent solutions to eliminate television interference caused by wind turbines. Many areas of the country already have these systems installed. Because of the recent strong interest by the business community in providing these communications systems, cable television and translator systems are being installed at a rapid rate throughout the country. This will be a definite advantage to the users of wind turbines.

Wind-Turbine-Generated Sound

As a result of the sound test program conducted on the Mod-1, the sound emitted by wind turbines is now defined, understood, and predictable. In addition, acceptable sound level requirements for wind turbines are being established for designers' use. The meteorological and topological effects on sound propagation and focusing will be important criteria in wind turbine site selections.

Drive Train Dynamics

When the Mod-1 was operated as originally designed at 35 rpm, the machine ran well, was compatible with the utility, and was dynamically very stable. When the Mod-1 was test configured at 23 rpm to reduce the sound emitted, the machine responded to its fundamental frequency in high turbulent winds, but it was compatible with the utility and was dynamically stable. A solution to the 23-rpm drive train fundamental frequency problem would be a more active blade pitch control system. This would increase the drive train damping and thus would permit the drive train to operate with less excitation of the first torsional mode in turbulent winds.

Public Reaction and Acceptance

The NASA, BREMC, and General Electric personnel involved with the Mod-1 program believe that the members of the public whom they have talked with at the site as well as the local residents around Boone have a very positive attitude toward using wind turbines to generate electric energy. The large number of visitors and groups from foreign countries and the United States visiting the Mod-1 site in this remote mountain community attests to the popularity of this method of energy conversion.

Contributions to Wind Turbine Technology

The Mod-1 program has made substantial contributions to the development of wind turbine technology. GE, through the experience gained during the design phase of the program, developed many low-cost design concepts for the benefit of the wind turbine industry. Metal and composite blade manufacturing technology was also developed. The Mod-1 first demonstrated that a megawatt-size wind turbine could be operated in an unattended, fully automatic mode and generate utility-quality power into a public utility system. Analytical computer codes for predicting wind turbine dynamic and loads analysis were verified from Mod-1 data. A significant contribution to the wind turbine industry was the discovery that the Mod-1 had an environmental impact on the community.

Project Objectives

The following specific Mod-1 project objectives, which were a part of the Federal Wind Energy program, have all been achieved:

(1) To provide operational and performance data for a megawatt-size wind turbine

(2) To demonstrate unattended, fail-safe operation

(3) To involve a utility as user and operator

(4) To identify maintenance requirements

(5) To involve industry in design, fabrication, and installation of the wind turbine

(6) To identify component and subsystem modifications to reduce cost, improve reliability, and increase performance

(7) To assess public reaction to and acceptance of large wind turbines

(8) To demonstrate compatibility with utility requirements

The following nationally recognized experts and their organizations have made major contributions to portions of the program. They adjusted their busy schedules to be available when needed for conducting field tests, analyzing results, developing analytical prediction techniques, writing reports, and attending meetings:

- D. L. Sengupta, T. B. A. Senior, J. E. Ferris of the University of Michigan
- J. F. X. Browne of John F. X. Browne Associates
- R. J. Wells of General Electric Corporate Research and Development
- General Electric Corporate Research and Development Staff
- N. Kelley of Solar Energy Research Institute
- G. C. Green and D. G. Stephens of NASA Langley Research Center

The two Mod-1 blade contractors and their project managers, J. Van Bronkhorst, Boeing Engineering and Construction, and W. Batesole, Kaman Aerospace Corp., also made important contributions to the program.

J. Brown of GE and T. Miller of BREMC were at the site during the machine's assembly and continued their outstanding support during the operational period.

REFERENCES

1. Puthoff, R. L.; Collins, J. L.; and Wolf, R. A.: Installation and Checkout of the DOE/NASA Mod-1 2000-kW Wind Turbine Generator, DOE/NASA/1010-80/6, NASA TM-81444, 1980.

2. Mod-1 Wind Turbine Generator Failure Modes and Effects Analysis. (DOE/NASA/0058-79/1, General Electric Co.; NASA Contract NAS3-20058.) NASA CR-15494, 1979.

3. Executive Summary: Mod-1 Wind Turbine Generator Analysis and Design Report. (DOE/NASA/0058-79/3, General Electric Co.; NASA Contract NAS3-20058.) NASA CR-159497, 1979.

4. Mod-1 Wind Turbine Generator Analysis and Design Report, Volume 1. (DOE/NASA/0058-79/2-Vol. 1, General Electric Co.; NASA Contract NAS3-20058.) NASA CR-159495, 1979.

5. Batesole, W. R.: Fiberglass Composite Blades for the 2 MW Mod-1 Wind Turbine Generator. Presented at DOE/NASA Workshop on Large Horizontal-Axis Wind Turbines (Cleveland, Ohio), July 28-30, 1981.

6. Sengupta, D. L.; Senior, T. B. A.; and Ferris, J. E.: Measurements of Interference to Television Reception Caused by the Mod-1 WT at Boone, N.C. Tech. Rep. No. 1, Univ. of Michigan, 018291-1-T, Jan. 1981.

7. Senior, T. B. A.; and Sengupta, D. L.: Large Wind Turbine Siting Handbook: Television Interference Assessment. Tech. Rep. No. 4, Univ. of Michigan, 014438-4-T, Apr. 1981.

8. Browne, J. F. X.: Television Translator Project, Boone, N.C. Final Report, John F. X. Browne and Assoc., Mar. 1981.

9. Wells, R. J.: Mod-1 Wind Turbine Generator Preliminary Noise Evaluation. General Electric Co., May 1, 1980.

10. Wells, R. J.: Mod-1 Wind Turbine Generator Statistical Noise Studies. 81-SDS-4214, General Electric Co., Mar. 1981.

11. Thomson, D. W.; and Roth, S. D.: Enchancement of Far Field Sound Levels by Refractive Focusing. Wind Turbine Dynamics, NASA CP-2185, 1981, pp. 397-400.

12. Robbins, W. H.; Thomas, R. L.; and Baldwin, D. H.: Large Wind Turbines - A Utility Option for the Generation of Electricity, DOE/NASA/23139-1, NASA TM-81502, 1980.

13. Spera, D. A.; and Janetzke, D. C.: Performance and Load Data from the Mod-0A and Mod-1 Wind Turbine Generators. Presented at DOE/NASA Workshop on Large Horizontal-Axis Wind Turbines (Cleveland, Ohio), July 28-30, 1981.

TABLE I. - DESIGN SPECIFICATIONS FOR MOD-1 WIND TURBINE GENERATOR

Rotor	
Number of blades	2
Diameter, ft	200
Speed, rpm	35
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable pitch
Cone angle, deg	9
Tilt angle, deg	0
Blade	
Length, ft	100
Material	Steel spar/ foam trailing edge
Weight, lb/blade	21 500
Airfoil	NACA 44XX
Twist, deg	11
Tip chord, ft	2.8
Root chord, ft	12
Chord	Linear
Tower	
Type	Pipe truss
Height, ft	131
Ground clearance, ft	40
Hub height, ft	140
Access	Hoist
Transmission	
Type	Three-stage conventional
Ratio	51
Rating, hp	2209
Generator	
Type	Synchronous ac
Rating, kVA	2225
Power factor	0.8
Voltage, V	4160 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive	
Type	Ring gear
Yaw rate, deg/sec	25
Yaw drive	Hydraulic
Control system	
Supervisory	Computer
Pitch actuator	Hydraulic
Performance	
Rated power, kW	2000
Wind speed at 30 ft, mph:	
Cut-in	11
Rated	25.5
Cut-out	35
Maximum design	125

TABLE II. - WEIGHT BREAKDOWN OF MOD-1

WIND TURBINE GENERATOR

	Weight, lb
Rotor assembly	
Hub	15 000
Blades	41 000
Bearings and structure	29 000
Pitch-change mechanism	11 000
Pitch-control hydraulics	12 000
	108 000
Nacelle assembly	
Bedplate	68 000
Fairing	5 000
Generator and exciter	14 000
Power generator equipment	1 000
Shafts, couplings, and clutch	18 000
Gearbox	58 000
Lubrication and hydraulic systems	4 000
Data acquisition system	1 000
Cables, lights, etc.	2 000
	171 000
Yaw assembly	
Bearing supports	47 000
Yaw brake	1 000
Yaw drive	8 000
	56 000
Tower assembly	
Structure	313 000
Elevator and miscellaneous	1 000
Cabling and conduit	6 000
	320 000
Total (excluding ground equipment)	655 000

TABLE III. - MOD-1A OBJECTIVES

Objective	Mod-1	Mod-1A
Wind regime, mph	18	18
Rated power, kW	2000	2000
Life, yr	30	30
Weight, lb	655 000	400 000
Second-unit cost[a], $/kW	2900	1000
Cost of energy[a], ¢/kW-hr	18	5

[a] 1978 dollars.

TABLE IV. - MOD-1 MANUAL FUNCTIONS

Function	Additional restrictive conditions
Pitch to any angle (±5°)	Wind speed[a], 15 mph
Yaw to any angle (±5°)	Wind speed[a], 35 mph
Yaw hydraulics pump motor on/off	———
Hub to any angle (±10°)	Wind speed[a], 25 mph
PCM pump motor on/off	———
Release and apply yaw brake	Wind speed[a], 25 mph
Main lubrication pump on/off	———
Hub to any speed (±0.5 rpm)	Break-away wind speed[a], 25 mph

[a] Wind speed measured at hub height.

TABLE V. - MOD-1 CONTROL SYSTEM FUNCTIONS

Function	Description
Monitor enable	Process lockout sensors; initialize commands
Initialization	Initialize yaw, pitch, and lubrication subsystems
Site enable	Process automatic restart sensors
Antistall	Limit pitch angle as a function of wind velocity to prevent "stall"
Overstress	Limit structural stress as a function of wind velocity and yaw error
Yaw correct	Align nacelle with wind vector
Pitch ramp	Ramp pitch angle 90° to 72° - maximum coefficient of lift
Speed ramp	Ramp generator speed 0 to 1200 rpm
Rate synchronization	Set frequency generator equal to frequency of utility
Voltage synchronization	Set voltage generator equal to voltage of utility
Angle synchronization	Enable switch gear synchronizer; wait for breaker close
Power ramp	Step power in 25-kW increments 2 sec apart
Shutdown	Disengage utility, feather blades, brake, and park rotor
Power peaking	Iterate power set point to maximum value for $11 \leq V_W \leq 24.6$

TABLE VI. - MOD-1 PITCH-CONTROL MODES OF OPERATION

Mode	Functional description	Operating conditions	
		Control parameters	Wind speed, mph
Startup	Ramp blade pitch angle to +72° with shaft brake on. Accelerate rotor to rated speed by pitching blade and using speed schedule after releasing brake	Time Shaft speed Blade angle	11 to 35
Rate synchronization	Closed-loop control of pitch to make f(utility) = f(generator)	Utility frequency Generator speed	
Angle synchronization phase angle	Closed-loop control of pitch to make φ(utility) = φ(generator)	Utility phase angle Generator phase angle	
Power control	Control process unit (CPU) ramps power reference command to set desired power output	Time Generator power Blade angle	↓
Manual	For testing and periodic "exercising," blade can be commanded over full range	Manual Blade angle Time	0 to 25
Pitch jam	"Pitch jam" status to nacelle multiplexer if pitch mechanism does not respond to position control	Time Voltage	Any
Power down	CPU ramps reference to zero power	Time Generator power Blade angle	11 to 35
Slowdown	Rotor shaft speed reduced to 1 rpm by slewing blade at 1 deg/sec	Blade angle Shaft speed	Any

TABLE VII. - YAW CONTROL

Wind speed, V_w mph	Drive	Brake	Notes
0 to cut-in	"Off"	"On"	No operation
Cut-in to cut-out	Corrects for yaw error of 5° for 5 min	"Off" when not rotating; "on" if rpm above 8 at lower pressure	1/4 deg/sec
Above cut-out	"Off"	"On"	Shutdown
0 to rated	Manual - to any angle	Manual	For test

TABLE VIII. - SHUTDOWN LOGIC

Type of shutdown	Control system functions	Criteria for shutdown
Normal	Yaw off if failure Power down (pitch change) Breaker open Slowdown (speed ramp) Rotor stop Apply parking brake	Manual command Dispatcher command Wind speed drops below 11 mph User subsystem failure Wind speed and yaw error out of band Temperatures out of band Average wind speed above 35 mph Emergency pitch hydraulic pressure low
Emergency	Yaw off if failure Pitch emergency feather Breaker open Rotor stop Apply parking brake	Frequency out of band Shaft speed too high Main breaker open while in generator Utility voltage dip below limit Wind speed and yaw error out of band Any vibration above limit Data link anomaly
Utility outage	Emergency feather Yaw motor off Brake on shaft brake off	Utility voltage drops out
Pitch jam	Emergency feather Yaw 90° to wind and track	Blade will not respond

TABLE IX. - TELEVISION CHANNELS AVAILABLE IN BOONE

Channel	Station location	Network affiliation	Effective radiated visual power, kW	Antenna location		Distance from wind turbine, km	Direction to transmitter, deg from N
				Latitude	Longitude		
2(a)	Sneedville, Tenn.	ABC	100	36°22'52"	83°10'48"	134	278
2(b)	Greensboro, N.C.	CBS	100	35°52'13"	79°50'25"	170	103
3	Charlotte, N.C.	CBS	100	35°17'50"	81°6'53"	116	154
5	Bristol, Va.	NBC	85.1	36°26'57"	82°6'31"	46	302
7	Spartanburg, S.C.	CBS	294.1	35°10'26"	82°17'26"	130	205
8	High Point, N.C.	None	316	35°48'47"	79°50'36"	171	105
9	Charlotte, N.C.	ABC	316	35°15'41"	80°43'38"	138	141
11	Johnson City, Tenn.	CBS	245	36°25'55"	82°8'15"	47	299
12	Winston-Salem, N.C.	NBC	316	36°22'31"	80°22'27"	118	82

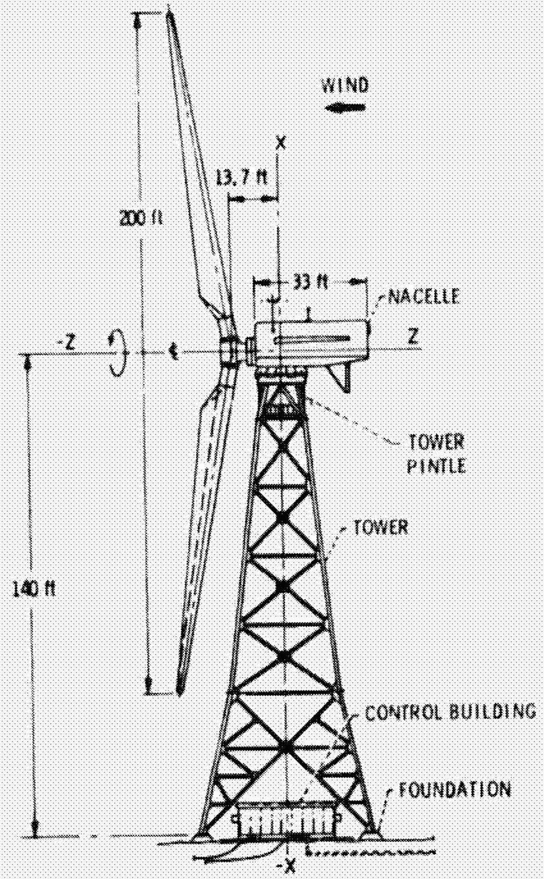

Figure 1. - Mod-1 2-MW wind turbine.

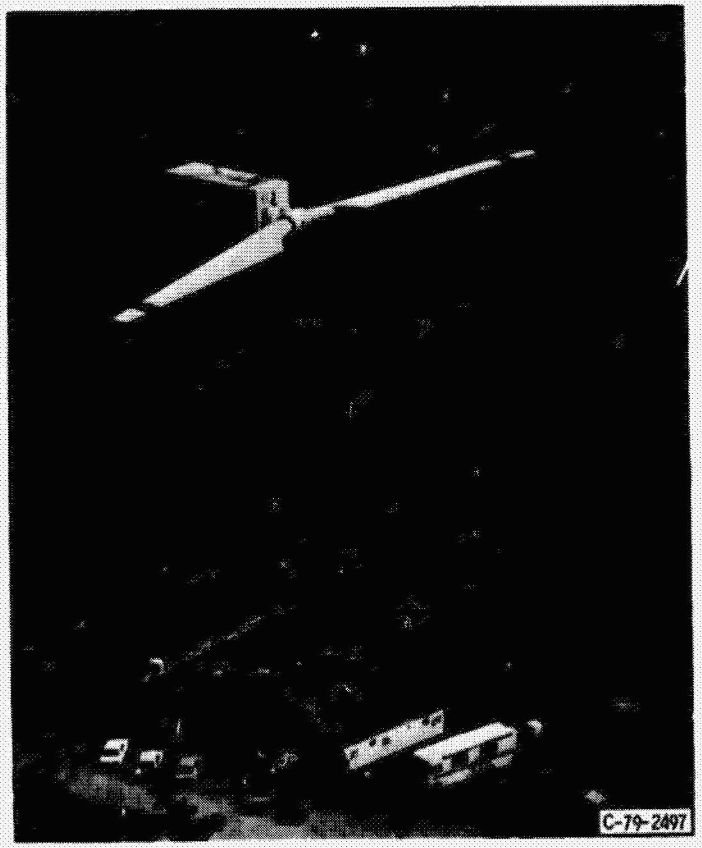

Figure 2. - DOE-NASA 2000-kW experimental wind turbine, Howard Knob, Boone, N. C.

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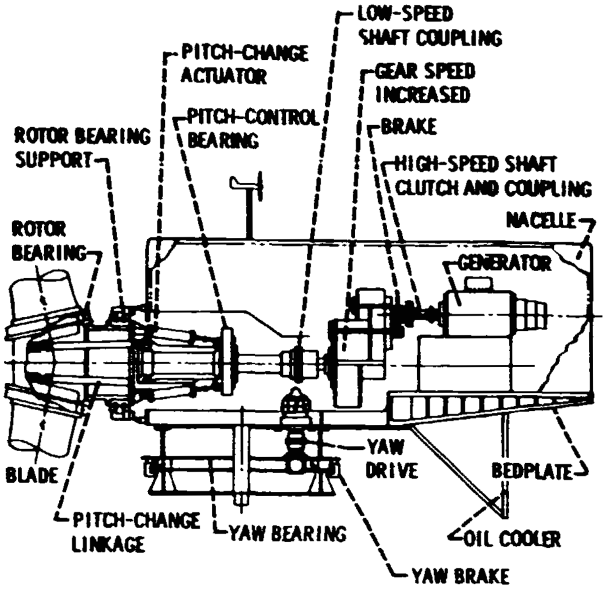
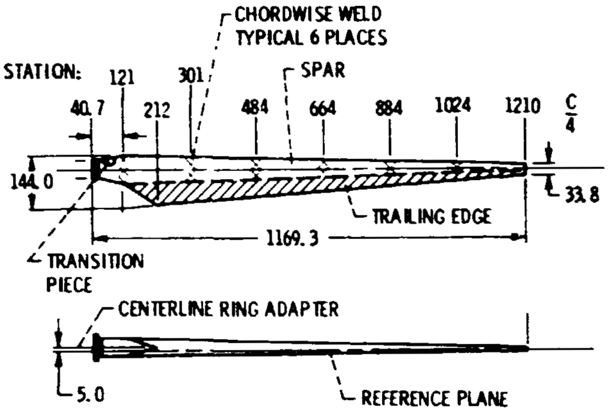
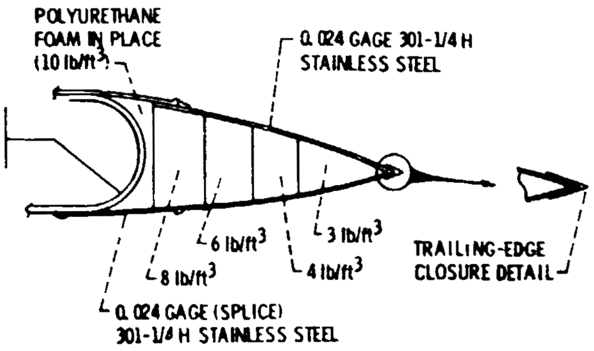


Figure 3. - Schematic diagram of Mod-1 wind turbine assembly.



(a) Blade geometry. Dimensions are in inches.



(b) Trailing-edge geometry.

Figure 4. - Blade and trailing-edge geometry.

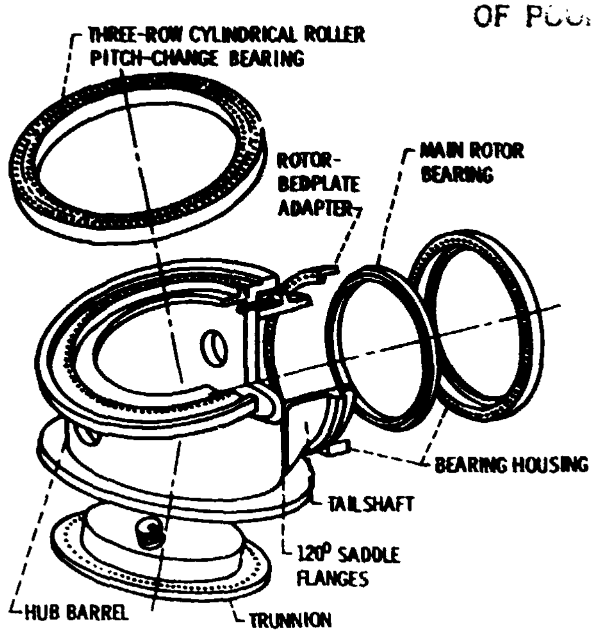


Figure 5. - Hub assembly.

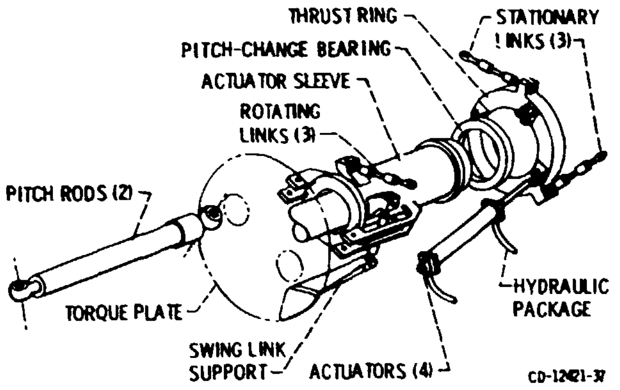


Figure 6. - Pitch-change mechanism.

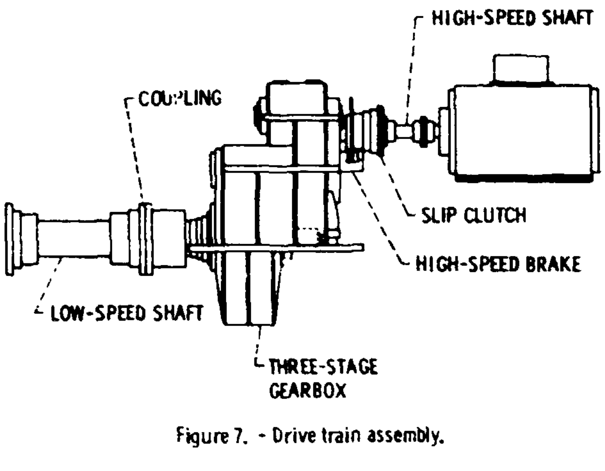


Figure 7. - Drive train assembly.

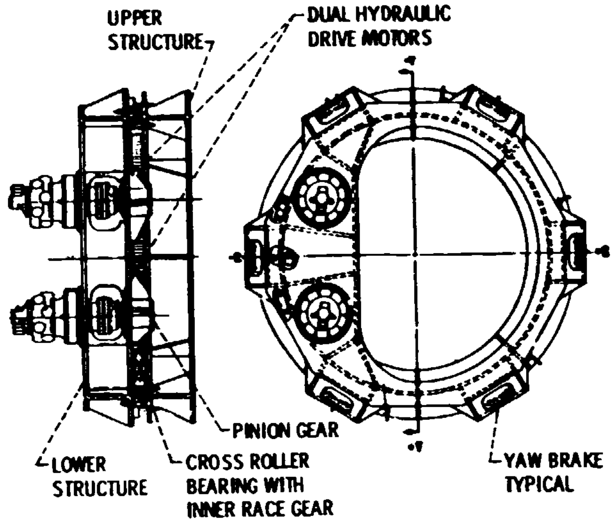


Figure 8. - Yaw drive assembly.

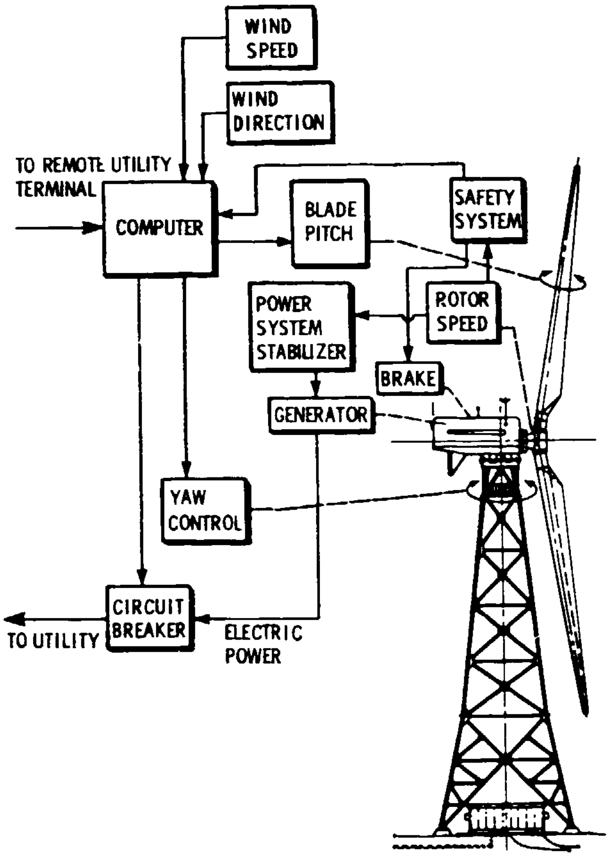


Figure 9. - Simplified Mod-1 control schematic.

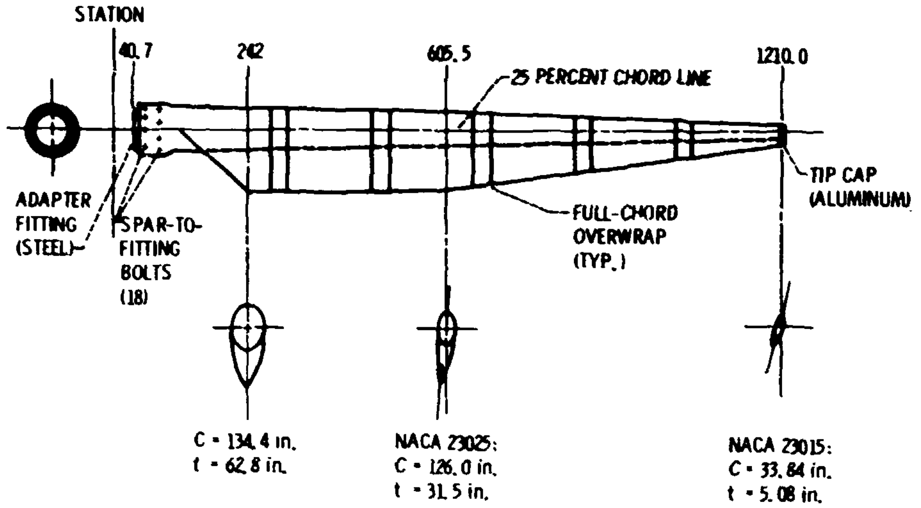
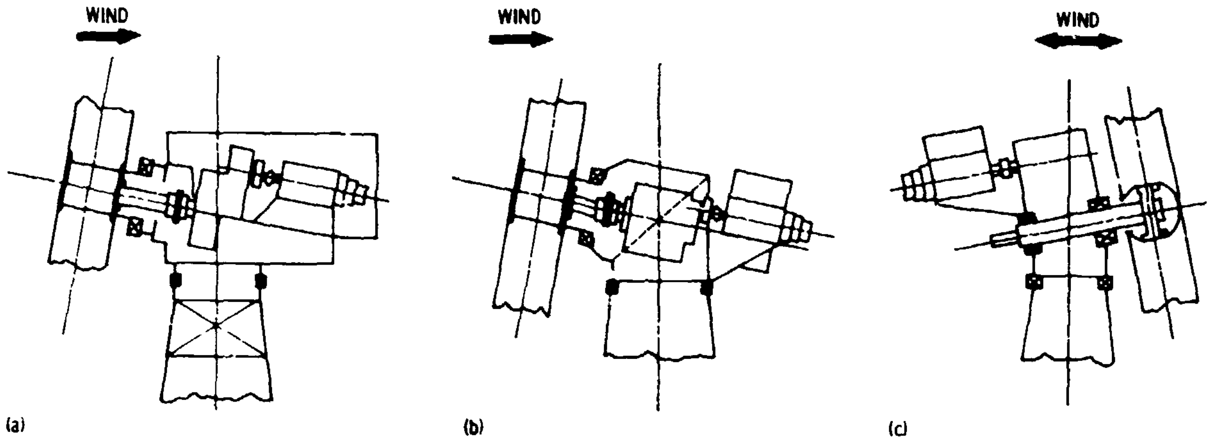


Figure 10. - MOD-1 composite blade. Twist, 11° linear (root to tip); airfoil, 23000 series; weight with adapter, 26 846 lb.



(a) Design concept 1 - reduced Mod-1: fixed hub; two blades; upwind rotor; partial-span control; Mod-1 gearbox; Mod-1 electric generator; truss tower (soft); total weight, 340 000 lb.

(b) Design concept 2 - epicyclic gear: fixed hub; three blades; upwind rotor; partial-span control; epicyclic gearbox; Mod-1 electric generator; shell tower (soft); total weight, 355 000 lb.

(c) Design concept 3 - integral gearbox: teetered hub; two blades; downwind or upwind rotor; partial-span control; Mod-1 gear drive; Mod-1 electric generator; shell tower (soft); total weight, 320 000 lb.

Figure 11. - Mod-1 trade-off study candidates. Favorable results as compared with Mod-1 weight of 655 000 lb.

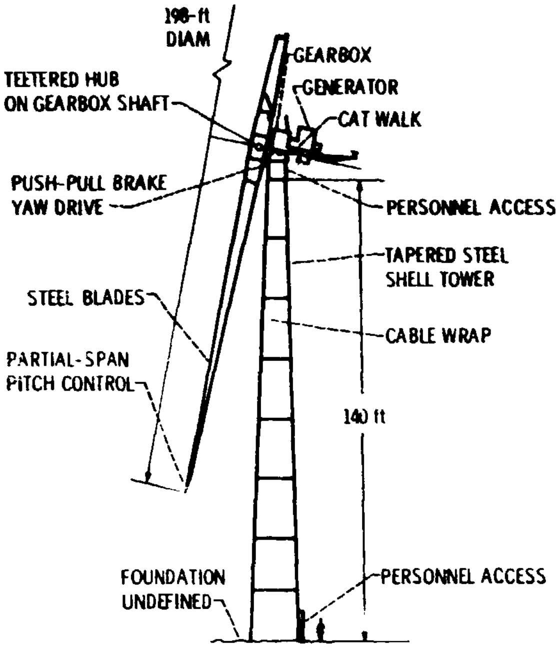


Figure 12. - Mod-1A configuration.

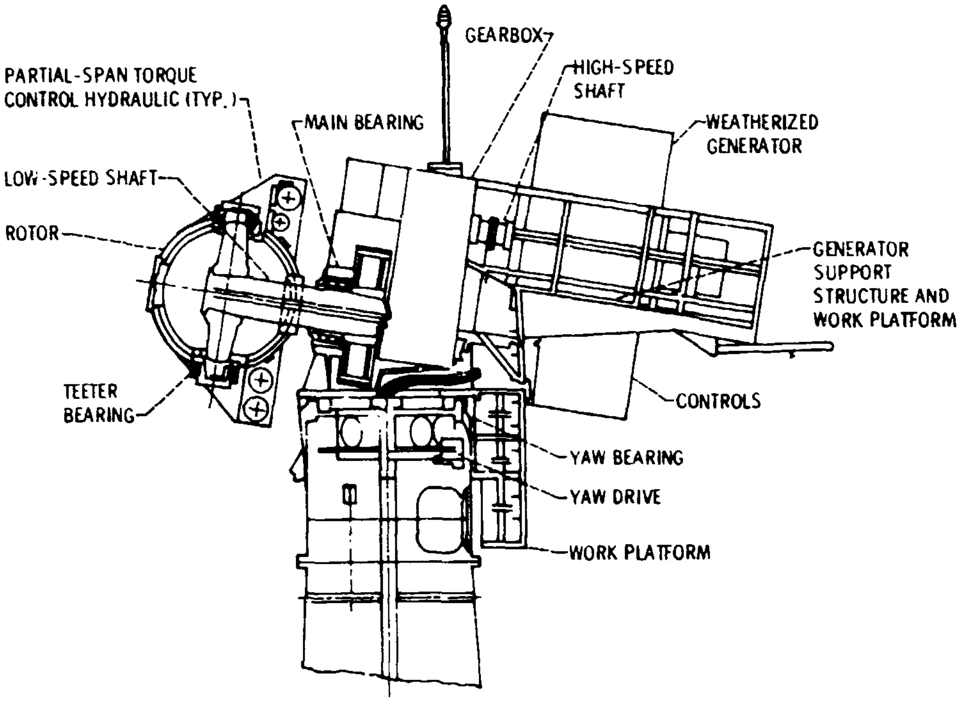


Figure 13. - Mod-1A nacelle.

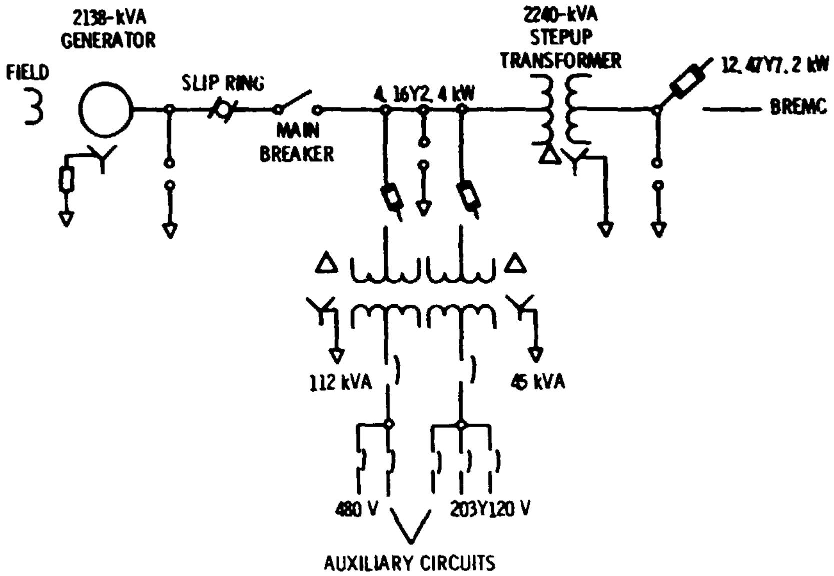


Figure 14. - Simplified one-line diagram of Mod-1 power system.

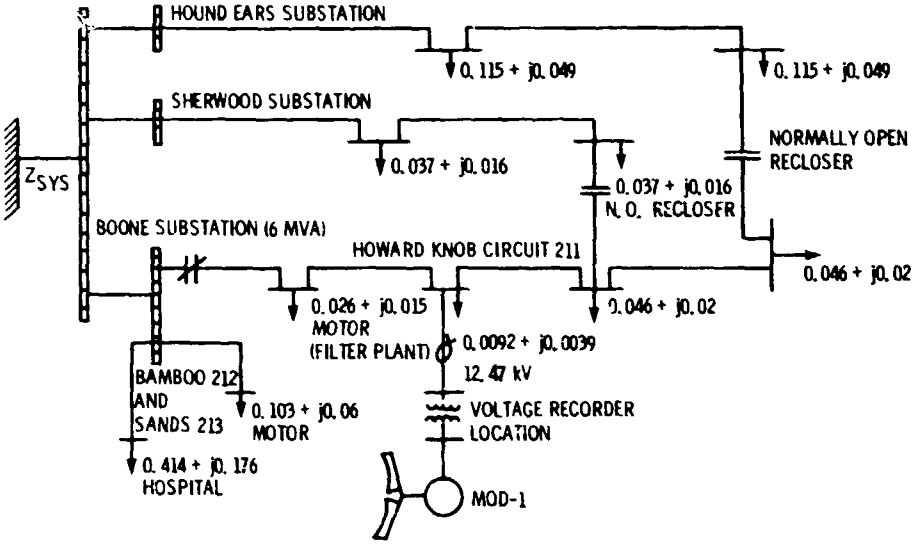


Figure 15. - Simplified one-line diagram of Blue Ridge Electric Membership Corp. distribution system. (All loads on 10-MVA base.)

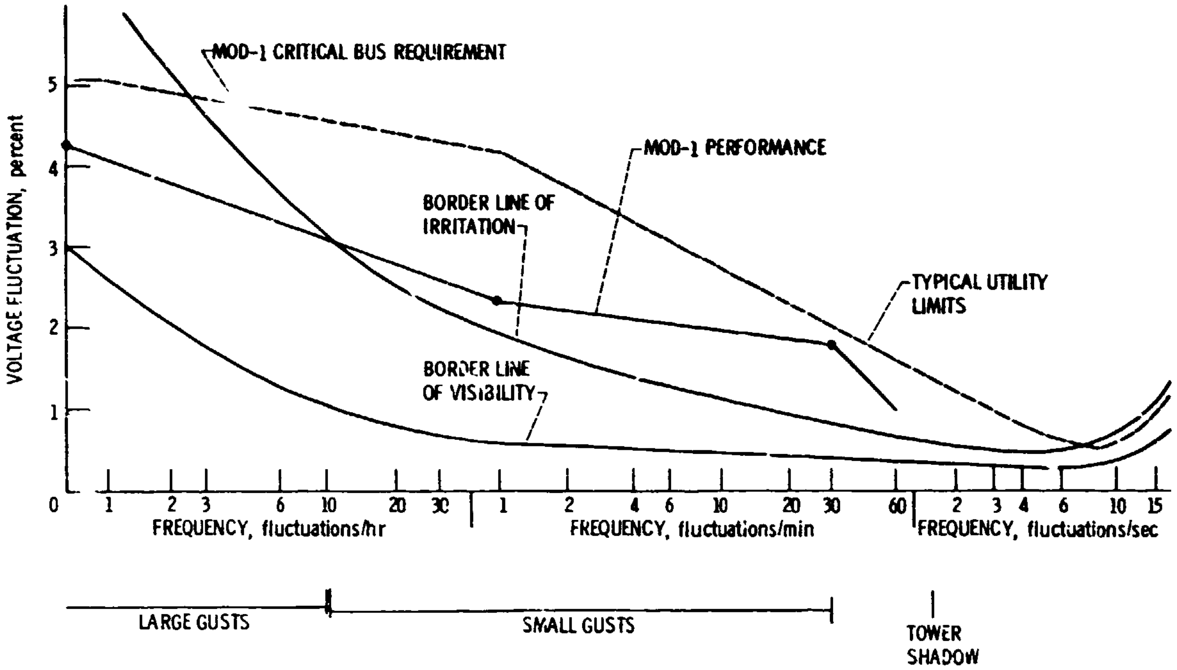
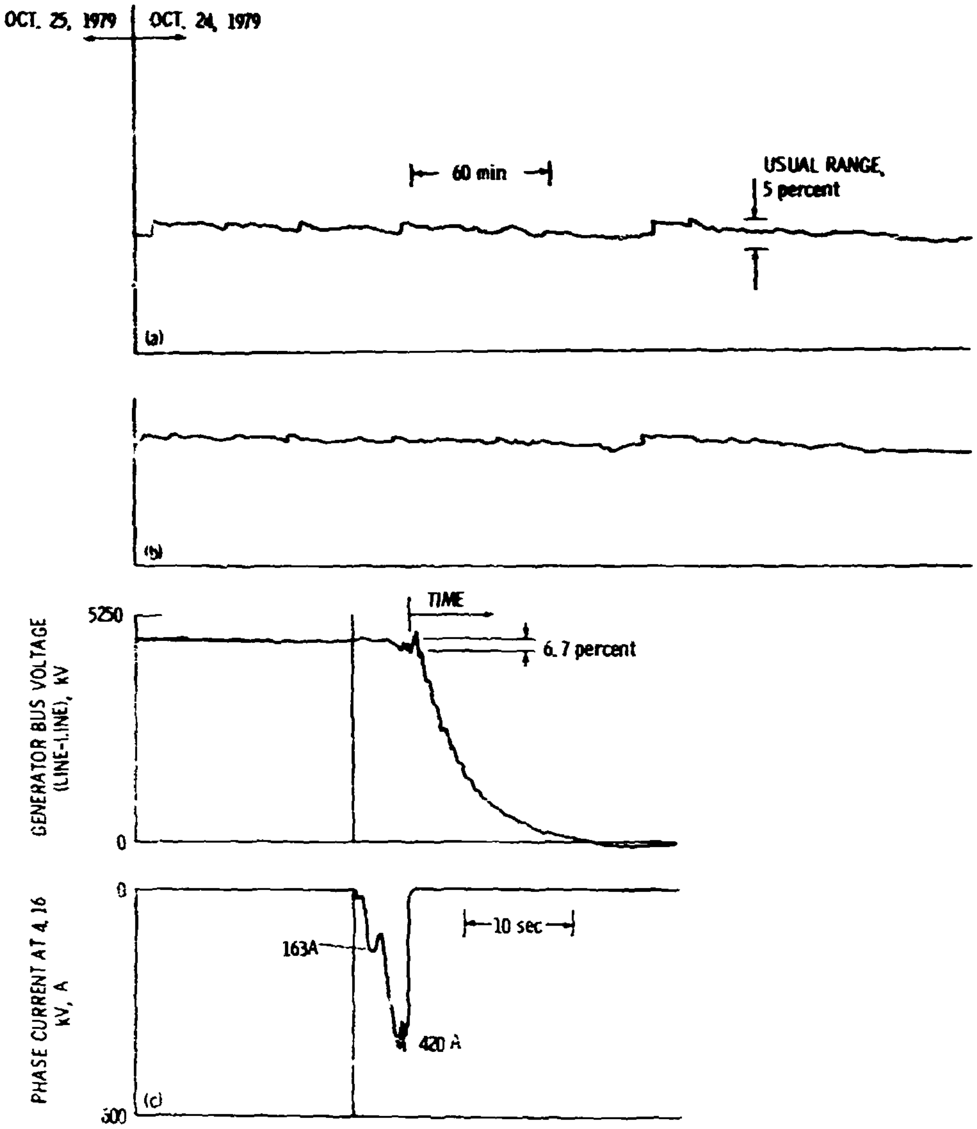


Figure 16. - Voltage flicker characteristics.



(a) Meteorological tower trace.

(b) Substation trace.

(c) Transient on Oct. 24, 1979.

Figure 17. - Utility voltage recorder traces and transient on Oct. 24, 1979. Overload shutdowns at 2253, 2316, and 2349 V; 30 min slow at 2130 V.

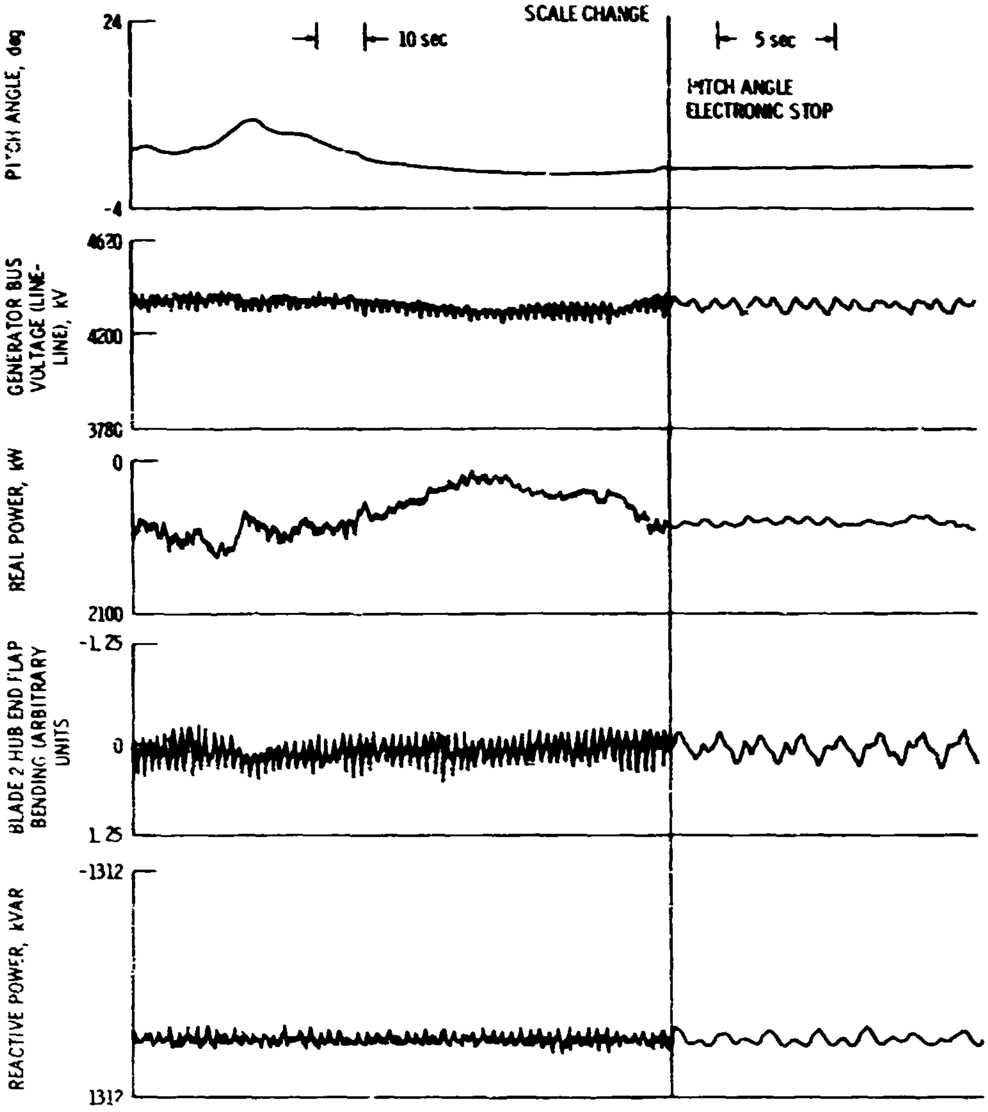


Figure 13. - Mod-1 operation at 35 rpm - Jan. 31, 1980.

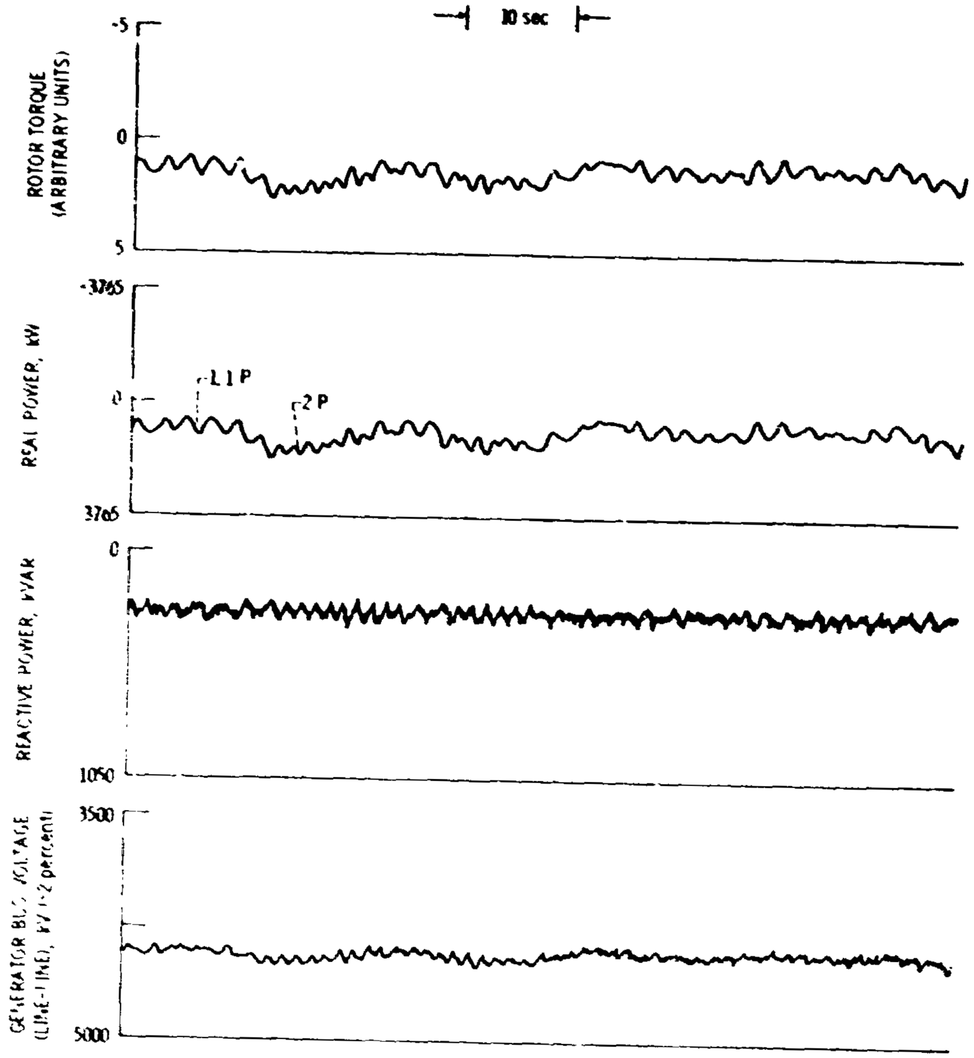


Figure 19. - Mod-1 operation at 23 rpm - Jan. 19, 1981.

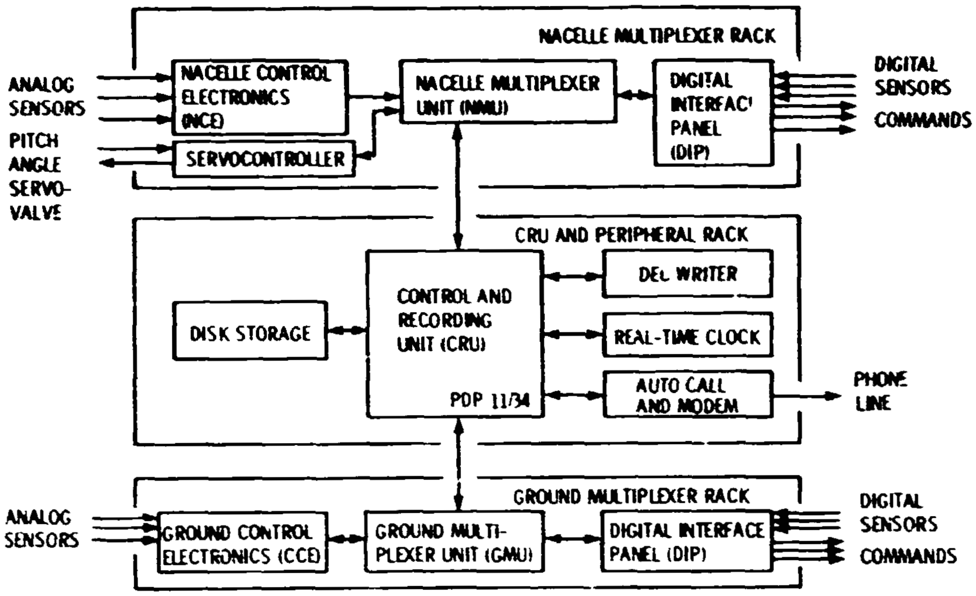


Figure 20. - Block diagram of Mod-1 control system.

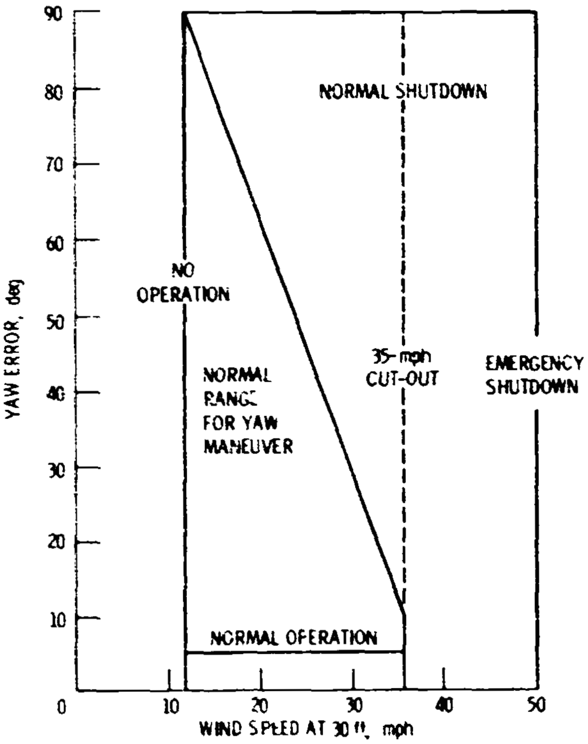


Figure 21. - MOD-1 operational envelope.

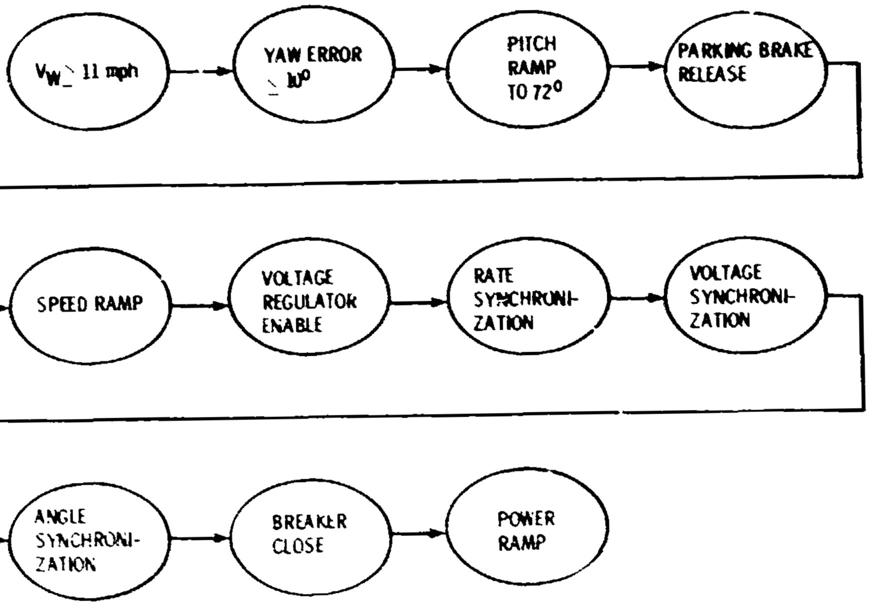


Figure 22. - Mod-1 startup control functions.

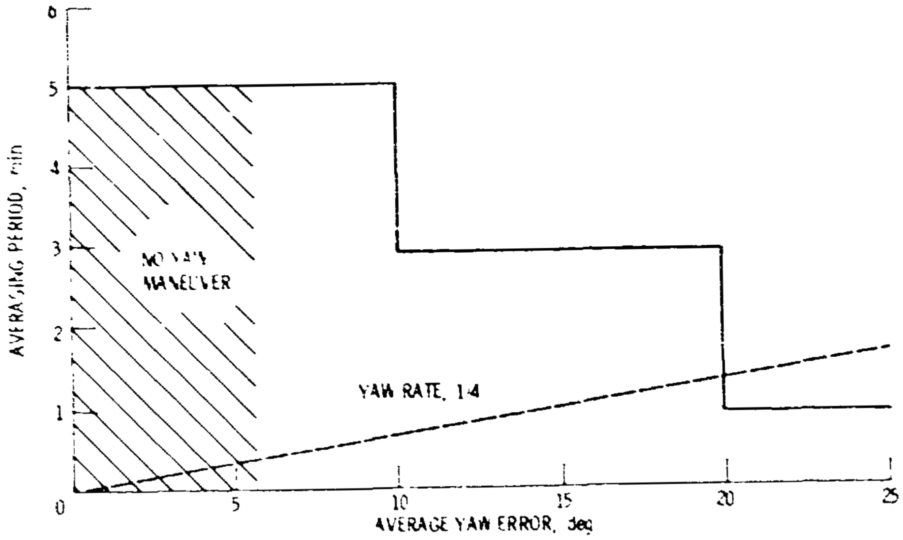


Figure 23. - Yaw correction averaging logic for Mod-1.

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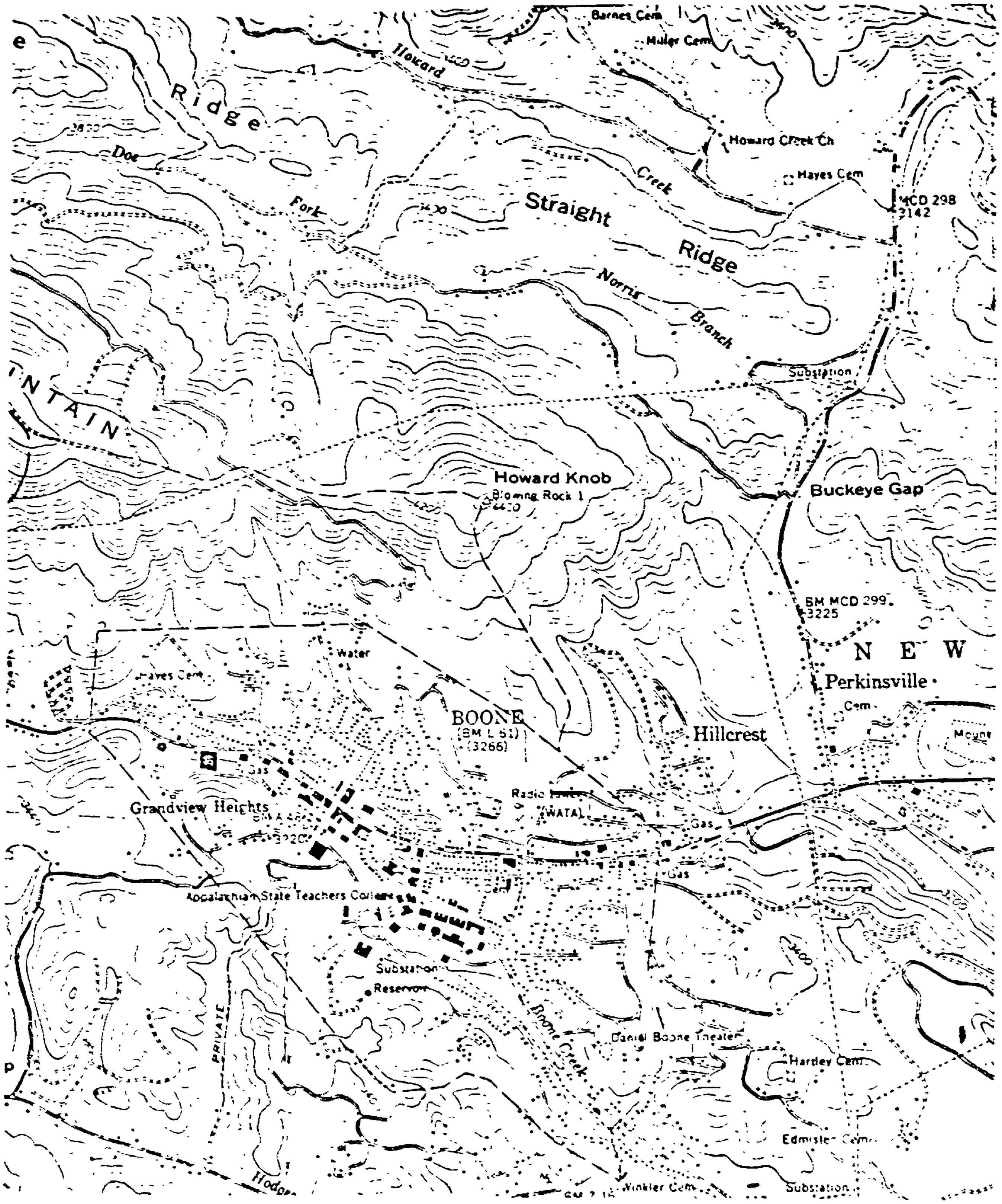

Figure 24. - Topographical map of Boone, N.C. area.

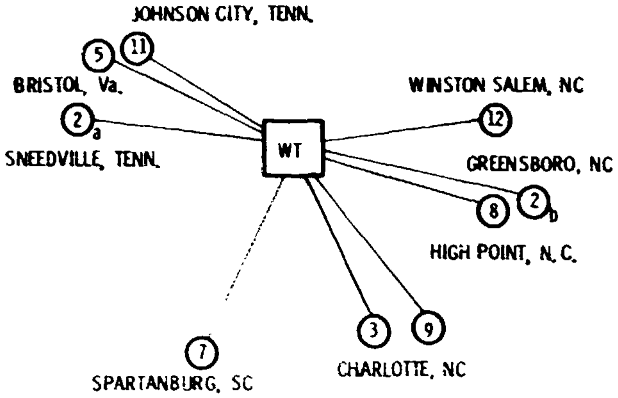

Figure 25. - Television stations received in Boone.

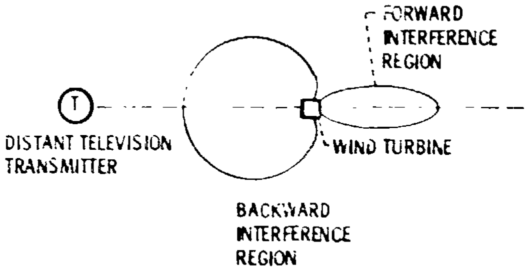

Figure 26. - Television forward and backward interference regions for a wind turbine.

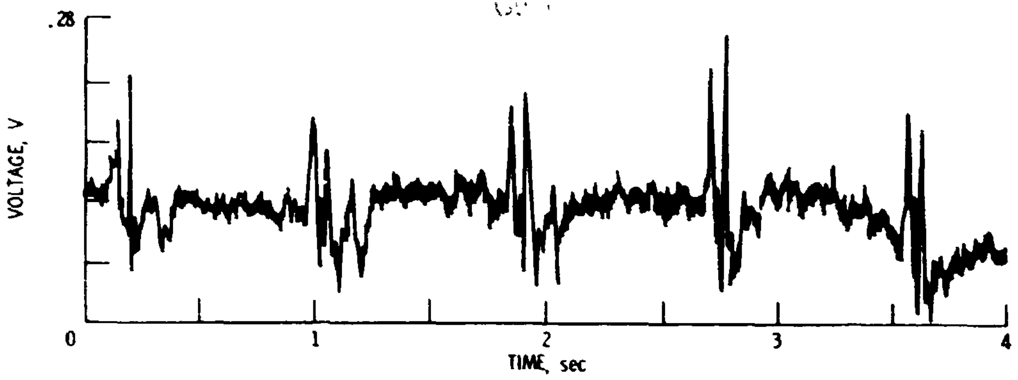

Figure 27. - Impulse sequence near Mod-1 operating at 35 rpm and generating 500 kW - Apr. 1, 1980.

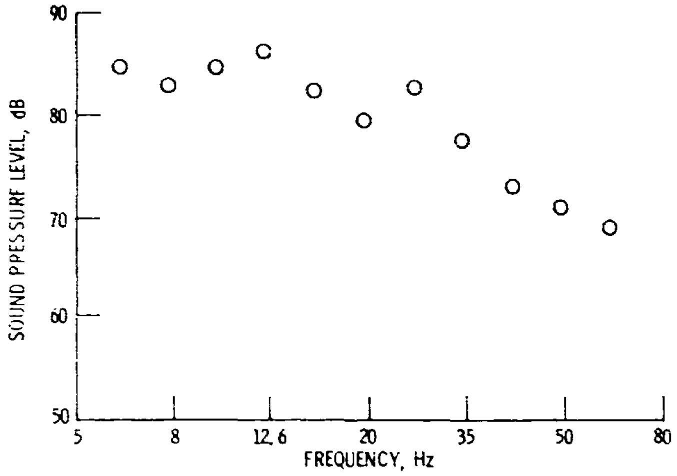

Figure 28. - Sound pressure levels 50 ft from wind turbine for Mod-1 operating at 35 rpm and generating 1000 kW-Feb. 12, 1980.

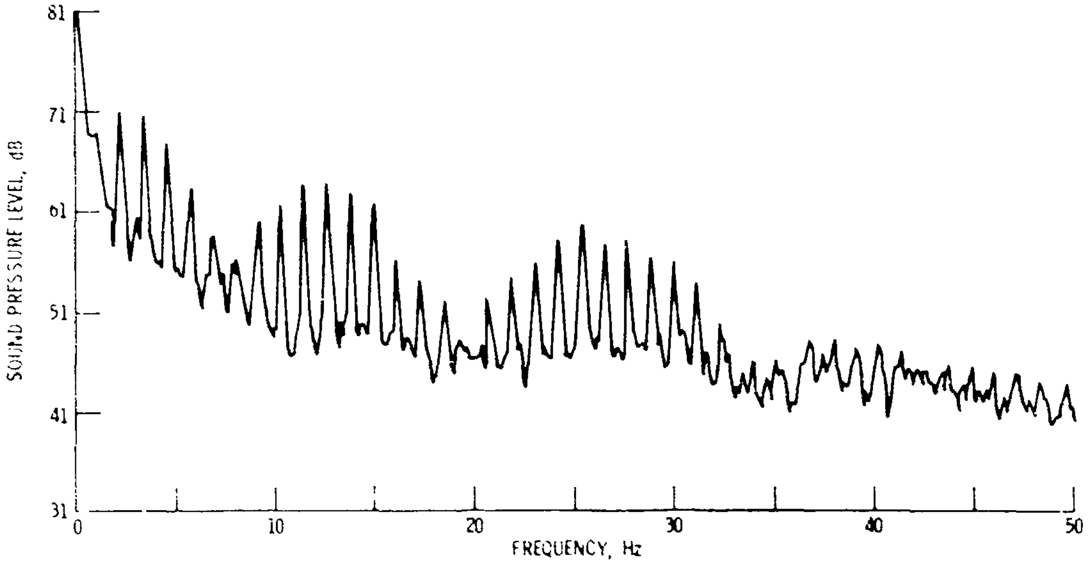

Figure 29. - Sound pressure level outside residence as a function of frequency - 12:07 a.m., Mar. 31, 1980.

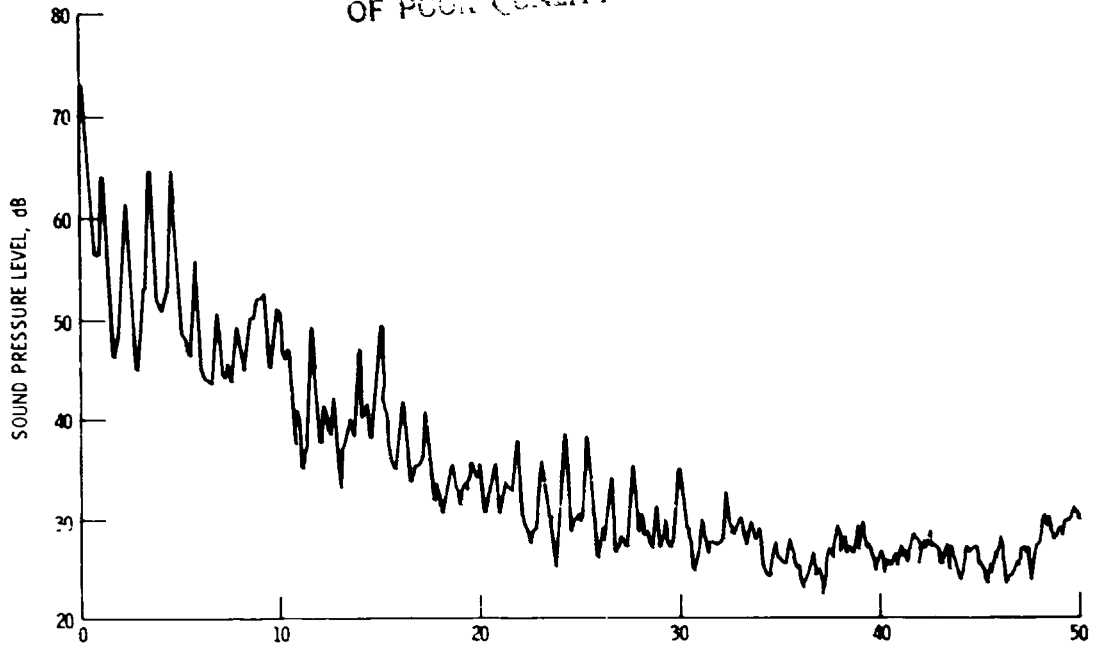

Figure 30. - Sound pressure level inside residence as a function of frequency - 12:07 a.m., Mar. 31, 1980.

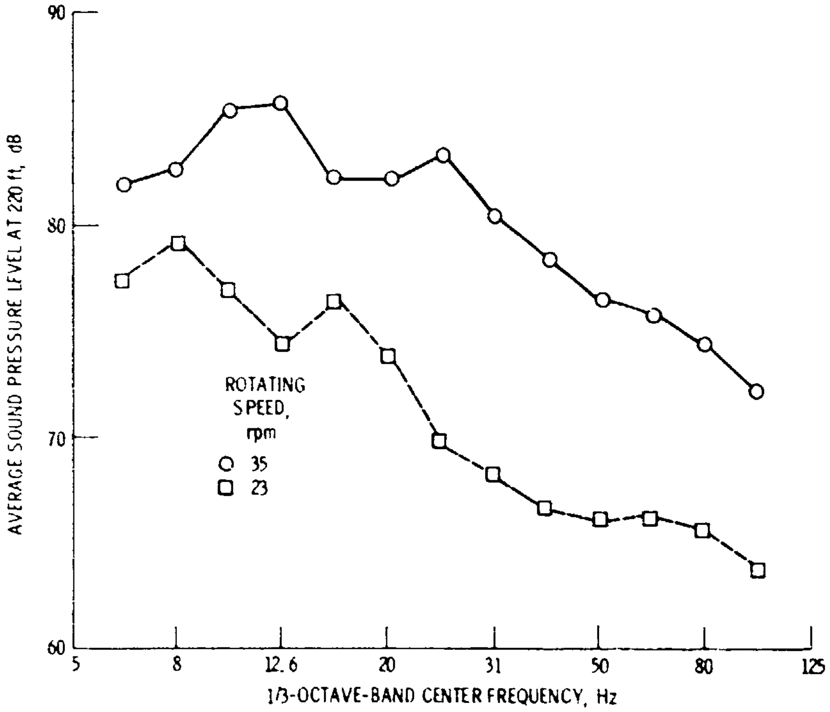

Figure 31. - Average sound pressure levels as a function of frequency at 35 and 23 rpm. Each curve represents average sound pressure levels for seven sets of data - with different but comparable wind conditions and load.

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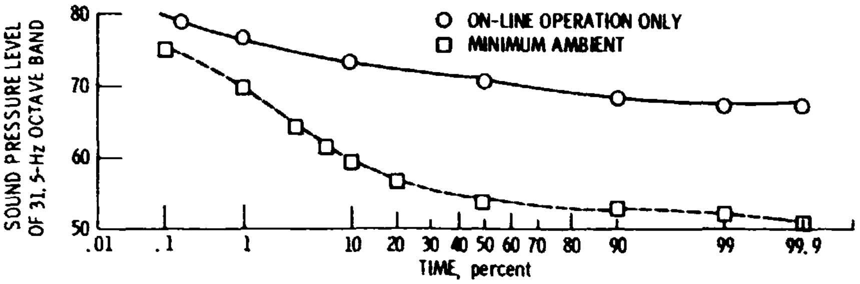

Figure 32. - Percentage of time sound exceeded specified levels - near-field sound pressure level distribution at 1269 ft from center of tower.

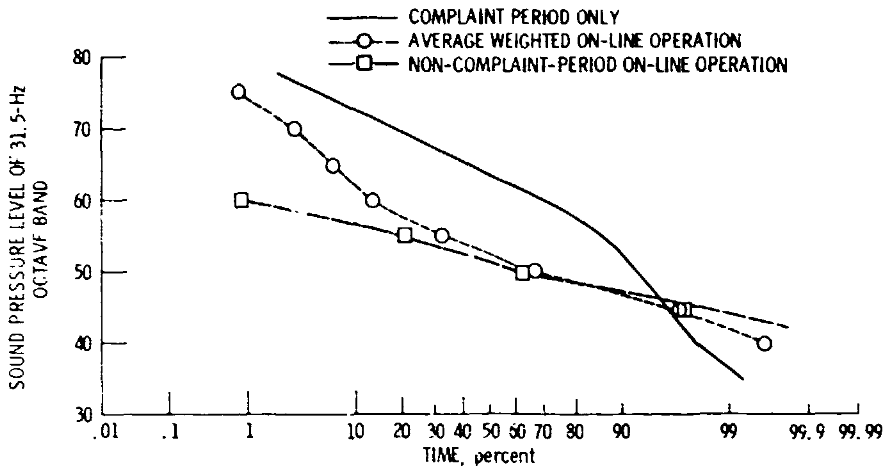

Figure 33. - Percentage of time sound exceeded specified levels-estimated long-period sound pressure level distribution at far-field position 1 for on-line operation only. (Assumes levels corresponding to those of the complaint period for 1/6 total time.)

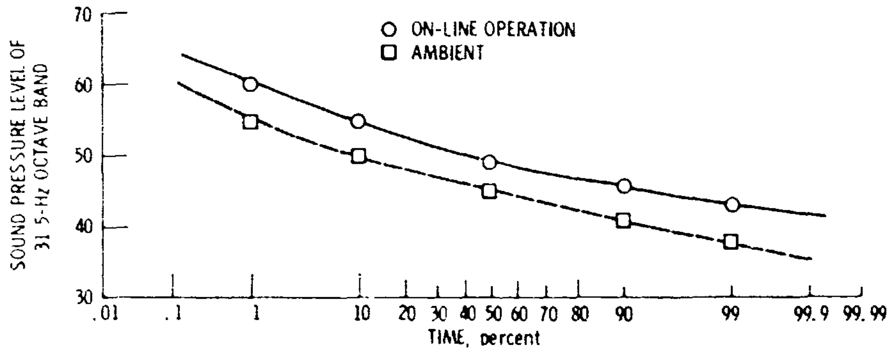

Figure 34. - Percentage of time sound exceeded specified levels-sound pressure level distribution at far-field position 2.

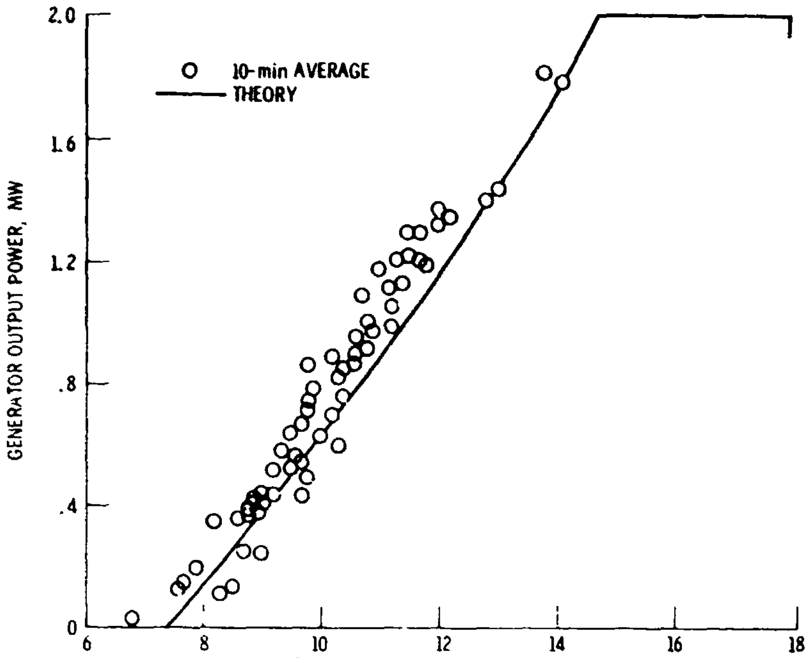

Figure 35. - Output power of Mod-1 2-MW wind turbine.

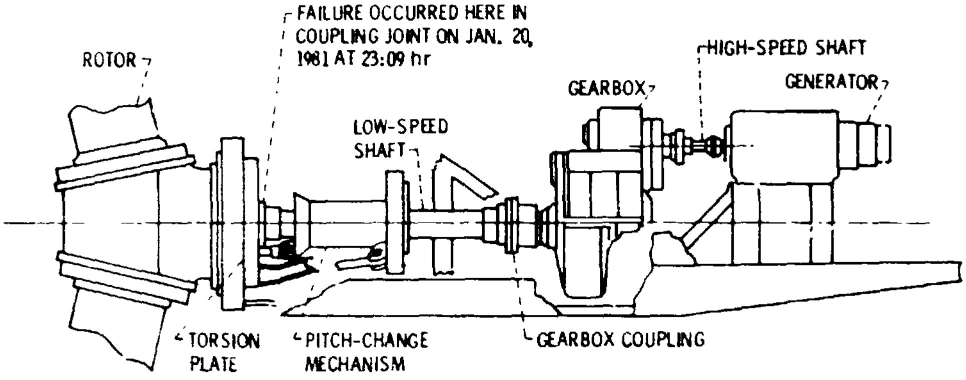

Figure 36. - Mod-1 drive train.

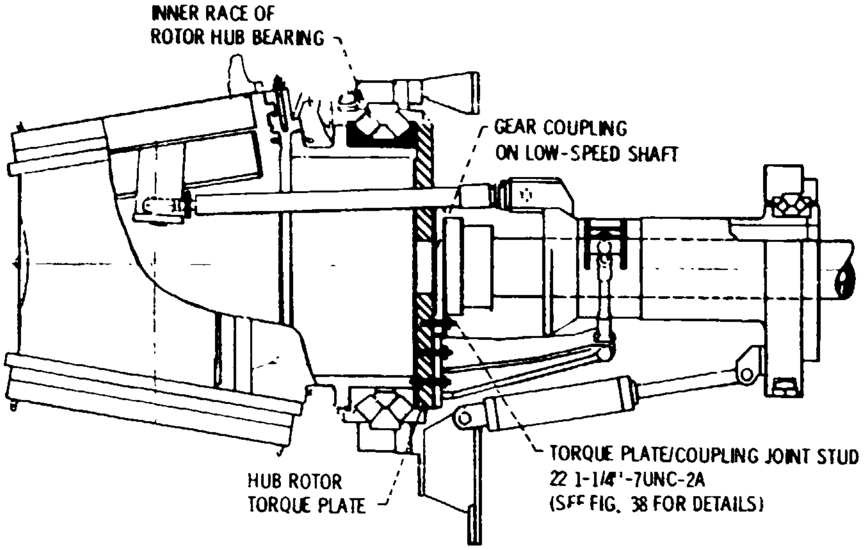

Figure 37. - Section view of hub-shaft interface showing stud location.

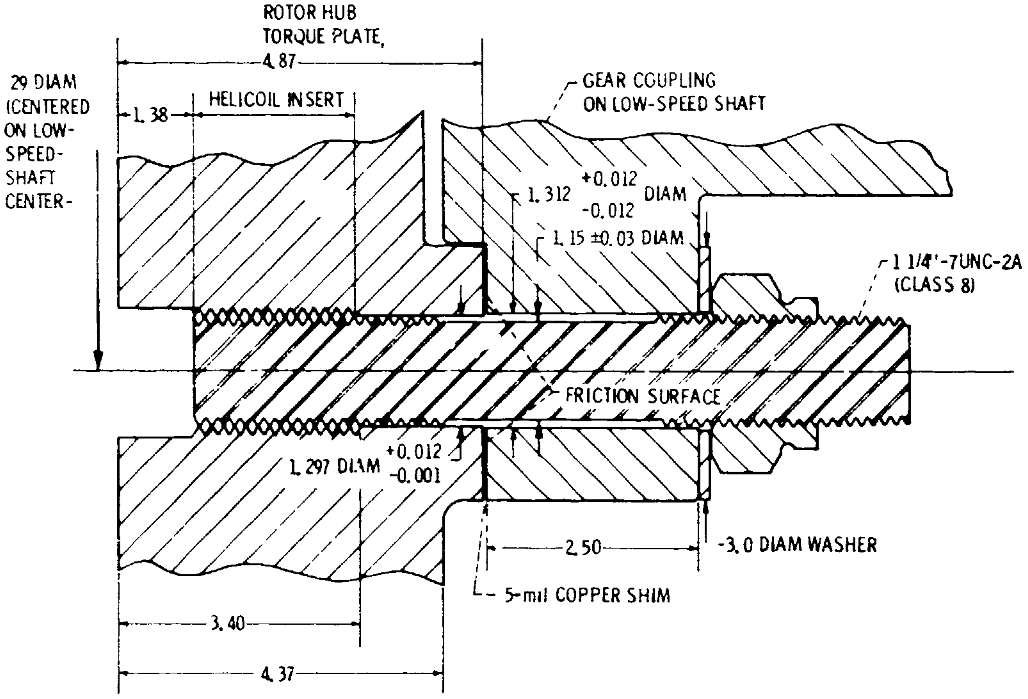

Figure 38. - Torque plate/coupling joint (stud detail). Dimensions are in inches.