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Operational Results for the Experimental DOE/NASA Mod-0A Wind Turbine Project

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R. K. Shaltens and A. G. Birchenough
National Aeronautics and Space Administration
Lewis Research Center

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Conservation and Renewable Energy
Wind Energy Technology Division

Prepared for
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R. K. Shaltens and A. G. Birchenough
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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MOD-OA WIND TURBINE PROJECT

R. K. Shaltens and A. G. Birchenough

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

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ABSTRACT

The objective of the Mod-OA wind turbine project was to gain early experience in the operation of large wind turbines in a utility environment. Four of the experimental 200 kW horizontal axis wind turbines, designed by the Lewis Research Center of the National Aeronautics and Space Administration, have been built and installed at utility sites. The experimental Mod-OA machines operated from November 1977 through June 1982. During this period the machines accumulated 38 092 hours of operation, and generated 3677 MWh of energy. The Mod-OA wind turbines were a first generation design, and even though not cost effective, the operating experience and performance characteristics have had a significant effect on the design of the second and third generation machines developed in the Federal Wind Energy Program. The Mod-OA machines have been modified as a result of the operational experience, particularly the blade development and control system strategy. An overview of the results of an in-depth study which investigated the interaction of a Mod-OA wind turbine with an isolated diesel generation system is discussed.

This report discusses the machine configuration and its advantages and disadvantages. It also describes the machine performance and availability.

1. INTRODUCTION

The Federal Wind Energy Program was established to enable research and development on various applications of wind energy systems. The program was originally administered by the National Science Foundation and is currently directed and funded by the U.S. Department of Energy. One phase of the program involves the design, fabrication, and experimental operation of large horizontal axis wind turbines. This part of the program is managed by the Lewis Research Center of the National Aeronautics and Space Administration. The first wind turbine generators to be placed into utility operation under this program (ref. 1) were four experimental 200-kW horizontal axis machines designated Mod-OA.

The purpose of experimental Mod-OA installations was to obtain early operation and performance data while gaining experience in the operation of a large wind turbine in various utility environments. These were the first wind turbines in 30 years to operate routinely on a utility grid. The key issues addressed through these operations included:

- o Compatibility with utility grid
- o Demonstration of safe unattended operation
- o Wind turbine reliability and maintainability
- o Operations and maintenance support requirements
- o Public and utility reaction and acceptance

The experimental Mod-OA machines were installed in four utilities of greatly differing size, technical capability, climate, geographic location, topography, and wind resource. The operations, routine maintenance, trouble-shooting and repair were performed by the utility whenever possible. This approach provided the best simulation of eventual commercial operations. Although these first generation experimental machines were not being operated for the prime purpose of producing power and thereby demonstrating commercial usefulness, they were maintained in a normal utility manner when possible. The major exception to this operating procedure was that major failures resulted in lengthy shutdowns for analysis, redesign and modification. Thus the operation represented a mix between utility simulation and experimental operations.

This report documents the operational experience of the experimental Mod-OA machines from November 1977 through June 1982, when the project was concluded. During this period the machines accumulated 38 092 hours of operation, and generated 3677 MWh of energy. Key Mod-OA project milestones and final performance data are given in tables 1 and 2.

2. CONFIGURATION

A cutaway view of the Mod-OA nacelle (Clayton, Culebra, and Block Island) is shown in figure 1(a). The machine had a two blade downwind configuration, using aluminum, laminated wood-epoxy or fiberglass blades. The hub housed the full span hydraulic pitch mechanism and spindle bearing, which supported the blades in a fixed coned position. The low speed shaft, to which the rotor was attached, was supported by two rolling element bearings. The 3-stage parallel shaft gearbox had a hollow input shaft through which the electrical wiring and pitch actuator hydraulic supply lines from the hub passed. The synchronous alternator was coupled to the gearbox through a V-belt drive, which allowed rotor speed changes while maintaining constant generator speed, and a fluid coupling which provided drive train softness and damping. A disk brake on the high speed shaft of the gearbox provided the critical overspeed shutdown capability and was used to secure the machine for maintenance. The bedplate was a box beam structure, and the nacelle housing was fiberglass. The yaw drive was electric, and used dual motors and gearing to provide sufficient torque. A yaw brake provided yaw axis stiffness and damping. The tower was a stiff 4-leg truss design, bolted to the reinforced concrete slab foundation. The switchgear, microprocessor based control system, safety system, and data systems were located in the control room located beneath the tower. A detailed description of the machine design is given in reference 2. The Hawaiian machine shown in figure 1(b) was slightly different in that the V-belt drive to the generator was eliminated, and the yaw drive was hydraulic (refs. 3 and 4).

3. SITE DESCRIPTION

The machines, shown in figure 2, are identified as Mod-OA1, 2, 3, and 4, corresponding to the order of installation. Mod-OA1 was installed in late 1977 in Clayton, New Mexico. The municipal utility, the Clayton Light and Water Plant, is a diesel facility isolated from other systems, and supplies from 1 to 3.5 MW to the town. The site has temperatures from 0° to 100° F. Icing conditions are common in the winter, but the site is very dry typically. The winds are above cutin two-thirds of the time, and exceed cutout 54 to 100 times a year. There are strong dinural variations with very smooth night winds. In mid-1978, the second installation was completed on the Island of Culebra, Puerto Rico, 20 miles off the coast of mainland Puerto Rico. Electric power is supplied from the mainland by the Puerto Rico Electric Power Authority (PREPA) through an underwater cable. The site is in a coastal tropical trade wind environment. There are minimal temperature variations, and the wind is smooth, and rarely above 30 mph. Corrosion from the salt laden air is severe, as at Block Island and Hawaii.

The third installation was completed in mid-1979 on Block Island, Rhode Island, located 12 miles off the coast of Rhode Island. This isolated utility, the Block Island Power Company (BIPCO), operates one or two diesel generators at a time supplying from 250 kW to over a megawatt. The Block Island site has temperature variations slightly less extreme than Clayton, but has higher humidity and rainfall. The average wind is slightly lower than Clayton, but much gustier, and is above cutout more often. The Block Island installation represented the highest wind power penetration of all the Mod-OA wind turbines.

The fourth machine, completed in mid-1980, was located on the north side of the Island of Oahu, Hawaii. The machine was connected to the electrical grid of the Hawaiian Electric Company (HECO) which is primarily supplied by oil-fired steam turbine generators. The only significant difference between the Hawaii and Culebra sites is the wind velocity. The wind at Hawaii is above cutin over 90% of the time, and above rated far more than at any other site.

4. UTILITY INTERACTIONS

One of the early concerns with wind energy was that the variable wind turbine output would not be compatible with the utility frequency and voltage requirements. Also, would there be any unusual constraints on the interconnection to the utility. A goal of the Mod-OA project was to resolve these issues.

What the utility supplies to the customer is a voltage, of well defined amplitude, waveshape, and frequency. And wind turbines, while generating power, do little to support, and may even adversely affect these values. All large wind turbines at this time use conventional synchronous generators and thus do maintain waveform control. But even waveform support may become a factor as advanced designs may incorporate inverters.

The Mod-OA installations created no significant interface difficulties. In Hawaii and Puerto Rico, the penetration was less than 1%. The Island of Culebra, Puerto Rico, is small, but it is tied through an undersea cable to the main island grid. In Clayton, New Mexico, the wind power penetration reached 20%, but did not affect utility operations (ref. 5). Increments of diesel power which could be added to or taken off line were large compared to the wind power available and, in fact, if a single diesel is used, its overload capabilities were sufficient to sustain the grid if the wind turbine output was lost.

The wind energy penetration at Block Island was very high and the interface was a concern. During the winter, with the Mod-OA in the 200 kW configuration, the penetration levels exceeded 70%. At this site, the generation equipment in operation was varied due to the wind turbine, and the effects were significant enough that the fuel efficiency of the diesels and the power quality delivered was a concern. The power quality was reflected in the grid frequency, which varied ±1/2 Hz when the wind turbine was on the line.

4.1 Utility Interaction Study

The experimental Mod-OA machine on Block Island, Rhode Island, provided a unique opportunity to evaluate the interaction of the wind turbine generator on an isolated diesel generation system. A three part study was developed to investigate and quantify this interaction (refs. 6 to 8). The study addressed: (1) fuel displacement, (2) dynamic interaction, and (3) three modes of volt-ampere regulation of the wind turbine. The study was conducted and data collected over a three month period of severely gusting winds (February through April 1982), during which the diesel units were lightly loaded. Up to 60% of the total load was supplied by the Mod-OA connected in its 150 kW configuration. Major characteristics of the BIPCO system during the 1981 Winter season are summarized in table 3. Electrical energy consumption during the winter months peaks in the morning and evening at about 450 kW. Minimum winter load occurs during early morning hours (2:00-4:00 a.m.) at 250 kW.

During this period BIPCO operated two diesel generators in parallel with the 150 kW Mod-OA wind turbine. This typically includes unit #8, a 225 kW diesel generator and unit #9, a 400 kW diesel generator. A 500 kW diesel generator (unit #10) was sometimes run in place of unit #9. The wind turbine was operated as wind was available. Typical unit loadings are given in table 4.

Unit #8 was run with constant throttle position (ungoverned) resulting in constant power output. Unit #9 maintained system frequency with a speed governor and also controlled bus voltage with an active voltage regulator. Changes in wind turbine output were compensated by unit #9 output.

The BIPCO diesel generators (units #8, 9 and 10) and the experimental Mod-OA wind turbine were instrumented for unattended data collection during the study period. Information about each of the diesel units was simultaneously recorded with wind turbine data on magnetic tape. Selected analog signals shown in figure 3 were also monitored with a strip chart recorder.

4.1.1 Fuel Displacement

The objective of the fuel displacement analysis was to determine the amount of diesel fuel displaced by the Mod-OA. Four factors that might influence diesel fuel consumption during parallel operation are: (1) gross wind turbine output, (2) wind turbine auxiliaries, (3) reduced diesel efficiency due to reduced diesel load, and (4) increased throttle activity.

Gross wind turbine output reduces overall diesel fuel consumption by contributing electrical energy without using fuel as illustrated in figure 4.

Wind turbine auxiliaries including controls, instrumentation, and control room heating increase diesel fuel consumption by using electrical energy that would otherwise serve utility customers. Auxiliary energy can be subtracted from the gross output and the result considered as the net wind turbine output.

Diesel efficiency under steady state conditions is primarily a function of load. Diesel engines are more efficient at higher loads. Increased wind generation drives diesel output down, causing the diesel to operate at lower efficiency and tending to increase specific fuel consumption.

Wind gusts cause rapid wind turbine output fluctuations which are compensated by diesel power output changes to hold constant frequency. Rapid or extreme diesel throttle variations required to compensate for the power fluctuations may increase fuel consumption by degrading diesel efficiency.

Overall influence of the wind turbine on fuel consumption was determined by quantifying the four factors to establish net displaced fuel.

Input/output curves were developed for each unit by measuring fuel input for various constant levels of power output while the unit was base loaded. Input/output curves for each unit are given in figure 5 based on a 15 minute average of input and output to account for small variations about the set point. The locus of input/output points for each diesel can be described by a straight line with reasonable accuracy.

As the wind turbine increased power output, each kilowatt of wind generation replaced a kilowatt of diesel generation. The amount of fuel displaced was determined by the slope of the diesel input/output characteristic, having units of pounds of fuel per kilowatt-hour. The slope of each line shown in figure 5 is given in table 5. This slope, the incremental fuel consumption, was found to be essentially constant for the diesel units under test. The change in diesel output (equal to the change in wind turbine output) multiplied by the incremental fuel consumption yields the displaced fuel. This incremental fuel consumption analysis can be related to the overall analysis objective because net wind turbine output (gross less auxiliaries) and the influence of changing diesel efficiency are taken into account.

The diesel unit responsible for load frequency control must continuously adjust power output to maintain electrical frequency. This is necessary because electrical load and wind turbine power output changed continuously. The diesel speed governor moved the engine throttle to maintain frequency. In order to examine the effect of throttle motion on engine efficiency, fuel consumption for each diesel was examined as a function of the rate of throttle movement. In this test, fuel consumption was monitored, as a function of throttle activity. Various average rates of throttle activity, measured in degrees of travel per second, were the result of power fluctuations caused by wind turbine operation in gusty winds. Fuel consumption under baseload conditions was subtracted from the measured consumption at various levels of throttle activity and expressed as a percentage change in consumption. Figure 6 show the results for engines #9 and #10. Engine #8 was always operated at constant throttle. There was no discernable change in fuel consumption as a function of throttle activity.

A summary of fuel usage and displacement is given in table 6. During the two month test period, unit #9 was used for load frequency control. Therefore, each kilowatt-hour generated by the wind turbine displaced 0.49 lb (0.067 gal) of fuel. Since the wind turbine auxiliaries consumed electrical energy, the wind turbine auxiliary energy meter reading was subtracted from gross wind turbine output before total displaced fuel was calculated. During the test period (February-March 1982), the Mod-OA wind turbine generated 11% of the system gross electrical energy requirement, and based on calculations, reduced fuel usage by 6.7%.

Conclusions reached for the fuel displacement phase of the study were:

1. The rate of fuel displacement by the experimental Mod-OA on Block Island was equal to the incremental fuel consumption rate of the diesel unit on load frequency control.
2. Diesel engine throttle activity resulting from wind gusts which change the wind turbine output did not significantly influence fuel consumption.

4.1.2 Dynamic Interaction

The objective of the dynamic interaction investigation was to examine four modes of wind turbine operation: (1) startup and synchronization, (2) shutdown and cutout, (3) fixed pitch generation, and (4) variable pitch (constant power) generation. Power, voltage and frequency transients were evaluated for the above modes. All of these modes for the Mod-OA WTG were automatically controlled and are discussed in greater detail in reference 9.

To serve as a basis for comparison, the BIPCO system operating with diesel generation alone was first examined.

Figure 7 shows the power output from two diesel units (#8 and #9) and the system frequency. Unit #8 was set at fixed throttle while the governor of unit #9 was operational. At a time of approximately 315 seconds, a load increase occurred causing the speed of both diesels -- and hence system frequency -- to decrease. Then the governor on unit #9 responded to maintain system frequency constant by increasing the power. This resulted in a 15 kW power and 0.4 Hz frequency peak-to-peak change. An apparent overshoot of some 20% could be interpreted to be the system characteristic damping; however, random load fluctuations made it difficult to accurately measure the actual value. This is more clearly seen in figure 8 where the load activity makes the system frequency (and thus governor control loop) appear to be in a condition of sustained oscillation. This does not imply a condition of marginal system instability; rather, the frequency of about 1 rad/s that dominates in figure 8 is a characteristic of the BIPCO diesel system.

A typical response following Mod-OA wind turbine generator synchronization is shown in figure 9. The unit #10 diesel was under governor control, so that the blade pitch angle was ramped up providing wind generated power. The governor action resulted in a near 'mirror image' power profile to meet the load demand. The power response showed a distinct oscillatory mode of about 6.6 rad/s, beginning shortly after synchronization at about the 162 second point. Also, after ramping to fixed pitch operation at 175 seconds, a damped oscillation of 0.8 rad/s occurred having a peak-to-peak power swing of about 15 kW. The frequency variation was 0.6 Hz peak-to-peak, and the average voltage at the Mod-OA bus rose to 1.4%. The 0.8 Hz frequency was largely dependent on the governor dynamics, while the 6.6 rad/s frequency was the result of the wind on the blade being blocked by the tower -- called the tower shadow effect (ref. 5). This effect did not seem to increase the normal 1% peak-to-peak voltage, nor was it visible in the system frequency.

The typical shutdown case is shown in figure 10. In this case, the damped power oscillation that occurred was somewhat lower in frequency and higher in amplitude compared to that produced during synchronizing. No abrupt transient was observed in power or voltage during the generator disconnection. The governor controlled #10 diesel power was observed to have successfully responded to the rapidly decreasing (5 to 10 kW/sec) Mod-OA power prior to generator disconnection.

In both startup and shutdown, the effect of the Mod-OA connection or disconnection to the BIPCO system was of about the same magnitude as that produced by normal load fluctuations.

An example of comparative performance between fixed, and variable pitch (constant power) control appears in figure 11. Between 60 and 70 seconds the windspeed was dropping, causing the wind turbine to fall below the 150 kW setpoint. The blade pitch controller in turn changed the blade pitch angle until it reached its maximum position. At the 95 second point the increased windspeed caused the power output to rise above the 150 kW setpoint and the blade pitch angle changed to reduce output power. At about 110 seconds an oscillation of about 0.9 rad/s developed and persisted for several cycles until decreased windspeed again resulted in fixed pitch operation. At this point the oscillation damped out. The 0.9 rad/s oscillation was readily apparent in the system frequency, resulting in a peak-to-peak variation of about 0.7 Hz. During the fixed pitch intervals, the peak-to-peak system frequency variations did not exceed 0.4 Hz.

These variations were among the most severe encountered and did not characterize all fixed-variable intermittent pitch intervals, since the behavior varied considerably with wind gusting conditions. However, even intervals where the oscillatory amplitudes are lower, they tended to oscillate at about the same dominant frequency, i.e., around 0.9 rad/s. This observation suggests that the oscillatory behavior was significantly related to the pitch controller dynamics.

Conclusions from the dynamic interaction phase of the study were:

1. Power and voltage transient due to Mod-OA normal startup and shutdown were of insignificant magnitude as were the cyclic power variations due to the tower-shadow effect.
2. Power fluctuations due to Mod-OA operation under fixed-pitch operation were successfully compensated for by the action of the diesel governor control. As a result, the frequency variations were approximately the same magnitude as those caused by the major load demand fluctuations during diesel operation alone.
3. Mod-OA operation under variable (constant power) pitch control resulted in an increase in the amplitude of the underdamped system natural frequency (0.9 rad/s). The accompanying frequency variation reached 1% under the most severe conditions for a 150 kW Mod-OA power setpoint.
4. Wind turbine generation, even when providing a large portion of the power required by an isolated utility can be a practical option resulting in system disturbances no greater than those found in conventional diesel systems.

4.1.3 Volt-Ampere Regulation Modes

The objective of the volt-ampere regulation study was to evaluate the three modes of operation of the Mod-OA alternator excitation: constant reactive power (VAR), constant power factor control (pf), and constant voltage. Normal voltage regulation on the BIPCO system is accomplished by operating a diesel with auto speed governor and auto voltage regulation settings. The other diesels operate at constant power, and have their regulators switched to manual to supply a relatively constant field voltage to the rotors. The Mod-OA regulator was controlling the field current for constant VARs.

Constant reactive power (VAR) was determined to be the most desirable operating mode for wind turbine regulation during early design studies. The major reason for this was to insure sufficient stabilizing generator torque during wind gusts at low power output.

Figure 12 shows the Mod-OA operation when set at constant 50 kVAR. The reactive power plot of the Mod-OA shows a small deviation from the average compared to the diesel units reactive power. The wind turbine reactive power varied no more than 5 kVAR peak-to-peak. Unit #8 reactive power with a constant field setting had variations of 20 kVAR on an average of 100 kVAR. Unit #9 was the regulating machine and had opposing swings of up to 55 kVAR on an average of 260 kVAR. The voltage measured at the diesel and at the wind turbine showed approximately 1% variations and lag the unit #9 reactive power by 90°. The data shows the Mod-OA constant reactive power mode contributed to the reactive power requirements of the system while not significantly affecting voltage control by the lead diesel generator. During the 0.9 rad/s oscillations, the variation in Mod-OA reactive power was significantly less than the reactive power variation in diesel #8 which was operating with fixed excitation.

Constant power factor (pf) control allowed the reactive power to vary in direct proportion to real power. The power factor is the ratio of real power to total voltamperes and is related to reactive power by the following:

$$pf = \frac{kW}{kVA} = \frac{kW}{(kW^2 + kVAR^2)^{1/2}}$$

The Mod-OA was switched to constant power factor control for a 12 week period. The 0.85 pf setting provided for a reactive power variation of 0 to 93 kVAR over a range of 1 to 150 kW output. Figure 13 shows an example of the Mod-OA operating under constant power factor with the pitch at a constant 0° angle. The wind was gusting, which caused the Mod-OA power to fluctuate. Unit #10 was the only diesel connected during this interval and was regulating both frequency and voltage. The voltage at the diesel bus appeared to be fluctuating more than at the WTG bus. The Mod-OA reactive power can be seen to rise and fall about 20% of the nominal value while following real power variations of about 25%. The reactive power on unit #10 was varying opposite that of the Mod-OA. These unit #10 variations, though small, could probably have been reduced if the Mod-OA was on constant VAR regulation rather than constant power factor.

The Mod-OA wind turbine had the capability of regulating the generator output voltage. On Block Island, the low impedance of the line and transformer between the Mod-OA and the BIPCO bus resulted in a maximum voltage drop between these buses of about 1% at the rated wind turbine output of 250 kVA.

A supervised test of the Mod-OA voltage regulation capability was undertaken. During the test the voltage droop resistance was decreased in four steps from 5% to zero droop. Figure 14 shows an example of the Mod-OA operating under constant voltage with a 5% droop setting. As the droop is decreased, the Mod-OA regulator took over an increasing share of the total system kVAR demands. The response of the Mod-OA to small voltage fluctuation was shown to be faster than that of unit #10. At 0% droop the Mod-OA reactive power fluctuations were large enough to warrant ending of the test when pitch action resulted in a sustained 10-second period oscillation. During the pitch action the unit #10 reactive power showed much smaller variation than the Mod-OA reactive power. This result indicated no instability existed between the two voltage regulators and shows no contribution to the 10-second period oscillation other than constant voltage control.

Voltage fluctuations on the bus were too large to allow unattended voltage regulation by the Mod-OA. Any manual change in the reference voltage of the diesel voltage regulator would have to be matched by an equal change in the reference on the Mod-OA voltage regulator.

The Mod-OA wind turbine generator operated successfully in all three volt-ampere regulation modes -- constant VAR, constant power factor, and constant voltage. The optimum operating mode for any specific Mod-OA installation was system dependent.

Wind turbine operation in constant VAR mode was optimum for the Block Island Mod-OA installation. Wind turbine operation in constant power factor mode was quite satisfactory, but operation in constant VAR mode minimized diesel reactive power output fluctuations. Operation in constant voltage mode was impractical for the Block Island installation.

5. MACHINE PERFORMANCE

Results of the Mod-0A machine availability and performance have been previously discussed by Birchenough in reference 15. Information concerning the actual and predicted performance of the machines and the major outages basically remain unchanged. This section will update the material that has been significant in recent machine operations and will review the results and trends due to major machine modifications. A detailed discussion of the failures, design deficiencies and resulting modifications are outside the scope of this report.

A review of the early Clayton operational data showed that the number of machine start cycles seemed to be excessive, the start cycle was too long (about 8 min) and could effect energy capture. Also, the number of yaw cycles seemed to be excessive. Changes in the start cycle criteria reduced the amount of time for the machine to synchronize (about 1-1/2 min) and therefore increased energy capture. Additional programming changes for the Mod-0A controls are described by Nyland in reference 9. A number of counters and timers were installed on the Mod-0A machines to document the effects of the control system. During the period from June 1981 through June 1982 each machine operated over 3000 hours. Table 7 compares measured data for the four machines during this period. This data shows the effect of site variability on the same machine.

Each machine operated over 8000 hours, which is enough operating time to calculate a meaningful Mean Time Between Failure (MTBF). Discrepancy Reports (DR's) documented all failures and discrepancies on the machines. The DR's were entered into a Wind Turbine Data Bank (WTDB) program which can calculate the MTBF for each machine, system or subsystem. The WTDB program is described by Klein in reference 16. Table 8 shows the number of discrepancies by system for each of the machines for the Mod-0A project life.

The Mean Time Between Failure is defined as:

$$\text{MTBF} = \frac{\text{Sync Time}}{\text{Number of Failures}}$$

The resulting MTBF curves for each machine are shown in figure 15. A MTBF approaching 400 hours was indicated for Clayton and Block Island. The Culebra and Hawaiian machine had a MTBF of about 500 hours. Data listed in the January 1970 issue of "Power" magazine show a range of 250 to 850 hours for diesel units. A table of MTBF values for established types of generating equipment was reported in the Generating Equipment Availability Data System Report for 1980 has been inserted in figure 15 for comparison.

Although a MTBF of between 400 to 500 hours sounds low, comparison to published data for commercial equipment indicated that the MTBF is excellent for an experimental project.

5.1 Component Experiences

Development of the rotor blades for the Mod-0A project was a major effort by NASA because this component: (1) was the highest cost item, (2) required long life and (3) exhibited design deficiencies early in the project. Operational blade history which is summarized for the Mod-OA Project are given in table 9.

The original Mod-OA blades were made of aluminum and were designed and constructed the same way as an airplane wing, with skins riveted to ribs and stringers. These blades were manufactured for NASA by the Lockheed Aircraft Company, Burbank, California. In April 1978, after the Clayton machine had completed about 600 hours (1.4×10^6 cycles), a blade inspection revealed discoloration adjacent to the heads of some of the fasteners. A similiar deteriation was experienced on the aluminum blades at Culebra and Block Island. Subsequent inspections revealed additional structural damage and a few design deficiencies which are discussed by Linscott in reference 10. The blades were modified and repaired several times during the operating period at Clayton. The aluminum blades were costly to repair and caused long down times for the field operations.

Experience from the operation of these blades was used to modify the aluminum blades for Culebra. Aluminum blade life was extended from 600 hours at Clayton (before modification) to over 4500 hours at Culebra (after modification) without further repair.

As a result of the early aluminum blade experience, a blade development program was undertaken which could use other materials and fabrication techniques. Blade designs were subsequently developed, using fiberglass-epoxy composites and wood-epoxy composites. Details of the NASA blade development program are discussed in reference 11 by Baldwin.

Wood-epoxy blades were designed and manufactured by Gougeon Brothers, Bay City, Michigan. These blades were fabricated by molding the blades in two halves. Thin wood veneers are contoured and laminated with epoxy resin in the mold. The two halves were then glued together to form the blade. Installation of metal studs at the root completed the blade assembly. The design and construction of the wood-epoxy blades is discussed in reference 12.

The first set of wood-epoxy blades was installed on the Hawaiian machine in May 1980. These blades operated 7844 hours (18.8×10^6 cycles) and generated 1171 MWh of electricity through November 1981. At that time, a broken stud (which connects the wood blade to the rotor) was discovered at the base of the tower. A review team later determined that corrosion of the high strength material (41L40) was the probable cause of the stud failing. Wood-epoxy blades were also installed on the Block Island wind turbine in August 1980 and the Culebra machine in August 1981. These three (3) sets of wood-epoxy blades combined for over 18 270 hours (33.6×10^6 cycles) of successful operation and produced 1926 MWh of electricity with no deterioration of the wood-epoxy composite construction. A review of the operational experience and detailed inspections of the wood-epoxy blades is discussed in reference 13 by Faddoul.

A set of fiberglass-epoxy blades was designed and manufacturered by Structural Composites Industries (SCI) of Pomona, California for use on a Mod-OA wind turbine. These blades were operated in Clayton, NM from August 1981 to June 1982 when the Mod-OA project was completed.

The SCI fiberglass-epoxy blades successfully operated 3059 hours (7.3×10^6 cycles) and produced 293 MWh of electricity. The operating experience of the SCI fiberglass-epoxy blades at Clayton is described by Sullivan in reference 14.

Operational experience with the rigid hub identified a number of components on the blade pitch mechanism which required design changes. These included the blade spindle/bearing subassembly and rotary actuator.

The blade spindle/bearing subassembly was required to react to high loads through a pair of preloaded roller bearings. After a short period of operation (usually less than 500 hr) the preload was lost, which resulted in damage to the seal surfaces, loss of lubricant, and a loose mechanism resulting in the fretting of the bearing surfaces. A redesign of the preload mechanism resolved this problem. Upgraded blade spindle/blade subassemblies were installed on the Block Island and Hawaiian machines and operated nearly 8000 hours each with no detectable loss of preload.

The rotary actuator, a rack and pinion mechanism used to rotate the blades was designed to be used in a stationary or fixed position. Due to the rotating application on the Mod-0A, the seals used to prevent leakage of the high pressure (1500 psi) hydraulic fluid wore prematurely. A number of changes in the seal configuration and hard chrome plating of the cyclinder walls was required before long life, typically 5000 hours, was obtained.

Experience with the drive train, yaw system, hydraulic and pneumatic systems and the control systems remain essentially unchanged. "Seals" in all the various systems seem to require regular refurbishment. Although these malfunctions are not frequent, they are not easily repaired due to component configuration and location. Attention to the maintenance requirements and refurbishment techniques are needed to further improve life and reduce maintenance cost on future machines.

Various machine components showed signs of deterioration due to corrosion from the salt ladden air at the island sites. All of the tower structure weldments have required painting. Exposed hardware at the upper levels (yaw drive, motors, control systems, electrical termination boxes, ladders and hoist cables) all have suffered from the corrosive environment and would have required extensive refurbishment. The Culebra and Hawaiian sites seemed to have the majority of the corrosive damage. Attention to the effect of corrosion on future machines will be required to further improve life and reduce O&M costs on future machines.

6. PROJECT ASSESSMENT

The objective of the Mod-0A project was to gain early operating experience with large wind turbines. The 4-1/2 years and over 38 000 hours of operation have fulfilled that objective and have been invaluable to the design of second and third generation machines, while offering a public and utility perception of wind power. Also, the machines themselves, even though first generation, are considered very successful. These experimental machines were watched very closely by utility and alternate energy groups as the best indicator of p actical wind energy generation.

There were also specific goals for the project. One goal was to demonstrate unattended failsafe operation. The machines ran unattended, and the protective systems successfully detected failures before the failures resulted in other serious damage. Two other related goals were to investigate the reliability of wind turbine systems and the required maintenance. The wind turbine reliability was initially below the levels required for commercially viable systems, but design and system deficiencies have been identified, and generally corrected in the second and third generation designs. Troubleshooting and repair is accomplished by the utility, generally by regular diesel mechanics and electricians. Most of the diagnosis could also be performed by the utility if the necessary manuals and troubleshooting guides were available.

A fourth goal was to assess the compatibility with the utility grid. The grid interaction with these machines has been negligible except at Block Island, where the impact has been studied in detail. The main conclusion of the Block Island study is that wind turbine generation, even when providing a large portion of the power required by an isolated utility, can be a practical option resulting in system disturbances no greater than those found in conventional diesel systems. The utility impact characteristics with Mod-OA machines have shown that the interface problems in general are very benign.

The final goal was to assess the public reaction, and it may be the most critical issue. The public should be divided into four groups: (1) the general public as visitors; (2) the residents of the local area; (3) utility personnel from other utilities and (4) the local utility personnel. The first group is the largest. Most visitors have a positive reaction. It looks good and wind energy is a good idea to pursue. Local residents are no longer in awe of the machines, and tend to be proud of having the machine. Visiting utility personnel typically are aware of the economics involved, and view the Mod-OA machines as an experiment which can be very useful, but realize that the machine is not currently viable and that improvement is necessary. The utility personnel involved with the machine are nearly universally enthusiastic, strong supporters of the machines.

7. CONCLUSION

The Mod-OA project provided early experience in wind power operation on various utility networks. The machines operated over 38 000 hours, and produced over 3.6 million kilowatt hours, exceeding the production of other large wind turbines. The machines have provided extensive data to verify the design codes, loads analysis, and to characterize wind turbine performance. Although these first generation experimental machines were not designed for economical power production, they have been valuable in assisting the technology development of advanced machines that have the potential to produce energy at competitive costs. The Mod-OA's have also been valuable in assessing utility compatibility and public reaction. The machines evolved until they provided a reliable energy source compatible with the utility requirements and capabilities.

8. REFERENCES

(1) Robbins, W. H. and Sholes, J. E.: ERDA/NASA 200-kW Mod-OA Wind Turbine Program. Third Wind Energy Workshop, CONF-770921/1, May 1977, pp. 59-75.

(2) Andersen, T. S., et al.: Mod-OA 200 kW Wind Turbine Generator Design and Analysis Report. (AESD-TME-3052, Westinghouse Electric Corp.; NASA Contract DEN3-163.) DOE/NASA/0163-2, NASA CR-165128, 1980.

(3) Lampe, R. F., et al.: Modification for Mod-OA Wind Turbine Direct Drive Generator, WAESD-TME-2950, Westinghouse Electric Corporation, 1979.

(4) Lampe, R. F.; Hughes, P. S.; and Anderson, T. S.: Redesigned Yaw Drive System Mod-OA. WAESD-TME-3039, Westinghouse Electric Corporation, 1980.

(5) Reddoch, T. W.; and Klein, J. W.: No Ill Winds for New Mexico Utility, IEEE Spectrum, vol. 16, no. 3, Mar. 1979, pp. 57-61.

(6) Stiller, P. H.; Scott, G. W.; and Shaltens, R. K.: Measured Effect of Wind Generation on the Fuel Consumption of an Isolated Diesel Power System. IEEE Trans. Power Appar. Sys., vol. PAS-102, June 1983, pp. 1788-1792.

(7) Scott, G. W., Kruse, V. J.; and Smith, R. F.: Wind Turbine Generator Interaction with Conventional Diesel Generators on Block Island, Rhode Island. AST-82-1728, Westinghouse Electric Corporation, Jan. 1983.

(8) Scott, G. W.; Wilreker, V. F.; and Shaltens, R. K.: Wind Turbine Generator Interaction with Diesel Generators on an Isolated Diesel System. Presented at IEEE/PES 1983 Summer Power Meeting, (Los Angeles, Calif.), July 17-22, 1983, paper no. 83 SM 329-0.

(9) Nyland, T. W. and Birchenough, A. G.: A Microprocessor Control System for the 200 Kilowatt Mod-OA Wind Turbine, NASA TM-82711, 1982.

(10) Linscott, B. S.; Shaltens, R. K.; and Eggers, A. G.: Aluminum Blade Development for the Mod-OA 200-Kilowatt Wind Turbine. NASA TM-82594, 1981.

(11) Baldwin, D. H. and Linscott, B. S.: The Federal Wind Program at NASA Lewis Research Center, NASA TM-83480, Sept. 1983.

(12) Lieblein, S., et al: Design and Evaluation of Low-Cost Laminated Wood Composite Blades for Intermediate Size Wind Turbines. (TRS-107, Technical Report Services; NASA Contract DEN3-101.) DOE/NASA/0101-1, NASA CR-165463, 1982.

(13) Faddoul, J. R.: Examination, Evaluation, and Repair of Laminated Wood Wind Turbine Blades after 1-1/2 Years of Service, NASA TM-83483, October 1983.

(14) Sullivan, T. L.: Structural Qualification Testing and Operational Loading on a Fiberglass Rotor Blade for the Mod-OA Wind Turbine. NASA TM-83309, 1983.

(15) Birchenough, A. G.; Saunders, A. L.; Nyland, T. W.; and Shaltens, R. K.: Operating Experience with Four 200 kW Mod-OA Wind Turbine Generators, Large Horizontal Axis Wind Turbines, NASA CP 2230, 1982, pp. 469-487.

(16) Klein, W. E.: Experience with Modified Aerospace Reliability and Quality Assurance Method for Wind Turbines, DOE/NASA/20320-38, NASA TM-82803, 1982.

TABLE 1. - MOD-OA MILESTONES

	Clayton	Culebra	Block Island	Hawaii
Site selected	1/77	6/77	6/77	8/78
First rotation	11/77	6/78	5/79	5/80
Dedication	1/78	7/78	6/79	7/80
1000 hr of operation	5/78	4/80	8/80	8/80
150 kW configuration	-----	1/81	10/81	----
Second generation blade	8/81	8/81	8/80	5/80
500 MWh	11/79	8/81	1/82	2/81
1000 MWh	1/82	----	-----	9/81

TABLE 2. - MOD-OA PERFORMANCE DATA

	Months of operation	Synchronous time, hr	Energy, MWh	Average power, kW
Clayton	55	13 045	1145	88
Culebra	48	8 094	683	84
Block Island	37	8 509	588	69
Hawaii	25	8 444	1261	149

TABLE 3. - BIPCO GENERATION AND LOAD/WINTER 1981

Peak load, kW	450
Minimum load, kW	250
Active generation capacity:	
Diesel, unit #8, kW	225
Diesel, unit #9, kW	400
Diesel, unit #10, kW	500
Mod-OA WTG, kW	150
System heat rate (average 5 yr), Btu/kWh	17 600
Fuel	No. 2 fuel oil

TABLE 4. - TYPICAL WINTER GENERATION UNIT LOADS

	Rating, kW	Output	
		Low wind, kW	High wind, kW
Diesel unit #8	225	100	100
Diesel unit #9	400	225	100
Mod-OA WTG	150	25	150
System load		350	350

TABLE 5. - DIESEL UNIT INCREMENTAL RATES

Unit #	Incremental rate
8	0.43 lb. fuel/kWhr
9	0.49 lb. fuel/kWhr
10	0.57 lb. fuel/kWhr

TABLE 6. - FUEL DISPLACEMENT RESULTS FOR TEST PERIOD

Diesel (unit #9) incremental fuel consumption, lb fuel/kWh	0.49
Gross Mod-OA wind turbine energy, kWh	56 900
Mod-OA wind turbine auxiliary energy, kWh	4470
Displaced fuel (line 2 - line 3) x line 1, lb (gal)	25 700 (3560)
Gross energy generated (diesel and wind turbine), kWh	496 000
Total fuel burned, lb (gal)	358 000 (49 800)

TABLE 7. - MOD-OA OPERATIONAL DATA FOR THE PERIOD JUNE 1981 - JUNE 1982

	Synchronous time, hr	Start cycles/ synchronous time, hr	Yaw time, hr	Yaw cycles	Yaw cycles/ synchronous time, hr
NM	3343	2.06	87	15 700	4.7
PR[a]	3321	.84	86	15 500	4.7
RI[a]	3731	.5	54	9 700	2.6
HA	3268	.24	92	[b]4 100	[b]1.3

[a]31 rpm, 150 kW configuration.
[b]Not measured - estimated on OA experience and modified from 0.25 deg/sec yaw speed.

TABLE 8. - DISCREPANCY REPORTS (DR'S) FOR MOD-OA MACHINES

System	Subtotals	NM	PR	RI	HA
Controls	45	22	7	7	9
Electrical	15	5	2	4	4
Safety system	32	21	2	7	2
Data system	24	18	2	2	2
Drive train	65	37	12	8	8
Pitch system	39	16	10	8	5
Auxiliary equipment	19	5	7	2	5
Yaw system	30	13	3	6	8
Totals	269	137	45	44	43

TABLE 9. - MOD-OA BLADE OPERATING HISTORY

	Type/manufacturer	Operating period	Operating time, hr	Operating cycles	Remarks
Clayton, NM	Aluminum/ Lockheed	Nov 77 - Mar 81	8070	19.4×10^6	See note 1
	Wood-Epoxy/ Gougeon Brothers(2)	Mar 81 - Aug 81	>1916	$>1.8 \times 10^6$	Operational - Experiment completed
	Fiberglass/ SCI	Aug 81 - Jun 82	>3059	$>7.3 \times 10^6$	Project Completed
Culebra, PR	Aluminum/ Lockheed	Jun 78 - Jul 81	5232	11.4×10^6	Structural Mods at 600 hr
	Wood-Epoxy/ Gougeon Brothers	Aug 81 - Jun 82	>2862	$>5.4 \times 10^6$	Project Completed
Block Island, RI	Aluminum/ Lockheed	May 79 - Jul 80	945	2.3×10^6	Structural Deterioration
	Wood-Epoxy/ Gougeon Brothers	Aug 80 - Jun 82	>7564	$>14.4 \times 10^6$	Project Completed
Oahu, HA	Wood-Epoxy/ Gougeon Brothers	May 80 - Nov 81	7844	18.8×10^6	Stud failure
	Wood-Epoxy/ Gougeon Brothers	Mar 82 - Jun 82	>600	$>1.4 \times 10^6$	Project Completed

Notes:

(1) Mod-OA blades upgraded after 1000 hr, required three field repairs, total operating time: 6684 hr. Mod-0 blades used twice, total operating time: 1386 hr.

(2) Experimental 92' diameter rotor.

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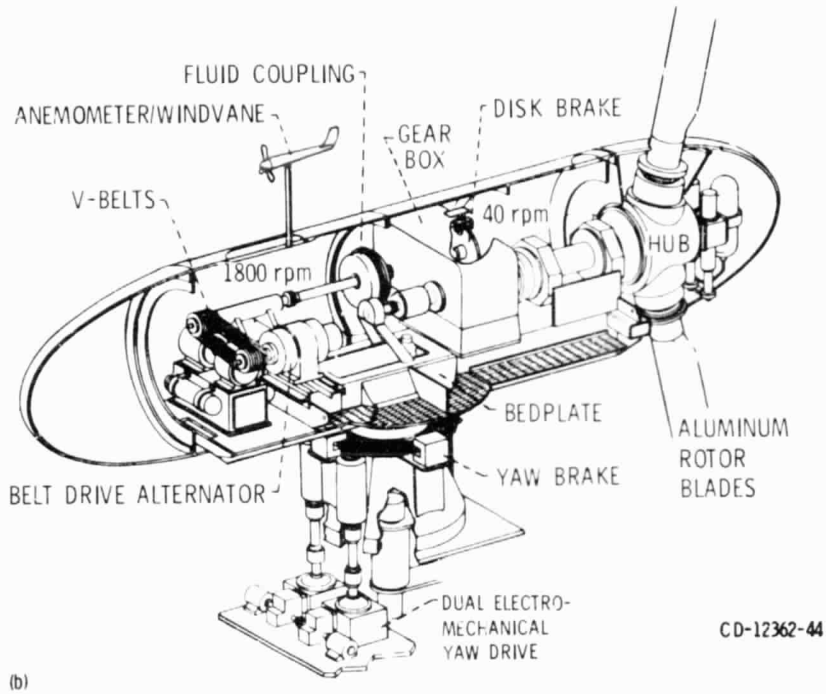
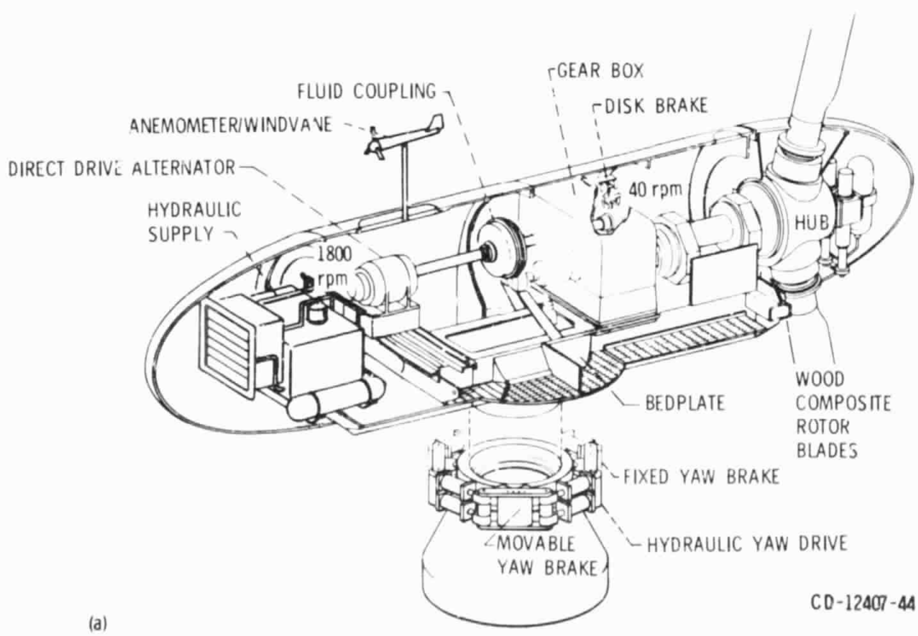


(b)



(a)

Figure 1. - Experimental Mod-OA wind turbine schematics.

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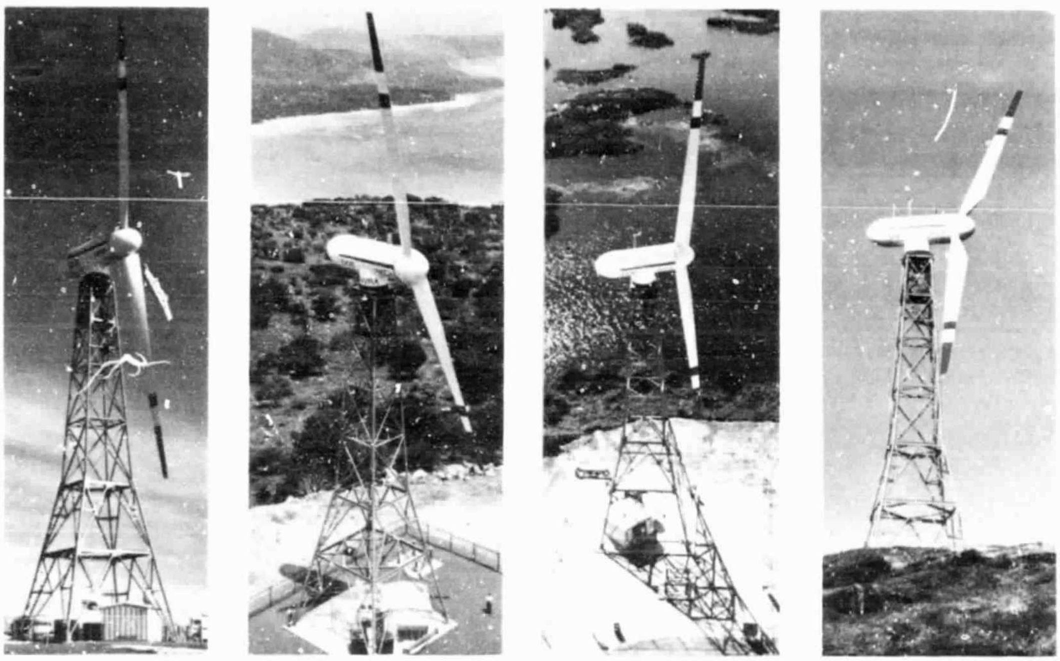
MOD-OA WIND TURBINES



CLAYTON, NEW MEXICO | CULEBRA, PUERTO RICO | BLOCK ISLAND, RHODE ISLAND | KAHUKU PT., OAHU, HAWAII

Figure 2. - Experimental Mod-OA wind turbines. C-80-3697

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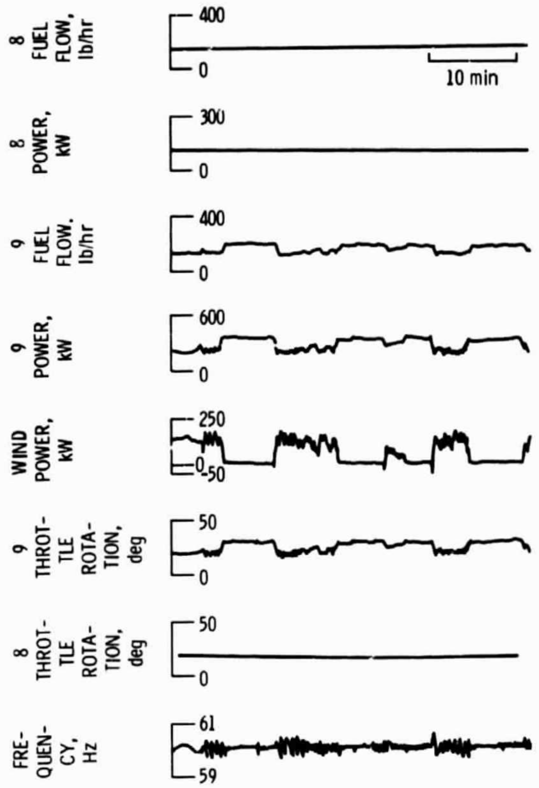

Figure 3. - Sample strip chart from the utility interaction study.

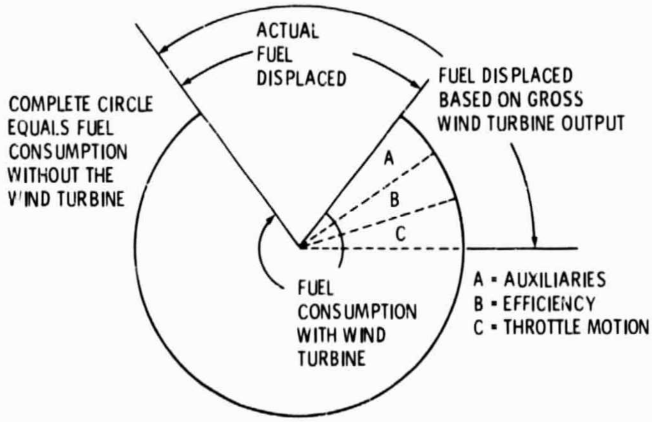

Figure 4. - Fuel displaced by wind turbine.

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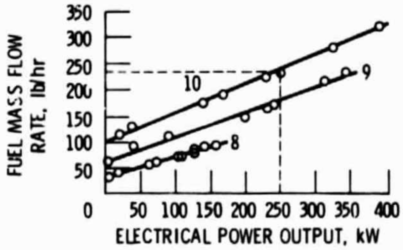

Figure 5. - Diesel input/output characteristics.

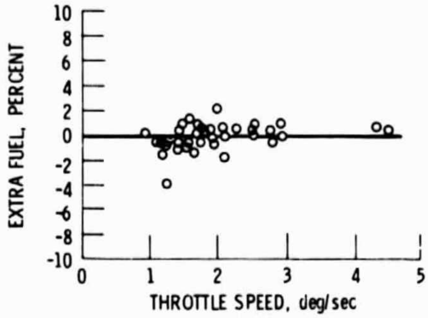

Figure 6. - Throttle motion versus extra fuel.

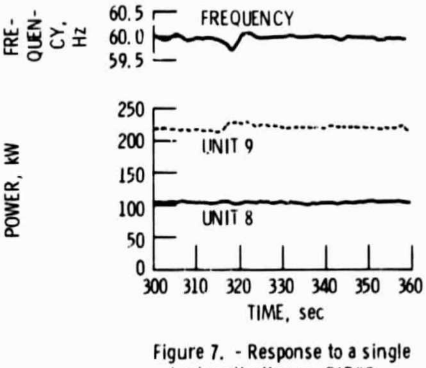

Figure 7. - Response to a single load application on BIPCO diesel system (without Mod-OA WTG).

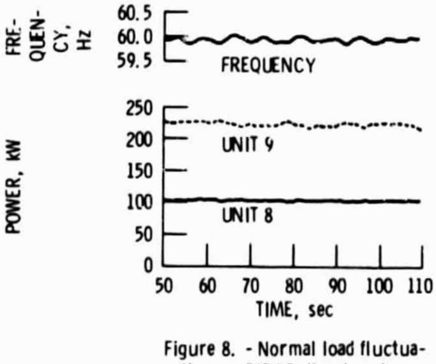

Figure 8. - Normal load fluctuation on BIPCO diesel system (without Mod-OA WTG).

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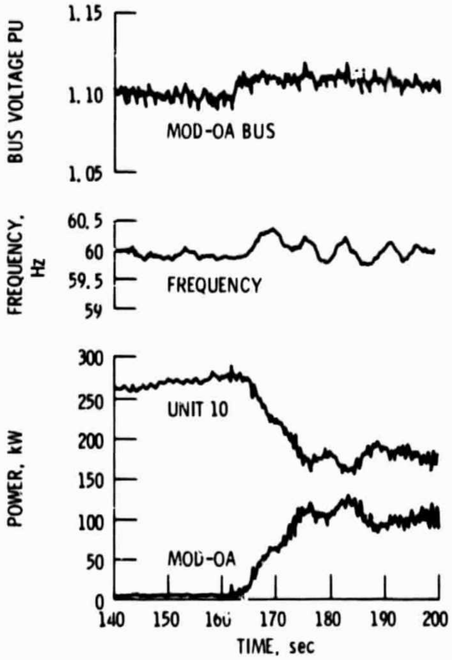

Figure 9. - Startup and synchronization of the Mod-OA WTG.

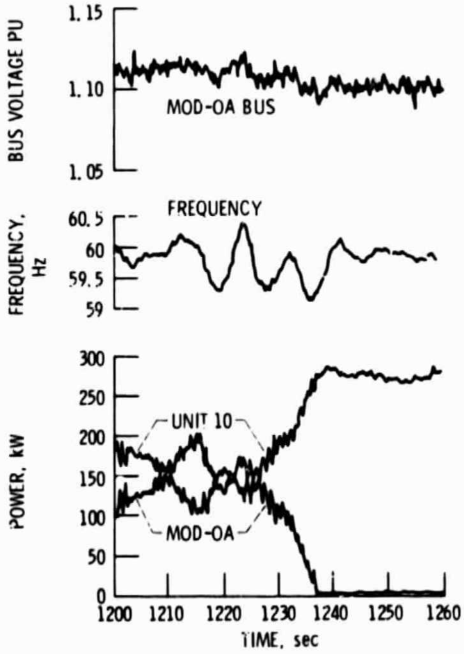

Figure 10. - Normal shutdown and cutout of the Mod-OA WTG.

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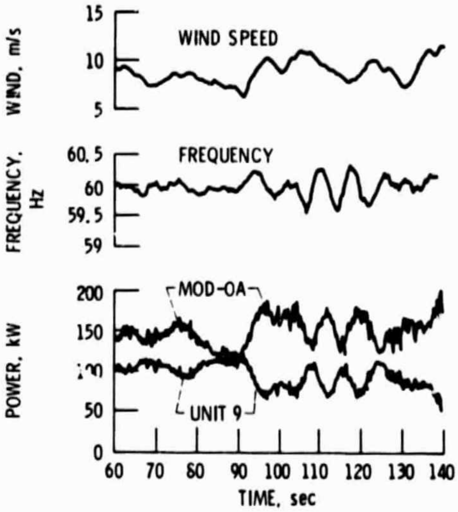

Figure 11. - Fixed pitch and variable pitch (constant power) variation of the Mod-OA WTG.

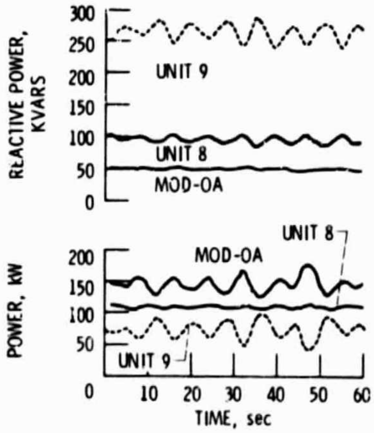

Figure 12. - Mod-OA response with reactive power (VAR) control.

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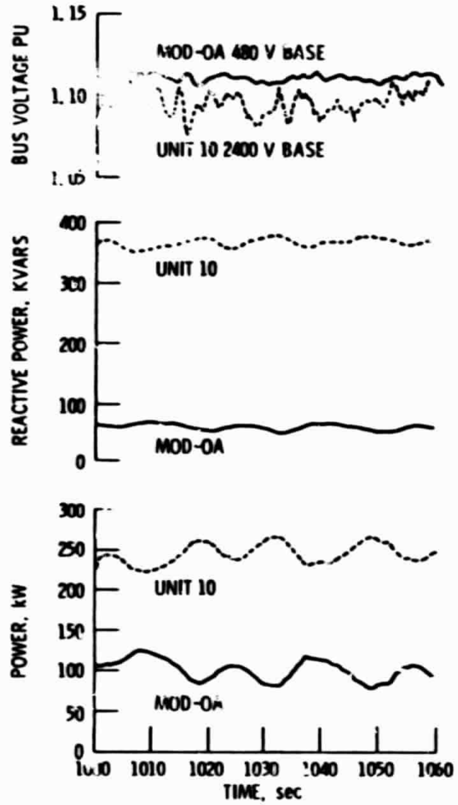

Figure 13. - Mod-OA response with power factor (pf) control.

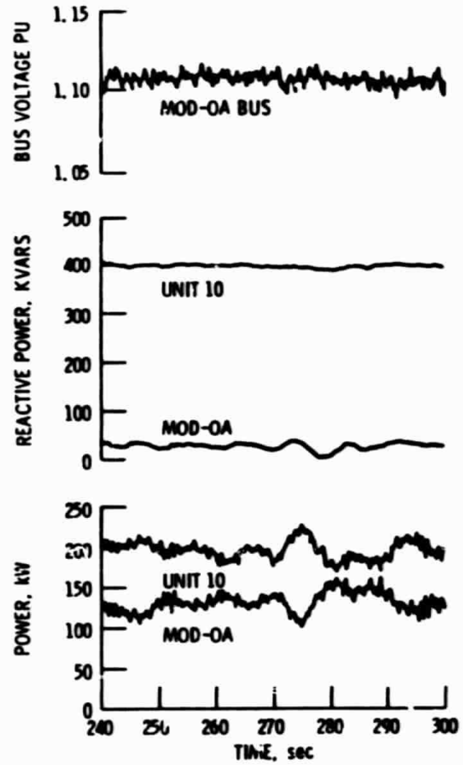

Figure 14. - Mod-OA response during 5% voltage droop test.

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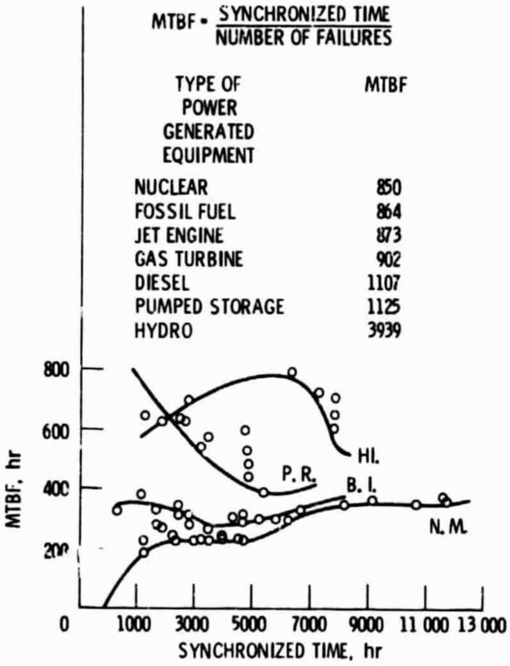

Figure 15. - Mod-OA mean time between failure (MTBF) versus synchronized time (hr).

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16. Abstract
The objective of the Mod-OA wind turbine project was to gain early experience in the operation of large wind turbines in a utility environment. Four of the experimental 200 kW horizontal axis wind turbines, designed by the Lewis Research Center of the National Aeronautics and Space Administration, have been built and installed at utility sites. The experimental Mod-OA machines operated from November 1977 through June 1982. During this period the machines accumulated 38 092 hours of operation, and generated 3677 MWh of energy. The Mod-OA wind turbines were a first generation design, and even though not cost effective, the operating experience and performance characteristics have had a significant effect on the design of the second and third generation machines developed in the Federal Wind Energy Program. The Mod-OA machines have been modified as a result of the operational experience, particularly the blade development and control system strategy. An overview of the results of an in-depth study which investigated the interaction of a Mod-OA wind turbine with an isolated diesel generation system is discussed. This report discusses the machine configuration and its advantages and disadvantages. It also describes the machine performance and availability.

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