

MOD-2 WIND TURBINE  
PROJECT ASSESSMENT AND CLUSTER TEST PLANS

By

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ABSTRACT

An assessment of the Mod-2 Wind Turbine project is presented based on initial goals and present results. Specifically, the Mod-2 background, project flow, and a chronology of events/results leading to Mod-2 acceptance is presented. After checkout/acceptance of the three operating turbines, NASA/LeRC will continue management of a two year test program performed at the DOE Goodnoe Hills test site. This test program is expected to yield data necessary for the continued development and optimization of wind energy systems. These test activities, the implementation of, and the results to date are also presented.

INTRODUCTION

Within the Federal Wind Energy Program, the U.S. Department of Energy (DOE) Office of Solar Power Applications has overall responsibility for conceiving and directing the development of technology for wind energy systems. The DOE has delegated project management responsibility to the National Aeronautics and Space Administration (NASA), Lewis Research Center (LeRC), in Cleveland, Ohio, for conducting successful design, fabrication, and field testing of large (100 kW and larger) horizontal-axis wind turbine systems for utility applications. The specific objective of the Federal Wind Energy Program and the projects by which it is implemented is the development of the technology necessary for commercially-feasible wind-powered generation of electricity.

The Mod-2 wind turbine project is the first in the Federal Wind Energy Program to be dedicated to the design, installation and demonstration of a wind turbine system of commercial scale, at a rated power of 2.5 MW. In addition, the installation of three such

machines clustered at a single site at Goldendale, Washington, is expected to test, evaluate and demonstrate the interactive and machine/grid effects of multiple, identical, machines integrated into a utility network.

The DOE selected the Bonneville Power Administration (BPA) as the participating utility of the Mod-2 wind turbine project. This utility was selected for the reasons of its scope as a large regional power-distributing organization in the Pacific Northwest and its capability of supplying valuable support in attainment of the DOE/NASA project goals.

Specifically, this paper presents the Mod-2 requirements, project flow, and a chronology of events/results leading to Mod-2 acceptance. After checkout/acceptance of the three operating turbines, NASA/LeRC will continue management of a two year test program performed at the DOE Goodnoe Hills Test site. This test program is expected to yield data necessary for the continued development and optimization of wind energy systems. These test activities, the implementation of, and the results to date are also presented.

## REQUIREMENTS

DOE/NASA awarded the contract to design and build a second generation, Mod-2, wind turbine in August 1977. The specific objective of the Mod-2 project is to establish the design and performance of a nominal megawatt-size wind turbine that can achieve a cost-of-energy for the 100th unit in production of less than 5¢/kWh including capital, and operating and maintenance costs in 1980 dollars. The wind turbines are assumed to be deployed in a twenty-five unit cluster at a site having an annual mean wind speed of 6.3 m/s (14 mph) at a height of 9.1 m.

Meeting those specifications, shown in figure 1, required use of lighter, more compact, less expensive components than those used in earlier models. The experience gained in operation of the Mod-0, Mod-0A, and Mod-1 suggested design refinements used in the Mod-2. The evolution of the technology base for the Mod-2 is shown in figure 2. From this base four major innovations evolved and formed an important part of the success of the Mod-2 design. These four major innovations were: (a) controlling the load on the blades by tip control; (b) the "soft" steel shell tower; (c) the compact, light gearbox; and (d) teetering the rotor at the hub to reduce blade loads.

The Mod-0 Experimental Wind Turbine near Sandusky, Ohio was used to simulate the soft tower, the teetered hub, tip control blades and the upwind rotor. Figure 3 shows the testing of the Mod-2 tip control configuration on the Mod-0 turbine.

## PROJECT FLOW

To meet the design requirements, the Mod-2 project was structured toward a program of comprehensive trade-off and sizing studies, use of innovative design ideas where advantageous, and design for simplicity and minimum operating and maintenance costs.

Shown in figure 4 is the overall program schedule which includes six important phases as follows:

1) Conceptual Design - Trade studies (particularly examining optimization of rotor size from 300 feet up), developmental tests and design criteria sensitivity studies were used to select a wind turbine configuration which best meets cost goals and technical requirements. This phase was extended four months to include additional trade-off studies, which resulted in a COE projection of less than 4¢/kwh in 1977 dollars. A conceptual design review was held June 1978 and written approval by the DOE and LeRC Wind Energy Project Office was given to proceed. An example of a typical trade-off study as well as a summary of all trade-offs are shown in figures 5 and 6, respectively.

2) Preliminary Design - Layout drawings were prepared and analysis and expanded testing were conducted to further define and evaluate the configuration selected in the Concept Design phase. Some long-lead procurement items were ordered. The design review was held in November 1978, and written approval to proceed was given by the DOE and the LeRC Project Office in January 1979.

3) Detailed Design - Final drawings and analysis and shop planning documents were prepared. Tooling design and fabrication began and long-lead materials were procured. Final developmental testing was performed. The detailed design review was held in May 1979 documenting the work to date, with updates in the analysis and planning as required. A key programmatic decision point occurred at this time when DOE approved the next phase, and specified a total of three machines to be procured. Site selection, which was also to be specified by DOE at this time, was deferred until October 1979. In October DOE selected the Goodnoe Hills site, near Goldendale, Washington, with the Bonneville Power Administration (BPA) as the participating electric utility.

4) Fabrication - This aspect of the project was probably the most difficult to coordinate and maintain on schedule. Figure 7 shows pictorially how the components literally came from all corners of the USA. Major assembly of the nacelle was performed by Bucyrus Erie in Pocatello, Idaho, the rotor was manufactured by Pittsburgh Des Moine Steel and the tower by Chicago Bridge and Iron in Salt Lake City, Utah. Although the primary gearbox was supplied by Stal-Laval in Sweden an alternate gearbox has been manufactured by Philadelphia Gear in Philadelphia, Pa., and is presently undergoing checkout spin testing.

5) Installation, Checkout and Acceptance - Site preparation work began at Goodnoe Hills in March 1980 following the selection of subcontractors and the conclusion of an interim agreement with the landowner to permit construction work to begin. BPA held a "ground-breaking" ceremony at the site in April 1980. Installation of meteorological towers (PNL and BPA) was completed by July 1980. All foundations were poured and cured and the first wind turbine tower erected by August 1980. Integration testing of the first nacelle was completed at Bucyrus-Erie and this nacelle was installed on its tower in September 1980. Following the successful first rotation of turbine No. 1 in November 1981, turbines No. 2 and No. 3 likewise began operating in March 1981 and May 1981, respectively. BPA held the official DOE Cluster Dedication on May 29, 1981 with all of the turbines capable of producing power to the BPA grid. Each of the three turbines is presently in the acceptance test phase.

Although originally targeted for completion by July 1981, the acceptance test schedule has been revised to reflect the recovery plan necessitated by the failure of the emergency shutdown system of turbine No. 1 on June 8, 1981. Failure analysis and corrective actions have been scheduled for completion by end of July 1981. Incorporation of the corrective actions during August 1981 will return turbine No. 2 and No. 3 to safe operating conditions in September 1981. With available winds, acceptance testing of turbines No. 2 and No. 3 is targeted for late September 1981. Turbine No. 1 damage assessment will be completed by August 1981 with replacement of the generator, quill shaft requiring long lead times. Consequently, acceptance testing on turbine No. 1 will not resume until late December 1981. This recovery activity for the Mod-2 cluster is noted in figure 4.

6) Two-Year Operational Field Test - During this phase, the Bonneville Power Administration (BPA) will provide operational and maintenance support for the wind turbines. This support is defined in an Interagency Agreement signed by LeRC and BPA in September 1980. BPA has agreed to purchase the net power generated by the three wind turbines for 2.5¢/kWh. Under a separate contract with BEC, technical support (including limited machine modifications to meet project goals and special maintenance) will be provided.

#### ASSESSMENT

The design, fabrication, assembly, and synchronization of the three Mod-2 turbines certainly represents a major advancement in the development of large horizontal axis wind turbines. It is believed that these turbines, manufactured on a mass-production basis, have retained the original busbar energy cost goal (100th unit) of less than 4¢ per kWh (1977 dollars). Single units produced in today's market are currently capable of producing energy at costs of about 8¢-10¢/kWh.

Although it is premature to assess the multiple year operation of the Mod-2's, preliminary performance testing over the entire power range in winds up to 45 mph has been quite encouraging. Minor problem areas, technical and operational, have occurred as in any testing associated with prototype units. Although some of these areas remain unresolved at the present time, none is believed to be of such a magnitude to preclude future planning and operation of large scale wind turbine farms.

With regards to the continued planning necessary to make wind farms a reality, it was interesting to observe that during the initial operation of the three Mod-2's, the time period from first rotation to first synchronization became increasingly less; from 1-1/2 months to less than a week. In fact, if winds had been available for sufficient duration, the third Mod-2 would have accomplished these two milestones within the same day.

This learning curve, so important in the confidence necessary in planning wind farms, was also evident during the construction phase. Nacelle lifts and rotor lifts were performed routinely by the time the third turbine was erected. Transporting five rotor sections for on-site assembly was reduced to three sections with the complete shipping of the rotor tip/mid sections as a single (120 ft.) load.

As initially stated, a detailed assessment of all aspects of the Mod-2 program is premature. However, a visit to the Goodnoe Hills site has already convinced many that large wind turbines are a reality. The commercialization of this reality depends on providing a high level of confidence in the long term operation of large wind turbines. After the first year of operation (June 1982), a detailed assessment of turbine operation will be made. At that time DOE will assess plans for continued experimental operations and/or the disposition of the turbines. The comprehensive test plan defining the roles and responsibilities of various organizations involved in the operational field test phase forms the basis for the Mod-2 Test Project.

#### TEST PROJECT

As presently scheduled, installation of the three clustered Mod-2 wind turbines at the test site, known as Goodnoe Hills near Goldendale, Washington, will be completed by the end of CY-81.

The Mod-2 wind turbines offer a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment. During the two years following acceptance of the three machines, the Mod-2s will act as a wind power laboratory, while also functioning as part of the Northwest power system through the Klickitat County Public Utility District.

During this cluster operational period, various organizations are expected to be conducting tests individually and/or jointly at the Mod-2 wind turbine site. The objective of this test project is to ensure orderly scheduling and performance of the respective tests and to maintain wind turbine system security. A Test Project Review Board (TPRB) and a Test Facility Operations contractor has been established by the Lead Test Center. However, implementation of the various test project areas will be the prime responsibility of the Lead Test Project organization. These Lead Test Project organizations are expected to include the LeRC, BPA, BEC, SERI, Battelle Pacific Northwest Laboratories (PNL) and others.

### TEST PROJECT PLAN

The fundamental strategy of the test project plan is both aggressive and flexible. In accordance with current priorities of the DOE Office of Solar Power Applications, primary emphasis will be placed on the field test operation of the wind turbine cluster. Secondly, the cluster can also be utilized as an experimental testbed for supporting related wind energy system development of a moderate degree. The flexibility of the plan's strategy is conducive to management and attainment of full development of the Mod-2 wind turbine cluster. Cooperation between the DOE and the NASA will be maintained through joint LeRC/BPA approval of field test operation activities entailed by the project.

The interrelationship of the test project plan, the LeRC/BPA Interagency Agreement and the controlling test plans describing test activities at the Mod-2 wind turbine cluster site is shown in figure 8.

The Interagency Agreement is the basic understanding of the working relationship between the LeRC and BPA for the purpose of implementing this project. It is entitled "Integration and Operational Field Testing of 2.5 MW Mod-2 Wind Turbines."

The test project plan defines not only the present responsibilities of the participants leading to the initial checkout and acceptance of the Mod-2 cluster (Integration), but also the cooperative management of an extended test program (Field Operation) that is expected to provide valuable data to be used in the continued development and optimization of wind energy systems (Experimental Machine Utilization).

The test plans are detailed descriptions of the work to be accomplished by the respective described activities or tasks. In respect to each activity or task described, the test plan states test objectives, conditions, facility requirements, operational impact, test matrix, documentation, resources and schedule.

## TEST SITE DESCRIPTION

To make the most of the research opportunities afforded by the Mod-2 turbines, each machine has been assigned a separate primary test function, while still working as part of the multi-unit wind farm.

As shown in figure 9 and 10, Unit 2 farthest from the road, will be kept in operation whenever possible, and will be quickly brought back on line by Boeing or BPA crews in the area when it shuts down, in order to determine the maximum energy yield which can be produced by the Mod-2 at the Goodnoe Hills site.

Unit 3, nearest the road, will run under "real world" utility conditions. When the machine shuts down and requires inspection, crews from BPA substations will be scheduled to work on it. This will give utilities an idea of the staff commitment necessary to maintain a wind turbine, and the energy production achievable under routine operating conditions.

Unit 1, nearest the visitor's center, is the machine where ideas for improving the design or operating limits on the Mod-2 will first be tested, to further develop wind turbine technology.

The spacing of the Mod-2 turbines at the test site is also considered as an important test feature. The three machines are purposely positioned at the corners of an irregular triangle whose sides are five, seven and ten blade rotor diameters (i.e: 1,500, 2100, and 3,000 feet) long. This will allow researchers to test the effects of the machines on one another at different spacings.

Two meteorological towers--a 200-foot BPA tower and a 350-foot Battelle PNL tower--collect windspeed, wind direction and other atmospheric data at the Goodnoe Hills site.

The data center is the heart of the Goodnoe Hills data acquisition system. A function block diagram of the intersite data system is shown in figure 11.

## TECHNICAL PLAN

As illustrated in figure 8, the activities provided by this test project consist of three major elements in the technology development and demonstration of the Mod-2 wind turbine. These elements are:

- 1) Integration - The tasks relating to this element are primarily concerned with the effort necessary to achieve first rotation of the three Mod-2 turbines and acceptance by LeRC for turnover to BPA. For this reason, the specific tasks have not been included in this paper.

2) Field Operation - For a period of approximately two years, this element will be devoted to verification of the baseline performance and establishing the operational characteristics of the Mod-2 wind turbine cluster.

3) Experimental Machine Utilization - This element is an important aspect of a planned long-term project within the Federal Wind Energy Program to extend operation of existing DOE/NASA wind, in the interest of maximizing data and component technologies development through real-time machine operation. Hence, this aspect of the test project will specifically be concerned with analysis and testing pertaining to areas of:

- o cluster/array analysis
- o array maintenance evaluation
- o advanced concepts verification

Since the Field Operation phase is the current active portion of the Mod-2 test project, a brief description of the various test areas to date is as follows:

Performance Test Plan - Performance evaluation of these machines in the three unit cluster configuration will commence with acceptance of each turbine. It is planned that the two year test period will evaluate baseline performance as well as performance improvements which can be achieved through modifications of hardware, software, and operating procedures. Specific performance tests planned to date include:

#### 1) Baseline System Performance Tests

The primary goal of this Baseline System Performance test is to evaluate the performance achieved (or achievable) by the baseline configuration. This will be measured in terms of power output as a function of wind speed and the energy produced as a fraction of the energy available in the actual wind environments experienced.

A secondary objective is to evaluate and correlate the calculated power output performance versus wind speed against the actual performance achieved at each wind speed.

#### 2) High Wind Cut-Out Speed Tests

The baseline Mod-2 is designed to shutdown when wind speeds at hub height exceed 45 mph. Shutdown is initiated when a specified value of blade pitch angle is exceeded. At some wind sites a significant increase in annual energy would be achieved by operating to higher wind speeds.

Operation at off-wind yaw angles in the high wind speed regimes results in higher rotor teetering motions and associated higher cyclic loads. At various combinations of wind speed and yaw angle,



the rotor teeter motion will be sufficient to cause impacting of the teeter stops.

The primary objective is to determine the maximum wind speed at which the Mod-2 may be operated, and what modifications are required to permit the Mod-2 to operate at wind speeds above 45 mph when the wind spectrum includes significant time in the above 45 mph wind speed regime.

### 3) Power Output Limit Tests

The Mod-2 generator is rated at 3125 KVA at 7000 ft. altitude. It therefore has capability for a power output of 3125 kW if operated at a power factor of unity. At lower altitude, the generator is capable of additional power output. The limiting power output of the generator is, in general, a function of internal temperature due to losses. It may be desirable to implement wind turbine power output control based on measured generator temperature.

The Mod-2 gearbox was designed and tested at a torque loading and rpm equivalent to 3750 kW. The ability to increase power output is therefore dependent on the structural capabilities of the rotor and drive shafts. Specific objectives will be to:

- (1) Evaluate capability of rotor and drive shafts to operate at higher torque.
- (2) Establish limiting values of torque.
- (3) Develop a recommended control concept to operate at the optimum power output limit.

### 4) Low Wind Startup/Shutdown Tests

The baseline configuration initiates shutdown when the power output averaged over 51.2 seconds is less than 125 kW. Considerable operating time is lost during startup during these low wind conditions. It is anticipated that many start/stops would be eliminated and that additional annual energy could be achieved by allowing some motoring at wind speeds of approximately 11 mph. Consequently, emphasis will be placed on:

- (1) Reducing number of start/stop cycles
- (2) Increasing annual net energy production

### 5) Pitch Setting Refinement Tests

Below rated power, the control system operates at two values of fixed pitch with rate damping. The values selected may not be optimum. Revised and/or additional settings may optimize power output at below rated power.

During startup the pitch settings have been programmed as a function of wind speed and rpm to provide maximum acceleration to 10 rpm. Above 10 rpm the pitch settings are controlled by hub rate error until synchronization is achieved at 17.5 rpm.

Specific objectives for these sub-test areas will be to;

- (1) Adjust the startup algorithms to assure acceleration through 10 rpm.
- (2) Evaluate algorithm changes to minimize the time to synchronization.
- (3) Adjust pitch settings at below rated power to optimize power output.

#### 6) Yaw Control Refinement Tests

The yaw control is based on time averaging of yaw values as determined by the nacelle wind sensors. Any refinement in control algorithms which will reduce the time spent at yaw angles will improve power output by the third power of the cosine of the yaw angle.

The primary objective is to increase the annual energy produced. Sublevel objectives are to:

- (1) Reduce yaw angle excursions
- (2) Reduce time spent at angles of yaw
- (3) Reduce the magnitude and frequency of cyclic loading associated with excessive yaw angles
- (4) Reduce number of shutdowns from excessive yaw angles
- (5) Establish optimum system with consideration of the duty cycle of the yaw drive system

#### System Verification and Improvement Tests

Tests will be performed relating to long term verification of system design adequacy and design improvement. Consideration will be given to:

- o evaluating system responses to actual wind environment
- o varying teeter brake release point
- o evaluating various yaw hydraulic duty cycles
- o studying emergency shutdown procedures
- o testing generator excitation control
- o evaluating system simplification

- o incorporating power control functions
- o evaluating maintenance program

During the first year of this overall project plan, this test area will be fully defined and implemented by a lead test project organization.

#### Environmental Impact Test Plan

This test area will evaluate site specific and machine specific environmental effects at the Goodnoe Hills site. Site specific effects shall include:

- o electromagnetic interference (EMI), TVI, RI, and other established service and systems utilizing radio transmission and reception.
- o audio and infrasound studies
- o ecological impacts in flora, fauna, wildlife habitat, weather, air pollution, etc.
- o visual impacts to the public
- o safety to personnel

Machine specific effects shall include:

- o air pollution in the form of saline spray, volcanic ash, mold, spores, etc.
- o ground effects in the form of freezing/thawing soil, rodents, landscaping, and grazing.

#### Power Transmission and Distribution Test Plan

The following describes the tests and analyses which shall be performed to evaluate the impact and effects of the Mod-2 cluster on the electrical grid. Primary consideration will be given to evaluating power factor and fault protection. In addition, analysis will be made of the impacts on the hydro system effect on the intertie operation and recommendations will be made for improved scheduling procedures for wind generation. Specific test activities will consist of:

- o Electrical Power and Reactive Surges on Weak Systems
- o Single and Cluster Machine Stability on Weak Systems
- o Reverse Power Surges
- o Cluster Interaction of Reactive Power Flow
- o Power Fluctuation and Impact on System

## Machine Dynamics and Structural Analysis Test Plan

During the first year of this overall project plan this test area will be fully defined and implemented by a designated lead test project organization. The main objective is to obtain appropriate deflections, stresses, and responses of the WTS that will permit correlation of analytical predictions made from using the NASTRAN, MOSTAB, NACA/AMES STABILITY, EASY, AND LSD computer codes. Another objective is to identify possible structural "hot spots" in the WTS.

Extensive data will be taken on unit 1 in both the parked and operating modes in order to establish the structural characteristics of various components and to determine system responses for comparison with analytical predictions. Any measurements identified in early testing of unit 1 that merit additional monitoring on units 2 and 3 will be included in abbreviated measurements on those units.

## Meteorological Data Test Plan

A detailed understanding of the temporal and spacial characteristics of wind patterns and other meteorological parameters is a critical requirement of the Mod-2 cluster test program. A lack of understanding of many meteorological parameters could generate gaps in understanding many of the performance characteristics of the turbines.

Since this program will produce an extensive meteorological data base for use in other research endeavors, meteorological parameters from the two meteorological towers, and turbine output parameters from the three machine, will be recorded continuously on a centralized digital data logging system. In addition, it is anticipated that several short-term, intensive field measurement programs will produce additional meteorological data from the site. All these data will be incorporated into a data base where information is readily retrievable. Specific objectives will:

- (1) Define general climatological conditions at the site, including mean and turbulent wind patterns measured temporally and spatially, vertical variation of wind characteristics, and vertical and horizontal temperature patterns.
- (2) Provide information to be used in evaluating turbine performance evaluations, including the effect that upwind turbines have on downwind turbines due to wakes.

## Wake Effects Test Plan

As the machines become operational wake studies will be undertaken. These studies will involve special, short-term, field measurement programs utilizing a variety of measurement platforms. The data will be used to test and validate existing and future numerical and

physical wake models, and to allow parametric analysis of critical characteristics to improve the models. Wake studies will include investigation of momentum deficits as a function of distance behind the machines and wake turbulence produced by the machines.

## MANAGEMENT PLAN

The Mod-2 Cluster Turbine Test Project encompasses a broad and diverse spectrum of activities and organizations which require coordinated planning, continuous evaluation of progress and full communication and interaction with DOE and with the appropriate utility, commercial and industrial sectors.

The DOE Wind Energy Systems Division has overall program responsibility for this effort. The project management functions at LeRC will be performed in the Wind Energy Project Office located in the Wind and Stationary Power Systems Division of the Energy Programs Directorate.

Key elements of the management approach are:

1) Project Management - The Lead Test Center will provide overall management including planning, integration and coordination of the involved field test organizations. It will focus on the field test activity needed to prove wind energy system feasibility and to encourage their future use.

Project objectives and plans will be formulated and will serve as the basis for an ongoing assessment of progress against plans and requirements. The planning process will include continued interaction with the field test organizations and with utility, commercial and industrial participants.

2) Project Implementation - Lead test, shown in Figure 12, organizations will be delegated prime responsibility and appropriate authority for the day-to-day management and implementation of their designated test project. The Lead Test Center will establish broad management processes, including planning, reporting and review procedures. Existing reporting practices will be used to the maximum extent. A Test Facility Operations contractor, managed by the Lead Test Center, will provide the test operations necessary to implement the test projects established by the Lead Test Organizations.

3) Test Project Review Board - As part of the management structure, a Mod-2 Test Projects Review Board (TPRB) has been formed and is composed of representatives of LeRC, BPA, LeRC Mod-2 Contractor, Battelle PNL and SERI. The TPRB is jointly chaired by LeRC and BPA. The TPRB will review detailed test plans, schedules, and procedures associated with the testing of the Mod-2 Cluster. The primary purpose of the TPRB will be to plan and manage the testing of the Mod-2 Cluster. Specific responsibilities will be to: (a) ensure

coordination of DOE Wind Energy Systems Mod-2 test program/facility; (b) review and approve test project plans submitted by the Lead Test Project Organizations; (c) ensure dissemination of all test results, analyses, and other relevant data, information and findings; (d) ensure security of the test facility, (e) ensure cost effective utilization of instrumentation, data acquisition/reduction facilities; and (f) provide status reports of periodic review meetings.

#### TEST PROJECT RESULTS TO DATE

Prior to the June 8 incident, the Lead Test Organizations had planned that noise, wake, and TV tests would be performed throughout the months of June thru September 1981. However, with the recovery plan for the Mod-2 turbines, these test plans have been revised for September/October 1981 schedule with only two turbines scheduled to be operational.

In preparation for these tests several preliminary areas were addressed pertaining to noise and TV interference. TV interference tests were performed by BPA in February 1981. BPA in these earlier tests did not locate any home with TV reception which should receive interference from the wind turbines. The primary reason is the terrain blockage which seems to prevent front lobe interference.

Noise tests performed by SERI and NASA LeRC in February 1981 and May 1981 respectively have also been quite encouraging. SERI's preliminary results show that the acoustic output of the Mod-2 is totally broadband in nature, with no strong periodic components. The rotor noise is highly incoherent, and no rotor discrettes could be found above 10 Hz, on the average. The sound produced by the Mod-2 has been described as a "heavy whoosh." Field personnel have reported that the "whoosh" could be heard clearly up to about 30-45 m (100-150 feet) away from the turbine, however, as the distance from the machine is increased further, the "whoosh" is rapidly covered by wind noise. NASA/Langley results in early May 1981 likewise indicated that only broadband characteristics were evident and the low db levels measured were similar to those commonly associated with "busy" street traffic. The noise starts to attenuate at distance of approximately 3 rotor diameters and is below recording levels at 1-3 miles downwind and 0.6 mile upwind for a single turbine.

When testing is resumed at Goodhoe Hills in September 1981 (targeted), wake tests will be performed with 5 rotor diameter information being obtained. Other testing (7 dia. and 10 dia. spacing effected) must be postponed until the entire cluster becomes operational in early CY-82. At the time of the June 8 failure and the temporary stop on continued operation of turbine No. 2 and No. 3, the performance of the three turbines were as follows:

	<u>Operating Time*</u>	<u>Energy Generated</u>	<u>Sync. Time</u>
No. 1	107 hrs	99.4 Mwh	84.0 hrs
No. 2	122 hrs	138.0 Mwh	113.5 hrs
No. 3	19 hrs	23.7 Mwh	18.5 hrs

\*One of five criteria for acceptance is 100 hours of operation

### Concluding Remarks

The Mod-2 wind turbine project described is the second generation phase of the Federal Wind Energy Program managed by the NASA for DOE. Industry, public utilities, and the government have been working parties in this program designed to produce the technology to supply wind generated electric energy. Industrial involvement in turbine development provides the necessary commercial base, while utility operation of the evolving machines in their networks assures a viable end product in this government supported program. The design, fabrication, assembly, and synchronization of the three Mod-2 turbines at Goodnoe Hills represents a major advancement in the development of large horizontal axis wind turbines. It is believed that these turbines, manufactured on a mass-production basis, have retained the original busbar energy cost goal (100th unit) of less than 4¢ per kWh (1977 dollars). Single units produced in today's market are currently capable of producing energy at costs of 8¢-10¢ per kWh.

The Mod-2 project is now in the experimental operations phase which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment during the next two years. To date, initial performance of the turbines has been acceptable but also has indicated areas for optimization. Corrective actions have been taken to modify the turbines as necessitated by the June 8, 1981 failure of turbine No. 1's safety system. Test operations are expected to be resumed in early Fall on turbine No. 2 and No. 3. Full cluster operation is anticipated in early CY 82.

### RELATED MATERIAL

1. Boeing Engineering and Construction Company, "Mod-2 Wind Turbine System Concept and Preliminary Design Report". Vol. I & II. DOE/NASA 0002-80/2, July 1979.
2. Bonneville Power Administration, "Building the World's First Wind Farm", DOE/BP-85, May 1981.
3. Lewis Research Center, "The Mod-2 Wind Turbine Development Project", NASA TM-82681, July 1981.

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- REQUIREMENTS:
  - 300 FT MINIMUM DIA.
  - HORIZONTAL AXIS
  - WIND MODEL DEFINED
  - FAILSAFE OPERATION
  - UTILITY COMPATIBLE
  - AVAILABILITY OF 0.90
- GOALS:
  - COE  $\leq$  4¢/KWH (1977 DOLLARS)  
IN PRODUCTION

Figure 1- Design Requirements/Goals

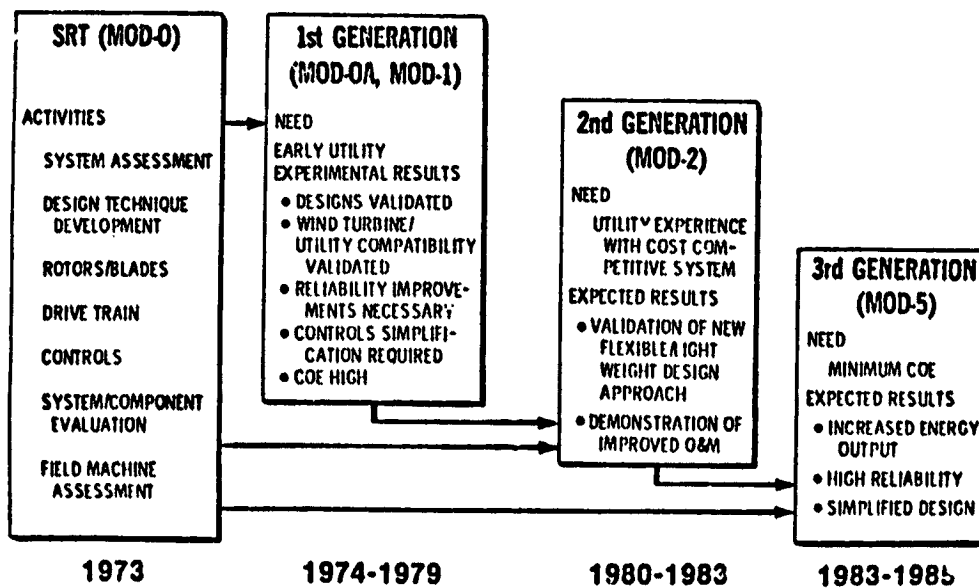
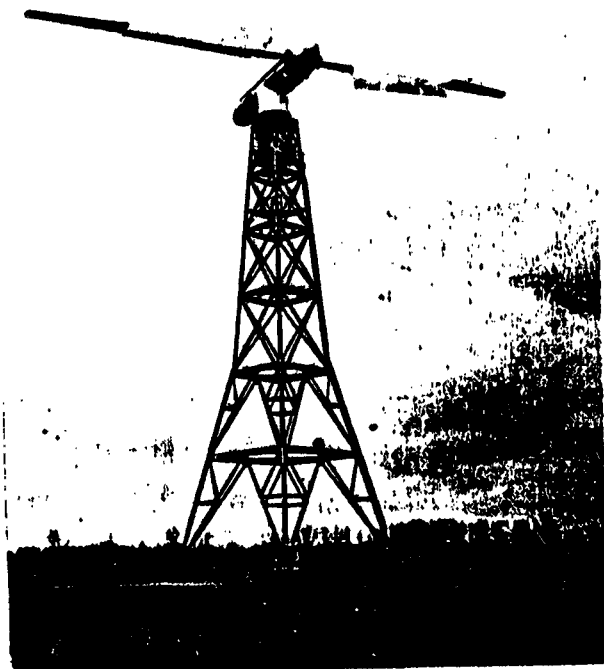


Figure 2- Evolution of Technology



MOD-0 ORIGINAL PAGE #1  
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MOD-2



- SOFT TOWER
- TIP-CONTROL BLADES
- UPWIND ROTOR
- TEETERED HUB

Figure 3-Mod-0 Technology Transfer

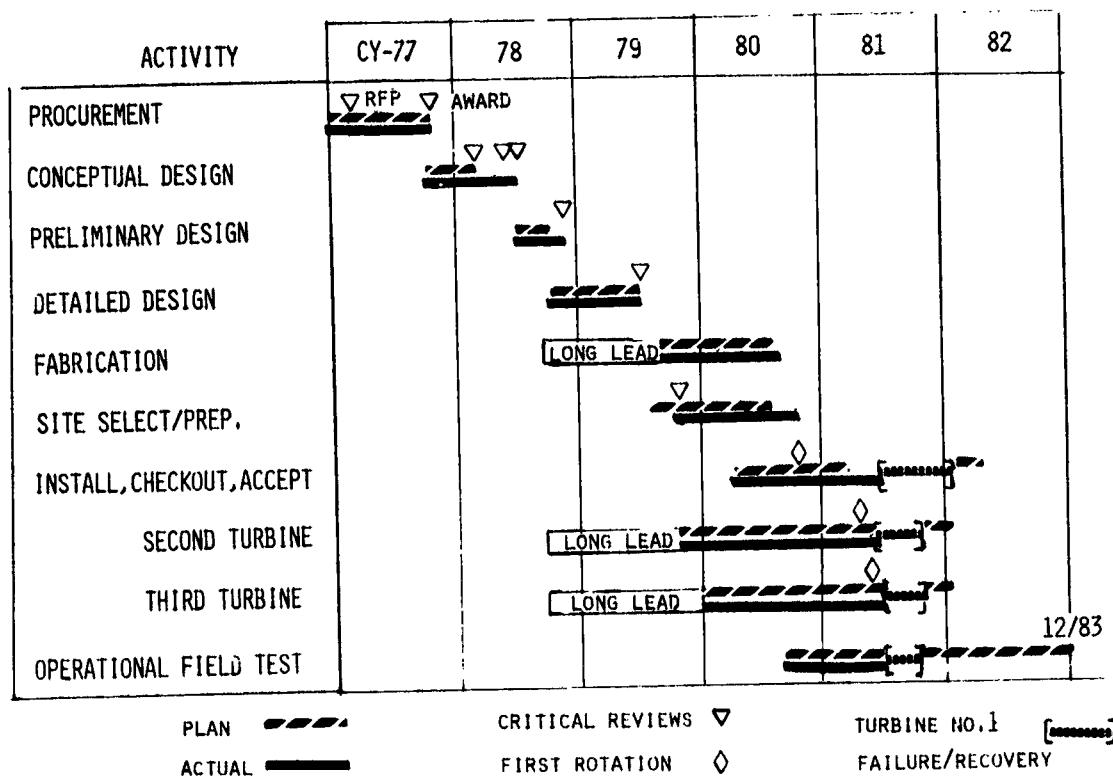


Figure 4- Mod-2 Project Schedule

TRADE STUDY  
2 vs 3 BLADE ROTOR

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CRITERIA	CONFIGURATION		REMARKS
	2 BLADE	3 BLADE	
ROTOR DIAMETER	300 FT	300 FT	60 FT GROUND CLEARANCE .USED FOR BOTH CASES
SYSTEM $C_p$ max	.300	.306	
YAW SYSTEM COST	\$85,000	\$72,000	3 BLADE SYSTEM REQUIRES SMALLER DRIVE & BRAKES
ROTOR COST	\$260,000	\$371,000	3 BLADE HUB REQUIRES SPLICES FOR SHIPPING
DRIVE TRAIN COST	\$462,000	\$538,000	3 BLADE CONFIGURATION REQUIRES LARGER GEARBOX
SYSTEM COST-100th UNIT	BASELINE	ADDS \$166,000	
OPERATIONS & MAINTENANCE COST PER YEAR	\$20,000	\$22,000	
ENERGY OUT ( $K_{wh}$ PER YEAR)	8,686,000	8,890,000	FACTORED TO ACCOUNT FOR DOWNTIME .
COST OF ELECTRICITY	-	ADDS .28 ¢/kwh	

CONCLUSIONS AND RECOMMENDATIONS:

- INCREASED ENERGY OUTPUT OF 3-BLADE ROTOR MORE THAN OFFSET BY INCREASED COSTS
- RETAIN 2-BLADE CONFIGURATION

Figure 5- Typical Trade Study

	Studied	Selected
<b>Rotor</b>	Two versus three blades Full versus partial span control Rigid versus teetered hub All steel versus honeycomb trailing edge, versus fiberglass Upwind versus downwind RPM optimization	Two blades Partial span control Teetered hub All steel construction Upwind 17.6 RPM
<b>Drive train</b>	Epicyclic versus parallel shaft gearbox Quill shaft versus fluid coupling	Epicyclic Quill shaft
<b>Nacelle</b>	Truss versus beam versus semi-monocoque Hydraulic versus electric yaw drive	Truss Hydraulic
<b>Tower</b>	Soft tubular versus stiff truss Braced versus conical base Soft versus soft-soft Tip to ground clearance	Soft tubular Conical base Soft 60 ft
<b>Electrical power system</b>	Direct versus gearbox driven generator Induction versus synchronous generator 1,200 versus 1,800 RPM	Gearbox Synchronous 1,800 RPM
<b>Control system</b>	Analog versus microprocessor (Digital) Ground versus nacelle location	Microprocessor Nacelle

Figure 6- Trade Study Summary

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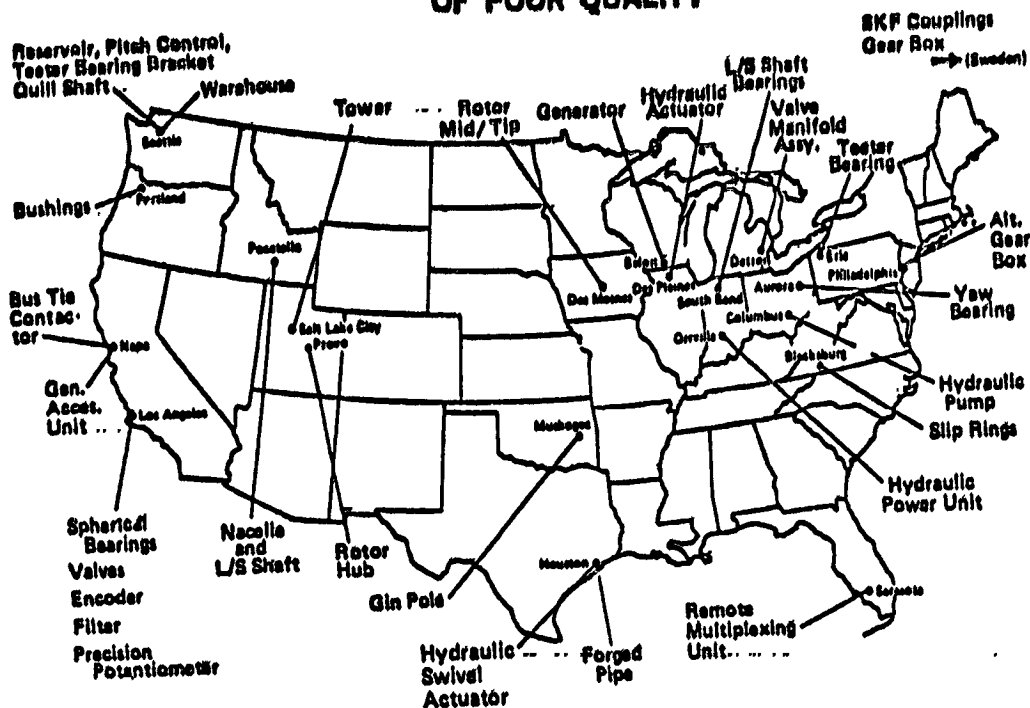


Figure 7- Major Supplier Location

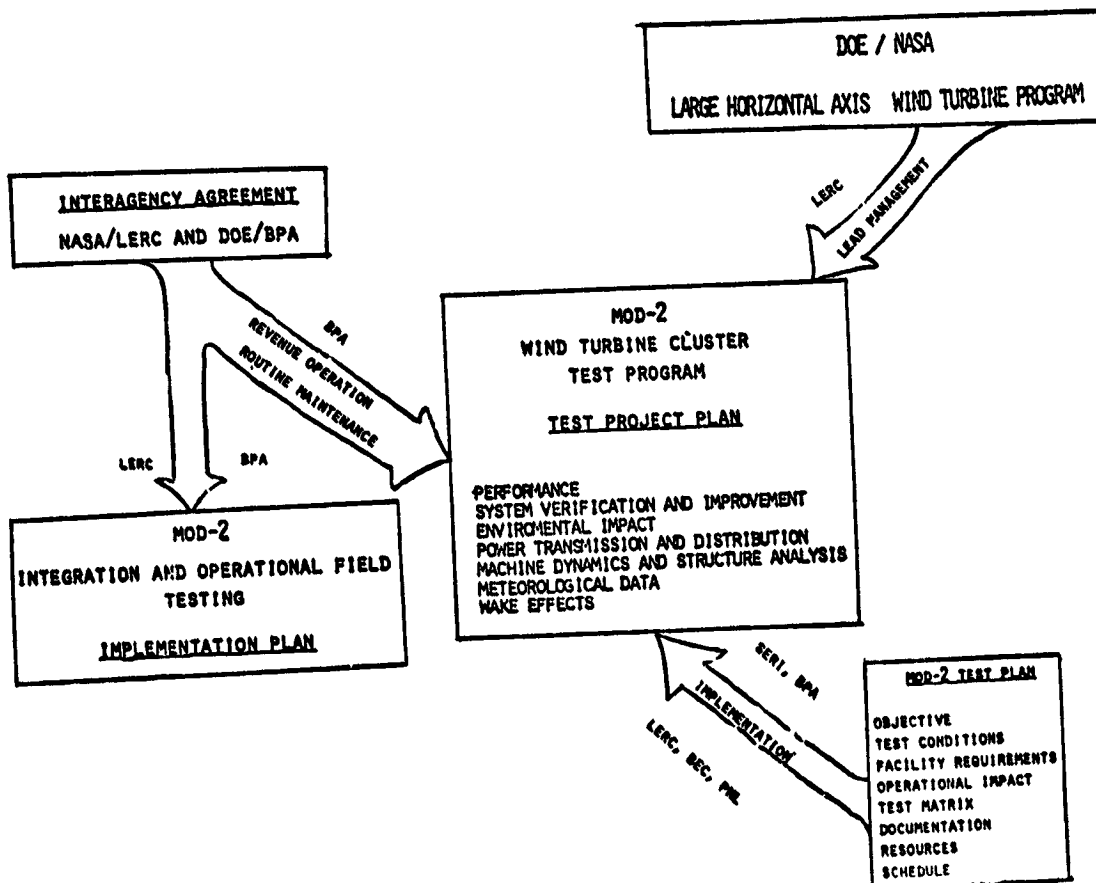


Figure 8- Test Project Planning Structure Flowchart

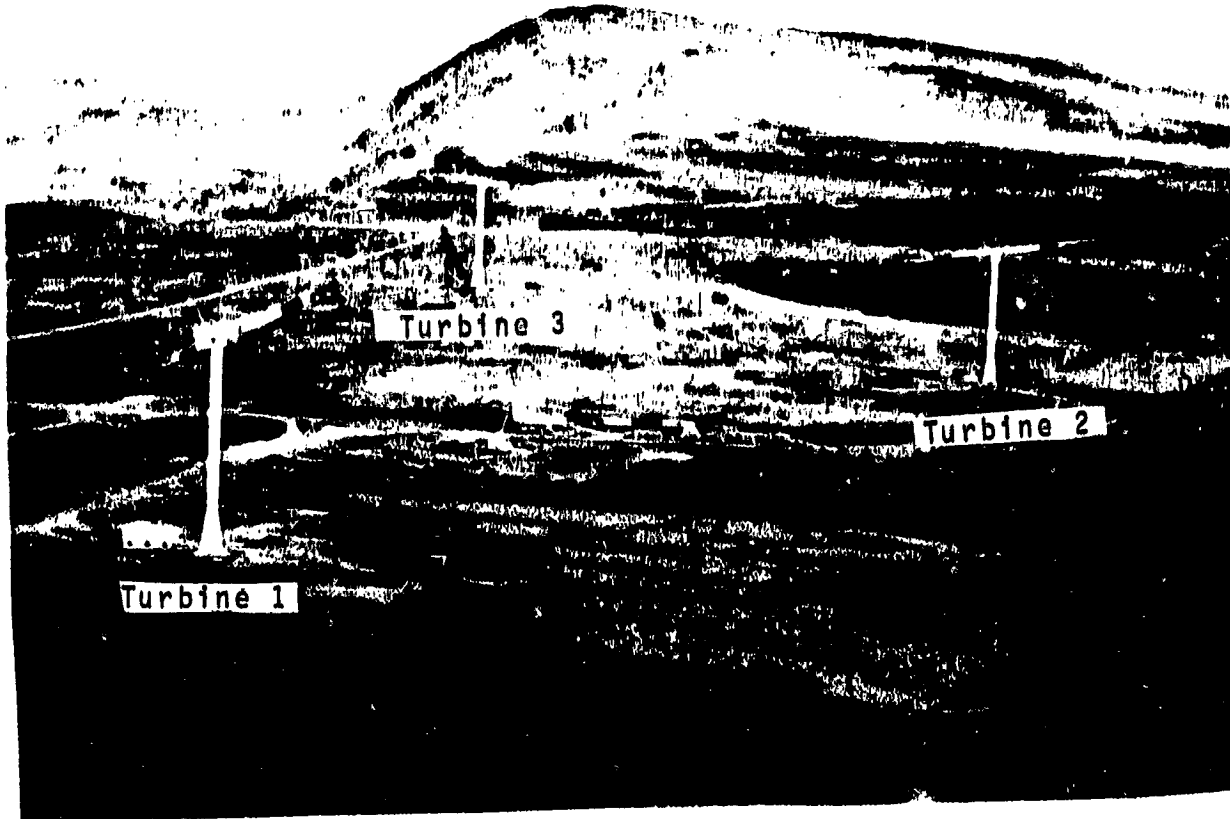


Figure 9- Mod-2 Goodnoe Hills Cluster

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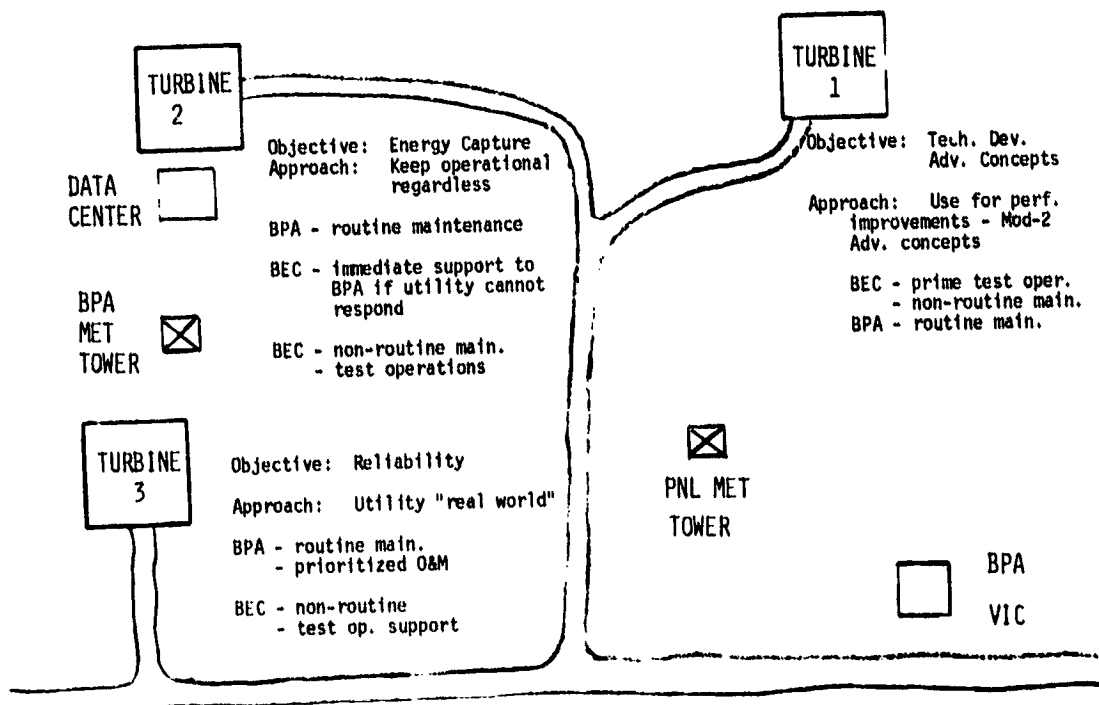


Figure 10- Mod-2 Turbine Operation Objectives

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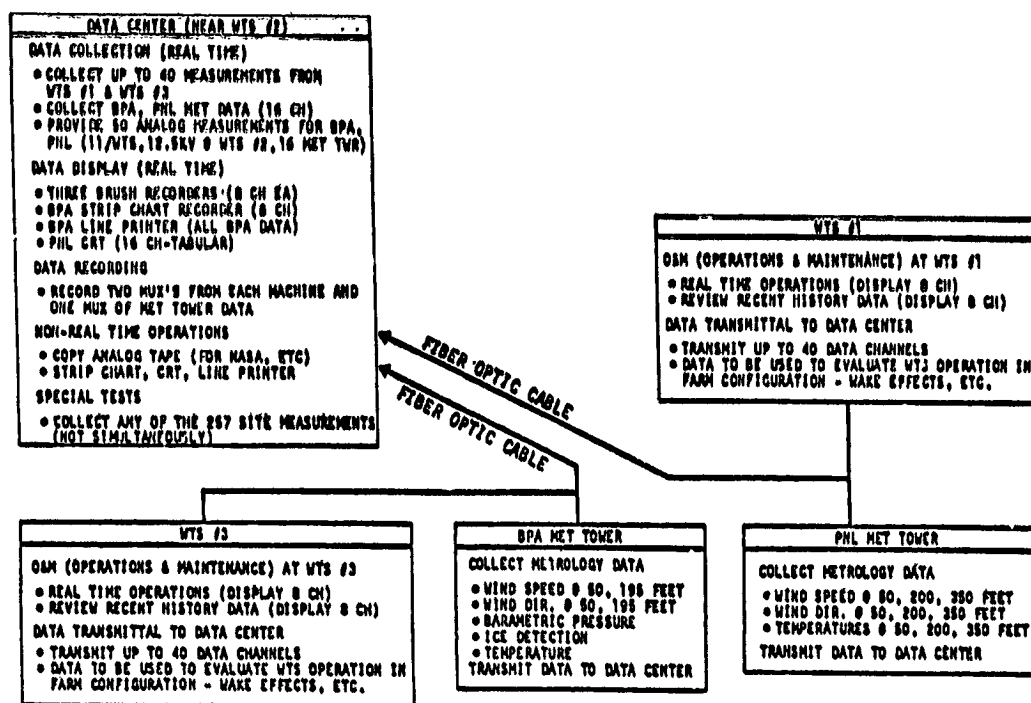


Figure 11- Intersite Data System Functional Block Diagram

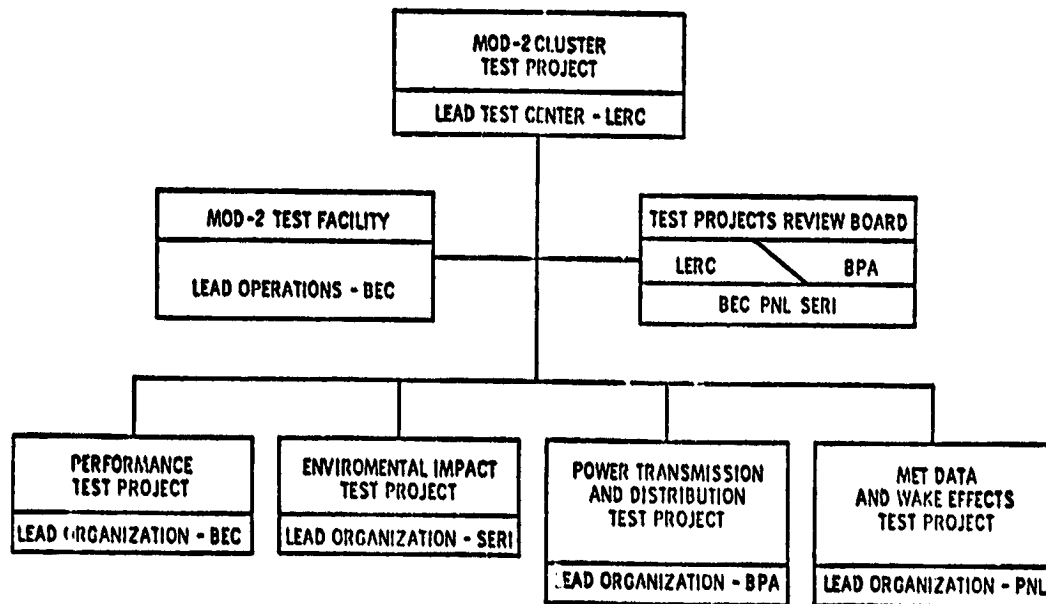


Figure 12- Mod-2 Test Project Management Structure