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# Test Plan for the 34 Meter Vertical Axis Wind Turbine Test Bed Located at Bushland, Texas

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# TEST PLAN FOR THE 34 METER VERTICAL AXIS WIND TURBINE TEST BED LOCATED AT BUSHLAND TEXAS

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## ABSTRACT

A plan is presented for the testing and evaluation of a new 500 kw vertical axis wind turbine test bed. The plan starts with the initial measurements made during construction, proceeds through evaluation of the design, the development of control methods, and finally to the test bed phase where new concepts are evaluated and in-depth studies are performed.

# INTRODUCTION

Sandia National Laboratories is the principle U.S. Department of Energy research facility for developing Vertical Axis Wind Turbine (VAWT) technology. Turbine development has been in progress at Sandia for about ten years. In spite of the fact that these designs have been successfully commercialized, they were based on research conducted in the 1970s that can now be considered obsolete if new predictions resulting from more recent research prove valid. As the next step in the evolution of these machines, a new turbine is being built to test new airfoils, structural designs, and modes of operation not previously available. (see Appendix A) The machine is designed to be used as a test bed so that changes and innovations can be made as new knowledge is acquired.

## THE TURBINE

The new turbine will be located at the U.S. Department of Agriculture Agricultural Research Facility in Bushland, Texas. This site was chosen because of the excellent wind conditions and the experienced personnel located there who will operate the machine under Sandia direction (Appendix B shows the site layout).

The turbine (specifications are given in Appendix C) has a diameter of 33.5 meters (110 ft) and a height of about 50 meters (164 ft). It is a two bladed machine, with each blade consisting of five sections that are specifically chosen for the differing aerodynamic regimes encountered as the distance from the center column increases. The top and bottom airfoils are 48 inches wide, two transition sections are 42 inches wide, and the outer section (center) is 36 inches wide. The power rating of the machine is 500 kilowatts when the rotor is turning at 37.5 rpm (center blade speed = 216 ft/sec) in a 28 mile per hour wind. A 47.5:1 transmission will turn the motor/generator at about 1800 rpm at this wind speed. The generator does not have to maintain a constant speed however, and can operate at from 1190 to 1900 rpm or from about 25 to 40 rpm for the turbine rotor. This variation in rotor speed will allow the efficiency of the machine to be maximized as wind speeds vary from about 15 to 24 mph. It should operate on a power surface similar to that shown in Appendix D. The variations in rotor speed will not affect the frequency of the generated power however, because a General Electric commercial power system will rectify the generator output and re-generate a 60 Hz output which will then be fed into the local power grid. Another example of using a previously unavailable operational technique is when the controller and the variable rpm motor are used to bring the rotor down to some lower speed before applying the mechanical brakes. This operation is referred to as regenerative braking.

## INTRODUCTION (continued)

An industrial computer based programmable controller will monitor inputs from numerous sensors located on the machine to protect it from possible malfunctions, and to perform various programmed operating sequences.

The instrumentation associated with the machine includes accelerometers, pressure transducers, many strain gauges, measurements of torques, rpms, blade position, currents, voltages, cable tensions, wind speeds and directions, temperatures, and barometric pressure. Two computer systems will gather data and evaluate the machines performance continuously.

## THE TEST PLAN

The combination of variables to be measured on the machine necessitates considerable planning to ensure that all the facets are addressed in a logical manner. This document is an attempt to organize the tests in sequences dictated by: machine assembly, unknowns in performance and structural integrity, base line characterization, and experimenter plans (both operational and hardware design evaluation).

The test plan for the machine does not list every detail. The first part of the plan however, contains considerably more detail than the latter part simply because more is known about these fundamental tests.

Phase I establishes baseline measurements on instrumentation and the machine, checks to see if any early changes need to be made before evaluation begins, and measures fundamental characteristics that need to be confirmed before writing the control algorithms, (some of which will be partially written in this phase). Conservative approaches are used throughout the plan.

Phase II examines the basic characteristics of the machine. Efforts are made from the start to treat it as carefully as is practical with regards to vibration and strain. Full evaluation of the machine is not started until everything has been done to reduce structural loading to a minimum. Control algorthims will be developed continuously throughout Phase II.

Once the machine has been characterized, and control methods evaluated, the plan moves on to Phase III where the system can be used as a test bed for performing experiments on various new concepts.

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## PHASE I ASSEMBLY & START UP TESTS

## PHASE II MACHINE CHARACTERIZATION

## PHASE III ADVANCED CONCEPTS

# CONTENTS

# GLOSSARY OF TERMS AND ABBREVIATIONS

Controller..Programmable control system to monitor turbine and power system parameters and control the LCI.

$C_p$...Performance Coefficient - refers to efficiency of aerodynamics, turbine system, etc. depending on context (should be specified).

DAS..Data Acquisition System - A 64 channel A/D multiplexer, and a Hewlett Packard 1000E computer for data collection, storage, and limited analysis.

HS...High Speed

LCI..Load Commutated Inverter - The AC power converter made by General Electric that controls the motor speed, rectifies its output, and regenerates 60Hz output power.

LS...Low Speed

PCM..Pulse Coded Modulator - The data transfer system that converts multiple analog strain gauge inputs on the turbine rotor to series digital format transmits it through slip rings to a transmitter that drives a fiber optic cable, and a receiver/decoder that converts the information back to multichannel analog format.

PNL..Pacific Northwest Laboratories

Ramp Slope..Programmed rate of speed change in turbine revolutions per minute.

SNL..Sandia National Laboratories

T.S.R...Tip Speed Ratio. The ratio of the blade speed at the equator of the turbine to the speed of the wind.

# SYNOPSIS OF PHASE I

The theme for Phase I is to make fundamental measurements which cannot be easily repeated after the machine is assembled, to test and calibrate new instrumentation and equipment as it is installed, and the step by step checkout of the measurements made by the DAS.

First, all parts of the center column are weighed (blade components will be weighed later). This establishes an accurate measurement for the mass, which will be used later for modal vibration analysis and inertia calculations. Column strain gauges are installed with the column in a "relaxed" horizontal position, and baseline readings recorded with a portable strain gauge tester. The column is then set upright, and the guy cables set to a "minimum" tension of 50,000 lbs. There is some possibility that the line tension signal conditioning equipment may not work as desired so step 1.6 calls for correlation with the strain gauge tester. (a check and re-check approach is used throughout the plan). The column strain gauge instrumentation boxes are now mounted, the PCM installed, and the first PCM-DAS measurements correlated with the strain gauge tester. Once the column is in place, the transmission can be positioned. The LS torque sensor (which is part of the drive system) can be connected and its instrumentation checked out to determine if it will work with the long cables associated with the turbine. It is 500 ft from the turbine base to the control building, and further for cable tension sensors at the guy cable tie-downs.

Part 2 first checks out each piece of equipment associated with turning the column. A General Electric representative is then called in for a week of tests on the power generating system (which requires turning the column as part of the checkout). After the power system checkout has been completed, the Allen Bradley controller is used to check the operation of the enable/interrupt functions. Some of these will have been checked during the power system tests and some Allen Bradley functions as related to the power system will also have been checked at that time. Part 2.4 then calls for full-up sensor, controller, power system checks. Part 2.5 adds more channels to the DAS. Checkout of these measurements can continue as testing progresses. In Part 2.6 the column is turned for the first time and checking of the DAS, the controller, the hardware, and basic control algorithms begins with no blades on the machine. Control problems may show up at this early stage and they should be addressed as soon as possible and for as long as it takes to achieve satisfactory performance.

SYNOPSIS OF PHASE I (continued)

Part 3 measures the power required to run just the motor/generator, the motor/generator and transmission, and of all the hardware except the blades. A series of guy cable tension tests could also be run in 3.8 if time allows, and depending upon how complex the changing of cable tensions proves to be. In part 3.9 the guy tensions are set to the final anticipated value required for operation with the blades installed.

Part 4 covers modal vibration testing (for resonance analysis) on just the column assembly. This part can be done any time after the transmission is installed and before the blades are installed.

Part 5 Brake Tests can also be moved as a unit depending on assembly schedules. The plan here is to assemble each caliper, (there are four) measure its coefficient of friction at some low level that the motor/generator can handle, then re-adjust the brake pressure to some higher calculated value that will allow testing of the brakes with just the column. Later, (5.6) the pressure is increased again for use with the blades installed.

In part 6, baseline strain gauge readings are taken with the blades on assembly stands, and again after they are installed and in the "droop" position. Checks between the strain gauge tester and the DAS are made again here.

Part 7 is similar to part 4 except that access is more difficult and analysis more complex.

For part 8 (the first turning of the blades), all instrumentation must be performing satisfactorily, calibration factors entered, baseline measurements completed, and limits set on some selected strain gauge measurements that will shut the machine down if exceeded. Maximum rates of acceleration and deceleration are programmed into the controller to minimize dwell time at any particular frequency of rotation (ie. resonance). The machine is first taken up to some speed where a low probability of resonances exists, and then brought back to a stop and all parameters listed in part 8.4 examined closely. If any changes or corrections to the machine or procedure are required the first speed is checked again. After satisfactory operation is achieved, a series of low resonance risk speeds are explored up to 40 rpm. Part 8.6 carefully checks power failure braking operation. 8.7 reviews all parameters measured thus far that concern the structural integrity, operational capability, and data gathering capability of the system before moving on to Phase II.

## PHASE I ASSEMBLY AND START UP TESTS

### 1. COLUMN PREPARATION

Objectives
- Weigh piece parts and assemble column
- Erect column and do initial line tensioning
- Install and test instrumentation
- Begin checkout of DAS
- Obtain baseline strain gauge measurements

Special Conditions None

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 5 weeks |
| Data Collection: | 2 weeks |

Procedure

1.1 Weigh all piece parts. Assemble column on stands with its major axis horizontal.

1.2 Install strain gauges on column and "age" as necessary.

1.3 Record initial strain gauge outputs using portable instrumentation.

1.4 Erect column on base and mount PCM.

1.5 Tension guy cables with initial tensions of 50,000 lbs.

1.6 Measure guy tension sensor outputs with portable instrumentation and compare with measurements made by the DAS. Calculate appropriate correction factors or add additional electronics as needed for correlation. Resolve any differences before proceeding.

1.7 Install column instrumentation cables and junction boxes.

# PHASE I

1.8 Record column strain gauge measurements as baseline data using DAS and portable instrumentation. Resolve any differences before proceeding.

1.9 Install transmission and LS (low speed) torque sensor.

## PHASE I

### 2. POWER SYSTEM AND CONTROLLER TESTS

Objectives - Checkout column turning hardware
- Test all parameters of power system
- Test operational capability of controller
- Checkout additional DAS channels
- Perform first controller algorithm tests

Special Conditions

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 1 week |
| Data Collection: | 3 weeks |

Procedure

2.1 Confirm that oil pumps, cooler fans, and any instrumentation associated with the power system or turning the column are installed and working.

2.2 Perform the power system checkout with a representative from General Electric. (Column may be turned, but be alert for malfunctions and be ready to stop tests, if necessary.) These tests are estimated to take about a week.

2.3 Confirm that the Allen Bradley controller is properly connected and that all enable/interrupt control functions are either working properly or can be simulated.

ENABLE/INTERRUPT FUNCTIONS

Temperatures:
- transmission
- motor
- ambient
- power building

## PHASE I

Switches:
- rotor overspeed
- brake valve
- pumps (motor, transmission)
- hydraulic pressure (2)
- vibration
- manual enable/disable in stand area

Strain Gauges:
- rotor
- column
- brakes (4)

Measurements Used For Control:
- rotor rpm
- windspeeds (2)
- guy cable tensions

2.4 Further verify operation of lockout, shutdown, and enabling sensors in controlling the complete power and controller system. (ie controller and LCI.)

2.5 Connect all available non-blade measurements to data acquisition system and use successive tests for any necessary troubleshooting.

### NON-BLADE MEASUREMENTS

column strain
rotor RPM
high speed torque & RPM
low speed torque & RPM
guy tensions
generator voltage
generator current
generator power
windspeeds

LCI frequency
LCI currents (3)
LCI voltages (3)
LCI power
LCI power factor
gen power factor
gen frequency
reactive power

2.6 With the data acquisition system recording torques, strains, rpms, and input power, use the controller to:

A. Start the column and run at a series of pre-determined constant rpms.

NOTE: Examine data (especially strain gauges) for unsatisfactory operating conditions and take any necessary corrective action before proceeding to each successive step.

## PHASE I

B. Select and use various start and stop ramps to achieve these rpms.

C. Re-adjust the column rpm up and down while running.

D. Test special algorithms using the controller computer to:

- vary ramp slopes
- vary times at rpms
- run combinations of slopes & rpms

E. Test the following shutdown functions:

- strain gauge cutout
- rpm upper limit (program & switch)
- rpm lower limit
- vibration sensor

F. Simulate inputs from the control anemometers and demonstrate auto control capability. (i.e., auto start and stop)

## PHASE I

## 3. DRIVETRAIN POWER LOSS TESTS

Objectives - Determine source and magnitude of power losses
- Data acquisition checkout
- Determine column resonances and test sweep algorithm
- Set guy tensions to final value

Special Conditions Guy cable tensions at 50k lbs

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 5 Days |
| Data Collection: | 10 Days |

Procedure

3.1 Disconnect motor/generator output shaft by removing rubber couplings and record start up and steady run power at various ramp slopes and rpms. (i.e. motor power, LCI power, etc.)

3.2 Re-connect motor/generator shaft and disconnect LS torque shaft by removing rubber couplings.

3.3 Record start up and steady run power at various ramp slopes and rpms. Examine data for indications of change versus run time indicating possible bearing problems or oil temperature changes.

3.4 OPTION - Depending on weather conditions, the above tests may be repeated at different times of the day or night to obtain other data points on the effect of temperature on transmission losses.

3.5 Re-connect LS torque shaft.

## PHASE I

3.6 Record start up and run power (column now turning) at various ramp slopes and rpms. Compare transmission losses with previous tests using HS (high speed) and LS (low speed) torque sensors. Examine strain gauge and guy tension data after each condition and take any corrective action necessary before proceeding to each successive step. Be aware of any changes versus time that might be attributed to rotor bearing break-in.

3.7 OPTION - Repeat 3.6 at different temperatures as in 3.4 to determine possible temperature effects on column bearings.

3.8 Change guy tensions and re-run step 3.6, with 100k lbs, and 186k lbs.

3.9 OPTION - Part 3.8 could be modified to include 150k lbs, and 220k lbs for future reference in changing guy tensions.

3.10 Re-set guy tensions to the desired value (if different from 3.8) for turbine operation when the blades are installed. Consider the effect of blade weight (if any) on rotor tare . Re-run 3.6 if necessary.

# PHASE I

## 4. COLUMN MODAL VIBRATION TESTS

Objectives Determine the modes of vibration of this part of the turbine.

Special Conditions Crane service could be needed. Guy cables tensioned to value desired for turbine start up.

Data Requirements Supplied by SNL org. 7544

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2 days. |
| Data Collection: | 1 day. |

Procedure

4.1 Install accelerometers and wiring using column spoiler for access. (SNL Org. 7544)

4.2 Move instrumentation trailer into position near base, and connect cables from trailer to accelerometers.

4.3 Connect force cable and hardware to connections provided on column and to ground anchor.

4.4 Conduct approximately 15 operations for modal vibration data (SNL Org. 7544 with Org. 6225 assisting).

4.5 Evaluate data for later use in part 8.0 and in Phase II part 1.0.

## PHASE I

### 5.0 BRAKE SETUP TESTS

Objectives - Determine coefficients of friction of brake pads
- Set brake torque to final or an intermediate value
- Test control algorithms
- Checkout brake strain gauge data channels

Special Conditions Controller and power system tests to be completed before proceeding beyond part 5.2.

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Collection: | 2 weeks |

Procedure

5.1 Clean and install the hydraulic system except lines to cylinders. Assemble calipers minus springs and cylinders. Install strain gauges on brake paddles.

5.2 Measure distance from brake disc to base plate and install first caliper with appropriate float spring shim. Measure distance from brake disc to lower caliper jaw. Install brake paddle bracket and paddles with pads and appropriate shims for specified clearances. Install disc springs and washers, cylinder, and hydraulic line from cylinder output to reservoir.

5.3 Using portable hydraulic equipment measure the pressure necessary to release the pads from the brake disc. With the pads held in the dis-engaged position turn the column at a constant rpm and release the hydraulic pressure. Measure the torque after a steady state condition is reached then re-apply hydraulic pressure to release the brake. CAUTION: Do not leave the pads engaged for an excessive period of time or overheating will result. A period of TEN SECONDS should be considered maximum at this point. Review strain gauge data to ensure

PHASE I

that both brake pads have similar characteristics and that column strain gauges show acceptable strain. Using the measured torque and hydraulic force, compute the coefficient of friction for the brake pads. Re-adjust the spring tension as required for stopping the column. Make any necessary changes in shims to maintain clearances and note final hydraulic pressure required to release brake pads. Lock pads in the released position with a block or devise some means to maintain hydraulic pressure.

5.4 Repeat parts 5.2 and 5.3 for each brake caliper assembly (4 total). Review the data to confirm that all brakes are applying force within acceptable limits then remove the means used to hold the brakes in released positions. Install and bleed the hydraulic pressure lines and adjust the accumulator pressure to a value that will provide a desired number of operations at the the operating value used in the previous steps. Test the system for proper release and clearances.

5.5 Perform start and stop tests using the controller and various enable/stop functions to start, run, and stop the column using the brake system. Use the brake strain gauges as a control input, (ie. warning! brake not working, or brake dragging) and accumulate baseline data using the DAS. Evaluate column strain gauge data during braking operations for indications of excessive strain. Watch for any indications of incomplete brake release. Compare measured stopping torque with calculated values.

5.6 Compute the desired brake pad pressure required for testing with blades installed and adjust each caliper for the new pressure.
NOTE: If more column operation is to be done before blade installation, it may be desirable to postpone this step until just prior to installing the blades.

5.7 OPTION: With the brakes locked, connect suitable mechanical hardware (line tension meter, clevises, cable, etc.) to rotor drive coupling discs and check torque sensors for calibration and proper operation of sensor signal conditioners.

## PHASE I

## 6.0 BLADE SECTION MODAL TESTS

| | |
|---|---|
| Objectives | Determine the modes of vibration of various sections of the turbine blades |
| Special Conditions | Blades sections suspended by "soft" suspension at multiple points using apparatus supplied by SNL org. 7544 |
| Data Requirements | Supplied by SNL org. 7544 |

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 7 days |
| Data Collection: | 5 days |

Procedure

6.1 Five test series are to be conducted on combinations of turbine blade sections.

| Designation | Description |
|---|---|
| A | 48 inch chord blade section |
| B | 42 inch chord blade section |
| C | 36 inch chord blade section |

Test 1 - Section A
Test 2 - Section B
Test 3 - Section C
Test 4 - Section A joined with B
Test 5 - Section B joined with C

6.2 Prior to testing, SNL org. 7544 shall install accelerometers, wiring, and instrumentation as required. Suspension apparatus, including bungee cord and any special frames or stands shall be supplied by SNL org. 7544.

6.3 Test 1
Suspend the section so that it is not deformed, or subject to stress, and is stable along the longitudinal and lateral axis. Apply a known (force and duration) impact at a pre-determined point and measure the vibrational modes. Repeat impact test as required for statistical confidence in results.

## PHASE I

6.4 Repeat 6.3 for tests 2,3,4, and 5.

6.5 Evaluate data for later use in blade and turbine modal vibration tests.

## PHASE I

## 7.0 BLADE STRAIN GAUGE VERIFICATION TESTS

Objectives - Establish the fidelity of selected blade section strain gauge installations

Special Conditions
- Low wind or indoors
- Crane service to pick up each blade section
- Photography to record lifting geometry
- Method of applying load at neutral axis if needed

Data Requirements DAS in time series mode

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 5 days |
| Data Collection: | 7 days |

Procedure

7.1 With blade section in unstressed condition (on blade stands etc.) measure output of subject strain gauge as baseline.

7.2 Apply known static load by:
A. lifting section suspended from ends and using gravity load
B. lift as in A. above and add additional known weight suspended on neutral axis

7.3 Measure strain under load.
Record geometry of experiment by photography.

7.4 Return blade section to unstressed condition and re-check strain gauge output.

7.5 Repeat 7.1 through 7.4 for all gauges of interest on each blade section.

7.6 Compare measured strains with predictions to establish gauge installation fidelity.

PHASE I

## 8.0 BLADE INSTALLATION

Objectives - Obtain baseline data on blade strain gauges before and after blade installation
- Install blades
- Install and checkout PCM blade channels on rotor
- Further checkout of DAS

Special Conditions - Brakes adjusted for stopping blades
- PCM, power supply, and 110vac available on portable pallet
- Low wind conditions for blade installation

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 5 days |
| Data Collection: | 15 days |

Procedure

8.1 Using portable instrumentation, check every strain gauge reading against DAS output to insure measurement accuracy. Resolve any differences before proceeding.

8.2 Prior to blade installation "age" blade strain gauges by operating for an extended period of time (days), while performing hourly measurements with the DAS until readings stabilize. Store this information as un-stressed blade data.

8.3 Disconnect PCM and install first blade. Install PCM on turbine and connect strain gauges. Use the PCM and DAS to make hourly measurements until gauge outputs have stabilized. Store this information as blade strain due to gravity (make final readings with no wind).

8.4 Repeat 8.1 through 8.3 for the second blade.

8.5 Check column strain gauge and guy tension measurements for any changes due to mounting blades.

## PHASE I

### 9.0 TURBINE MODAL VIBRATION TESTS

Objectives - Determine modes of vibration of the entire turbine.

Special Conditions Crane service needed

Data Requirements Supplied by SNL Org. 7544

Estimated Time for Performance

Engineering: 3 days.

Data Collection: 3 days.

Procedure

9.1 Using crane bucket for access, install approximately 15 accelerometers on turbine blades and column.

9.2 Move instrumentation trailer into position and connect signal cables between sensors and trailer. Connect force cables and hardware to column, blade, and ground anchor.

9.3 Determine modes of vibration of turbine by applying step function force to blades and column from two directions (SNL Org.7544 with 6225 providing assistance, if required.)

9.4 Record and analyze data for use in part 8.0 and in Phase II part 1.0.

9.5 Remove instrumentation and trailer in preparation for turbine startup.

## PHASE I

## 10.0 INITIAL START UP TESTS

Objectives - Fundamental electrical and mechanical operation to check for abnormalities.
- Final checkout of instrumentation and control functions prior to characterization tests.

Special Conditions Windspeeds less than 10 MPH. Brakes adjusted for additional blade load. Starting and stopping to be done using motor drive set at maximum ramp slope. Brakes to be applied initially only at minimum motor speed.

Data Requirements DAS in time series mode.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 5 days |
| Data Collection: | 7 days |

Procedure

10.1 Prior to startup, confirm that all desired baseline data on gauges and sensors have been recorded and stored for future reference.

10.2 Add selected strain gauge inputs to controller for temporary blade and guy cable strain limit control capability. Calculate reasonable limits for these parameters and set thresholds that will stop the turbine if exceeded.

10.3 Using speeds and guy cable tensions calculated to be least likely to have resonance problems, accelerate the turbine at maximum rate to the lowest speed first while recording and observing output data. After turbine speed has stabilized bring the speed down at a maximum rate then stop and secure the machine.

# PHASE I

10.4 Examine all channels of data for indications of abnormal operation in:

A. blade strain
B. resonances anywhere
C. input power
D. controller operation
E. brake operation

Compare start and stop ramp slopes (acceleration, deceleration) with those observed when running just the column and make adjustments if necessary. Observe regenerative and mechanical braking operation (brakes set to estimated torque in 5.6). Use "Braker" program to calculate brake torque for desired operation. Before proceeding, take corrective action in any area of concern.

10.5 After taking any corrective action found necessary, repeat parts 10.3 and 10.4 until satisfied that turbine operation is acceptable. Using the speeds chosen in part 10.3 repeat parts 10.3 and 10.4 up to 40 rpm.

10.6 Using the speeds selected in 10.3 and starting with the <u>lowest</u>, apply full braking power to stop the turbine (emergency stop). Examine structural data and consult with structural designers before proceeding to the next speed. Proceed in this manner to the maximum speed desired to demonstrate power failure braking capability.

10.7 When the following criteria have been satisfied proceed to Phase II part 1.0 Resonance Surveys.

Resonances:

None remain that are considered destructive when passed through at maximum ramp slope.

Braking:

A. Emergency braking appears adequate for worst case situation.
B. Regenerative/mechanical braking methods appear adequate to perform testing (ie strains considered acceptable).

## PHASE I

Strain measurements:

Strains measured thus far are acceptable, or..abnormal operating conditions have been identified and operational procedures have been outlined that will not allow operation in these areas.

Control:

Controller and algorithms for controller appear capable of performing tests outlined in Phase II part 1.0.

Data Acquisition:

All channels are checked out and working properly including the capability to simultaneously collect data in time and bins modes.

10.8 OPTION: If braking techniques thus far indicate that new approaches may be of some benefit, consider implementing the brake control tests outlined in Phase III. This work could be done in parallel with Phase II and Phase III tests.

# SYNOPSIS OF PHASE II

Phase II is entered after Phase I tests have shown that the machine can be controlled properly, with acceptable strain levels, and that any undesirable characteristics have either been corrected or identified. Phase II is the performance evaluation phase of the test plan where the characteristics of the existing design are identified and analyzed. Because these characteristics are unknown at the beginning, the control techniques will necessarily have to be developed as the testing proceeds. Changes in data acquisition methods are a distinct possibility also. These items are mentioned here because of their impact on the Estimated Time For Performance listed for each test series.

Part 1 Resonance Surveys, measures the occurence of mechanical resonances in the machine. Resonances are a potentially destructive occurence in wind machines. The tests must be performed with care lest unnecessary strain be applied to components, or possible damage to the machine occur. The resonance surveys are divided into two parts: the no wind or motor driven part (1.1), and the wind driven part (1.2). The scheme here is to move as rapidly as possible through the full range of turbine operating speeds, not dwelling longer than necessary anywhere. The data are then analyzed and changes made to the turbine if necessary (i.e. guy tension or component changes). The tests are then repeated at slower rates of rpm change, and finally dwelling for extended periods of time at selected or (hopefully) all turbine operating speeds. If incurable resonances are identified at which it is not desirable for the turbine to operate, the control algorithms may have to be written to minimize dwell time at these speeds.

Part 2 is designed to take a brief look at the turbine characteristics at selected rotor speeds in order to determine what speeds will be best suited for the in depth large data base to be collected in part 3. The development of algorithms for unattended operation is begun, along with the incorporation of any strain limiting features for starting, stopping, or running that may be feasible. The investigation of methods to reduce torque ripple is also listed as an option in this part.

Part 3 is conducted jointly with PNL. Six anemometer towers will be erected about the equator of the turbine to measure turbulence. The turbine will be operated at selected fixed speeds chosen from data acquired in part 2. A large characterization data base will be collected here. Strain and other measurements will be monitored for long term changes. Automatic operation algorithms will be used and evaluated. Maintenance records on the machine will begin to reveal down time data.

SYNOPSIS OF PHASE II (continued)

Part 4 uses the operating data acquired thus far to develop algorithms for variable speed operation. Items such as avoiding resonances, shaped acceleration and deceleration slopes, letting strains limit but not shut down operation, are some of the items that can be investigated.

Part 5 will use the final product developed in part 4 to operate the turbine in a variable speed mode to maximize rotor Cp as the wind varies in speed. Considerable work may be required for signal conditioning and algorithm development as several approaches are being considered.

Part 6 will investigate machine control using maximum system power generated as the control algorithm criteria.

Part 7 is also a control method test. In this plan the feasibility of a combination of rotor Cp and system power for control will be investigated to see if a combination of the two can better cover the entire operating range of the machine.

Part 8 will investigate the feasibility of using a constant selectable rotor torque as the control algorithm criteria.

Part 9 will use an accumulation of everything learned thus far about controlling the machine to develop a set of algorithms for the desired mode of operation. This will probably be in the form of a menu with options selectable by the operator.

Part 10 is optional, and may be used to obtain additional information on modal vibrations of the machine under dynamic conditions. This test could be inserted earlier in the plan depending on the results obtained in part 1.

## PHASE II MACHINE CHARACTERIZATION

### 1.0 RESONANCE SURVEYS

Objectives
- Define occurence of vibrations
- Determine cause & significance of vibrations
- Determine appropriate remedial action if necessary
- Test control algorithms
- Measure response of input and output power versus start and stop ramps
- Set brake torque vs. blade strain to appropriate value

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 0-4 weeks depending on changes needed |
| Data Collection: | 2-4 weeks depending on winds |

Procedure

1.1.0 Low Wind

Special Conditions Winds less than 10 MPH

Data Requirements DAS in time mode

1.1.1 Select desired strain channels and use for over limit cutout capability with controller.

1.1.2 Select maximum up and down ramp slopes for controller.

1.1.3 Program controller to accelerate turbine to a chosen "peak" rpm and decelerate to minimum rpm and stop.

1.1.4 Operate turbine with this "sweep" algorithm and examine data for location of resonance areas. Start with lower "peak" rpms and proceed to a maximum of 40 rpm as confidence is acquired.

1.1.5 Decisions should be made at this time to determine if better resolution is needed, if some areas are to be avoided, or if some corrective action is needed.

1.1.6 If more resolution is needed, repeat 1.1.4 at successively slower rates until the required information is obtained.

## PHASE II

1.1.7 If an area of resonance occurs that cannot be reduced in amplitude, the experimenter may wish to program the maximum ramp slope at this point into future programs in order to reduce time at this rpm to a minimum.

1.1.8 A final survey can be made by programming a series of steps in the control program to dwell at speeds desired, for selected periods of time.

1.1.9 OPTION: The experimenter may wish to repeat steps 1.1.4 through 1.1.8 for other values of guy cable tension.

## PHASE II

### 1.2.0 With wind

Special Conditions Winds variable 20 MPH to 40 MPH

Data Requirements DAS in time & bins modes all channels.

1.2.1 Select overlimit strain channels as in 1.1.1, maximum ramp slopes, and an appropriate speed at the lower end of the turbines expected operating range that has not exhibited resonance symptoms.

1.2.2 Accelerate the turbine to this speed and observe the speed control capability of the system. (rotor is driving the system for the first time)

1.2.3 If control in 1.2.2 appears good, accelerate to successively higher speeds that are not expected to exhibit for resonance problems. Continue watching for any large resonance responses and be prepared to shut down if necessary. Stop at 40 rpm and decelerate back to zero.

1.2.4 Examine data for:

-Resonance responses (all channels)
-Strain responses (from ramps, braking, rotor drive)
-Power parameter responses
-Operation of torque sensors under drive conditions
-Control system response with wind

Take any corrective action needed before proceeding.

1.2.5 If no problem areas exist (ie speeds to be avoided) proceed with a "sweep" algorithm to cover the entire turbine speed range at maximum ramp slope. Run at successively slower ramps until adequate resolution of resonance areas are obtained.

## PHASE II

1.2.6 Study the data to determine if special algorithms need to be used to avoid dwelling or running at various speeds. If so, write and test these algorithms along with anemometer control tests to demonstrate automatic (fail safe) control of the turbine. Use this capability while under operator observation in succeeding tests.

1.2.7 Final surveys can then be made using selected speeds and dwell times as in 1.1.8.

1.2.8 Check turbine mechanical condition and perform any necessary lubrication or maintenance.

CHECKLIST:
__bolts, nuts, pins, on stand & blades
__transmission & motor oil
__brake fluid
__brake pads
__rotor bearing condition
__lightning arrester cables & terms
__enable-disable switch

1.2.9 OPTION: The experimenter may wish to repeat steps 1.2.2 through 1.2.7 for other values of guy cable tension.

# PHASE II

## 2.0 BASIC AERODYNAMIC AND STRUCTURAL CHARACTERIZATION

Objectives
- Initial measurements of Cp, strain, rotor power, torque, and generated power characteristics at selected constant speeds.
- Test automatic control.
- Test speed control algorithms.
- Determine feasibility of adjusting power system to minimize torque ripple.

Special Conditions Winds 0 to 45 MPH

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2 weeks |
| Data Collection: | 3 weeks-or-sufficient time to place a minimum of 1000 points in all wind speed bins between 0 and 45 MPH |

Procedure

2.1 Using an algorithm to avoid resonances and to automatically start and stop (under operator supervision) from 1.2, select three specific rotor speeds and collect data using stochastic winds for each of these speeds.

2.2 OPTION 1. Using data obtained in 2.1 investigate the feasibility of adjusting the LCI response to minimize torque ripple.

2.3 OPTION 2. If desired, the rubber couplings on the drive shafts may be changed in an attempt to reduce torque ripple. Consider any changes in resonant responses if this action is taken.

2.4 Analyze strain, torque, and aerodynamic data and update the control algorithm to incorporate information acquired thus far, i.e. resonance avoidance, start and stop ramp adjustments, strain limiting, and auto start-stop criteria. Analyze all strain gauge data before proceeding. Repeat tests to check algorithm changes before proceeding.

## PHASE II

2.5 Review power generation data to determine suitability for use by power grid. Perform harmonic distortion analysis.

2.6 Review braking data acquired thus far and consider implementing changes in braking techniques if desired.

2.7 Establish the fundamental integrity of the machine and controller for running at selected constant speeds in unattended mode. Confirm that the data acquisition system is fully operational for unattended operation.

2.8 Analyze strain, torque, and aerodynamic data and select new or additional operational speeds and start-stop windspeeds for large database tests in 3.0.

2.9 Perform maintenance checklist from Phase I part 1.2.8.

## PHASE II

### 3.0 HORIZONTAL PLANE ARRAY WIND MEASUREMENTS AND TURBINE CHARACTERIZATION (JOINT WITH PNL)

Objectives - Measure turbulence surrounding wind turbine
- Collect major characterization data base on turbine at selected constant speeds
- Attempt unattended automatic operation

Special Conditions Six anemometer towers surrounding equator of turbine rotor, winds 0 - 45 MPH

Data Requirements - PNL data acquisition equipment located in control building. Selected inputs from Sandia DAS supplied to PNL, i.e. rpm, rotor position, strain gauges, LS torque, etc.
- Maximum channels of data acquisition (all types) for characterization data base

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 8 days |
| Data Collection: | 6 weeks |

Procedure

3.1 Install six anemometer towers spaced equally in an equator-height circle around turbine per PNL test plan.

3.2 Set up instrumentation in control building and connect to selected channels of SNL data acquisition system.

3.3 Connect a Disturbance Analyzer to power system to monitor power used and power generated. Analyze data after this test series and decide if continued monitoring is desired.

3.4 Continue turbine characterization at selected constant speeds (chosen from data collected in 2.0). Work is to be performed in parallel with PNL rotational sampling experiment. (See PNL test plan).

## PHASE II

3.5 Analyze data after each speed setting to determine if any changes are needed in the control algorithm or sampling methods. Data should be examined for evidence of strain changes as tests progress. If changes in control or sampling are needed repeat tests for a complete data base.

3.6 Perform maintenance checks per part 1.2.8 in Phase I at the end of this series and during the various steps as deemed necessary. Make notes in maintenance log on desirable intervals versus hours of operation. Perform maintenance at regular intervals based on operating hours or other suitable criteria.

3.7 Remove PNL anemometer towers after completion of this test series.

## PHASE II

### 4.0 TEST CUSTOM SPEED RESPONSE ALGORITHMS

Objectives - To avoid undesirable speeds observed in parts 2.0 & 3.0
- To prepare algorithms for automatic variable speed operation
- Investigate speed control based on structural conditions.

Special Conditions Winds 0 to 45 MPH

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2 weeks |
| Data Collection: | 6 weeks |

Procedure

4.1 Write algorithm to vary speed from 0 to 40 rpm and avoid undesirable conditions observed in 2.0. and 3.0.

4.2 Using this algorithm collect data and compare with 2.0 and 3.0 data. Make changes as desired.

4.3 Incorporate this algorithm with final algorithm used in 3.0.

4.4 Test this combination to eliminate resonances and other undesirable operating points.

4.5 Using shaped acceleration/deceleration slopes, attempt to minimize structural loads when changing speeds.

4.6 Using structural response feedback (strain gauges), attempt to limit structural loads when changing speeds.

4.7 OPTION: Investigate the feasibility of using the torque measurement to limit the response time of speed changes (ie structural loading).

## PHASE II

4.8 Test the final algorithm developed in preparation for variable speed automatic operation. Operate under operator supervision until sufficient confidence is established to go on to part 5.0. Using the data acquired thus far the algorithm should take into account:

-resonance avoidance
-strain limiting
-special ramp slopes
-power line considerations
-torque ripple
-start-stop criteria
-braking (see part 8.7 Phase I)
-power fail/computer control considerations

4.9 Perform a maintenance check on the turbine.

# PHASE II

## 5.0 SPEED CONTROL TO OPTIMIZE ENERGY CAPTURE

Objectives Attempt to extract maximum energy from wind using rotor Cp as criteria

Special Conditions Winds 0 - 45 MPH

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2-8 weeks (programming and developing control model) |
| Data Collection: | 2-3 weeks or enough time to acquire 1000 samples in each bin. Some thought should be given to the choices made for data collection as this data will be used as a baseline for comparison with other control techniques to follow. |

Procedure

5.1 Prepare to use rotor Cp as an input that will allow the turbine to start and run and adjust its own speed to satisfy the controller program. The first step will be to start by using the information from the algorithms developed in 4.8. The low speed (rotor) torque measurement will need to be conditioned or averaged either electronically or via computer so that it will be suitable for use in calculating rotor Cp.

5.2 Develop an algorithm that will adjust turbine speed for maximum rotor Cp over the full operating range of the turbine.

5.3 Incorporate a variable upper limit on output power by limiting turbine rotor speed.

## PHASE II

5.4 Collect data over the full range of turbine operation letting the turbine adjust its speed accordingly. CAUTION: This operation should be done under operator supervision with special attention being paid to any tendency for the control system to oscillate or hunt. The operator should endeavor to operate the turbine over a wide range of operating conditions before assuming that this tendency does not exist.

5.5 Approach 1. (closed loop)
If feedback problems occur, the control program can be modified to provide a slower response time or proportional control may be attempted (less drive as the error signal is reduced).

5.6 Approach 2. (open loop)
If all else fails a look up table approach might be used, i.e. if wind speeds = x, then run at speed = y.

5.7 Additional consideration may also need to be given to wind measurement averaging methods used for the variable speed approach, ie.averaging time, how much error before correction(dead band)? The methods chosen for start-up shut-down control may not be suitable for this application.

5.8 Using the final algorithm, collect data over the full operating range of turbine. Analyze the data and compare with single speed operation.

## PHASE II

### 6.0 SPEED CONTROL TO OPTIMIZE POWER OUT

Objectives - Develop an algorithm to optimize power out using system Cp as criteria.

Special Conditions Winds 0 - 45 MPH

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2 weeks (programming) |
| Data Collection: | 3 weeks |

Procedure

6.1 Develop an algorithm that will use a selected output power as input and allow the turbine speed to be adjusted to optimize this parameter over the operating range. As in part 5.0 this measurement may need to be conditioned before being suitable for use as a variable in the Cp calculation.

6.2 Incorporate a variable upper limit on output power.

6.3 Follow cautions and procedures outlined in 5.0 with regards to possible feedback problems.

6.4 Collect data in the same manner and over the same operating range used in 5.0 and compare results. If data appears identical, skip part 7.0.

# PHASE II

## 7.0 SPEED CONTROL USING BOTH OUTPUT POWER AND Cp AS CONTROL INPUTS

Objectives - Attempt to improve operation of the turbine over the full operating range by combining features of the control algorithms developed in parts 5.0 and 6.0

Special Conditions Winds 0 - 45 MPH.

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

Engineering: 2 weeks (programming)

Data Collection: 3 weeks

Procedure

7.1 Starting with algorithms developed in 5.0 and 6.0, use a combination of Cp and power out to develop a new algorithm in order to better control the turbine output over the entire operating range.

7.2 Probable approaches would be to use rotor Cp over the lower part of the speed range and system Cp at the upper end, or combinations of the two.

7.3 Take data by the same methods used in 5.0 and 6.0 and over the same operating range. Evaluate data and compare with the two previous methods.

## PHASE II

## 8.0 AERO AND STRUCTURAL CHARACTERIZATION USING TORQUE CONTROL

Objectives - Develop method for using torque measurement for turbine control.
- Determine machine characteristics using selected constant torque algorithms.

Special Conditions Winds 0 to 45 MPH.

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

Engineering: 3 weeks programming & signal conditioning

Data Collection: 8 weeks

Procedure

8.1 Starting with the work done in 5.0 through 7.0, develop a technique for best using a torque waveform for control (i.e., smoothing, averaging, chopping, etc.) of the turbine. Consider the low speed torque as the primary choice, but also investigate the waveforms that might be used from the high speed torque and possibly generator current.

8.2 Starting with the algorithms developed for constant speed testing in 3.0, develop an algorithm using this waveform to vary the turbine drive to maintain a constant adjustable torque with adjustable upper and lower limits.

8.3 Operate the turbine with the torque of choice long enough to establish some fundamental characteristics as in part 2.0. Experiment with other torque choices and compare results. Compare the operation of the variable upper limit torque function to that of the upper limit on power out from 5.3

8.3 Perform characterization tests as in 3.0 and compare the results with the constant speed mode.

## PHASE II

### 9.0 HYBRID SPEED CONTROL TESTS

Objectives - Finalize the development of an algorithm incorporating all the desirable and worthwhile features investigated thus far.

Special Conditions Winds 0 - 45 MPH.

Data Requirements DAS time & bins all chan.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 2 weeks |
| Data Collection: | 8 weeks |

Procedure

9.1 Consider the following list of factors and develop a control algorithm or family of algorithms that includes the logical and desirable features.

- Resonance avoidance
- Minimal structural loading
  via: special ramp slopes
  strain gauge inputs
  braking techniques
- Ramp slopes for power line considerations
- Start-stop criteria
- Braking techniques
- Power or torque limiting
- Speed limiting
- Power fail routines
- Manual control
- Unattended operation
- Constant adjustable speed operation
- Constant adjustable torque operation
- Variable speed with selectable inputs
  ie: Cp, torque, power
- Combinations of the above

9.2 Evaluate this hybrid control approach by operating the turbine over a wide range of weather conditions. Establish confidence in the ability of the programs to handle unattended operations.

## PHASE II

### 10.0 OPTIONAL ROTATING MODAL VIBRATION TESTS

Objectives - To determine the modes of vibration of the entire turbine under motor driven and wind driven conditions

Special Conditions May be possible to insert this test series in between other tests early in Phase II or to run concurrently

Data Requirements Instrumentation and hardware to be furnished by SNL Org. 7544

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 3 days |
| Data Acquisition: | 3 days |

Procedure

10.1 Using crane bucket for access, install approximately 15 accelerometers on turbine blades and column.

10.2 Move instrumentation trailer into position and connect signal cables between sensors and trailer. Using slip rings for access, or possibly PCM system.

10.3 Operate turbine with no wind using "sweep" algorithm and selected constant speeds.

10.4 Operate turbine in winds to 45 MPH and investigate effect of different control modes on vibration (if this test is inserted late enough in Phase II).

## SYNOPSIS OF PHASE III

Once the operation of the machine has been characterized in Phase II, the test plan moves on to areas where research is required on specific aspects of wind turbine technology. Time schedules, funding constraints, and new knowledge acquired will probably change the order and content of the Phase III tests as they are listed.

Vertical axis wind turbine blades operate with widely varying angles of attack, and in fact portions often pass through a stall condition twice during each revolution. Parts 1, 2, and 3 of Phase III are experiments designed to better understand the aerodynamics of this condition. The data acquisition method used previously will have to be modified for these tests. It will be necessary to correlate blade position to the wind at the time a sample is taken, and sample the wind measurements and strain gauges at that same time. This technique, known as rotational sampling, will require that each sample is correlated with a known rotor position as contrasted with many samples averaged for a rotor revolution as used in previous tests. A higher sample rate data acquisition system as well as video and other equipment mounted on the rotor center column will be required.

Part 1 will try to visualize the existing flow conditions by recording the action of surface mounted (on the airfoils) filaments, injected colored tracer gases, and liquid crystal material coating the surfaces. The installation of valves and a gas reservoir on the turbine center column will be necessary, and tubing will have to be installed in the center section of a turbine blade. Experience on this series will help determine the best locations for instrumentation in parts 2 and 3.

Part 2 will attempt to define in depth, the flow fields observed in part 1. This will be done by using instrumentation in or close to the actual airflow. Proposed measurements include surface pressure, and velocities by hot film sensors, and pitot tubes.

Part 3 will attempt to modify the airflows measured in parts 1 and 2 by using vortex generators and surface modifications as passive approaches. Active airflow modification will use suction slots, tangential blowing, and transverse jets.

Part 4 will attempt to operate the machine with a single blade. Because the blades of vertical axis wind turbines represent a major portion of their cost, a substantial cost saving could be effected by using a single blade. This test may be scheduled prior to parts 1, 2, and 3 so that the removed blade can be modified for those tests. Most of the tests from Phase II would have to be rerun for the single blade tests.

SYNOPSIS OF PHASE III (continued)

Part 5 evaluates an entirely new blade design constructed of composite materials with a continuous (not stepped) change in cross section and chord. Extensive instrumentation installation and resonance testing would be required on this blade before proceeding with a Phase II type evaluation.

Part 6 Braking Investigations, may have already been completed by the time Phase III is reached, depending on the brake performance noted in Phase II. The general idea is to reduce the braking strains on the machine to a minimum, depending on environmental conditions, torque, and rotor rpm, while maintaining a fail-safe design.

Part 7 investigates another approach to braking by using aerodynamic drag brakes mounted on the turbine column.

Part 8 will investigate a new blade root section designed specifically for that environment. As with other blade designs it will be necessary to start with resonance testing and repeat many of the experiments from Phase II.

Part 9 calls for replacing the center blade sections of the turbine with a new design based on new information acquired on this machine. The same general testing pattern followed in part 8 will be followed here as well.

Part 10 evaluates the concept of centrifugal pumping of the turbine blades to control maximum power and possibly improve energy capture. A Phase II re-run will be required.

Part 11 is yet another new blade design, only this time with a cambered airfoil to improve energy capture and upwind-downwind torque balancing. Resonance testing followed by a Phase II type evaluation will be performed.

## PHASE III ADVANCED CONCEPTS

### 1.0 DYNAMIC STALL EXPERIMENT PART 1.
### FLOW VISUALIZATION TESTS

Objectives - Qualitatively define the state of the boundary layer flow over selected sections of airfoil.
- Derive some indication of overall three-dimensionality of the flow field.
- Determine best instrumentation positioning for subsequent tests.

Special Conditions - New blade sections required with fluid injection tubing located within airfoil, reservoir located within rotating column, with appropriate control mechanisms.

Data Requirements - Will require high speed data acquisition system for checkout here and for data collection on succeeding tests. Color video camera mounted on column, video recorder and monitor located in control building. Rotor position, windspeed, and direction to be indicated on video screen.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Collection: | 10 weeks |

Procedure

1.1 Inject tracer gases of various colors to determine flow patterns while turbine is in operation.

1.2 Compare gas flow with surface mounted filaments to determine flow patterns.

1.3 Use pre-coated applicators of liquid crystals whose color response is shear dependent to exhibit flow patterns.

1.4 Inject liquid crystals while turbine is rotating and compare with results obtained in 1.3.

## PHASE III

### 2.0 DYNAMIC STALL EXPERIMENT PART 2. FLUID-DYNAMIC MEASUREMENTS

Objectives - Define unsteady flow fields which develop over airfoil surfaces.

Special Conditions - G-load-compensated pressure transducers mounted below airfoil surface.
- Flush-mounted or probe-mounted hot-film sensors.
- Surface mounted pitot tubes.

Data Requirements - High speed data acquisition system. Instruments first calibrated in laboratory under controlled conditions.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Collection: | 10 weeks |

Procedure

2.1 Define, in as much detail as possible, the unsteady flow fields which develop over the airfoil surface.

# PHASE III

## 3.0 DYNAMIC STALL EXPERIMENT PART 3. PASSIVE AND ACTIVE BOUNDARY LAYER MODIFICATION/CONTROL

Objectives - Investigate the influence of various passive and/or active "modifiers" on boundary layer flows.

Special Conditions - Addition of vortex generators, blade sections with slots, transverse jets.

Data Requirements - High speed data acquisition system

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 6 weeks |
| Data Collection: | 10 weeks |

Procedure

3.1 Perform tests to measure the influence of distributed roughness.

3.2 Use vortex generators to modify/improve conditions.

3.3 Use active slot suction to modify airflow.

3.4 Use tangential blowing to modify airflow.

3.5 Use transverse jets to modify dynamic stall to regulate performance.

# PHASE III

## 4.0 SINGLE BLADE PERFORMANCE TESTS

Objectives - Investigate performance of turbine using single blade.

Special Conditions - One blade removed

Data Requirements - Additional vibration and strain gauges added.

Estimated Time for Performance

| | |
|---|---|
| Engineering: | 3 weeks |
| Data Collection: | 12 weeks |

Procedure

4.1 Follow general procedures in Phase I Section 8.0 and Phase II Section 1.0 for resonance investigation.

4.2 Proceed as in Phase II Section 2.0 to determine aero and structural characteristics.

4.3 Modify control algorithms as required.

# PHASE III

## 5.0 ADVANCED BLADE EVALUATION

Objectives - Evaluate the aerodynamic and structural dynamic characteristics of a blade whose chord and cross-section continuously change and is constructed of composite materials

Special Conditions - Replace remaining blade (after single-blade tests) with new dual blade design.

Data Requirements - Follow the same or modify procedures from Phase I Section 6.0.

Estimated Time for Performance

Engineering: 4 weeks

Data Collection: 12 weeks

Procedure

5.1 Follow general procedure for start up and resonance investigation from Phase I and Phase II.

5.2 Perform aerodynamic and structural evaluation following the general procedure used in Phase II Section 2.0.

# PHASE III

## 6.0 MECHANICAL BRAKING TECHNIQUE INVESTIGATIONS

Objectives - Investigate various methods of applying mechanical brakes to stop turbine rotor with minimal blade strain

Special Conditions Additional brake instrumentation

Data Requirements DAS in time series mode

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Acquisition: | 2 weeks per method or can be integrated with other testing |

Procedure

6.1 METHOD 1.
Plumb hydraulic system to use one, two, three, or four calipers for proportional braking. Use computer to rotate duty among calipers. Measure strains and temperatures as tests proceed.

6.2 METHOD 2.
Install digitally controlled valve to bleed off brake pressure on all four calipers. Use battery operated microprocessor to apply proportional braking depending on parameters such as rpm, windspeed, and strain.

# PHASE III

## 7.0 AERODYNAMIC BRAKE INVESTIGATION

Objectives - Evaluate the stopping dynamics of the test bed with tower mounted aerodynamic brakes

Special Conditions - Fit the center column with aerodynamic drag brakes
- Start testing at near zero wind speed

Data Requirements DAS in time series mode

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 2 weeks |
| Data Acquisition: | 3 weeks-also may be integrated with other testing |

Procedure

7.1 Using normal turbine regenerative slowdown, deploy aerodynamic brakes just prior to LCI cut-out without applying hydraulic brake. Evaluate turbine structural and dynamic response.

7.2 Repeat Step 1, but increase the rotor rotational speed at which the aerodynamic brakes are deployed.

7.3 Repeat Step 2 until the maximum desired rotational speed is reached.

7.4 Repeat Steps 2 and 3, but cut-out LCI at increasing rotor rotational speeds in order to evaluate the aerodynamic brakes as the only braking system.

# PHASE III

## 8.0 LOW REYNOLDS NUMBER BLADE ELEMENT DESIGN INVESTIGATION

Objectives - Evaluate improved energy capture and structural dynamics of a rotor whose root section blade elements use a section designed specifically for that environment

Special Conditions Replace NACA0021 with SAND Low Reynolds Number Airfoil

Data Requirements Follow the same or modify procedures from Phase I part 6.0

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Acquisition: | 12 weeks |

Procedure

8.1 Follow the general procedure for start up and resonance investigation from Phase I and II.

8.2 Perform aerodynamic and structural evaluation following the general procedure used in phase II part 2.0

## PHASE III

### 9.0 HIGH REYNOLDS NUMBER BLADE ELEMENT DESIGN INVESTIGATION

Objectives - Evaluate the improved energy capture and structural dynamics of a rotor whose equatorial blade elements use a section designed for a high Reynolds number VAWT environment

Special Conditions Replace SAND0018/50 with a SAND high Reynolds number airfoil

Data Requirements Follow the same or modify procedures from Phase I part 6.0

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Acquisition: | 12 weeks |

Procedure

9.1 Follow the general procedure for start up and resonance investigation from Phase I and II.

9.2 Perform aerodynamic and structural evaluation following the general procedure used in Phase II part 2.0.

# PHASE III

## 10.0 CENTRIFUGAL PUMPING INVESTIGATION

Objectives - Evaluate a rotor which uses centrifugal pumping to selectively control maximum power and enhance energy capture

Special Conditions Install centrifugal pumping rotor

Data Requirements Follow the same or modify procedures from Phase I part 6.0

Estimated Time For Performance

| | |
|---|---|
| Engineering: | 4 weeks |
| Data Acquisition: | 14 weeks |

Procedure

10.1 Follow the general procedure for start up and resonance investigation from Phase I and Phase II.

10.2 Perform aerodynamic and structural evaluation following the general procedure used in Phase II part 2.0.

# PHASE III

## 11.0 CAMBERED AIRFOIL BLADE ELEMENT DESIGN INVESTIGATION

Objectives - Evaluate improved energy capture, upwind-downwind torque balancing, and structural dynamics of a rotor whose equatorial blade elements use a cambered natural laminar flow section designed specifically for that environment.

Special Conditions Replace SAND0018/50 with SAND cambered design

Data Requirements Follow the same or modify procedures from Phase I part 6.0

Estimated Time For Performance

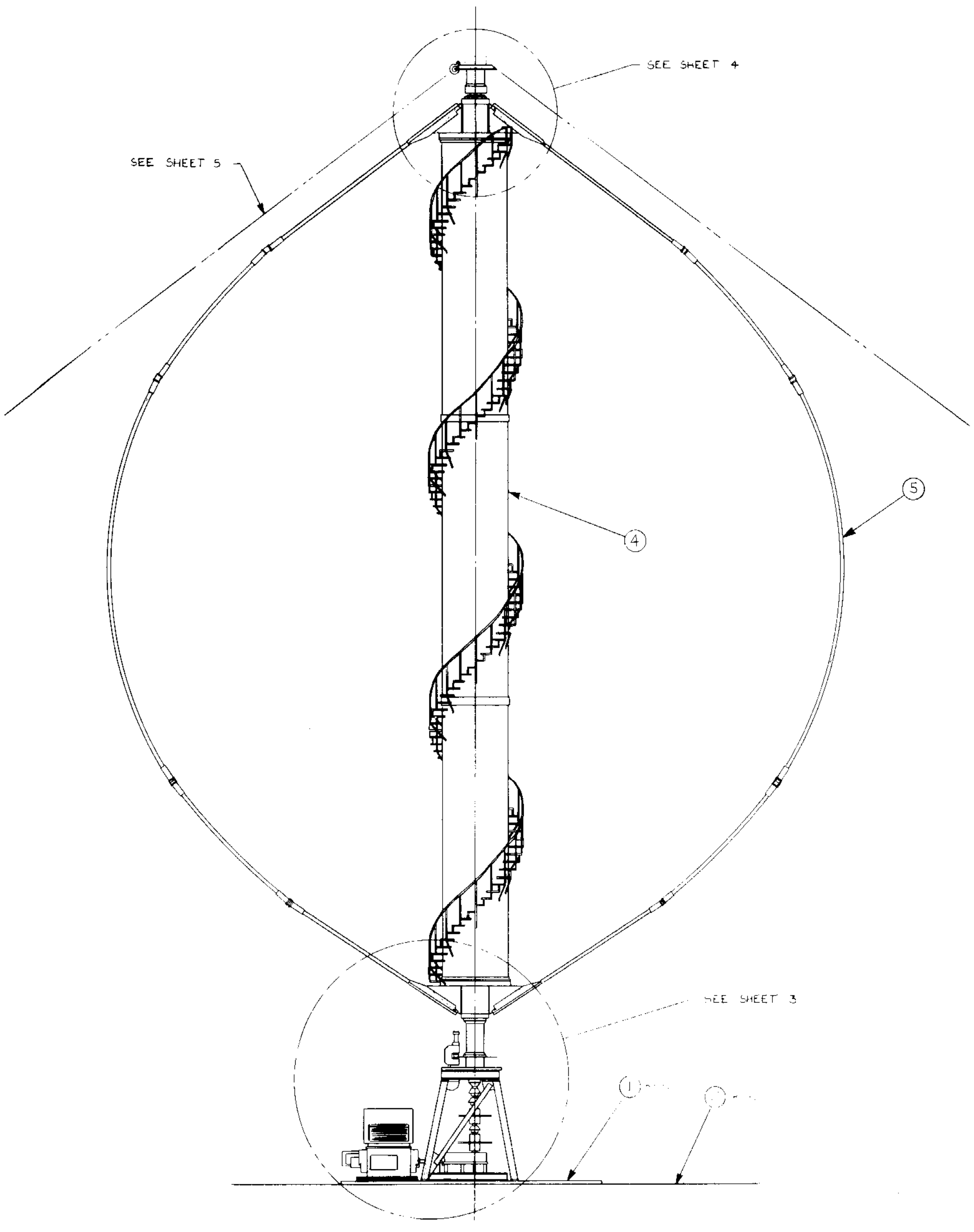
| | |
|---|---|
| Engineering: | 2 weeks |
| Data Acquisition: | 14 weeks |

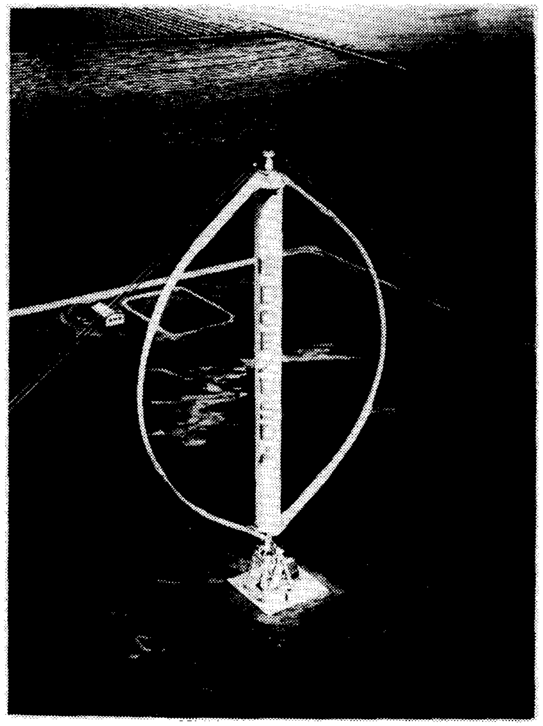
Procedure

11.1 Follow general procedure for start up and resonance investigation from Phase I and Phase II.

11.2 Perform aerodynamic and structural evaluation following the general procedure used in Phase II part 2.0.

# APPENDIX A





AY-568385-000

| | | |
|---|---|---|
| A | FORSYTHE 2858/<br>GROVER 6225 | |
| B | FORSYTHE 2858/<br>GROVER 6225<br>MINOR REVISIONS | |
| C | REVISED SHEET 3 ITEM 56<br>FORSYTHE 2858/ ASHWILL 6225 | |

| | | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| | C | B | C | B | B |

UNCLASSIFIED

UNCLASSIFIED

VAWT TEST BED
ASSEMBLY

E 14213 AY-568385

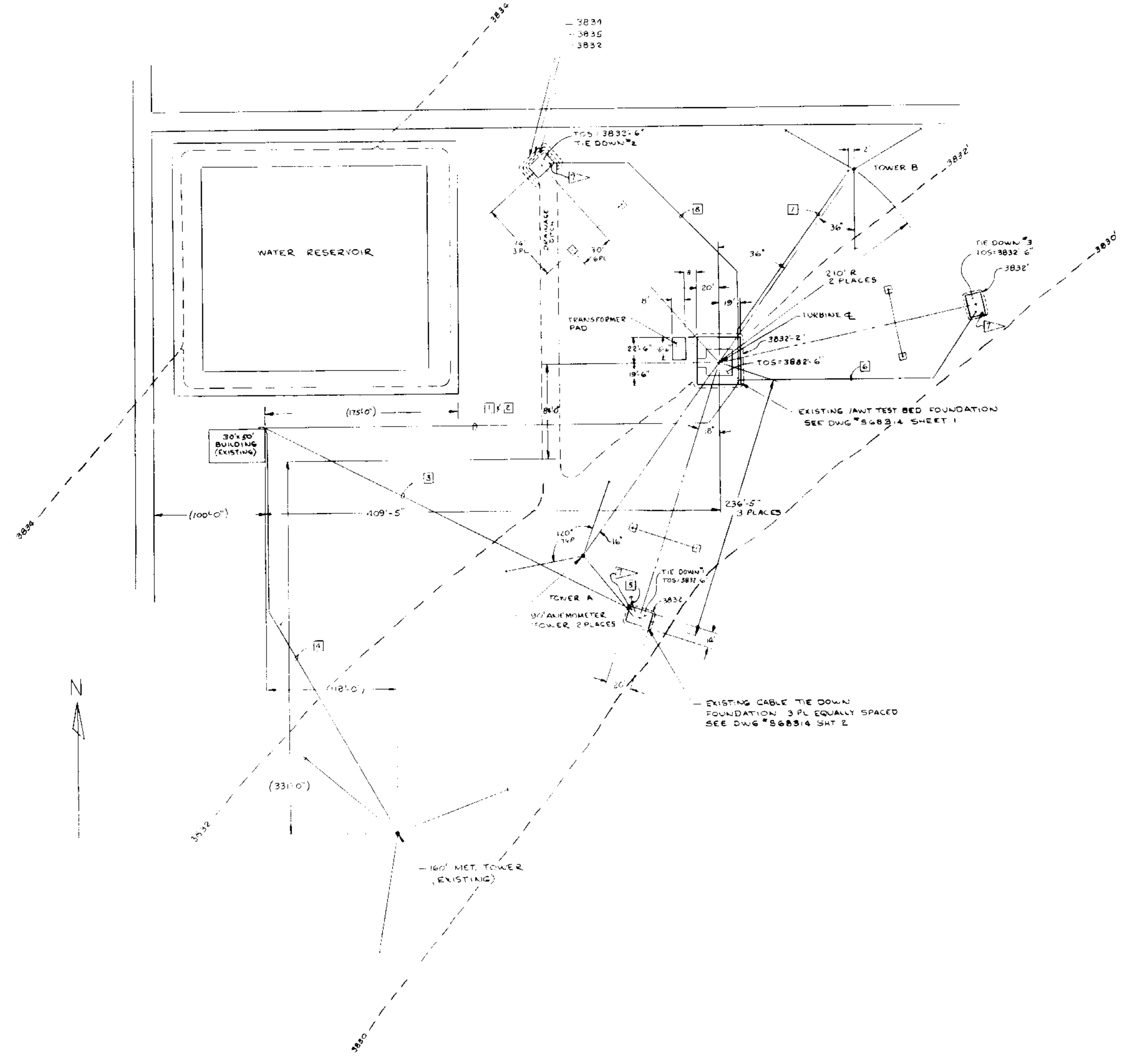
.05 = 40"

1 of 5

DWG NO AY-568385

# APPENDIX B

| DESIGN AGENCY CONTROL NO. | SYM | ZONE | DESCRIPTION / PREPARED BY | DATE | | |
|---|---|---|---|---|---|---|
| 568490-000 | A | | GARDNER 2858/ASHWILL 6225 | 5/10/86 | | |
| | B | | FORSYTHE 2858/ASHWILL 6225<br>REVISED TRANSFORMER PAD | 9/24/86 | | |



NOTES

1. THE SIX 7'x7'x2' PADS ARE TO BE CONSTRUCTED BY GENERAL CONTRACTOR.
2. TRANSFORMER PAD TO BE CONSTRUCTED BY GENERAL CONTRACTOR.
3. ALL CONCRETE TO BE 3000 PSI & REBAR 60,000 PSI USE #5's @ 12 O.C. EACH WAY @ 3" BELOW SURFACE. FOR ALL SLABS.
4. ANEMOMETER TOWERS TO BE SUPPLIED AND INSTALLED BY OTHERS.
5. ELEVATION LINES ARE APPROXIMATE.
6. ▢ REFERS TO CONDUIT SCHEDULE IN ELECTRICAL SPECIFICATION.
7. INSTALL 12 X 2 X 4 NEMA TYPE 4 JUNCTION BOX (TT1, TT2, TT3) ON UNISTRUT 3' ABOVE SLAB. MOUNT BOX (TT1C, TT2C, TT3C) IN [illegible] CABLE TENSION TRANSDUCER WITH PIPE CLAMPS.

DWG NO 568490

| AGENCY APPROVALS | | | SHEET 1 | TITLE |
|---|---|---|---|---|
| ORG | DATE | APPROVAL | ISSUE B | SITE, 34 M TEST BED |
| | | | SHEET INDEX | |
| | | | PART CLASSIFICATION<br>UNCLASSIFIED | |
| | | | DWG CLASSIFICATION LEVEL<br>UNCLASSIFIED | SIZE E · FSCM NO 14213 · DWG NUMBER 568490 |
| | | | | SCALE 1" = 100' · SHEET |

# APPENDIX C

## TEST BED SPECIFICATION SHEET

Change Order No.: 6

Date: 1/3/86

### A. GEOMETRY

| 1. Blade | Root | Intermediate | Center |
|---|---|---|---|
| a. Blade Shape and Length of each Airfoil | Straight<br>35 ft upper<br>35 ft lower | 98 ft R<br>25 ft | 56 ft R<br>63 ft |
| b. Airfoils and Chord Lengths | 48 in.<br>NACA 0021 | 42 in.<br>0018/50 | 36 in.<br>0018/50 |
| c. Number of Ribs | 11 | 9 | 7 |
| d. Rib Thickness | .32 in. | .25 in. | .25 in. |
| e. Wall Thickness | .32 in. | .25 in. | .25 in. |
| f. Nose Thickness | .5 in. | .5 in. | .5 in. |
| g. Tail Thickness | 1.92 in. | 2.52 in. | 2.34 in. |
| h. Number of Extrusions/ Blade | 3 | 2 | 2 |
| i. Area and Moments of Inertia – Area: | 57.4 in.$^2$ | 32.7 in.$^2$ | 26.0 in.$^2$ |
| $I_{LL}$: | 9447.0 in.$^4$ | 3976.0 in.$^4$ | 2358.0 in.$^4$ |
| $I_{FLT}$: | 535.0 in.$^4$ | 170.3 in.$^4$ | 101.6 in.$^4$ |
| $I_{TORS}$: | 1432.2 in.$^4$ | 478.0 in.$^4$ | 296.0 in.$^4$ |
| j. Material | 6063-T5 | 6063-T5 | 6063-T5 |

k. Blade/Tower Angles – Top: 53.5°
Bottom: 57°

l. Swept Area – 10,280 ft$^2$

2. Tower

a. Diameter – 10 ft

b. Wall Thickness – 0.5 in.

c. Material – Aluminum

d. Lower Shaft Diameter = 32"

e. Upper Shaft Diameter = 20"

3. Cable

   a. Number of Cables - 3 sets of 2 cables

   b. Cable Angle - 35° with ground

   c. Type of Cable - STRAND-ASTM-A586

   d. Cable Diameter/Area - 2-7/16 in./3.57 in.$^2$

4. Joints

   a. Blade Joints/Dimensions - 4 joints - 5 ft long

   b. Blade Mounts/Dimensions - 8 ft lengths

   c. Moments of Inertia -

| | $I_{FLT}$ | $I_{LL}$ |
|---|---|---|
| 36" | 195 in.$^4$ | 4450 in.$^4$ |
| 42" | 320 in.$^4$ | 7300 in.$^4$ |
| 48" | 880 in.$^4$ | 15000 in.$^4$ |

   d. Material - Aluminum

6. Rotor

   a. H/D Ratio = 1.25/1

   b. Diameter - 110 ft

   c. Ground clearance - 23 ft

B. LOADS

   1. Stand Stiffnesses - 3 x 10$^6$ lb/in.

   2. Drive Train Stiffness - 60 x 10$^6$ in-lb/radian (with no hockey pucks)

   3. Rotor Inertia - 750,000 slug ft$^2$

   4. Brake Torque - 600,000 ft lb

   5. Design Aero Torque and Power - 122,000 ft lb and 650 kW @ 37.5 rpm and 37 mph

6. Cable Loads
    a. Pretension - 93,000#/cable
    b. Maximum and Minimum Tension - 118,000# and 68,000#
       Percent of Ultimate = 16.4% @ 118,000# tension
7. Cable Stiffness - 45,000 lb/in. horizontal
8. Loads on Bottom Bearing - 490,000 vertical
9. Loads on Top Bearing - 320,000 vertical

C. FREQUENCIES

1. Cables - .8125 Hertz @ 93,000# tension
2. Drive Shaft - 0.4 Hertz with drivetrain stiffness = $60 \times 10^6$ in.-lb/radian

D. OPERATING CONDITIONS

1. RPM - 37.5 rpm
2. Tipspeed - 216.0 ft/sec @ 37.5 rpm
3. Expected Rated Power
    a. Rated kW - 500 @ 37.5 rpm
    b. Annual Energy @ 14 mph - $1.15 \times 10^6$ kW-hr
4. Rotor Weight - 152,000 lb
5. Turbine Weight - 215,000 lb
6. Start Time - 30 sec
7. Stop Time - 7.5 sec with 600,000 ft/lb torque at maximum $K_p$
8. Maximum Cutout - 45 mph

Change Order No.: 6

Date: 1/3/86

## E. MECHANICAL

### 1. Bearings

a. Bottom Thrust Bearing - Spherical Roller Thrust No. 294/600
Dynamic Rating - 3.0 x $10^6$ lbs
Life = 1.0 x $10^8$ cycles

b. Top Thrust Bearing - Spherical Roller Thrust No. 294/530
Dynamic Rating - 2.36 x $10^6$ lb
Life = 1 x $10^8$ cycles

c. Top Radial Bearing - Spherical Roller Radial No. 23096
Dynamic Rating - 740,000 lbs
Life = 1.0 x $10^8$ cycles

### 2. Transmission - Brad Foote Gear Works, Inc., #3RV2250S
950 HP at 1800 rpm w/1.0 Service Factor
Gear Ratio - 47.56/1, 37.5 VAWT rpm
Min high speed shaft rpm to be 1150

### 3. Brakes

a. Spring-Applied Hydraulic Release Disc/Caliper -

Brake Caliper Spring - Rolex Co. Model AM25012716, 110,351 lbs;
500,000 lbs/in. spring rate
Hydraulic Cylinder - 8" diameter

b. Brake Disc - 80" diameter
1" thick
Material - ASTM A572 Grade 65 Steel

## F. ELECTRICAL

### 1. Generator

a. Rating (kW) - 625

b. Voltage - 1200 V

c. Operational Speed - from 1190 to 1900 rpm

d. Type of Variable Speed - Synchronous Motor Drive, Current
Source Load Commutated Inverter

Change Order No.: 6

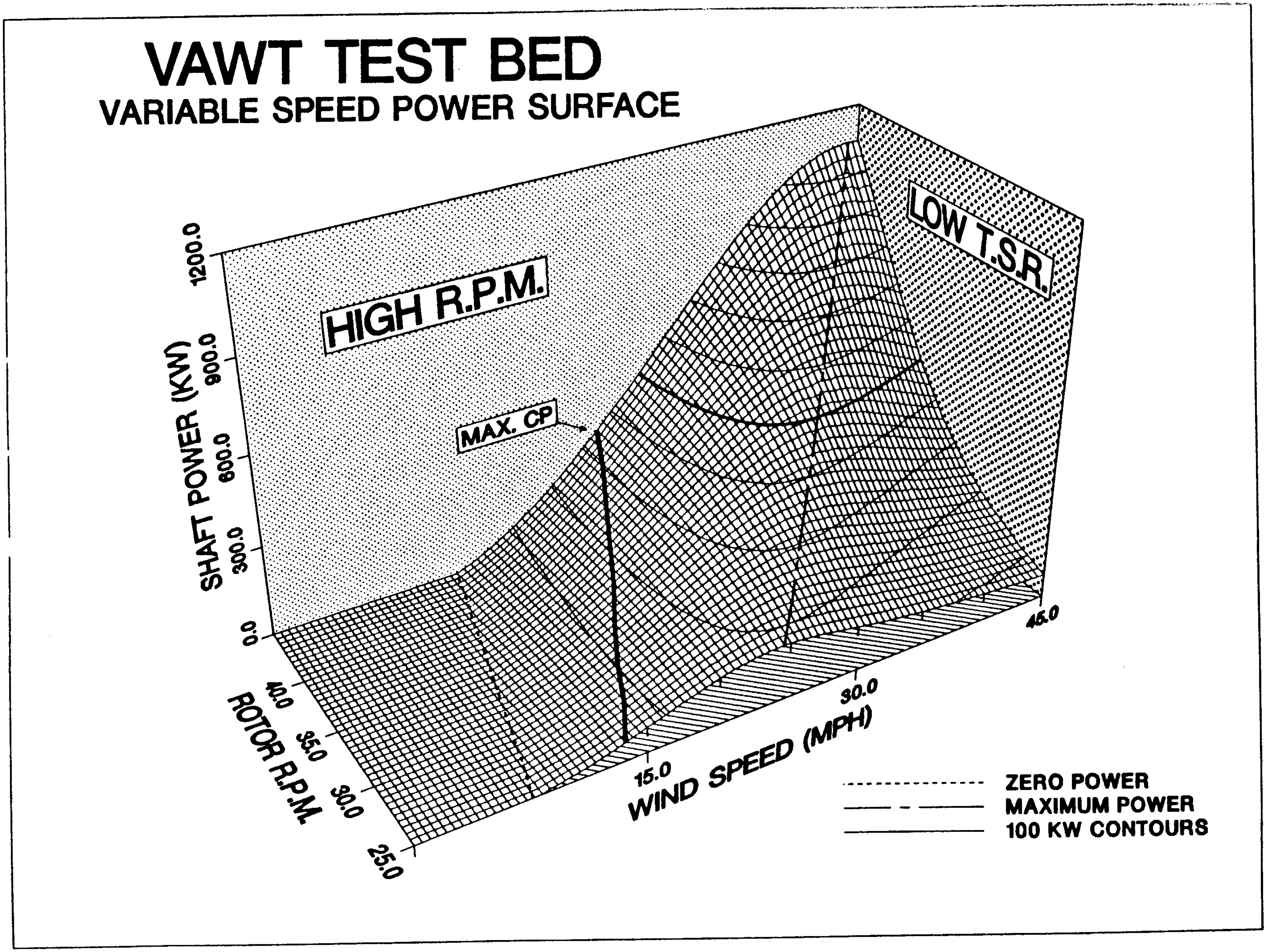
Date: 1/3/86

2. Transformer - 750 kVA, 13.2 kV delta, 1200 V delta

3. Slip Ring Assembly - Fabricast Model 1738
   Number of Slip Rings - 50

4. Control System - Allen Bradley Programmable Controller 2/30

APPENDIX D



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