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ENERTECH 15 kW WIND SYSTEM DEVELOPMENT

PHASE II - FABRICATION & TEST

December 1982

C. R. ZICKEFOOSE

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Rocky Flats
Wind Energy Research Center

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For
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Energy Systems Group
Rocky Flats Plant
Wind Energy Research Center
Golden, Colorado 80402-0464

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UNITED STATES DEPARTMENT OF ENERGY
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MASTER

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Technical Report

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C. R. Zickefoose

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Enertech 15 kW Wind System

ABSTRACT

This Phase II report presents a description of the Enertech 15 kW prototype wind system hardware fabrication; results of component tests; and results of preliminary testing conducted at Norwich, VT and the RF Wind Energy Research Center. In addition, the assembly sequence is documented. During testing, the unit experienced several operational problems, but testing proved the design concept and demonstrated the system's ability to meet the contract design specifications for power output.

ACKNOWLEDGMENT

The successful operation of the 15 kW wind turbine represents the culmination of two years of work to develop and prove the Enertech concept on a larger scale wind machine. This was made possible through the coordinated efforts of Rockwell and Enertech. The author gratefully acknowledges the contribution of the Enertech staff involved in the program.

The following specific individuals are thanked for their contributions: Ken Knowles, Henry Clews, Larry Staudt, and Bruce Johnson, for design, and Lewis McKeon and Neil Hochstedler, for assembly and installation.

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CONTENTS

	<u>Page</u>
1. Introduction	1
2. Schedule Summary	4
3. Fabrication and Assembly	5
4. Component Test Program	27
4.1 Blades	27
4.2 Hub	34
4.3 Generators	34
4.4 Brake	34
4.5 Gearbox	35
4.6 Mainframe	35
4.7 Nacelle	36
4.8 Tower	36
5. Manufacturer's Prototype Test Program	43
5.1 Output	43
5.2 Yaw Response	44
5.3 Vibration Monitoring	44
5.4 Freewheeling Characteristics	44
5.5 Cycling Data	45
5.6 Tip Brake Effectiveness	45
5.7 Control System Testing and Tuning	46
5.8 Blade Pitch Optimization	46
5.9 System Natural Frequency	47

	<u>Page</u>
6. Manufacturer's Test Summary	48
7. Machine Design Modifications During Manufacturer Testing	51
8. Preliminary Rocky Flats Test Data	53
9. Conclusions	58
10. References	58

FIGURES

	<u>Page</u>
1 Schematic of Enertech 15 kW Design	3
2 Summary of Milestones in Phase II	4
3a Mainframe Weldment	7
3b Mainframe Weldment Stiffeners	8
3c Mainframe Nacelle Mounting Extension	9
4 Turntable Yaw Bearing Assembly	10
5 Leveling Adjustment	11
6a Blade Pitch Adjustment	12
6b Hub Tapered Bushing	13
6c Spinner Mounting Bracket and Hole Pattern for Mounting Blade on Hub	14
7a Mounted Generator	15
7b Gearbox to Generator Coupling	16
7c Electrical Slip Ring Assembly	17
7d Yaw Potentiometer Mounting	18
8 Mounted Brake Assembly	19
9a Installing Tower Cross Braces	20
9b Gin Pole for Raising Tower Components	21
9c Assembled Tower	22
9d "I"-Beam Tower Base	23
10a Unit Ready for Installation	24
10b Tip Brake Installation	25
10c Crane Preparing to Lift Unit	26
11a Simulated Blade Deflection Test	28
11b Measuring Blade Deflection	29
12 Plot of Blade Deflection Test Results	30
13a Blade Fatigue Test Specimen	31
13b Blade Fatigue Test Specimen	31
13c Blade Fatigue Test Specimen Tip	32
13d Blade Fatigue Test Specimen Root Mounting Fixture	32
13e Blade Actuator	33

FIGURES - contd.

	<u>Page</u>
14 Engine Dynamometer Generator and Brake Testing Facility	37
15 Brake Assembly Mounted for Testing	40
16 Tower Vibration Testing	41
17 System Power Output vs. Wind Speed	43
18 Failed Gearbox Casting	49
19 Circulute Gearbox	50
20 Preliminary Rocky Flats Performance Data (Adjusted Power vs. Wind Speed)	54
21 Preliminary Rocky Flats Performance Data (Unadjusted Power vs. Wind Speed)	55
22 Preliminary Rocky Flats Performance Data (Coefficient of Performance vs. Wind Speed)	56
23 Preliminary Rocky Flats Performance Data (Wind Distribution vs. Wind Speed)	57

TABLES

	<u>Page</u>
I. Blade Deflection Test Results	30
II. Blade Fatigue Test	33
III. Gould One-Phase Generator Performance Data	38
IV. Gould One-Phase Generator Performance Data	38
V. Gould Three-Phase Generator Performance Data	39
VI. Tower Vibration Test Results	42
VII. Blade Pitch Settings	47

NOMENCLATURE

A or amp	- ampere
ac	- alternating current
Btu	- British thermal units
cm	- centimeter
Cp	- power coefficient
dB	- decibels
dBA	- decibel, A-weighted
dc	- direct current
ft	- foot
hp	- horsepower
Hz	- Hertz
in.	- inch
kg	- kilogram
kVA	- kilovolt-ampere
kW	- kilowatt (1000 watts)
kWh	- kilowatt hour
lb	- pounds
LTDC	- Long Term Data Collection
m	- meter
mfd	- microfarad
mph	- miles per hour
m/s	- meters per second
RF	- Rocky Flats
rpm	- revolutions per minute
SWECS	- Small Wind Energy Conversion System
V	- volt
W	- watt
WERC	- Wind Energy Research Center
WTG	- wind turbine generator
°	- degrees

1. INTRODUCTION

This report presents Phase II results (fabrication and testing) of an Enertech Corporation development project to design, fabricate, and test a SWECS capable of producing a rated output of 15 kW in a 9 m/s (20 mph) wind. Work described in this report is sponsored by the United States Department of Energy and administered by Rockwell International Corporation, Rocky Flats Plant, Golden, Colorado. Results of Phase I activities (design and analysis) are presented in Reference 1.

The Enertech 15 kW system has a 13.4 m (44 ft) rotor diameter and utilizes three fixed-pitch, highly rigid, wood-epoxy-laminate blades. The blades are coupled to a massive cast steel hub. The concept is similar to that used in the Enertech Model 1800 SWECS. Steel studs embedded in the blades provide the hub interface.

The hub is a four-piece casting with one central part and three legs. The central hub is directly mounted to a speed increaser. The use of a four-piece system allows some flexibility in initial adjustment of the running blade pitch.

The gearbox is a three-stage helical gear design with a nominal 1-to-35 ratio. The low-speed shaft gear is of greater than standard length to allow hub mounting via a large tapered bushing.

A double "C" face induction generator is mounted directly to the gearbox through a flexible coupling. Nominal generator speed is 1,850 rpm. A hydraulic brake, designed to energize upon control system command or loss of utility power, is mounted to the other generator "C" face.

The drive train is bolted to a structural steel mainframe which, in turn, is mounted to a turntable-type yaw bearing. The unit is free in

yaw. The drive train and mainframe are housed in a fiberglass nacelle. The baseline tower is a 60-ft Rohn SSV self-supporting, dynamically "hard" tower.

The machine utilizes aerodynamic stall of the rotor to achieve high wind output stability. In the event of a rotor overspeed for any reason, tip brakes mounted to the blade ends deploy centrifugally. Figure 1 is a schematic of the overall assembly design.

COMPANY	ENERTECH CORP. LARSEN, VT
SCALE	1:4
DESIGNER	ISK ASSOCIATES
DATE	5/28/80 DSK-00-002

Figure 1
Schematic of Enertech 15 kW Design

2. SCHEDULE SUMMARY

This section presents a summary of the major events that occurred during Phase II. Beginning at the end of Phase I with a completed 15 kW design, four major activities were completed (Figure 2).

With the completion of Phase I in October 1980, authorization was received to commence Phase II fabrication. Fabrication was completed in February 1981 and the unit was installed at Enertech's Norwich, VT test site. The unit ran approximately one month before experiencing a gearbox casting failure. At that time the system was removed from the tower. In June 1981, the unit was reinstalled with a different gearbox. The unit was tested throughout the summer until a second gearbox failure removed it from operation in October 1981. The first gearbox was rebuilt by the manufacturer and refitted to the machine, which was then shipped to Rocky Flats in December 1981. Rocky Flats installed the machine for testing in February 1982.

Figure 2
Summary of Milestones in Phase II

	1980			1981								1982						
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
1. Hardware Fabrication	_____																	
2. Norwich Testing					_____					_____								
3. Shipment to Rocky Flats																Δ		
4. Installation at Rocky Flats																Δ		

3. FABRICATION AND ASSEMBLY

Major components of the Enertech 15 kW, including the nacelle, blades, tower, and drive train, were fabricated by outside vendors. The remaining parts were completed at Enertech's Norwich, VT prototype shop. The mainframe is a structural steel weldment (see Figure 3a). Gusseted "ears" or shelves provide a gearbox mounting surface and welded internal stiffeners provide protection against channel buckling (Figure 3b). A mainframe extension allows provision for the nacelle mounting (Figure 3c). The mainframe is bolted to a turntable yaw bearing (Figure 4) through holes which are drilled and tapped in the mainframe underside. The yaw bearing is a turntable-type and the inner race is bolted to the mainframe. The outer race is bolted to a leveling plate.

The leveling plate provides tower interface by means of three studs which bolt through the leveling plate and tower top. The leveling plate is ground flat and so is a spacer plate that is "sandwiched" between the bearing and mainframe (Figure 4). This ensures a flat bearing mounting surface. A fabricated sheet metal cover protects the bearing from water entrapment. Leveling adjusters are positioned between the leveling plate and tower top (Figure 5).

The hub assembly is bolted together by means of sixteen 5/8-inch bolts which hold each leg to the central hub. The bolt holes in the legs are actually slots which effect as much as 3 degrees pitch variation (Figure 6a). The center hub is held to the gearbox shaft by a tapered bushing (Figure 6b). As the bushing is drawn into the tapered hub, more pressure is exerted on the gearbox shaft. A safety retaining washer and bolt further serve to prevent the rotor from coming off the shaft (Figure 6b). Figure 6c shows the blade hole pattern and also the angle bracket which allows spinner attachment to the hub.

The generator is bolted directly to the gearbox after the gearbox is bolted to the mainframe (Figure 7a). A flexible coupling links the gearbox and generator shafts (Figure 7b). The generator is wired down through the mainframe to slip rings which are mounted in the center of the yaw axis below the machine (Figure 7c). The slip ring shaft and yaw potentiometer are shown in Figure 7d. The hydraulic brake bolts directly to the generator "C" face and mounts through a flexible coupling to the generator shaft (Figure 8).

The tower was installed utilizing only hand equipment (winches and gin poles). Figures 9a through 9c show the sequential installation procedure. An "I"-beam mounting system (Figure 9d) was used at the base to allow testing of both 60-ft and 80-ft towers. Unit installation on the tower was accomplished through the use of a crane. The unit was mounted on a flatbed truck and the blades and tip brakes were installed on the ground (Figures 10a through 10c). The unit needed to be lifted 11 feet off the ground before the third blade could be installed.

Figure 3a
Mainframe Weldment

Figure 3b
Mainframe Weldment Stiffeners

Figure 3c
Mainframe Nacelle Mounting Extension

Figure 4
Turntable Yaw Bearing Assembly

Figure 5
Leveling Adjustment

Figure 6a
Blade Pitch Adjustment

Figure 6b
Hub Tapered Bushing

Figure 6c
Spinner Mounting Bracket and Hole Pattern for Mounting Blade on Hub

Figure 7a
Mounted Generator

Figure 7b
Gearbox to Generator Coupling

Figure 7c
Electrical Slip Ring Assembly

Figure 7d
Yaw Potentiometer Mounting

Figure 8
Mounted Brake Assembly

Figure 9a
Installing Tower Cross Braces

Figure 9b
Gin Pole for Raising Tower Components

Figure 9c
Assembled Tower

Figure 9d
"I"-Beam Tower Base

Figure 10a
Unit Without Blades

Figure 10b
Tip Brake Installation

Figure 10c
Crane Preparing to Lift Assembled Unit

4. COMPONENT TEST PROGRAM

Several component tests, conducted during Phase II to verify analytical results, are summarized in this section.

4.1 BLADES

The blades were subjected to two tests--both to verify strength. The first test consisted of a static load test. A design load was distributed over the length of the blade flatwise section on the upwind side. This was done by positioning twelve people along the blade at predetermined points (Figure 11a). The people had "weighed-in" previous to the test. The hub was fixed rigidly to a shaft placed in concrete and was wedged to prevent shaft deflection. A measuring arm was attached to the hub to reference the blade-end movement.

An 1,848-lb loading represents a 120-mph wind loading on the blade with no dynamic gust factor. Table I shows results of this test while Figure 12 is a plot of the results. As can be interpreted from the results, the blade is very rigid. After applying a 1.5-to-1 dynamic gust factor, results suggest that the blade tip will deflect 11.8 in. under real conditions. This agrees very well with the originally calculated deflection of 13.2 in. and indicates the blades are in no danger of tower contact at the design survival wind speed.

The second blade test was a fatigue test conducted at Ft. Eustis, VA. In this test a blade section was subjected to repeated load reversal to test endurance strength. A special 18-ft-long blade was constructed by Gougeon Brothers, Bay City, Michigan, with a special end fitting to allow adaptation to the Ft. Eustis test device (Figures 13a, 13b, and 13c). The blade was mounted to a bed plate (Figure 13d) and activated by a power cylinder (Figure 13e). The blade was subjected to a point loading at the

18-ft length varying from 1,500 lb to 2,500 lb in 500-lb increments. The blade survived over 2×10^6 cycles at its design survival load. This is equivalent to a machine surviving over two million 120-mph gusts. Results of the test are summarized in Table II.

Figure 11a
Simulated Blade Deflection Test

Figure 11b
Measuring Blade Deflection

Figure 12
Plot of Blade Deflection Test Results

TABLE I
BLADE DEFLECTION TEST RESULTS

<u>% of 120 mph Design Load</u>	<u>Deflection at Tip (in.)</u>	<u>Load (lb)</u>	<u>Moment at Blade Root (ft-lb)</u>
30	2.0	545	6,002
40	3.1	774	8,413
50	3.8	961	10,320
60	4.5	1,154	12,420
80	6.2	1,535	16,590
100	7.6	1,848	20,530

Figure 13a
Blade Fatigue Test Specimen

Figure 13b
Blade Fatigue Test Specimen

Figure 13c
Blade Fatigue Test Specimen Tip

Figure 13d
Blade Fatigue Test Specimen Root Mounting Fixture

Figure 13e
Blade Actuator

TABLE II
BLADE FATIGUE TEST

<u>Loading at 18 ft Length</u>	<u>Moment at Blade Root (ft-lb)</u>	<u>Equivalent Wind Loading (mph)*</u>	<u>Test Results</u>
1,500 lb	27,000	122	Withstood 10^6 cycles
2,000 lb	36,000	140	Hub failed at 800,000 cycles. New hub allowed completion of 10^6 cycles
2,500 lb	45,000	157	Stud failure after 2,000 cycles

* Assumes 1.8 drag coefficient with no dynamic gust factor.

4.2 HUB

Due to limited test equipment, testing of the hubs was coincident with the blade tests. Such tests were only for the hub arms, not the center hub. However, the first arm failed at $1/8 \times 10^6$ cycles, or above its design survival load. This, like the blade test, represents a very stringent test.

Additionally, the hub sections were completely x-rayed. Although some small shrinkages were noted in the hub legs, nothing of a magnitude to affect structural integrity was noted.

4.3 GENERATORS

Generators were tested on an engine dynamometer (Figure 14). The dynamometer was used to measure maximum output and efficiencies at all operating outputs. In addition, loaded rotor torque and inrush current were recorded. Results of these tests appear in Tables III through V.

4.4 BRAKE

Brake testing included engine dynamometer mounting to set the braking torque and check braking smoothness and duration. Further testing was done by mounting the brake on a generator and then motoring the generator to check unit temperature and noise characteristics when the brake was applied. Figure 15 shows the brake as mounted for testing.

The pump was set to develop a torque of 150 ft-lb at 1,870 rpm, which represents a unit shutting down under high wind speed conditions at full load. The pressure relief valve setting at that torque is 2,250 psi.

After the test, the brake was connected to a generator that was motored, as it would be during normal running, to test noise and heat

generation characteristics. Operating temperature was approximately 160-170°F and the pump exhibited classic gear pump noise--but not enough to be objectionable when mounted on the tower. In addition, the pump was cycled on and off several times to check for sticking solenoid valves.

4.5 GEARBOX

Due to the lack of a dynamometer facility capable of driving the gearbox as a speed increaser, the gearbox was not load tested. It was disassembled, however, to view general construction and assembly techniques. Several areas of concern were noted and steps were taken to remedy the problems:

- 1) The presence of molding sand in the sump area. This was relayed to the manufacturer and the system flushed to remove all sand particles.
- 2) Bolts holding the internal bearing register to the main casting were safety wired and Loctite was applied to prevent the possibility of their loosening.
- 3) The bolts holding the low-speed shaft external bearing were thought to be too short and replaced with longer bolts to achieve more thread to housing contact.
- 4) The counter shaft double keys were replaced with hardened keys and Loctite applied to the gear-retaining washer and bolt.
- 5) The unit was filled with synthetic lubricant to allow all weather operation.

4.6 MAINFRAME

No mainframe testing was conducted with the exception of a welding inspection. No welding discrepancies were found.

4.7 NACELLE

The nacelle was tested to determine whether its natural frequencies corresponded to any machine running frequencies. This was accomplished by attaching a direct current motor to the unit mainframe and rotating an imbalance attached to the motor shaft. By varying the speed of the motor, it was determined at which speed the nacelle was "tuning" to the input speed. The nacelle showed a tendency to shake at approximately 900 rpm--well out of unit operating range.

4.8 TOWER

As with the nacelle, the tower was tested to determine its natural frequencies and verify analytical calculations relative to its vibrational characteristics. The dc motor shaking device was mounted at two different places on the tower: first, at the top to generate the first tower bending mode and second, at approximately two-thirds the tower height to check the second bending mode.

The shaking device is shown mounted to the tower in Figure 16. The device was operated by means of batteries connected to the shaker via the regular wind system power leads. Results of tower vibration tests appear in Table VI. The tower with the machine mounted was never actually tested due to time constraints, but estimated results are given in Table VI. The tower's natural frequencies did not coincide with either 1-per-revolution (52 rpm) or 3-per-revolution (156 rpm). The first mode of the tower corresponds closely to a 2-per-revolution condition, but because a three-bladed machine has never been known to exhibit a 2-per-revolution forcing function, this was not judged significant. This assumption was later verified during actual operation.

Figure 14
Engine Dynamometer, Generator, and Brake Testing Facility

TABLE III
GOULD ONE-PHASE GENERATOR PERFORMANCE DATA

Power Output (kW)	Torque (ft-lb)	RPM	Power Input (kW)	Volts	Amps	Power Factor	Efficiency
3.5	16.4	1,810	4.21	230	15.4	.99	.83
5.0	23.0	1,813	5.92	230	22.0	.99	.84
10.0	44.2	1,826	11.46	230	44.5	.98	.87
20.0	99.8	1,861	26.38	230	101.0	.86	.76
22.4	119.0	1,881	31.79	230	124.0	.79	.70

NOTES: 80 mfd run capacitance.
Wired for opposite direction of rotation.
Data taken after heat run.
Tests performed by Gould, July 1980.

TABLE IV
GOULD ONE-PHASE GENERATOR PERFORMANCE DATA

Power Output (kW)	Torque (ft-lb)	RPM	Power Input (kW)	Volts	Amps	Power Factor	Efficiency
3.5	20.8	1,809	5.34	230	27.5	.55	.65
5.0	26.6	1,812	6.84	230	31.0	.65	.73
10.0	45.8	1,823	11.90	230	44.8	.99	.84
15.0	66.2	1,833	17.30	230	66.0	1.00	.86
20.0	89.0	1,850	23.30	230	88.8	.98	.85
25.6	125.0	1,879	33.30	230	130.0	.86	.77

NOTES: 100 mfd run capacitance.
Wired for opposite direction of rotation.
Data taken after heat run.
Heat run indicated 18 kW continuous rating (Class B insulation).
Tests performed by Gould, July 1980.

TABLE V
GOULD THREE-PHASE GENERATOR PERFORMANCE DATA

Power Output (kW)	Torque (ft-lb)	RPM	Power Input (kW)	Volts	Amps	Power Factor	Efficiency
0.0	0.8	1,800	0.20	230	8.8	.00	.00
4.175	18.0	1,810	4.63	230	14.8	.71	.90
7.815	32.8	1,820	8.48	230	23.5	.81	.92
12.015	50.0	1,830	13.00	230	35.0	.87	.92
14.715	62.0	1,840	16.20	230	43.0	.86	.91
17.615	75.0	1,850	19.70	230	52.0	.85	.89
19.615	84.2	1,860	22.20	230	58.0	.85	.88
21.615	93.6	1,870	24.80	230	64.0	.84	.87
32.015	151.0	1,942	41.66	230	108.0	.74	.77

NOTES: Data taken after heat run.
Heat run indicated 20 kW continuous rating (Class B insulation).
Tests performed by Gould, July 1980.

Figure 15
Brake Assembly Mounted for Testing

Figure 16
Tower Vibration Instrumentation

TABLE VI
TOWER VIBRATION TEST RESULTS

Measured Tower Natural Frequencies

<u>Mode</u>	<u>Less Machine</u>	<u>Estimated With Machine</u>
First Mode	161 rpm	90 rpm
Second Mode	527 rpm	353 rpm
Torsional Mode	425 rpm	--

Calculated Tower Natural Frequencies

<u>Mode</u>	<u>Less Machine</u>	<u>Estimated With Machine</u>
First Mode	175 rpm	98 rpm
Second Mode	753 rpm	504 rpm

5. MANUFACTURER'S PROTOTYPE TEST PROGRAM

5.1 OUTPUT

Throughout the system test period, power output versus wind speed was recorded on a strip chart recorder. Figure 17 shows a power output curve for the unit. As illustrated by the curve, the unit easily attains 15 kW at 9 m/s (20.1 mph). This was a major design criterion. The unit actually attained 15 kW output at 7.6 m/s (17 mph). In addition, cut-in was found to be between 3.1-3.6 m/s (7-8 mph), which suggests low drive train friction.

Figure 17
Manufacturer's System Power Output vs. Wind Speed

5.2 YAW RESPONSE

The unit was observed for yaw response and smoothness immediately after it was put into operation. This test was heavily subjective, but all those observing were impressed with both the responsiveness and smoothness of yaw. Observation suggests a maximum yaw rate of 30° per second. Several attempts were made to stabilize the rotor upwind by manually starting the motor when the unit was in the wrong direction. However, the nacelle immediately oriented normally as soon as the rotor attained approximately 20 rpm. It was concluded that the combination of mainframe length and coning angle gives satisfactory yaw characteristics. A yaw potentiometer was connected to the mainframe for recording yaw rate data at Rocky Flats.

5.3 VIBRATION MONITORING

Because no noticeable vibration could be manually detected in the tower nor seen in the unit, vibration monitoring was not conducted during the test period.

5.4 FREEWHEELING CHARACTERISTICS

Freewheeling characteristics of the rotor are important because they determine the duration of motoring startup needed to bring the rotor up to the speed at which the wind will keep the rotor freewheeling. If the motoring startup period is too short, the rotor speed will decay and the startup will be aborted. For this test, different motoring startup periods were used to bring the rotor up to speed at various wind speeds before the rotor was allowed to freewheel. A 10-second motoring startup period appeared to be adequate to accomplish a successful startup, provided normal startup wind speeds are attained.

In a sustained wind speed of 1.3-2.2 m/s (3-5 mph), the rotor would continue to freewheel slowly. At wind speeds over 3.4 m/s (12 mph), the rotor speed would increase very quickly once the rotor reached 20 rpm. Accelerations of 6-7 rpm per second were observed in these conditions. Thus, the rotor was shown to be quite responsive to sudden wind gusts.

5.5 CYCLING DATA

During testing, start cycles, run cycles, and brake cycles were recorded. These data were used to determine cut-in wind speed, cut-out wind speed, and the duration of the starting cycle. It was found that a 4.9 m/s (11 mph) startup and a 3.6 m/s (8 mph) low wind speed cut-out provided satisfactory operating characteristics with less than 1 percent aborted startups.

5.6 TIP BRAKE EFFECTIVENESS

The tip brakes were tested to ensure their ability to deploy. This was done on a day when winds were relatively steady and averaging between 4.5-6.7 m/s (10-15 mph). The brake was switched off manually and the rotor was allowed to freewheel up to speed without loading the generator. The goal was to have the tip brakes deploy at 72-75 rpm, which represents an approximate 50 percent overspeed condition.

The initial test showed no deployment even up to a rotor speed of 100 rpm. The spring tension of the tip brake was adjusted down from 21 lb to 16 lb. A single deployment was then achieved at 57 rpm, but this setting was too close to operating speed. At this point the spring tension was reset to 18 lb which yielded a 72 rpm deployment of all tip brakes. This was the final tip brake setting.

5.7 CONTROL SYSTEM TESTING AND TUNING

Throughout the testing period, the control system was altered to achieve better operating characteristics and greater reliability. Changes made during testing and incorporated on the control system sent to Rocky Flats, include:

- 1) Mercury Contactors - Solenoid-actuated contactors were used originally but found to be noisy. These were replaced by mercury-type contactors which were found to be quieter.
- 2) Limited Freewheeling Characteristic - The original control system was designed to freewheel up to speed and cut in at a generator speed of 1,800 rpm. With the analog electronics used, it was found that this set point would vary with temperature and time, and cause a cycling on-off condition of the system. This system was thus abandoned and a rpm/wind-based system was used. When a cut-in wind speed is achieved, the unit receives motoring current for ten seconds. It is then allowed to freewheel up to a noncritical motor speed (1,750 rpm) at which point it was connected to the line. When the wind decays, the unit is disconnected from the line and the brake applied.

5.8 BLADE PITCH OPTIMIZATION

The blade hubs were slotted to allow a blade tip pitch variation of 3-1/2 degrees. The design setting was zero degrees and the unit was operated in this condition for the duration of the test program. The power curve presented in this report is applicable to the 0° setting, which is referenced to the flat bottom blade tip. This pitch was found adequate to meet the design criteria output. Table VII shows the estimated changes in blade pitch necessary to maintain a peak output of 25 kW at various altitudes.

TABLE VII

BLADE PITCH SETTINGS

<u>Blade Pitch*</u> <u>to Allow</u> <u>25 kW Output</u> <u>(Degrees)</u>	<u>Altitude</u> <u>Above</u> <u>Sea Level</u> <u>(ft)</u>
-1-1/2	0-2,500
-1	2,500-5,000
-1/2	5,000-7,500
0	7,500-12,000

* Referenced to the blade tip flat bottom with respect to the rotor plane.

5.9 SYSTEM NATURAL FREQUENCY

Because of time constraints, the unit was not tested on a 60-ft tower at Enertech. However, vibration calculations, verified by actual data on the 80-ft tower, indicated the 60-ft tower and unit would be completely adequate from a vibrational standpoint.

6. MANUFACTURER'S TEST SUMMARY

Unfortunately, much of the test period was consumed in resolving two gearbox failures, neither of which was unique to wind system applications. The first gearbox experienced a casting failure as a result of insufficient rating and a control system malfunction. Due to excessive control system drift, the unit was connected to the utility line at a relatively high generator speed (1,900 rpm+) which put excessive loading on the gearbox. The countershaft retaining casting fractured due to excessive shaft thrust (Figure 18). This caused rotor overspeed and deployment of the tip brakes which caused the unit to slow.

The unit was subsequently rebuilt into a three-stage (previously two-stage) increaser which increased the unit rating from 32 hp to 43 hp. In addition, the helical gearing was turned around to force countershaft thrust forward into the main gearbox housing and away from the previously failed flange. This rebuilt gearbox was shipped to Rocky Flats on the Enertech 15 kW prototype.

While this gearbox was being rebuilt, a second increaser was installed on the unit. This increaser was of circulate design (Figure 19). The unit proved to be extremely noisy and caused severe tower vibration. The unit bound up after only 27 hours running time. The gearbox was then shipped to the manufacturer where an incorrectly installed bearing was found bound against an internal rotating part. Because of the gearbox's excessive noise, its use on the prototype was not pursued.

Figure 18
Failed Gearbox Casting

Figure 19
Circulute Gearbox

7. MACHINE DESIGN MODIFICATIONS DURING MANUFACTURER TESTING

During unit testing at Enertech, the following design modifications were performed:

- 1) Yaw Lock Modification - The yaw lock location was changed and yaw lock pin diameter increased from 1/2 in. to 1 in. During testing, the original yaw lock was severely distorted while the unit was locked in yaw, due to winds buffeting the machine. As a result, the mechanism was moved out further from the center of yaw and a one-inch-diameter pin of drill rod material was applied, including a pin which slides through a holder mounted on the unit mainframe into the yaw bearing mounting plate. Three locked unit positions are possible.
- 2) Control system modifications were made as described in Section 5.
- 3) Tip Brake Size Modifications - After field testing showed a possible peak output in excess of 20 kW, the tip brake end plates were resized to provide more drag when deployed. Total tip brake area was increased 50 percent. In addition, brake shape was changed to trapezoidal (from semicircular ends) for ease of manufacture. These larger tip brake end plates were provided to Rocky Flats subsequent to prototype shipment.
- 4) Generator Modifications - When prototype testing revealed an output in excess of 20 kW, it became obvious that the original generator did not have adequate capacity. A larger generator (25-kW continuous capacity) was specified and supplied to Rocky Flats after prototype delivery. Generator frame size was increased to 324 TC¹ from 286 TC. This change necessitated the manufacture of an adapter ring to allow generator to gearbox interface.
- 5) Tip Brake Adjustments - As was explained in Section 5, the final tip brake spring tension was set at 18 lb. Originally the prescribed tension had been calculated to be 21 lb.
- 6) Tapered Bushing Modifications - The tapered bushing which retains the hub to the gearbox shaft warped after a longitudinal saw cut was made in it. This made the bushing difficult to slide on or off the gearbox shaft. To correct this problem, holes were

¹ T = style of generator frame; C = face.

drilled and tapped in each end of the tapered bushing at the saw cut. The holes are tapped 1/4-inch, National Pipe Thread (NPT). This tapered thread allows the installation of pipe plugs which, when screwed into the bushing, expand the inside diameter to allow installation or removal of the bushing from the gearbox shaft.

- 7) Blade to Hub Adapter Modifications - Subsequent to shipment to Rocky Flats, the blade adapter hubs were modified to strengthen that area of the rotor. The casting supplier was changed, cores were removed from the adapter (making them solid pieces) and the flange which fits to the center hub was thickened. All these steps dramatically increased rotor hub strength. Also, studs were embedded in the center hub to interface with the adapter nylon locking nuts providing adapter hold down. Previously, socket head cap screws were used which required more adapter machining to provide bolt clearance.
- 8) Brake - The original hydraulic brake supplied with the unit proved to be of inadequate torque to stop the unit under high wind speed shutdown conditions. After the prototype was shipped to Rocky Flats, a multiple disk electric brake was perfected which provided adequate stopping torque under all conditions. The brake is a multiple disk, dry, spring-applied, electrically released unit which incorporates an air dashpot to prevent torque peaks during application.

8. PRELIMINARY ROCKY FLATS TEST DATA

Preliminary testing of the Enertech prototype at the DOE Rocky Flats Test Center produced the results shown in Figures 20 through 23. These data represent parts of two days of running time and are considered preliminary. Data points from 3/19/82 and 3/23/82 were combined to form the plots shown. Figure 20 represents data that were adjusted to sea level.

Data show a higher peak output than was obtained at Enertech's test facility, but shows considerably lower outputs at wind speeds from 10 to 25 mph. No attempt will be made to reconcile these differences due to the very limited amount of data points obtained at both sites. Future testing at Rocky Flats, along with availability of the Enertech production version of the 15 kW, will resolve this issue.

Figure 20
Preliminary Rocky Flats Performance Data
(Adjusted Power vs. Wind Speed)

Figure 21
Preliminary Rocky Flats Performance Data
(Unadjusted Power vs. Wind Speed)

Figure 22
Preliminary Rocky Flats Performance Data
(Coefficient of Performance vs. Wind Speed)

Figure 23
Preliminary Rocky Flats Performance Data
(Wind Distribution vs. Wind Speed)

9. CONCLUSIONS

Various results obtained during Phase II have proven the application of the Enertech concept to a 44-ft-diameter wind turbine. The 15 kW system proved to have stable yaw characteristics and higher than expected power output. In addition, a control system was developed which allows motorized startup based upon wind speed/rpm logic. The use of free yaw and fixed-pitch blades have presented opportunities for significant cost reductions based on quantity production. Testing at Rocky Flats will provide additional data for overall system evaluation.

10. REFERENCES

1. Enertech Corporation, Enertech 15 kW Wind System Development, Phase I - Design and Analysis, September 1981, Volume I - Executive Summary (RFP-3341/1); Volume II - Technical Report (RFP-3341/2). (Available from NTIS.)

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