January 2000 • NREL/SR-500-26926

Subcontractor Report

NWTC AWT-26 Research and Retrofit Project — Summary of AWT-26/27 Turbine Research and Development

October 1998

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National Renewable Energy Laboratory

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1. Introduction

1.1 Background

Development of Advanced Wind Turbine, Inc; AWT-26/27 wind turbines started in 1990, when R. Lynette & Associates (RLA) was awarded the first of a series of contracts to develop an advanced wind turbine in cooperation with the National Renewable Energy Laboratory (NREL). In 1992, after initial testing of the first prototype showed promising results, Advanced Wind Turbine Incorporated (AWT) was formed to produce and market the turbine. At that time, FloWind Corporation made an investment in AWT and became a 30% owner. Simultaneously, RLA agreed to transfer all of the turbine related technology to AWT in return for continuing development support and royalty payments to be made upon the sale of turbines. In 1994, FloWind and AWT signed agreements under which FloWind would acquire 81% of AWT.

Three 26-meter (AWT-26) prototypes were designed, manufactured, and installed: two in Tehachapi, CA, and one at NREL's National Wind Technology Center (NWTC) in Boulder, CO. In August, 1995, a prototype 27-meter turbine (AWT-27) was installed in Tehachapi. All three of the Tehachapi prototypes were used for extensive testing of power performance, loads, dynamics, and noise.

In late 1994, AWT received an order and made commitments for 222 AWT-27 turbines to be delivered to India in 1995 and 1996. In early 1996 problems with the wind turbine market in India limited the number of turbines actually delivered to India to about ninety. This development, combined with rapid advancements in competitors' turbines, made selling the AWT-26/27 turbine increasingly difficult. These problems, along with other factors, contributed to FloWind filing bankruptcy under Chapter 11 of the Federal Bankruptcy Act in mid-1997. Subsequently, a major sale of AWT turbines to the Bonneville Power Administration fell through, attempts to sell turbines to China were unsuccessful and creditors forced the auction of AWT's inventory. AWT was closed in 1998. Several of the key technical personnel from AWT formed Kamzin Technology Inc., to provide technical support to the wind energy industry and AWT users.

1.2 Purpose

This report has several principle purposes:

1. Summarize the present status and development history of the AWT turbine design.
2. Summarize problem areas in the design and the status of problem resolution activities.
3. Summarize the activities required to commercialize the design.
4. Provide a ready reference for persons interested in AWT design or technology.

1.3 Scope

This document summarizes the AWT design, the testing and modeling completed on the design, the operating history of AWT turbines, and the additional work required to commercialize the design. References are used extensively. Additional details concerning each area of this report can be found in the references.

2. Turbine Description

2.1 General

The general descriptions in this section cover 50 and 60 Hz models of the AWT-26 and AWT-27 wind turbines. Where turbine characteristics differ between models, a range of values is presented. Configuration parameters for the 60 Hz AWT-27 are provided in Table 2-1. Specific values for other models are available in Ref. 1.

The AWT-26/27 is a utility-grade wind turbine designed for multi-unit power stations. It is a downwind-oriented, two-bladed machine that uses passive-aerodynamic stall control to limit its peak power. Correct orientation to the wind does not require an active yaw drive; however, a yaw mechanism is provided that is capable of changing the turbine's orientation to unwind the droop cable when the turbine is not operating, and for maintenance purposes. The AWT-26/27 turbines have been installed on both lattice and guyed-tube style towers, as shown in Figure 2-1. Figure 2-2 illustrates the major turbine components.

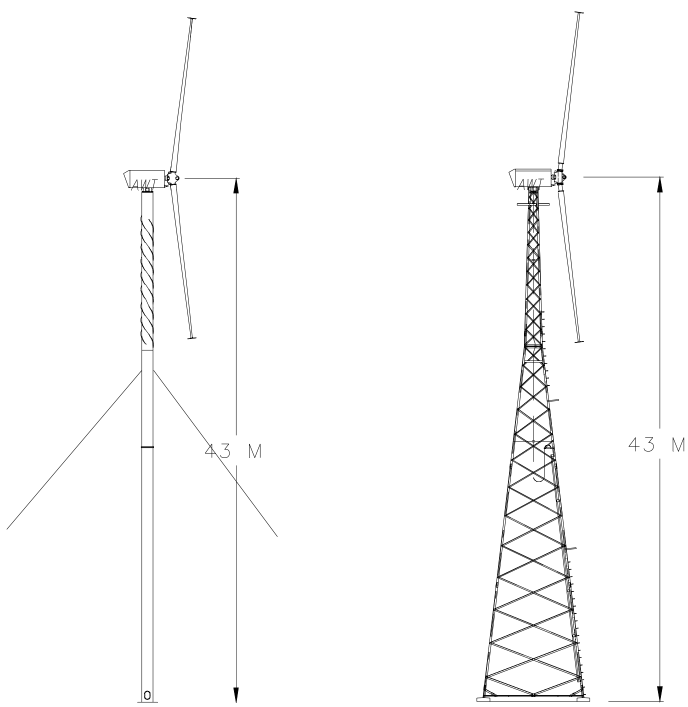

Figure 2-1. Typical AWT-26/27 turbine configurations.

The 26/27 meter diameter rotor rotates at a nominal speed of 57.1/53.0 rpm. It consists of two blades, aerodynamic tip brakes, and a rotor hub that keeps the blades fixed in pitch, but free to teeter about an axis perpendicular to the axis of rotation.

The rotor is attached to the low speed shaft of the integrated gearbox, which mechanically links the rotor to the 400/480 volt induction generator turning at a nominal speed of 1,500/1,800 rpm. The generator speed is regulated by the 50/60 Hz utility power frequency. The rotor speed increases only slightly with increasing wind speed. Increasing power output is primarily the result of increased rotor torque. Peak nominal power output under standard sea level conditions is 275-300 kW.

Start-up is accomplished by using the generator as a motor (requires electric power) and stopping is achieved through a two-phase process, first using aerodynamic tip brakes and then applying mechanical brakes.

The braking system consists of two independent, magnetically held aerodynamic tip brakes and a high-speed-shaft disc brake with two spring-applied, hydraulically released calipers. The machine is controlled by an off-the-shelf programmable logic controller (PLC) that is located in a control house adjacent to the tower. The controller also provides performance and maintenance diagnostic information. The switch gear and controller for a number of machines may be contained in a single control house.

The nacelle assembly has a floor hatch for access and is enclosed by the nacelle cover, which can be opened to allow for maintenance activities. A manual yaw-lock device allows the nacelle to be locked in position for maintenance.

Figure 2-2 shows a photograph of the AWT-27 installed in Tehachapi, California

Figure2-2. AWT-27 Installed in Tehachapi, California

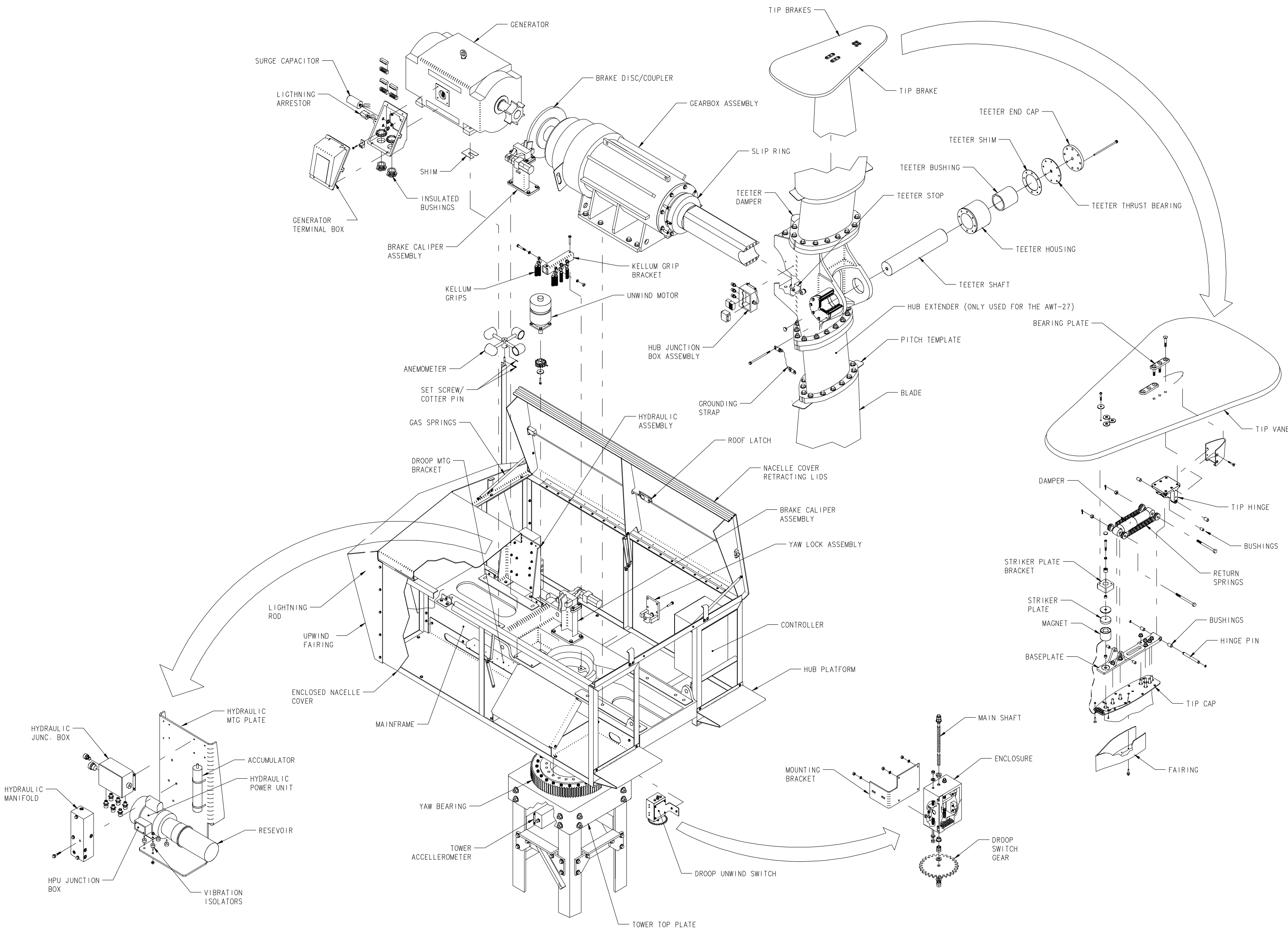

Figure 2-3. AWT-26/27 turbine assembly.

2.2 Major Subsystems / Components

The following sections describe the major system sub-assemblies. Detailed information for each component is contained in the AWT engineering drawings, Appendix A of Ref. 1.

2.2.1 Blades

The blades are made up of airfoil sections that use aerodynamic lift to convert the wind's momentum into forces that are used to generate electric power. During operation, they are fixed in pitch. The blade shape and twist are designed to provide a high energy conversion efficiency in a wide range of wind speeds, while limiting peak power with passive stall control.

Each AWT-26/27 blade is approximately 12.6 m (41 ft) long and weighs about 450 kg (990 lbs). When the rotor is assembled, the blades span 26.2/27.4 m (86/90 ft). The blades are lofted from NREL S815/S809/S810 thick-airfoil sections. A smooth gelcoat exterior covers a structural interior made up of layers of Douglas fir veneer sheets, epoxy, fiberglass, and carbon fiber tape. The hollow interior is sealed with a layer of fiberglass and epoxy resin.

The blades are bolted to a flange on the hub (or hub extender for AWT-27), as shown in Figure 2-2. The bolts go through slotted holes in the flange into threaded inserts in the blade root. The slotted hole pattern in the flange allows for adjusting the blade pitch setting. The pitch setting is controlled by the appropriate choice of pitch plates.

2.2.2 Blade Tip Brakes

There are aerodynamic brakes located at the tip of each blade. The tip brakes are attached to the blades by means of threaded studs embedded in the blade tip, as shown in Figure 2-2. The tip brakes provide aerodynamic rotor braking when deployed. Each tip brake is made up of eight basic parts: vane, hinge, fairing, magnet, spring, damper, baseplate, and striker plate.

The vane is composed of structural foam covered in carbon fiber, epoxy, and gelcoat. The hinge assembly allows the brake to move from the operating to the braking position. The fairing provides an aerodynamic cover for the hinge assembly. In the normal operating position, the magnet and spring hold the tip closed so that it slips through the air with minimal resistance as the rotor turns. The tip brake is activated when the electric current to the magnet is removed, causing the magnet to lose its holding power. If this occurs while the rotor is turning, the trailing edge of the tip brake moves outward due to the centrifugal force, and the leading edge drops inward, exposing the flat surface of the tip brake to the apparent wind direction, slowing down the rotor.

The mechanical brake can either be applied gradually after the tip brakes are applied (normal stop) or simultaneously with the tip brakes (fast stop). When the rotor has stopped, the spring slowly draws the tips to their normal operating position.

2.2.3 Teetering Hub Assembly

The AWT-27 hub assembly is shown in Figure 2-2. The assembly consists of a cast hub, hub extenders (AWT-27 only), a teeter shaft, two teeter housings, two teeter thrust bearings, two teeter housing caps, two teeter bushings, teeter shims (as required), two teeter dampers, and two teeter stops. The AWT-26 hub assembly is the same as the AWT-27 hub assembly without hub extenders.

The hub assembly provides the structure for mounting the blades to the main shaft. The flanges on the hub are angled to provide a downwind coning angle of 7° for the blades. Slotted bolt holes in the hub flanges allow the blade pitch to be adjusted. The hub is free to rotate around the teeter shaft until one of the teeter dampers begins to retard the teeter motion. The teeter motion is limited by contact of one of the teeter stops with the mainshaft.

2.2.4 Slip Ring and AC to DC Rectifier

A bearingless slip ring carries electric power from the nacelle to the rotor, energizing the electromagnets that hold the tip brakes closed during operation. It consists of four rings (two operational, two spares) attached to the low-speed shaft and two associated brush pairs mounted on the gearbox snout. A removable cover provides environmental protection and allows access for brush replacement.

Of the four rings, two carry the AC current required for the electromagnets (one "hot" and one "neutral"). The other two provide a spare circuit. Proximity switches mounted in the slip-ring cover detect rotor position and main-shaft rotation speed from a slotted aperture plate mounted inside the slip-ring assembly.

An AC to DC rectifier is located in a small junction box on the hub. It consists of a diode-rectifier bridge circuit that converts the AC electricity coming from the controller to DC electricity used to energize the electromagnets in the blade tips.

2.2.5 Gearbox

The AWT-26/27 gearbox consists of a central snout mounted directly to the turbine mainframe and a planetary gearbox mounted to a flange on the upwind side of the snout. The snout contains the main bearings, the main shaft, and an end cap securing the teeter shaft.

The planetary gearbox has two stages with a fixed gear ratio of between 25 and 35 to 1, depending on the rotor diameter and generator output frequency. An oil temperature sensor monitors the gearbox lubricant condition. A sight glass and a dipstick provide the means to verify the oil level when the rotor is not moving. Oil is added through the capped opening on top of the gearbox and removed from a spigot on the bottom. "Lifting eyes" are provided for removal and installation by crane.

2.2.6 Coupler / Brake Disk

The coupler/brake disc is on the upwind side of the gearbox. This single assembly contributes to both power transmission and mechanical braking. The coupling consists of an outer "sleeve" with an integral brake disc, an inner "hub" which is fixed to the generator input shaft, and several replaceable rubber elements. The two portions of the coupler are keyed together with the rubber elements to allow for slight misalignments and reduce shock loads on the generator. The brake disc provides the friction surface for the spring-applied brake calipers.

2.2.7 Generator

Depending on the frequency of utility power, the generator will rotate at either 1,500 or 1,800 rpm and convert mechanical power from the rotor and gearbox to 3 phase, 50 or 60 Hz AC electric power. It is an open drip-proof induction generator with Class H insulation. It is bolted and electrically grounded to the mainframe and connected to the gearbox by an elastomeric-element coupler. The droop cable is attached to the terminal block on the generator's side and transmits the electricity down the tower. Three temperature switches detect excessive operating temperatures and a heater prevents moisture damage. A lifting eye is provided for removal and installation.

2.2.8 Mainframe / Nacelle Cover Assembly

The mainframe/nacelle cover assembly is shown in Figure 2-2. The mainframe is a cast ductile-iron structure that provides a "backbone" on which to mount the turbine's drive train. The gearbox, brake calipers, and generator are all bolted to the mainframe, which in turn is connected to the tower by the yaw bearing. By this connection, the mainframe transfers thrust, yaw, and pitch forces and moments to the tower. Directly upwind of the yaw bearing, the droop unwind device provides a means to apply a yaw torque between the nacelle and the tower top. Power and control cables are routed down the tower through the center of the yaw bearing.

The nacelle cover assembly bolts to the side of the mainframe to provide an aesthetic and environmental cover for the mechanical components of the drive train, as well as a work platform from which to perform maintenance activities. Access to the nacelle cover is provided through floor hatches on either side of the tower. The roof of the nacelle cover opens with the assistance of gas springs, providing the necessary space in which to perform maintenance and repair activities. The mainframe control electronics are mounted in an electrical enclosure inside the nacelle cover.

2.2.9 Hydraulic System

The main components of the hydraulic system are a hydraulic power unit, a manifold, an accumulator, two mechanical brake calipers, and a cable unwind mechanism (yaw motor). The system has three main purposes: actuating the mechanical brake, turning the nacelle to unwind the electrical cables, and adjusting the turbine's yaw orientation when not in operation. Electronically controlled valves in the manifold control the braking and yaw functions.

The mechanical brake is located on the high-speed shaft and functions as a parking brake and overspeed protection. The mechanical brake is a fail-safe in that the brakes are spring-applied and hydraulically released. Solenoid control valves cause the brakes to be applied when they are de-energized.

The yaw system can only be actively engaged when the mechanical brake is applied. Fluid flow turns a hydraulic motor that is capable of yawing the turbine. During normal turbine operations, when the mechanical brake is released, hydraulic fluid is free to flow in either direction through the yaw motor and the turbine yaws freely. When the brake is applied, hydraulic fluid can turn the motor in either direction, or the flow can be blocked, fixing the turbine orientation. The yaw mechanism is used to unwind the droop cable or to align the turbine for maintenance purposes.

2.2.10 Tower

The AWT-26/27 can be made available with a number of different tower configurations. The 140-foot lattice and guyed-tube towers are shown in Figure 2-1. The tower supports the nacelle structure and is designed to withstand winds of up to 133 mph.

All lattice towers are equipped with a ladder or foot pegs, protective rings or a safety cable, and a tip work platform for providing access to the turbine for maintenance. Access below the mainframe is provided by a work platform. The tower lattice members are bolted together. The upper braces are round to minimize the tower wake effects.

2.2.11 Control System

The control system uses two Programmable Logic Controllers (PLC) that monitor the status of the wind turbine systems, log performance and reliability information, and direct-turbine functions by actuating specific relays and switches. The PLCs operate in a master-slave configuration. The master PLC is located in the switchboard control cabinet and the slave is located in the nacelle control cabinet. A high-speed, asynchronous serial-link cable running up the tower and through the yaw bearing provides a communication path between them.

There are two user interfaces to the control system. The primary interface is located on the external panel of the switchboard control cabinet. From there, the operator may review the turbine's current status and fault history, start and stop the wind turbine, and manually control specific turbine functions to assist with troubleshooting during maintenance. The switchboard control cabinet interface consists of the following features:

- Operator interface terminal (OIT)
- Lock-out relay switch and indicator lights
- Emergency stop button.

The secondary operator interface is located on the external panel of the nacelle control cabinet and provides only limited control features. From the nacelle control cabinet, the operator can read the high-speed shaft and low-speed shaft rotation rates, and stop the turbine in case of an emergency. The nacelle control cabinet interface consists of the following features:

- Rate/ratio indicator
- Emergency stop button.

2.2.12 Electrical Control and Lightning Protection System

The generator is protected from utility-line electrical faults by a microprocessor-controlled, three-phase protective relay. This relay is called the line protection relay (LP1) and is located in the switchboard. It provides the following protection for the generator:

- Loss of one or more phases
- Phase reversal
- Phase unbalance
- Phase shift
- Under voltage

- Over voltage
- Line under frequency
- Line over frequency.

The generator has over-temperature sensors in each winding and the turbine will shutdown if the stator windings begin to overheat. Additionally, the stator windings are fitted with heaters to reduce condensation during off-line periods.

The utility line is protected from the generator by two methods. The first is generator overcurrent. The main circuit breaker, in the switchboard, contains overcurrent trips and will disconnect the generator from the utility line if the generator current exceeds a preset value for a certain period of time. Another circuit breaker is located on the 480-volt line at the pad mount transformer. When it is tripped, it disconnects the entire system at the transformer.

The second method of protection is the ground fault relay in the switchboard. This device monitors the three-phase line currents to see that they are balanced. A short circuit will cause an unbalance of the line currents and a fast acting relay will trip the main circuit breaker.

The soft-start is provided with logic to cause the main circuit breaker to trip if one of the short circuit relays fails closed.

The utility line is bypassed with surge protectors and lightning arrestors at the service entrance in the switchboard and at the generator terminals. This protects the switchboard from surges and low-energy strikes and also similarly protects the generator windings. The 120-VAC control voltage for critical components is filtered and bypassed with protection for any power line abnormality. The switchboard and nacelle control circuits have individual protection. The system is grounded in such a way as to minimize lightning damage. However, there is no protection that can be provided for a direct strike of high-energy lightning.

2.3 Operating Modes

The manual and automatic operation of the AWT-26/27 is controlled by Programmable Logic Controllers mounted inside the switchboard and the nacelle control cabinet. The switchboard control cabinet is located in the control house at the base of the turbine's tower and the nacelle control cabinet is located inside the turbine's nacelle enclosure.

The AWT-26/27 has six operational modes:

1. Standby - The turbine is ready to operate. The rotor is stopped with brakes applied and the generator is not connected to utility power.

2. Startup - The turbine is starting. This is a transition state between Standby and Operate. The generator is connected to utility power via the soft-start contactors accelerating the rotor to full speed.

3. Operate - The turbine is operating. The rotor is turning at full speed and the generator is connected to utility power. All monitored conditions are within normal limits.

4. Shutdown - The turbine is stopping. This is a transition state leading to either Standby or Lock Out. The aerodynamic and mechanical brakes are applied and the generator disconnects from utility power as the rotor decelerates to a stop. Depending on conditions, a shutdown can be a normal stop, a fast stop, or an emergency stop.

5. Lock Out - A fault has occurred and the turbine cannot start until the Lock-Out relay is manually reset. The rotor is stopped and the generator is disconnected from utility power.

6. Manual - The Manual Mode permits manual operation of turbine subsystems for maintenance purposes.

2.4 Predicted and Measured Power Performance

The predicted and measured power curves for the AWT-26 and AWT-27 are shown in Figures 2-3 and 2-4, with annual energy production (AEP) calculations given in Table 2-1. The AWT-26 power curve was measured during an independently audited performance and reliability test conducted for the Bonneville Power Administration (Ref. 2). The AWT-27 power curve was measured by NREL personnel (Ref. 3), and agrees well with AWT's measurements (Ref. 4). Additional information regarding predicted and measured power curves for AWT turbines is available in References 5 and 6.

The predicted AWT-26 power curve (shown in Figure 2-3) was based entirely on calculations using the PROP93 design and analysis code. Measured drivetrain losses were used to adjust the PROP93 output from rotor to generator power. Inspection of Figure 2-3 shows that the predicted and measured AWT-26 power curve agrees very well at low-to-moderate wind speeds, with the power performance only slightly overpredicted below 9 m/s. The PROP93 calculations underpredict power levels in the turbine pre-stall, and overpredict power in the post-stall, but this is not surprising due to the known limitations of the analysis code. Because of a partial balancing of over and underpredicting, the variation between predicted and measured AEP is less than 1% (for an 8.5 m/s annual average wind speed).

The predicted AWT-27 power curve (shown in Figure 2-4) was based on both PROP93 calculations and on scaling of measured performance of AWT-26 prototypes (Ref.6). The predicted and measured curves therefore show better agreement in the near-stall region. However, at low-to-moderate wind speeds, the measured curve falls significantly short of the predicted curve, so that the AEP differential is 5.7%.

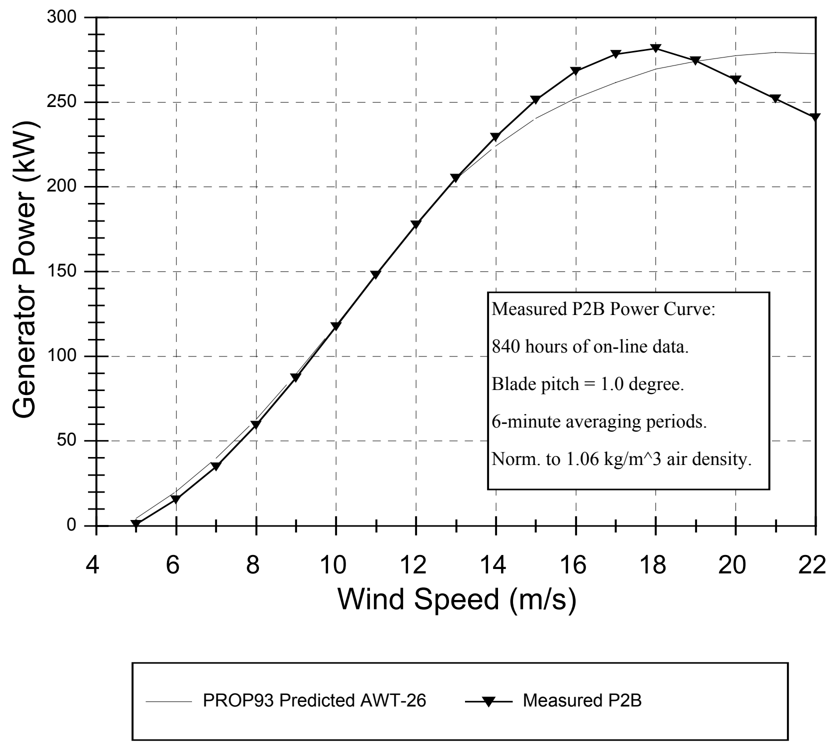

Figure 2-2. Predicted and measured AWT-26 power performance.

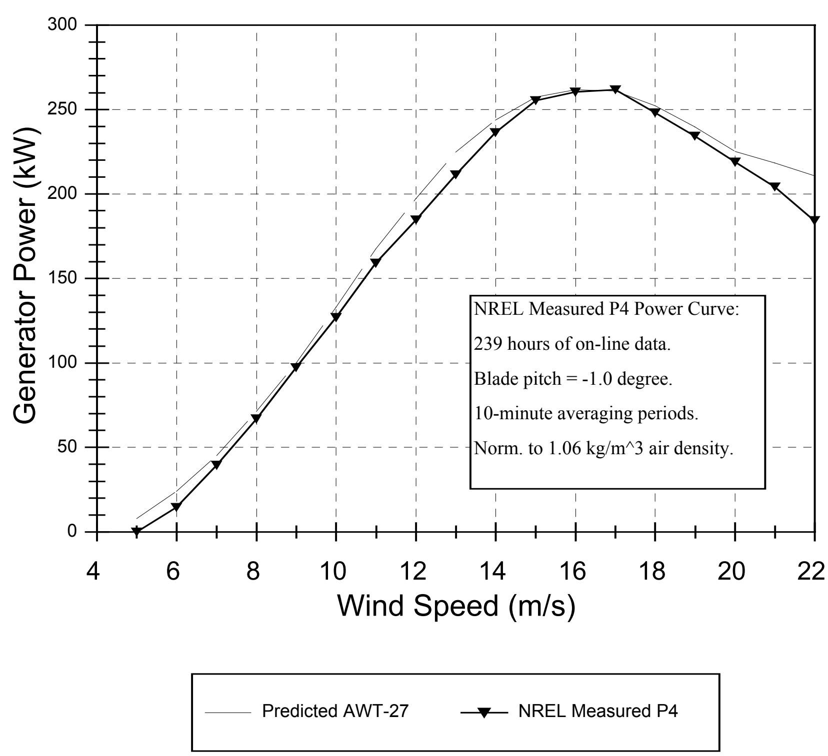

Figure 2-3. Predicted and measured AWT-27 power performance

Table 2-1. AEP Calculations for AWT-26/27 Turbines at 8.5 m/s Annual Average Wind Speed

Hub Wind Speed Bin Center (mph)	Number of Hours per Year in WS Bin	Measured P2B		PROP Predicted P2B		Measured P4		Predicted P4	
		Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)	Power (kW)	Energy (kWh)
5.0	724.0	1.1	789	4.6	3,348	0.0	0	8.0	5,756
6.0	771.0	15.6	12,007	20.3	15,680	14.5	11,201	24.2	18,671
7.0	781.2	35.1	27,385	39.9	31,171	39.5	30,853	45.2	35,338
8.0	758.7	59.4	45,099	62.8	47,643	67.0	50,860	71.4	54,164
9.0	709.8	87.4	62,005	89.5	63,528	97.2	69,009	100.0	70,982
10.0	641.7	117.8	75,612	118.7	76,195	126.9	81,469	133.2	85,470
11.0	562.1	148.2	83,291	147.9	83,147	159.2	89,474	167.5	94,135
12.0	477.8	177.8	84,949	178.2	85,137	184.8	88,301	197.5	94,351
13.0	394.6	205.2	80,966	204.7	80,773	211.6	83,498	224.9	88,746
14.0	317.1	229.5	72,768	224.2	71,082	236.5	75,003	243.8	77,312
15.0	248.0	251.3	62,326	240.4	59,633	255.5	63,362	257.6	63,879
16.0	189.0	268.5	50,744	252.5	47,718	260.4	49,213	261.8	49,475
17.0	140.4	278.4	39,077	261.9	36,759	261.9	36,759	261.2	36,660
18.0	101.7	281.7	28,637	269.7	27,417	248.3	25,246	252.3	25,656
19.0	71.8	274.5	19,718	274.3	19,705	234.3	16,835	239.8	17,229
20.0	49.5	263.3	13,041	277.6	13,752	219.1	10,852	225.4	11,164
21.0	33.3	252.1	8,404	279.5	9,316	204.3	6,810	218.4	7,282
22.0	21.9	240.9	5,277	278.9	6,109	184.2	4,035	210.8	4,618
	AEP Total	(kWh):	772,096		778,113		792,780		840,888

Note: Power normalized to Tehachapi air density (1.06 kg/m^3).

3. Innovative and Unique System Attributes

Since its inception, AWT has believed that simple, highly reliable wind turbines will provide the lowest cost of energy, and thus, be the most economically competitive. This philosophy resulted in development of the AWT-26/27 turbine architecture, which avoids the cost and maintenance associated with variable pitch, variable speed or active yaw systems, and is very competitive in terms of energy production per unit of swept-rotor area. The AWT architecture is also relatively light, reducing the costs associated with transporting and installing large turbines. This is a significant issue in developing countries where the transportation systems and crane capability are not as sophisticated as in more developed countries. Specific system attributes that lead to increased simplicity and decreased cost and weight are:

- Two-bladed rotor operating at relatively high tip speed reduces blade costs and torque/cost in drive train.
- Fixed pitch blades, with passive-stall power control, eliminates need for pitch system.
- Lightweight-tip vanes for aerodynamic braking.
- Wood epoxy rotor blades, using advanced NREL S-Series airfoils, lightweight, reduced system cost.
- Downwind, free-yaw operation reduces size of yaw drive and eliminates yaw brake.
- Teetered hub to reduce bending loads transmitted to low-speed shaft and mainframe.

Figure 3-1, extracted from Reference 7, shows that the AWT tower top weight is at the low end of the range compared to similarly sized turbines.

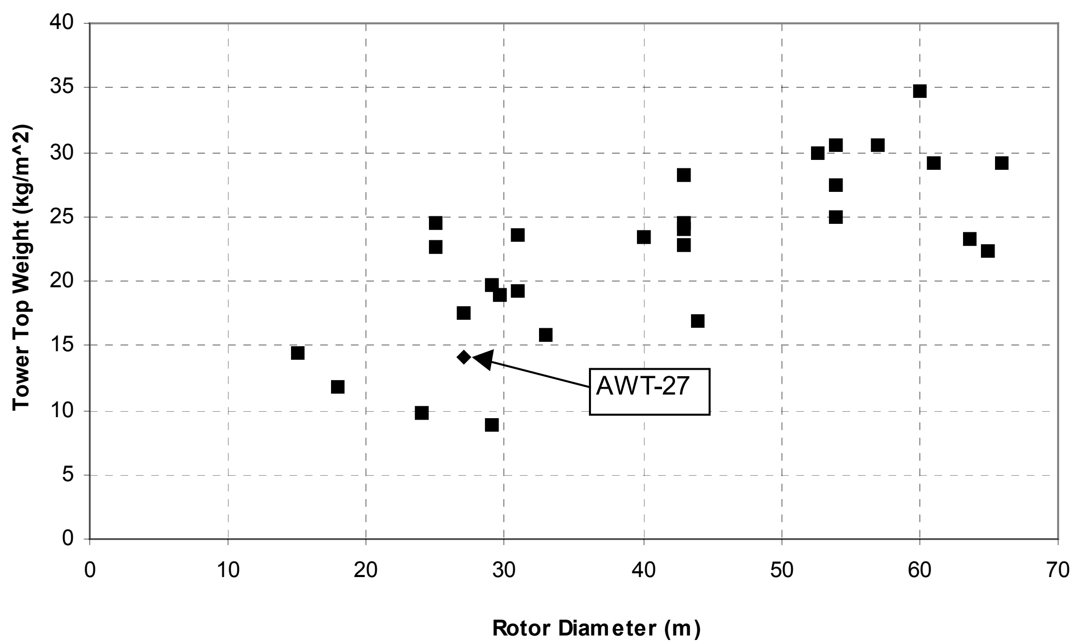

Figure 3-1. Comparison of wind turbine tower top weight per unit swept area

4. Deployment Status

The current deployment status of the AWT-26/27 turbines is given in Table 4-1. The table also briefly summarizes some of the operation and maintenance history of the turbines. Operation and maintenance is discussed in greater detail in Chapter 7 of this report.

Table 4-1. AWT Deployment Status and Turbine Operating Data Summary

Turbine(s)	Operating Hours	Energy Production (MWh)	Operation and Maintenance History
Prototype AWT-26, P1 Installed 2/93 Tehachapi, CA Removed 8/98 Shipped to NWTC	15,454	2,452	• Generally excellent reliability and power performance. • Generator replaced.
Prototype AWT-26, P2 Installed 11/93 Tehachapi, CA Removed 8/98 Shipped to NWTC	14,812	1,968	• Generator replaced. • Gearbox seal problems. • Excessive wear of teeter bearings, modifications developed
Prototype AWT-26, P3 Installed 8/94 NWTC, Boulder, CO	3,337	Not Available	• Controller problems, resolved • Mainframe stiffened.
Prototype AWT-27, P4 Installed 7/95 Tehachapi, CA Removed 8/98 Shipped to NWTC	6,152	881	• Generator replaced. • Tower bracing cracked, retrofitted. • Mainframe cracked, retrofitted. • Excessive wear of coupling elements, reduced with mainframe stiffener.
Production AWT-27 48 ea., Installed by RES, 10/96 - 3/98, various sites in India	Not Available	Not Available	• Some controller problems, particularly nuisance overspeed faults, solution developed. • Generally, problem reports from RES installations have been infrequent.
Production AWT-27 30 ea., Installed by WESCARE, 3/98 - 3/99, (Installation and commissioning ongoing.) Kanyakumari, India	Not Available	Not Available	• Insufficient data at this time.
Demonstration AWT-27 2 ea., Installed by AWT / North China Power, 5/97, Zhangjiakou, China	11,393 (combined) through 9/98	1,055 (combined) through 9/98	• Generally reliable operation. • One broken tip-brake wire, repaired 10/98.

5. Modeling of AWT Wind Turbines

5.1 Historical Development Outline

The mathematical models available for simulating the response of a wind turbine to its environment evolved rapidly during the development of the AWT wind turbine. At the time the basic design was completed, the computer codes available were FLAP and YAWDYN. Those codes did not consider the total system but were restricted to the rotor only and to limited modes of deformation of the blades. Furthermore, at that time (1990-1993) those codes could accommodate only limited turbulence in the inflow.

During the course of the turbine development, it became clear that machines such as the AWT were dynamically active in a manner that involved the entire structure and that a more comprehensive model was required. Concurrently, there was discussion in the wind energy industry in the United States, concerning the development of a more general computer code for Horizontal Axis Wind Turbine (HAWT) dynamics. One proposal was to develop a finite element code based on work already completed at Sandia National Laboratories. Another proposal was to adapt the commercial code ADAMS (Advanced Dynamics of Mechanical Systems) from Mechanical Dynamics of Ann Arbor, Michigan, to HAWT aerodynamics by linking with user-written routines. The second approach was being developed at the time within NREL and was selected as the course to be pursued.

For a number of years (approximately 1992 to 1995) RLA/AWT cooperated with NREL staff in applying the ADAMS code to AWT wind turbines and in developing the required routines. Initial results were frustrating, but, as with any code, this technology continues to evolve, especially in the aerodynamic representation, and starting in 1996, some confidence has been achieved in use of ADAMS for structural/mechanical representation. The creation of ADAMS models has been greatly assisted by the development of preprocessors made specifically for this application.

5.2 Modeling of the AWT-26/P1 and AWT-26/P2

The results of the modeling efforts on the AWT-26/P1 and AWT-26/P2 are reported in Ref. 8. That document describes how the results of modal tests carried out by NREL on isolated blades (Ref. 11) were used to tune the ADAMS representation of the blades.

In November 1993, an extensive set of modal tests were carried out by NREL staff on both AWT prototypes. Ref. 8 summarizes these results and compares them to equivalent results from ADAMS models.

The results of modeling the operating response of P1 are limited to the presentation of typical frequency spectra of the root flap and root-edgewise bending and comparison with the equivalent field data. The modeling included wind shear and tower shadow, but did not include turbulent inflow.

The AWT-26/P1 wind turbine exhibited considerable high-frequency nacelle motion (both vertically and horizontally), especially during high winds. This phenomenon was dubbed the “7P response” because of the dominant frequency in the blade-root edgewise signal. Considerable efforts were made to understand and to solve this phenomenon without any immediate success. However, it was noted that similarly severe response could be simulated by the ADAMS model if the stiffness of the upper portions of the tower were reduced.

The same report (Ref. 8) also presents results from the modeling of the operational response of P2. Efforts were made to extract information on the operating natural frequencies by examining the frequency spectra following an applied impulse. As explained in Reference 9, the periodic nature of the system stiffness leads to sets of multiple natural frequencies, each term separated by 2P (two times the rotor speed), which complicates the task.

The ADAMS model of the AWT-26/P2 was also used to examine the aerodynamic loading, the model response at the significant harmonic frequencies, and to compare with field results. This was done for the root flap and edgewise bending moments. These results confirmed that considerable dynamic amplification existed in some modes at some harmonic frequencies.

In addition, Reference 8 presents the predicted effects of rotor rpm on the blade edgewise response. The results suggest the existence of resonance at certain rotor speeds.

5.3 Modeling of the AWT-27/P4

Considerable modeling of the AWT-27/P4 prototype was done during the NREL supported Near-Term Prototype Testing Project and a full description is included in the final report on that project (Ref. 5).

In October 1996, a set of static modal tests were carried out on the AWT-27/P4, which allowed comparison with the predictions with the ADAMS model of that machine. The comparison indicated substantial differences, and the ADAMS model was modified in a number of ways, the most significant of which was the reduction of the shear stiffness of the tower by a factor of 0.55.

The operating natural frequencies were extracted using the ADAMS models and compared with the natural frequencies apparent from the field data. The agreement with the field data was much better for the modified ADAMS model than for the initial model.

Reference 5 also presents some comparisons between model and field data for operating response in high winds. Results for rainflow counts of flap bending, shaft bending, and yaw-bearing pitching moments are shown. Agreement is, in general, good. However, the ADAMS results were obtained using turbulent inflow that was extreme and probably exceeded site conditions.

5.4 Investigation of delta-3 on AWT-27/P4

Starting in April 1997, a program was carried out to determine the effect of various delta-3 settings in the teetered hub of the AWT-27/P4. The reason for the field tests was to confirm the ADAMS predictions that the incorporation of negative delta-3 would increase the stability of the hub in high winds, and thereby reduce the occasional high loads experienced by the machine.

Reference 10 presents a full report on the field test program and the results obtained. It includes a comparison of the predicted ADAMS results and field data for the three delta-3 configurations tested for the case of a turbulent flow with mean of 18 m/s. The ADAMS predictions of reduced loads with negative delta-3 configurations were confirmed by the field data. However, the agreement between the predictions and the corresponding field data were not always good. For example, the model tended to underpredict the root flap bending and to overpredict the mainframe bending. In addition, the lack of a hard teeter stop on the ADAMS model, caused it to not predict high loads associated with impacting the hard stop. It should be noted that the intensity of the turbulence used in conjunction with the ADAMS model was not identical to that measured at the site.

5.5 Validation of ADAMS applied to the AWT-27/P4

A project is under way at Kamzin Technology Inc. to validate the predictions obtained by the ADAMS model of the AWT-27/P4. This project makes use of the considerable field data collected during and before the negative delta-3 tests, including the data from the u-v-w sonic anemometer. From the anemometer, the nature of the inflow is to be determined, and this will be used as input to the simulation of the turbulence used by the ADAMS model.

Results from this study are planned to be available in December 1998 and will be the first time that careful measurement of the inflow has been combined with a model that has been tuned to agree with the apparent dynamic characteristics of the wind turbine.

6. Summary Test Data

AWT/RLA conducted field and laboratory tests from 1992 through 1998. Most of this testing was conducted on full-scale prototype wind turbines, although some laboratory testing of selected components has been conducted. The testing completed can be divided into several categories: performance, loads, modal, structural/stress, efficiency, aerodynamics, noise, and miscellaneous. The following paragraphs and tables summarize the testing completed in the various test categories.

6.1 Field Test Summary

Four different types of field tests were conducted on AWT prototype turbines: performance tests, load tests, modal tests, and noise tests.

Performance testing is done to obtain a power versus wind speed curve. Measurements include wind speed and direction, turbine electrical power output, air temperature and pressure, and sometimes turbine status. Generally, the data is measured and stored as 1 to 10 minute averages in time series form. Measurement blocks (data files) vary from several hours to several days, with a complete test generally involving hundreds of hours of data. Table 6-1 summarizes the performance tests conducted on AWT turbines.

Loads testing was done to obtain an understanding of the turbine mean and variable loading in a variety of operational and transient modes across a range of wind speeds. Measurements generally included blade root bending, shaft torque and bending, teeter and yaw position, tower bending, turbine electrical power, wind inflow, and component stresses. Measurements varied considerably for each given test, depending on test objectives, instrument availability, and test schedule and resources. Data was typically collected in time-series form at sample rates ranging from 10 Hz to 50 Hz in 10 minute data files. Complete tests ran from several days to several months, depending on test objectives, schedule, and the wind available. Complete test data sets are generally a few hours to several tens of hours of data. Table 6-2 summarizes the loads testing completed on the AWT turbines.

Modal testing was performed in order to gain an understanding of the wind-turbine dynamic behavior. This data was generally used to aid in the development of computer models of the wind-turbine structural response. Testing was generally performed over the course of several days. Measurements taken were based on accelerometers and the response obtained when the turbine was excited by wind or hydraulic actuators. Table 6-3 summarizes the modal tests completed on AWT turbines.

Noise tests were performed in order to obtain permitting for turbine installation. They were performed by Bruce Walker. Table 6-4 summarizes the noise tests completed on AWT turbines.

Table 6-1. Performance Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
REP (ESI-80 w/ AWT Blades)	San Gorgonio, CA	5/92 - 10/92	30 rpm w/tips 30 rpm w/out tips 60 rpm Clean/dirty blades	Backup tapes in AWT office	*ESI-80 Rotor Performance and Reliability Enhancement Program Final Report*, R. Lynette & Associates, March, 1993.
P1	Tehachapi, CA	2/93 - 7/98	57 rpm 61 rpm Various pitch angles Vortex generators	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P2A	Tehachapi, CA	11/93 - 7/94	Two pitch angles	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P2B	Tehachapi, CA	8/94 - 7/98	Various pitch angles	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P3	NWTC, Boulder, CO	10/97 - 8/98	57 rpm 42 rpm 32 rpm Variable speed	NWTC	NREL subcontractor report to be submitted by EPC at project completion.
P4	Tehachapi, CA	8/95 - 4/97	+1° pitch 0° pitch -1° pitch	Backup tapes in AWT office	*DB273011: AWT-27 Power Curve Design Book*, AWT, April, 1996.
P4/Delta-3	Tehachapi, CA	7/97 - 7/98	0°, -30°, -45° Delta-3	Backup tapes in AWT office	*TR270005: Variable Delta-3 Prototype Hub Field Test and Simulation Results*, AWT, July/98.

Table 6-2. Loads Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
REP (ESI-80 w/ AWT blades)	San Gorgonio, CA	5/92 - 10/92	Elastoroid dampers Jarret dampers	Backup tapes in AWT office	*ESI-80 Rotor Performance and Reliability Enhancement Program Final Report*, R. Lynette & Associates, March, 1993.
P1	Tehachapi, CA	2/93 - 7/98	57 rpm, 61 rpm Various tips Various tower shadow Various dynamics Vortex generators	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P2A	Tehachapi, CA	11/93 - 7/94	Two pitch angles Two damper stiffnesses W/ and w/out strakes	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P2B	Tehachapi, CA	8/94 - 7/98	Various pitch angles Single guy wires W/ and w/out tower dampers	Backup tapes in AWT office	*Advanced Wind Turbine Near-Term Product Development Final Technical Report*, R. Lynette & Associates, Nov./95.
P4	Tehachapi, CA	8/95 - 4/97	+1°, 0°, -1° pitch Various teeter dampers Various tower lattice Mainframe stiffener	Backup tapes in AWT office	*TR260004: Development and Testing of Extended Diameter Rotor of the AWT-26 Wind Turbine*, AWT, Dec./96.
P4/Delta-3	Tehachapi, CA	7/97 - 7/98	Delta-3 = 0°, -30°, -45° Various damper settings	Backup tapes in AWT office	*TR270005: Variable Delta-3 Prototype Hub Field Test and Simulation Results*, AWT, July/98.

Table 6-3. Modal Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
REP (ESI-80 w/ AWT blades)	San Gorgonio, CA	9/92	Blades horizontal Blades vertical	See Ref.	*Specialized Testing Service Report #9282*, 9/23/92.
Blade	NWTC Boulder, CO	5-6/93	W/ and w/out tips weights	See Ref.	*Modal Survey Test Results for RLA AWT-26 Wind Turbine Blade*, NREL, June, 1993.
P1	Seattle, WA Tehachapi, CA	1/93 4/93 12/93	Test stand, blades horizontal Blades horizontal, vertical	See Ref.	*Specialized Testing Service Report #9327*, 1/18/93 *Specialized Testing Service Report #9355*, 4/15/93 *AWT-26 P1 Modal Survey*, NREL, 1/12/94.
P2A	Tehachapi, CA	12/93	Blades horizontal, vertical	See Ref.	*AWT-26 P2 Modal Survey*, NREL, 1/12,/4.
P3	NWTC Boulder, CO	7/98	Operating 32-58 rpm	NWTC	*Dynamic Characterization of the AWT-26 Turbine for Variable Speed Operation*, NREL, July, 1998.
P4	Tehachapi, CA	10/96	Blades horizontal., vertical	See Ref.	*Advanced Wind Turbine Program Near-Term Prototype Testing Project*, R. Lynette & Associates, March, 1997.

Table 6-4. Noise Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
REP	San Gorgonio, CA	8/92	ESI-80 w/ AWT blades	See Ref.	Report by Bruce Walker, Walker, Celano & Associates, Oct./92.
P1	Tehachapi, CA	3/94	P1 as built	See Ref.	Report by Bruce Walker, Walker, Celano & Associates, April/94.
P2A	Tehachapi, CA	3/94	P2A as built	See Ref.	Report by Bruce Walker, Walker, Celano & Associates, April/94.
P2B	Tehachapi, CA	10/95	P2B as built	See Ref.	Report by Bruce Walker, Hersh Acoustical Engineering, Nov./95.
P4	Tehachapi, CA	8/95	P4 as built	See Ref.	Report by Bruce Walker, Hersh Acoustical Engineering, Sept./95.

6.2 Laboratory / Miscellaneous Test Summary

Several structural or stress tests were performed in the laboratory in order to validate stress analysis of particular components. “Static” tests were conducted by applying a known load to a structure and recording the results from strain gages and dial indicators. Data were typically taken at one second averages with a given run lasting several minutes while load was stepped up and then back down in stair step fashion. Like the modal tests, these tests generally occurred over about one to two weeks. Fatigue tests were conducted by subjecting the test article to a predetermined cyclic loads specification. Table 6-5 summarizes the structural/stress tests conducted on AWT turbines.

Efficiency tests were performed on gearboxes and generators. These tests were performed in the laboratory and generally, input and output power equal whereas variables such as oil type and temperature were varied. These tests generally ran for one to two weeks, and the data collected were hand written off of instrument displays. Table 6-6 summarizes the efficiency tests conducted on AWT components.

The aerodynamic tests were conducted in wind tunnels with the objective of obtaining lift and drag characteristics for various aerodynamic devices and configurations. Test methods and data collection varied depending on test objectives and resources. Table 6-7 summarizes the aerodynamic tests conducted on AWT components.

Table 6-5. Structural/Stress Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
Blades	NWTC, Boulder, CO	10/95 - 3/98	Static (one test) Fatigue (six tests)	NWTC, AWT office	*TR270002: AWT-26/27 Blade Static and Fatigue Test Report*, AWT, Feb, 1996. *TR003003: Test Report for AWT-26/27 Blade Fatigue Test #6*, AWT, March/98.
Studs	Gougeon Mfg, MI		10”, 7.5”, drill method, Static, Fatigue	AWT office	*DB273008 Rev A: Design Book: Blades*, July, 1996.
Wood laminate	Gougeon Mfg, MI	3/97-12/97	Manufacturing process	See Ref.	Various letter report deliverables under Sandia project # AN-0166.
Mainframe and Truss	Seattle, WA (The GearWorks)	11/97	Improved mainframe w/ and w/out truss	Floppy disks in AWT office	*TR260005: Mainframe Proof Test Report*, AWT, Dec./97.
Delta-3 Hub	Seattle, WA (The GearWorks)	7/97	Delta-3 = 0°, -45°	Floppy disks in AWT office	*TR270004: Delta-3 Hub Proof Test Report*, AWT, Dec./97.

Table 6-6 Efficiency Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
Flender PZ-170 Mark V	Seattle, WA (The GearWorks)	2/96	Various oil types, levels, and temperatures	See Ref.	*TR270001: AWT-26/27 Gearbox Efficiency Test Report*, AWT, Feb., 1996.
Flender PZ-170 Mark III	Seattle, WA (The GearWorks)	4/97	Various rpm, temperatures	See Ref.	*Comparison of Drivetrain Component Efficiencies for a Constant Speed and a Variable Speed Utility Scale Wind Turbine*, NREL TR in progress Sept./98.
U.S. Motors 275 kW	Corvallis, OR (EPC)		Production	See Ref.	Same as above.

Table 6-7. Aerodynamic Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
Vortex Generators	Seattle, WA (Univ. of Wash)	4/95	Various layouts	AWT Office	*TR260002: Investigation of Vortex Generators for Augmentation of Wind Turbine Power Performance*, AWT, June/96.
Trailing Edge Devices	Wichita, KS (Wichita State Univ.)	11/95	Spoiler flap Flip tip	AWT Office	*TR260003: Investigation of Aerodynamic Braking Devices for Wind Turbine Applications*, AWT, Oct./96.

Table 6-8. Miscellaneous Test Summary

Test Article	Test Site	Dates (mo/yr)	Configurations Tested	Data Location	References
P2B	Tehachapi, CA	1995	P2B as built	See Ref.	*TR26001: P2 Wear and Durability Assessment, Pre-Production Operational Test Report BPA/CARES Project*, AWT, July/95.
Controller	Tehachapi, CA	6/97-3/98	Various	See Ref.	*TR003002: Turbine Control System Investigation and Upgrades*, Final Report, AWT, Jan./98.
Teeter bearings	Tehachapi, CA China	6/97-3/98	Grooves, grease, seals	See Ref.	*TR260006: Teeter Assembly Redesign and Retrofit*, AWT, March/98.
Blade quality	Pinconning, MI	1996-1997	As built	See Ref.	*TR270003: AWT-26/27 Blade Nondestructive Testing Report*, AWT, Oct./96. *TR003001: Analysis of Inspection Data for ABM Inventory*, AWT, Oct./97.

7. Operation and Maintenance Experience

The operation and maintenance experience with the AWT-26 turbines has been generally good. The AWT's rotor efficiency is among the highest in the world, and a 26-meter prototype successfully passed an independently audited performance and reliability test conducted for the Bonneville Power Administration (Ref. 2). This test demonstrated availability over 97% and the turbine's performance was shown to be within 3% of projections made several years prior. Operating experience with the AWT-27 turbine has also been generally good. An independent power curve measurement showed performance is within 6% of projections. Turbine availability has been high, the turbines installed in India and China are reported to be operating very well, and loads are generally within design limits. There are, however, several notable exceptions that are detailed below.

7.1 Noted Problems

1. The pitching loads affecting mainframe and low-speed shaft bending for winds in excess of 13 m/s are higher than design limits for Class 2 sites. The cause of these loads is teeter motion that causes the teeter damper to introduce excessive loads into the shaft and mainframe. Although the margins in the shaft are more than adequate to accommodate the higher loads, the mainframe is more problematic. This problem caused cracking of the mainframe on the P4 AWT-27 prototype. Excessive flexibility of the mainframe also caused accelerated wearing of the high-speed coupling elements. The excessive teeter motion, which introduces the problematic loads, is caused by a reduction in the dynamic stability of the rotor as the rotor stalls. This decrease in stability is believed to be caused by a reduction in the aerodynamic damping as the rotor stalls.

2. The early teeter dampers have exhibited a service life of under one year. Several causes for the shorter than anticipated life were identified and design solutions developed. These solutions were not tested or implemented because there is a high degree of confidence in their adequacy.

3. The teeter bushings are continuing to wear at an excessive rate. Several improvements were designed and tested and it is believed that the current configuration can deliver acceptable service life with some minor modifications. However, the bushings are expensive and difficult to replace. As a result it is desirable to develop a lower maintenance teeter bushing configuration.

4. The lattice tower on the P4 prototype was vibrating in a manner that caused cracking of the bracing members. This behavior was not observed on the turbines in India. The reason for the difference is believed to be that the turbines in India operate at a rotor speed approximately 5% lower than the P4 turbine. This data, as well as other experiences AWT had with the prototype turbine, suggests that the configuration is highly sensitive to dynamic interaction among the components. This illustrates the importance of reliable dynamics models and extensive field-test data.

5. The turbines exhibited various control system bugs and nuisance faults, with the most disruptive being nuisance overspeed faults. The majority of these have been corrected in the most recent version of the AWT software.

6. Through a series of laboratory blade fatigue tests several design and manufacturing concerns have been identified, primarily in the root region of the blade. The original bolted blade-root connections showed poor fatigue capability, and were deemed too complex for reliable field assembly. In critically loaded areas, the blade root studs were inadequately bonded. Inadequate bonding was also identified in the root veneer of some blades. Although these problems were identified in laboratory fatigue tests and subsequent inspection of AWT blade inventory, no blade or root-connection failures have occurred in field service of AWT blades.

7.2 Implemented Configuration Modifications

Several modifications have been implemented to address the known operation and maintenance problems, as detailed in the following sections.

7.2.1 Mainframe Stiffener

Two methods for stiffening the AWT-27 mainframe have been designed and tested. The first uses a truss mounted to the original AWT-27 mainframe casting. The truss is made of four turnbuckles, as shown in Figure 7-1. Attachments are made at the mainframe, and at a plate which is bolted on to the gearbox snout. The truss-style stiffeners have been installed on the P3 and P4 prototypes and the C1 and C2 turbines in China.

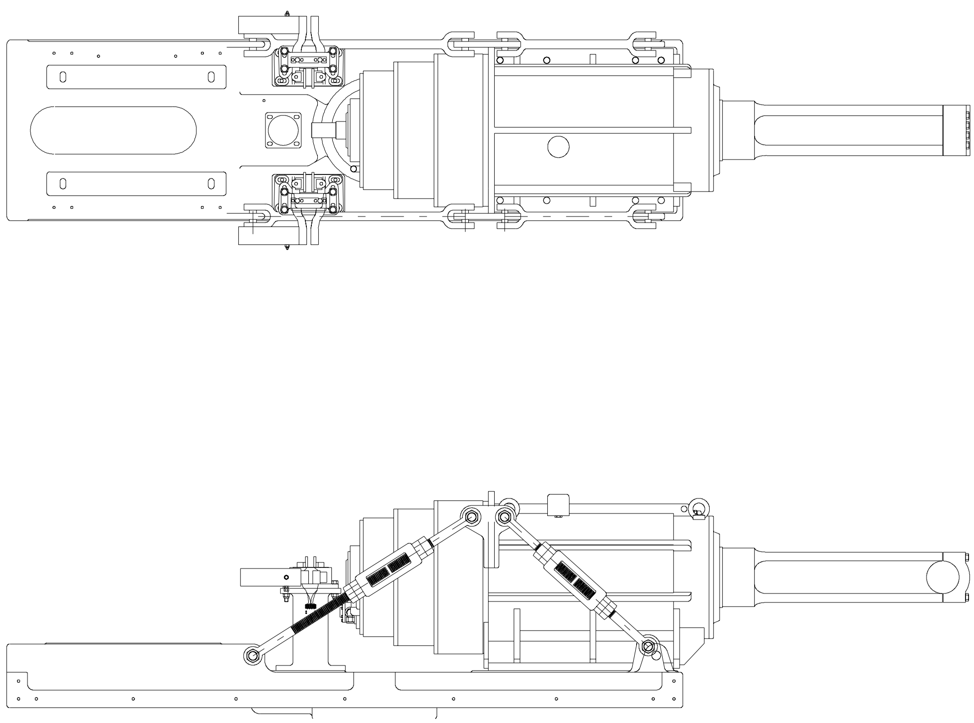

Figure 7-1. Truss-style mainframe stiffener.

Although the truss-style stiffeners have proven to be effective, a more elegant and lower cost method of stiffening was desired for AWT-26/27 production. To this end, the AWT mainframe casting pattern and machining drawings were modified, and accompanying plate-style stiffeners were designed. Prototypes of the modified truss and stiffening plates were manufactured and proof-tested (Ref. 12). The current production drawings for the AWT-26 show the modified mainframe casting with the plate stiffeners. However, the pattern for this casting has been destroyed, so that any future production of AWT mainframes would require a new pattern. This presents an opportunity for a fundamentally improved mainframe design, as addressed in Section 7.3.1.

7.2.2 Modified Damper Mounts

To determine the cause of excessive damper wear, the original AWT teeter damper configuration was assessed (Ref. 13). It was determined that during operation, the point-of-contact of the damper and low speed shaft translated along the shaft, resulting in significant side loading of the damper cylinder. An angled block-style adapter was designed for mounting the damper cylinders (Dwg. 6061110). Accompanying wedge-shaped contact blocks were designed for mounting on the low-speed shaft (6061120). This retrofit minimizes side loading on the dampers during operation, and a subsequent increase in damper wear life is anticipated.

7.2.3 New Teeter Bearing Design

The AWT prototype turbines have been used to test several iterations of teeter bearing designs and vendors. Many of these design iterations are documented under the work of Reference 5. The most recent design tested was a bushing with grooves (to allow distribution of grease along the teeter shaft) and seals (to contain the grease and prevent contamination of the bushing). This design is now the production configuration for both the AWT-26 and AWT-27 turbines. Under field testing and inspection, the bushing showed an acceptable wear rate, but the inspection and analysis identified several areas in which the design could be further improved (Ref. 14).

7.2.4 Prototype Delta-3 Hub

RLA staff have, over the past year, extensively researched ways to reduce the teeter related pitching loads experienced by the turbine. ADAMS simulations are used to examine several dozen potential configuration changes, including changes in coning, mass distribution, rotor speed, tower configurations, and teeter damper characteristics. Only the addition of negative delta-3 to the hub geometry resulted in a significant increase in stability and decrease in loads.

Figure 7-2 illustrates a hub design with negative delta-3. A number of two-bladed wind turbines have incorporated delta-3 in the configuration of the teetering hub, however, it has generally been positive delta-3. The rationale for this has been that a positive delta-3 was believed to create aerodynamic forces that would restore any teeter motion. However, validation of this concept, especially on stall-controlled rotors, has not been possible.

Research predicted that negative delta-3 in a teetering hub would increase the post stall stability of the rotor without adversely affecting the pre-stall stability. It has been shown, by ADAMS simulations and by spreadsheet calculations, that the angle of attack changes implied by this configuration, combined with the 2P symmetric flapwise motion of the blades and the stall behavior of the blades, will cause aerodynamic moments of a type that will restore the teeter displacement. As a result, negative delta-3 is expected to attenuate the large teeter moments that have governed both the peak and the fatigue design of several components. Computer simulations predicted that peak teeter damper moments will be reduced by a factor of about 4 relative to the baseline design.

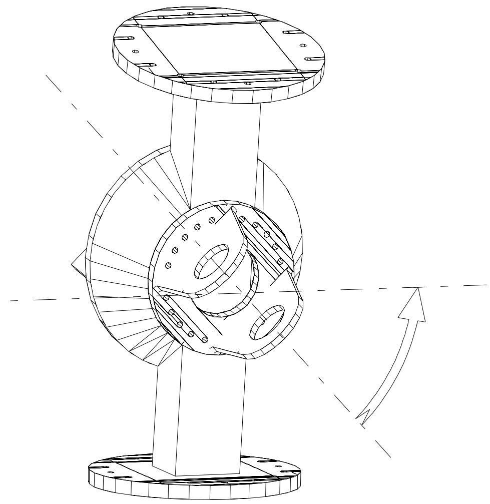

Figure 7-2. Teetering hub with negative delta-3.

To confirm these predicted benefits, a variable delta-3 hub was manufactured and field tests completed on the AWT-27 prototype, P4 (Ref. 10). It was concluded that the addition of negative delta-3 improved the overall yaw-teeter stability of the AWT-27 rotor. However, the degree to which teeter moments are attenuated is also dependent on the characteristics of the teeter dampers and the positioning of teeter stops. Realizing the full potential benefit of negative delta-3 will require further engineering effort to optimize the design of teeter damping and hard-stop placement.

An unexpected degradation in power performance was observed during the field tests. The magnitude of the degradation appears proportional to the delta-3 angle, but the cause of the degradation is not known.

7.2.5 Control System Upgrades

To address known nuisance faults and other controller problems, AWT undertook a rigorous control system investigation and subsequent upgrade was completed (Ref. 15). The control system concerns, which were addressed during the effort, can be grouped into the following broad categories:

- Software bugs
- Electrical noise
- Signal processing problems
- Brake fault detection algorithms
- Loose wires and wire routing issues
- Operator interface improvements.

During the control system investigation, a method was developed to convert ladder logic programs to Microsoft Word documents. This allowed comment lines to be added to the programs, which made the ladder logic programs easier to follow and less prone to errors. Next, programmable logic controllers and a Durant overspeed monitor were set up in a bench test arrangement. The bench test rig was used to identify the root causes of the problems and to test solutions. After solutions were tested on the bench, they were confirmed through field testing on the P4 prototype. After final debugging on P4, Service Bulletins and Engineering Change Notices (ECNs) were written for use on production turbines in service.

Appendix A of Reference 15 lists all of the ECNs and Service Bulletins written, and the software revision levels at the start and end of the controller investigation and upgrade project.

The most prolific of the controller problems to address was nuisance overspeed faults, that were caused by excess electrical noise. This problem, among others, was addressed by the resulting upgrades.

7.2.6 Improved Blade-Root Connection

Several improvements have been made to increase the strength and reliability of the AWT-26/27 blade root connection:

- Non-destructive inspection techniques were developed to qualify the AWT blade inventory at the factory (Refs. 16 and 17). Blades with notable defects were not used in service.

- The AWT-27 blade-root adapter was redesigned, with a shorter pitch-adjustment slot (Ref. 18).

- The bolted connection at the blade root was redesigned (Ref. 19). When combined with shorter pitch slots, the new bolted connection provides a stiffer joint, with:
  improved fatigue capability of the bolts,
  an assembly that requires less labor and is less complex, and
  reduced parts count and cost.

- Prior to deployment, selected root studs were removed and replaced with larger studs. This increased the strength of the most critically loaded studs.

All of the above improvements were made to address failure modes that were observed during laboratory fatigue testing. However, it is worthwhile to note that, to date, no blade root failures have occurred for AWT blades in field service, the vast majority of which do not have the benefit of the modifications and procedures listed above.

7.3 Proposed Configuration Modifications

In addition to the modifications already implemented in the design documentation, several additional modifications would be required to address known problems within the AWT-26/27 turbines.

7.3.1 Redesigned Mainframe

As discussed in Section 7.2.1, the casting patterns for the production AWT-26/27 turbine no longer exist. Prior to any new production, fundamental improvements should be made to the mainframe design to increase static strength and fatigue life, and to achieve a 30-year design life with IEC-specified safety factors. Increased mainframe stiffness will reduce coupler deflection and will reduce the frequency of replacing elastomeric coupler elements.

The design should be optimized for weight and strength using computer modeling and finite element analysis (FEA). Specific structural changes to the existing casting should include increased bending strength and stiffness in the mainframe mid-section by increasing the section modulus. The stress concentration in the downwind well-to-yaw boss fillet radius (where cracks have occurred) should be reduced by increasing the fillet radius to the yaw-bearing boss.

Relative to the original AWT design, weight gain associated with strengthening could be offset by removing non-essential casting material at the upwind and downwind ends. This concept is illustrated in Figure 7-3. In addition, the grade of ductile iron used for the mainframe casting must be changed from 80-55-06 to material similar to 65-45-12, to increase ductility. The exact material requirement must be coordinated with the certifying agency.

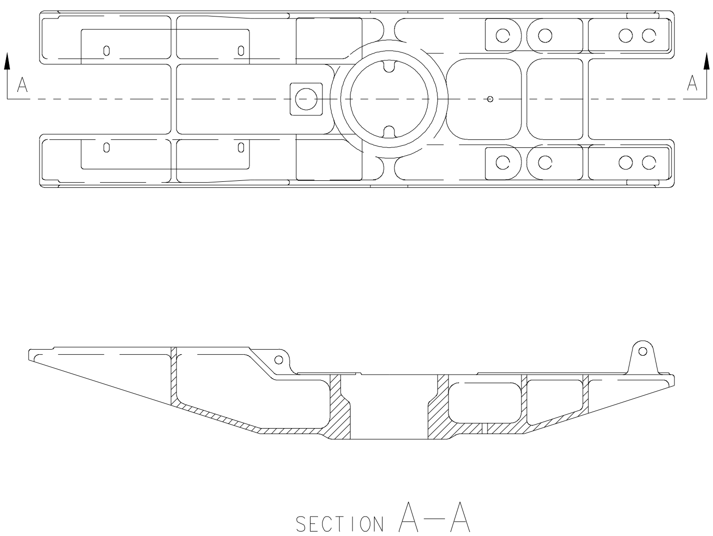

Figure 7-3. Possible design for stiffened mainframe casting.

7.3.2 Reduction of Peak Teeter Moments

In addition to a stiffened mainframe, commercial viability of the AWT configuration requires a reduction in peak teeter moments. Developing a successful production delta-3 hub, appears to be the approach with the highest probability of success. As discussed in Section 7.2.4, this effort would need to include a determination of the best damper characteristics, hard-stop placement, and field testing of the resulting design. In addition, changes in the rotor speed, blade geometry, or turbine structural dynamics may increase post-stall stability and thereby further reduce teeter moments.

7.3.3 PC Based Controller

Although significant engineering effort has been spent to improve the reliability of the AWT ladder-logic- based controller, this was only to address known problems in turbines already produced. Any future production of AWT turbines would incorporate a more modern, PC-based controller with logic based on “C” or similar programming language.

7.3.4 Fiber-Reinforced Plastic Rotor Blades

The Advanced Blade Manufacturing (ABM) wood-epoxy blades have performed well on AWT turbines, and significant engineering effort has been spent to improve their strength and reliability. However, due to lack of blade sales, the ABM facility has been shut down. The blade molds and associated tooling were purchased by Atlantic Orient Corporation of Norwich, Vermont. Manufacture of new wood-epoxy blades for AWT turbines is likely to be prohibitive, unless unexpected changes occur in the market for wood-epoxy blades or AWT-sized turbines. To address this need, AWT has sought to identify alternate suppliers for AWT blades, and has investigated the feasibility of using fiber-reinforced plastic (FRP) blades for future turbine production (Ref. 20).

Three vendors (ATV, LM, and Rotorline) have been identified as potential suppliers of FRP blades for AWT-27 turbines. However, each would require the resolution of significant technical issues. Given the limitations on available (Flender) gear ratios, it appears unlikely that the LM and Rotorline blades could be operated within their tip-speed limitations. As they are currently operated on (Lagerway) 2-bladed turbines, the ATV blades appear to be the best suited for AWT configurations. However, suitability of the ATV blades would depend on further investigation of the structural integrity, and whether the blade-root connection could be accommodated. The summary configuration presented in the next section assumes that the ATV Model 13.5 can be modified to work in an AWT type configuration. This would result in a rotor of nominally 28.5 meters in diameter. Of course, new blade design could be developed if the benefit outweighs the cost.

7.4 Summary of Current Configuration and Proposed Modifications

Table 7-1 presents a summary of three AWT configurations. The baseline turbine in table 7.1 is the AWT-27 delivered to customers in India. The improved AWT-27 incorporated known and proposed improvements and used a commercially available FRP blade. The AWT-30DS incorporated a dual-speed generator and a 30-meter rotor to increase energy production and reduce the cost of energy. Supporting details for the cost and figure of merit calculations are given in Table 9-2 of Section 9.0.

Table 7-1. Summary of AWT-27 Turbine Configuration

	Baseline	Improved "AWT-27"	Concept AWT-30DS
General Configuration			
Type	Utility Class	Utility Class	Utility Class
Rotation Axis (H/V)	H	H	H
Orientation (upwind/downwind)	Downwind	Downwind	Downwind
Number of Blades	2	2	2
Rotor Hub Type	Teetered	Teetered, Neg. Delta-3	Teetered, Neg. Delta-3
Rotor Diameter (m)	27.4	28.5	30
Hub Height (m)	42.6	42.6	45
Performance			
Rated Electrical Power (kW)	275	275	275
Rated Wind Speed (m/s)	17	17	17
Cut-in Wind Speed (m/s)	4.9	4.9	3.6
Cut-out Wind Speed (m/s)	22.5	22.5	22.5
Extreme Wind Speed (m/s)	59	59	59
Annual Energy Production @ 5.8 m/s site (MWh/yr) (Net)	567	597	681
COE @ 5.8 m/s site ($/kWh)	$0.0576	$0.0535	$0.0498
Rotor			
Swept Area (m^2)	590	637	707
Rotational Speed (rpm)	53	53	45.8 / 30.5
Coning Angle (deg)	7	7	7
Tilt Angle (deg)	0	0	0
Blade Pitch Angle (deg) (sea level)	-1	-1.5	-1.0
Hub Material	Ductile Iron	Ductile Iron	Ductile Iron
Direction of Rotation	Clockwise from Upwind	Clockwise from Upwind	Clockwise from Upwind
Power Regulation	Stall	Stall	Stall
Over-speed Control	Fail-safe redundant aerodynamic tips and high-speed shaft brake	Fail-safe redundant aerodynamic tips and high-speed shaft brake	Fail-safe redundant aerodynamic tips and high-speed shaft brake
Teeter Damper Type	Hydraulic (Enidine)	Hydraulic (Enidine)	Hydraulic (Enidine)
Blades			
Make	ABM	ATV	ATV
Material	Wood Epoxy	Fiberglass Epoxy	Fiberglass Epoxy
Length (m)	12.57	13.5	14.3
Root Chord (mm)	774	500	500
Max Chord (mm)	1143	1200	TBD
Tip Chord (mm)	368	368	TBD
Twist (deg)	5.85	15	TBD
Airfoil Type	S815 Root S809 Midspan S810 Tip	NLF 422 Root NLF 418 Midspan NLF 416 Tip	TBD TBD TBD
Drive Train			
Gearbox: Make	Flender	Flender	Flender
Type	Planetary	Planetary	Planetary
Ratio	33.8:1	33.8:1	39.3:1
Generator: Make	U.S. Motors	U.S. Motors	TBD
Type	Induction, ODP	Induction, ODP	Induction, ODP
Speed	1800 RPM	1800 RPM	1800/1200 RPM
Voltage and Frequency	60 Hz, 480V	60 Hz, 480V	60 Hz, 480V

Table 7-1 Summary of AWT-27 Turbine Configuration (continued)

		Baseline	Improved "AWT-27"	Concept AWT-30DS
Braking System				
Parking/Service:	Make	Horton	Horton	Horton
	Type	Hydraulic/Spring Applied	Hydraulic/Spring Applied	Hydraulic/Spring Applied
	Location	High-Speed Shaft	High-Speed Shaft	High-Speed Shaft
Normal Shutdown:	Make	Same	Same	Same
	Type	Same, Partial Application	Same, Partial Application	Same, Partial Application
	Location	Same	Same	Same
Emergency:	Make	Same	Same	Same
	Type	Same, Full Application	Same, Full Application	Same, Full Application
	Location	Same	Same	Same
Yaw System				
Wind Direction Sensor		None	None	None
Yaw Control Method		Free	Free	Free
Yaw Bearing Type		Ball	Ball	Ball
Tower				
Type		Lattice	Lattice/Free Standing Tube	Guyed-Tube
Material		Steel	Steel	Steel
Height (m)		41	41/30	45
Control/Electrical System				
Controller:	Make	Cutler Hammer	Second Wind	Second Wind
	Type	PLC	Micro/DSP Chip	Micro/DSP Chip
Power Converter:	Make	N/A	N/A	N/A
	Type	N/A	N/A	N/A
Logic System		Ladder	"C" Programming Lang.	"C" Programming Lang.
Monitoring System		Second Wind	Second Wind	Second Wind
Electrical Output	Voltage	480	480	480
	Frequency	60 Hz	60 Hz	60 Hz
	No. of Phases	3	3	3
Costs & Weights				
Blades ($)		$19,034	$19,800	$23,560
(kg)		900	1,080	1,285
Rotor Assembly ($)		$30,050	$26,216	$29,612
(kg)		2,495	1,830	2,285
Nacelle Assembly ($)		$50,612	$52,983	$58,254
(kg)		4,980	5,100	5,450
Tower Assembly ($)		$29,000	$27,000	$30,000
(kg)		15,150	15,150	16,500
Control Electrical System ($)		$26,061	$26,521	$26,721
Total Parts ($)		$135,723	$132,720	$144,587
(kg)		22,625	22,080	24,235
Assembly, G&A, Profit		$43,284	$42,396	$45,908
Total FOB Cost		$179,007	$175,116	$190,495

8. Certification Status

8.1 Historical Outline

During the time that the AWT-26/27 was being developed, the requirements around the world for certification of wind turbines were evolving. This was especially true in India where AWT's main market lay at that time. When sales discussions first took place in 1994, there were no government requirements for turbine certification in India. However, the need for certification gradually grew, and at present, all new wind turbines in India must have "type approval" from a recognized agency.

A review of the available certification agencies initially led to a choice of Lloyds Register (LR) of the United Kingdom. This selection was based on the greater flexibility of LR's criteria and approach, an expectation of fewer communication problems, and LR's ability to respond quickly to AWT's needs. However, when LR was not included in the list of agencies acceptable to India's Ministry of Non-conventional Energy Sources (MNES), AWT was obliged to change to another agency which was Germanischer Lloyd (GL).

Initially, it was intended to obtain certification of the design only. However, it became clear that the "type approval" referred to by MNES of India included certification of the manufacturing process and confirmation of the loads from test data. This led to an increase in activity at AWT/RLA to support the certification work.

Approval of the design by GL required initial submission of documents defining the loads and the safety system, followed by submission of the remaining details of component design. Formal approval was obtained for the loads document, but financial constraints at AWT/RLA caused the work to stop before approval for any of the other documents could be obtained.

Between August 1995 and December 1996, considerable effort went towards securing certification. In addition to approving the loads, GL reviewed some of the other documentation submitted and had raised questions. AWT/RLA were in the process of answering these questions and completing the document submission when work was stopped. A chronology of the major steps completed in the certification process, and the issues raised by GL, are given in the following sections.

8.2 Major Steps Towards Certification

Table 8-1 presents a chronology of the certification efforts completed by AWT/RLA.

Table 8-1. Chronology of AWT-27 Certification Efforts

Date	Item
December 1993	Initial contact with GL. Receipt of GL guidelines.
August 1995	Contact with and appraisal of GL, Det Norske Veritas (DNV), ECN, and Lloyds Register (LR).
September 1995	Selection of LR as agency to use.
October - November 1995	Indian MNES issues list of acceptable certification agencies. List does not include LR.
November 1995	AWT selects GL as agency to use.
December 1995	Establishment of contract, fees, & schedule with GL.
December 1995	Submission of Loads and Safety Concepts to GL.
January 1996	Inquiries concerning performance curve certification at GL and at NREL.
January - February 1996	Correspondence with GL concerning Loads document.
February 1996	Submission to GL of remaining design books (controls/FMEA, nacelle cover, mechanical/FMEA, electrical/controls, mainframe & yaw bearing, tip brakes, hub, blades, tower, drive train).
February 1996	Meeting with Christian Nath in Boulder.
March 1996	Revised loads document submitted to GL..
March-April 1996	Question concerning loads received from GL. Additional loads information sent to GL.
April 1996	Discussions with GL concerning extending certification to performance curve, quality control, and field testing.
April 1996	Loads document approved.
May 1996	Performance information submitted to GL.
May 1996	Quality assurance document submitted to GL.
July 1996	Revised drive train and blade design books sent to GL. O & M manual and commissioning procedure sent to GL..
August 1996	Finite element information on hub sent to GL.
August 1996	Flender asked to send gearbox information direct to GL.
August 1996	Pre-audit of ABM/blade manufacture.
September 1996	Correspondence concerning electrical design and controls.
November 1996	Report from GL concerning drive train and electrical transients.
December 1996	Communications with GL ceased.

8.3 Outstanding Issues

Although most technical issues required for design certification were resolved, there were a number of items that were left outstanding. These are summarized in the following table.

Item	GL Issues/Comments
Yaw Lock	Design loads, conditions for use, stress analysis of pin.
Torque Load from Electrical Short Circuit	Drive train not designed to sustain such a load and no “load relief” provided in drive train.
Braking Loads	Documentation inconsistent, adequacy without tip brakes?
Brake Wear Sensor	Should be fail-safe.
Generator Switch	Failure during braking could lead to brake overheating.
Shrink Fit to High Speed Shaft	Coefficient of friction too high.
Blade-root Strength	Design strength from one test questioned; estimate of strength of 10-inch studs questioned.
Yaw Bearing	Adequacy questioned.

Other steps in the path towards type approval and their status are:

Performance curve. Measurements were taken under the supervision of NREL (Ref. 3) and these were acceptable to GL. Little remains for this part of the certification to be approved.

Test loads. The process of obtaining loads data under the supervision of NREL was initiated but never completed.

Blade manufacturing. An audit of the blade manufacturing process was not carried out. Any future blade manufacturer will have to be approved by the certifying organization.

Although substantial progress was made with GL on the certification efforts, the problems encountered with their remote location in Germany and their lack of familiarity with the AWT-turbine architecture can not be understated. Any future certification efforts should consider the use of Underwriters Laboratory (UL) in cooperation with NREL as the certifying agency. This agency may gain the necessary international acceptance for certifying of wind turbines.

9. Commercialization of Technology

9.1 Technical Philosophy and Strategy

Downwind, two-bladed, stall-controlled technology has historically been supported by those who believe that simple, highly reliable wind turbine design will ultimately provide the lowest cost of energy, and thus, be the most economically competitive. This philosophy resulted in development of the baseline turbine architecture. This architecture avoids the cost and maintenance associated with variable pitch, variable speed or active-yaw systems and is very competitive in terms of energy production per unit of swept-rotor area. The AWT architecture is also relatively light, reducing the costs associated with transporting and installing turbines. This has been a significant issue in developing countries, where the transportation systems and crane capability are not as sophisticated as in more developed countries. Although the AWT architecture potentially offers the lowest cost of energy, and is highly suitable for developing countries, it does not offer some other attributes desired or required in some markets. For example, very low noise emissions, or a tower that provides protected access to the nacelle were not available on AWT turbines.

Recognizing these "limitations," the focus on further developments of the technology should be increasing the reliability and cost-effectiveness of the architecture, while working to minimize the limitations. This approach, if successful, should make the AWT architecture a clear choice where cost of energy is the primary consideration. As of this writing, there are significant markets where noise is not the overriding concern and cost of energy is very important. AWT turbines operating in India have generated no negative comments with regard to noise, and the open lattice tower is superior to an enclosed tube for access in hot climates. Table 9-1 summarizes the markets that AWT was targeting in late 1996. Demand in these markets was expected to approach 4,000 MW between 1996 and the year 2001.

Table 9-1. AWT's Target Market - Late 1996

Wind Speed (m/s*)	Wind Shear	Low Temp. (C)	High Temp. (C)	Crane Availability	Location	Estimated Market Size (MW)
6.0 - 6.5	0.1	4	46	Poor	India	750
6.0 - 6.5	0.2	-40	43	Good	Mid-West	300
6.5 - 7.0	0.1	4	46	Poor	India	750
6.5 - 7.0	0.1-0.15	-40	42	Poor	China	400
6.5 - 7.0	0 - 0.08	-4	42	Good	Altamont Pass	300
6.5 - 7.0	0.08-0.14	0	46	Good	Palm Springs	200
6.5 - 7.0	0.2	-17	43	Good	E. Europe	145
7.5-8.0	0.1	-6	40	Good	Tehachapi	400
8.0-8.5	0.14	5	45	Poor	Latin America	675
					Total:	3,920

* At 20 meters height

Although this was AWT's target market in 1996, the subsequent re-powering of large projects in Tehachapi, Altamont Pass, and Palm Springs demonstrated that larger turbines could be competitive in those markets. In addition, as of this writing, there are plans for substantial World Bank-supported procurements of larger turbines for the Chinese market. These developments are likely to limit the market for any turbine in the 300-kW-size range. However, if the technical problems experienced by AWT, in particular excessive dynamic activity in the post-stall region, can be solved, there is no reason the technology can not be applied to larger turbine sizes. As the size of turbines grow, the costs of the blades are expected to increase faster than the increase in swept area as diameter increases. As a result, the economic advantages of two blades, rather than three, should increase as turbine sizes increase. In addition, some of the emerging offshore markets would be expected to place a premium on simplicity and reliability, and would not be expected to be noise sensitive. Another potential market may be in small wind turbines for operation in conjunction with diesel systems. These markets may also not be highly noise sensitive and would benefit from simplicity and low turbine weight. The noise levels of the design would be reduced through refinement of the tip design. Reducing the noise emissions from the rotor should be one of the priorities of any further research to broaden the potential markets.

9.2 Intellectual Property Summary

The AWT downwind, two-bladed, teetered architecture has been used by turbine designers for many years and the AWT design was essentially an evolution of the ESI 80, which was produced by Energy Sciences Incorporated in the mid-1980s. Therefore, the architecture itself is not the property or intellectual property of AWT or any other organization. There is, however, some patented and proprietary data associated with the designs.

9.2.1 Patented Aspects of Intellectual Property Issues

There is one patent outstanding on the AWT design. That patent is Patent # 08/120,685 on the turbine blades. It specifically claims the use of NREL S809, S810, and S815 airfoils on wind turbine blades between 25 and 50 feet in length. That patent was issued on December 12, 1998 and expires on December 12, 2012. The legal ownership of the patent is disputed. Mr. Lee Richartz, Mr. Robert Lynette and Mr. Robert Poore all claim an ownership interest. Mr. Richartz claims an ownership interest because he was the owner of FloWind, Inc., which purchased the patent from R. Lynette & Associates. As part of the FloWind bankruptcy, FloWind's interests in AWT were transferred to Green Power Partners, another organization controlled by Mr. Richartz. Messrs. Poore and Lynette claim an ownership interest because AWT never made the payments it was obligated to make under the sale agreement with RLA. Messrs. Lynette and Poore were the owners of RLA.

In addition, Kamzin Technology, Inc., has applied for a patent for the use of negative delta-3 in a wind turbine rotor. This patent has not yet been issued, but was applied for on April 24, 1998. At this time, Mr. Robert Poore is the owner of Kamzin Technology, Inc.

9.2.2 Non-patented Aspects of Intellectual Property

The ownership of drawings and other intellectual property associated with the AWT design are also currently being disputed by the same parties disputing ownership of the AWT blade patent, for the same reasons. However, much of AWT's intellectual property has been provided to the National Renewable Energy Laboratory as part of various cost-shared turbine development contracts. The intellectual property was provided to NREL as "Protected Wind Technology Data." As such, it will be made public five years after being provided to NREL. Much of the intellectual property of AWT is of little or no value because the markets for wind turbines have moved toward machines that are either larger or smaller than the AWT. As a result, most of the AWT drawings would have to be redone for a new turbine design. Many of the key technical personnel from AWT are presently with Kamzin Technology, Inc.

9.3 Steps to Commercialization

In its present embodiment, the AWT design is not yet fully commercial. The AWT-26 and AWT-27 both experience loads that are higher than acceptable if the design is to meet IEC certification requirements. The turbine design modifications needed to meet certification requirements are outlined in the preceding sections of this report. Once these modifications are made, it is believed that the resulting turbine would be marginally competitive with other utility-scale wind turbines currently in the market. However, to be commercially viable, it is believed that the turbine must be clearly more economically competitive than the existing, well established alternatives. This is due to market perception with regard to two-bladed technology, the design's relatively higher noise emissions and the tower configuration limitations. Also, the additional risk inherent in the application of a new design will require a cost advantage for it to be successful. Therefore, it is believed that alternative, more economically competitive, configurations of the turbine must be developed for the technology to achieve commercial success.

The authors see four approaches to commercializing a two-bladed, downwind wind turbine. The first approach, which was the approach being proposed by AWT, is to develop a new, larger diameter version of the AWT-27 wind turbines, maintaining the 275-300 kW rating. A second approach would be to develop a substantially larger version of the turbine, perhaps in the 750-2,000-kW-size range to compete in the present mainstream utility-scale wind turbine market. A third approach would be to develop a smaller turbine to work with wind diesel systems or for utility interconnect for homes, farms, and businesses, and the fourth approach would be to develop a stall-controlled, teetered hub/rotor design that could be licensed to turbine or blade manufacturers for use on their designs.

In the authors' opinion, it is highly unlikely that any of these approaches can be successful for the long term until there is a better understanding of how to predict and control the dynamics of two-bladed, downwind, stall-regulated teetered turbines. Whether the required stability is gained through the application of negative delta-3, aero-elastic blade design, advanced aerodynamics, advanced damping systems, aerodynamic towers, variable speed operation, a combination of the preceding items or as-yet unforeseen developments is unknown. However, control of the dynamics is essential if the potential load alleviation benefits of the teetered hub are to be realized. A better understanding of the noise generated by the architecture and ways to limit it is also needed.

Once the ability to predict and control the architecture with confidence is achieved, the technical steps to commercialization are similar to any other turbine or component development program. The conceptual, preliminary and detailed design processes need to be completed, prototypes need to be built and tested, and design certification testing and documentation must be completed. Beyond the technical steps, commercialization will require coupling the technology with an organization that can provide financing, marketing, manufacturing, and management expertise.

9.4 Cost of Energy Projections

Table 9-2 presents the estimated costs (1997) of the baseline turbine, an improved "AWT-27" and a commercialized 30-meter, dual-speed version of the turbine. As shown in the table, the costs of energy is substantially improved through the use of a larger diameter rotor. These costs are based on costs incurred in a 100-unit production run of the original AWT-27 turbine. They do not reflect cost reductions that would be achieved if a larger, longer-term production run were initiated. They also do not reflect the potential cost reductions associated with integrating the gearbox and mainframe into a single unit and other similar potential cost reductions. Based on data available from the industry, the baseline turbine costs are competitive with turbines that were generally available in 1996/1997. Industry trends indicate further cost of energy reductions should also be available from increasing the size of the turbine to the 750-2,000-kW-size range.

Table 9-2. Cost Summary and Economic Figure of Merit

	Baseline	Improved "AWT-27"	AWT-30DS
Rotor Assembly	**$32,050**	**$26,216**	**$29,612**
Blades	$19,034	$19,800	$23,560
Aerodynamic Control System	$1,812	$853	$853
Rotor Hub, Teeter Assembly, and Extenders	$9,204	$5,564	$5,199
Misc.	$0	$0	$0
Nacelle Assembly	**$50,612**	**$52,983**	**$58,254**
Gearbox	$25,560	$25,560	$30,560
Generator	$7,650	$10,650	$10,650
Other Drivetrain	$1,627	$1,627	$1,627
Mechanical / Electrical brake system	$4,341	$3,766	$3,766
Mainframe	$3,456	$3,802	$3,802
Yaw System Including Bearing, Lock, Unwind Motor	$3,111	$2,711	$2,982
Nacelle Cover	$4,463	$4,463	$4,463
Work Platform	$0	$0	$0
Misc.	$404	$404	$404
Tower & Tower Top	**$29,000**	**$27,000**	**$30,000**
Control and Electrical Systems	**$26,061**	**$26,521**	**$26,721**
Parts Subtotal (current dollars)	**$135,723**	**$132,720**	**$144,587**
Factory Assembly	$2,400	$2,400	$2,400
Subtotal Before G&A, Shipping, and Profit	**$138,123**	**$135,120**	**$146,987**
General & Administrative Fee = 8.0%	11,050	$10,810	$11,759
Subtotal Before Profit & Direct Overhead	**$149,333**	**$145,930**	**$158,746**
Profit & Direct Support Overhead = 20.0%	$30,267	$29,186	$31,749
Turbine Cost, FOB Plant	**$179,599**	**$175,116**	**$190,495**
Shipping Costs & Insurance (in & out) **3.25%**	$4,489	$4,313	$4,699
Total On-Site Cost Per Turbine/Tower	**$183,153**	**$179,429**	**$195,194**
Balance of Station	$48,187	$48,187	$48,187
Total Initial Capital Cost per Turbine	**$231,683**	**$227,616**	**243,381**
Annual O&M Per Turbine (including land lease)	**$6,868**	**$5,868**	**$5,868**
Levelized Replacement Costs	**$445**	**$445**	**$445**
Net Annual Energy Production per Turbine (kWh)	**566,662**	**597,000**	**681,266**
Cost of Energy	**$0.0576**	**$0.0535**	**$0.0498**
% Change Relative to Baseline		-7.1%	-13.5%

9.5 Costs to Complete Steps to Commercialization

The costs to commercialize a downwind, two-bladed wind turbine will vary greatly, depending upon the approach taken. Development of a multi megawatt turbine would clearly cost substantially more than development of a hub and rotor design or development of a larger diameter version of the AWT-27. In a series of cost proposals provided to NREL from late 1996 to early 1998, the technical costs of developing a commercial, certified AWT turbine with a 30-33 meter rotor diameter were estimated to be between $5.1 and $7.4 million, depending upon the number of prototypes developed and the number of configuration changes made. These costs were broken down as follows:

Parts: $700,000 - $1,000,000
Labor, Certification Services, Test Support: $4,000,000 - $5,700,000
Patterns, Molds, other Equipment: $200,000 - $400,000
Other: $200,000 - $300,000

These costs include an estimate of the costs required to achieve post-stall stability of the teetered rotor. There is considerable uncertainty regarding what will be required to obtain this stability. Negative delta-3 hub configurations appear to offer a partial solution, however, additional work in this area is clearly required.

9.6 Justification for Future Development

As outlined in the preceding sections of this report, downwind, two-bladed, stall controlled rotors have the potential to reduce the cost of energy. If the post stall dynamics of the turbine can be controlled, while maintaining the loads alleviation characteristics available from the teetered rotor, the reduction in system cost and complexity relative to three-bladed, active-yaw, pitch-controlled turbines will be significant. Although it is unlikely that the two-bladed rotor will ever be as quiet as a three-bladed rotor, many of the emerging wind energy markets are less noise sensitive than the existing land-based European markets. For example, the offshore market in Europe is rapidly developing. In this market, maximizing reliability, while minimizing cost, must be a priority, and, the majority of the turbines installed are expected to be over one megawatt in size. The potential savings associated with eliminating a blade and the pitch system on machines this size are significant. If the yaw drive can also be eliminated, further savings can be realized. Similar conditions may exist in many of the U.S. states with strong wind resources such as the Dakotas and other parts of the western United States.

The argument has been made that a three-bladed rotor will be more efficient than a two-bladed rotor. However, the AWT-26 demonstrated that a two-bladed rotor can have equivalent or better efficiency than a three-bladed rotor, by moving at a higher tip speed.

Although the potential of the two-bladed, downwind teetered architecture has been recognized for many years, the technical challenges associated with developing commercially viable, certified, turbines have been underestimated. Despite the significant advances that have been made in understanding the technology, fundamental technological challenges continue to exist. However, the industry's understanding of the problem has improved, and the investigative tools currently available are vastly superior to those that were available at the beginning of the AWT development program.

For this architecture to be a technical success, the post stall behavior of the rotor must be controlled. The research needed to reach this goal includes:

1. Improving the codes used for modeling three dimensional aerodynamics, particularly in the post-stall environment.
2. Improving the industry's understanding of the inflow to the rotor and the tools for adequately modeling it.

3. Improving the tools for relating the inflow characteristics to the structural response of the turbine. While the existing tools provide different responses to different inflows, it is difficult to understand the cause of the response and thus difficult to develop a means of reducing it. Improving the tools would be facilitated by additional high quality inflow and associated turbine response data, for different rotor configurations.

In summary, while the potential offered by the technology is considerable, a real understanding of the technical problems has only recently been available to those working to develop the technology. If recently-developed tools can be combined with additional research in the areas noted above, the potential exists to reduce the cost of wind energy with a simple high-reliability architecture applicable to a wide variety of machine sizes and types.

10. References

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