CALIFORNIA
ENERGY
COMMISSION

The Next Generation Wind Turbine Development Project

CONSULTANT REPORT

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Prepared By:
The Wind Turbine Company
1261-120th Avenue NE
Bellevue, WA 98005
Contract No. 500-97-032,

Prepared For:

Dora Yen
Valentino Tiangco
Contract Manager

George Simons,
Project Manager

Terry Surles,
Deputy Director
Technology Systems Division

Steve Larson,
Executive Director

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WTC would like to recognize the hard work of the Company's employees and its supporting consultants and vendors for their efforts.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental research
- Strategic Energy Research

What follows is the final report for The Next Generation Turbine Development Project, Contract Number 500-97-032, conducted by The Wind Turbine Company. The report is entitled The Next Generation Turbine Development Project, Final Report. This project contributes to the PIER Renewable Energy program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

It has long been recognized that commercially available, utility scale wind turbines are not able to produce competitively priced electricity. Recently, the Federal Production Tax Credit for wind energy was again extended. Further, under the Commission's Renewables Program, many wind energy producers in the State also receive production payments ranging from 0.5¢ to 1.5¢ per kilowatt-hour (kWh).

In 1994, the Department of Energy (DOE) created the "Next Generation Turbine Development Project" to help develop a new wind turbine capable of generating lower cost electricity. In 1995, The Wind Turbine Company (WTC) won a competitive solicitation under this program and began work on its new turbine. In June 1998, the Commission, again through a competitive solicitation, chose to support WTC's project with the intent of accelerating the development of this new design in order to achieve a more rapid entry into the commercial marketplace.

The goal of the DOE and the Commission was a commercial wind turbine that could produce electricity at good wind resource sites for an unsubsidized price of 3.0-3.5¢/kWh. WTC believes this goal can be attained by 2005, if not sooner. The DOE's target is 2010. The overall project goal identified in Contract No. 500-97-032 Work Statement was "to design, develop and demonstrate a 350 kW rated-capacity wind turbine that will produce electricity at prices that do not need subsidies or premiums to compete in the emerging electricity market-place. This overall project goal supports PIER program objectives by; improving energy cost/value of California's electricity, causing substantial reduction in air pollution deriving from fossil-fuel electricity generation, and providing positive impacts to California's state and local economies by the creation of new jobs and new tax revenues."

Objectives

Two technical objectives were identified:

- Demonstrate the feasibility of employing all the wind turbine concepts (the proof of concept (POC) and the Wind Turbine Company (WTC) 350).
- Achieve the identified weight reduction targets. This target will provide comfort that WTC's targeted "should cost" objectives for the commercial WTC 350 can be achieved.

The economic objective was:

- To develop a 350 kW wind turbine capable of producing electricity at prices competitive with the lowest cost sources of conventional electricity generation. The specific economic objective is to produce electricity for $0.035/kWh or less when installed in annual quantities of 100 units or more in windfarms featuring Class 5 wind resources (or at 6.7 m/s (15 mph) sites).

In a collaborative effort between WTC, the Commission, and the DOE, through the National Renewable Energy Laboratory, two prototype wind turbines were developed.

WTC's proof-of-concept (POC) turbine, rated at 250 kilowatts (kW) was installed in February 2000 near Denver, Colorado, and has operated successfully since May 2000. Although minor system bugs have occurred, they have for the most part been eliminated. The POC has accomplished all design objectives. Most importantly, through measurement of stress loads at

approximately 60 locations on the turbine it has been demonstrated that (1) the computer models used to predict loads and to establish component configuration and system design were slightly conservative in their predictions, and (2) the stress loads encountered by the POC are significantly (approximately 3 orders of magnitude) less that the loads encountered by conventional wind turbines. The POC has also demonstrated the turbine control system works as desired.

A 500 kW prototype was installed in December 2001 in Los Angeles County. This "pre-commercial" turbine was grid connected in February 2002 and began initial testing in early March. This turbine will be placed in a commercial operating mode in May/June 2002.

In addition to test objectives, WTC's commercial objective is to develop engineering and manufacturing plans that will demonstrate a clear path to the manufacturing cost targets for this turbine and its commercial derivatives. Based on the cost of the 500 kW turbine and the DOE's goal of producing 3.0¢/kWh wind power when cumulative production reaches 500 turbines, WTC determined it must achieve a production learning curve of 88 percent (every time cumulative production doubles the average cost of the new machines decreases by 12 percent from the previous level), which is well within the range achieved by manufacturers of large scale equipment.

Outcomes

It is too early to demonstrate that the overall project goal, development of a wind turbine that does not need subsidies or premiums to produce competitively priced electricity has been or can be met; however, there is evidence to suggest WTC is on the right track.

Technical Objectives

- WTC accomplished the first technical goal identified above. Since May 2000, when the POC began test operation, the turbine has operated almost 1,400 hours. Data gathered to date provides valuable information about stress and fatigue loads encountered by the machine.
- The identified turbine weight objective was not achieved. This is attributable to the fact that the rated capacity of the final turbine objective has more than doubled from 350 kW to 750 kW. Although the absolute weight target identified in Contract No. 500-97-032 has been exceeded, the relative weight relationship is strong evidence that the turbine weight objective has been reached.

Economic objective

- WTC's turbines have yet to attain the PIER Program economic goals, however, as will be discussed in the Program Outcomes section, WTC believes these goals are in reach and could even be attained within the targeted timeframe.

As was painfully demonstrated during the 12 months from May 2000 to May 2001, California needs a significant amount of new electricity generating capacity that does not depend on the vagaries of the natural gas markets. Wind energy clearly has a major role to play in creating a long-term, stable supply of electricity for the State from a non-polluting source. Although California already has a considerable number of wind turbines installed in the main wind energy resource areas, the potential for future development is much larger and only now

beginning to be better understood. The availability of a commercially viable wind turbine that does not require subsidization will only increase the potential for wind energy.

Not only will stable, low-cost supplies of wind energy benefit the State's residents, businesses, and governmental agencies, the resulting new production facilities and the local manufacture of wind turbines will provide important new jobs. This is particularly true in rural regions of the State where higher winds are usually found and which often suffer from higher unemployment and fewer job opportunities than the more urbanized parts of the State.

Achievement of the cost reduction goal will require one additional hardware development effort, the development of a new, purpose-designed rotor blade for use on the turbine. This new blade set will increase the turbine's rated capacity to 750 kW with no additional cost and therefore will result in an immediate, significant improvement in the turbine's economic performance.

Conclusions

The following conclusions were reached.

- The principle conclusion of the NGT Project was that WTC's wind turbine concept works very well. Data gathered to date incontrovertibly supports the conclusion that WTC's hinged-blade coupled with its proprietary flap motion restraint system significantly reduces the largest source of fatigue stress loading on a wind turbine – the loads resulting from the wind bending rigidly attached blades in the downwind direction.
- A finding important for all future wind turbine development efforts is that the predictive system structural dynamics models used to design the POC and WTC 500 wind turbines were surprisingly accurate in loads prediction. The ADAMS and BLADED models have convinced WTC's engineering team of their value. It is critical for the future of the wind industry that hardware designers take advantage of and benefit from the most sophisticated tools available and that the tools get better.
- During the execution of this program WTC's engineering team moved steadily away from the simpler is better school of thought to the school that relies on understanding the complexity of the environment in which wind turbines operate. Better understanding is required in order to achieve better results, and such understanding is not possible in the absence of better tools such as the dynamic analysis models ADAMS and BLADED.

Commercialization Potential

WTC believes the case for a commercially viable version of its new wind turbine is stronger today than ever. Although it is clear that the WTC 500, configured with all components designed for application on a 750 kW capacity turbine thus incurring the additional expense of a machine with 50 percent greater capacity, would struggle commercially, once the purpose designed blade set is available the turbine will quickly achieve its commercial potential. This machine will be commercially available in 2003 and within a year if not sooner will be capable of beating the COE target of 3.5¢/kWh contained in WTC's proposal to the Commission by up to ½ cent per kWh. Subsidies will then no longer be necessary.

Recommendations

- The PIER Program is a powerful source of funding for new technology development in the renewable energy industry. WTC encourages the State of California make every effort to assure that the DOE's renewable programs are lined up in support of the Commission's programs.
- During the execution of contracts, WTC suggests that, depending on contract duration, the Commission require a regular, quarterly or semi-annual sit-down debriefing on project progress and plans with critical Commission staff and management.
- To enable the Commissioners to obtain a better first hand understanding of the agency's programs, the Commission should strongly recommend contractor attendance at important policy and program review meetings involving the Commissioners.
- The Commission's Contract Manager position changed hands three times in four years. Thus there was some discontinuity and re-education. As suggested in the Observations above, a good balance is required to achieve a desirable level of project involvement by an agency's Project / Contract Manager. It seems the Commission's staffing limitations may, unfortunately, preclude a deeper involvement in the Commissions PIER projects.

Benefits to California

Although California has yet to see the major benefit of the NGT Project – lower cost wind energy – several less consequential benefits have already occurred:

- WTC has identified and worked closely with a number of component suppliers and these relationships are expected to continue into future commercial production.
- WTC has California-based employees and will add to its California payroll as quickly as commercial considerations permit.
- The Company has identified one promising location where it could establish a wind turbine assembly facility as soon as commercial business opportunities develop.
- Within its resource constraints, WTC has made a concerted effort to identify opportunities to deploy its wind turbines in commercial developments in the state.
- WTC has an agreement with a Los Angeles-based developer to develop one or more wind projects totaling approximately 100 MW of installed capacity with the electricity to be sold to the DWP.
- WTC is working with a major utility-affiliated wind development company to evaluate the feasibility of deploying WTC's new 750 kW wind turbines in a major project in Southern California. WTC believes the lower cost and increased capacity factor achievable by its turbines will make the difference between a decision to go forward with the project or not.
- WTC believes it has helped, to a limited extent, enhance the role of the Commission PIER Program Renewables Group with NREL's Wind Program organization.

The longer term and major benefit to California remains the goal of lower cost wind energy that does not require subsidies for either on going operation or for project development in the first place.

Abstract

The Wind Turbine Company's new wind turbine is based on concepts employed in earlier wind turbines. It incorporates a proprietary, hinged-rotor-blade, a concept from the helicopter industry that operates with a blade "Flap Motion Restraint System" which controls movement of the blades in the out of plane direction. This concept was expected to significantly reduce the major source of wind induced stress loading on the machine – that associated with bending rotor blades that are rigidly attached to the rotor shaft. Computer models predicted this configuration would reduce loads by three orders of magnitude compared with conventional upwind turbines. By reducing loads the turbine designer can safely eliminate material required in conventional wind turbines to absorb them. Material reduction means cost savings. The initial cost of a utility scale wind turbine represents about 70 percent of the resulting electricity cost. Significant reductions in the cost of wind-generated electricity must come from turbine cost reductions.

The goal of the "proof-of-concept" turbine was to demonstrate predicted load reductions could be achieved and measured loads are less than were predicted. With this finding, it is possible to reduce material requirements across all major turbine structural components by approximately 40 percent compared with similarly rated upwind turbines. This will translate into a 20-25 percent cost reduction. Combined with a guy-cable supported tower, a more economic means of elevating the rotor hub height to capture higher winds aloft to produce more energy, which can only be effectively employed on downwind turbines (blades operate downwind of the tower), the effect is expected to result in an electricity cost reduction of 30 percent or more compared with upwind turbines.

Goals for the second prototype turbine are to demonstrate the technology on a commercial scale and provide the basis for manufacturing economic analyses to assure manufacturing cost targets can be achieved.

Figure 1: WTC Proof-of-Concept

250 kilowatts rated capacity, Installed February 12, 2000, National Wind Technology Center, Jefferson County, Colorado, 38-meter tower, 33-meter rotor

Figure 2: WTC 500
500 kilowatts rated capacity, Installed December 12, 2001, Fairmont Reservoir, Antelope Valley, Los Angeles County, California, 62-meter tower, 48-meter rotor

1.0 Introduction

On June 24, 1998, The Wind Turbine Company (WTC) entered into Contract No. 500-97-032 with the California Energy Commission (Commission). Awarded under the Public Interest Energy Research (PIER) Program, this contract provided funding enabling WTC to complete and test the first prototype of its new wind turbine concept (Figure 1) and build and install a second, pre-commercial prototype turbine (Figure 2). WTC's proposal to the Commission was titled "The Next Generation Turbine (NGT) Development Project." This report, the final deliverable under Contract 500-97-032, describes the activities leading to the completion of these two wind turbines, the results to date from the operation of the first turbine, and also describes the relationship between WTC, the Commission, and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), which is the primary source of funding for this project.

Appendix V provides project cost sharing details among WTC, the Commission, and NREL.

1.1. Background

On December 31, 2001, the Federal Production Tax Credit, worth over 1.7 cents per kilowatt-hour (kWh) of electricity generated by qualifying wind turbine installations, expired. It was subsequently extended through December 31, 2003, in March 2002. As a result of the expiration of this credit, it was widely anticipated that new wind turbine generating capacity installed in the United States in 2002 would plummet in comparison with the record 1,694 megawatts (MW) of capacity installed during 2001. A forecast recently issued by the American Wind Energy Association suggests capacity installation in 2002 will do well to reach 1,000 MW.[1]

Since the beginning of the modern wind energy era in the late 1970s, it has been recognized in the United States and elsewhere, that existing wind technology cannot generate competitively priced, low-cost electricity without subsidization. Market acceptance of this promising form of non-polluting electricity generation has languished as a result.

The U.S. Department of Energy (DOE) recognized the non-competitive nature of wind energy and in the early 1990s established the "Next Generation Turbine (NGT) Development Project," under its "Advanced Wind Turbine Program." The intention of this program was to create new wind technology that could produce competitively priced energy without need for on-going operating subsidies. In October 1995, as the result of a competitive solicitation, WTC was selected to develop an all-new, low-cost of electricity wind turbine under this program. After extensive negotiations, WTC began design of its new turbine concept in February 1997 under a contract administered by NREL.

In 1995, the unsubsidized cost of electricity from then existing state-of-the-art wind turbines installed in large-scale wind projects was 5.0-6.0¢/kWh. The NGT program goal was a wind turbine capable of producing <u>unsubsidized</u> electricity for 2.5-4.0¢/kWh depending on the winds available for electricity production (the "wind resource"). By December 31, 2001, the unsubsidized electricity production cost of contemporary wind technology had dropped to 4.5-5.0¢/kWh. However, the cost of electricity (COE) from combined cycle natural gas generation

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[1] Wind Energy Weekly, Vol. 21, #968, 15 March 2002, "Project Development Beginning To Roll Again – U.S. could install 650-1,000 MW in 2002."

units was in the 3.0-4.0¢/kWh range depending on gas prices. Contemporary wind turbine technology is still too expensive to compete without subsidization.

The importance of government funding of new wind technology cannot be over-emphasized. The modern wind industry got its start in the late 1970s as a result of dramatically increasing oil prices attributed to the actions of the Organization of Petroleum Exporting Countries earlier in the decade. Support for alternative energy technologies occurred around the world for a multitude of different technologies. As the result of ensuing events, on-going government support of wind energy technology development became mandatory if improved machinery was to be produced. To its credit, the California Energy Commission saw the need and wanted improved technology moved quickly into the commercial marketplace.

1.2. California Energy Commission PIER Program Goals

In awarding WTC a contract, the Commission had two primary objectives – lowering the cost of wind-generated electricity and providing a quick path to commercial deployment of a promising new turbine. The Commission did not want an extended duration research and development project. PIER Program Request for Proposals #500-97-503 identified three types of projects on which the Renewable Technology area was focused:[2]

1. "Projects that develop renewable energy products or services with reduced costs, thereby enabling renewable energy to be a more cost-effective option for ensuring energy diversity and reliability in the electricity markets. In particular, projects that will reduce or eliminate the need for economic supports for renewables by the year 2002 (i.e., when the renewable funding supports provided under AB 1890 end) are highly encouraged. Applicants should identify the percentage cost improvements needed to achieve market cost-competitiveness for the renewable technology in question, and then compare it with expected percentage cost improvement goals of the proposed RD&D project. Cost reductions of at least 40 percent of the amount needed to attain market competitiveness for the type of renewable energy products and/or services contained in the proposal is generally considered to be an appropriate 'stretch goal' in this area.

2. Projects that develop products or services to better capture the non energy benefits of renewable energy, e.g. developing innovative ways to obtain economic gains from non energy benefits such as reduced environmental or public health impacts. Capturing non-energy benefits in either revenues or cost savings of at least 20 percent above current best practices is generally considered to be an appropriate 'stretch goal' in this area. An example of such a project would be the development of an integrated renewable products system that can produce multiple market products, thereby increasing the revenue streams for either existing or new renewable facilities.

3. Near-term projects (e.g. market ready within 5 years) that can demonstrate to the financial community the technical reliability and financial viability of advanced renewable technologies, and offer the potential for significant value in the electricity market."

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[2] "California Energy Commission Public Interest Energy Research (PIER) Program First General Solicitation," Request for Proposals RFP 500-97-503, Released February 13, 1998, California Energy Commission Contracts Office, 1516 9th Street, MS-18, Sacramento, California 95814.

WTC believed its new wind turbine met each of these requirements.

1.3. WTC Turbine Development Project Overview

In 1995, commercially available wind turbines were rated in the 400-750 kilowatt (kW) range though several European manufacturers were testing prototypes in the 750-1000+ kW range. WTC proposed to NREL to build a 1000 kW (1 MW) "proof-of-concept (POC)" turbine, then manufacture three pre-commercial prototype 1000 kW turbines. After negotiations with NREL, it was agreed the POC would be developed as a "subscale" prototype, rated at 250 kW. Once the POC turbine was tested, WTC would design a full-scale, 1000 kW pre-commercial prototype. Figure 3 presents the timeline of this development effort, which began in early 1997.

Task Name	Duratio	Start	Finish
PROTO-250 Turbine Design, Manufact	**641 days**	**Fri 2/28/97**	**Wed 9/15/99**
Design and Analysis	**116 days**	**Fri 2/28/97**	**Tue 8/12/97**
Authorization to Proceed	0 days	Fri 2/28/97	Fri 2/28/97
POC Analytic Model Version 1	**80 days**	**Fri 2/28/97**	**Fri 6/20/97**
Design Wind Regime	**20 days**	**Fri 3/14/97**	**Thu 4/10/97**
System Design Criteria	5 days	Fri 4/25/97	Thu 5/1/97
Permissible Design Stress	10 days	Fri 5/2/97	Thu 5/15/97
Design Load Cases	5 days	Fri 5/16/97	Thu 5/22/97
Trade-off Studies	**80 days**	**Fri 2/28/97**	**Fri 6/20/97**
POC Analytic Model Version 2	**21 days**	**Mon 6/2/97**	**Mon 6/30/97**
Eng Methods & Procedures	**88 days**	**Fri 2/28/97**	**Wed 7/2/97**
FEA Structural Models	**70 days**	**Fri 3/14/97**	**Fri 6/20/97**
Turbine Config Update	15 days	Mon 6/23/97	Mon 7/14/97
Certification Plan	20 days	Fri 3/14/97	Thu 4/10/97
Program Cost Update	20 days	Fri 4/11/97	Thu 5/8/97
Program Schedule Update	20 days	Fri 5/9/97	Fri 6/6/97
Design Review Package	**30 days**	**Mon 6/9/97**	**Mon 7/21/97**
Design Review	1 day	Tue 8/12/97	Tue 8/12/97
Final Design , Build, and Test Authori	0 days	Wed 9/10/97	Wed 9/10/97
Design, Maunfacture, Assemble, ar	**255 days**	**Wed 9/10/97**	**Wed 9/16/98**
Loads Analysis and Control Stst	**238 days**	**Wed 9/10/97**	**Fri 8/21/98**
Structural Dynamics Analysis	**238 days**	**Wed 9/10/97**	**Fri 8/21/98**
Rotor Design, Mfg, and Assembl	**244 days**	**Wed 9/10/97**	**Mon 8/31/98**
Tower and Nacelle Design, Mfg,	**254 days**	**Wed 9/10/97**	**Tue 9/15/98**
Geartrain Design, Mfg, and Asse	**255 days**	**Wed 9/10/97**	**Wed 9/16/98**
Hydraulic & Lubrication System	**235 days**	**Wed 9/10/97**	**Tue 8/18/98**
Roto Bearings and Mainframe D	**252 days**	**Wed 9/10/97**	**Fri 9/11/98**
Rotor and Nacelle Shop Assemb	**17 days**	**Tue 8/11/98**	**Thu 9/3/98**
PROTO-250 Operational	0 days	Wed 9/16/98	Wed 9/16/98
PROTO-250 Testing	**250 days**	**Thu 9/17/98**	**Wed 9/15/99**
POC-1000 Commercialization	**495 days**	**Thu 10/22/98**	**Tue 10/10/00**
WTC-1000 Commercialization	**325 days**	**Mon 2/7/00**	**Mon 5/21/01**

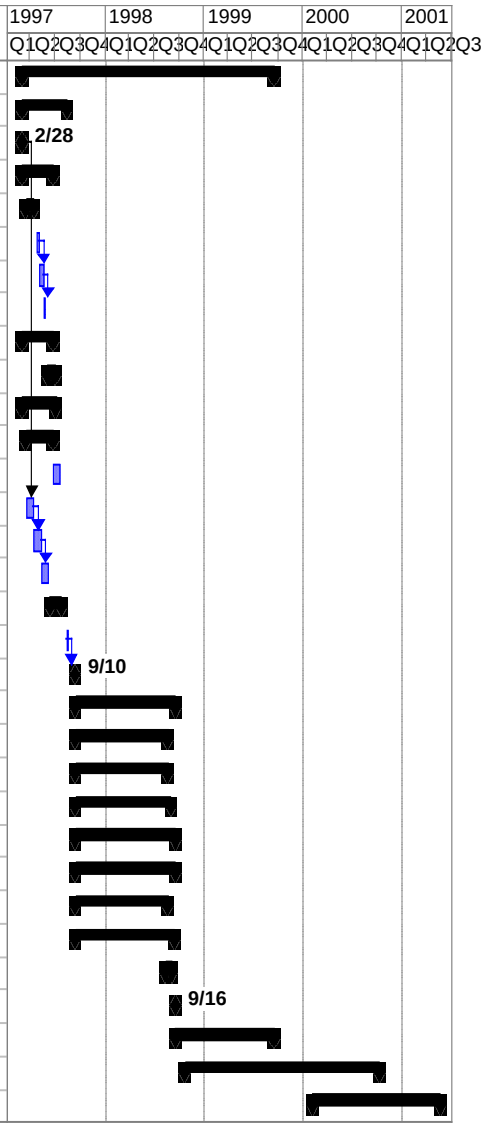

Figure 3: Timeline for Development of WTC Wind Turbines under DOE/NREL NGT Project

Under the NREL project timeline, it was expected to take three to four years beyond completion of the POC before WTC could field a commercial wind turbine. However, WTC recognized the importance of quickly offering a commercial turbine. By 1997, WTC believed a direct scale-up of the POC, involving component level redesign, could result in a commercial turbine rated at 350 kW within two years of completing the POC. WTC also believed this turbine could be developed in parallel with the larger machine to be developed under its NREL contract. These beliefs formed the basis of WTC's proposal to the Commission under the PIER Program solicitation.

Under WTC's PIER contract, limited funding was available to complete the POC turbine. Upon completion of the POC, WTC's contract efforts with the Commission and with DOE / NREL were to run on parallel paths as depicted in Figure 4.

Project Phases

Proof-of-concept (POC) turbine development	Commercial POC (WTC 350) turbine development	Sustained commercial production of WTC 350	
Funding Sources: WTC, DOE / NREL Proposed: CEC	Funding Sources: WTC Proposed: CEC		
	Prototype WTC 1000 turbine development	Commercial WTC 1000 turbine development	Sustained commercial production of WTC 1000
	Funding Sources: WTC, DOE / NREL	Funding Sources: WTC, DOE / NREL	

Figure 4: Relationship between proposed CEC PIER Program project to develop WTC 350 and DOE/NREL project to develop WTC 1000

NGT Project proposed for PIER funding piggybacks on larger DOE/NREL funded project.

WTC installed the POC wind turbine at the DOE's National Wind Technology Center (NWTC) near Boulder, Colorado, in February 2000, approximately 17 months behind schedule. (The NWTC is managed by NREL.) The reasons for this schedule delay are identified in the Project Outcomes section below.

By the time the POC was installed, the DOE / NREL, the Commission, and WTC recognized the practical course was to combine the development programs. Reasons for this decision were:

(a) As the result of design modifications, most critical components of the POC enjoyed substantial excess safety margins. These safety margins allowed the POC to be scaled-up to 500 kW and anticipated a further scale-up to 750 kW with modest additional engineering.

(b) It was apparent to all that WTC's engineering team was fully taxed developing a single turbine and could not develop two different machines in parallel.

This resulted in a modification to WTC's NREL contract wherein NREL agreed that the second turbine to be developed by WTC would be a direct scale-up of the POC. WTC had determined it was feasible to scale the POC to 500 kW and agreed with NREL that a further scale up to 750 kW was possible with the development of purpose-designed blades for WTC's turbine. The Commission staff agreed to this modification with WTC and NREL, allowing the rated capacity of the NGT Prototype turbine in Contract No. 500-97-032 to increase from 350 kW to 500 kW, although no formal contract modification was issued.

Under the combined Energy Commission–DOE / NREL programs, WTC redesigned and scaled-up the POC to a 500 kW turbine ("prototype WTC 500", the "Next Generation Turbine [NGT] Prototype" in the Commission contract and the "Engineering, Manufacturing, and Development [EMD]" turbine in the NREL contract), in 2000. Component procurement began in late 2000. Assembly of the nacelle structure was complete by September 2001. After resolving site-permitting issues, the turbine was installed on December 12, 2001, and grid-connected February 5, 2002, 23 months behind the original schedule. Reasons for this schedule delay are addressed in Project Outcome section.

The prototype WTC 500, pictured in Figure 2, is located at the Fairmont Reservoir in Northern Los Angeles County, California, 15 miles west of Lancaster, on property owned by the Los Angeles Department of Water and Power.

1.4. NGT Development Project Goals and Objectives

The overall project goal identified in Contract No. 500-97-032 Work Statement was "to design, develop and demonstrate a 350 kW rated-capacity wind turbine that will produce electricity at prices that do not need subsidies or premiums to compete in the emerging electricity market-place. This overall project goal supports PIER program objectives by; improving energy cost/value of California's electricity, causing substantial reduction in air pollution deriving from fossil-fuel electricity generation, and providing positive impacts to California's state and local economies by the creation of new jobs and new tax revenues."

Two technical goals were identified:

- "Demonstrate the feasibility of employing all the wind turbine concepts (the proof of concept (POC) and the Wind Turbine Company (WTC) 350).
- Achieve the weight reduction target identified in Table 1 below. This target will provide comfort that WTC's targeted "should cost" objectives for the commercial WTC 350 can be achieved.

Table 1: Weight comparison – WTC 350 versus 3-blade, upwind, 350 kW turbine

Weight in kg	WTC 350 2-blade, downwind	350 kW 3-blade, upwind
Rotor	3,250	4,400
Weight on tower	10,500	17,100
Tower*	21,300	34,200
Total Turbine Weight	31,800	51,300

Source: WTC estimates, Vestas product literature
*WTC 350 features 60-meter tower, upwind turbine features 35.5-meter tower. Lightweight downwind versus heavyweight upwind – cost/turbine is proportional to weight.

The economic goal was:

- "To develop a 350 kW wind turbine capable of producing electricity at prices competitive with the lowest cost sources of conventional electricity generation, currently recognized to be natural gas-fired combined-cycle combustion turbines. The specific economic objective is to produce electricity for $0.035/kWh or less when installed in annual quantities of 100 units or more in windfarms featuring Class 5 wind resources (or at 6.7 m/s (15 mph) sites)."

In May 1999, WTC notified the Commission's Contract Manager that analysis indicated that an opportunity existed to increase the rated capacity of the NGT Turbine from 350 kW to 500 kW by incorporating rotor blades made from carbon fiber instead of more traditional fiberglass blade material. WTC believed that achievement of the economic objective was more likely with the slightly larger machine, and could be accomplished at no additional program cost. Subsequent discussions with the Commission staff and NREL's program management team lead to an agreement, mentioned above and described in more detail below, to change the size of WTC's second prototype wind turbine to 500 kW.

It is too early to demonstrate that the overall project goal, development of a wind turbine that does not need subsidies or premiums to produce competitively priced electricity has been or can be met; however, there is evidence to suggest WTC is on the right track.

Technical goal #1: WTC has accomplished the first technical goal identified above. Since May 2000, when the POC began test operation, the turbine has operated almost 1,400 hours. Data gathered to date provides valuable information about stress and fatigue loads the machine has encountered. This is further discussed in the Project Outcomes section and results presented in Appendix III compare predicted turbine loads with measured results, demonstrating a close correlation between the two sets of data. These findings support another technical objective – validation of the predictive capability of the two dynamic analysis models used to design the turbine. WTC has also gained critical experience with the turbine's software-based operating control system. In almost two years of operation, the POC has proven that WTC's new wind turbine concept works, and that it exhibits the desired load reduction characteristics.

The POC has had minor sensor failures and has had one component failure, this to the patented "Flap Motion Restraint System (FMRS)," in this period. These failures, which have been corrected, are discussed in the Project Outcomes section. The turbine has exhibited stability in all wind conditions and has otherwise performed very well for a first of a kind machine.

Technical goal #2: As is described in more detail in the Project Outcomes section, the turbine weight objective identified in Table 1 has not been met. This is attributable to the fact that the rated capacity of the final turbine objective has more than doubled from 350 kW to 750 kW. Considering weight in relation to the turbine size, e.g., in relation to rated capacity or rotor swept area, Table 2 illustrates that the target weight of the WTC 750 is almost exactly the same as the weight goal identified in Table 1.

Table 2: Weight comparison – proposed WTC 350 versus WTC 750

	WTC 350	WTC 750
Rated capacity (kW)	350	750
Rotor diameter (meters)	33	60
Tower head weight (kg)	10,500	24,000
Rotor swept area (m^2)*	800	2,700
Weight/swept-area (kg/m^2)	13.1	8.9
Weight/rated capacity (kg/kW)	30.0	32.0
Tower weight (kg)	31,800	60,000

* Note: rotor swept area calculated assuming a 12° rotor cone angle when in operation.

Although the absolute weight target identified in Contract No. 500-97-032 has been exceeded, the relative weight relationship is strong evidence that the turbine weight objective has been reached. A further comparison with the wind industry's leading commercial wind turbine is presented in the Project Outcomes section.

Economic goal: In its proposal to the Commission, under the heading Benefits to California IOU Ratepayers and Citizens, WTC identified the following benefits that were expected to

result if the economic goal of producing unsubsidized wind energy for 3.5¢/kWh could be achieved:[3]

Benefit 1: "At 3.5¢/kWh, unsubsidized wind energy will be an important source of clean, renewable energy to California's electricity consumers.

Benefit 2: The WTC 350 could save California's floundering wind energy industry, and could easily cause the generation of wind energy to double or triple in the state.

Benefit 3: This would bring a significant number of new jobs and new tax revenues to the state, cause a substantial reduction in air pollution deriving from fossil-fuel electricity generation, and help California become the world leader and exporter of renewable power generation."

In March 1998, no one anticipated the situation that would occur in California's electricity market from mid-2000 to mid-2001. Actual events have provided seemingly compelling evidence of the need for a much larger supply of stable, low-cost electricity from wind than is now available.

However, total wind generating capacity in California has only increased from 1,247 MW to 1,713 MW, or 37 percent, in the four years from March 1998 to the present, while total U.S. wind capacity has grown 260 percent and worldwide growth has been 305 percent.

WTC's turbines have yet to attain the PIER Program economic goals, however, as will be discussed in the Program Outcomes section, WTC believes these goals are in reach and could even be attained within the targeted timeframe.

The following section describes why WTC believes its concept will reduce the cost of electricity (COE) compared with the COE from existing wind turbine technology.

1.5. Project Approach

WTC's PIER NGT Development Project was and is a hardware development program. WTC was formed in 1990 to design and manufacture an all-new, low COE wind turbine. By 1995, a promising turbine concept had emerged and patent opportunities identified. This concept was the basis of WTC's proposal to, and subsequent contract with, NREL under the DOE's NGT Development Program. By the time WTC submitted its proposal to the Energy Commission for PIER Program funding, considerable analytic work had been performed and component design was underway. WTC's initial focus was to build the machine to demonstrate the technical viability of the Company's concept. Sufficient cost analysis had been performed to convince WTC that if the turbine worked as intended the costs could be brought into line.

This section describes WTC's turbine design and compares it with existing state-of-the-art wind turbines. This will explain why WTC believes its concept will be competitive.

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[3] "THE NEXT GENERATION TURBINE DEVELOPMENT PROJECT a renewable energy project," submitted March 30, 1998, by The Wind Turbine Company in response to Request for Proposals No. RFP 500-97-503, California Energy Commission PUBLIC INTEREST ENERGY RESEARCH (PIER) PROGRAM First General Solicitation, to California Energy Commission.

1.6. Wind turbine design considerations

The cost of wind energy depends on a number of variables, including:

- Cost of the wind turbine (design and production volume dependent)
- Productive capability of the turbine (design and above ground rotor elevation dependent)
- Reliability of the turbine (design, manufacturer quality control, and maintenance dependent)
- Size of the wind project (determinant of volume economies)
- Location of the project (determinant of other infrastructure costs)
- Permitting issues (determinant of project development costs)
- Financing costs (manufacturer, turbine, and developer track records dependent, critical determinant of COE)
- Wind resource (determinant of energy production potential)

Of the variables identified above the biggest opportunity for COE reduction that is controllable by a turbine manufacturer is the cost of the wind turbine. A wind industry rule of thumb is that the cost of the wind turbines in a project represents approximately two-thirds of the resulting cost of electricity, thus turbine cost reduction offers easily the biggest opportunity for COE reduction.

To meet the objective of designing a wind turbine capable of reducing COE, WTC focused on the 2-blade, downwind design. This design provides opportunities for loads mitigation and thus turbine weight reduction compared with the prevalent 3-blade, upwind turbines. It also permits the use of a slender, guy-cable supported tower to more economically elevate the rotor hub height in order to capture higher winds aloft.

A wind turbine designer's challenge is to make a lower cost machine that does not sacrifice energy production or reliability. There are numerous books addressing design considerations.[4] In the California wind industry in the early 1980s many designs were pursued. Most common were "horizontal axis" machines (axis of rotor rotation parallel with the ground), featuring two or three rotor blades oriented upwind or downwind of the tower in operation, and "vertical axis" machines (axis of rotor rotation perpendicular to the ground).

By 2001, almost all of the utility scale wind turbines installed worldwide were horizontal axis machines featuring three blades oriented upwind of the tower. None of these machines could produce competitively priced electricity in a utility scale setting, particularly in the United States. (Undoubtedly, there are locations in less well-developed countries where unsubsidized wind can compete with existing generating technologies if any. There are remote locations in Alaska, for example, where wind may be competitive with existing diesel-fired generation.)

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[4] A particularly instructive book for the non-technical reader is "Windturbines, Fundamentals, Technologies, Application, Economics," by Erick Hau, Springer, 2000, first published in Germany

Figure 5 pictures a 3-blade, upwind turbine manufactured by the Danish company, Vestas, the wind industry's leading turbine manufacturer. This machine, the Vestas V-47, rated at 660 kW, is the company's leading, albeit smallest product. It is believed to be the most economic wind turbine available today. This turbine has been in commercial production since 1997, with over 5,000 units in operation around the world.

Figure 5: Vestas V-47, 660 kW, leading 3-blade upwind turbine

In contrast with Figure 5, WTC's turbine design, pictured in Figure 1 and Figure 2, clearly features only two blades. Less obvious, these blades are oriented downwind of the tower in operation.

This presents a clear configuration difference – 3-blade, upwind versus 2-blade, downwind.

Design considerations – 3-blade, upwind machines:

This design has been popularized by Danish companies and may have originated in Denmark. It is a rigid (robust) machine. In operation, the wind pushes the blades toward the tower and also attempts to turn the rotor downwind. Rigidity is required to prevent the blades from striking the tower and electro-mechanical rotor orientation is required to align the rotor in the prevailing wind direction. Rigidity is achieved by adding material to components. The design evolved to its present state through efforts of small European companies supported by various government agencies. In fact, this is the turbine design selected by the Danish government in the late 1970s to receive support. Design refinements include electronic control systems to improve power quality. Some turbines allow the rotational speed of the rotor to vary with wind speeds in an attempt to improve energy capture and reduce loads.

Design considerations – 2-blade, downwind machines:

This design was initially deployed in the California market in the early 1980s by two small U.S. wind companies, ESI Inc. and Carter Wind Systems. (A division of United Technologies Corporation also built two multi-MW machines of this design in the early 1980s, but these machines were never produced commercially.) In operation, the wind pushes the blades away

from the tower so blade and tower stiffness is of less concern. A 2-blade downwind turbine will self-orient to changes in wind direction, thus not requiring electro-mechanical orienting devices or additional structure to absorb off-centered winds. Both of these considerations are important load mitigation, thus material and cost reduction, opportunities.

This design is not without shortcomings. Blades passing behind the tower go through an area of disrupted airflow. In some circumstances this creates unacceptable low-frequency noise.

More importantly, however, early manufacturers of this design, ESI and Carter, were unable to overcome design flaws that led to unreliable performance. Technical failures led to commercial failures and the 2-blade, downwind design became widely discredited within the wind industry. This attitude exists in the industry to this day.

Table 3: Figures of Merit – Vestas V-47 versus WTC Turbines

, compares the two design approaches by looking at the weight on top of the tower (the turbine and rotor) of the Vestas V-47 with the POC, the prototype WTC 500 and the WTC 750. Also included in this table is the rotor-swept-area (the area of the rotor plane) of each machine, and the ratio of weight to swept area.

Table 3: Figures of Merit – Vestas V-47 versus WTC Turbines

	Vestas V-47	POC	WTC 500	WTC 750
Rated capacity (kW)	660	250	500	750
Rated wind speed (m/s)	15	14	13	13
Rotor diameter (meters)	47	33	48	60
Tower head weight (kg)	27,600	18,800	23,000	24,000
Rotor swept area (m^2)*	1,735	800	1,700	2,700
Weight/swept-area	15.9	23.5	13.5	8.9

* Note: WTC rotor swept area calculated assuming a 12° rotor cone angle when in operation.

As has been previously indicated, weight is a proxy for system cost. All wind turbines employ similar materials that undergo comparable machining and other value-added enhancements, thus the relationship between weight and cost is roughly linear over the range of consideration, however, it is not directly proportional.

Swept-area is a proxy for power production. With equally efficient rotors, power production is directly proportional to rotor swept area although 2-blade machines produce about 97 percent of the energy produced by 3-blade machines.

The difference in rated capacity wind speed is a design choice. Vestas rates its machine at a higher wind speed, 33.6 mph (15 meters/second [m/s]), while WTC will rate its turbines at a 29.1 mph (13 m/s) wind speed. This is a trade-off of slightly higher electricity production for Vestas versus better system optimization as reflected in a higher system capacity factor for WTC.

The technical arguments favoring the downwind design relate to the structural (fatigue and extreme event) loads placed on wind turbines by the wind. A wind turbine suffers catastrophic failure in two primary ways (1) a blade(s) striking the tower will destroy the blade(s) and

possibly the tower, or (2) the tower buckles and the structure falls over. Upwind turbines avoid these events by absorbing accumulated fatigue and extreme event loads. This is accomplished by making components rigid, robust, or “beefier”, i.e., by employing more material. The downwind design mitigates or “sheds” loads by allowing components to bend and/or by employing articulating components. By far the largest source of wind turbine fatigue loading originates with the blades. This led WTC to develop and patent its hinged-blade FMRS. The downwind design can significantly lower material requirements, but it requires a greater engineering effort to avoid mistakes. The sophisticated engineering tools and low cost computing power available in 1995 when WTC began its turbine development work did not exist for turbine designers, i.e., ESI and Carter, in the early 1980s.

A second important COE reduction opportunity open to downwind turbines is the ability to effectively employ slender, guy-cable supported towers (see Figure 2). In operation, a slender tower sways back and forth (in the process relieving bending loads) more than is feasible with an upwind design (towers of upwind machines bending in the upwind direction close the distance between the rigidly attached blades and the tower). Allowing the tower to sway permits use of much smaller diameter, straight-pipe towers. In large-scale manufacture, WTC’s tower will be machine-manufactured natural gas transmission pipe that is very low cost per unit of length. Employing a guy-cable support system also significantly reduces foundation cost. On sites featuring good windshear (higher winds aloft), the low cost, guy-cable supported tower makes it much more economical to install tall towers than if the tower is cantilevered or freestanding. This results in higher electricity production on a given site with a guy-cable supported downwind turbine than is feasible with upwind turbines.

It is the combination of a lower cost wind turbine and higher electricity generation potential due to the ability to economically exploit higher winds usually found at higher above ground elevations, which translates into WTC's cost advantage over today's leading wind turbines. This advantage is large enough that WTC's turbines will compete directly with low-cost natural gas generators without the need for Federal Production Tax credits, support from California's Renewable Resource Accounts or other subsidies. Table 4 identifies the cost reduction potential.

Table 4: Comparison of Economic Performance – Vestas V-47 versus WTC 750

	Vestas V-47	WTC 750
Turbine system cost	$412,500	$375,000
Turbine system cost (per kW rated capacity)*	$625.00	$500.00
Tower height (meters)	50	75
Annual electricity production (MWh)**	2,570	3,225
AEP per kW rated capacity (kWh)	3,894	4,300

*Vestas value estimated from published reports. WTC commercial production target.
**Based on wind data from Sacramento Municipal Utility District's Solano County wind project.[5]

The following section describes the work undertaken by WTC and the outcomes of this work.

[5] Request for Proposal No. 1669.GVM, Solano Wind Project – 10 MW (Phase 1), Volume 2 of 2, Appendix B, "Summary of District's Relevant Wind Data.", Prepared by Supply Chain Services, Sacramento Municipal Utility District, P.O. Box 15830, Sacramento, CA 98852-1830, undated, issued in January 2002.

2.0 Project Outcomes

2.1. Development of the POC and prototype WTC 500

When WTC began work under Contract 500-97-032, engineering analysis and design of the POC was underway. POC development was on a fast track with numerous activities executed in parallel during the course of the project. In its proposal to the Commission, WTC submitted an extensive, 55-page Project Work Plan Gantt chart. This chart is summarized in Figure 6.

Task Name	Start	Finish
1.0 Project Planning and Management	**Mon 2/2/98**	**Fri 12/29/00**
2.0 Conceptual Design	**Mon 2/2/98**	**Fri 9/8/00**
3.0 Proof of Concept (POC) Turbine	**Mon 2/2/98**	**Mon 12/11/00**
3.1 Preliminary Design	**Mon 2/2/98**	**Tue 10/27/98**
3.2 Detailed Design (Component Development)	**Fri 4/24/98**	**Fri 2/4/00**
3.3 Final Design (Systems Integration)	**Mon 3/9/98**	**Thu 10/21/99**
3.4 Fabrication	**Fri 6/12/98**	**Mon 4/26/99**
3.5 Site Selection	**Fri 5/22/98**	**Mon 3/8/99**
3.6 Installation	**Mon 3/8/99**	**Wed 6/9/99**
3.7 POC Turbine Field Tests	**Thu 3/18/99**	**Mon 12/11/00**
3.7.1 Test Preparation	Thu 3/18/99	Mon 4/12/99
3.7.2 Checkout and Commissioning	Mon 6/7/99	Fri 6/11/99
3.7.3 Test Readiness Review (Meeting #4)	Fri 6/11/99	Tue 6/15/99
3.7.4 Field Testing	**Tue 6/1/99**	**Wed 8/16/00**
3.7.5 Analysis of Test Results	**Tue 6/15/99**	**Mon 12/11/00**
4.0 Next Generation Production Prototype (NGT) Turbine	**Tue 4/13/99**	**Tue 10/10/00**
4.1 Preliminary Design (Deliverable #7; Meeting #5)	**Tue 6/1/99**	**Fri 11/12/99**
4.2 Detailed Design (Component Development)	**Tue 4/13/99**	**Mon 7/17/00**
4.3 Final Design (Systems Integration) (Deliverables #9 and	**Mon 7/19/99**	**Thu 4/27/00**
4.4 Fabrication	**Fri 7/23/99**	**Mon 6/5/00**
4.5 Site Selection	**Wed 5/12/99**	**Fri 3/17/00**
4.6 Installation	**Tue 5/23/00**	**Fri 7/14/00**
4.7 NGT Field Tests (Meeting #7)	**Thu 2/10/00**	**Tue 10/10/00**
5.0 Production Readiness, Maintenance & Commercialization Pl	**Fri 1/1/99**	**Tue 12/26/00**
6.0 Final Report (Deliverable #11)	**Mon 7/24/00**	**Fri 12/29/00**

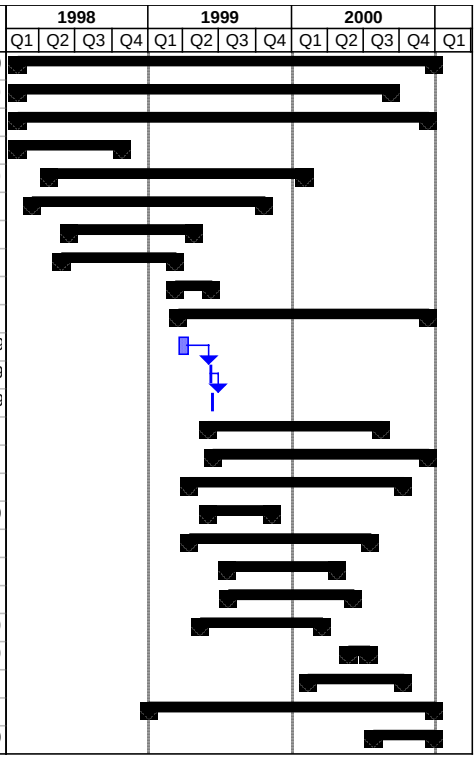

Figure 6: California Energy Commission Next Generation Turbine Project Work Plan

<u>Analytic models and modeling:</u>

Engineering analysis and design was an iterative process of refining computer models predictive of turbine behavior under a wide range of operating conditions. The strength of WTC's internal engineering team is component design, fatigue analysis, and system integration. Expert industry consultants performed turbine system structural dynamic analysis.

The leading dynamic analyst in the U.S. wind industry is Dr. Craig Hansen, President, Windward Engineering, Salt Lake City. Dr. Hansen began his career with the DOE's Solar Energy Research Institute (SERI) in 1977. (SERI became NREL in 1991.) He managed SERI's Wind Engineering Department and was Chief Engineer before leaving to join start-up wind turbine manufacturer, ESI Inc. From 1986-96, Dr. Hansen was on the Mechanical Engineering Department faculty at University of Utah. In 1989, under contract with SERI, he developed a wind turbine structural dynamic analysis module for use with the general-purpose dynamic analysis software ADAMS™, a code widely used in the U.S. automobile industry. WTC employed Windward extensively in the design of the POC and the prototype WTC 500.

The leading dynamic analysts in the wind industry are Garrad Hassan & Partners (GHP) Ltd., Bristol, England, with a professional staff of over 50 people. In the late 1980s, under contract with the European Union, GHP developed the dynamic analysis model, BLADED™. GHP's founders' backgrounds are in aerospace control systems and wind turbine control systems, as a result, BLADED has become a more useful code to WTC than has ADAMS.

Initially unfamiliar with the idiosyncrasies of these models, and unwilling to choose between them, WTC elected to use both in its analysis efforts. Like a second medical opinion, WTC reasoned that since the models were developed independently, if the same input conditions to each model resulted in consistent outcomes, there was a low probability both would be wrong. However, if the models did not provide consistent output, this provided grounds for further investigation on the theory that one was wrong.

The outcome of this analysis effort was, and continues to be, a voluminous stream of data representing predicted fatigue, extreme event, and other loads on various components of a given wind turbine configuration under a wide variety of input conditions. This analytical work will continue into the foreseeable future.

Thorough analysis of turbine system performance and behavior is the only means of assuring the development of a reliable new wind turbine.

Component design and analysis:

WTC's engineering team designed turbine components and integrated them into the turbine system. This consisted of configuring component shapes and specifying material properties so components could, when manufactured, accept predicted fatigue and other loads. WTC employed the 3-dimensional modeling software SolidWorks™. SolidWorks enabled designers to draw 2-dimensional pictures and provide other input for component design and the software would produce the component in 3-dimenstional solid-form on the computer screen. With input from other models, SolidWorks presents pictorial information, such as stress concentrations, critical to the designer's work.

A second analytical code, ANSYS™, is a finite element analysis model that takes as its input stress loads, material properties and shapes to calculate stress concentrations.

WTC developed software enabling SolidWorks and ANSYS to freely communicate, thus simplifying data management between the two models. This allowed WTC to set up analytical work tasks during the workday and leave the models to produce results overnight. Since the output of the system dynamic models was input for the component design and analysis models, the goal was to minimize time spent managing data and to maximize the depth and breadth of cases analyzed (simulations performed).

Management of analysis and configuration:

Integrating dynamic analysis model results with component design and fatigue analysis was the responsibility of WTC's Vice President Engineering. Identification of promising wind turbine configurations was dynamic. Particular configurations were modeled and analyses performed. Model output would be digested by GHP or Windward then dissected by the modeler and WTC. This was iterative, with new component and system configurations being regularly developed, modeled, accepted, modified or discarded. WTC's engineering team

usually had several components in design at any point in time. In parallel with turbine design, the dynamic analysis models were continually refined by GHP and Windward to more accurately reflect the actual configuration of the emerging design.

Differing schools of thought:

WTC's engineering development work proceeded in complete recognition of two opposing schools of thought with respect to wind turbine design. These are:

- The keep it simple school, which believes that the more complicated the machine, the more expensive it is to manufacture and maintain due to complexity.
- A second school that subscribes to the belief that a better understanding of the environment in which the machine operates will offer opportunities to improve performance more rapidly than the costs of complexity increase.

Two notable trade-off decisions:

As WTC's design efforts progressed, configuration changes were evaluated in light of the trade-off between simplicity and complexity. Most were minor issues, but two were notable:

(1) WTC's patented rotor concept, hinged rotor blades with a hydraulic-damping control system enabling control of blade flapping in the out-of-plane direction (the Flap Motion Restraint System or FMRS) has demonstrated on the POC a dramatic decrease in fatigue loading at the blade root and bending loading on the rotor shaft. The importance of this concept is pictured in Figure 7, which compares predicted cumulative blade-root fatigue loads for WTC's hinged blade with the fatigue loads encountered on a typical rotor-blade rigidly attached to the rotor shaft (characteristic of all 3-blade, upwind turbines). The decrease in fatigue loading is clearly several orders of magnitude.

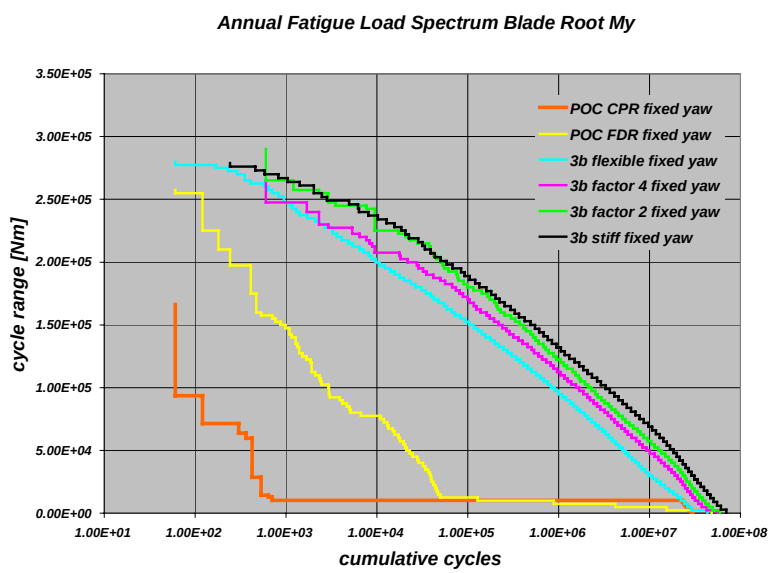

Figure 7: Comparison of Annual Cumulative Blade Root Fatigue Cycles

POC (yellow), WTC 500 (orange) and Various Rigidly Attached (3-blade, upwind) Blade Configurations

However, in its original proposal to NREL, WTC proposed using a “teetering rotor” in addition to hinged blades. Teetered rotors, which swing about a single pivot point at the end of the rotor shaft like a child’s teeter-totter, were previously employed on the 2-blade downwind machines of ESI and Hamilton Standard as a means of relieving loads. WTC believed that if teetering relieved loads and hinging relieved loads, then combining these concepts would relieve even more loads. This concept is depicted in Figure 8. After preliminary modeling and analysis it was quickly apparent that combining these concepts significantly increased complexity, making modeling almost impossible, and resulted in a system that would be extremely difficult if not impossible to control. The configuration could lead to undesirable outcomes, e.g., teetering could force the hinged blades in an upwind direction exacerbating the tower strike concern. The combined hinged-blade/teetered-hub concept was dropped by late 1997.

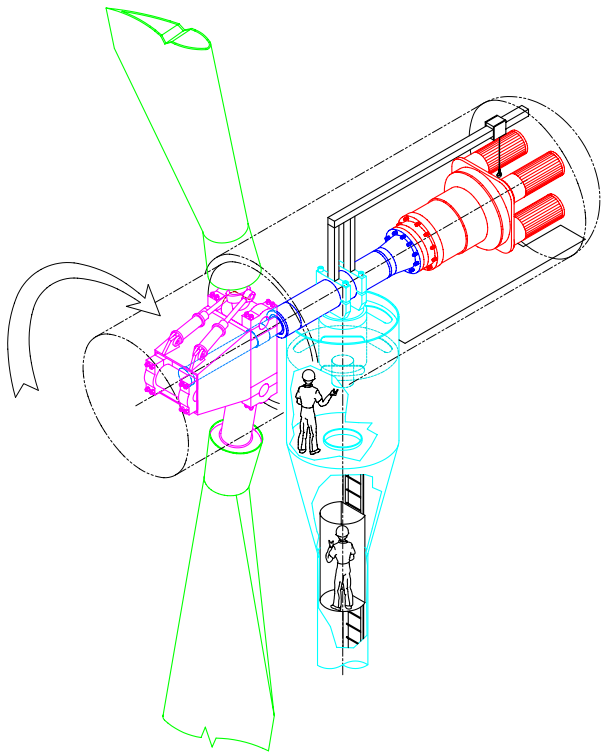

Figure 8: Proposed WTC 1000 Featuring Hinged Blades and Teetering Hub
Original configuration proposed to DOE/NREL in September 1995

(2) More challenging was how to regulate power. Regulating power above rated capacity can be accomplished by allowing the blades to aerodynamically stall, or by pitching them. Stall regulation is simpler – the blades twist in operation inducing aerodynamic stall, which limits (not precisely) power output. Pitch regulation employs mechanical or electro-mechanical devices to turn the blade about its longitudinal axis. Active blade pitching is also the means to aerodynamically stop the rotor. WTC had concluded the arguments favoring pitch regulation outweighed the additional complexity and cost.

Wind turbine blades can be pitched to stall or pitched to feather. Initially, pitching to stall seemed to be more advantageous than pitching to feather. The strongest argument was that when pitching to feather, the blades can be driven upwind (toward the tower) under certain

wind conditions. There is a transition phase between pitching to regulate power at near cutout wind speeds, above which the turbine is not designed to operate, and pitching to stop blade rotation above cutout wind speed (approximately 53 mph, 24 m/s). If the machine lost power during this transition, stopping the pitching process, the blades could continue upwind until striking the tower.

As modeling of the pitch to stall continued it became clear that in an extreme wind direction change event predicted loads increased. The only resolution was to increase the size of the structure. After initial extreme event modeling, designs were finalized for the POC's primary structural (and long-lead procurement) components, the rotor shaft and rotor shaft support, and procurement was initiated.

As modeling continued, however, subsequent analysis revealed extreme event pitch to stall loads were much larger than initially anticipated, much larger than corresponding pitch to feather loads and, in fact, unacceptably large. This discovery, made after components were ordered, led to a re-examination of arguments against pitching to feather and an examination of solutions to the loss of power during an emergency stop. It was determined that an uninterruptable power supply to pitch the blades would complete an emergency pitch to stop shut down and avoid tower-strikes. As a result, the decision was made to pitch the blades to feather for power regulation and aerodynamic braking.

Pitching to feather placed significantly less loading on the previously ordered components than the loads for which they were designed. This change in operating configuration allowed WTC to use existing POC rotor shaft and rotor shaft support designs and the material and tooling acquired for these components to develop the WTC 500. Subsequent modeling indicated that with minor configuration changes to other components, these structural pieces would support rotor blades of sufficient length to produce 750 kW rated capacity.

In both of these cases, informed decisions would have been impossible in the absence of the dynamic analysis models.

Design and build process:

From the outset of the NREL project, WTC has conducted the engineering analysis/design and component procurement in parallel, working from primary structural components and long-lead items to non-structural and short-lead items. This allowed the best utilization of the Company's resources.

Component procurement:

Component procurement crossed the spectrum from purposed-designed, extensively processed components, e.g., the rotor shaft, rotor shaft support, blade support units, mechanical brake, etc. to catalog or distributor procured fasteners. WTC's experience with vendors also crossed a broad spectrum. Many vendors, particularly those supplying critical custom specified components, proved to be responsive and easy to work with. Because it was a one-off project, however, many prospective vendors had no interest. Some vendors seemed willing to work with WTC, but were less than satisfactory with respect to delivering quality products on a

timely basis. During POC development WTC identified several vendors with whom it worked on the prototype WTC 500, and with whom it plans to work when in commercial production.

POC turbine configuration:

The final configuration of the POC turbine drivetrain is illustrated in Figure 9. In this representation, the wind moves from the right side of the page to the left although at a slight angle into the page.

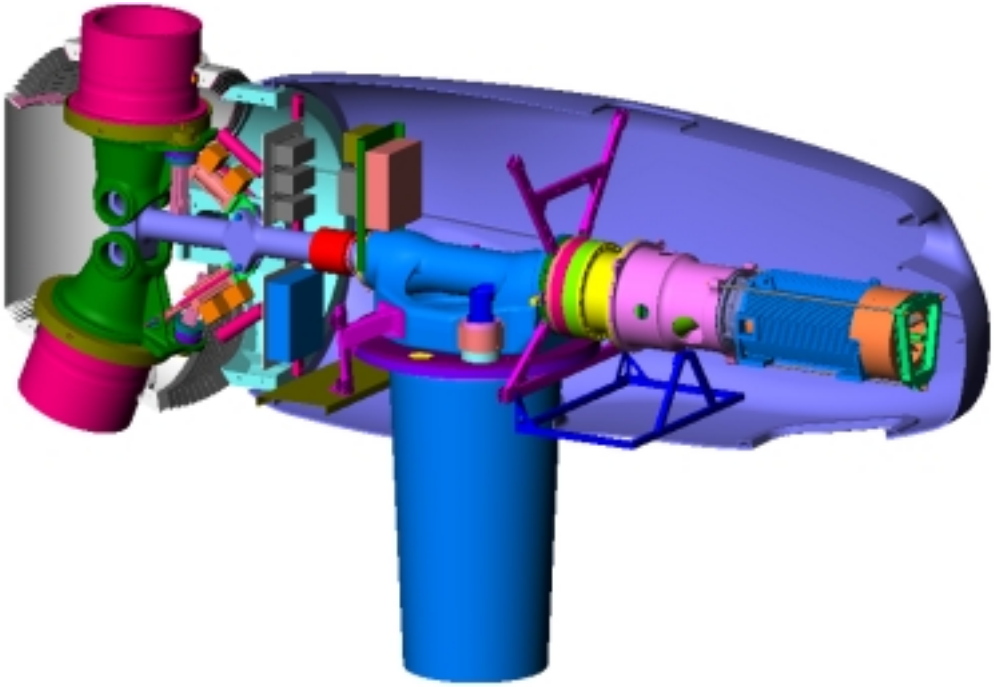

Figure 9: Cut-away illustration of POC drive train

The root ends of the blades are illustrated on the left side of the picture with the rotor in a vertical position. The blades are attached to the blade supports, which feature a hinge pin that runs through the rotor shaft. Also illustrated are the two FMRS units, attached at one end to the rotor shaft and to the blade supports at the other. The rotor shaft terminates at the right end of the rotor shaft support, which rests directly on the tower (the yaw bearing is under the rotor shaft support). Attached to the upwind side of the rotor shaft support are the mechanical brake, the gearbox, and the generator, moving left to right in the picture. Access to the nacelle is through one of two openings in the rotor shaft support (one of which is illustrated in Figure 9) via a ladder inside the tower. Some of the internal nacelle support structure is illustrated. Missing are a considerable number of electrical components (boxes) that would otherwise clutter the illustration.

POC turbine assembly:

POC turbine assembly took place at a Seattle machine shop with which WTC was familiar. Two of the shop's senior employees had previous experience assembling wind turbines. WTC retained on a consulting basis a manufacturing engineer with whom WTC was familiar and who had experience managing the assembly of large machines considerably more complex than the POC. Assembly commenced in the absence of detailed assembly plans and drawings.

In-shop assembly was initially planned to begin in February 1999 and be completed in April. Actual assembly began late in May 1999. This three-month delay was entirely due to WTC's underestimation of the time it would take to design and procure the major turbine components. Turbine assembly proceeded smoothly, though with additional delays due to the late arrival of components to be assembled in a particular order. There was also last minute procurement of small, fabricated components. Though not intended for mass production of utility scale wind turbines, the machine shop was well enough equipped to execute turbine assembly.

In August the by then assembled components, consisting of the drive train but no electrical components, were shipped as a unit to the NWTC where final in-shop assembly was to be completed. This decision was made because the NWTC had facilities to install and test electrical system components. By mid-October the fully assembled turbine nacelle system was ready to have the blades attached and then be lifted onto the installed tower. The assembly process took three months longer than had been projected, partially due to delays in receiving components, which was generally attributable to the last minute design of components, and partially to the difficulty encountered in working in a remote government controlled facility.

Turbine erection:

Site preparation began at the NWTC in June 1999. In August the foundation was installed. In early September the tower was installed on the foundation. A month later the nacelle, complete with blades, was installed on the tower and plans were set to grid-connect the turbine and begin checkout and commissioning. However, at the end of October it was discovered that the nuts holding the tower to the foundation had lost tension. Over the next two months WTC discovered the foundation suffered very serious installation related defects; all the while attempting to identify a corrective solution. In December a decision was made to take the turbine down, remove the faulty foundation, install a new foundation and re-erect the machine. This was accomplished in January 2000. On February 12, the turbine was re-installed on the new foundation. By early March it was grid connected and began an extensive testing program.

The foundation problem was the result of sloppy workmanship by a subcontractor during the pouring of concrete, compounded by the absence of construction management oversight. The foundation is a concrete tube with a 5-foot inside diameter, 2-foot thick walls, a 9-foot outside diameter, and is 30-feet long (deep). Running the length of the foundation are 80 threaded rods, anchored at the bottom, to which the tower is bolted at the top. When concrete was poured into the foundation containment walls, three critical mistakes were made –

(1) The hole was not de-watered. The contractor must have realized water was in the bottom of the hole (which according to available geotechnical reports was not supposed to be present), but failed to pump it out before pouring the concrete.

(2) The concrete was dropped into the hole from the surface, an initial distance of 30-feet. With such a long drop, concrete will disaggregate. It should have been pumped down the hole.

(3) The first load of a 4.5 truck-load pour was poured and allowed to sit overnight before the remaining 3.5 truck loads were poured. The water and mud in the hole was forced up inside the foundation retaining walls by the first load of concrete where it rested on top of the first load of concrete and had several hours to seep through the freshly poured concrete.

Full responsibility for this occurrence has yet to be resolved and restitution made. The foundation problem resulted in an additional three-month delay from the original schedule. The POC, which had been scheduled to be operational in June 1999, was now nine months behind schedule but, fortunately, not over budget.

Turbine checkout, commissioning and initial testing:

The POC featured a new turbine control system that had to be tested and WTC had to ascertain that the mechanical elements of the machine actually performed as intended.

After the turbine electrical system was connected to the electrical grid, providing power to the turbine, a multi-step system checkout process began. The general steps are identified below. A detailed enumeration is provided in the Turbine Commissioning Plan (Appendix I):

- Assure all electrical and mechanical components worked as intended, e.g., pitch drives, yawing motors, blade FMRS units, etc.
- Assure the software control system controlled operation of components as intended.
- Assure sensors operated and provided proper signals to the data acquisition and turbine control systems.
- Assure alarms and emergency shutdown signals were functional.

As identified in the Turbine Commissioning Plan an extensive checklist of activities was performed before the turbine rotor was unlocked and the rotor first rotated. Nine weeks after grid-connection the initial turbine checkout phase was complete.

A series of operational tests to assure all systems functioned as intended, with specific emphasis on turbine shutdown routines, followed. For example, demonstrating that the emergency stop blade pitch routine would stop the rotating blades was critical. This was accomplished by motoring the blades. Emergency mechanical brake evaluations were performed from a motored start. These activities were executed in a manner intended to provide WTC's test personnel with increased understanding of the operational characteristics of the turbine and increased confidence in its performance.

Turbine testing and test outcome:

By the end of April, the POC was ready to begin a rigorous operating test program intended to gather operating and component stress load data to determine if the turbine would perform as designed and to establish the accuracy of the predictive models. This Test Matrix is presented in Appendix II.

Although the POC has a rated capacity of 250 kW, the control system enables operation of the turbine at rated capacities above and below 250 kW. The turbine was initially operated at 150 kW. The purpose of testing in this mode was to assure that blade pitch and software control systems controlled power production in increasing wind speeds, but to make this demonstration at a low rated power so if previously undetected problems arose, the braking systems would be more lightly taxed in an emergency stop.

In the ensuing 12 months the Test Matrix was completed. During this period the turbine did not operate in an unattended mode. Detailed records were maintained of test results and all aspects of operation. On October 31, after 380 accumulated hours of operation, the turbine experienced its first component failure when a rod-end eyebolt in the FMRS failed. The turbine spinner suffered minor damage. As a result of this failure, a thorough evaluation of the FMRS was undertaken. It was determined that the catalog part that failed suffered material defects. It had previously been determined, however, that the entire FMRS system would be re-designed for the prototype WTC 500 turbine and during re-design a new counterpart of the failed component would be made to WTC's specification. As an interim measure two new rod ends were manufactured to specification and installed in existing, spare FMRS cylinders, which replaced the cylinders originally installed on the machine. There have been no further FMRS problems relating to these components .

After reinstallation of the modified FMRS cylinders, the POC resumed attended mode operation in December. In February 2001, after three straight days of downtime due to sensor failure during a period of high winds, a concerted effort was begun to eliminate all such failures. By April, minor shutdowns due to sensor and other small device failures were almost entirely eliminated. In April the Test Matrix objectives were also achieved. Accordingly, a decision was made to operate the turbine in unattended mode. The POC began operating as a commercial wind turbine. In the absence of a data collection system intended for the job, WTC personnel began recording by hand the duration of downtime with the goal of determining the availability of the POC to produce electricity.

In October 2001, one of the FMRS cylinders experienced a loss of pressure that was attributed to a relief valve being stuck in a partially open position. It was determined that contaminants in the hydraulic fluid caused the valve to not properly seat. The system fluid was purged and replaced and the machine returned to duty. However, in early November a fastener holding one of the two FMRS cylinders in place failed. After a temporary fix it was decided the POC would not operate in unattended mode until both FMRS units could be replaced with entirely new units that had been redesigned for the prototype WTC 500. In mid-January 2002, the POC was taken out of service and the new FMRS units were installed. The POC was back in service by the end of January.

Results of POC operations to date:

Performance of the POC since its installation in February 2000, through February 2002 should be put into context. The turbine was an all-new design. All critical components were custom designed and fabricated and control system software was written for the turbine. The project benefited from a generous DOE grant and critical additional funding from the Commission, but it was not executed with an unlimited budget or an unlimited amount of time during which components, subsystems, and complete systems could be tested for strength, reliability, and

functionality. Further, though WTC had an experienced engineering team, this was the first wind turbine ever designed by the team. In this context, the POC has proven to be an excellent design and an outstanding performer. With the exceptions of the annoying failures attributable to system sensor choices made early on, and the need to redesign the FMRS, the turbine has met all of WTC's expectations.

Goals for the POC:

The technical goals of WTC's contract with the Commission were (1) to demonstrate the feasibility of employing all the wind turbine concepts (the proof of concept (POC) and the Wind Turbine Company (WTC) 350) and (2) to achieve the identified weight reduction targets.

WTC translated the feasibility demonstration in to a few, more concrete goals it hoped to accomplish with the POC. They were:

Goal – Demonstrate the load-relieving ability of WTC's proprietary hinged-blade, FMRS.

Outcome – As depicted in Figure 7, the dynamic analysis models predicted enormous load reduction potential. Through February 2002, the turbine has accumulated 1,400 operating hours. Loads data to date clearly demonstrate a significant reduction of stress loading on all critical structural components from the blade though the drive train and the tower. A summary of measured loads compared with predictions is found in Appendix III.

Goal – Demonstrate the accuracy of predictive models.

Outcome – Actual loads have generally been slightly less than were predicted by the codes used to design the machine. The codes accurately predicted actual loads while leaving an acceptably small level of conservatism in the predictions, as indicated in Appendix III. With further refinement of the codes, based on measured results from the POC, the prototype WTC 500, and subsequent turbines, this conservatism (i.e., safety margin) will be driven down through value engineering, thus cost will be taken out.

Goal – Develop a better understanding of software system controlling turbine operations.

Outcome – The control software system works as intended. All detected bugs have been eliminated and no anomalous behavior has been witnessed. Operation of the POC has enabled WTC and GHP to significantly refine the control system for the prototype WTC 500 with plans to make further turbine configuration refinements on the WTC 750 commercial wind turbine. In 2000, WTC trademarked the expression "Smart Turbine" reflecting the increasing sophistication of the control system.

Goal – Demonstrate that WTC could design and build a functioning wind turbine.

Outcome – The POC not only works well, it is a distinct and stylish looking wind turbine. It has met all technical objectives and has warranted the additional expenditure to refine and develop the second-generation prototype WTC 500.

There were many things WTC was not attempting to accomplish with the POC. Specifically, many otherwise critical turbine components such as the blades, gearbox, and generator were articles of convenience and simply needed to work.

Although the ultimate objective of the DOE / NREL and Commission programs, and WTC's commercial goal, is the lowest cost of electricity possible from a wind turbine, WTC recognized that the quest to obtain an accurate assessment of cost could not be accomplished until the turbine configuration neared a commercial state of readiness. At the POC stage, WTC focused on the budgeted and actual costs of designing, developing and testing the machine. Neither did WTC focus on electrical output or the turbine's power curve, although both are of critical commercial importance. A wind turbine's power curve is a function of blade airfoil shape and rotational speed. The gearbox and generator also influence electrical output. However, these components would not be used in future wind turbines, so their performance was of little interest.

However, WTC was always cognizant of the importance of the cost of turbine manufacture to the achievement of the ultimate goal of low cost electricity. The focus throughout the POC development effort was on component weight. The decision to find a workable solution enabling the POC to be operated as a pitch to feather machine fully illustrates the importance WTC placed on achieving weight targets. In fact, WTC's decision to procure the major structural components while still attempting to resolve the pitch to stall versus pitch to feather configuration issue lead directly to components that were oversized for the final pitch to feather configuration. Instead of downsizing future components to stick with original rated capacity targets, the simplest and most practical approach was to increase the rated capacity targets to take advantage of build in excess structural capacity.

Prototype WTC 500 (EMD and / or NGT) turbine analysis, design, and development:

WTC's computer-based turbine system structural dynamic analysis, component design, and turbine configuration approach to the prototype WTC 500 was the same as for the POC. The same models, consultants, and people employed to design the POC also participated in the prototype WTC 500 design. There was, however, a change of emphasis from the POC. Since much was known about the performance of the POC, the dynamic modeling effort focused on tower dynamics, rotor size, and control system optimization. The new, larger turbine required a new tower to accommodate forces it would experience with a larger diameter rotor. The new, taller tower was to employ the lower cost guy-cable supported configuration, thus resulting in a considerable change in dynamic behavior. WTC's engineering team also focused on two components that had been given only slight attention with the POC – the gearbox and generator. As mentioned, a decision to improve the FMRS design was made before the POC was installed.

WTC believed the main structural components of the POC, specifically the rotor shaft and rotor shaft support, were designed with sufficient excess capacity that they required no design changes of consequence to support the larger WTC 500 rotor. Dynamic modeling confirmed this.

The remaining components of consequence, the rotor blades, were once again components of convenience.

All other components and subsystems of the turbine were reviewed and evaluated for suitability since WTC intended to move as quickly as possible to a commercial wind turbine.

The WTC 500 was to be a pre-commercial prototype turbine. This was consistent with the Company's proposal to the Commission.

Unfortunately, WTC had failed to recognize the full implications of its compromise with NREL (see page 4 above). In agreeing to a further scale up of the POC structural components beyond 500 kW to 750 kW when a purpose designed blade was developed, NREL and WTC agreed as a cost-saving measure to retrofit the prototype WTC 500, thus permitting an increase in rated capacity to 750 kW. This meant all components for the prototype WTC 500 had to be developed to accept loads imposed by the larger 750 kW rotor. The prototype WTC 500 became a 750 kW rated capacity wind turbine temporarily de-rated to 500 kW, and would therefore prove to be a commercially uneconomic machine.

As the result of delays encountered in the design, component procurement, turbine assembly and installation phases of the POC effort, initial work on the prototype WTC 500 began nine months behind WTC's original schedule.

WTC 500 component design decisions:

During development of the POC, WTC established a working relationship with Alstom, the major French electrical equipment manufacturer. For the prototype WTC 500, Alstom agreed to build a generator meeting WTC's configuration requirements. This was fortunate since such an effort from a major equipment supplier does not occur often, and the generator is not a component WTC had the capability of designing, procuring at the component level, and assembling. The resulting Alstom generator was capable, with configuration and voltage changes, of being operated at 500 kW or 750 kW.

One of the most consistently troubling components in large wind turbines is the gearbox. Out of necessity (a cooperative gearbox manufacturer could not be identified) WTC decided to design its own gearbox, drawing on the experience of its engineering team with drive-train design for large diameter tunnel boring machines. The resulting gearbox design drew from a discontinued model of German manufacturer Lohmann-Stolterfoht that had a successful track record in tunnel boring applications. The gearbox, rated for 750 kW capacity, will be tested on the WTC 500.

WTC decided to employ a modified version of an existing rotor blade manufactured by French blade manufacturer ATV. ATV manufactured rotor blades for turbine manufacturers for several years, producing 21-meter blades for German manufacturer Tacke (now part of Enron Wind Corporation), which used the blades on its 600 kW 3-blade upwind machine. Subsequently, ATV extended the blade mold to permit manufacture of a 23-meter blade. Though not previously manufactured, WTC elected to go with this new, unproven blade. ATV is the only known manufacturer of carbon fiber-based wind turbine blades. Though more expensive than fiberglass, carbon fiber is dropping in price and, since less material is required due to its strength, overall blade cost is about the same as fiberglass blades. Unlike upwind turbines, WTC's design can take advantage of carbon fiber's strength and lower weight.

The other major component development effort was the tower. Not only was the tower, at 62-meters, more than 1.5 times higher than the POC tower, it was to be supported in the upright position by guy-cables instead of by the foundation. WTC chose the guy-cable supported tower in the belief that it would be much more economic than a freestanding or cantilevered tower.

This is particularly true the higher off the ground the nacelle is elevated. Tower dynamics are different for a guy-supported tower than for a freestanding tower, however, WTC and its consultants had previously developed computer predictive models of this configuration.

There was a continuous engineering effort on the WTC 500 for a period of approximately 18 months. Component procurement began within 6 months of initial engineering.

Component procurement:

WTC recognized that it did not have the personnel to conduct a professional procurement effort and hired a Procurement Director in March 2001. The procurement process was similar to that of the POC although a number of new component vendors were brought into the picture. Unlike the POC, which was a one of a kind turbine, the WTC 500 was a pre-commercial prototype. Important goals were to keep the procurement process on schedule, on budget, and create a database for subsequent commercial endeavors. The last two of these goals were realized, however, the first was again missed by about three months. As with the POC, this was attributable to delays in component design from WTC engineering and to vendor delays.

WTC 500 turbine configuration:

Except for the component changes described above, the turbine configuration of the WTC 500 is in all material respects as depicted in Figure 9.

WTC 500 turbine assembly:

WTC initially approached prototype WTC 500 assembly intent on establishing a working relationship with a company believed to have the capability to assemble multiple wind turbines at the same time. Unfortunately, WTC misjudged the project management capability of the company, and also did not have its own personnel capable of managing the assembly activity. This was quickly recognized and WTC moved the work back to the shop that had assembled the POC. WTC also hired as its Manufacturing Director the consultant who had managed the POC assembly. This delayed assembly by over one month.

Once again, WTC did not have detailed manufacturing plans or drawings (a deficiency that is being remedied), thus assembly relied on experience and intuition. Fortunately, the machine shop employees who assembled the POC were available to assemble the WTC 500.

Assembly began in May 2001 and was scheduled for completion in July. Primarily as the result of vendor failures to deliver components as specified and on time, the assembly process stretched into September. As the result of site related delays, the assembled nacelle unit was not shipped to the site until late November. Delays encountered during the assembly period, not including the above-mentioned relocation of the turbine assembly added another two months to the process. As with the POC, these delays were attributable to late component procurement due to delayed engineering design, and vendor miscues which took time to remedy. Several vendors fell out of favor as a result of poor performance on this turbine.

Turbine erection, checkout, and test plans:

In 1999 WTC began discussions with the Los Angeles Department of Water and Power (DWP) that eventually led to an agreement allowing WTC to install the prototype WTC 500 on the DWP's Fairmont Reservoir located 15 miles west of Lancaster, California, in Northern Los

Angeles County. WTC began measuring wind resources at the site in September 1999, and found a good wind resource. The DWP managed site environmental assessments with support from a consulting firm WTC retained and in April 2001 provided a Conditional Use Permit (CUP) for the site. After receiving the CUP, which was based on completing a California Environmental Quality Act (CEQA) checklist, it was subsequently determined that because Federal funds were being used, a National Environmental Policy Act (NEPA) checklist also had to be completed. Correcting this oversight required approximately one month.

Building and electrical installation permits were more challenging. DWP Engineering Department personnel, who had the authority to issue building and electrical permits, requested WTC obtain independent verification of design and installation plans, thus enabling DWP's legal staff to authorize construction of foundations and site electrical work. Permitting issues delayed installation by approximately six months, although assembly delays were occurring in parallel.

On December 12, 2001, the prototype WTC 500 was installed with no difficulties. Following installation, the modification to electrical connection boxes by WTC and additional delays imposed by Southern California Edison (SCE), the turbine was grid connected on February 5, 2002. Following recovery from a WTC induced component failure, which took two weeks to remedy, and another two weeks of control system and other functional checkout, the turbine's first rotation occurred on March 5, 2002. The turbine then entered into a test program similar to that of the POC to assure operating functionality. By May / June 2002, the WTC 500 prototype is expected to go into unattended operation as a pre-commercial machine to begin accumulating operating hours.

The cumulative project schedule slippages including the nine-month delay with the POC and another nine months delay with the prototype WTC 500 left WTC almost exactly 18 months behind the original Contract No. 500-97-032 schedule. Table 5 summarizes the details of these delays.

Table 5: Planned and Actual Duration of Project Activities

	Planned		Actual		Months
	Start	Finish	Start	Finish	Delay
POC Engineering	2/28/98	10/21/99	2/28/97	7/99	(3)
POC Assembly	6/12/98	4/26/99	7/98	9/99	5
POC Installation	3/8/99	6/9/99	8/99	2/12/00	8
WTC 500 Engineering	4/13/99	4/27/00	3/00	6/01	14
WTC 500 Assembly	7/23/99	6/5/00	11/99	11/01	17
WTC 500 Installation	5/23/00	7/14/00	5/01	12/12/01	17

Goals for the WTC 500 (EMD-1, NGT) turbine:

As with goals for the POC, goals for the prototype WTC 500 are both technical and economic. Technical goals, consistent with the PIER contract technical objective to demonstrate the feasibility of employing all WTC's wind turbine concepts in a single turbine, include:

(1) Confirmation of the WTC 500's power production capability.

(2) Demonstration of the functionality of the tubular, guyed-tower concept.

(3) Demonstration of the functional reliability of the WTC designed gearbox.

(4) Continuing refinement of system dynamic models and collection and assessment of fatigue and other load data.

(5) Continuing refinement of turbine control system.

(6) Assessment of benefit of carbon fiber-based rotor blades

In addition to these goals, WTC has continued to focus on turbine weight as the proxy for cost. In this regard, the weight on top of the tower of the WTC 500 is 23,000 kg, 4,200 kg more than the POC, but 40 percent less on a per kilowatt of rated capacity basis. As indicated in Table 3, WTC expects the weight of the 750 kW turbine to be only slightly more than that of the WTC 500, thus reducing the per kW weight by another 30 percent.

Figure 10 illustrates the expected power curves for both the WTC 500 and the subsequent WTC 750 and compares them with the Vestas 660 power curve. The Vestas curve is based on actual, published data. The WTC 500 power curve was calculated by GHP based on the airfoil shape of the ATV blades used, while the WTC 750 power curve is a simple extrapolation of the WTC 500 curve. Data to be collected from operation of the WTC 500 during the balance of year 2002 will confirm the accuracy of the predicted power curve. As WTC moves into the development of the purpose-designed blade for the 750 kW turbine, a refined power curve calculation will be developed. The WTC 750 power curve will be certified by an internationally recognized certification agency such as Underwriter's Laboratories, as will the entire turbine design.

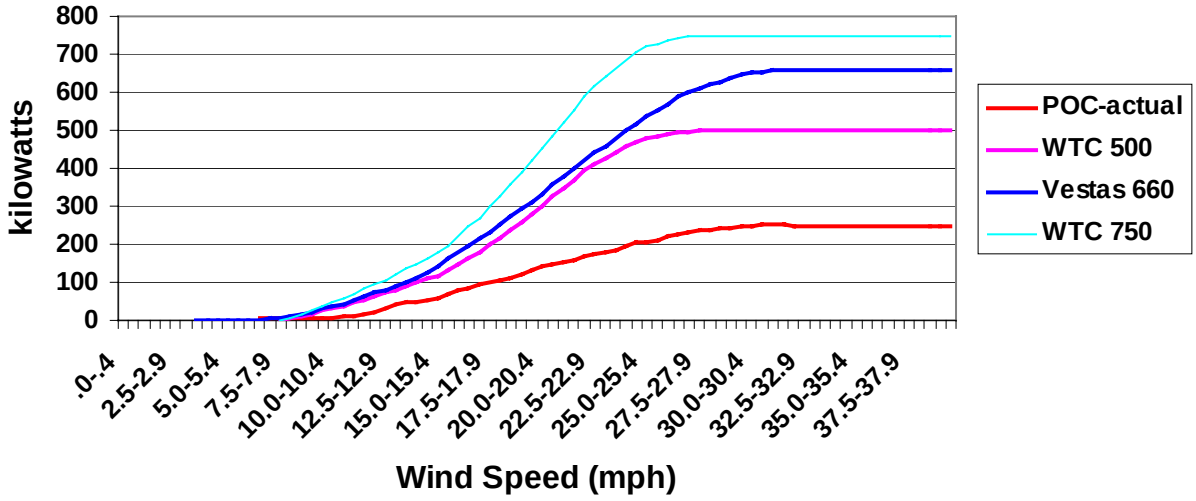

Figure 10: Comparison of WTC expected power curves with Vestas power curve
WTC's turbines shut down (i.e. zero power) at approximately 53 mph, Vestas shuts down at 55 mph.

Specific project outcomes of PIER Contract 500-97-032, as of March 2002, as they relate to the identified contract objectives are:

Objective #1 – Demonstrate feasibility of employing all the wind turbine concepts.

Outcome – WTC has produced two fully functional, state-of-the-art, prototype, utility-scale wind turbines. Though the POC is a first-of-a-kind prototype and cannot be expected to achieve commercial turbine reliability standards, 18 months of operating experience with the POC and only one component failure of consequence (and that previously identified for redesign) provides evidence that commercial reliability standards can be met.

The turbine loads data from the POC and presented in Appendix III indicate a close correlation with loads predicted by the dynamic analysis models, and corroborate the belief that WTC's proprietary hinged-blade, FMRS would significantly reduce blade-root and other turbine system loads. WTC's substantial and growing technical database will permit its engineering team to refine the turbine concept well into the future.

Objective #2 – Achieve turbine weight targets.

Outcome – In the Contract 500-97-032 Work Statement turbine weight objectives were identified as absolute weight values for a 350 kW wind turbine. As a result of turbine configuration changes during the execution of the project, the turbine size objective increased. Considering turbine weight relative to turbine size, as measured by either rated capacity or power production potential (using rotor swept area as a proxy), the weight goals have not been reached with the prototype WTC 500, but will be achieved by the WTC 750, as illustrated in Table 2.

Objective #3 – Develop a (350 kW) wind turbine capable of producing electricity at prices competitive with the lowest cost sources of conventional electricity generation, with a specific economic objective to produce electricity for $0.035/kWh or less.

Outcome – WTC has not achieved this target because it is not yet in commercial production. Using the DOE's COE calculation guidelines, in a Class 4 wind resource (one wind class below the baseline Class 5 resource identified in Contract No. 500-97-032), WTC has determined that it must sell its wind turbines for $575/kW of rated capacity ($431,250 for a 750 kW turbine) to hit the DOE's 3.0¢/kWh COE goal (3.5¢ is Contract No. 500-97-032 goal). Figure 11 presents the relationship between turbine cost per kilowatt and electricity price per kilowatt-hour using the DOE guidelines.

WTC's manufacturing cost database now consists of the fully detailed cost of the prototype WTC 500 including freight and assembly labor. The total cost of manufacturing the WTC 500 was $1.08 million. Adding a 20 percent profit as dictated by DOE guidelines brings the total price of the prototype WTC 500 to $1.35 million or $2,700/kW. Adjusting for the increase to 750 kW, and assuming the component costs for a one-off 750 kW turbine would be the same (the WTC 500 was designed to be retrofitted to 750 kW and procurement work to date suggests little difference in cost) reduces the cost per kilowatt to $1,800. Figure 12 illustrates that WTC will have to achieve an 88 percent production learning curve to reach the above identified target sales price by the time 512 turbine units have been produced.

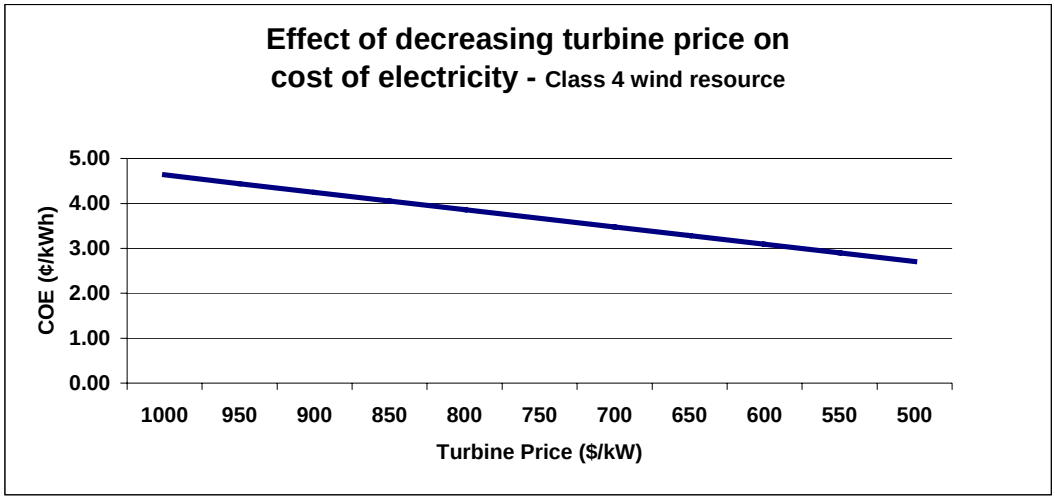

Figure 11: Turbine Sales Price/kW Required to Achieve COE Values
Selling WTC's 750 kW Wind Turbine for $575/kW will result in 3.0¢/kWh Electricity

WTC has begun an intensive effort to identify volume manufacturing costs and initial development of this database suggests WTC's cost-to-manufacture goals are achievable. With confirmation of the WTC 500's power production capability, achievability of COE goals will also be confirmed. Appendix IV summarizes WTC's cost to manufacture data.

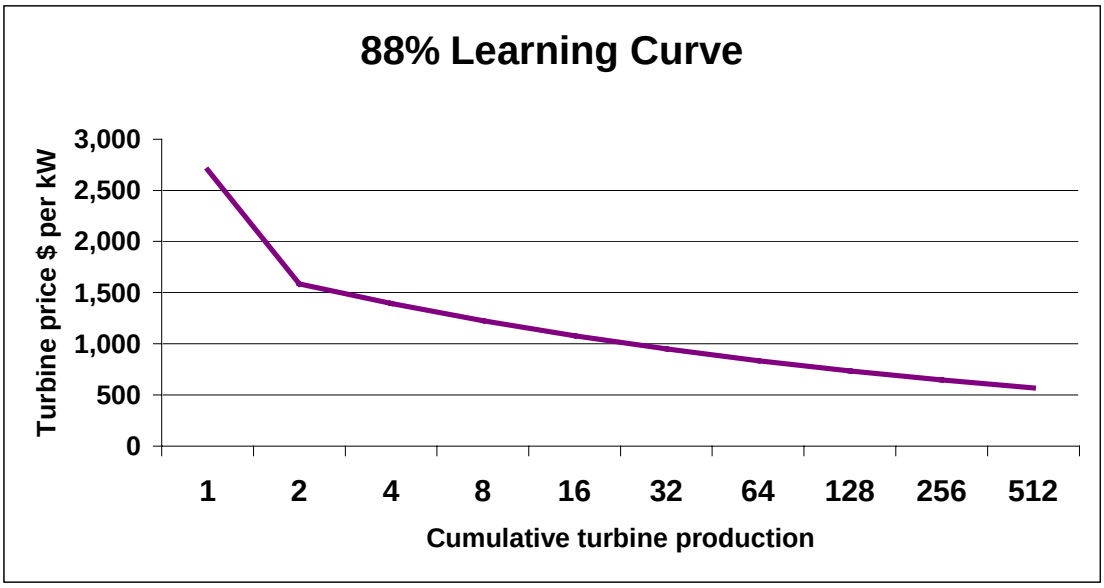

Figure 12: Learning Curve WTC Will Have to Obtain to Achieve COE Goals

Every time WTC doubles cumulative production the average cost of the most recent doubling will equal 88 percent of the average cost of the previous most recent doubling. The bend in the curve at 2 reflects the switch from the prototype WTC 500 to the first WTC 750.

In addition to the goals and objectives specifically identified in Contract No. 500-97-032, WTC identified some additional objectives (benefits) that the Company believed would arise from this project. These are identified on page 7 above.

Benefit 1: "At 3.5¢/kWh, unsubsidized wind energy will be an important source of clean, renewable energy to California's electricity consumers.

Benefit 2: The WTC 350 could save California's floundering wind energy industry, and could easily cause the generation of wind energy to double or triple in the state.

In light of California's "energy crisis" of 2000-2001, the availability of low-cost wind energy in the state is perhaps more important than ever.

Benefit 3: This would bring a significant number of new jobs and new tax revenues to the state, cause a substantial reduction in air pollution deriving from fossil-fuel electricity generation, and help California become the world leader and exporter of renewable power generation."

This is a longer term goal the achievement of which is expected to occur when WTC's turbine begins to achieve its commercial potential.

During the execution of Contract No. 500-97-032, however, there has been a net economic benefit to the state. WTC can identify California spending to date on this project in excess of $1.7 million compared with the Contract's $950,000. Two of the Company's twelve employees are residents of the State. WTC plans to open an office in the state and has investigated turbine assembly opportunities.

Much has happened in the wind energy industry and the electricity industry in the United States, particularly in California, since WTC entered into Contract 500-97-032 with the Commission in June 1998. Although it will take a few more years for WTC's new turbine to make a significant impact on the state's electricity generation system, and the state needs to adopt rules that will facilitate renewable energy generation, the potential is considerably larger today than it was in June 1998.

3.0 Conclusions and Recommendations

This section presents conclusions and observations arising from WTC's experience in executing Contract 500-97-032 and the NGT Project.

Commercialization potential, obstacles to successful commercialization, and the steps taken and to be undertaken to assure successful commercialization are described herein. Recommendations regarding next steps for turbine development and how program execution might benefit other projects are made. Last, an identification of benefits to California is offered.

3.1. Conclusions

The following conclusions relating to the objectives of the project can be reached.

Objective – Demonstrate that WTC's load shedding and mitigating concepts could be made to work in an operating wind turbine, thus prospectively leading to the use of less material with a resulting reduction in turbine cost.

Conclusion – The principle conclusion of the NGT Project is that WTC's wind turbine concept works very well. Data gathered to date incontrovertibly supports the conclusion that WTC's hinged-blade coupled with its proprietary flap motion restraint system significantly reduces the largest source of fatigue stress loading on a wind turbine – the loads resulting from the wind bending rigidly attached blades in the downwind direction. This has tremendous implications regarding the ability to safely take material out of the wind turbine and thereby reduce turbine cost.

Objective – Demonstrate the accuracy and thus the value of dynamic analysis models for predicting wind turbine performance and behavior.

Conclusion – A finding important for all future wind turbine development efforts is that the predictive system structural dynamics models used to design the POC and WTC 500 wind turbines were surprisingly accurate in loads prediction. The ADAMS and BLADED models have convinced WTC's engineering team of their value. It is critical for the future of the wind industry that hardware designers take advantage of and benefit from the most sophisticated tools available and that the tools get better.

During the execution of this program WTC's engineering team moved steadily away from the "simpler is better" school of thought to the school that relies on understanding the complexity of the environment in which wind turbines operate. Better understanding is required in order to achieve better results, and such understanding is not possible in the absence of better tools such as the dynamic analysis models ADAMS and BLADED.

Objective – In light of the wind energy industry's history, WTC had the overriding objective of demonstrating that its team could successfully design and build its new concept wind turbine.

Conclusion – WTC's management had no doubts about the capabilities of its team. However, the wind industry has seen capable people try before, only to fail. Some skepticism was well justified. WTC has proven it can make successfully functioning wind turbines. The road to commercial success, however, is by no means certain.

3.2. Observations

In addition to conclusions that can be reached regarding the goals of the project, certain observations about project management and how the project was executed including the relationships between WTC and the funding agencies – the California Energy Commission and the DOE / NREL can be made.

(1) As a small, under-funded company with limited demonstrable wind energy experience when it won its DOE / NREL contract, WTC regularly had to convince people in the agency that it might have something to offer. It was sometimes difficult to separate important issues from agendas and personalities. At the agency management level it is important to assure that personalities do not get in the way of success.

(2) Although the primary goal of all parties was one of economics – the generation of low-cost electricity – the means of achieving the goal is technical – a better wind turbine. Sometimes technical differences of opinion and biases get in the way of progress. When an agency funds a contractor, there is an obvious desire to assist the contractor to avoid known potholes; however, it is the contractor who has been selected and is responsible for executing the project.

(3) When WTC entered into its Commission contract there was a clear recognition that WTC's objectives for its Commission project might come into conflict with NREL's objectives for its project with WTC. It is clear that until conflicting objectives could be rationally discussed and conflicts resolved, all parties suffered.

(4) The reason WTC is in business is to achieve commercial success. Commercial success as defined by the Commission – getting commercially viable products into the field so that consumers may enjoy the benefits of these products in whatever form – is more consistent with WTC's objectives than is an on-going research and development project intended to increase the technical community's knowledge of wind turbine behavior.

Other observations will be taken up below in the form of recommendations.

3.3. Commercialization Potential

WTC stated in its PIER proposal that, if selected the Company would use PIER funding to create a commercially viable wind turbine that would be available for commercial deployment in year 2000. As described in the Project Outcomes section, WTC clearly missed this target. However, the commercialization potential of the new wind turbine is certainly greater today, as a result of the Commission's funding, than it was in June 1998 when it was still a paper wind turbine.

Although the turbine size has grown from 350 kW to 500 kW, compromises made with NREL led to a machine smaller than WTC would like and in the hybrid prototype WTC 500, a machine that is less economic than is desirable. Neither of these conditions are insurmountable barriers to successful commercialization of the derivatives of the prototype WTC 500.

In 1999, WTC made a connection that has led to a viable opportunity to develop a commercial demonstration wind project that will employ 20-30 WTC 750 turbines. Development of this project should be completed in 2003. The "Roosevelt Landfill Windfarm Project" is located on a major regional landfill immediately north of the Columbia River in the southern part of

Washington State. This project will provide the track record needed to convince wind project developers to use the Company's turbines. WTC has obtained a Conditional Use Permit for the site and has a customer for the electricity. WTC is seeking support from the DOE and is working to secure project financing.

WTC believes the case for a commercially viable version of its new wind turbine is stronger today than ever. Although it is clear that the WTC 500, configured with all components designed for application on a 750 kW capacity turbine thus incurring the additional expense of a machine with 50 percent greater capacity, would struggle commercially, once the purpose designed blade set is available the turbine will quickly achieve its commercial potential. This machine will be commercially available in 2003 and within a year if not sooner will be capable of beating the COE target of 3.5¢/kWh contained in WTC's proposal to the Commission by up to ½ cent per kWh. Subsidies will then no longer be necessary.

3.4. Recommendations

On May 21, 2001, the Commission awarded WTC follow-on Contract No. 500-00-019 in the amount of $1.3 million to help complete development of the prototype WTC 750 wind turbine. For this WTC is extremely grateful.

The recommendations that follow are based on the experiences of WTC in the execution of Contract 500-97-032 and the previous experience of WTC's management:

(1) WTC commends the Commission, the California Legislature and Administrations past and present for conceiving the PIER Program. The critical role of government funding in development of new technologies, in whatever their field, cannot be denied. The development of new wind technology could not and would not be fully funded by private industry. Getting this message out to the public is, in WTC's opinion, very important.

(2) The PIER Program is a powerful source of funding for new technology development in the renewable energy industry. It is the second largest source of funding in the U.S., behind only the DOE's programs, and possibly in 3rd place worldwide behind combined European Union funding. It dwarfs funding provided by Canada. WTC encourages the State of California make every effort to assure that the DOE's renewable programs are lined up in support of the Commission's programs. WTC believes the Commission's goals are pragmatic and its personnel are lined up squarely behind the agency's objectives. It would be beneficial if California's Congressional Delegation were informed of the Commission's programs and successes.

(3) During the execution of contracts, WTC suggests that, depending on contract duration, the Commission require of its contractors a regular, quarterly or semi-annual sit-down debriefing on project progress and plans with critical Commission staff and management. For out of state contract recipients such as WTC the cost of attending these meeting should be the contractor's.

(4) The Commission should strongly recommend contractor attendance at important policy and program review meetings involving the Commissioners. In fact, providing an opportunity for contractors to make a brief presentation on an annual basis to enable the Commissioners to obtain a better first hand understanding of the agency's programs seems worthwhile.

(5) The Commission's Contract Manager position changed hands three times in four years. Thus there was some discontinuity and re-education. As suggested in the Observations above, a good balance is required to achieve a desirable level of project involvement by an agency's Project / Contract Manager. It seems the Commission's staffing limitations may, unfortunately, preclude a deeper involvement in the Commissions PIER projects.

3.5. Benefits to California

Although California has yet to see the major benefit of the NGT Project – lower cost wind energy – several less consequential benefits have already occurred:

(1) As stated above approximately 80 percent more money has been spent in the state than has been reimbursed under Contract 500-97-032.

(2) WTC has identified and worked closely with a number of component suppliers as the result of a "buy California" focus and these relationships are expected to continue into future commercial production.

(3) WTC has California-based employees and will add to its California payroll as quickly as commercial considerations permit.

(4) The Company has identified one promising location where it could establish a wind turbine assembly facility as soon as commercial business opportunities develop.

(5) Within its resource constraints, WTC has made a concerted effort to identify opportunities to deploy its wind turbines in commercial developments in the state. This effort has been hampered by the lack of a managerial presence in California and by uncertainty surrounding the changing California electricity industry.

(6) WTC has an agreement with a Los Angeles-based developer to develop one or more wind projects totaling approximately 100 MW of installed capacity with the electricity to be sold to the DWP. The commitment is to deploy a minimum of 27.7 MW of WTC's turbines.

(7) WTC is working with a major utility-affiliated wind development company to evaluate the feasibility of deploying WTC's new 750 kW wind turbines in a major project in Southern California. WTC believes the lower cost and increased capacity factor achievable by its turbines will make the difference between a decision to go forward with the project or not.

(8) WTC has also attempted to engage the Sacramento Municipal Utility District (SMUD) in a demonstration project employing the Company's wind turbines.

(9) WTC believes it has helped, to a limited extent, enhance the role of the Commission PIER Program Renewables Group with NREL's Wind Program organization.

The longer term and major benefit to California remains the goal of lower cost wind energy that does not require subsidies for either on going operation or for project development in the first place. The Commission's Renewables agency has subsidized wind energy producers approximately $33.5 million over the past four years. With a commercially available wind turbine capable of generating 3.0¢ / kWh electricity within 2-3 years, the funds currently expended for these subsides can be made available for other purposes.

4.0 Glossary

Term	Definition
AB	Assembly Bill (State of California legislation)
ADAMS™	Advanced Dynamic Analysis Model, a computer-based engineering model or code
ANSYS™	Analysis Systems, a software code for accurately modeling combined behaviors resulting from multiphysics interactions
ATV	A French wind turbine blade manufacturer, formerly known as Atout Vent
BLADED™	GHP's software code for modeling wind turbine performance and loading
CEC	California Energy Commission
CEQA	California Environmental Quality Act, the State legislation governing the environmental restrictions surrounding permissible activities at particular sites
COE	Cost of energy or cost of electricity
CUP	Conditional Use Permit, the local governmental authority (e.g., Los Angeles County) issued permit allowing a site to be used for a particular purpose

DOE	U.S. Department of Energy
DWP	Los Angeles Department of Water and Power
EMD	Engineering, Manufacturing and Development, NREL's name for WTC's second prototype wind turbine, also known as the WTC 500, and the NGT prototype in this contract
ESI	Energy Systems Inc., an early U.S. manufacturer of 2-blade, downwind turbines
FMRS	Flap motion restraint system, WTC's patented turbine rotor blade control technology
GHP	Garrad Hassan & Partners Ltd., a Bristol, England-based wind energy consulting firm
IOU	Investor-owned utilities, such as Southern California Edison
kg	Kilogram(s)
kW	Kilowatt(s)
kWh	Kilowatt hour
m	Meter(s)

m/s	Meters per second
mph	Miles per hour
MW	Megawatt(s)
MWh	Megawatt hour(s)
NEPA	National Environmental Protection Act, the Federal counterpart to CEQA
NGT	Next Generation Turbine, either the NGT turbine or the NGT Development Project
NREL	National Renewable Energy Laboratory, a U.S. Department of Energy research laboratory
NWTC	National Wind Technology Center, NREL's wind research testing facility near Boulder, Colorado
PIER	Public Interest Energy Research Program of the California Energy Commission
RD&D	Research, Development, and Deployment
POC	Proof-of-concept, WTC's first prototype wind turbine

SCE	Southern California Edison
SERI	Solar Energy Research Institute, the DOE's predecessor to NREL
SMUD	Sacramento Municipal Utility District
WTC	The Wind Turbine Company, the contractor

5.0 References

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APPENDIX I

TURBINE CHECKOUT AND COMMISSIONING CHECKLIST

5.1 Checkout and Commissioning

Descriptions of the test Phases are given below. The detailed procedures for conducting the tests are given in Section 6.

5.1.1 Phase A – Communications and Control Checkout. Please refer to WTC Document #1890 for detailed descriptions and procedures for the communications and control checkout. These checkouts are required to be completed before the rotor lock. is released.

5.1.2 Phase B – Initial Calibration. Perform the blade root calibration. Detailed procedures for this calibration are yet to be worked out.

5.1.3 Phase C – Initial Startup and Checkout Testing. Table 5.3 is the Test Matrix for Phase C testing. The wind class is given in Table 5.2. Detailed procedures for conducting the Phase C tests are given in Section 6.5.

Table 5.2 – Wind Classifications

Classification	Wind Speed (m/s)
above rated	above 14
rated	10 to 14
below rated	7 to 10
marginal	4 to 7
low	2 to 4
calm	below 2

The test priorities are given by the following code:

1 = Can not be bypassed on the schedule, WTC Document 1495.

2 = Can be bypassed on the schedule by winds of lower wind category

3 = Can be bypassed if appropriate

4 = Useful but not essential

Any time a category 2 or 3 test is bypassed, the bypassing test must be conducted with extra caution.

1.0 Table 5.3 – Phase C Test Matrix

Test #	Wind Class	Description	Priority	Acceptance Criteria
100	low or calm	manual control	1	system operates as specified
101	low or calm	initial pinwheel in low to moderate wind	1	brake works without problems
102	low or calm	slow motoring	1	cegelec works in vector mode
103	variable	parked rotor loads	2	none
104	variable	rotor speed with generator unloaded at 40deg pitch	2	none
106	low or calm	standby to startup with a normal stop	1	successful transitions and stop
108	low or calm	standby to startup with e-stop	1	e-stop as specified
109	low or calm	standby to startup to synchronization with a normal stop	1	successful transitions and stop
110	calm	standby to startup with loss of load	1	stop & recovery as specified
111	low or calm	standby to startup to synchronization with an e-stop	1	e-stop and lockout as specified
112	marginal	power production with a slow stop	1	successful transitions and stop
114	marginal	power production with an e-stop	1	e-stop & lockout as specified
116	marginal	power production with a loss of load	1	stop & recovery as specified
117	marginal	one blade stopping the machine while the other blade is at full power pitch	3	successful stop & lockout
118	marginal	loss of load with both blades fixed at full power pitch	3	stop & lockout as specified
119	Below rated	e-stop from power production mode	1	e-stop & lockout as specified
120	Below rated	power production for 30 minutes with a normal stop	1	no unusual behavior or alarms

Test #	Wind Class	Description	Priority	Acceptance Criteria
	rated	normal stop		or alarms
121	Below rated	loss of load from power production mode	1	stop & recovery as specified
122	Below rated	one bladed stop form power production mode	3	successful stop & lockout
123	Below rated	e-stop with blades fixed at full power pitch	1	successful stop & lockout
124	rated	power production for 30 minutes	1	no unusual behavior or alarms
126	rated	e-stop from power production mode	2	e-stop & lockout as specified
127	rated	loss of load from power production mode	2	stop & recovery as specified
128	rated	one bladed stop from power production mode	3	stop & lockout as specified
129	rated	e-stop with blades fixed at full power pitch	3	stop & lockout as specified
131	above rated	e-stop from power production mode	2	e-stop and lockout as specified
132	above rated	power production for 30 minutes	3	no unusual behavior or alarms
133	above rated	loss of load from power production mode	2	stop & recovery as specified
134	above rated	one bladed stop from power production mode	3	stop & lockout as specified
135	above rated	e-stop in blades fixed at full power pitch	2	stop & lockout as specified
136	as needed	if overspeed have not occurred in the previous tests, overspeeds should be tested for the different wind classes	3	stop & lockout as specified
137	calm	rotating rotor modal test	3	none

Appendix II - POC Test Matrix

Test Matrix

Phase D1 - Baseline Configuration 1 Testing. Phase D1 can begin when the appropriate tests of Phases A-C are accepted using the priority table, or if a formal decision has been made to proceed to Phase D1. The baseline configuration operates at a fixed speed of 1200 rpm (generator, nominal), with standard pitch control.

Table 5.4 is the test matrix for Phase D field testing, and will apply for each configuration tested. There is a significant difference between the character of the wind during the day, the night, and the transition period, and it is preferable to fill in the bins of Table 5.4 for each stability period. These periods are defined as follows:

Daytime (D): 0900-1500

Transition (T): 1500-0200

Nighttime (N): 0200-0900

Table II-1: Phase D Test Matrix, Minimum and Preferred Number of 10-Minute, 40 Hz Data Sets by Case and Bin

Wind Speed (m/s)	Turbine Control Configuration													
	1 Baseline		2 Tower Feedback		3 Flap Feedback		4 Individual Pitch		5 Two-Speed		6 Variable Speed		7 Pitch to Stall	
	Min	Pref	Min	Pref	Min	Pref	Min	Pref	Min	Pref	Min	Pref	Min	Pref
5 – 8	2	6	2	6	2	6	0	6	0	6	0	6	0	6
9 – 12	2	6	2	6	2	6	0	6	0	6	0	6	0	6
13 – 16	2	6	2	6	2	6	0	6	0	6	0	6	0	6
17 – 20	2	6	2	6	2	6	0	6	0	6	0	6	0	6
21 - 23	0	0	0	0	2	6	0	6	0	6	0	6	0	6

In addition for Phase D1, acoustic testing should begin with low frequency acoustic data being taken concurrently with filling the bins in Table 5.4. The acoustic data collection should continue until Table 5.4 is satisfied independently of the progression of the test Phases.

Appendix III - POC Measured vs. Predicted Loads (Consultant Reports, Not Available for Public Release)

Appendix IV - Turbine Manufacturing Costs Summary

General Comments on Turbine Manufacturing Cost Trends

Manufacturing cost is by nature sensitive to rate of production. Increased rates of production can generally be expected to result in a declining cost per article. The declining cost trend may be considered the result of a "learning curve" phenomena which encompasses the affects of several factors, including quantity price discount policies of suppliers, improvements in process methods and techniques and improvements in design and application of alternative materials.

The learning curve concept has gained particular credence in the aircraft industry where the following expression has been developed:

$$Cost_n = Cost_1(n)^{\ln Lcf / \ln 2}$$

where

$Cost_n$ is the cost for the nth unit in the production series

n is the number of units

$Cost_1$ is the cost for the first unit

Lcf is a Learning Curve Factor which governs the slope of the declining cost curve

The cost trend decline is normally quite steep for highly complex, advanced technology products such as aircraft where Learning Curve Factor values of 0.80 - 0.90 are reported[1] as being typical. The same source suggests a Learning Curve Factor of 0.90 - 0.95 for conventional 3 blade wind turbine designs. The WTC Turbine, being a new technology design, is expected to realize a Learning Curve Factor of 0.85 - 0.90, which is slightly steeper than for a conventional 3 blade wind turbine but not as steep as for aircraft.

Using actual incurred costs for prototype manufacture and assuming an overall average value of 0.88 for the Learning Curve Factor, i.e., in the middle of the expected range, the WTC 750 will achieve the 3.0 cent/kWh NREL Cost of Electricity (COE) target when production reaches 250 turbines per year, a rate which is consistent with the production levels of the present industry leaders. The 0.88 Learning Curve Factor corresponds to a cost reduction of 64 percent from the prototype cost.

Cost Impact of Quantity Price Discounting

To evaluate the contribution of quantity price discounting in the overall cost trend picture, solicitations were issued to suppliers of components used on the EMD-1 turbine. Price discount policy was found to be specific to each particular supplier, discount schedules ranging between 5 percent and 85 percent with a mean just over 30 percent. Thus nearly half of the expected cost reduction can be attributed to quantity price discounting from suppliers.

Improvements in Process Methods and Techniques

Several of the process methods employed for prototype manufacture, while suitable for fabricating a first article, are recognized to be labor intensive and thus present opportunities for cost reductions in series production. Notable in this category are the Spinner the Tower and the Nacelle Assembly.

The Spinner was manually formed and welded from aluminum sheet and plate, which resulted in a functionally satisfactory structure but at a substantial cost in direct labor. Options to reduce labor cost for the Spinner are several, including:

- Welded aluminum construction employing robotic welding equipment in conjunction with positioning fixtures and tooling.
- Spray form glass fiber as used on the Nacelle Enclosure
- Vacuum form or rotationally cast thermoplastic with welded steel frame

The cost reduction potential of these options ranges from approximately 60 percent for robotic welded aluminum to in excess of 90 percent for vacuum formed or rotationally cast thermoplastic.

The Tower was formed and manually welded from 8-foot sections of steel plate without benefit of automated processing. As with the Spinner, the resulting structure is functionally satisfactory but the process was labor intensive. Labor cost can be reduced by utilizing segments of gas transmission line pipe in place of the manually formed and welded sections of steel plate. Preliminary cost analysis indicates that cost can be reduced by some 80 percent due to the highly automated process techniques employed for gas line pipe. The automated nature of the gas line pipe process does require certain minimum order quantities, which prevented its use on the prototype turbine but is not a limitation under conditions of series production.

The Nacelle Assembly process as performed on the prototype turbines was very labor intensive due to several factors that are typical for first article situations and include the following:

- The facilities employed for prototype assembly were less than ideal, notably with respect to crane capacity and material flow. A facility configured to provide optimum material flow and material handling will reduce labor considerably.
- Techniques for assembly were being created and learned “on the spot” as the prototype machines were built. The benefits of this learning will accrue on subsequent machines.
- Fixtures, tooling and other assembly aids were minimally employed for the prototype machines. Developing and implementing assembly fixtures and tooling suitable for series production conditions can substantially reduce assembly labor.

The aggregate affect of these labor saving techniques is an expected decline in Nacelle Assembly cost by some 90 percent compared with the prototype.

Improvements in Design and Application of Alternative Materials

A further aspect of the Learning Curve is learning with respect to the design itself, including the selection of materials called for in design specifications. Cost reductions realized as design learning are often referred to as Value Engineering.

Value Engineering opportunities exist to varying degrees throughout the entire turbine design. The most notable in terms of cost reduction potential are the Blade Support System, the Guy Cable System, the Generator and the Nacelle Enclosure. Value Engineering of the Blade Support System is presently underway as part of the overall design process for the 750 kW Rotor. Concepts for a simplified lower cost Guy Cable System and lower cost Generator have been identified and defined to the point of indicating their potential. The Nacelle Enclosure will benefit principally from detailed structural analysis and material placement optimization; an engineering activity intended to be undertaken as soon as time permits.

References

1. Hau, Erich, *Wind Turbines, Fundamentals, Technologies, Applications, Economics*, Section 18.3.2, Springer Verlag, 2000.

Appendix V - NGT Project Cost Sharing Details

Break down of NGT project costs by cost category by source of funding. Beginning February 1, 1997 through March 18, 2002 (end of Contract No. 500-97-032):

	Cost Category	NREL Cost Share	CEC Cost Share	WTC Cost Share	Cumulative Total Costs
1.	Direct Materials	346,536	95,679		442,215
2.	Material Overhead				
3.	Direct Labor	1,770,246	51,665		1,821,911
4.	Labor Overhead & Fringe Benefits	1,114,070	37,217		1,151,287
5.	Equipment	2,671,913	248,555	45,810	2,966,278
6.	Travel	325,571			325,571
7.	Lower-Tier Subcontractors	231,819			231,819
8.	Consultants	2,897,189	473,963	383,390	3,754,542
9.	Other Direct Costs				
10.	Total Direct Cost & Overhead	10,693,618			10,693,618
11.	General & Administrative Expense	1,489,693	42,921	135,005	1,667,619
12.	Facilities Capital Cost of Money				
13.	Royalties				
14.	Total Project Cost	10,847,033	950,000	564,205	12,361,238