A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory
Innovation for Our Energy Future

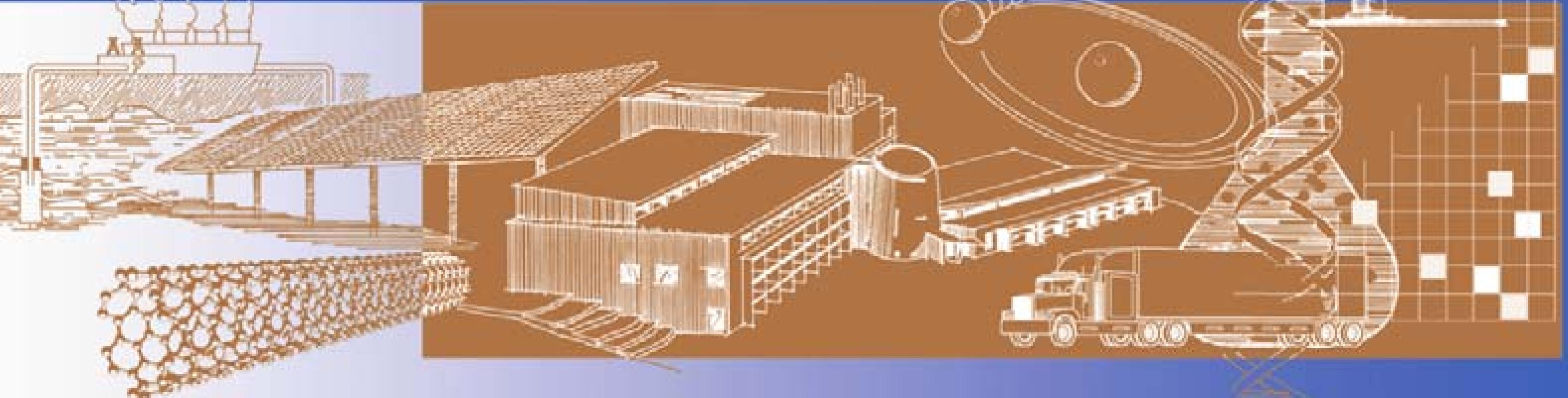
Semi-Submersible Platform and Anchor Foundation Systems for Wind Turbine Support

August 30, 2004 – May 31, 2005

Subcontract Report
NREL/SR-500-40282
December 2007

G.R. Fulton, D.J. Malcolm, H. Elwany,
W. Stewart, E. Moroz, and H. Dempster
Concept Marine Associates Inc.
Long Beach, California

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



Semi-Submersible Platform and Anchor Foundation Systems for Wind Turbine Support

August 30, 2004 – May 31, 2005

Subcontract Report
NREL/SR-500-40282
December 2007

G.R. Fulton, D.J. Malcolm, H. Elwany,
W. Stewart, E. Moroz, and H. Dempster
Concept Marine Associates Inc.
Long Beach, California

NREL Technical Monitor: Walt Musial
Prepared under Subcontract No. YAM-4-33200-10

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Contents

Figures

Tables

Executive Summary

In 2002, the U.S. Department of Energy (DOE) established the Low Wind Speed Technology (LWST) Program to develop technology that will enable wind energy systems to generate cost-competitive electrical energy at low wind speed sites. The program goal is to reduce the cost of electricity from large wind systems in Class 4 winds to 3.6 cents/kWh for land-based systems and to 7 cents/kWh for offshore systems in a Class 6 wind regime.

Much of the United States' strong wind resource is located away from load centers, and limitations of the transmission system reduce the ability of land-based wind energy projects to meet the needs of these centers. Many load centers are relatively near the nation's coasts, where there is a considerable wind resource; however, much of it is in areas with relatively deep water. There are also challenges associated with locating wind energy projects within view of the nation's coasts. If wind energy technology can be developed to cost-effectively establish wind turbines in deeper water, where there is an abundant wind resource and the projects are not visible from shore, significant additional power could be installed.

The National Renewable Energy Laboratory (NREL) issued a Request for Proposals in 2003 for a second round of contracts within the LWST program. Concept Marine Associates, Inc. (CMA) was awarded a Conceptual Design Study contract to examine the feasibility of various semi-submersible platform configurations for an offshore deep water wind turbine.

This report describes the results of that subcontract, the design work involved, the design loads identified, and the overall estimated cost of energy (COE).

CMA assembled a team of experts from the following firms to work with NREL on this concept study:

- Coastal Environments (CE)
- Garrad Hassan America, Inc. (GH)
- Global Energy Concepts, LLD (GEC)
- Stewart Technology Associates (STA)

Configuration

After evaluating various potential configurations and mooring concepts, the team selected a preferred configuration (see Figure ES-1). It consists of a semi-submerged triangular platform and superstructure on which the wind turbine is mounted. The platform is stabilized and held in place via tension legs that connect the platform to a gravity anchor. The gravity anchor and platform are hollow, compartmentalized cast concrete. This construction allows the platform and anchor to use water as ballast, and adjustments to the platform and anchor buoyancy can be made quite easily. The adjustable buoyancy permits the system to be fabricated and assembled in conventional floating or custom dry docks, then floated to the operating site and installed.

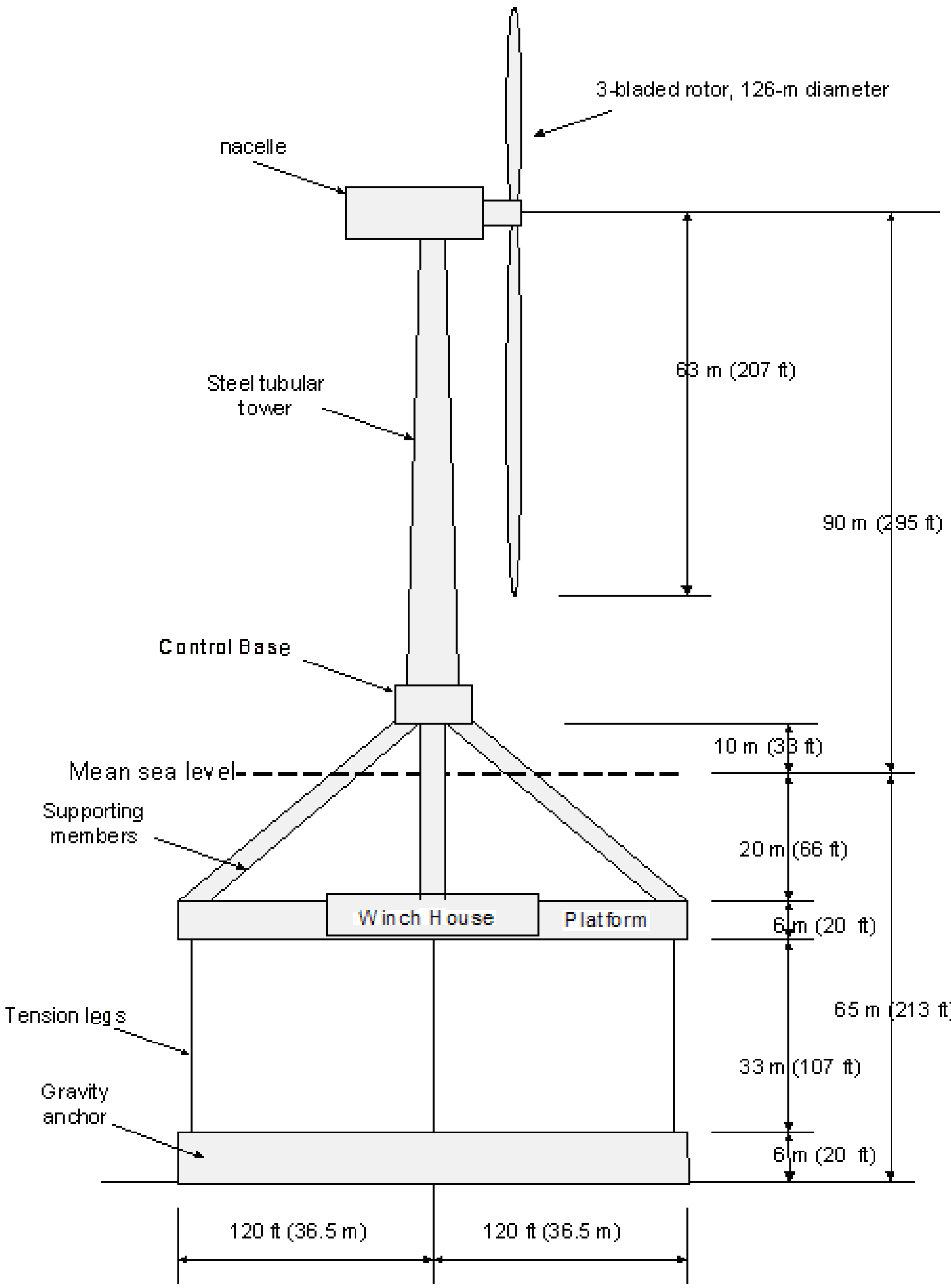


Figure ES-1. Selected configuration

The installation sequence is shown in Figure ES-2. At Stage 1, the fully assembled wind turbine and platform are floated to the site. The platform and anchor can be partially filled with water to maximize the stability of the system. Once at the deployment site, the anchor is fully ballasted with water and the wire ropes are extended until the anchor rests on the bottom (Stage 2). The platform is then submerged with winches that pull on the wire ropes. The platform may be partially filled with water to minimize the size of the winches. Once the platform is at operating depth, the wire ropes are secured and the ballast may be removed to maximize its buoyancy and the stability of the installation (Stage 3).

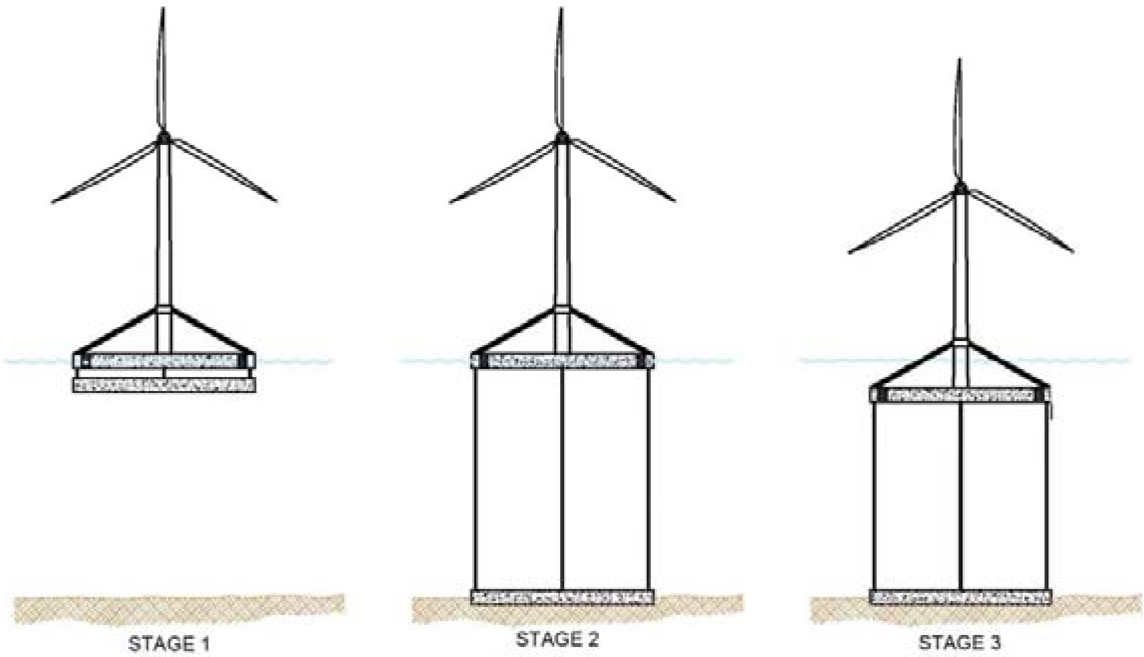


Figure ES-2. Installation sequence

This configuration offers several advantages over other potential deep water mooring systems. These include:

- It is fully assembled onshore and self-deploying, so it eliminates floating cranes offshore and minimizes the potential for weather delays and associated costs.
- It is insensitive to bottom conditions, as long as the bottom is relatively flat.
- Its reusable molds can be used to make cast concrete structures in a production line fashion in dry docks.
- It provides the stability of a tension leg platform without the costs and risks associated with installing anchors in variable bottom conditions.
- It is quite stable because the platform is submerged below the wave action.
- The system can be brought to the surface for repair, relocation, or removal.

Design and Costing

NREL provided environmental conditions that are representative of a site off the eastern United States to develop the design of the system. This work focused on the design of the platform and anchoring system. Thus, NREL also provided the basic wind turbine design; however, the costs were adjusted based on the results of system dynamic modeling. Three codes—Bladed, FAST, and Orcaflex—were used to complete dynamic modeling. None has provided all the information needed to design the system with high confidence. Bladed and FAST are wind turbine codes that are being adapted to offshore applications. Consequently, their ability to model wave loading is limited. Orcaflex is an offshore engineering code that models wave loading, but not the interaction of the wind with the wind turbine. Thus, the outputs from these codes were used to complete the design; engineering judgment was used to reconcile differences in the results.

These codes were used to obtain initial loads, which were used to complete trade-off studies and conceptual system designs. Once selected, the concept design was modeled again to refine loads that were subsequently used to adjust the design and estimate costs.

The costs of the platform and mooring system were developed based on experience with other offshore installations. The costs of large wire ropes, pre-stressed concrete, the wire rope control system, and the installation costs of similar systems are understood by the offshore engineering industry.

Costs for the wind turbines were developed based on tools that were developed for NREL for this purpose and have been checked against market conditions. Adjustments have been made to reflect recent increases in the costs of raw materials such as steel.

Costs for the electrical interconnection of the project and operations and maintenance (O&M) costs were provided by NREL.

Table ES-1 summarizes the key inputs and results of the COE analysis.

Table ES-1. Cost and COE Summary

Distance from shore (mi)	**15**	**15**	**15**	**60**
Rating (kW)	5000	5000	5000	5000
Component	**Baseline Component Costs**	**HIGH Projected Component Costs**	**LOW Projected Component Costs**	**Projected Component Costs**
Rotor	**1,070**	**1,070**	**1,070**	**1,070**
Blades	691	691	691	691
Hub	235	235	235	235
Pitch mechanism and bearings	144	144	144	144
Drive train, nacelle	**2,111**	**2,111**	**2,111**	**2,111**
Low speed shaft	79	79	79	79
Bearings	65	65	65	65
Gearbox	706	706	706	706
Mechanical brake, HS coupling, etc.	10	10	10	10
Generator	260	260	260	260
Variable speed electronics	270	270	270	270
Yaw drive and bearing	45	45	45	45
Main frame	354	354	354	354
Electrical connections	200	200	200	200
Hydraulic system	23	23	23	23
Nacelle cover	99	99	99	99
Control, safety system	**10**	**10**	**10**	**10**
Tower	**796**	**796**	**796**	**796**
Turbine capital cost (TCC)	**3,987**	**3,987**	**3,987**	**3,987**
Balance of station (BOS): semi-submersible platform				
Mobilization, plant and equipment		232	200	232
Permits, engineering		57	57	57
Gravity anchor structure		1,602	1,252	1,602
Semi-submersible platform		1,783	1,343	1,783
Tension legs, winches, and porches		1,823	910	1,823
Deployment		161	161	161
Electrical infrastructure		1,475	1,475	3,275
BOS: seabed mounted baseline				
Port and staging equipment	100			
Design and project management	112			
Pre-construction site assessment	73			

Monopile foundations	1,488			
Personnel access system	60			
Scour protection	270			
Turbine installation	527			
Electrical infrastructure	1,405			
BOS cost	**2,630**	**7,133**	**5,398**	**8,933**
Project uncertainty				
Initial capital cost	**6,617**	**11,120**	**9,385**	**12,920**
Installed cost ($)/kW for 5-MW turbine	**1,323**	**2,224**	**1,877**	**2,584**
Turbine capital cost ($)/kW without BOS	**797**	**797**	**797**	**797**
Levelized replacement costs ($10.7/ kW/yr)	54	54	54	54
O&M $20/kW/yr (O&M)	100	100	100	100
Land ($0.00108/kWh/yr/turbine)				
NET 6.7 m/s annual energy production MWh	19107	18965	18965	18965
Fixed charge rate (FCR)	11.85%	11.85%	11.85%	11.85%
COE at 6.7 m/s $/kWh	**0.0470**	**0.0755**	**0.0646**	**0.0867**

Conclusions and Recommendations

The configuration selected for detailed analysis in this project offers many advantages relative to other possible systems for deep water offshore wind turbines. The primary advantage is the ease with which the system can be constructed, transported, and installed on the site relative to other technologies that can provide a suitably stable platform for a wind turbine in deep water.

The completed analysis indicates that the rotor and nacelle loads associated with deep water offshore operation are similar to those of land-based wind turbines. However, the tower loads are significantly higher because of the platform's motion.

No single dynamics code without substantial modification is available that can model the combined wind and wave action of a floating semi-submerged wind turbine structure. By using multiple codes and engineering judgment, this study has arrived at credible results; however, development of a single code with the required capabilities would facilitate future research.

The advantages of the proposed concept relative to other available technologies will increase at greater water depth. That is, the costs of the system rise only marginally as water depth increases.

The estimated COE for the systems is higher than the DOE shallow water target of $0.07/kWh. As the concept is refined, the costs of the mooring system fabrication and installation can likely be reduced. However, other costs that are not the subject of this study are major contributors to the COE. With no BOS cost and using the specified energy production estimation methodology, reasonable estimates for the cost of the wind turbine and NREL's specified O&M costs, contingency, and FCR, the COE would be approximately $0.041, leaving $0.009 for BOS costs.

The conceptual design developed in this study needs further refinement if we are to better understand the peak loads it will experience and refine cost and performance estimates. Wave tank modeling would be a valuable tool for comparison with the predictions of the available dynamics models.

1 Introduction

1.1 Background

In 2002, the U.S. Department of Energy (DOE) established the Low Wind Speed Technology (LWST) Program to develop technology that will enable wind energy systems to generate cost-competitive electrical energy at low wind speed sites. The onshore sites targeted by this program have annual average wind speeds of 5.8 m/s, measured at a height of 10 m. Such sites are abundant in the United States and will increase by twenty-fold the available land area that can be economically developed. The current program goal is to reduce the cost of electricity from large wind systems in Class 4 winds to 3.6 cents/kWh for onshore systems and to 7 cents/kWh for offshore systems in a Class 6 wind regime.

The United States possesses extensive lands with wind regimes that are sufficient to generate considerable wind energy at competitive costs. However, these regions are often far from demand centers. In addition, conflicts with other land uses often mean that some wind energy potential cannot be developed. In Europe such pressures have led to the deployment of offshore wind turbines, usually in water depths less than 20 m, which are common in the North and Baltic Seas.

Regions such as the east coast of the United States also have attractive wind regimes (Manwell 2004), but much of this is in water deeper than 20 m. If technology can be developed to establish wind turbines in deeper water, this renewable energy can be captured close to the demand centers of the east coast.

In 2003, the National Renewable Energy Laboratory (NREL) issued a Request for Proposals for a second round of contracts within the LWST program. Concept Marine Associates Inc. (CMA) was awarded a Conceptual Design Study contract to examine the feasibility of various semi-submersible platform configurations for an offshore deep water wind turbine.

This report describes the results of that subcontract, the design work involved, the design loads identified, and the overall COE estimated.

1.2 Current Technology

Offshore wind turbines have been developed mainly in Europe, where there are approximately 900 megawatts (MW) of installed power in the Baltic and North Seas. All those installations are in water that is shallower than 20 m and are mounted on the seabed by a variety of fixed foundations. Europe has plans for 150 gigawatts of additional offshore seabed-mounted turbines by 2030. However, as some limitations on shallow water developments have emerged and deeper water development is considered, the need for alternative technology has become apparent.

Possible configurations for deep water installations have been explored in a number of conference presentations (Musial 2004) and at several workshops (DOE 2003, 2004). Figure 1-1 shows a typical progression from onshore to deep water offshore scenarios; Figure 1-2 shows concepts that have been previously studied.

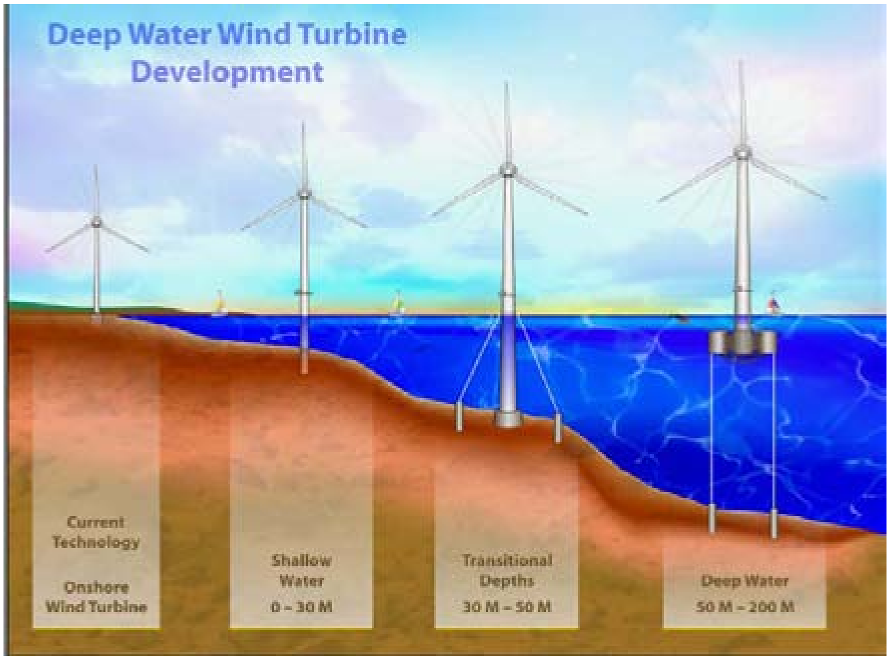


Figure 1-1. Illustration of progression from onshore to deep water offshore wind turbines

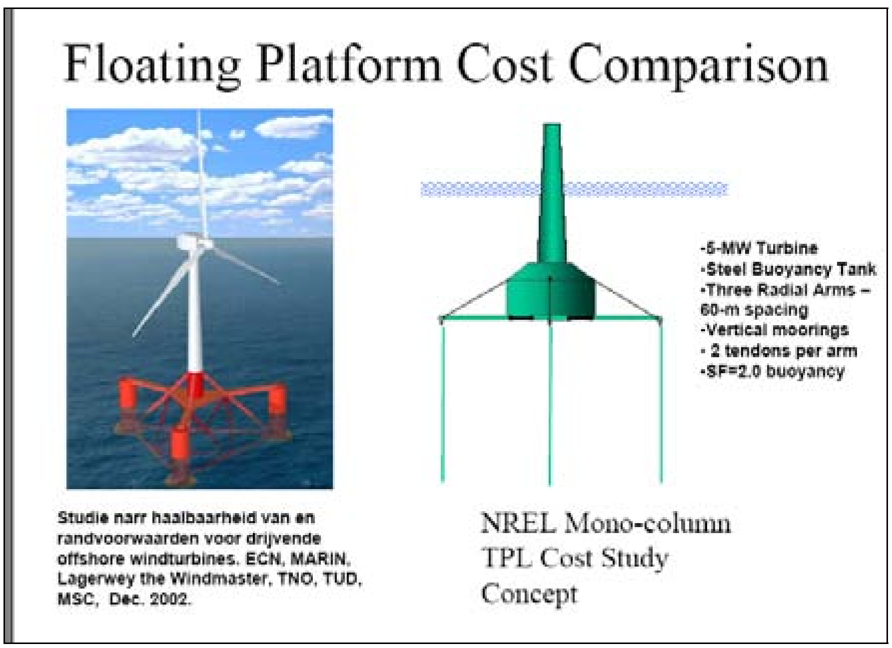


Figure 1-2. Floating platform concepts previously explored

The primary issues under evaluation when considering deep water wind turbine installations have been:

- A floating or a semi-submerged platform
- A tension leg, taut wire rope, or catenary leg restraining system
- The type of anchor: gravity, suction pile, or tension embedment.

1.3 Objectives

The objective of this concept design study was to investigate the technical and economic feasibility of semi-submersible wind turbine platforms for offshore wind turbine installations. More specifically, the goals are to:

- Identify the optimal platform configuration for the specified turbine and design environment.
- Estimate the cost of energy (COE) from such a platform and turbine combination.
- Identify technical challenges to the successful development of the selected concept.

1.4 Organization of the Report

The remainder of this report is organized as shown in Table 1-1. Most sections make reference to the appendices, which contain considerable technical and background information.

Table 1-1. Outline of Report Contents

Section	Title	Contents
2.0	Site Conditions	The source of the sea state description and the accompanying wind regime.
3.0	Loading Conditions	Specifications of the load cases to be considered.
4.0	Platform and Mooring System	Detailed information on the proposed layout of the platform and mooring systems and anchor. Installation procedure. Design loads on all major components.
5.0	Wind Turbine Design	Selection of the turbine characteristics. Modeling of the turbine. Representation of the semi-submersible platform. Peak and fatigue loads on major components. Comparison with onshore design. Costs.
6.0	Cost of Energy	Estimate of total energy capture of wind farm. Estimate of total capital costs of all phases: fabrication, transportation, installation, maintenance, and operation.
7.0	Development Schedule	Describes a possible schedule for further development and testing of the concept.
8.0	Conclusions and Recommendations	Lists the conclusions of the study and makes recommendations for how the regarding the work required to further develop the concept.

1.5 Project Team and Approach

The project team and associated roles and responsibilities are shown in Table 1-2.

Table 1-2. Project Team

Name of Firm	Acronym	Role
Concept Marine Associates	CMA	Main subcontractor
Coastal Environments	CE	Marine environment
Garrad Hassan America, Inc.	GH	Wind turbine simulation
Global Energy Concepts LLC	GEC	Wind turbine design
Stewart Technology Associates	STA	Platform dynamics

The overall approach to the project is summarized in the following bullet points; additional detail is provided in Figure 1-3.

- Identify the wind and wave environments related to a location offshore from the east coast of the United States, as set forth by NREL.
- Consider the various mooring systems for a semi-submersible platform and determine which is the most suited for a wind turbine platform.
- Identify the approximate dimensions and design characteristics of a large wind turbine that is suitable for installation offshore on such a platform.

- Carry out analyses to determine the stability of such a platform and wind turbine under extreme loading.
- Determine design loads in all major components to allow costs to be estimated.
- Estimate the costs and performance of such a system and the COE.
- Draw conclusions about the feasibility of the concept.

At the start of the project we did not know which software and modeling would be used for the wind turbine, the platform, and the combined system. Clearly no mathematical model was readily available to simulate the complete system with wind and wave loading. Some progress toward this goal has been made at the Massachusetts Institute of Technology (MIT) (Sclavounos 2003), but implementing the software would have required considerable resources.

We decided to use the Bladed software from GH to model the complete system, even though it cannot represent yawing and heave degrees of freedom. Those deficiencies did not seriously impair preliminary design for operational conditions. STA used the Orcaflex code, which has been extensively used in the offshore oil and gas industry, to model the platform and mooring system. However, all details of the wind turbine and its control system cannot currently be included in that code.

NREL staff determined the initial configuration of the wind turbine by reviewing current multimegawatt machines or known plans for large wind turbines. The selected configuration was strongly influenced by the RePower 5MW, which is intended for offshore use. The information on this selected configuration was transmitted to GEC in the form of an input for the FAST code. GEC carried out some preliminary analyses with the FAST model to determine the loading that was caused by the 50-yr return extreme wind load, which was provided to STA for initial design of the platform.

The wind turbine configuration was also given to GH, which prepared a Bladed version of the same configuration. Once the initial design of the platform was completed, the Bladed model was modified so that the base of the tower and its restraints were equivalent to those of the platform.

The Bladed model was run to simulate a set of loading conditions that formed a subset of the full International Electrochemical Committee (IEC) loads (IEC 2004), as agreed to with NREL. GEC processed the results of those simulations to determine the fatigue loading environment and the peak loads. Time series of loads equivalent to the 50-yr and 1-yr extreme loads were transmitted to STA to allow the platform to be simulated with turbulent wind loading.

GEC used its experience in the industry to estimate the costs of the wind turbine. CMA and STA estimated the costs of the platform, mooring system, and installation based on the completed conceptual designs and the costs of constructing similar equipment in the maritime environment. NREL specified the operation and maintenance (O&M) costs, electrical interconnection, and other costs that are not under investigation in this study, as was the wind regime and wave environment to be used for the design.

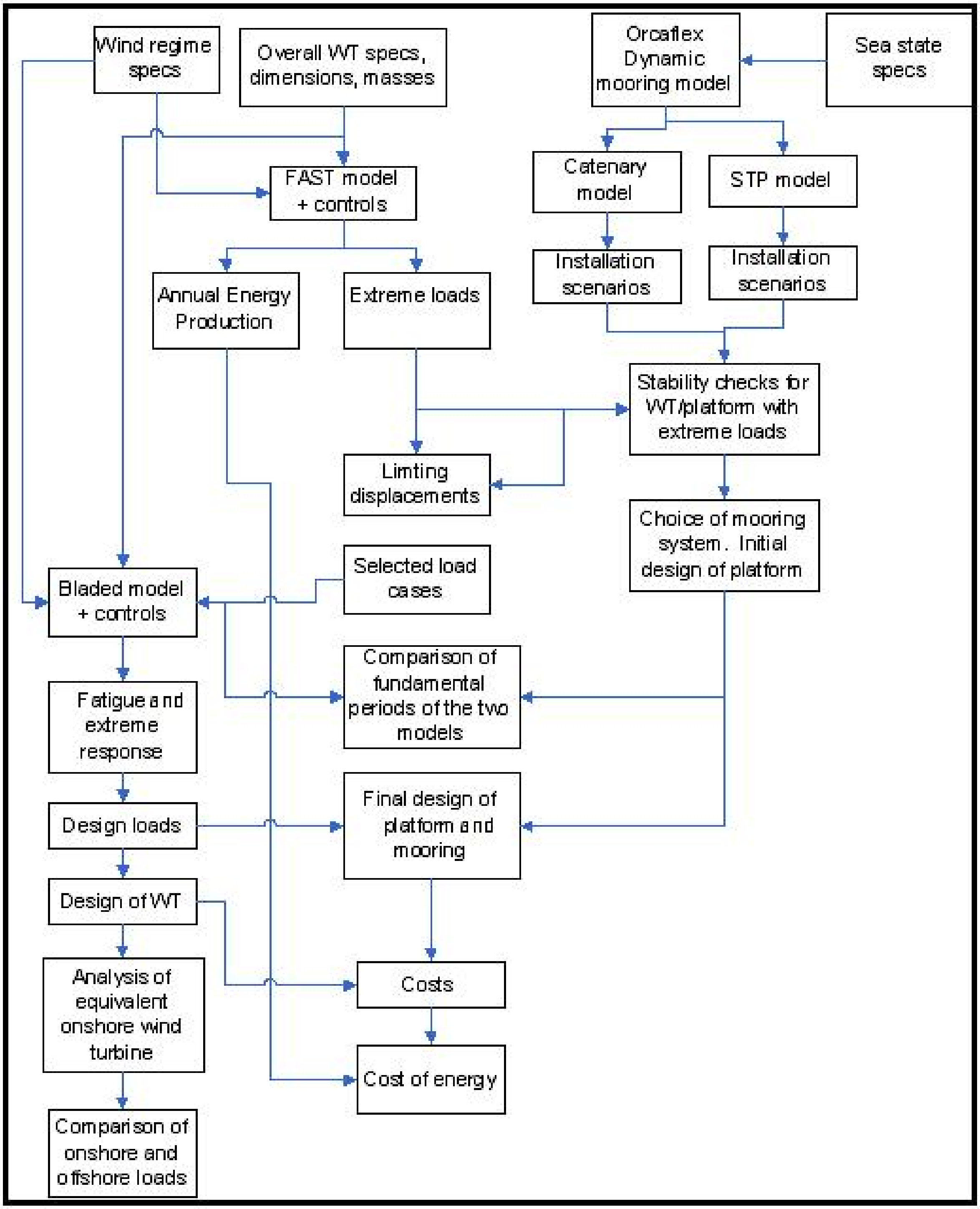


Figure 1-3. Flowchart of project activities

2 Site Conditions

NREL specified the particular sea state conditions used for this concept study to be those obtained from the National Oceanic and Atmospheric Administration/National Data Buoy Center (NOAA/NDBC) Buoy 44008. That buoy is located at 40.50 N, 69.43 W, about 54 nautical miles (NM) southeast of Nantucket Island (see Figure 2-1). The data from this buoy were processed to obtain the relevant parameters, which are summarized in Table 2-1 and given in full detail in Appendix B. The data used in this study provide a 22-yr record between August 1982 and October 2004. The buoy is still in place and collecting additional data.

The largest recorded storm wave, which occurred on September 19, 1999, had a significant wave height of 11.51 m, an average wave period of 11 s, and a peak wave period of 14.3 s.

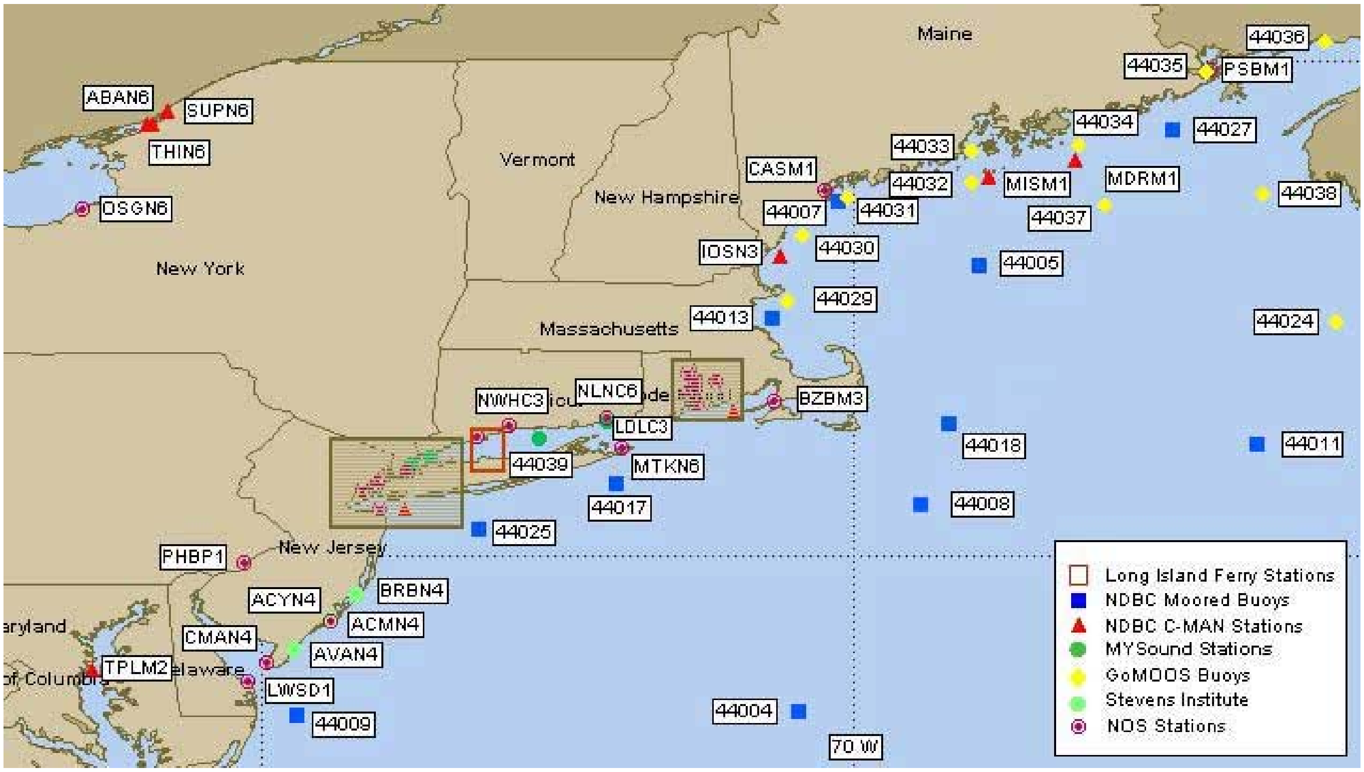


Figure 2-1. Location of NOAA/NDBC Buoy 44008 and other NOAA/NDBC buoys in the area

2.1 Soils Data

Data regarding the soils off Nantucket Island were not obtained for this report. A gravity anchor was chosen for this concept design since it can work in a variety of soil conditions. Flat sites should be chosen for installation of such a large gravity anchor.

2.2 Design Wind Regime

NREL specified the design wind regime to be in accordance with IEC (2004) design class IB. This classification corresponds to the inflow characteristics at hub height shown in Table 2-1. Details of these conditions are provided in Appendix C.

Table 2-1. Summary of Design Wind Regime (at hub height)

Item	Units	Value
Mean annual wind speed	m/s	10.0
Wind speed distribution type		Rayleigh
Characteristic turbulence intensity at 15 m/s		0.16
Maximum 10-min wind speed	m/s	50.0
Maximum 3-s wind speed	m/s	65.0
Vertical wind shear exponent		0.12
Air density	kg/m^3	1.225

2.3 Environmental Data

Sections 2.3.1 through 2.3.4 provide a summary of wave, tide, current, and wind data southeast of Nantucket. A detailed description of the oceanographic and meteorological data and the design parameter estimation method and results is presented in Appendix B.

2.3.1 Waves

The NOAA/NDBC Buoy Station “Nantucket” (44008) provides 22 years of unidirectional wave data. These data include significant wave heights (H_s), peak wave periods (T_p), and average wave periods (T_a). A significant wave height of 1 m occurs more than 50% of the time; significant wave heights of 2 and 3 m occur approximately 28% and 12% of the time, respectively. Maximum monthly Hs range is 2−11.5 m. Major wave storms occur during the winter and autumn. However, the largest waves occur during hurricanes, which usually occur during the summer.

Significant wave heights are highest in August and September because of the hurricane season. The largest recorded storm wave, which occurred on September 19, 1999, had a significant wave height of 11.5 m, a peak wave period of 14.3 s, and an average wave period of 11 s.

Peak wave period (T_p) is defined as the period (in seconds) of the inverse of the frequency band containing the maximum energy density in the frequency spectrum. The frequency distribution mode for peak wave period is 8 s. An 8-s peak wave period during summer and spring occurs 25%−30% of the time; an 8-s peak wave period during winter and autumn occurs 20%−25% of the time. Average wave period (T_a) is the average wave period (in seconds) of all waves during the 20-min measuring period. Maximum monthly peak and average wave period data collected between November 1982 and October 2004 are 9−20 s and 5−14 s, respectively.

2.3.2 Tides

According to the tidal epoch (1983−2001), the mean higher high water with respect to mean lower low water is about 1.09 m. Mean high water is 0.98 m, mean water level is 0.54 m, and mean low water is about 0.06 m. The maximum recorded water level was about 2.4 m on October 30, 1991.

2.3.3 Coastal Currents

One of the predominant patterns of New England Shelf water involves the seasonal temperature change and the breakdown and setting up of the thermocline. In general, during the fall and winter the breakdown of thermal stratification, which is due to mixing by winter storms and convective overturning of the surface waters, occurs while the spring thermocline reforms (Glenn et al. 2001). The spring development of stratification is often interrupted by wind-driven mixing events. During the summer, a strong thermocline is present at approximately 20 m with mid-shelf near-surface temperatures of 20°C, and near-bottom temperatures lower than 10°C. During the Coastal Mixing and Optics (CMO) experiment, this pattern was evident.

The CMO hourly current speed data (Shearman and Lentz 2003) showed that storms with scales of about 1,000 km are primarily responsible for the correlation between depth averaged currents and wind stress for fluctuations in current velocity on the scale of days to weeks. Consequently, the orientation of the shoreline on a 1,000-km scale is the best match for wind stress. However, the low frequency flow on the order of months or longer does not appear to be wind driven, but is caused by the cross-shelf density gradient associated with the seasonal cycle in surface heating and cooling.

Surface currents are stronger at the 4.5-m depth than at deeper locations. The maximum surface current speed at the 4.5-m depth is 87.8 cm/s, with a mean speed of 24.3 cm/s and standard deviation of 14.2 cm/s. The maximum bottom current speed at the 65-m depth is 73.05 cm/s with a mean speed of 16.53 m/s and a standard deviation of 8.88 m/s.

2.3.4 Winds

Weather in the vicinity of Nantucket is subject to rapid change and a range of climatic conditions. The prevailing winds are from the west. However, winds are variable and may come from any direction. Northerly and northwesterly winds bring cold, dry air from Canada. Westerly winds bring Canadian air that has been warmed over the Great Lakes. Southwesterly winds are variable, depending on the origin of the air mass and atmospheric conditions they encounter on their trajectory. Canadian air that has been forced south by a mid-Atlantic state high pressure area is generally cool and dry, but it can be hot and dry during the summer. Southwesterly winds also form after a warm front passes, and transport warm, humid air from the Gulf of Mexico and the Caribbean. South and southeasterly winds are warm to hot and humid, and occur infrequently except along the south shore of New England. Easterly and northeasterly winds become cool and humid after passing over the Labrador Current and North Atlantic Ocean. In addition, extreme climatic events such as blizzards, ice storms, hurricanes, rainstorms, and tornadoes have variously affected the climate of the area.

Average wind speeds (at 5 m height) during winter and autumn are about 7−8 m/s; during the spring and summer the average is closer to 4−5 m/s. Wind direction is highly variable. Wind speed is highest during autumn and winter, with wind speeds of 12−13 m/s about 90% of the time, compared to summer and spring, during which wind speeds of 8−9 m/s occur about 90% of the time. Maximum wind speeds were about 27 m/s; wind gusts as strong as 36 m/s occurred.

2.3.5 Design Waves and Wind Parameters

The “Seasonal Maxima Distribution Model” (SMDM) developed by the U.S. Army Corp of Engineers was used to compute the distribution of the design parameters for waves and winds for various return periods. The methods and results are presented graphically and in tabular form in Appendix B. Table 2-2 presents a summary of waves, winds, and wind gusts.

Table 2-2. Summary of Design Wave and Wind Parameters for Various Return Periods Offshore Southeast of Nantucket

Return Period	Significant Wave Height (m)	Periods		Wind Speed at 5-m Height (m/s)	Wind Gust at 5-m Height (m/s)
		Peak (s)	Average (s)		
5	9.1	18.8	12.1	23.8	31.5
10	10.2	20.1	13.2	25.9	34.1
25	11.5	22.2	14.3	28.8	38.0
50	12.5	23.8	15.2	30.6	41.0
100	13.6	25.1	17.1	31.4	44.0

2.4 Distance from Land

Although the actual distance from land of the NOAA Buoy 44008 is approximately 54 NM southeast of Nantucket, for the purpose of this report and the COE calculations, the distance is assumed to be 24 km, as directed by NREL for the purpose of calculating reasonable cable lengths.

3 Design Load Conditions

3.1 Platform

The platform and mooring system were designed to survive a 50-yr return wind and wave condition. These conditions are summarized in Table 3-1.

3.2 Wind Turbine

The load cases listed in the IEC document (IEC 2004) were used as a basis for the selected load cases. Since this project is a feasibility study, we did not apply all load cases, but selected a subset of loads. Full details of the selected load cases are provided in Appendix C; the key parameters are listed in Table 3-1 and the load cases are summarized in Table 3–2.

At the time of this writing, the IEC offshore code IEC 61400-3, was still a draft document and there was ongoing discussion about the design load cases. In particular, the combination of extreme sea state with operating conditions or extreme wind loading was not settled. Design load case 1.3b, which is included in Table 3–2, is an example; it is based on the possibility that, after a storm, the wind speed will drop and allow the turbine to start while the wave conditions are still extreme. As the results presented in Section 5 illustrate, this load case governs the peak loads in several components.

Future design work should focus with care on load cases that include extreme sea states. The latest approach of the IEC working group should be consulted and the sea conditions applicable to the particular site must be considered.

At any mean wind speed are a range of sea states and associated probabilities. The distribution of sea states for each mean wind speed could be extracted, but such a refinement would greatly increase the number of simulations required to build up the complete fatigue loading of the system and was not considered essential for this study. Therefore, only a single sea state was defined for each wind speed. Table 3-3 presents the expected parameters of the sea states.

Only unidirectional regular waves were considered and the wind was assumed to be always aligned with the direction of the waves. These assumptions were considered justified in view of the preliminary nature of the study.

Table 3-1. Design Load Case Parameters

Item	Units	Value
Mean water depth	m	62
50-yr extreme water depth	m	Assumed at mean
50-yr significant wave height, Hs_{50}	m	12.5
50-yr peak spectral period, Tp_{50}	s	14.0
50-yr individual wave height (m)	m	18.75
50-yr individual wave period (associated with above wave height)	s	11.3–12.7
50-yr tidal current surface velocity	m/s	None
50-yr storm surge current surface velocity	m/s	None
1-yr extreme water depth	m	Assumed at mean
1-yr significant wave height, Hs_1	m	7.0
1-yr peak spectral period, Tp_1 (s)		10.0
1-yr individual wave height (m)		10.0
1-yr tidal current surface velocity (m/s)		None
1-year storm surge current surface velocity (m/s)		None

Table 3-2. Summary of Selected Load Cases

Load Case	Wind Specs	Sea State	Load Factor	Fatigue/ Ultimate	Comments
1.2	NTM Vin < Vhub < Vout Vhub = 4,6,8,..24	NSS	1.0	F	Hs and Tp values appropriate for Vhub. Yaw error = 0. V, Hs, & Tp from Table 3-3 3 x 10-min simulations
1.3a	ETM Vhub = Vr, Vout (12, 25 m/s)	NSS Hs=E[Hs|V]	1.35	U	Choose mean Hs & Tp from Table 3-3
1.3b	NTM Vhub = Vr, Vout	ESS Hs50(V=12) = 7.44 m Hs50(V=25) = 12.22m	1.35	U	50-yr significant wave height Tp selected for highest response 3 x 1-h simulations
1.4	ECD Vhub = 10, 12,14	NWH H = E[Hs|V]	1.35	U	Hs & Tp from Table 3-3 Both direction changes.
2.3	EOG V = 10, 12, 14, 25	NWH Hs = E[Hs|V]	1.10	U	Combine with loss of load. Pitch rate = 7.5°/s & 0.2 s delay. Several gust start times.
6.1a	EWM50 (turb) Vmean = Vref50 = 50.0 m/s	ESS Hs = Hs50 (constrained H50 wave)	1.35	U	Stationary/idling rotor, fully feathered, brake off. 3 x 10-min simulations. Tp = 14.0 s
6.4	NTM Vmean = 0.7 Vref = 35 m/s	NSS	1.0 (importance factor = 1.15)	F	Brake off, fully feathered Hs and Tp from table
7.1a.f	EWM (turb) Vmean = V1 = 40 m/s	ESS Hs = Hs1 (constrained H1 wave)	1.35	U	Brake off, 2 blades feathered. Tp = 10.0 s One blade pitched 0, 30, 60 deg Yaw error = 0, 90, 180 deg 3 x 10-min simulations
8.0					Fabrication, transportation, assembly

<u>Notation:</u>

Vref = 50 m/s
Vr = rated wind speed (12 m/s)
Vin = cut in wind speed (4 m/s)
Vout = cut out wind speed (25 m/s)
NTM = normal turbulent model
ETM = extreme turbulent model
ECD = extreme coherent gust with direction change
EWM = extreme wind model
EWM50=1.3 Vref = 65 m/s
EWM1 = 0.8 EWM50 = 52 m/s
NSS = normal sea state
ESS = extreme sea state
Hs50 = 12.5 m
Hs1 = 7.0 m

Table 3-3. Normal Sea Conditions

Hub-Height Wind Speed* (m/s)	Significant Wave Height Hs (m)	Peak Spectral Period Tp (s)
4	1.1	8.2
6	1.2	8.0
8	1.5	7.9
10	1.6	7.7
12	1.8	7.6
14	2.4	7.9
16	3.0	8.1
18	3.3	8.4
20	3.6	8.6
22	4.1	8.9
24	4.9	9.6
25	5.3	9.8
45.5	9.1	11.1

*A shear exponent of 0.12 was used to scale wind speed from 6-m data to hub height.

4 Platform and Mooring Concept Design

4.1 Requirements

The platform has to satisfy the following general requirements:

- It must be able to support a 5-MW wind turbine.
- It must survive the 50-yr return wind and wave loading.
- It must offer sufficient rigidity to the wind turbine to control dynamic loads during operation.
- It must operate for a design life of at least 20 years.
- It must be inexpensive enough to allow the power to be competitive.
- It must be compatible with the chosen installation scheme.
- It must allow adequate access for maintenance.
- The legs of a tension leg platform (TLP) must not be allowed to become slack.

NREL presented a set of turbine specifications at the project kick-off meeting on November 10, 2004. Those specifications are repeated in full in Section 5 of this report, and those most relevant to the platform design are listed here.

- Rating 5 MW
- Rotor diameter 126 m
- Hub height 90 m
- Rotor mass 110,000 kg
- Nacelle mass 250,000 kg
- Tower mass 347,460 kg

4.2 Alternative design concepts

Wave forces on an ocean structure are strongest at the surface, where the water velocities are greatest. The forces decay exponentially with water depth and, in deep water, become negligible at a water depth equal to one-half wave length. Deep water can therefore be defined as having a depth in excess of half the greatest expected wave length.

The objective of the semi-submersible concept is to locate most of the structure far enough below the surface so the wave forces are greatly reduced from what they would be at the surface.

Table 4-1 shows that if the maximum wave period is approximately 14 s, as in Buoy 44008, the optimum platform depth is 153 m. This is considerably greater than the total water depth available at the specified site, which implies that it is not a true deep water site. Nevertheless, some benefits of the semi-submersible platform can be achieved in less than optimal depths.

Table 4-1. Deep Water Wave Length Effects

Wave Period	Wave Length	Depth Affected
2 s	6.2 m	3.1 m
4 s	25.0 m	12.5 m
6 s	56.2 m	28.1 m
8 s	99.8 m	49.9 m
10 s	156.0 m	78.0 m
12 s	224.6 m	112.3 m
14 s	305.8 m	152.9 m
16 s	399.4 m	199.7 m
18 s	505.4 m	252.7 m
20 s	624.0 m	312.0 m
22 s	755.0 m	377.5 m

4.2.1 Platform alternatives

The principal alternatives evaluated for the plan area of the platform are rectangular and triangular. A rectangular plan requires one extra tether and associated attachments, but will provide 1.5 times the rotational constraint for the platform. Neither system will provide overall stability in the event of a mooring line failure, but the triangular system is statically determinate, whereas the four-line system requires adjustment to equalize line tensions. The main advantages and disadvantages of each configuration are summarized in Table 4-2.

Table 4-2. Alternative Platform Configurations

Item	Advantages	Disadvantages
Rectangular platform	• Simple to construct • Used extensively in offshore oil and gas industry • Twice the pitching restraint for a given platform side dimension	• Tensions must be adjusted for full effectiveness of TLP • Required additional three-part tendon increases cost of materials and deployment
Triangular platform	• Does not require sensitive adjustment of tendon tensions of TLP • More efficient use of material for overall pitching restraint • More efficient geometry: less square footage to accomplish stability goals	• Construction geometry is more complex • Failure of one tendon will lead to overall collapse
Material: concrete	• Local supply is usually possible • Easily formed to shapes • Durable in saltwater environment • Conventional building material in coastal and port facilities	• Quality assurance • Reinforcing steel must be protected against corrosion • Difficult to repair at sea
Material: steel	• Ease of construction and connection of modules	• Steel is expensive and prices could increase further • Local shortages may govern • Reinforcing steel must be protected against corrosion

The rectangular TLP has been extensively used in the offshore industry, but installation tolerances are critical as the structure is statically indeterminate.

4.2.2 *Alternative mooring configurations*

There is a choice of three principal types of mooring systems: a catenary system, a taut leg, and a tension leg type. These are illustrated in Figure 4-1 and more discussion of their relative merits can be found in Musial (2004). A summary of their advantages and disadvantages is presented in Table 4-3.

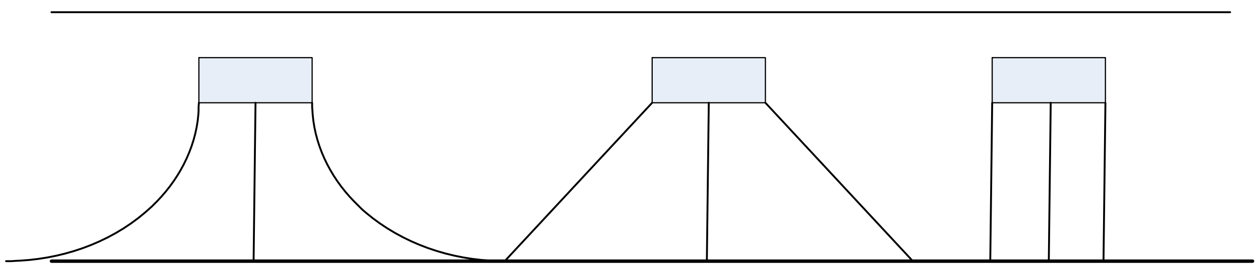


Figure 4-1. Alternative mooring approaches

The design considerations dealt with the selection of the mooring system, anchoring, support to the turbine, and the installation process. Some of these alternatives are listed and compared in Table 4-3.

Table 4-3. Alternative Mooring Configurations

Item	Advantages	Disadvantages
Catenary mooring system	• Simple low-cost anchors • Easy installation • Suitable for shallower water	• Large footprint (long mooring lines) • Ballast or wide buoyancy distribution is needed • Increased platform dynamics
Taut leg system	• Provides good lateral and vertical restraint • Suitable for shallow to moderate depths	• Expensive anchors • Large footprint in deep water • Each anchor must be able to restrain the entire structure • Difficult deployment
TLP	• Stable platform—pitch, roll, and heave motion controlled • Smallest footprint—short mooring lines • Buoyancy tank below surface wave action • Ease of deployment and installation	• Expensive vertical mooring system • Not practical in shallow water

The TLP concept mitigates the first order heave, roll, and pitch motions, although the lateral motion can be considerable and restraint relies on the preload in the tensioned cables. The requirement of rotational rigidity to support the wind turbine is likely to preclude the catenary system; the application to deep water may rule out the use of the taut leg system. More discussion of the design selected is included in Section 4.3. The preferred mooring configuration for the proposed design concept is a TLP.

4.2.3 *Anchor systems*

Several types of anchors can be used in conjunction with one or more mooring systems. The advantages and disadvantages of these anchors types are summarized in Table 4–4.

Table 4-4. Alternative Anchoring Schemes

Item	Advantages	Disadvantages
Gravity anchor	• Suitable for any soil condition provided bottom is flat • No surface preparation needed	• Large quantity of material and ballasts required, especially with tension leg mooring
Suction piles	• Tested in offshore industry	• Suitable soil conditions only • Specialized equipment needed • Expensive in deep water
Driven piles	• Tested in offshore industry • Can resist considerable lateral tension	• Suitable soil conditions only • Specialized equipment needed
Plate anchors	• Suitable with catenary system	• Suitable soil conditions only • Not suitable for TLP-type uplift requirements
Gravity anchor with suction embedment or skirt plates	• Reduced lateral movement ("creep")	

All, except the gravity anchor, require penetrable soils and expensive specialized equipment that would have difficulty operating in a deep water environment. Further, many anchoring systems perform best with catenary (lateral load) mooring and are not efficient with vertically loaded tension-leg mooring.

4.3 Selected Concept

A systematic evaluation of the configurations of the platform, mooring systems, and anchor types and their respective costs has not been attempted in this project. Instead, the project team has made decisions based on broad principles and has arrived at a design that can be used as a baseline for comparing alternatives.

A fundamental choice was the selection of the mooring system (see Section 4.2.2). The rotational restraint required for the wind turbine and the wish to apply the design to deep water led to the adoption of the tension leg concept. That choice, in turn, required an anchor system that will resist the upward tension of the cables under all conditions, for which either a gravity anchor, suction pile, or driven pile is best suited (see Section 4.2.3). The use of piles depends on the soil conditions; the gravity anchor can be used in almost any condition. Therefore, the gravity anchor was selected, but a final choice will be made based on the particular site conditions.

A triangular shape was chosen for the platform, since this obviated any need for balancing cable tensions and implied simpler load calculations. Any added construction complexity was not considered important.

Standard weight concrete was selected for the platform because of its adaptability, low cost, and local availability. Lightweight concrete would enhance the flotation characteristics of the platform. The attachment of the wind turbine tower to the platform is through a tripod plus a vertical tube. More details are presented in the following sections.

Standard weight concrete was also selected for the gravity anchor. This was the best choice, since it can be cast to be similar in shape and size to the platform and may be floated into position under the platform. It should have an installed weight of at least 44,500 kN, which may be accomplished by de-ballasting or adding weight before sinking.

For initial concept design, the depth of the triangular platform was chosen to be equal to one-third of the water depth. In deeper water the platform may be placed deeper; however, for the depth specified for this project the one-third, or 20 m, depth was considered an acceptable compromise.

The selected configuration is shown in Figure 4-2 and Figure 4-3.

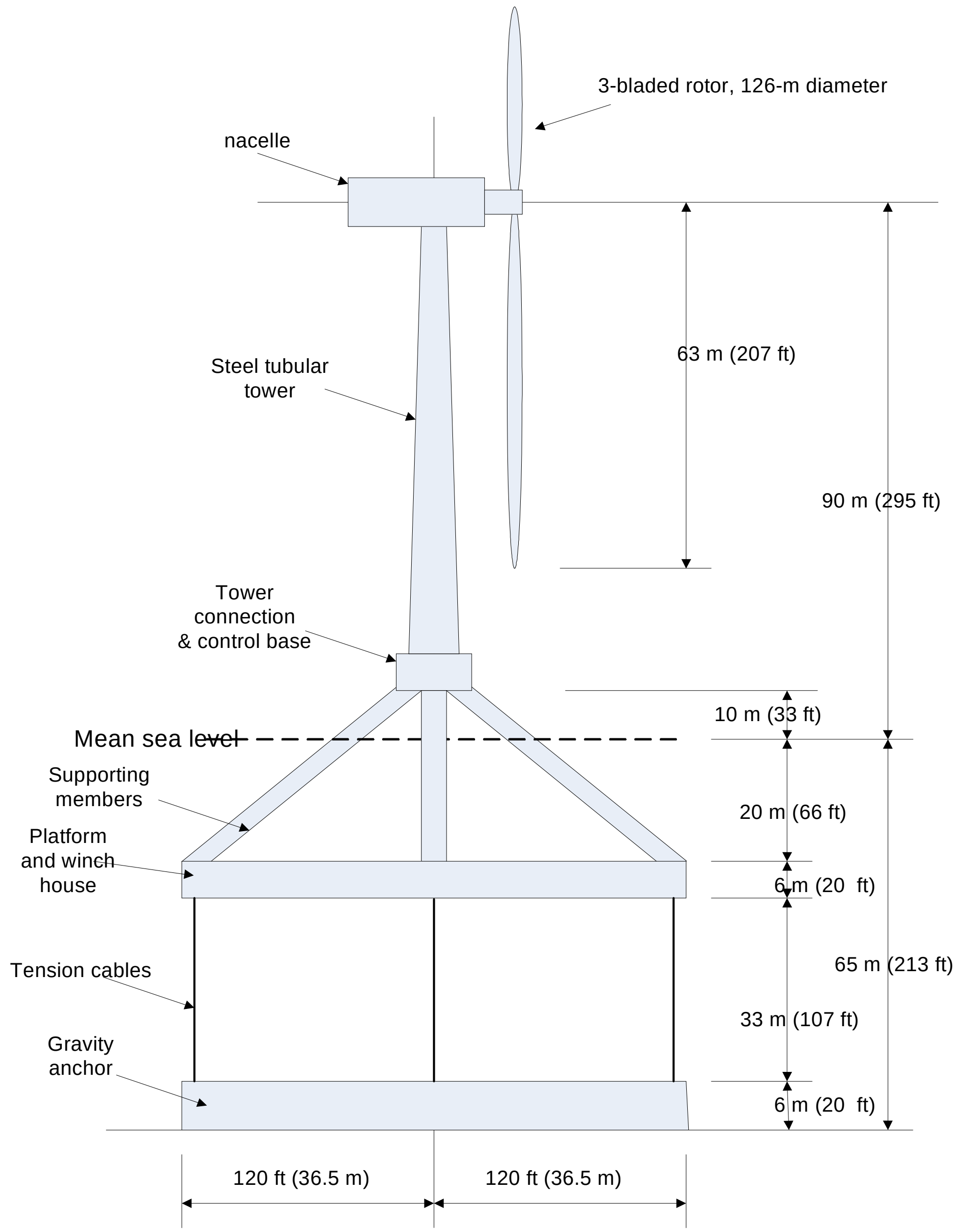


Figure 4-2. Submerged TLP

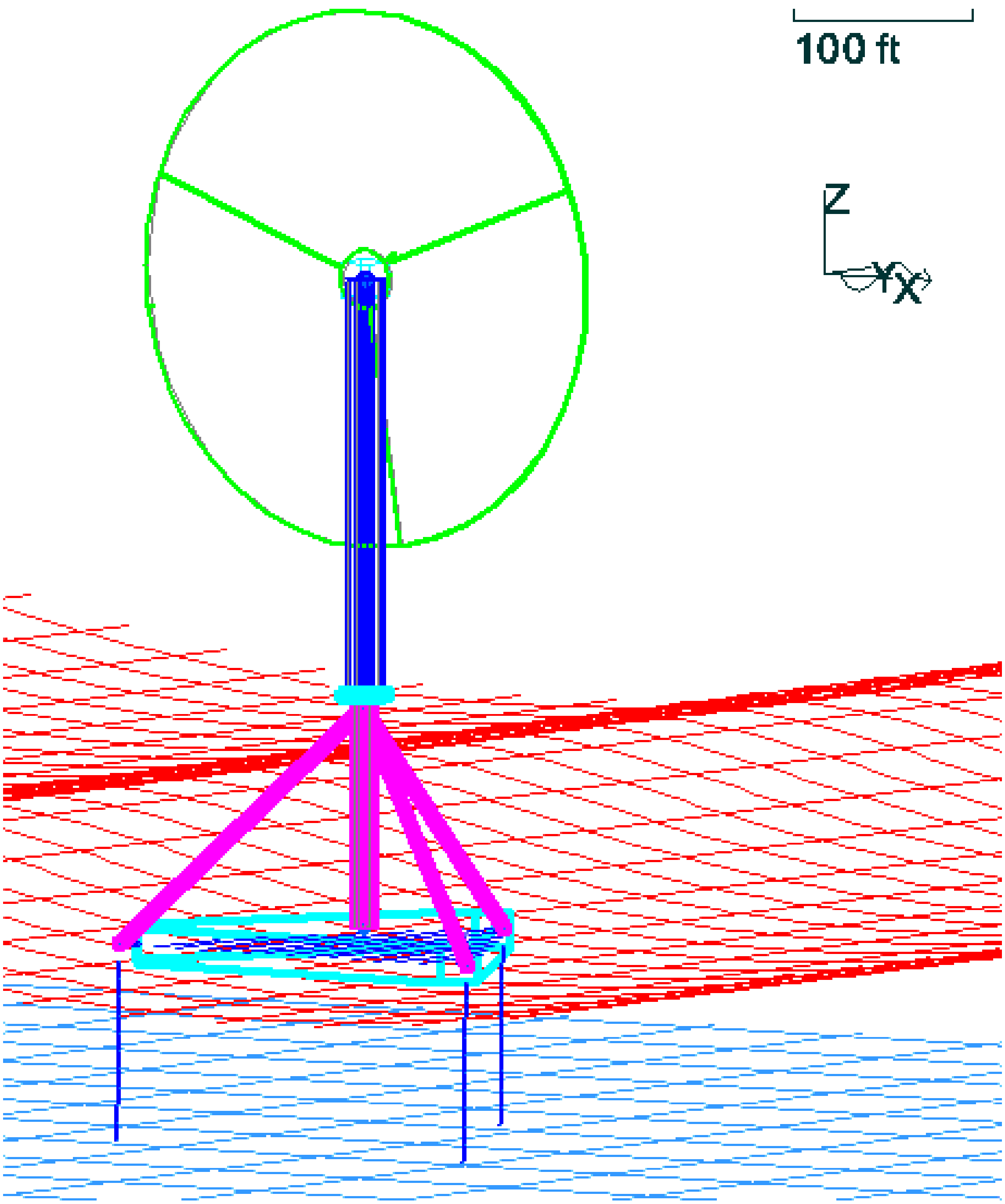


Figure 4-3. Submerged TLP (anchor not shown)

4.3.1 Platform and tripod support

An outline of the selected platform, winch house, tripod, and control base is shown in Figure 4-4.

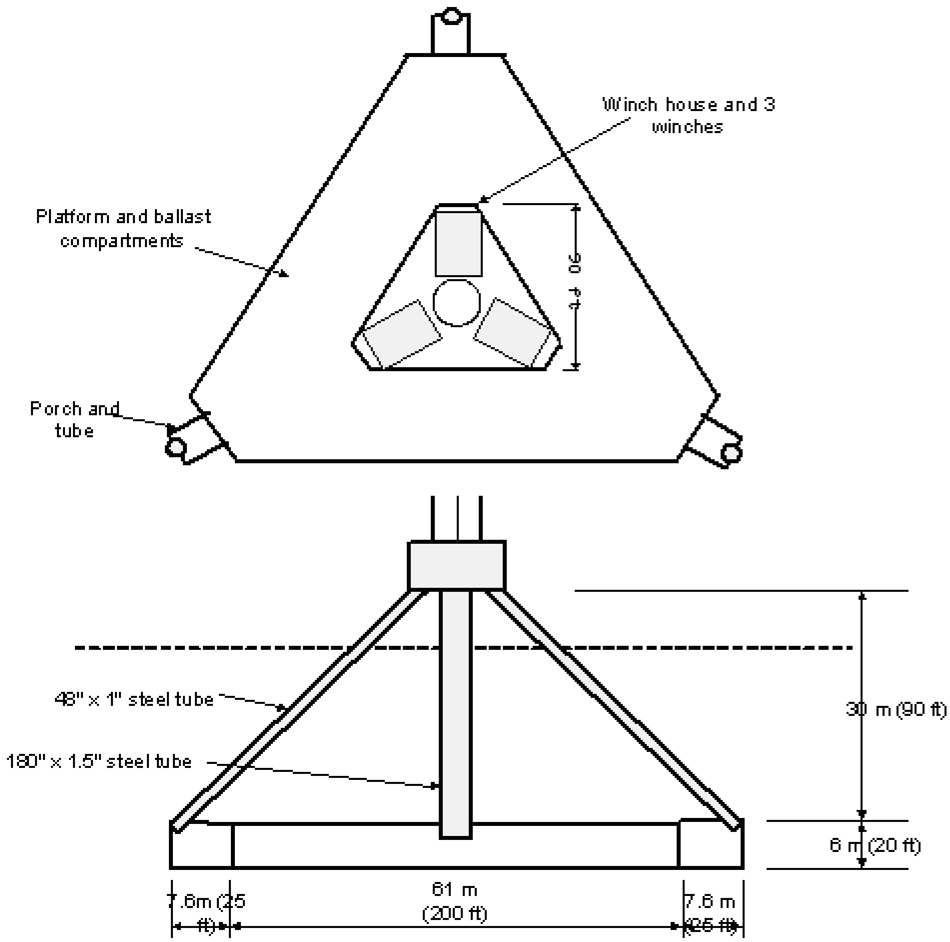


Figure 4-4. Proposed arrangement of platform and support members

The tripod was selected to replace a single wind turbine tower tube for several reasons:

- The connection of a single tube to the platform would be challenging.
- The wave loading on a single tube of diameter up to 9 m would be considerable.
- The connections to the tripod tubes do not have to be rigid.
- The wave loading on a series of smaller, sloping tubes would be lower and would not peak at the same time.
- The tripod tubes and lower vertical tube may be perforated to reduce wave loading.

Three “porches” at the corners of the triangular platform contain steel brackets where the tension legs are attached to the platform. These tensioned tendons hold the structure in place after installation (see Section 4.4.2).

The platform, including the porches and the bulkheads, is designed to be made of reinforced concrete. The thicknesses of the side shells, bulkheads, and slabs from which the platform is constructed are given in Table 4-5.

Table 4-5. Properties of the Platform and Support Members

Item	Description
Top slab	0.2-m concrete
Bottom slab	0.2-m concrete
Side shell thickness	0.2-m concrete
Primary bulkhead thickness	0.2-m concrete
Secondary and tertiary bulkheads thickness	0.15-m concrete
Porch thickness	0.175-m concrete
Circular ring beneath central tube	0.3-m concrete
Diagonal tubes	1.2 x 0.025 x 30 m
Central tube between platform and control house	4.5 x 0.037 x 27 m
Winch house	27-m truncated equilateral triangle
Center of mass of superstructure	19.0 m below Mean Sea Level (MSL)

The platform may be constructed in one of several ways. It may be made of post-tensioned pre-cast modules, a single monolithic casting, or a combination of pre-cast wall members and cast-in-place bottom slab, top slab, and closure pours. The platform will include a number of compartments that can be used as adjustable ballast.

The platform will also house the set of three winches to which the three tendons are attached and which will be activated during installation and in any subsequent adjustment. This is shown in Table 4–4.

4.3.2 Tension leg tendons and control system

The average tension in each of the three mooring tethers was estimated to be 5,340 kN. Using a safety factor of 2, the breaking strength of the selected rope should be greater than 10,680 kN. The equivalent wire rope chosen to represent the tether has properties as given in Table 4-6.

Table 4-6. Tether Properties

Outside diameter	0.264 m
Weight in air	0.290 kg/m
Weight in water	0.234 kg/m
Displacement	0.056 kg/m
Axial stiffness	3,700,000 kN

Each of the three mooring tendons will consist of three, 0.15-m diameter wire ropes. Each wire runs from the winch house within the platform to a turning sheave within the porch, then down to the deadweight anchor. Each winch is associated with a drum that can accommodate the required 65 m of wire rope.

The hydraulic winches will be operated with a hydraulic power hookup from an installation support vessel. Hydraulic hoses will run up the 4.5-m diameter tower to the control base where a watertight door will allow provide access.

The winch house is a structure within the platform. The inside diameter of cable reels for 0.15-m wire rope is approximately 6.1 m; the outside diameter is approximately 6.7 m, and each drum is approximately 0.61 m wide. The winch house will support three sets of large triple-drum winches. Each drum may have level winds for wire rope spoiling. The winch house will be triangular, approximately 27.4 m x 7.6 m, as shown in Figure 4-4. The drum mechanism, bearings, main shaft bearings, and platform support will be designed to operate in seawater without being affected by fouling, and corrosion will be kept to a minimum with coatings.

The loads in all three tension legs (nine wire ropes total) will be kept in equilibrium by an “equalizer.” The equalizer will allow for anticipated offsets of the platform, and will be robust enough to remain in equilibrium should a single cable break.

4.3.3 Anchor

The use of a gravity anchor minimizes seabed preparation requirements. It must have sufficient mass to provide the necessary tension in the wire rope system and maintain the associated stability.

The selected configuration is a triangular concrete structure that will match the shape of the platform. The outline is shown in Figure 4-5. The depth of the anchor is 6.1 m and the standard thickness is 0.2 m. The variety of construction methods available (transferring the platform onto the anchor via launch ways, floating the platform onto the anchor in a dry dock) makes triangle geometry the least expensive to construct and install.

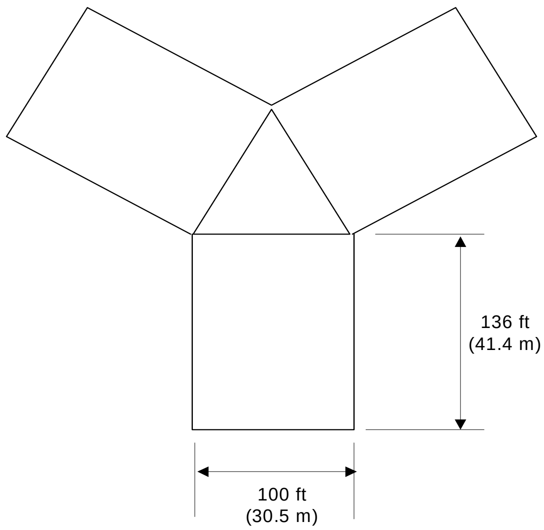


Figure 4-5. Gravity anchor

Not shown in Figure 4-5 are the end compartments filled with inexpensive fixed granular ballast (gravel) material with an estimated mass density of around 1,763 kg/m^3. This may be necessary to achieve the required weight of the gravity anchor in water. Most of the volume available for ballast will be empty before installation and filled with water when the anchor is placed on the seabed. For the preliminary design shown in Figure 4-5 the volume of structural concrete is approximately 2,044 m^3.

With a target anchor weight on the seabed of 133,500 kN, approximately 1,435 m^3 of concrete ballast or 2,823 m^3 of gravel ballast may be required to reach this goal. With a total displaced volume of approximately 23,219 m^3, the ballast volume accounts for approximately 20% of the total displaced volume for concrete and approximately 35% for gravel. The deadweight anchor will float without ballast water, with a 1.36- to 1.8-m freeboard, depending on whether the ballast is concrete or gravel.

4.4 Assembly and Installation

4.4.1 Construction and Manufacturing

The system is expected to be manufactured at fabrication sites with waterfront access, within approximately 241 km of the installation site. To manufacture 100 units in one year, as required by the scope of this study, there will need to be four such sites. The manufacturing process is depicted in Figure 4-6.

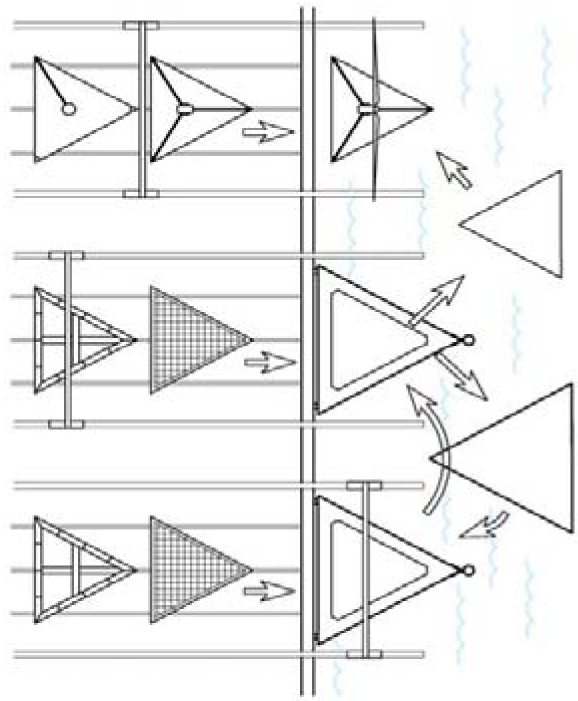


Figure 4-6. Manufacturing process

As envisioned, each facility will have three manufacturing lines. Line A will manufacture the triangular anchor structure, Line B will manufacture the platform, and Line C will install the tower and turbine. Each line will have an appropriately sized overhead gantry crane that runs on tracks to move materials and equipment along the manufacturing line.

At the water end of Line A is a custom floating dry-dock mold onto which the completed anchor is moved. The anchor and dry dock are then moved to the water end of Line B. The completed platform is moved onto the anchor. The two structures are thus “stacked.”

At this point the dry dock is lowered in the water. The stacked anchor/platform assembly floats freely and is positioned into the water end of Line C. The dry dock is then moved back to the water end of Line A, and the process is repeated.

As the stacked unit floats in the water end of Line 3, the porches, winches, control base, tower, and turbine are all installed.

4.4.2 Deployment

The completed unit, including the anchor, platform, tower, and turbine, will be floated out of the manufacturing yard and towed to the installation site. The towing speed will probably be less than 7.1 km/h, resulting in a towing duration of 37 h to Buoy 44008.

Figure 4-7 shows the proposed installation sequence. Initially (Stage 1), the buoyancy of the anchor/platform supports the tower and nacelle and superstructure, plus installation devices to control tendon line tensions and lengths. Once the system is at the predetermined site location, air is released from the anchor’s ballast chambers causing the anchor to sink in a controlled manner. The triangle deadweight anchor is lowered to the seabed by a combination of ballasting of the triangle and paying out the tendons (Stage 2). As the anchor sinks, the floating platform will control and guide the anchor to the ocean bottom.

In the final stage, the platform is pulled down, again by a combination of ballasting (the platform) and pulling in the tendons. Air is released from the floating platform's ballast chambers while the winches pull the buoyant platform below the wave action into an operational position.

The platform may be further lowered in the water to facilitate maintenance and repair of the turbine by placing it within a reasonable distance of the water. A two-bladed configuration would also assist in this operation. Figure 4-8 shows a potential maintenance configuration.

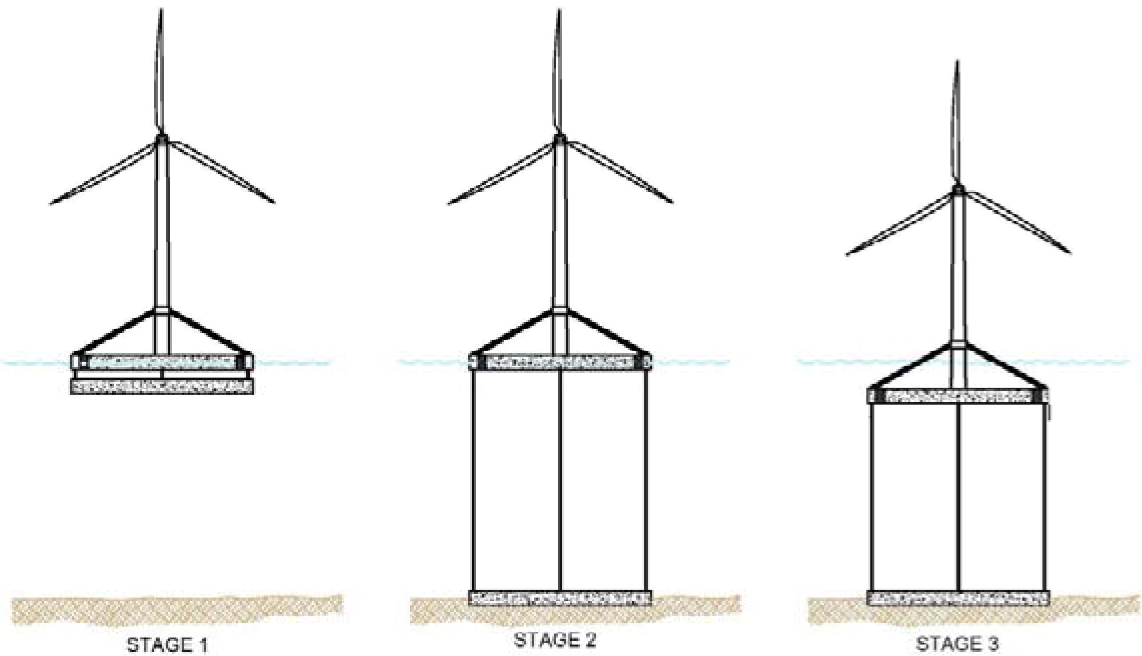


Figure 4-7. Installation sequence

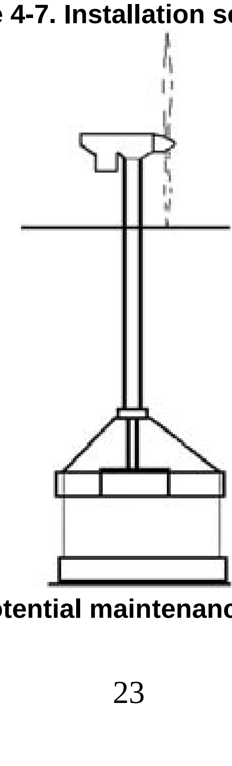


Figure 4-8. Potential maintenance configuration

4.5 Modeling tools

Predicting the dynamic response of the complete system subject to wind and wave action is a complex task. A group at MIT attempted this task (Sclavounos 2003), but their procedure was not considered mature enough for this project. There are plans to create a suitably generalized code at the National Wind Technology Test Center in Colorado, but the code was not complete in time for this project.

Therefore, the team was obliged to compromise and to use two codes: the Orcaflex code that is intended to model hydrodynamic systems, and a version of the Bladed code that models a wind turbine with the inclusion of a partially restrained base and wave action on the tower. One challenge in this project was to suitably marry these two codes to achieve solutions for the total combined system.

4.5.1 Orcaflex software

Orcaflex is used extensively in the offshore oil and gas industry to predict the loading and responses of semi-submerged structures with or without mooring lines. In this project Orcaflex was used to model the platform, mooring lines, and wind turbine. However, only pseudo-static loads could be applied to the wind turbine, and these were estimated for the 50-yr extreme load cases. The model was used to examine alternative configurations for the platform and for the tripod that supports the wind turbine.

Orcaflex was used to calculate irregular waves and took into account slow drift, wind, waves, and current. This was handled in all six degrees of freedom (heave, yaw, pitch, roll, sway, and surge). It also generated a detailed description of loading on the structure, including:

- Frequency domain analysis
- Nonlinear time history simulations
- Response to first- and second-order forces (slow drift analysis)
- Response to large survival waves.

4.5.2 Bladed software

Bladed is a proprietary code that belongs to GH. It is intended primarily to simulate the loading of a wind turbine under operating and nonoperating conditions. The code also models the control systems that most modern turbines have to vary the pitch angle of the blades.

Bladed has been modified to include the action of waves on the towers of offshore installations, and a recent version includes additional degrees of freedom at the tower base that can be used to simulate the motion of an elastically restrained supporting platform. The parameters of the restraint to the tower base were adjusted so that the fundamental natural frequencies agreed with those of the Orcaflex model.

The degrees of freedom at the tower base do not include those of yaw or heave. However, for this project (which adopted a tension leg configuration), the motion in heave was estimated as small, and the neglect of platform yaw was compatible with other approximations made in this preliminary study.

4.6 Analysis and Design

Analysis and design of the platform system includes buoyancy calculations, mooring analysis, and transportation and installation loads. Further design analysis of the control base and structural analysis of the platform are recommended in a preliminary design phase.

4.6.1 Buoyancy

The platform buoyancy during installation and during normal operation is calculated as: (Weight of water displaced) – (Weight in Air). The densities used for the calculation are provided in Table 4-7.

Table 4-7. Densities Used for Calculations

Seawater	1,025 kg/m^3
Steel	7,850 kg/m^3
Reinforced concrete	2,400 kg/m^3

Table 4-8 shows the buoyancy calculation of the entire structure during and after installation. The platform is expected to be submerged 20 m, or approximately one-third the water depth, from the water surface. For transportation to the site and installation, the internal compartments have various stages of controlled flooding.

Table 4-8. Structure Buoyancy Properties

Members	Mass = Weight in Air without Internal Fluid	Displaced Weight	Buoyancy
Concrete platform	37,015 kN	156,800 kN	119,800 kN
Steel tower	7,553 kN	7,982 kN	−472 kN
Nacelle	3,400 kN	0	−3,400 kN
Diagonal braces	1,140 kN	1,824 kN	685 kN
Winch house	445 kN	0	−455 kN
Total	**49,458 kN**	**165,655 kN**	**116,202 kN**

The tension in each wire rope is one-third of the total values in Table 4-8. Using a safety factor of 2, the breaking strength of the selected wire rope should be greater than 77,070 kN. The tension leg chosen to represent the tether in Orcaflex has properties as given in Table 4-6. Each leg consists of three, 0.125-m diameter wire ropes.

4.6.2 Mooring loads

The system was analyzed for the following:

- Operational parameters: conditions under which the wind turbine will generate usable energy. The boundaries of the operational parameters were made as large as possible.

- Survival parameters: conditions under which the structure will maintain a reasonable safety factor. The limits of survival were based on parameters such as probability of storm occurrence, (i.e., a 50-yr storm for a particular location) and strength of material constraints.

As a preliminary design check, the largest anticipated wave was combined with a constant lateral load at the nacelle representing a 50-yr return wind averaged over 30 s. The height of the design wave was 18.7 m with a period of 15 s. The longitudinal wind load at the nacelle was 1,100 kN. Some of the results of the Orcaflex analysis of this combination are shown in Figure 4-9. 18.7-m, 15-s wave X dir and 250,000-lb wind load at hub 3 x 9.14-cm (3 6-in) wires. The maximum predicted leg tension was 53,400 kN based on a mean tension of 35,600 kN.

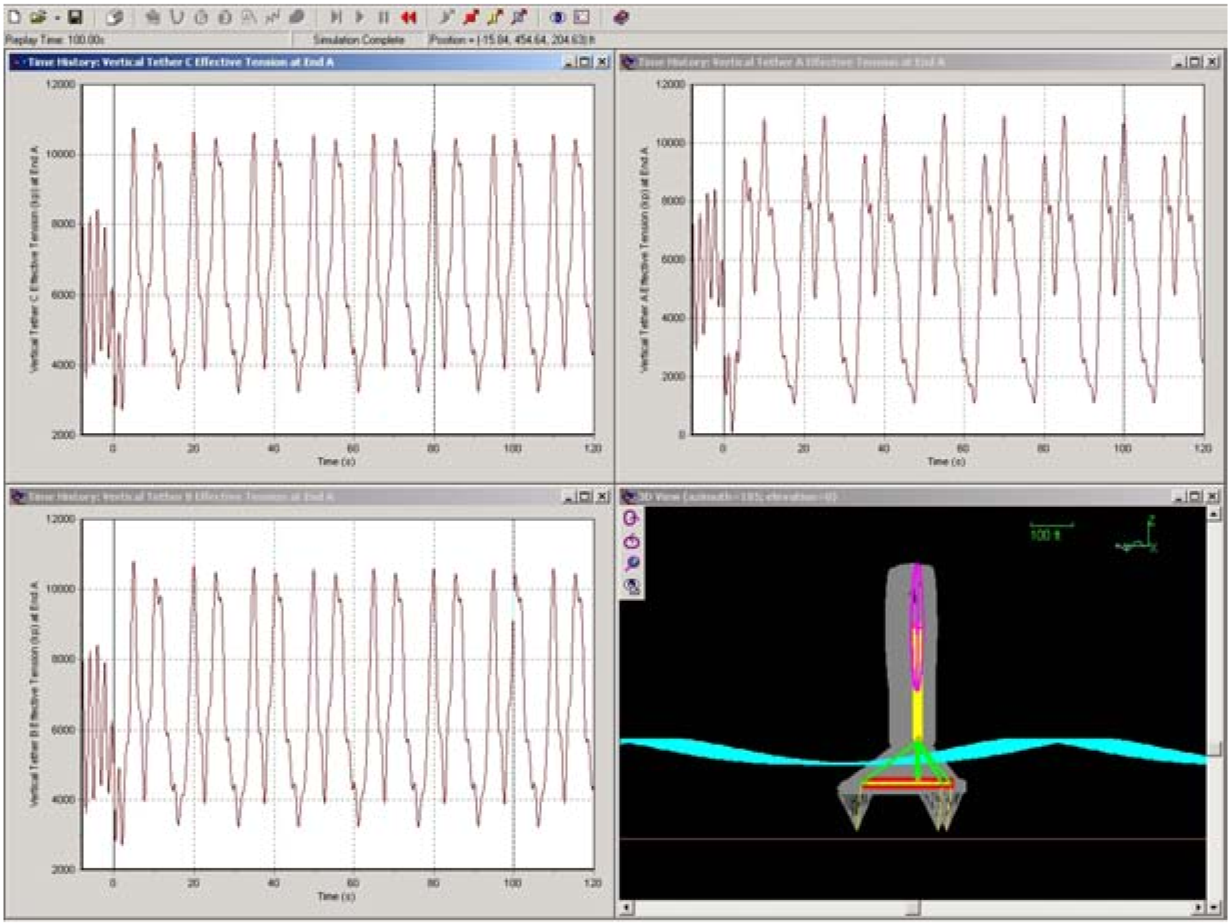


Figure 4-9. 18.7-m, 15-s wave X dir and 250,000-lb wind load at hub 3 x 9.14-cm (3 6-in) wires

In addition, the mooring forces were predicted based on the time series wind forces only as shown in Figure 4-10. This demonstrates a maximum tension on each leg of approximately 29,400 kN caused by wind forces alone.

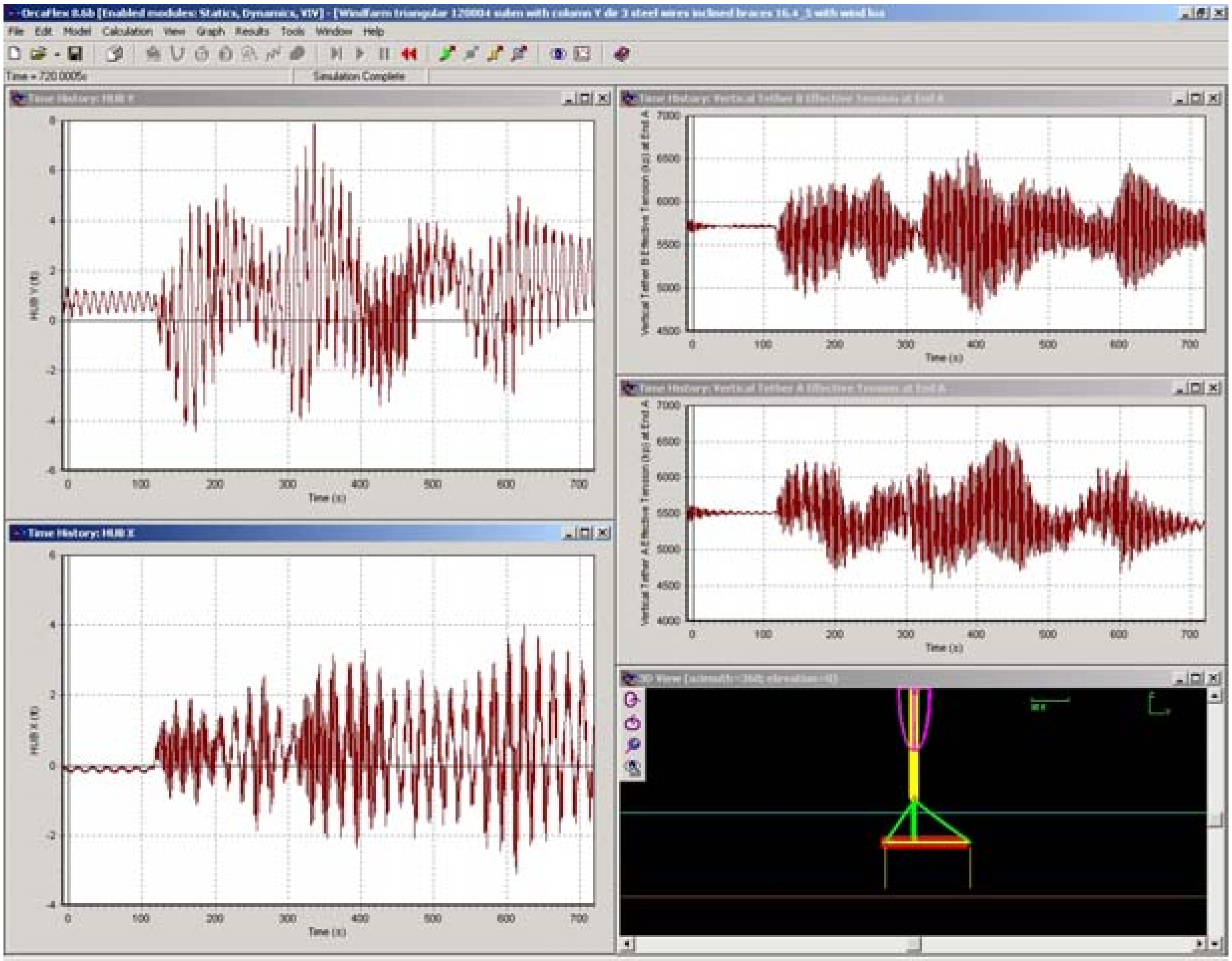


Figure 4-10. Mooring forces based on the time series wind forces only

A more complete calculation of the dynamics of the platform under extreme conditions was attempted later in the project, when the time series of the turbulent wind loading on the nacelle and tower were available. The wind loading during design load case 6.1a-a1 (see

Table 3-2 and Appendix C) was extracted from the Bladed results and used as input into the Orcaflex model and combined with a regular series of 18.7-m waves with a period of 15 s.

4.6.3 Transportation Loads

During transportation, the structure will be towed from the dock to the location. More benign weather conditions are typically assumed for the transportation and installation period than for the structure's design life.

The forces assumed for transportation are shown in Figure 4-11. The overturning moment is used to analyze the stability of the structure floating on the water with horizontal wind load applied and no mooring loads. For a 1,575-kN force with the lever arm of 109 m, the moment is 171,700 kN m.

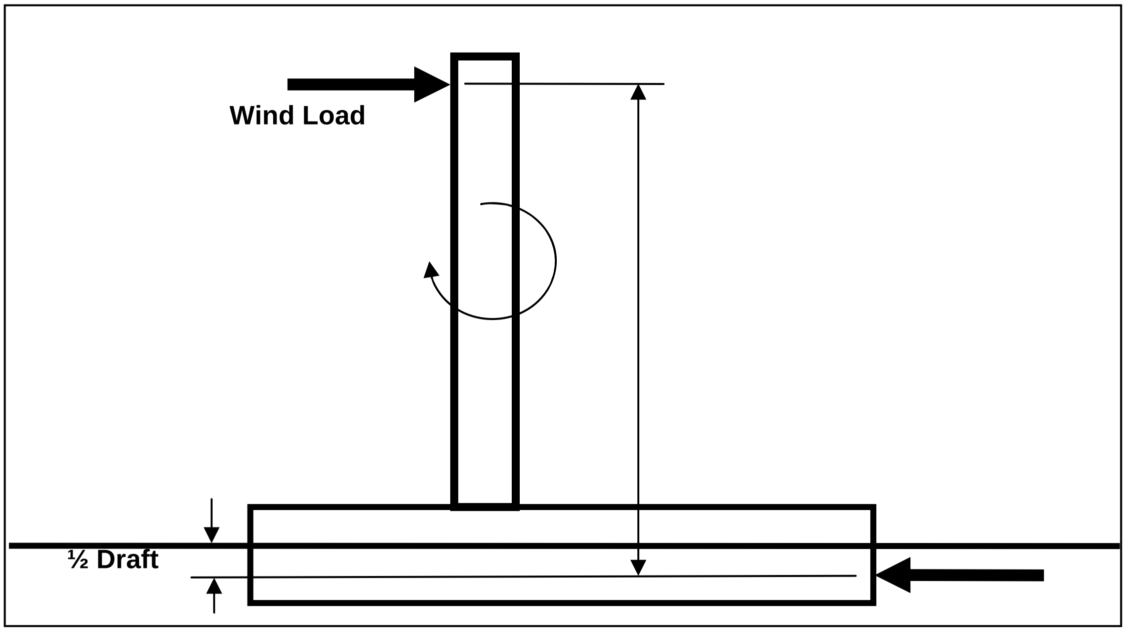


Figure 4-11. Principle of horizontal loads and overturning moments

Orcaflex was used to perform an initial analysis of the floating structure, without the deadweight anchor attached, but with the wind force of 1,575 kN applied, and a nominal wave (4.6 m and 8 s) applied. The result shows that the structure does not capsize, but has expectedly large and undesirable motions. The structure trim angle is within the envelope of −19.5º and 12º. Figure 4-12 shows the trim angle variation.

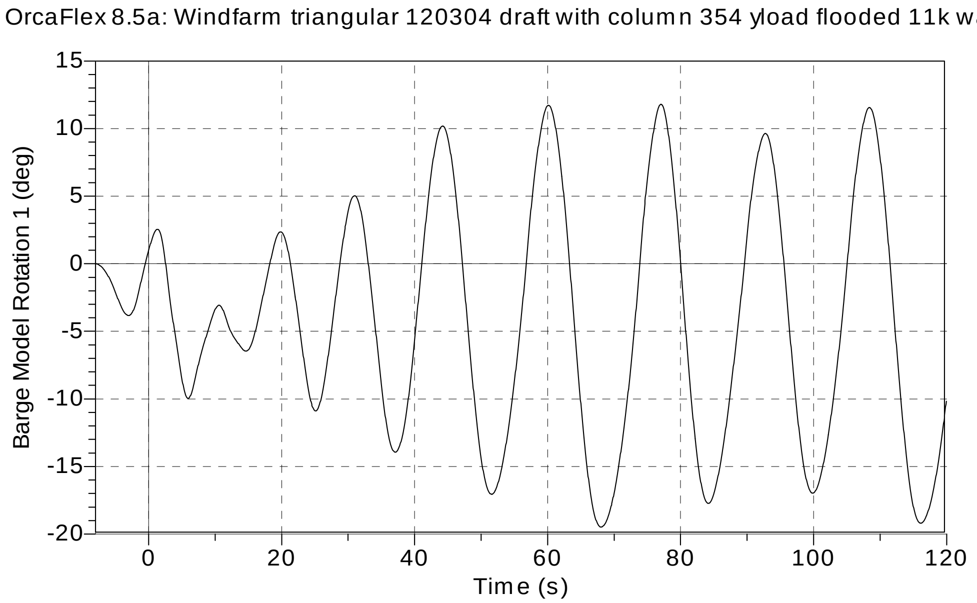


Figure 4-12. Time history of trim angle
(large wave and wind load, no deadweight anchor attached)

With reduced wind load and wave height appropriate to an installation weather window, motions are reduced to ± 5º, without the deadweight anchor attached. With the deadweight anchor attached, the motions are reduced to ± 2.5º with no optimization of the design. This is considered an acceptable result and illustrates the value of transporting the structure with the anchor suspended below the platform. A more detailed transportation load analysis is recommended in the preliminary design phase.

4.6.4 Installation loads

After much trial and error, we considered that the platform (if installed without the deadweight anchor) should be flooded with 4,950 m^3 of water during the installation, so that the total weight of the structure will be 98,760 kN. The platform's draft for this weight is 3.8 m. If the platform is installed with the deadweight anchor attached, different ballasting is proposed and the stability will be significantly improved.

Results of trim angle from the 1,575 kN (354,000-lb) force are tabulated in Table 4-9 from manual calculation, general hydrostatic stability (GHS) analysis, and Orcaflex analysis.

Table 4-9. Results of Trim Angle from 1,575-kN Force

Hand Calculation	GHS Analysis	Orcaflex Analysis	Average
1.93º	1.84º	1.5º	1.76º

5 Wind Turbine Design

5.1 Selection of Configuration and Modeling Code

The wind turbine's rating and configuration were selected in conjunction with NREL, which reviewed a number of multimegawatt wind turbines and arrived at the specifications shown in Table 5-1.

Table 5-1. Multimegawatt Wind Turbine Specifications

Item	Units	Value
Rated electrical power	kW	5000
Rotor diameter	m	126
Orientation		Upwind
Number of blades		3
Hub height (above mean sea level)	m	90
Rotor speed at rated power	rpm	12.1
Control system		Full span collective pitch, variable speed
Mass of one blade	kg	17,728
Mass of hub	kg	56,780
Nacelle and drive train mass	kg	240,000
Tower dimensions at top	mm	Steel tube 3870 x 25
Tower dimensions at sea level/ground	mm	Steel tube 6000 x 35
Tower mass (to control room)	kg	347,460
Tower head mass	kg	350,000

In addition, the platform, twist schedule, and airfoil properties of the blades were supplied by NREL.

These specifications were obtained from a number of sources. Some published information was available from two prototype machines: the REpower 5 MW, and the Multibrid M5000. The former has a more conventional drive train, so information from it was favored. Additional sources of information were the WindPACT study (Malcolm and Hansen 2002) and the RECOFF and DOWEC (Hendriks and Zaaijer) studies. The blade properties were obtained from the DOWEC 6MW study with the span suitably reduced.

The configuration was supplied in the form of a number of FAST input files. GEC used them to carry out some initial simulations, including a simulation of the 50-yr return wind loading. However, the FAST code does not have options for including wave loading or for a movable base such as a moored semi-submersible. Therefore, the "Bladed" wind turbine simulation code from GH was used, since that code has the facility to include wave loading and can represent some features of a moored base.

MIT used the ADAMS code to model the response of moored platforms (Sclavounos 2003), but GEC would have needed considerable development time to prepare an acceptable model with this software. Other codes have been used in Europe to model wave action on wind turbine towers, but these are not believed to have been developed sufficiently to model floating or semi-submersible platforms.

5.2 Preparation of the Model

The Bladed model was prepared by GH based on the properties implied in the FAST model. The lower portions of the model were selected to represent the properties of the platform and its restraints. This was done by using the mass of the platform and tripod structure received from STA together with the specified buoyancy. The apparent mass and damping coefficients of the structure also had to be estimated to calculate the hydrodynamic forces.

These characteristics of the model below sea level were selected by comparing the natural frequencies of the Bladed model with corresponding natural frequencies of the Orcaflex model. The latter were obtained by plucking the model and observing the time history of certain displacements; the former were obtained from a linearization module within Bladed.

Full details of the Bladed model are attached as Appendix C, but some aspects of the underwater parts of the model are listed in Table 5-2.

Table 5-2. Characteristics of the Bladed Modeling of Platform Support

Item	Units	Value
Equivalent diameter of platform	m	73.15
Equivalent thickness of platform	m	6.0
Damping coefficient of platform		1.15
Apparent mass coefficient of platform		2.0 (all but dlc 6.1) to 4.0 (dlc 6.1)
Lateral restraining spring	kN/m	1.0E4
Rotational restraint against pitching and rolling	kN m/rad	2.6E8
Fundamental natural frequency in platform sway	Hz	0.05
Fundamental natural frequency in tower bending	Hz	0.34

5.3 Design of the Turbine

The time series for all selected signals from all the load cases were generated by GH and delivered to GEC for post-processing. GEC used the program CRUNCH from the National Wind Technology Center and other proprietary software and spreadsheets to extract peak values and fatigue cycles, and to check the adequacy of the design of the major turbine components. Cost models were applied to determine the approximate cost of the major components, as discussed in Section 6.2.

5.3.1 Results

Table 5-3 presents the initial sizing of some of the major components and how they were adjusted in the design process.

Table 5-3. Design of Major Components

Component	Initial Design	Adjustments	Comments
Blade root	Diam =3.542 m, mass = 678 kg/m	Mass reduced to 400 kg/m	Governed by My fatigue. $12/kg
Blade 25% span	Chord = 4.652 m, t/c = 0.30, mass = 349 kg/m		Governed by Mx fatigue
Blade 50% span	Chord = 3.748 m, t/c = 0.21, mass = 263 kg/m		Governed by My fatigue
Hub	Radius to pitch bearing = 1.5 m, mass = 56,780 kg		Ductile iron, $4.75/kg, fatigue governed
Low-speed shaft	OD = 0.800 m, ID = 0.400 m, length = 3.000 m		$7.00/kg
Gearbox	Mass = 40,000 kg		
Mainframe	Mass = 83,389 kg		Ductile iron, $475/kg
Generator	Mass = rating * 3.3 + 471		

Component	Initial Design	Adjustments	Comments
Power electronics	$67/kW		Cost from WindPACT
Tower	6,000 x 35 mm at 0.00 m 3,800 x 25 mm at top	7,200 x 42 mm at + 11 m 3,850 x 15 mm at top	EuroCode 3, category 90 used, design governed by fatigue
Tripod support	1,200 x 25 mm steel tubes		No design checks made

5.4 Comparison with Onshore Baseline

An equivalent wind turbine model was built to represent the same machine on land so the effects of placing the turbine on the offshore semi-submersible could be quantified. The loading environment (a subset of the IEC IB loads) was maintained with a hub height of 90 m aboveground. Table 5-4 presents a comparison of some of the major loads within the machine.

Table 5-4. Comparison of Loads from Baseline and Offshore Turbines

		Characteristic Extreme Loads (and load case)		**Equivalent Fatigue Loads**	
Load	**Units**	**Onshore**	**Offshore**	**Onshore**	**Offshore**
Blade root Mx	kN m	16,560 (dlc7.1-f3)	17,580 (dlc7.1-f2)	6,687	6,695
Blade root My	kN m	14,010 (dlc1.3a-12 ms)	14,700 (dlc7.1-d1)	6,681	7,163
Blade 50% My	kN m	3,780 (dlc1.3a-12 ms)	3,790 (dlc2.3-c)	1,988	2,126
Shaft thrust	kN	1,070 (dlc2.3-b)	1,460 (dlc(1.3b-b3)	105	152
Shaft bending at hub	kN m	13,540 (1.3a-25 ms)	14,230 (dlc7.1-e3)	3,486	3,491
Yaw bearing Mx	kN m	5,950 (dlc1.3a-25 ms)	6,360 (dlc1.3b-b1)	580	625
Yaw bearing My	kN m	13,270 (dlc1.3b-25 ms)	14,440 (dlc 1.3b-b3)	2,771	2,800
Yaw bearing Mz	kN m	13,250 (dlc7.1-d2)	14,470 (dlc7.1-d1)	2,707	2,705
Tower Mx at +11.0 m	kN m	96,500 (dlc7.1-f3)	152,060 (dlc 7.1-b2)	10,621	9,672
Tower My at +11.0 m	kN m	123,580 (dlc2.3-b)	265,630 (dlc 1.3b-b3)	11,648	27,653
Tower Mx at platform	kN m	NA	218,400 (dlc 7.1-b2)	NA	
Tower My at platform	kN m	NA	378,000 (dlc1.3b-b3)	NA	

Notes:

- Extreme and fatigue loads are characteristic values and include no safety factors.
- The equivalent fatigue loads are based on S-N fatigue gradients of m = 12 for the blades and m = 4 for all other locations. They are based on a 1.0-Hz frequency over the design life of the turbine (20 years).
- Loads terminology is compatible with coordinate directions defined by IEC (x is downwind, y is lateral, z is vertically upward).

The results in Table 5-4 show that the governing peak and fatigue loads in the offshore wind turbine rotor are slightly greater than those in the onshore equivalent machine. However, the extreme loads in the drive train are increased further (36% in the shaft thrust). In the tower the extreme and the fatigue loads are increased considerably (82% in the extreme base bending, and 137% in the fatigue at the base bending). The possible nature of this response is discussed further in the following section. The tower fatigue might be attenuated by tuning the rotor controller to the frequency of the platform motion, but this has not yet been demonstrated.

5.4.1 Tower fatigue loading

The fatigue loading in the tower supported by the submerged platform is considerably greater than the equivalent loading in the onshore baseline tower. Figure 5-1 compares the (power spectral density) PSDs of samples of the fore-aft bending in the tower under operating conditions in mean wind speeds of 20 m/s.

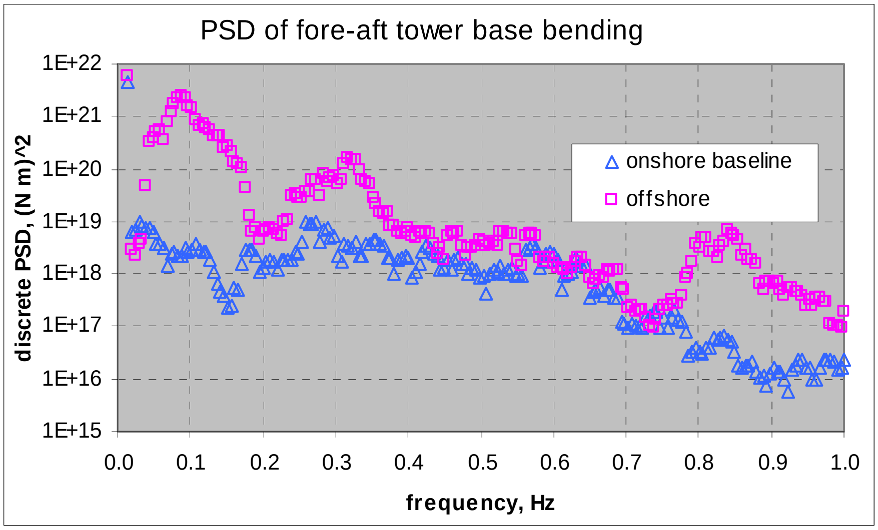


Figure 5-1. Comparison of PSDs of tower base bending from onshore and offshore turbines

The two spectra differ mostly in the added response in the offshore spectrum below 0.3 Hz, which is associated with the wave loading and motion of the platform. The peak near 0.1 Hz corresponds to the peak of the wave energy spectrum at 0.11 Hz. In addition, the offshore spectrum contains higher response near 3.1 Hz and 8.3 Hz. These frequencies are close to the predicted values of the first and second tower bending natural frequencies (see Appendix C).

The loads at which the tower accumulated fatigue damage were investigated for both configurations. For the offshore turbine, the fatigue damage was not dominated by the larger but less frequent excursions (which might correspond to the sway motion of the platform), but by smaller excursions that probably corresponded to the response near 3.1 Hz. From this we conclude that the pitching restraint of the platform may play an important role in the design of the tower.

5.5 Peak Loads in the Platform System

According to the Bladed analysis, the peak overturning moment on the platform is predicted to be 378,000 kN m (Table 5-4) during extreme wave loading on the operating wind turbine. This overturning moment can be converted to equivalent change in tension in the mooring lines which is ± 5171 kN. If the mean preload on each tension leg is 37,800 kN, the peak tension will be 42,995 kN.

This value of the peak leg tension can be compared to the peak value of 53,400 kN predicted by Orcaflex. The Bladed model is limited in the hydrodynamic effects it includes, but that many load cases have been simulated by Bladed and scanned for the peak value.

The same peak overturning moment can be used to estimate the peak load change in the diagonal tubes. This results in a tube force of ± 20,684 kN, which is in addition to the mean force in the tubes that is caused by neutral conditions.

6 Cost of Energy

In compliance with the contract requirements, and in accordance with the COE guidelines specified by NREL, we calculated the COE by assuming a 100 turbine installation.

6.1 Energy Production

The annual energy production was obtained by integrating the expected power curve with the specified hub height wind regime and adjusting for drive train losses, availability, and wake losses specified by NREL. We assumed that the variable-speed rotor is controlled to operate at maximum aerodynamic efficiency from cut-in wind speed until rated power is reached.

The wind regime specified for energy production calculations is a Class 6 (6.7 m/s mean) at a reference height of 10 m and with a wind shear exponent of 0.12. This implies a mean wind speed at a 90-m hub height of 8.73 m/s. The gross and net annual energy production are presented in Table 6-1.

Table 6-1. Annual Energy Production

Item	Annual Energy
Gross energy capture by rotor, Cpmax = 0.491 @ TSR = 7.5	21,109 MWh
Drive train losses	5% max
Availability losses	2%
Array losses	5%
Soiling losses	3.5%
Net annual energy capture per turbine	18,965 MWh

6.2 Cost Models

A combination of standard marine construction costs and methodologies, as well as direct estimates from component suppliers, was used to prepare cost estimates for the semi-submersible system (anchor, platform, and tension leg system). Costs are based on current labor and materials. Details are provided in Appendix F.

Cost models for the wind turbine components were adopted from the WindPACT study (Malcolm and Hansen 2002), with some adjustments for inflation. The blades were assumed to be made of fiberglass and design was based on recent values for design strains (0.7% in both tension and compression) and S-N fatigue gradients of m = 10 in both tension and compression. The cost of finished blades was taken as $12.00/kg.

The cost of fabricated steel was increased from $1.50/kg to $2.00/kg because of recent increases in the cost of steel. The cost of finished ductile iron casting was taken as $4.25/kg.

The approved NREL methodology and NREL's values for O&M costs, design wind regime, and electrical interconnection costs, were used to calculate the COE.

6.3 Cost Analysis Results

The cost estimates for each item and the overall total are listed in Table 6-2.

Table 6-2. Cost Summary

Distance from shore km (miles)	25 (15)	25 (15)	25 (15)	100 (60)
Rating (kWs)	5000	5000	5000	5000
Component	Baseline Component Costs	HIGH Projected Component Costs	LOW Projected Component Costs	Projected Component Costs
Rotor	**1,070**	**1,070**	**1,070**	**1,070**
Blades	691	691	691	691
Hub	235	235	235	235
Pitch mechanism and bearings	144	144	144	144
Drive train, nacelle	**2,111**	**2,111**	**2,111**	**2,111**
Low-speed shaft	79	79	79	79
Bearings	65	65	65	65
Gearbox	706	706	706	706
Mechanical brake, HS coupling, etc.	10	10	10	10
Generator	260	260	260	260
Variable-speed electronics	270	270	270	270
Yaw drive and bearing	45	45	45	45
Main frame	354	354	354	354
Electrical connections	200	200	200	200
Hydraulic system	23	23	23	23
Nacelle cover	99	99	99	99
Control, safety system	**10**	**10**	**10**	**10**
Tower	**796**	**796**	**796**	**796**
TCC	**3,987**	**3,987**	**3,987**	**3,987**
Balance of station (BOS): semi-submersible				
Mobilization, plant and equipment		232	200	232
Permits, engineering		57	57	57
Gravity anchor structure		1,602	1,252	1,602
Semi-submersible platform		1,783	1,343	1,783
Tension legs, winches and porches		1,823	910	1,823
Deployment		161	161	161
Electrical infrastructure		1,475	1,475	3,275
BOS - seabed mounted baseline				
Port and staging equipment	100			
Design & project management	112			
Pre-construction site assessment	73			
Monopile foundations	1,488			
Personnel access system	60			
Scour protection	270			
Turbine installation	527			
Electrical infrastructure	1,405			
BOS Cost	**2,630**	**7,133**	**5,398**	**8,933**
Project uncertainty				
Initial capital cost (ICC)	**6,617**	**11,120**	**9,385**	**12,920**
Installed cost ($)/kW for 5-MW turbine	**1,323**	**2,224**	**1,877**	**2,584**
Turbine capital cost (TCC) ($)/kW without BOS	**797**	**797**	**797**	**797**
Levelized replacement costs (LRC)	54	54	54	54
O&M $20/kW/yr (O&M)	100	100	100	100
Land ($0.00108/kWh/yr/turbine)				
NET 6.7 m/s annual energy production MWh	19,107	18,965	18,965	18,965
Fixed charge rate (FCR)	11.85%	11.85%	11.85%	11.85%
COE at 6.7 m/s $/kWh	**0.0470**	**0.0755**	**0.0646**	**0.0867**

The “baseline cost” is the cost for a seabed-mounted version of the 5-MW wind turbine. The water depth is assumed to be less than 20 m and the configuration of the wind turbine above the water line is assumed to be the same as that of the turbine design arrived at for the current study. This implies that the tower cost for the baseline may be conservative since the loading on a seabed-mounted tower is likely to be lower than that on a submerged platform. The BOS costs for the baseline have been supplied from proprietary sources through NREL.

The “projected costs” are the cost estimates based on the work in this project. They are based on the loads that were identified from the structural analysis of the platform and the turbine, and are based on the unit costs specified earlier in this report. Three columns are titled “Projected Costs.” The “HIGH” and “LOW” projected costs are for a distance from shore of 25 km and are comparable to the baseline costs. The right-most column is for a distance offshore of 100 km and allows the effect of this change to be highlighted.

The high BOS cost represents the semi-submersible system as it is currently configured, without optimizing either design or refining manufacturing techniques. The lower BOS cost represents estimates of probable modifications and optimizations of the system, and do not represent possible cost reductions that may result from lower weight and smaller size of the wind turbine drive train.

The final COE, even for the baseline, is higher than the DOE target of $0.07/kWh, and Table 6-2 shows that this is due more to the BOS costs than to the costs of the wind turbine. The cost target will be reached more easily if the hub-height wind regime is improved. The mean wind speed of 8.73 m/s at 90 m is conservative for many offshore sites. If the mean wind speed is increased by 10% to 9.60 m/s, the annual energy production will increase by approximately 13% and the final COE will be reduced by 13%.

Several factors may be investigated in the future that will lower the cost of the system:

- Much of the cost of the semi-submersible foundation system relates directly to the weight of the turbine and tower. Design improvements that reduce their mass will considerably reduce the costs of the platform and mooring systems.

- A significant factor in the COE for deep water offshore wind farms will be the cost of transmitting energy. The cost estimate used in the above calculations is based on conventional electrical cabling that would run from the wind farm to a land connection to the power grid. An alternate strategy, albeit one that would take some research and development, would be to convert the wind farm energy to hydrogen in situ, for transport to land via either pipeline or a subsurface collection facility from which vessels might carry the gas to facilities in adjacent ports. A white paper written by Mr. Harry Dempster on the subject is included as Appendix G for NREL’s consideration.

- Roughly 18% of the BOS unit cost is for large triple-drum winches that are used to control the tension legs. We may reasonably assume that future deployment strategies will either provide for a single set of winches that can be used for multiple installations or do away with the winches entirely.

- The buoyancy of the platform may be enhanced by the use of lightweight concrete, but the consequences of its use to the durability of the system should be examined.

- The anchor system may be improved by adding bottom “legs,” “skirts,” or other features that will enhance its bond with the sea bottom.

- The system presented in this study was based on having the anchor and platform operate as a single stacked unit during deployment. Further study should optimize the system to reduce the platform weight as well as the weight of the anchor and the size of the tension legs.

- The depth of the water study site was 62 m, and the platform depth was 20 m. The 50-yr peak wave period is 14 s. A wave period of 14 s will generate significant wave energy up to 153 m below the water's surface. Accordingly, the platform portion of the proposed system was subjected to greater forces than if it had been located in deeper water. Locating the platform in deeper water would have necessitated the development of a stronger, slender monopile or composite tower. Locating the proposed system in deeper water (90 m plus) will likely reduce the cost of the system, but this may be offset by an increase in tower cost. This would be a useful area for further study.

- Relationships between the overturning moments result from wind and wave action, the tension required in the tendons, and the weight and cost of the anchor. The optimum set of parameters should be explored to minimize cost.

7 Development Schedule

This study has considered the feasibility of the semi-submersible type of wind turbine platform. Complete validation of the concept will require a carefully planned testing of a prototype system. It can include laboratory-scale models as well as testing in ocean conditions. A possible breakdown and schedule for such a test program is shown in Figure 7-1.

	Task Name	Duration
1	Concept Design	1 day
2	Review of Multiple Concept Designs	1 mon
3	Model Development / Validation	2 mons
4	Preliminary Design	6 mons
5	Updated Commercial Projections	2 wks
6	Component Testing	3 mons
7	Design, Fabrication and Testing of Prototype	4 mons
8	Small Scale Model Test	4 mons
9	Modifications to Design	3 mons
10	At Sea Full Model Test	12 mons
11	Modifications to the Design	4 mons
12	Commercialized Design and Cost Projections	2 wks
13	Design and Manufacturing of Dry Dock	12 mons
14	Full Size Manufacturing	6 mons

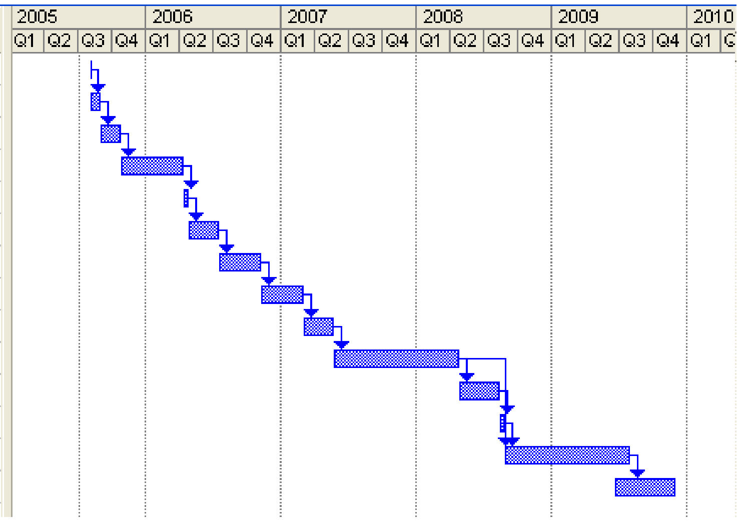


Figure 7-1. Possible schedule for further testing and development

7.1 Model Development and Validation

Accurate load predictions have presented challenges in this initial study. The Orcaflex code appears to be sufficient for wave-loading simulations, but it does not incorporate turbine operational loads. The modified Bladed code includes loading from wave and turbine operations, but has reduced degrees of freedom that may compromise the simulation results. A third modeling option is to add wave loading to the FAST/ADAMS codes. This code development effort is ongoing at NREL, and so was not available in time to support the initial concept study. In taking the next steps to develop CMA's semi-submersible platform concept, some effort toward additional modeling capability is warranted. CMA and GEC will work to identify the most promising path toward building this modeling capability.

Wave-tank testing should be conducted in parallel with the modeling efforts. Wave tank modeling would be a valuable tool for comparison with the predictions of the available dynamics models and should be conducted. The intent of the test will be to simulate wave loading, with particular emphasis on survivability under extreme environmental conditions. To the extent practical, these tests will also incorporate the effects of mean wind loading. Because the turbine will likely be shut down (parked or free-wheeling) under these conditions, the mean wind loading may be simulated via either aerodynamic or mechanical methods. The purpose of the wave-tank testing will be twofold: (1) to acquire empirical data for determining the peak structural loading; and (2) to validate and tune the computational models for selected conditions, so that the models can then be used to evaluate the system's dynamic response for combinations of turbine operation and environment beyond what can be wave-tank tested.

7.2 Preliminary Design

Based on the conceptual design, the fabrication, installation, and operation of the semi-submersible support platform appears feasible. However, additional design work is necessary to fully evaluate its technical feasibility and commercial viability. In particular, design details are required for the system to deploy and draw the wire ropes, the tripod with steel tubes and wire ropes, and the platform and stowage compartments for the wire rope. These components will need to be designed to include considerations of structural integrity, mechanical function, and robustness in the marine environment. Trade-offs in the preliminary design effort will include considerations of cost, technical uncertainties, planned path to commercialization, and market opportunities.

7.3 Updated Commercial Projections

Cost projections will be continually updated through the preliminary design process, with the intent of converging on a system that minimizes the COE. Conversely, some factors that affect the competitiveness of this system need to be considered in the design phases. In particular, the TLP is considered to be most cost-effective at 100 m or deeper. This will need to be factored into the design of a prototype system and corresponding test location.

7.4 Component Testing

This phase will include the fabrication and testing of major components. These may include a scaled version of the semi-submersible/TLP, wire rope stowage and deployment mechanisms, and other critical structures and mechanical systems. Results from these tests will be used to guide the detailed design of the prototype turbine/platform system.

7.5 Design, Fabrication, and Testing of the Prototype

The cost of prototype fabrication and testing will be strongly dependent on turbine size. Although the optimal size for long-term commercial deployment may be multimegawatt, the cost and risk in this size range may be prohibitive for initial prototype testing. Conversely, although a much smaller machine (e.g., 750 kW) might capture most of the major features in demonstrating the proof of the concept, significant up-scaling would be required to reach the range of potential commercial application, which could result in additional cost and technical risks in the overall development path.

Based on these considerations, we recommend that, if possible, the initial prototype be at the lower end of typical offshore applications 1.5−2 MW). The turbine should have well-characterized operational loads and power performance, and a proven history of robust operation. This should minimize any additional cost that results from uncertain operating characteristics or unexpected O&M issues.

The primary objective of the prototype test is to demonstrate the technical feasibility of the fabrication, installation, and operation of the semi-submersible wind turbine support system. Secondary objectives will be to collect operational data (e.g., load measurements) to validate model predictions, refine the design for commercialization, and optimize costs.

7.6 Commercialized Design and Cost Projections

Following the prototype testing, the design will be refined with the intent of maximizing cost-effectiveness. In this design revision, all aspects of the system performance would be considered, including ease of deployment, stability, structural efficiency, and manufacturability. This final design would form the basis for final cost projections and a business plan for commercialization.

8 Conclusions and Recommendations

The purpose of this study has been to investigate the concept of an offshore wind turbine mounted on a semi-submersible platform in deep water. The technical and economic feasibility has been investigated. The design calculations have made some assumptions compatible with the preliminary nature of the study but these will not affect the conclusions.

8.1 Conclusions

With the experience of work performed to date, a self-installing tension-leg-type structure has been conceptually designed that will withstand 27-m high waves in 62 m of water and support a 5-MW wind turbine. The horizontal motions are quite large, and the tower remains essentially vertical. The tower, as on land, has a flexural response. Additionally, the differential stretch of the tendons results in some slight inclination of the submerged TLP. The system becomes complicated, inasmuch as it is a flexible system with several important flexibilities:

- Tower flexure—hence mast natural period, as if it were rigidly mounted on a land-based foundation
- Tendon stretch and heave natural period
- Tendon differential stretch and pitch/roll periods
- TLP platform side-sway (platform stays horizontal and tower stays vertical, but the tower moves sideways with the platform).

Since the waves induce platform motions with more effect closest to the surface, the platform should ideally be kept as far beneath the water surface as practicable. The complete system (nacelle, blades, mast, platform, moorings and anchor, etc.) should ideally be self-installing to significantly reduce the capital costs associated with installation.

The following points summarize the findings of this study.

- Both software codes that were used to model the system response have had limitations. The Orcaflex code is designed to simulate hydrodynamic effects; the Bladed code is designed primarily to model the aerodynamics of wind turbines. Bladed was modified to include wave loading and some degrees of freedom of a submerged platform, but some significant hydrodynamic forces may be excluded.

- More confidence can be had in the response of the system, especially in extreme conditions, when a single code has been validated for the combined aerodynamic and hydrodynamic system.

- The design loads on the rotor are affected only slightly compared with those for equivalent onshore wind turbines. However, the peak and fatigue loads in the nacelle and the tower are increased considerably by the offshore environment.

- The TLP concept has proven to be suitable for a deep water installation. The relative economic efficiency of the system with regard to bottom fixed structures is expected to increase as the depth of water increases. A maximum depth limit has not been identified. However, this configuration may be better suited to water that is deeper than 62 m. This is based on the possibility that a pile-supported structure may be more economically suitable for 62-m water depth (the shallow end of the original 46–183 m deep water definition). In water depths of about 61 m, a bottom-founded (gravity/piled) structure is likely to be more economical than a moored structure, depending on the maximum ocean environment.

- The proposed fabrication and installation procedure promises to accelerate these processes and to allow installation in conditions that would otherwise preclude activity.

- The provisional estimates of peak tether loads are acceptable to the proposed configuration. Further refinement may allow some components, such as the mooring legs, to be reduced in size.
- The concrete platform and gravity foundation must be manufactured so as to achieve a cost-effective system.
- The cost of the electrical connection to the land-based substation is a major item in determining the overall COE. The design of that subsystem is important.

8.2 Recommendations

Available dynamics codes should be upgraded to allow accurate modeling of wind and wave loads for floating or semi-submerged platforms. Three-dimensional diffraction/radiation and Froude-Krylov Forces need to be investigated in the preliminary design. We recommend that Advanced Quantitative Wave Analysis (AQWA) be used to conduct the next analysis. The AQWA suite can be used to analyze motions and loads on floating structures such as semi-submersibles, and to investigate complex marine operations, including jacket installation, upending and docking, and deck mating operations. It can also be used to generate detailed description of loading on fixed structures such as concrete platforms.

Future wind turbine designs should place more of the nacelle operating equipment inside, rather than atop the tower, to lower the center of gravity of the entire system.

9 References

Hendriks, H.B. and Zaaijer, M. "Dutch Offshore Wind Energy Conversion. Executive summary of the public research activities," www.ecn.nl/docs/dowec/dowec-execsum.pdf.

International Electrotechnical Committee, "Safety Requirements for Offshore Wind Turbines," draft standard IEC 61400-3, July 2004.

Malcolm, D.J., Hansen, A.J., "WindPACT Turbine Rotor Design Study," National Renewable Energy Laboratory, NREL/SR-500-32495, August 2002.

Manwell, J., Rogers, A., McGowan, J., and Elkinton, C., "Characterization of External Conditions For the Design of Offshore Wind Energy Systems for the United States," proceedings ASME Wind Energy Symposium, 42^{nd} AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January 2004.

Musial, W., Butterfield, C.P., and Boone, A., "Feasibility of Floating Platform Systems for Wind Turbines," in Proceedings ASME Wind Energy Symposium, 42^{nd} AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January 2004.

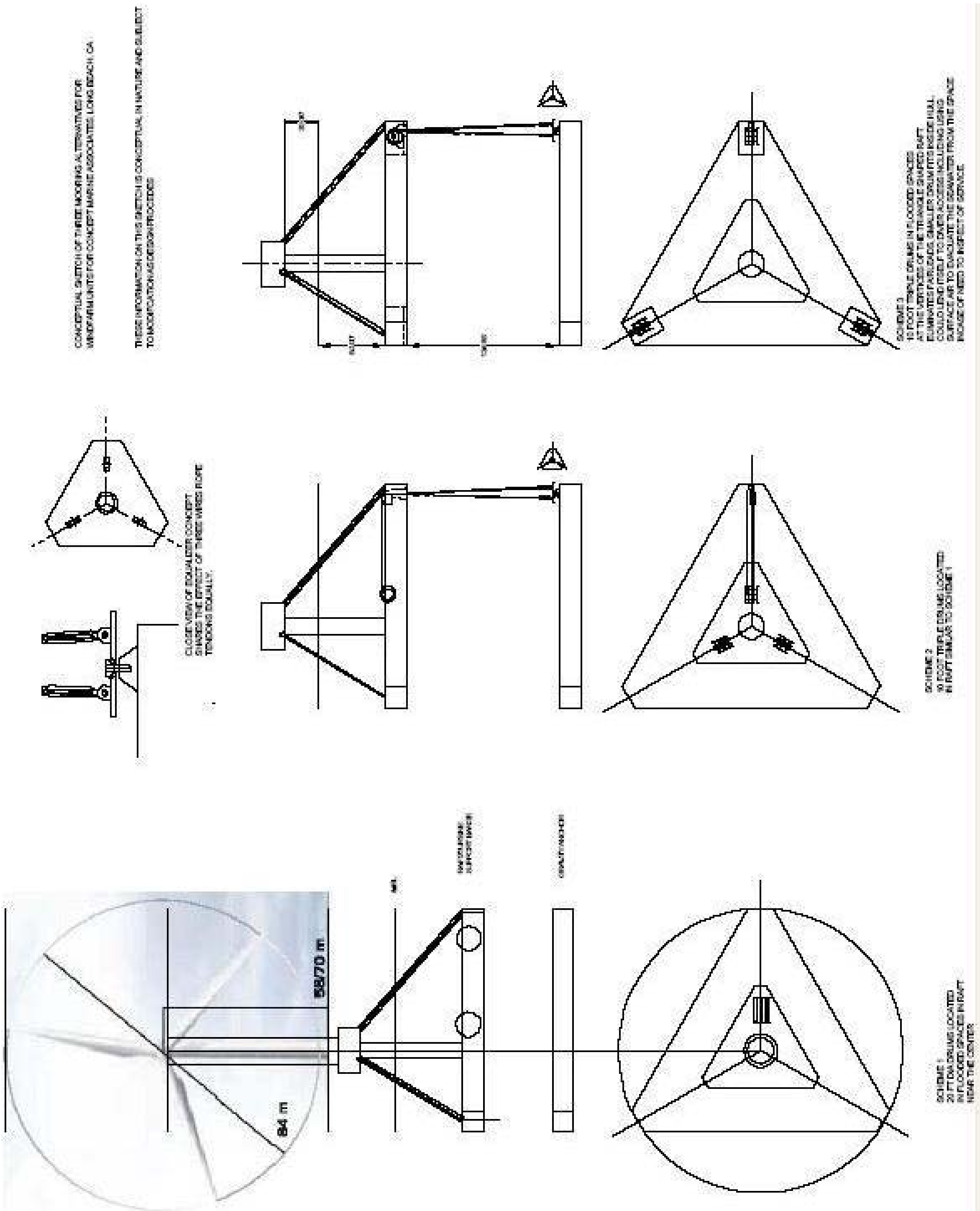
Sclavounos, P., "Coupled Wind Turbine Floater Dynamics," Workshop on Deep Water Offshore Wind Energy Systems, U.S. Department of Energy, Washington, D.C., October 2003.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Workshop on Deep Water Offshore Wind Energy Systems," Washington, D.C., October 2003.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Deep Water Wind Energy Research & Development Planning," a workshop organized DOE, Washington, D.C., October 2004.

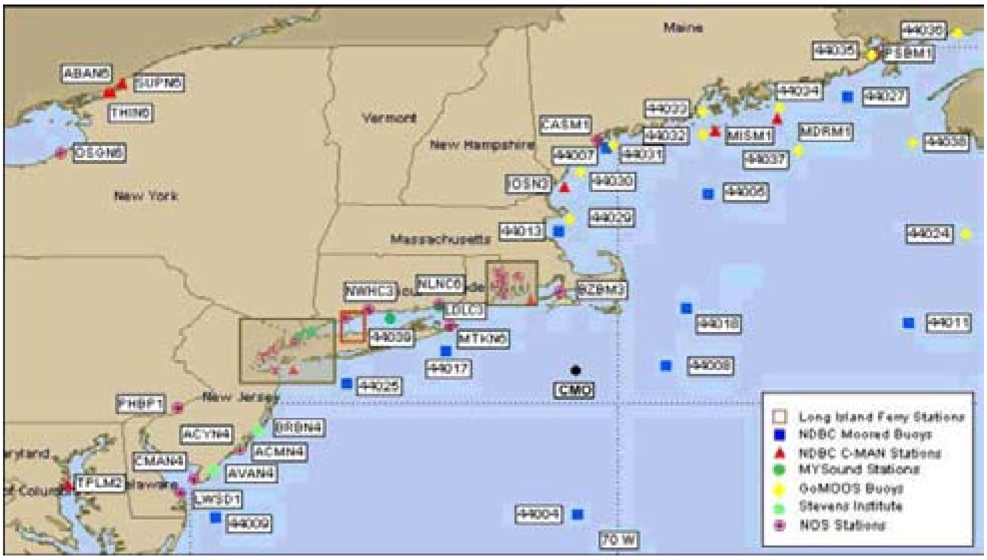
10 Appendices

Appendix A – Drawings



Appendix B – Environmental Report

DESIGN PARAMETERS FOR AN OFFSHORE WIND TURBINE SOUTHEAST OF NANTUCKET ISLAND



by

Hany Elwany, Ph.D.

Prepared for

Concept Marine Associates
1853 Embarcadero
Oakland, CA 94606

COASTAL ENVIRONMENTS
2166 Avenida de la Playa, Suite E
La Jolla, CA 92037

01 July 2005
CE Reference No. 05-09

DESIGN PARAMETERS FOR AN OFFSHORE WIND TURBINE SOUTHEAST OF NANTUCKET ISLAND

1 INTRODUCTION

This report presents the results for the design parameters of an offshore wind turbine located approximately 54 nautical miles (or approximately 48 statute miles) southeast of Nantucket Island on the east coast of the United States. The National Oceanographic and Atmospheric Administration (NOAA) has several buoys near the project area. Figure 1.1.1 provides the locations of these buoys. Of interest to this project is NOAA Buoy 44008. Buoy 44008 is located 54 nautical miles southeast of Nantucket (at 40°30'00"N 69°25'53"W) in a water depth of 62.5 m. It is owned and maintained by the National Data Buoy Center (NDBC). The station is a 3-meter discus buoy with assorted sensors. Figure 1.1.2 presents the available data from the NOAA/NDBC buoy site.

The data from Buoy 44008 that was used in this study covers the time period between August 1982 and October 2004. The buoy is still in place and continues to collect additional data. Available data from Buoy 44008 provides information about waves (significant wave height, peak wave period, and average wave period) and wind and wind gust (speed and direction). In this data, the winter time period is defined as January through March, spring as April through June, summer as July through September, and autumn as October through December.

The information on coastal currents was derived primarily from the Coastal Mixing and Optics (CMO) experiment that was funded by the Office of Naval Research (Shearman and Lentz, 2003). This study, conducted from August 1996 through June 1997, measured currents, temperature, conductivity, bottom pressure, and surface and near-bottom stress at a combination of four sites to characterize flow over the New England Shelf. The location of the study site was approximately 100 km (or 62 miles) southeast of Cape Cod and west-southwest of Buoy 44008. The location of the CMO measurement station is also indicated in Figure 1.1.1. A time-line plot of the data from CMO and Buoy 44008 is shown in Figure 1.1.2. For the CMO data, an up-looking acoustic Doppler current profiler (ADCP) was deployed at 65 m depth. The hourly data were presented in cm/s for the U and V velocity vectors. This instrument was sampled 16 times per hour at depths of 4.5, 15, 50 and 65 m. Sampling strategies and data processing techniques are described by Galbraith et al. (1999).

This report consists of three sections. Section 2 describes the waves, tides, currents and wind conditions, and Chapter 3 provides wave and wind design parameters for 5-, 10-, 25-, 50- and 100-year return periods.

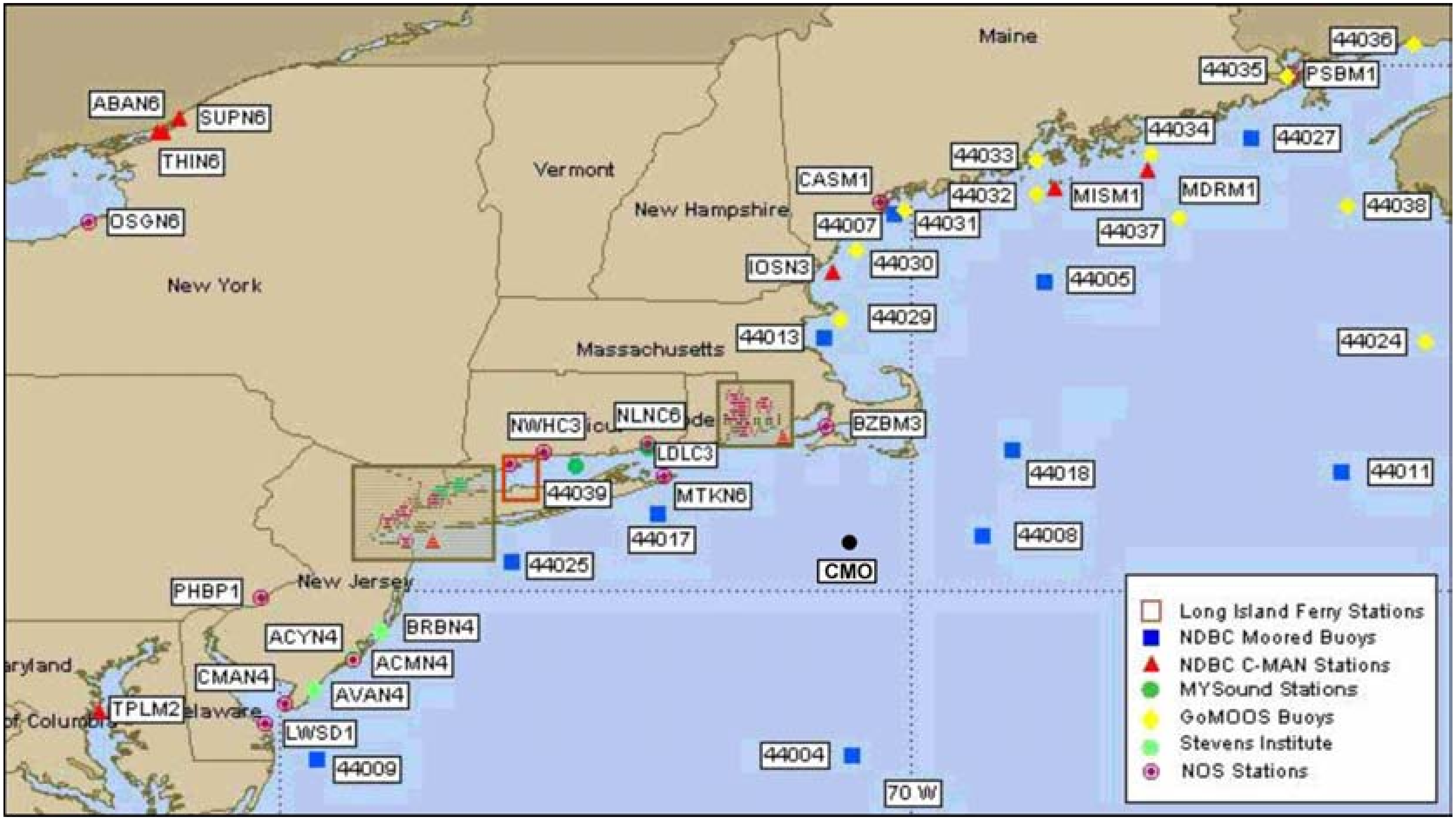


Figure 1.1.1. Locations of NOAA Buoy 44008 and additional NOAA buoys in the area. Coastal current measurements were carried out at station CMO.

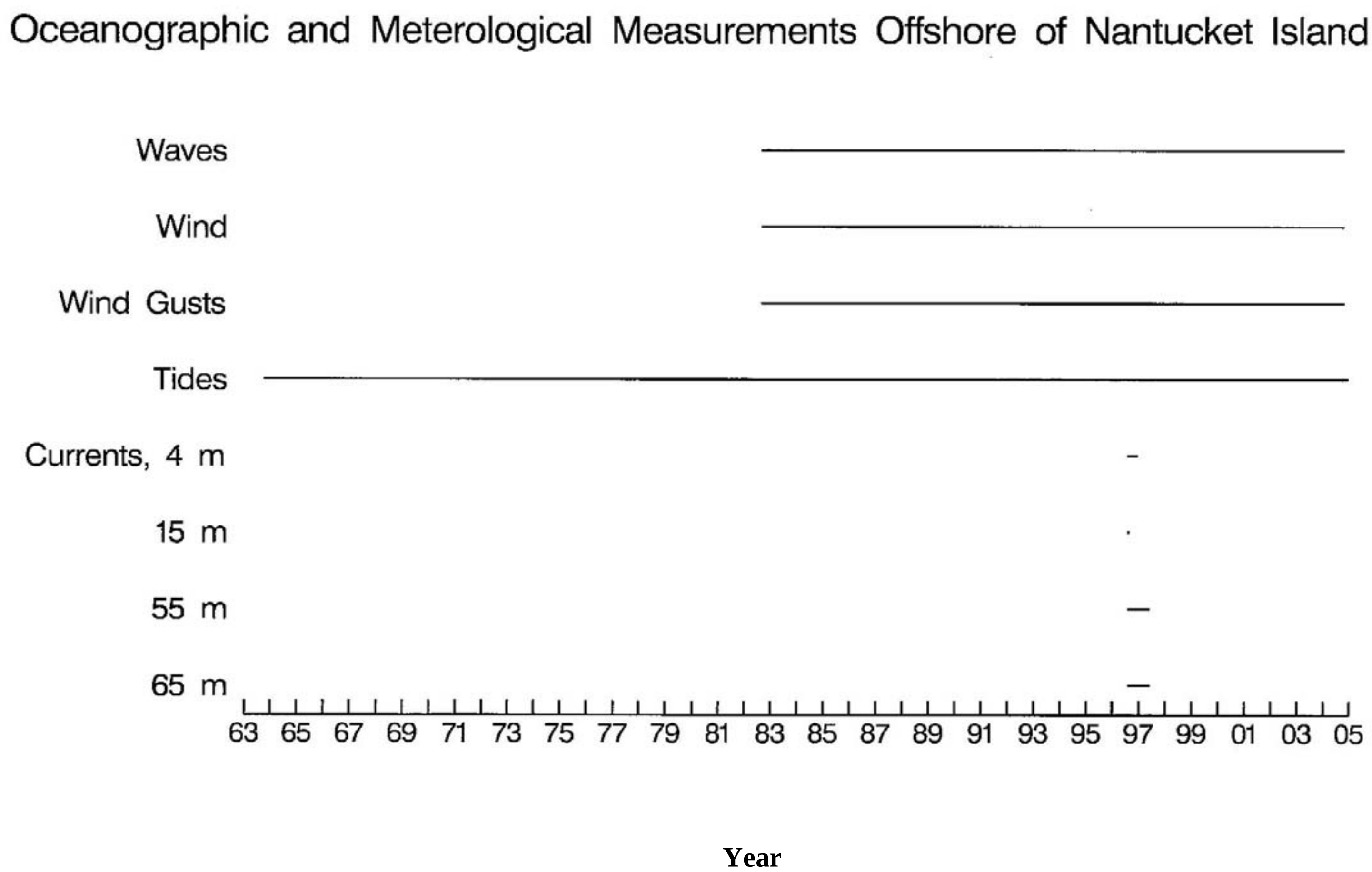


Figure 1.1.2. Timeline plot of oceanographic and meteorological data used in this study.

2 DESCRIPTION OF OCEANOGRAPHIC AND METEOROLOGICAL ENVIRONMENT

2.1 WAVES

The NOAA/NDBC Buoy Station, “Nantucket” (44008), provides 22 years of unidirectional wave data. This data includes significant wave heights (Hs), which are defined as the average heights of the highest one-third of the waves of a given wave train, during a 20-minute sampling period, reported hourly. In Figure 2.1.1, histograms of significant wave heights are presented for the winter, spring, summer, and autumn seasons from data collected at Buoy 44008. These histograms provide the percentage of the time that an event will occur. The frequency distribution mode is equal to about 1 m, and large waves occur frequently during the winter and autumn. Figure 2.1.2 provides the cumulative percentages of significant wave heights for the four seasons. Figure 2.1.3 provides histograms of significant wave heights and the cumulative percentage of significant wave heights for all data (combined). For all data combined, the significant wave height of 1 meter occurs over 50% of the time, with significant wave heights of 2 and 3 meters occurring approximately 28 % and 12% of the time, respectively (Figure 2.1.3).

Peak wave period (T_p) is defined as the period in seconds of the inverse of the frequency band containing the maximum energy density in the frequency spectrum. Figures 2.1.4 and 2.1.5 provide histograms of peak wave periods and cumulative percentages of peak wave periods, respectively, for winter, spring, summer, and autumn. A comparison indicates that an 8-second peak wave period in summer and spring occurs between 25 and 30% of the time, while an 8-second peak wave period in winter and autumn occurs between 20 and 25% of the time. Average wave period (T_a) is the average wave period in seconds of all waves during the 20-minute measuring period. Histograms of average wave period and cumulative wave period for winter, spring, summer, and autumn seasons are presented in Figures 2.1.6 and 2.1.7, respectively. Average wave period is about 5.5 seconds, occurring between 15 to 20% of the time in winter and autumn, and between 20 and 25% of the time in summer and spring. Maximum monthly significant wave height data between November 1982 and October 2004 are presented in Figure 2.1.8. Maximum monthly significant wave heights over this period range between approximately 2 m and 11.5 m. Figure 2.1.9 provides the maximum monthly peak wave period data collected between November 1982 and October 2004. Maximum monthly average wave period data collected between November 1982 and October 2004 are shown in Figure 2.1.10. In Figures 2.1.9 and 2.1.10, peak wave periods range between 9 and 20 seconds, and average wave periods range between 5 and 14 seconds.

Tables 2.1.1 and 2.1.2 provide statistics for significant wave height, peak wave period, and average wave period by year and month, respectively, at the subject site. According to Table 2.1.1, significant wave heights are highest in August and September due to hurricane season. Table 2.1.2 indicates that the largest recorded storm wave, which occurred on 19 September 1999, had a significant wave height of 11.51 m, a peak wave period of 14.3 sec, and an average wave period of 11 sec.

2.2 TIDES

Buoy Station 44008 is located at 40.50 N, 69.43 W, about 54 nautical miles southeast of Nantucket Island. Also, NOAA/NDBC Buoy Station "SE Cape Cod" (44018) is located at 41.26 N, 69.29 W, about 30 nautical miles east of Nantucket Island. Tides on the east coast of the United States, including the area off Nantucket Island, are semidiurnal. This means that there are two high tides and two low tides each day, which are respectively nearly equal in height. Tide range represents the difference in elevation between successive high and low tides.

At Nantucket, NOAA Station 8449130, water level measurements are available from 1965 on. The mean tide range, or difference between mean high water and mean low water (MHW-MLW), is about 93 cm. The tide range decreases offshore toward the southeast, as illustrated in Figure 2.2.1. However, this decrease in range between Nantucket and Buoys 44008 and 44018 is too small to be of practical significance. As also shown by Figure 2.1.1, the tide wave in the North Atlantic progresses counterclockwise around the ocean, as indicated by the direction of progressively increasing hour numbers. This means that the tide off Nantucket progresses from northeast to southwest.

According to the tidal epoch (1983-2001), the mean higher high water (MHHW) with respect to mean lower low water (MLLW) is about 1.09 m. Mean high water (MHW) is 0.98 m, mean water level is 0.54 m, and mean low water (MLW) is about 0.06 m. The maximum recorded water level was about 2.4 m on 30 October 1991.

2.3 COASTAL CURRENTS

One of the predominant patterns of the New England Shelf water is the seasonal change in temperature and the breakdown and setting up of the thermocline. In general, during fall through winter, the breakdown of the thermal stratification, which is due to mixing by winter storms and convective overturning of the surface waters, occurs while the spring thermocline reforms (Glenn et al., 2001). The spring development of stratification is often interrupted by wind-driven mixing events. During the summer, a strong thermocline is present at approximately 20 m with mid-shelf near-surface temperatures of 20^{o}C, and near-bottom temperatures of less than 10^{o}C. During the CMO experiment, this pattern was evident, with the exception that stratification set up after December due to anomalous conditions that caused the shelf-slope front to migrate inshore further up onto the shelf.

The CMO hourly current speed data (Shearman and Lentz, 2003) showed that storms with scales of about 1000 km are primarily responsible for the correlation between depth averaged currents and wind stress for fluctuations in current velocity on the scale of days to weeks. Consequently, the orientation of the shoreline on a 1000 km scale is the best match for wind stress. However, the low frequency flow, on the order of months or longer, does not appear to be wind-driven, but due to the cross-shelf density gradient associated with the seasonal cycle in surface heating and cooling.

Timeline plots for hourly current speed at 4.5, 15, 55, and 65 m water depths are presented in Figure 2.3.1. For these depths, the current speeds generally peak during early September, late October, late November, and mid-December. Figure 2.3.2 presents histograms of current speed at 4.5, 15, 55, and 65 m water depths. Figure 2.3.3 provides cumulative distribution of current speed at 4.5, 15, 55 and 65 m water depths. The current statistics for various water depths are presented in Table 2.3.1. Currents are stronger at the 4.5 meter depth than at deeper locations. The maximum speed at the 4.5 m depth is 87.8 cm/s with a mean speed of 24.3 cm/s and standard deviation of 14.2 cm/s.

2.4 WINDS

Weather in the vicinity of Nantucket is subject to rapid change and a range of climatic conditions. The prevailing winds are from the west. However, winds are variable and can come from any direction. North and northwesterly winds bring cold and dry air from Canada. Westerly winds bring Canadian air that has been warmed while transiting over the Great Lakes. Southwesterly winds are variable in character, depending on the origin of the air mass and the atmospheric conditions encountered on their trajectory. Canadian air, which has been forced south by a mid-Atlantic state high-pressure area, is generally cool and dry, but can be hot and dry in summer. Southwesterly winds also form following the passage of a warm front transporting warm humid air from the Gulf of Mexico and the Caribbean. South and southeasterly winds are warm-to-hot and humid, and occur infrequently, except along the south shore of New England. East and northeasterly winds are cool and humid after passing over the Labrador Current and north Atlantic Ocean. In addition, there are extreme climatic events that should be mentioned. Blizzards, ice storms, hurricanes, rainstorms, and tornadoes have impacted the climate of the area to various degrees and frequencies of occurrence.

To measure average wind speed and direction, NOAA/NDBC utilized a true vector average. The vectors are separated into U and V components. U is the wind speed observation, and the V vector is used for orientation. The wind is measured in degrees from true North. The U and V vectors are then averaged separately. Average wind speed and direction are calculated by the Pythagorean theorem and arctan (u/v), respectively (Gilhousen, 1987). The anemometer was located 27 m above water level or ground level. In this study, wind speed is an hourly average collected for 8 minutes per hour. Wind gust is a 5 to 8 second gust speed measured during the 8-minute sampling period and reported hourly.

Histograms of wind speed and wind direction for the winter, spring, summer, and autumn seasons are presented in Figures 2.4.1 and 2.4.2. Average wind speeds during winter and autumn are about 7 to 8 m/s, while in spring and summer the average is closer to 4 to 5 m/s. Wind direction is highly variable, with higher occurrences (about 7% of the time) to the south in summer and spring and to the northwest in winter and autumn. Cumulative percentages of wind speed for the four seasons are presented in Figure 2.4.3. Wind speed is highest in autumn and winter, with wind speeds of 12 to 13 m/s about 90% of the time, compared to summer and spring during which wind speeds of 8 to 9 m/s occur about 90% of the time. Histograms of wind speed and cumulative percentage of wind speed for all data are presented in Figure 2.4.4. Figure 2.4.5 presents the cumulative percentage of wind gust for the four seasons. Figures 2.4.6 and 2.4.7 present the maximum monthly wind speed and maximum monthly wind gust, respectively, from data collected between November 1982 and October 2004. Maximum wind speeds were about 27 m/s, while wind gusts occurred up to 36 m/s.

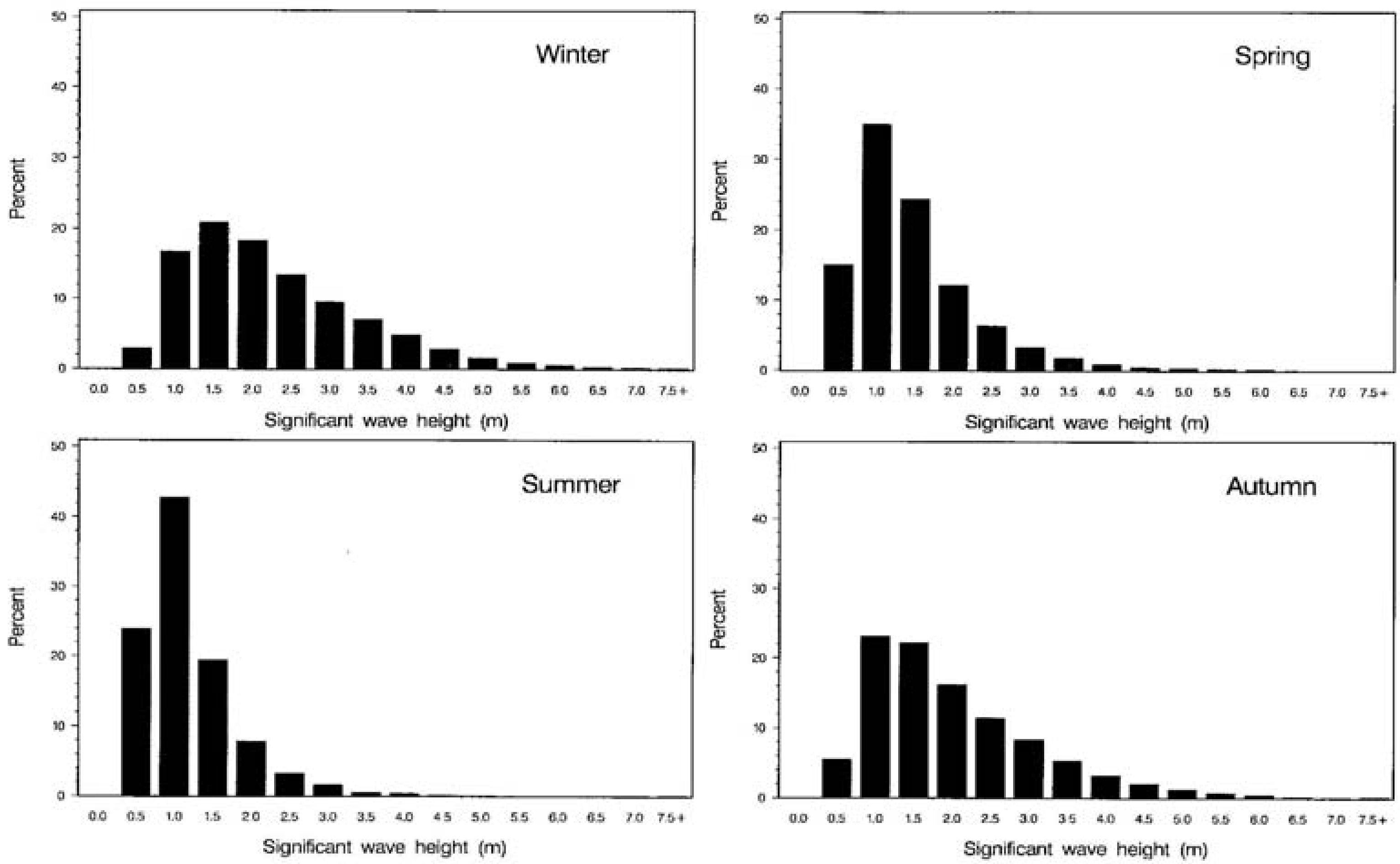


Figure 2.1.1. Histogram of significant wave height for winter, spring, summer, and autumn seasons, from data collected at NOAA Buoy 44008.

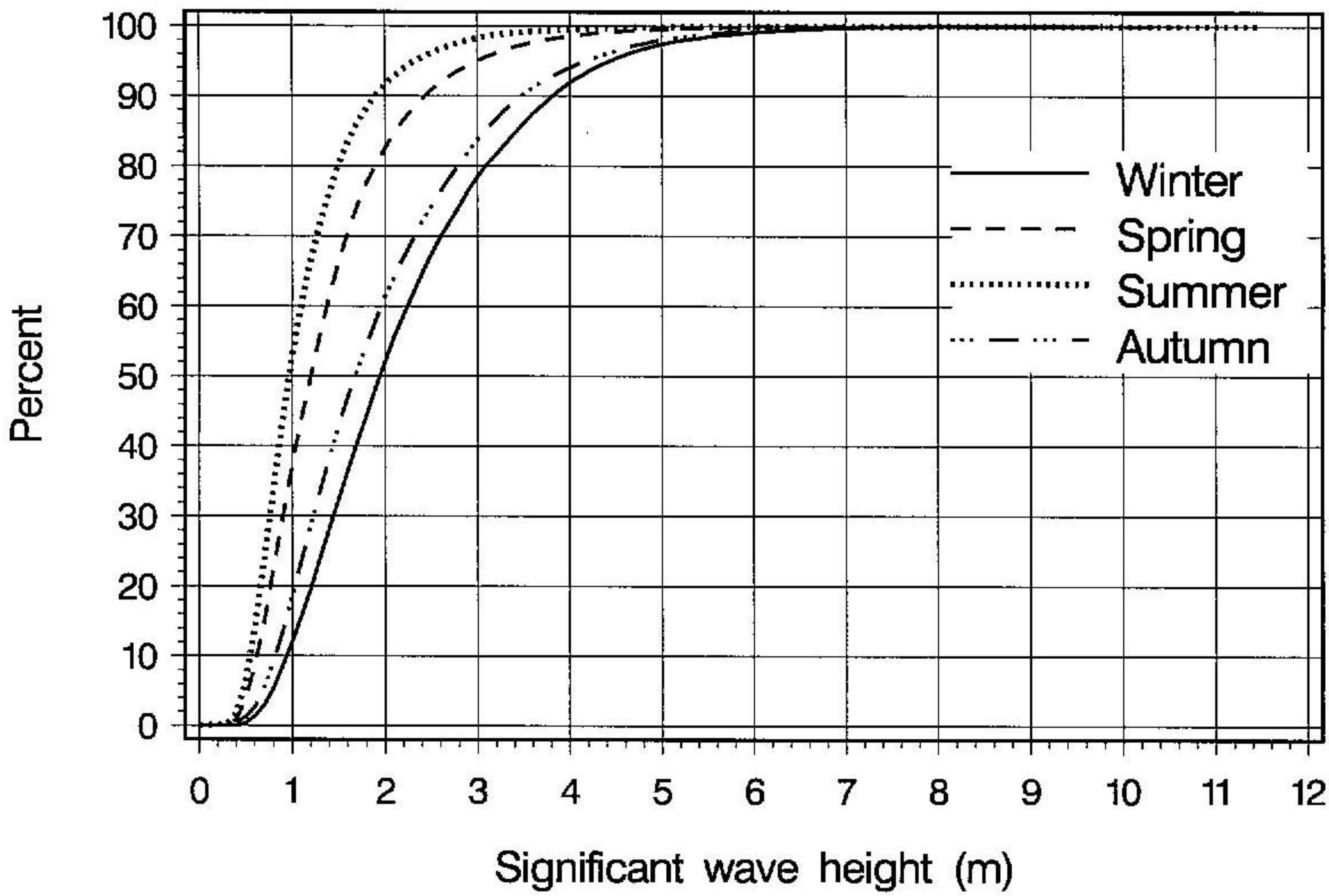


Figure 2.1.2. Cumulative percentage of significant wave height for winter, spring, summer, and autumn seasons.

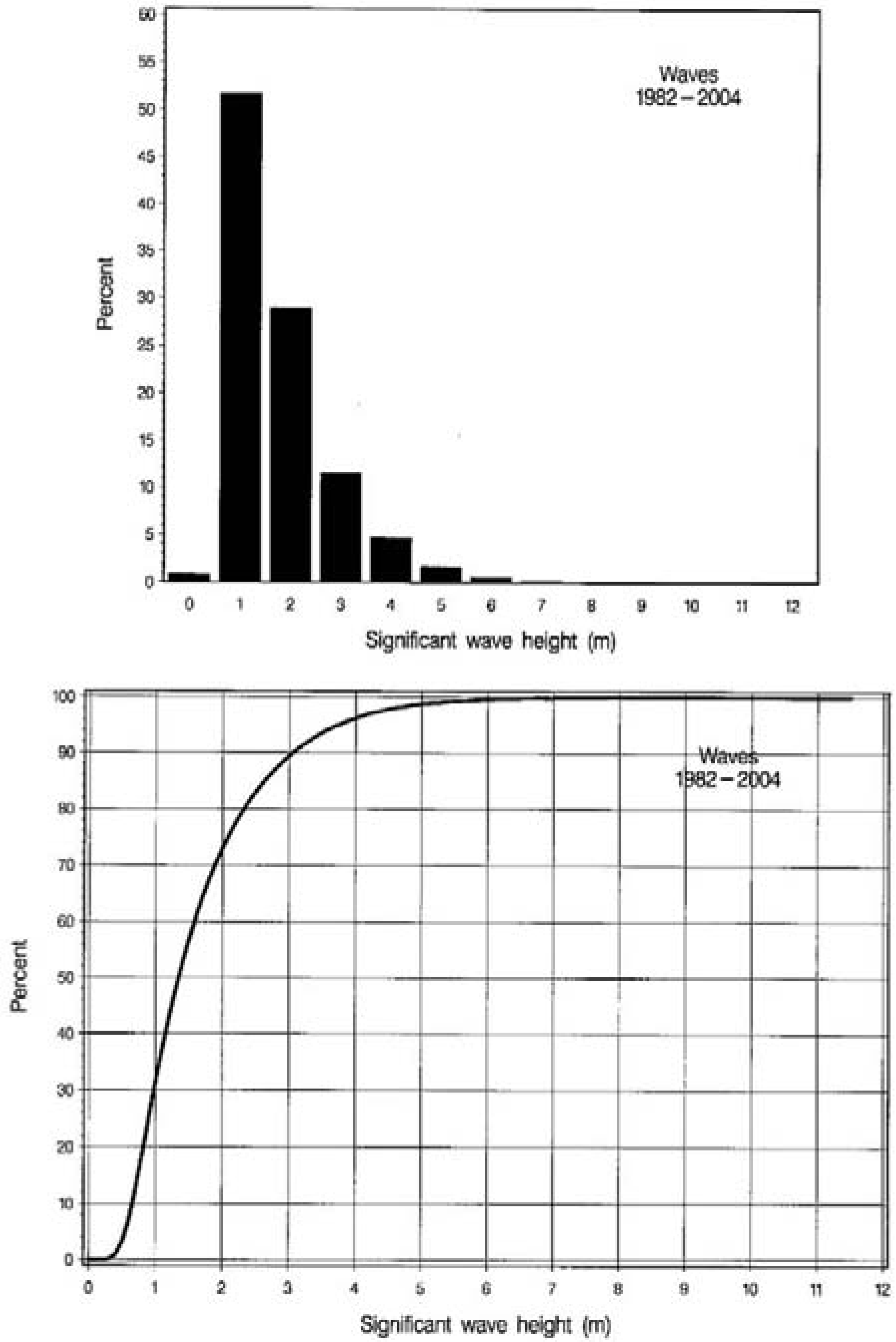


Figure 2.1.3. Histogram of significant wave height, all data (top), and cumulative percentage of significant wave height, all data (bottom).

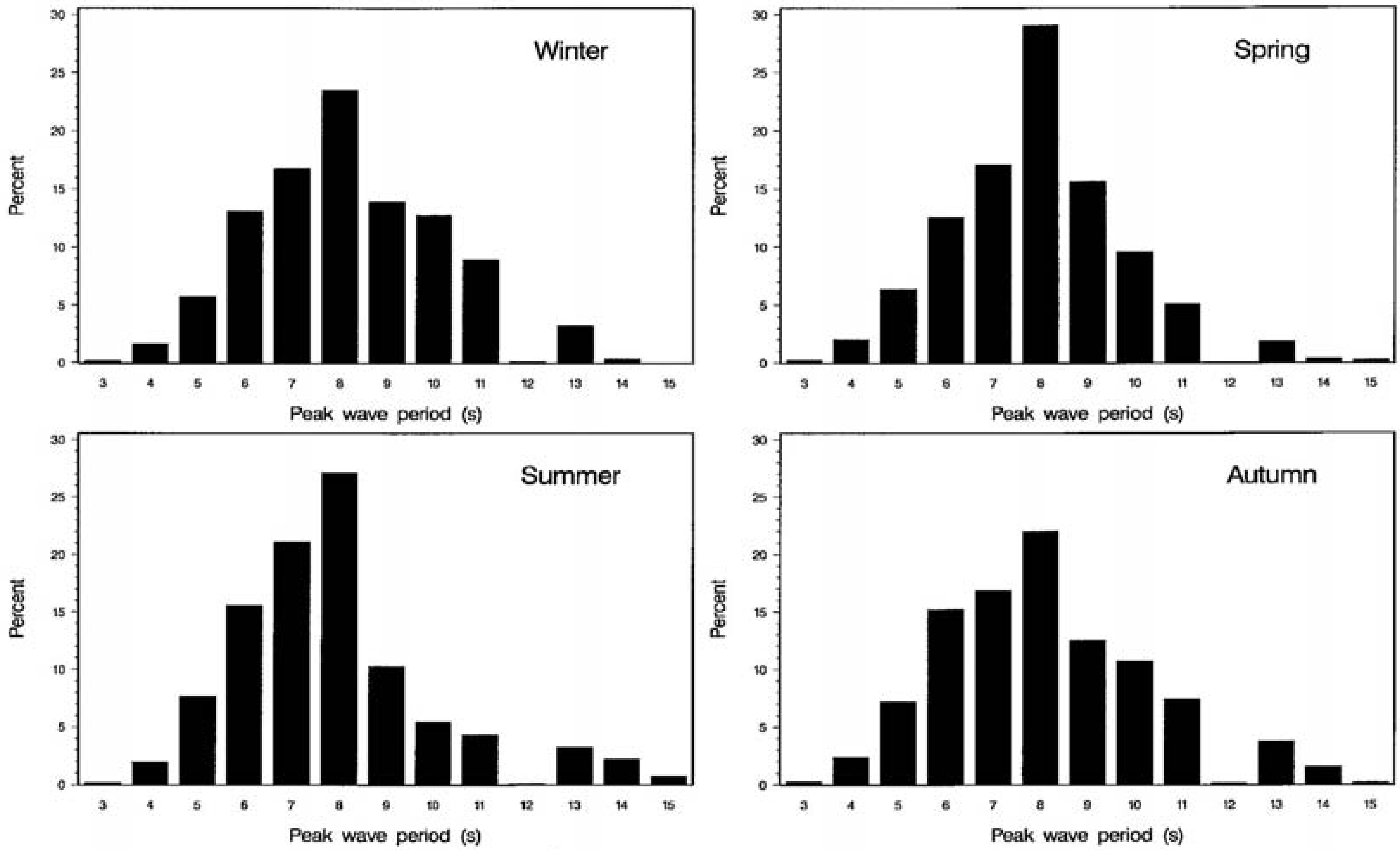


Figure 2.1.4. Histogram of peak wave period for winter, spring, summer, and autumn seasons, from data collected at NOAA Buoy 44008.

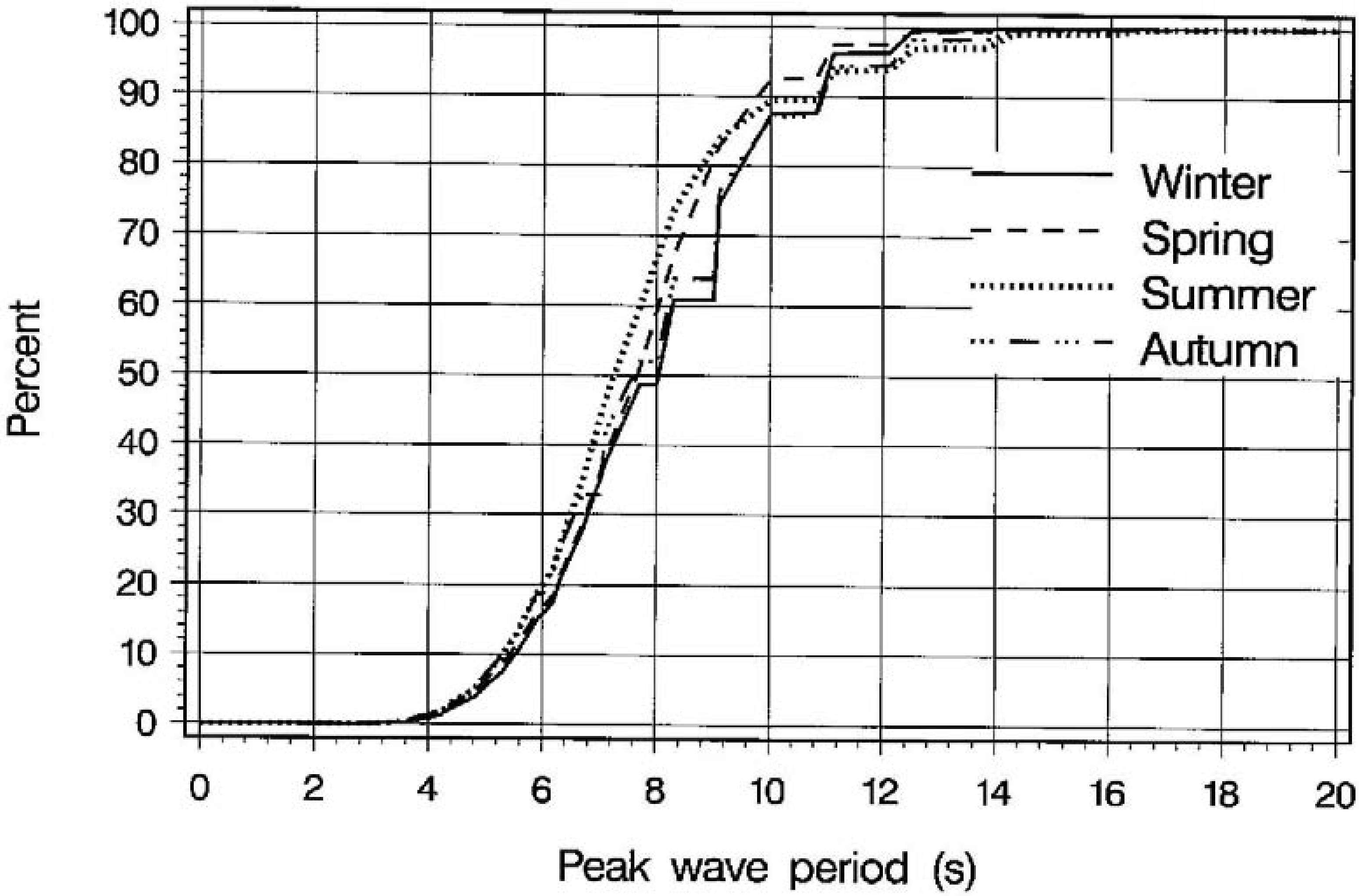


Figure 2.1.5. Cumulative percentage of peak wave period for winter, spring, summer, and autumn seasons.

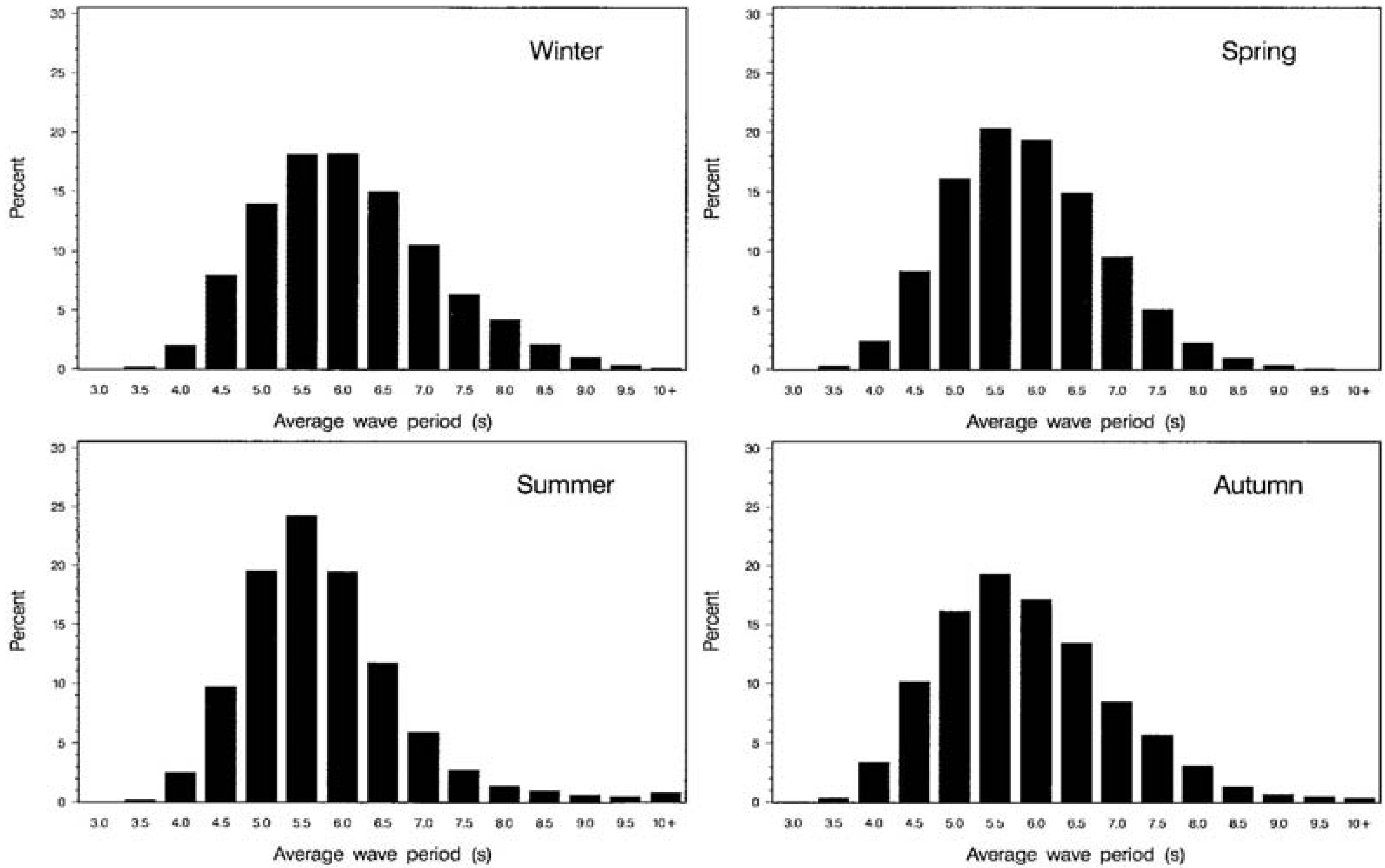


Figure 2.1.6. Histogram of average wave period for winter, spring, summer, and autumn seasons, from data collected at NOAA Buoy 44008.

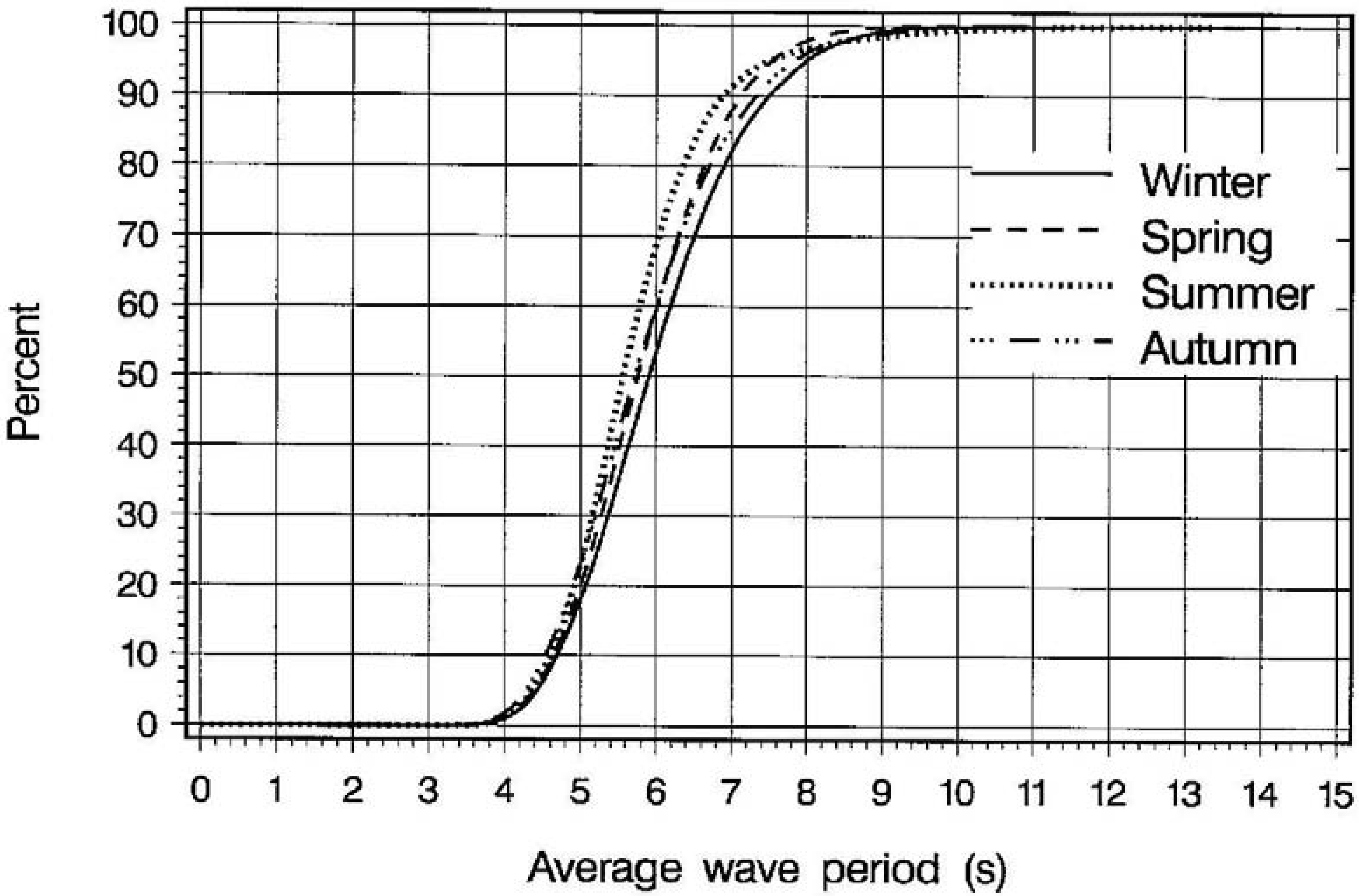


Figure 2.1.7. Cumulative percentage of average wave period for winter, spring, summer, and autumn seasons.

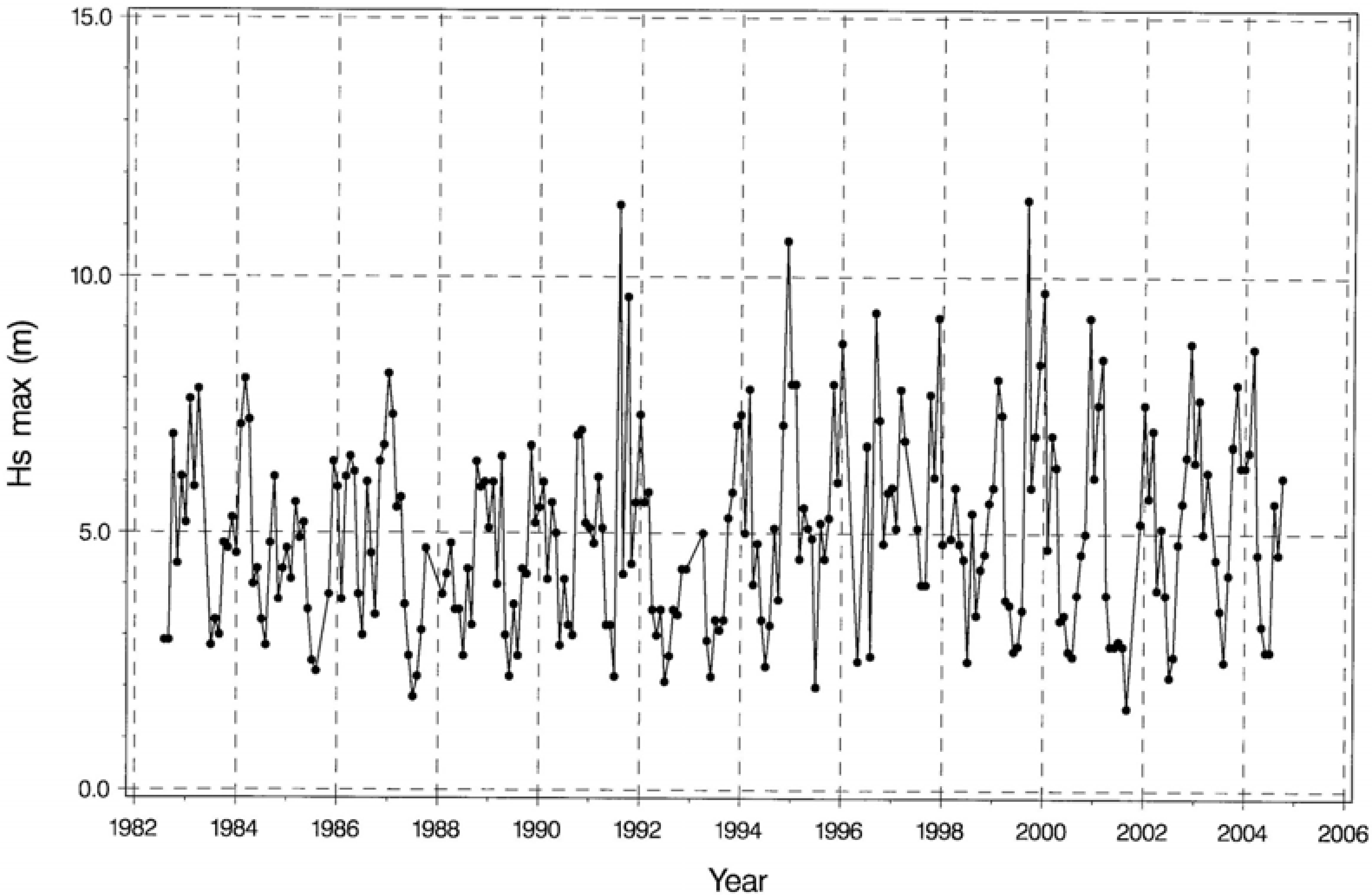


Figure 2.1.8. Maximum monthly significant wave height (Hs) from data collected at NOAA Buoy 44008 between November 1982 and October 2004.

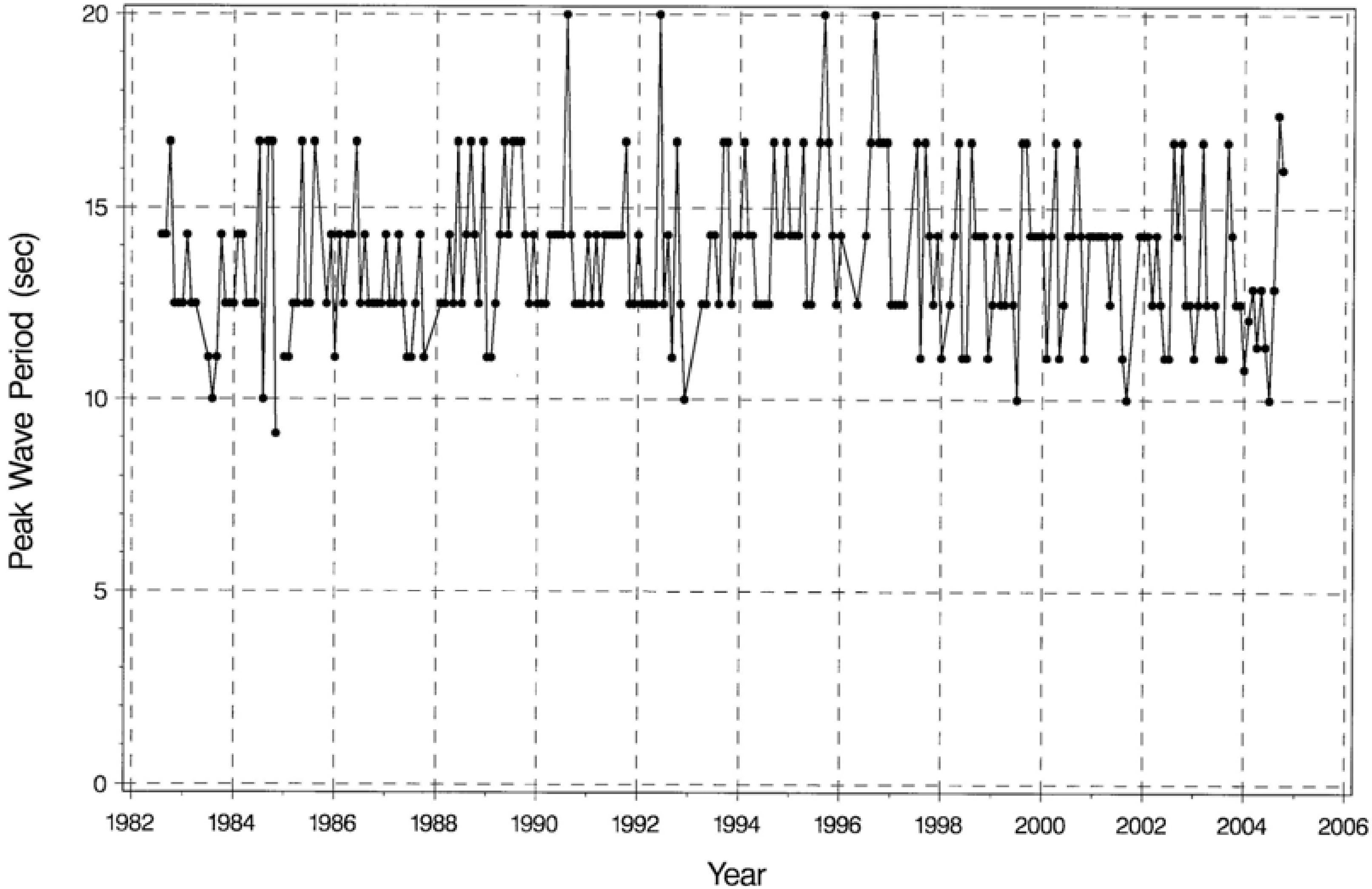


Figure 2.1.9. Maximum monthly peak wave period (T_p) from data collected at NOAA Buoy 44008 between November 1982 and October 2004.

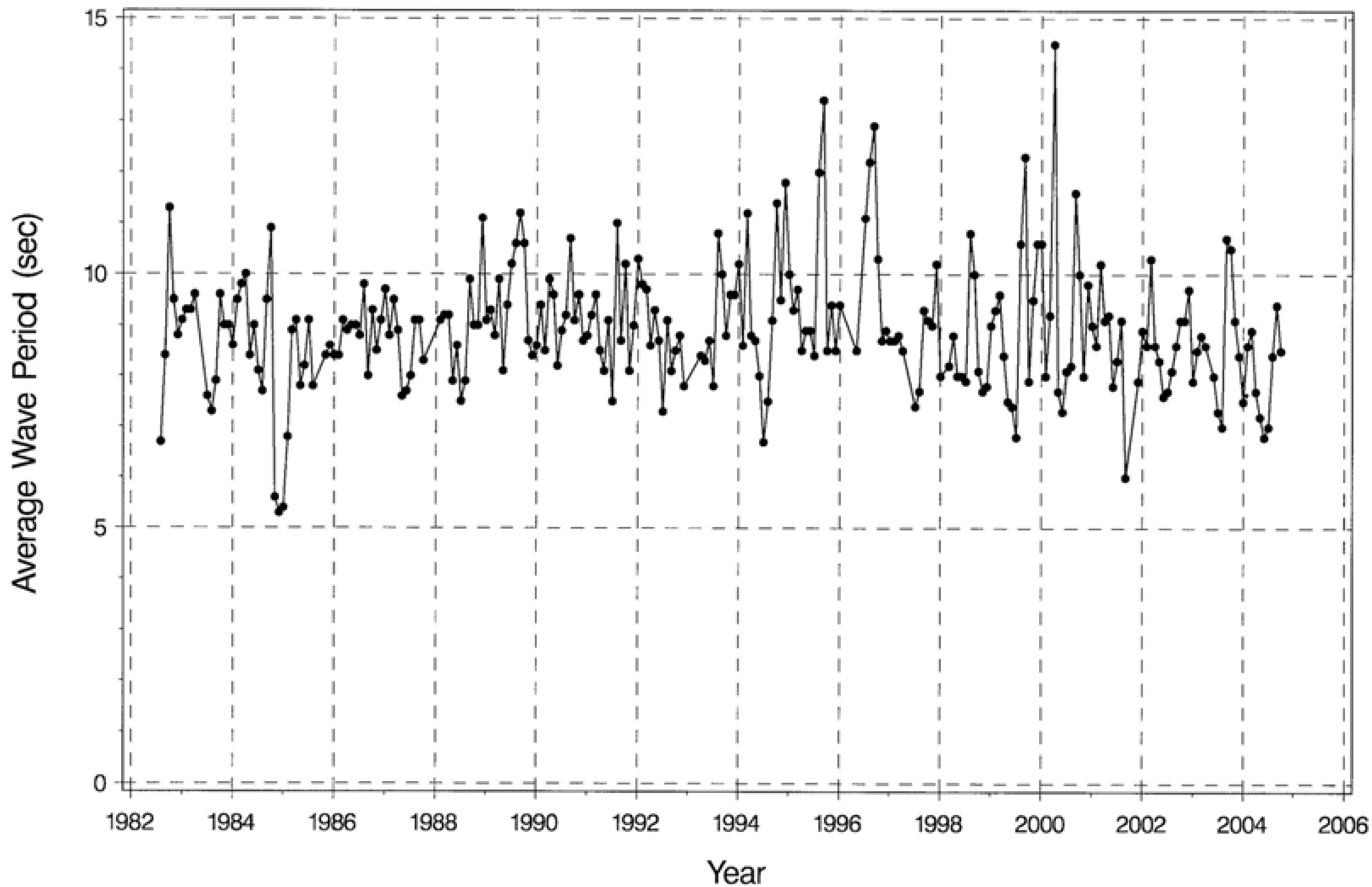


Figure 2.1.10. **Maximum monthly average wave period (T_a) from data collected at NOAA Buoy 44008 between November 1982 and October 2004.**

Table 2.1.1. Statistics for significant wave height (H_s), peak wave period (T_p), and average wave period (T_a) by year.

Year	Maximum			Mean		
	H_s	T_p	T_a	H_s	T_p	T_a
1982	6.90	16.7	11.3	1.69	7.8	5.7
1983	7.80	14.3	9.6	1.83	8.1	5.9
1984	8.00	16.7	10.9	1.75	7.9	5.6
1985	6.40	16.7	9.1	1.61	7.4	5.6
1986	6.70	16.7	9.8	1.63	8.1	5.9
1987	8.10	14.3	9.7	1.58	8.1	5.9
1988	6.40	16.7	11.1	1.57	7.9	6.0
1989	6.70	16.7	11.2	1.66	8.2	6.2
1990	7.00	20.0	10.7	1.64	8.2	6.1
1991	11.40	16.7	11.0	1.58	8.0	6.0
1992	7.30	20.0	10.3	1.53	8.1	6.2
1993	7.10	16.7	10.8	1.47	7.9	6.1
1994	10.70	16.7	11.8	1.71	7.8	5.9
1995	7.90	20.0	13.4	1.87	8.4	6.0
1996	9.30	20.0	12.9	1.80	8.6	6.1
1997	9.20	16.7	10.2	1.90	8.0	5.9
1998	5.90	16.7	10.8	1.51	7.8	5.7
1999	11.50	16.7	12.3	1.79	8.0	5.8
2000	9.70	16.7	14.5	1.80	8.0	5.8
2001	8.40	14.3	10.2	1.67	7.8	5.8
2002	8.70	16.7	10.3	1.79	7.9	5.7
2003	7.90	16.7	10.7	1.79	8.1	5.8
2004	8.60	17.4	9.4	1.69	7.8	5.4

Table 2.1.2. **Statistics for significant wave height (H_s), peak wave period (T_p), and average wave period (T_a) by month.**

Month	Maximum			Mean		
	H_s	T_p	T_a	H_s	T_p	T_a
1	9.70	14.3	10.6	2.35	8.0	6.0
2	8.00	16.7	9.8	2.24	8.2	6.1
3	8.60	16.7	11.2	2.16	8.3	6.1
4	7.80	16.7	14.5	1.79	8.3	6.1
5	6.20	16.7	9.6	1.39	7.9	5.9
6	4.90	20.0	9.4	1.15	7.7	5.7
7	6.70	16.7	11.1	1.05	7.4	5.6
8	11.40	20.0	12.2	1.12	7.8	5.7
9	11.50	20.0	13.4	1.39	8.4	6.0
10	9.60	16.7	11.4	1.75	8.3	5.9
11	7.90	16.7	9.6	2.07	7.7	5.8
12	10.70	16.7	11.8	2.25	8.1	5.9

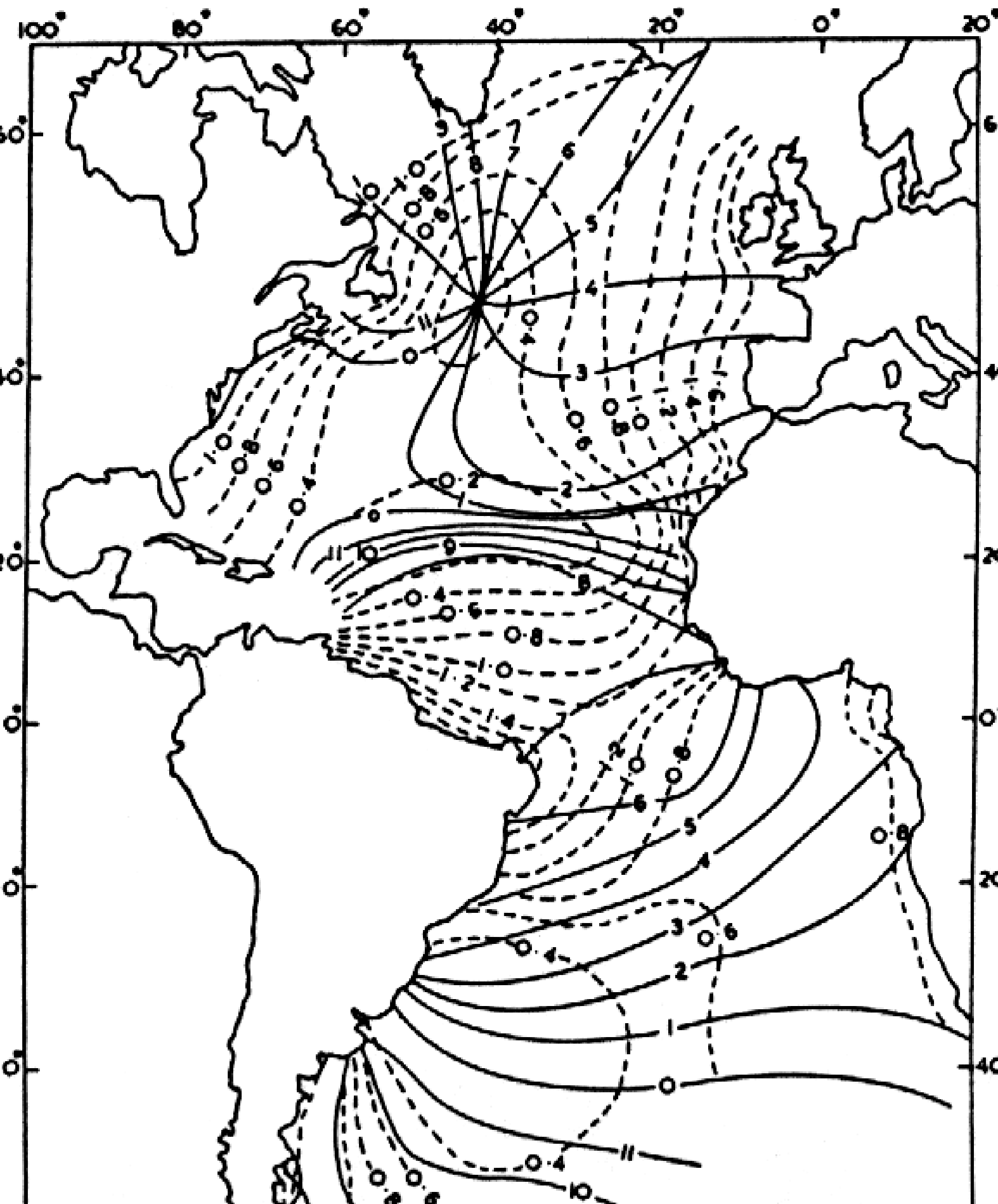


Figure 2.2.1. Tidal chart of Atlantic Ocean for dominant tidal component (M_2). Solid lines represent co-tidal curves, indicating locations of simultaneous occurrence of high (or low) tide in hours relative to other lines. Dashed lines represent co-range curves, showing approximate tide range in meters.

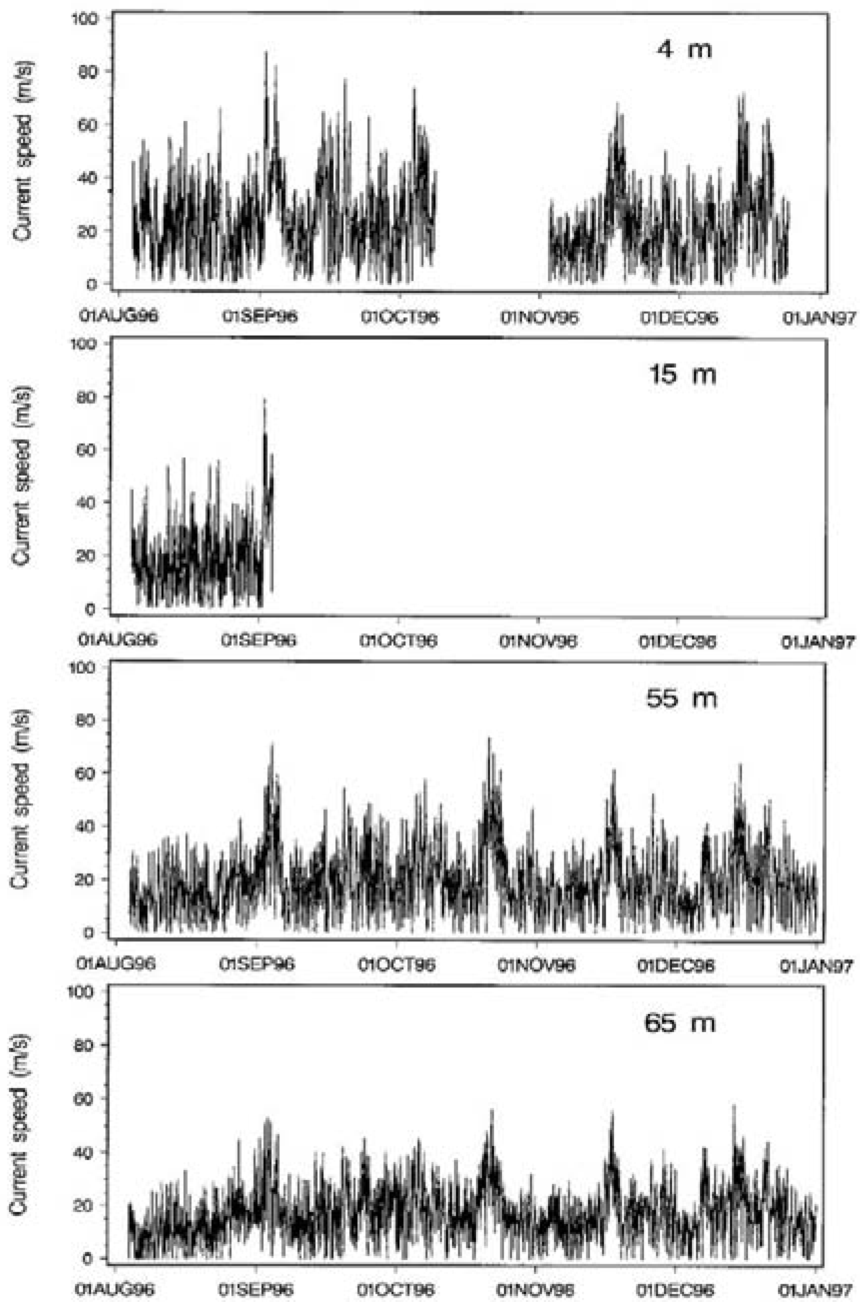


Figure 2.3.1. Timeline plots for hourly current speed at 4.5, 15, 55, and 65 m water depths.

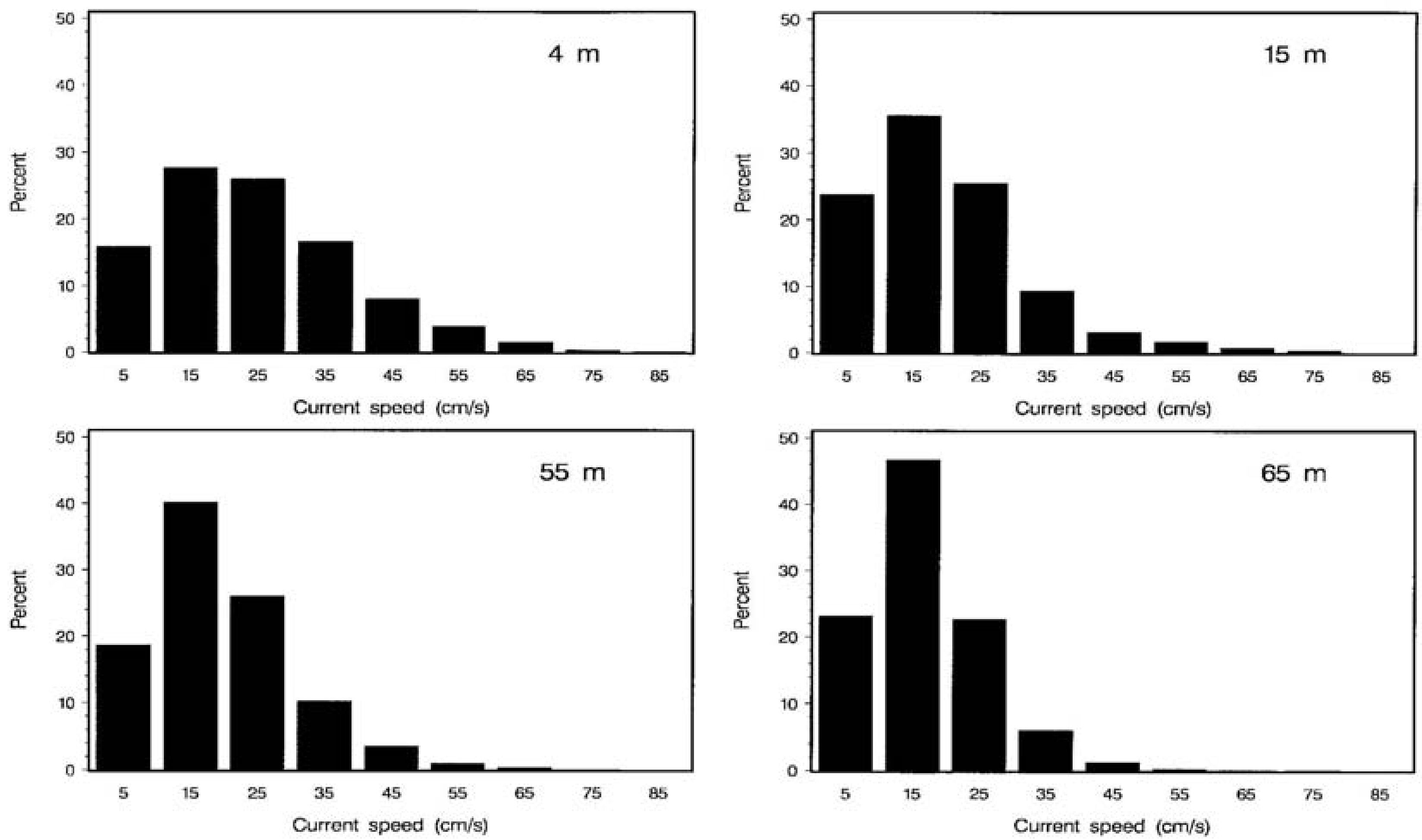


Figure 2.3.2. Histograms of current speed at 4.5, 15, 55, and 65 m water depths.

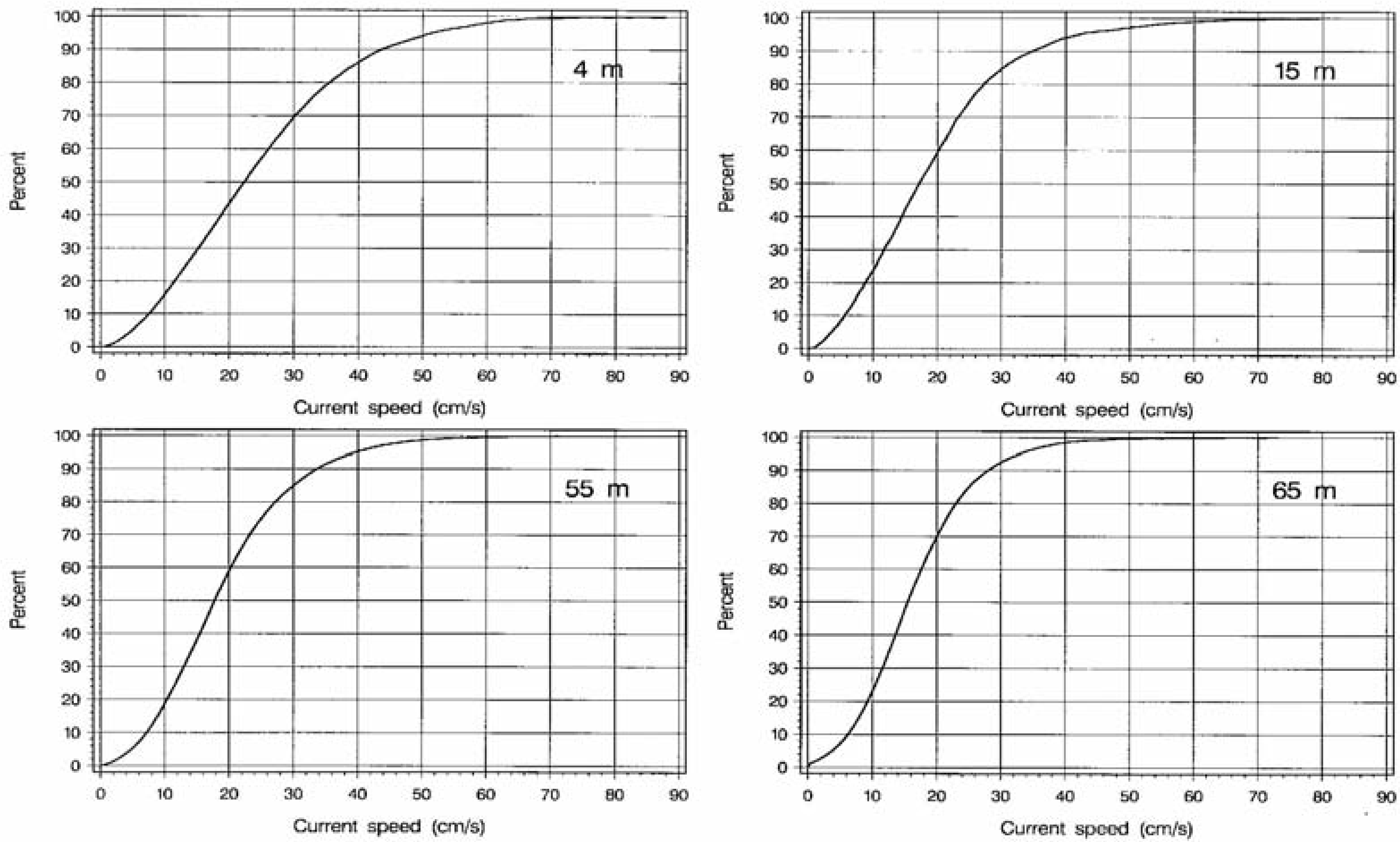


Figure 2.3.3. Cumulative distribution of current speed at 4.5, 15, 55, and 65 m water depths.

Table 2.3.1. Current statistics southeast of Nantucket for various water depths.

Depth (m)	Vn (positive)			Vn (negative)			Ve (positive)			Ve (negative)			Speed			
	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std	Max.	N
4.55	11.17	8.96	10337	-13.15	10.08	12329	10.81	9.74	5599	-20.98	14.85	17067	24.29	14.23	87.75	22666
15	11.19	8.60	3278	-9.08	6.71	2695	6.81	5.86	1544	-16.47	13.01	4429	19.13	12.18	79.47	5973
55	10.77	7.28	33690	-9.65	7.35	25910	10.16	8.03	20738	-16.53	12.11	38882	19.39	10.74	75.43	59620
65	8.25	5.67	31441	-8.50	6.34	28179	9.81	7.48	22424	-14.16	10.12	37196	16.53	8.88	73.05	59620

Vn = Current in north direction +
Ve = Current in east direction +
Speed = Current speed

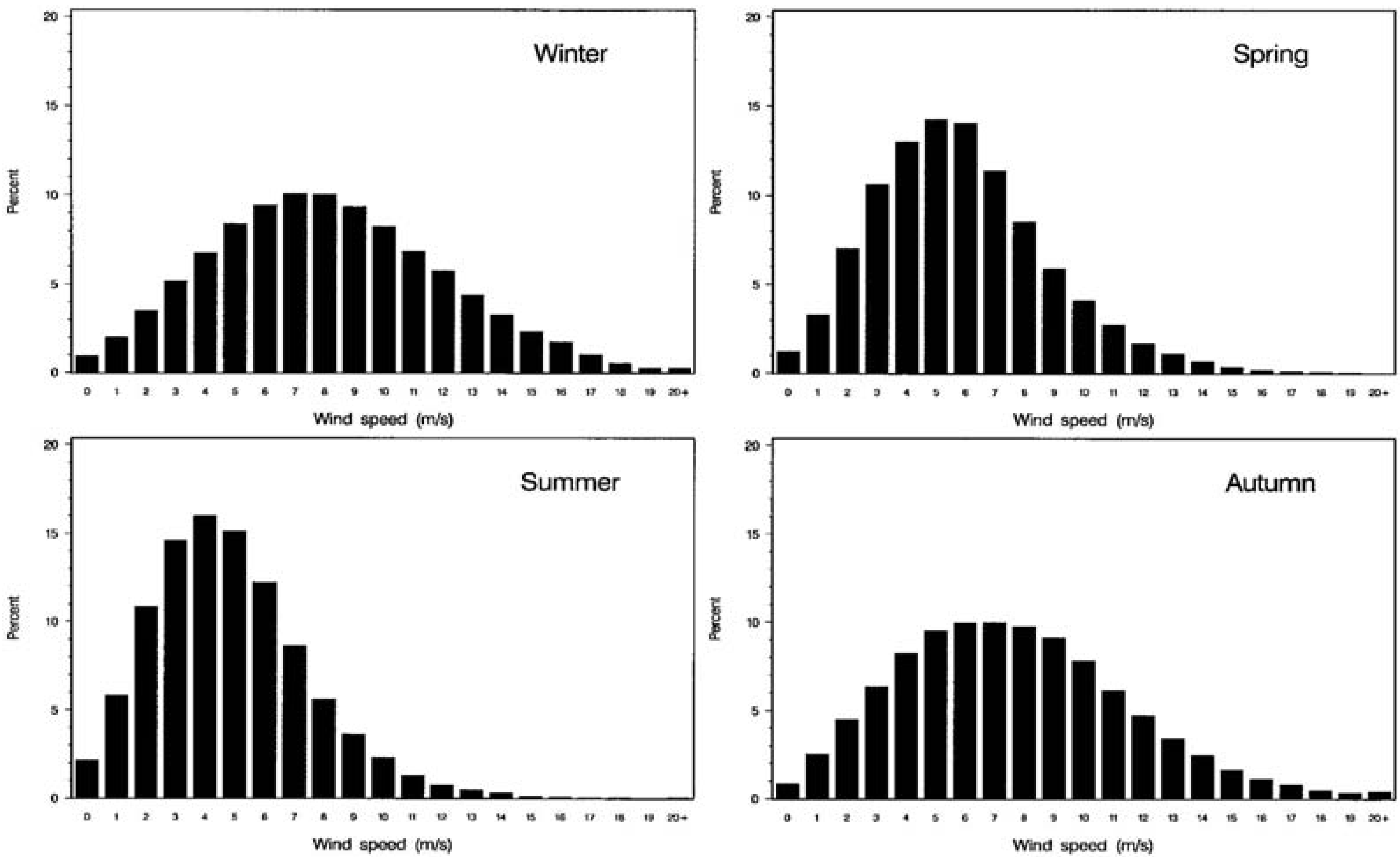


Figure 2.4.1. Histogram of wind speed for winter, spring, summer, and autumn seasons, from data collected at NOAA Buoy 44008.

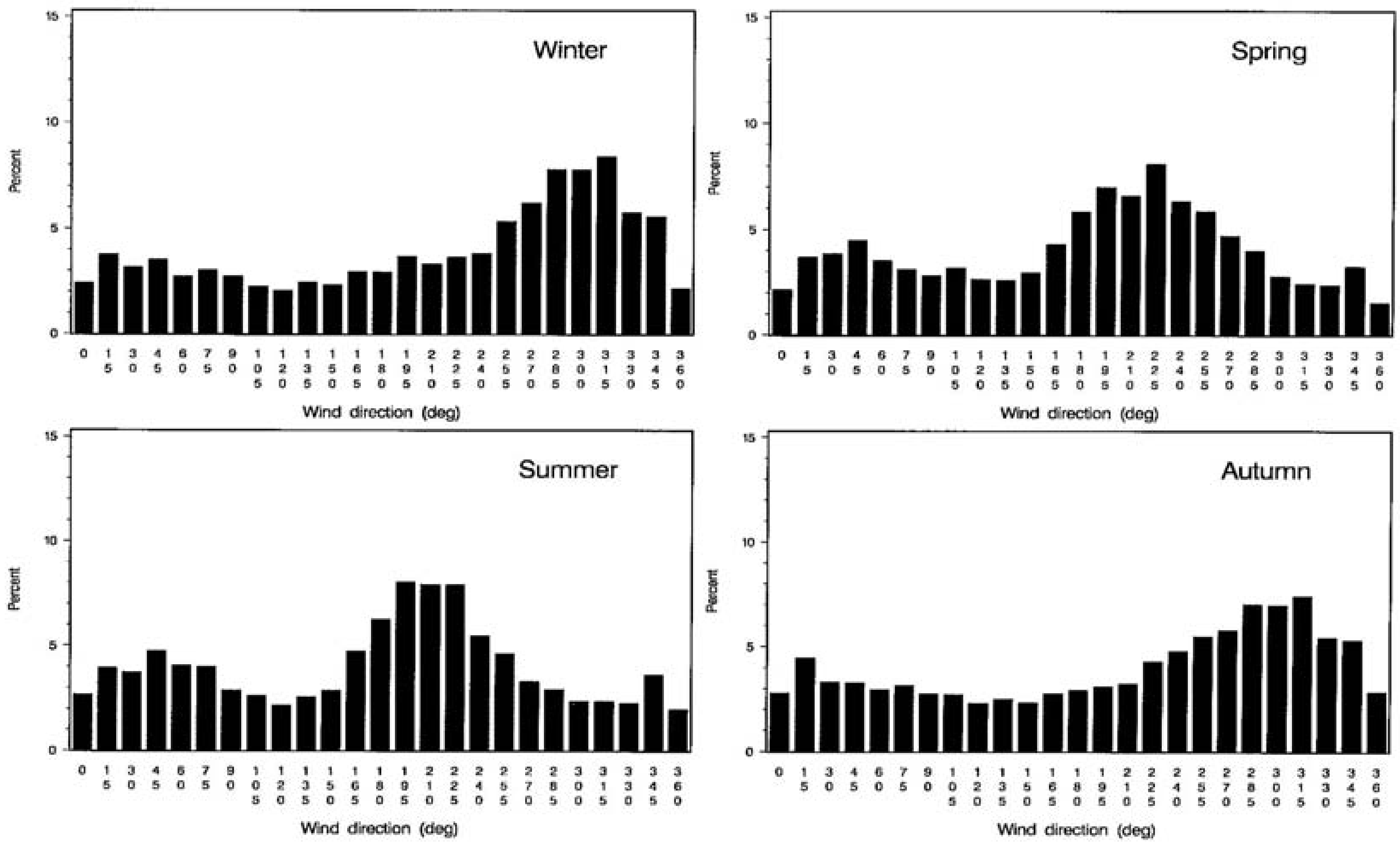


Figure 2.4.2. Histogram of wind direction for winter, spring, summer, and autumn seasons, from data collected at NOAA Buoy 44008.

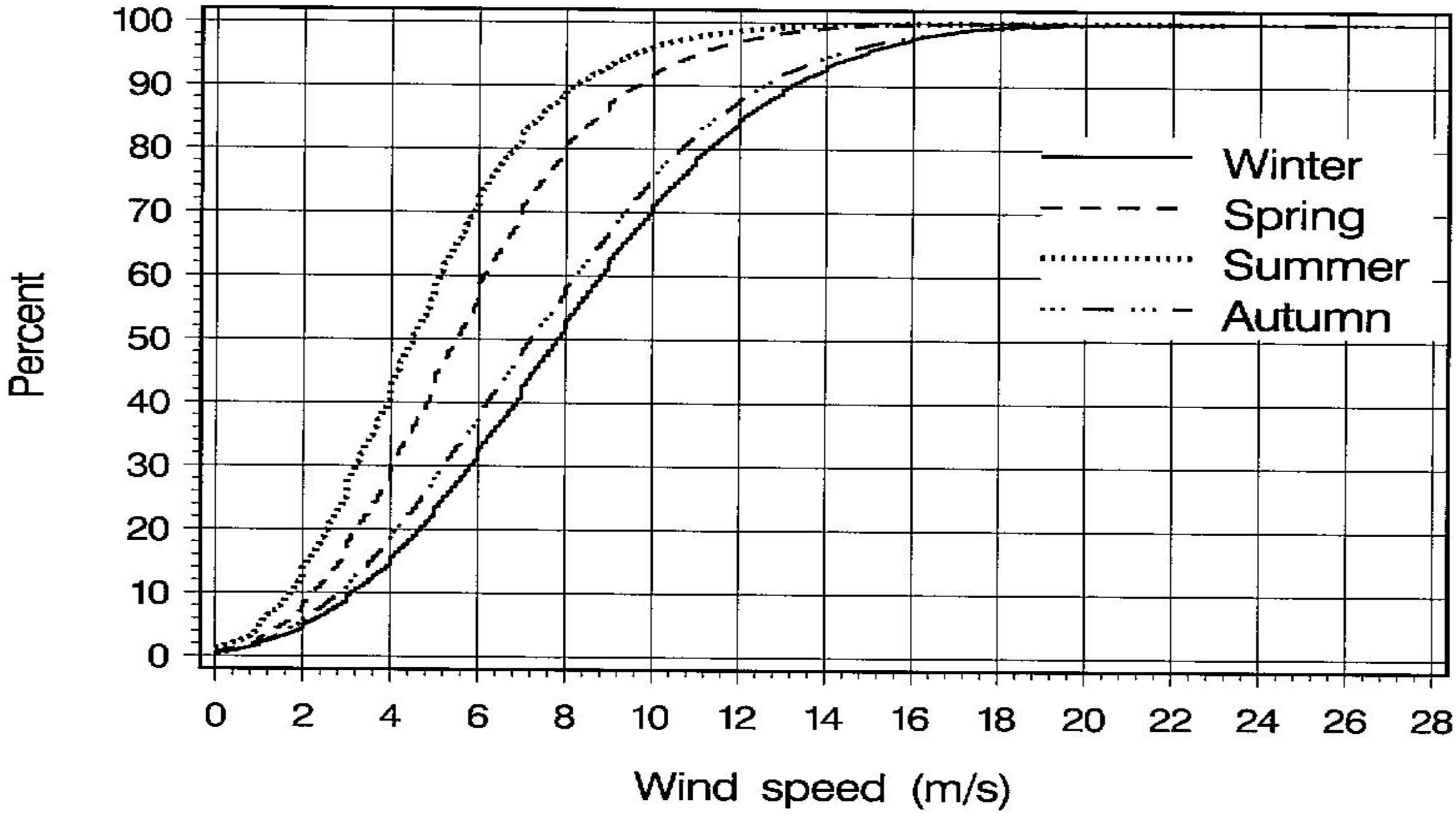


Figure 2.4.3. Cumulative percentage of wind speed for winter, spring, summer, and autumn seasons.

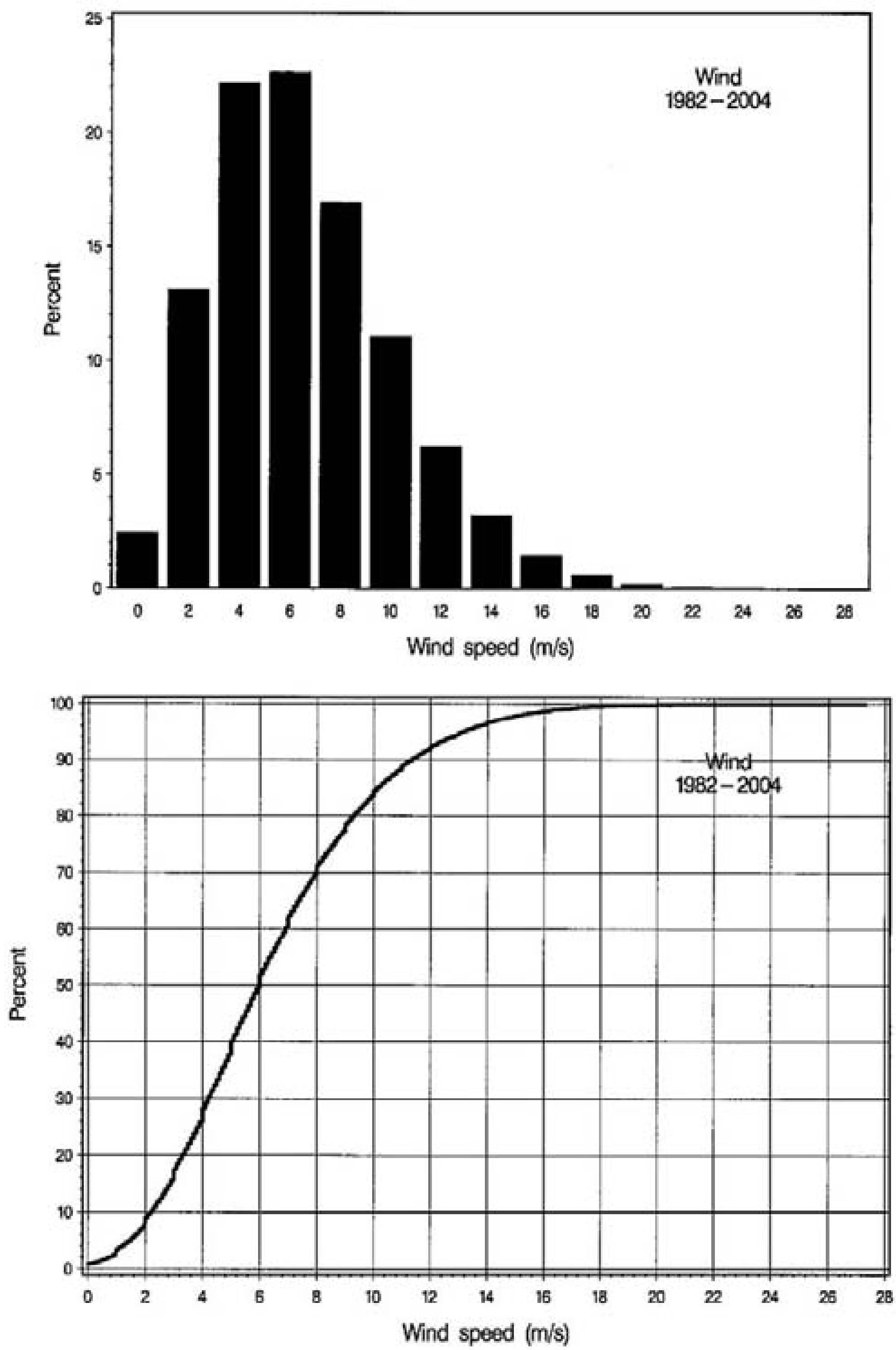


Figure 2.4.4. Histogram of wind speed, all data (top), and cumulative percentage of wind speed, all data (bottom).

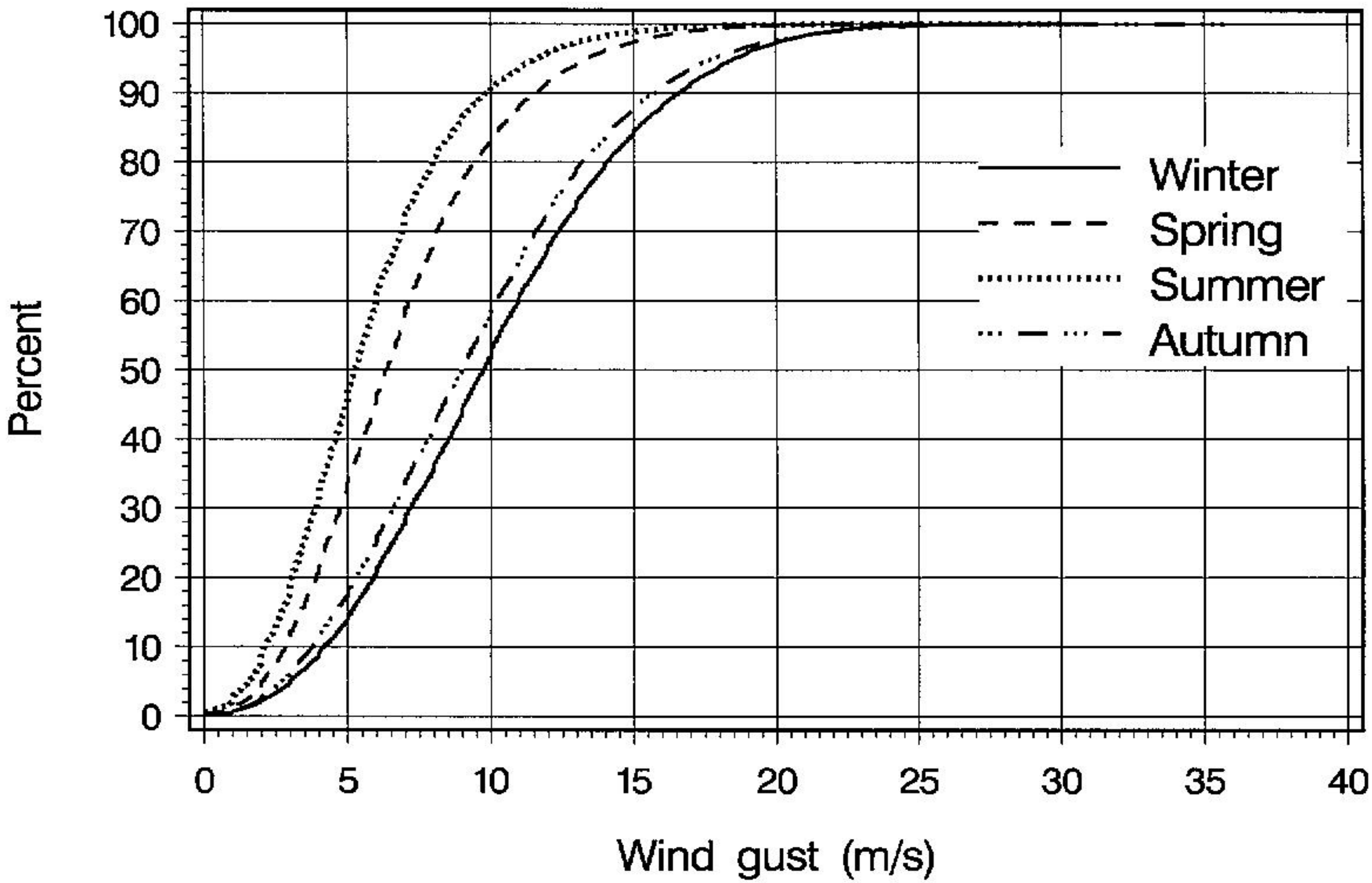


Figure 2.4.5. Cumulative percentage of wind gust for winter, spring, summer, and autumn seasons.

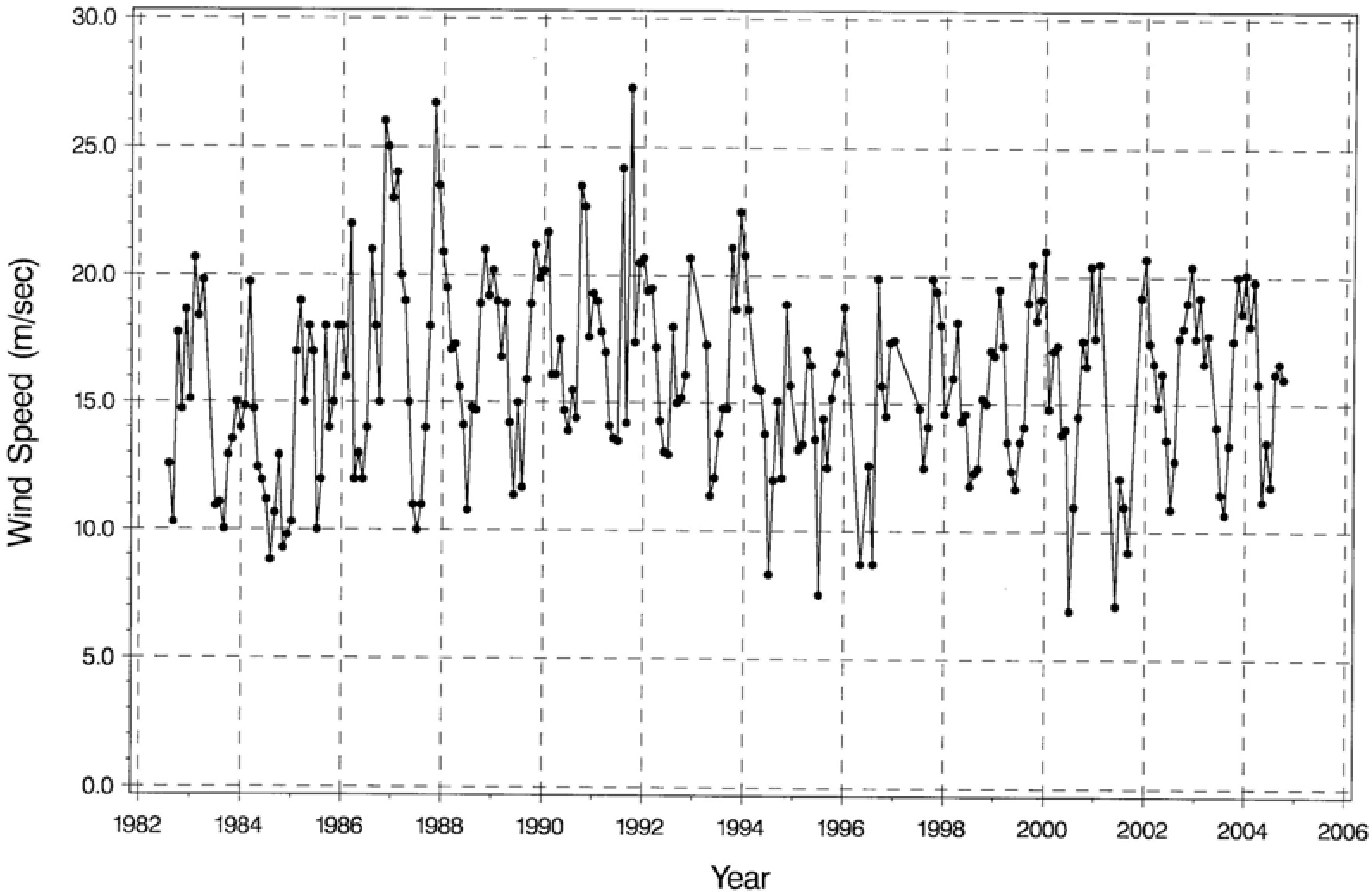


Figure 2.4.6. Maximum monthly wind speed from data collected at NOAA Buoy 44008 between November 1982 and October 2004.

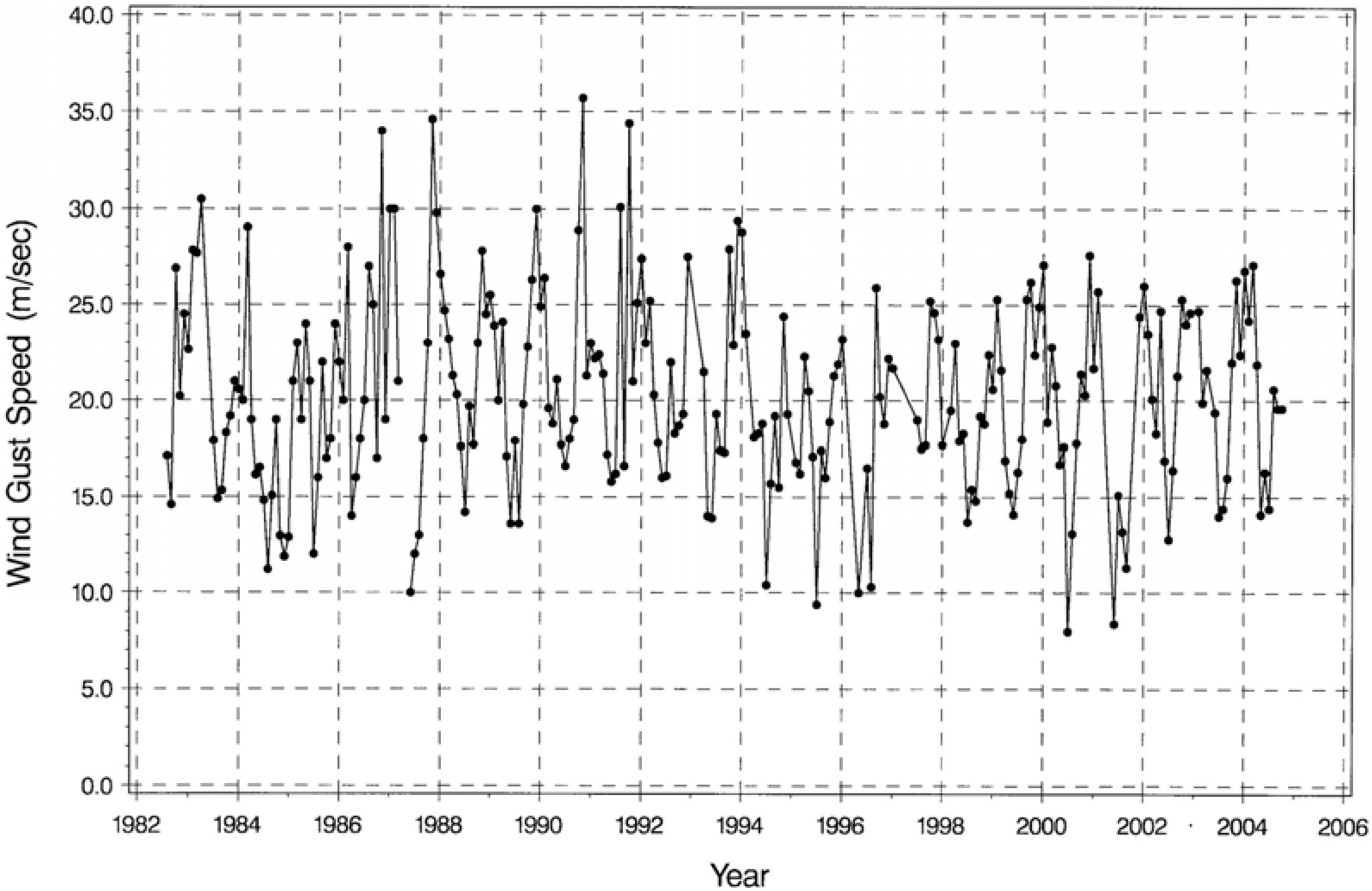


Figure 2.4.7. Maximum monthly wind gust speed from data collected at NOAA Buoy 44008 between November 1982 and October 2004.

Appendix C: Estimation of Design Parameters

C.1 Seasonal Maxima Distribution Model

The "Seasonal Maxima Distribution Model" (SMDM) developed by the USACOE (1988) was used to compute the distribution of the design parameters for waves and winds for various return periods. In arriving at an estimate of the distribution function for annual maxima, precision can be gained by dividing the year into four seasons: winter (January−March), spring (April−June), summer (July−September), and autumn (October−December). Within each season, the characteristics of waves or winds are reasonably similar. The four seasonal distribution functions were estimated individually, and then multiplied together to produce the annual maximum distribution.

$$F_a\,(y) = F_w\,(y\,)F_{sp}\,(y)\,F_s\,(y)\,F_a(y) \qquad \text{(C-1)}$$

This relation follows from the fact that any distribution function $F(y)$ is by definition the probability that some random variable Y is less than or equal to the argument y:

$$F(y) = Prob\,\{Y \le y\}$$

For Y to be an annual maximum, the maxima in all four seasons must be no greater than its value, and assuming the seasonal wave heights independent of one another,

$$Prob\,\{Y_a \le y\} = Prob\,\{Y_w \le y\}\;Prob\,\{Ysp \le y\}\;Prob\,\{Ys \le y\}\;Prob\,\{Y_a \le y\}$$

which is identical to (A-1).

To obtain estimates of the seasonal maximum distribution functions, F_w, F_t, and F_s, the product relationship (3-1) was used again, where the factors on the right are the distribution functions of maximum waves in the months making up the season. Assuming these to be equal, the expression for the winter season is:

$$F_w\,(y) = [F_{wm}(y)]^3, \qquad \text{(C-2)}$$

where $F_{wm}\,(y)$ is the distribution function for a typical month in the winter season, which consists of six months. However, the monthly maxima are not altogether independent. For example, the maximum waves and winds from January through March could very well occur during the same storm. The exponent 3 is therefore replaced by 3*r*, where *r* is a number less than 1. The product 3*r* represents the number of equivalent, independent, monthly maxima that occurred during the winter season. It was determined as a least squares estimate from the observed data.

To do this, the winter monthly maxima were ranked from lowest to highest: Y_1, Y_2,.Y_n. The value of F_{wm} (Y_1) is approximated as $i/(n+1)$. Similarly, the winter seasonal maxima are ranked, and their distribution function approximated as $k/(n+1)$, k being the rank and N the number of different winter seasons represented in the data set.

To simplify the least squares procedure, logarithms were taken of both sides of (2) as modified by replacement of the exponent 3 with 3r:

$$log[F_w\,(y_k)] = r\{3\,log[F_{wm}\,(y_k)]\} \qquad \text{(C-3)}$$

The N values for y_k provide N points from which to estimate r. Equation (C-3) is of the form $Y_k = rX_k$, and the least squares estimate of r is:

$$r = \frac{\sum X_k Y_k}{\sum X_k^2} \quad \text{(C-4)}$$

A final step in the process was converting the approximate distribution function of monthly maxima to a smooth curve so that it could be used in equations C-3 and C-1. The least squares method was again used to estimate the slope. Extreme values of many one-sided random variables that arise from the measurements of natural phenomena are well represented by a double exponential:

$$F(y) = exp\{-exp\,[\,-(a+by)]\} \quad \text{(C-5)}$$

The straight line equivalent was obtained by taking negative logarithms of both sides twice:

$$-log\{-log[F(y)]\} = a+by \quad \text{(C-6)}$$

There are n values of y available, and the constants a and b were again calculated by least technique regression analysis of X_k on Y_k, where X_k and Y_k stand for observed values of y and $-log(-logF(y))$, respectively.

With values of a, b, and r determined for each of the four seasons, equations C-5 and C-1 allow the annual maximum distribution function to be plotted for arbitrary values of the wave height y. Recurrence intervals, RI, for a specific wave height were then determined using:

$$RI = \frac{1}{[1 - F(y)]} \quad \text{(C-7)}$$

C.2 Results

Figure C.2.1 presents the design wave heights for various return periods. For a 5-year return period at Buoy 44008, the design wave height is estimated at about 9.2 m. For a 100-year return period, the design wave height is estimated at 13.7 m. Figure C.1.2 presents the design wave heights for various return periods for winter, spring, summer, and autumn. The design wave heights for autumn and winter are higher than for spring and summer. For 25- to 100-yr return periods, the design wave heights for autumn, summer, and winter are similar; the design height for spring is about 2 m lower. The design average wave period for various return periods is shown in Figure C.2.3. The design average wave period fluctuates, from about 12.15 s for a 5-yr return period to about 16.15 s for a 100-yr return period. Design peak wave period for various return periods (Figure C.2.4) and design wind speeds for various return periods (Figure C.2.5) are also attached. Figure C.2.6 presents design wind gust speeds for various return periods. Table C.2.1 is a summary of design wave and wind parameters for various return periods. In Table C.2.1, the significant wave height for the 100-yr return period is 13.6 m, and the average and peak wave periods are 12−17 s and 18−25 s, respectively. Wind speed and wind gust are 23−32 m/s, and 32−44 m/s, respectively.

Table C.2.2 presents parameters for wind and waves from hourly data. This table gives the number of points used in the computation (N), mean and maximum (max) significant wave heights, mean and maximum (max) peak and average wave periods, and mean and maximum (max) wind gusts for various measured wind speeds

.

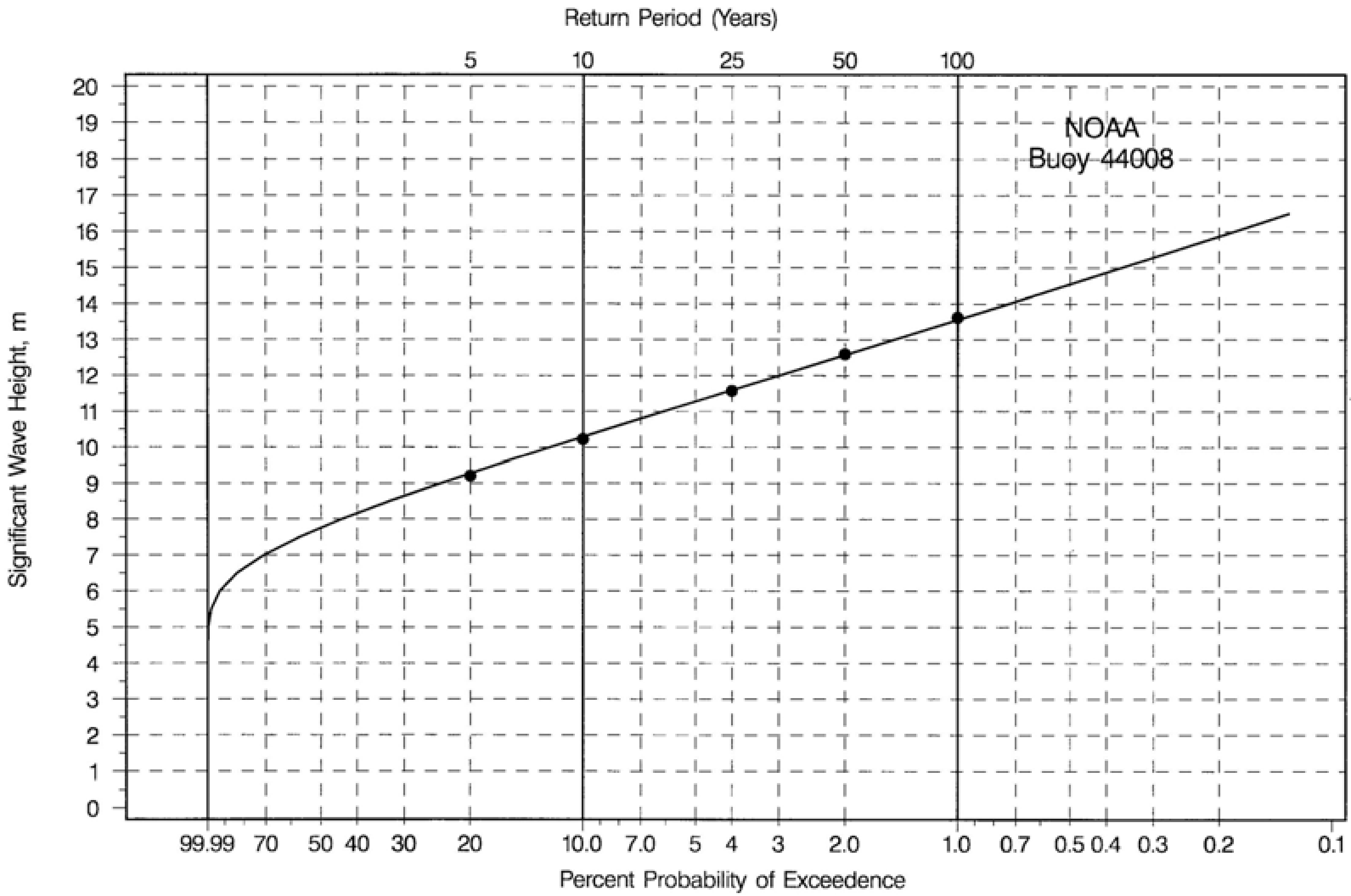


Figure C.2.1. Design wave height for various return periods

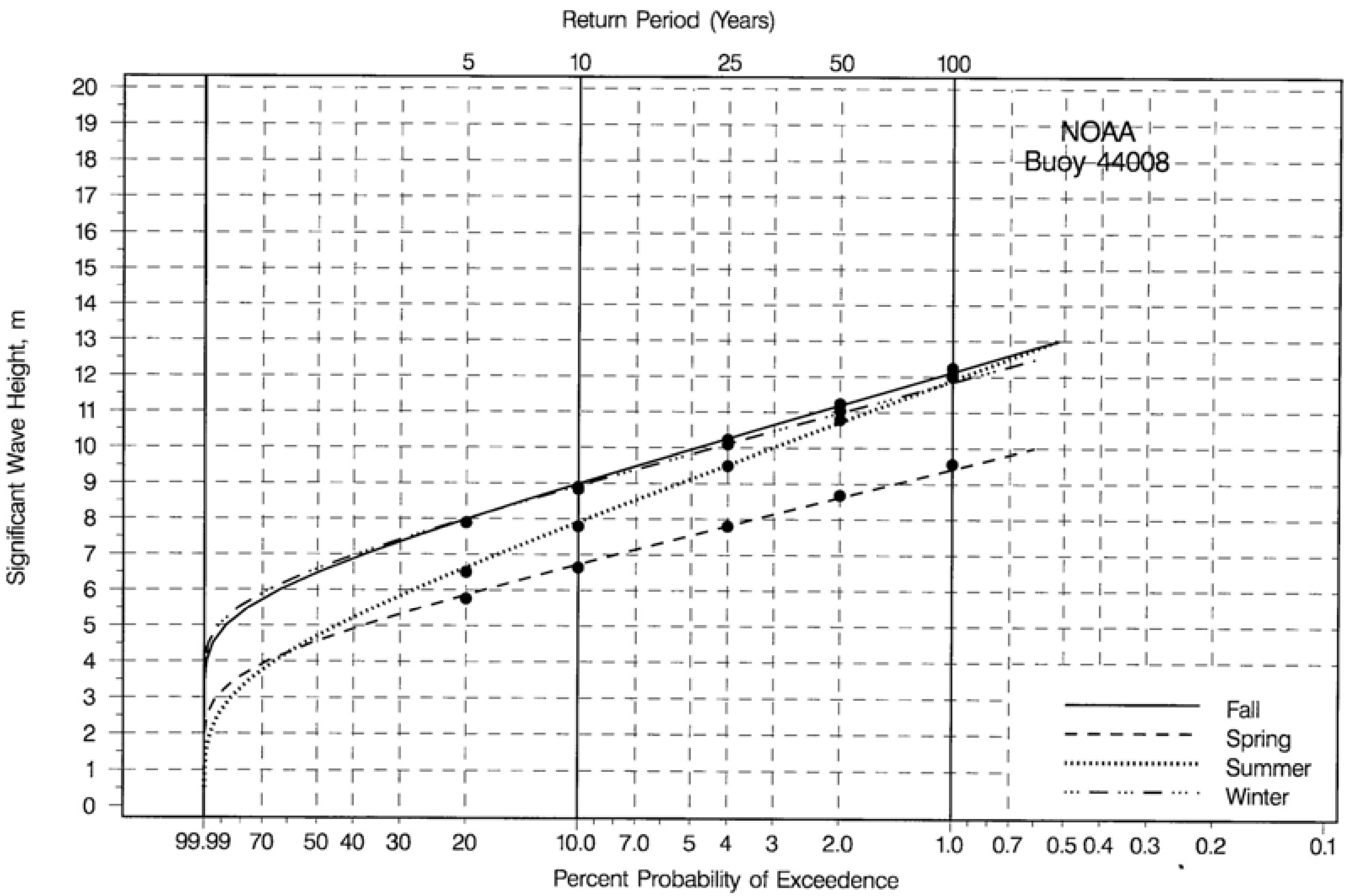


Figure C.2.2. Design wave height for various return periods for winter, spring, summer, and fall seasons

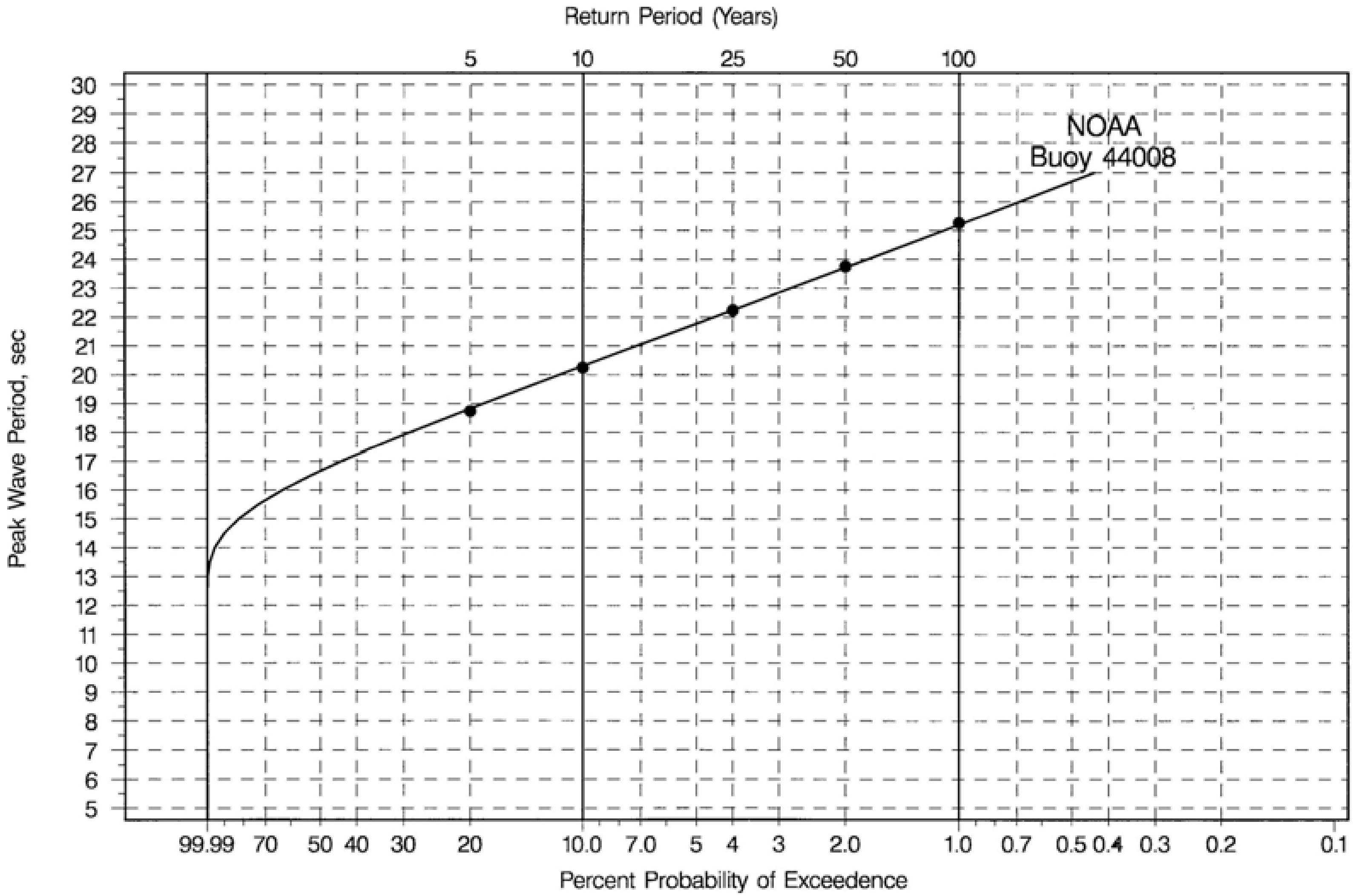


Figure C.2.3. Design peak wave period for various return periods

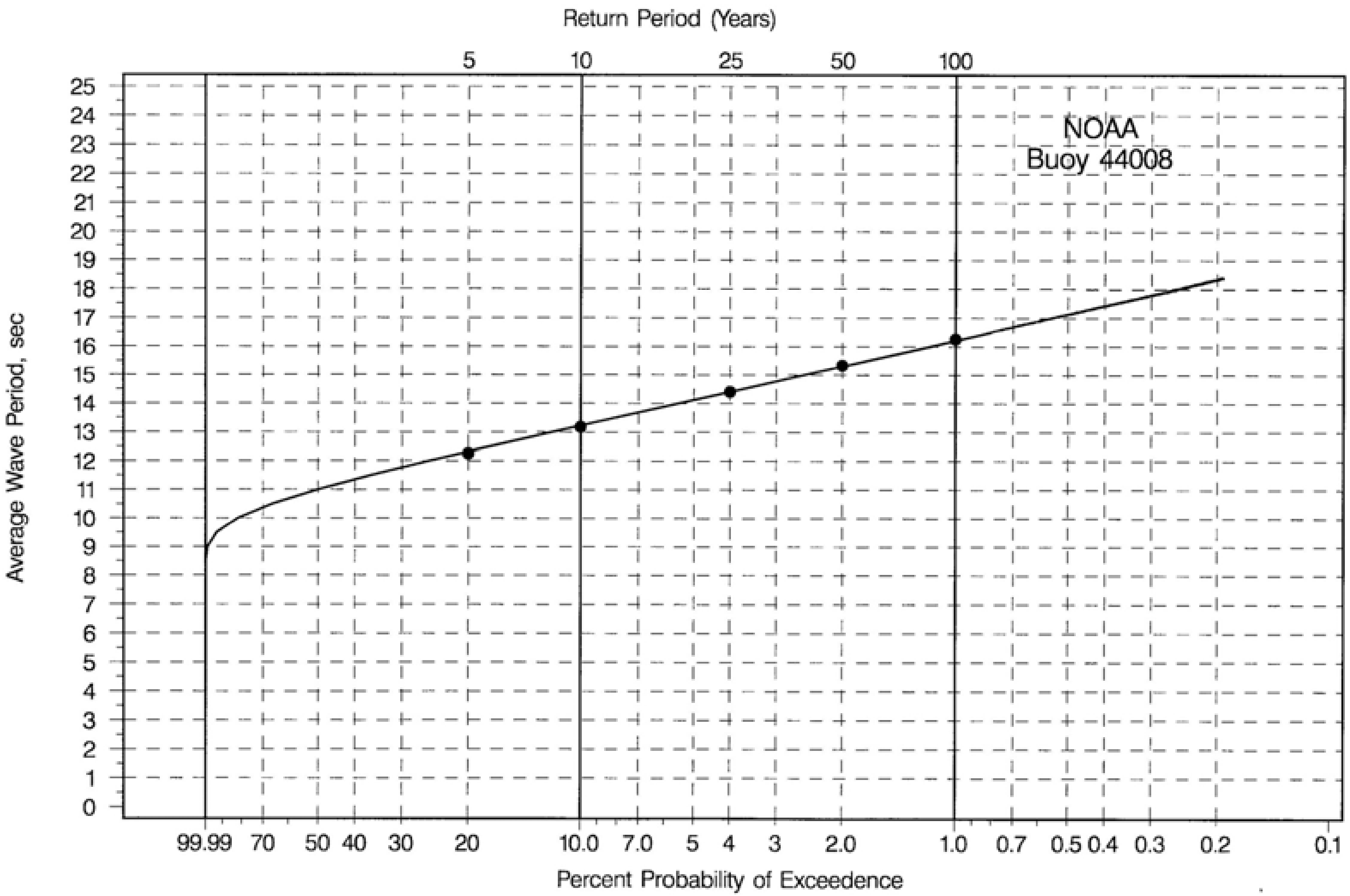


Figure C.2.4. Design average wave period for various return periods

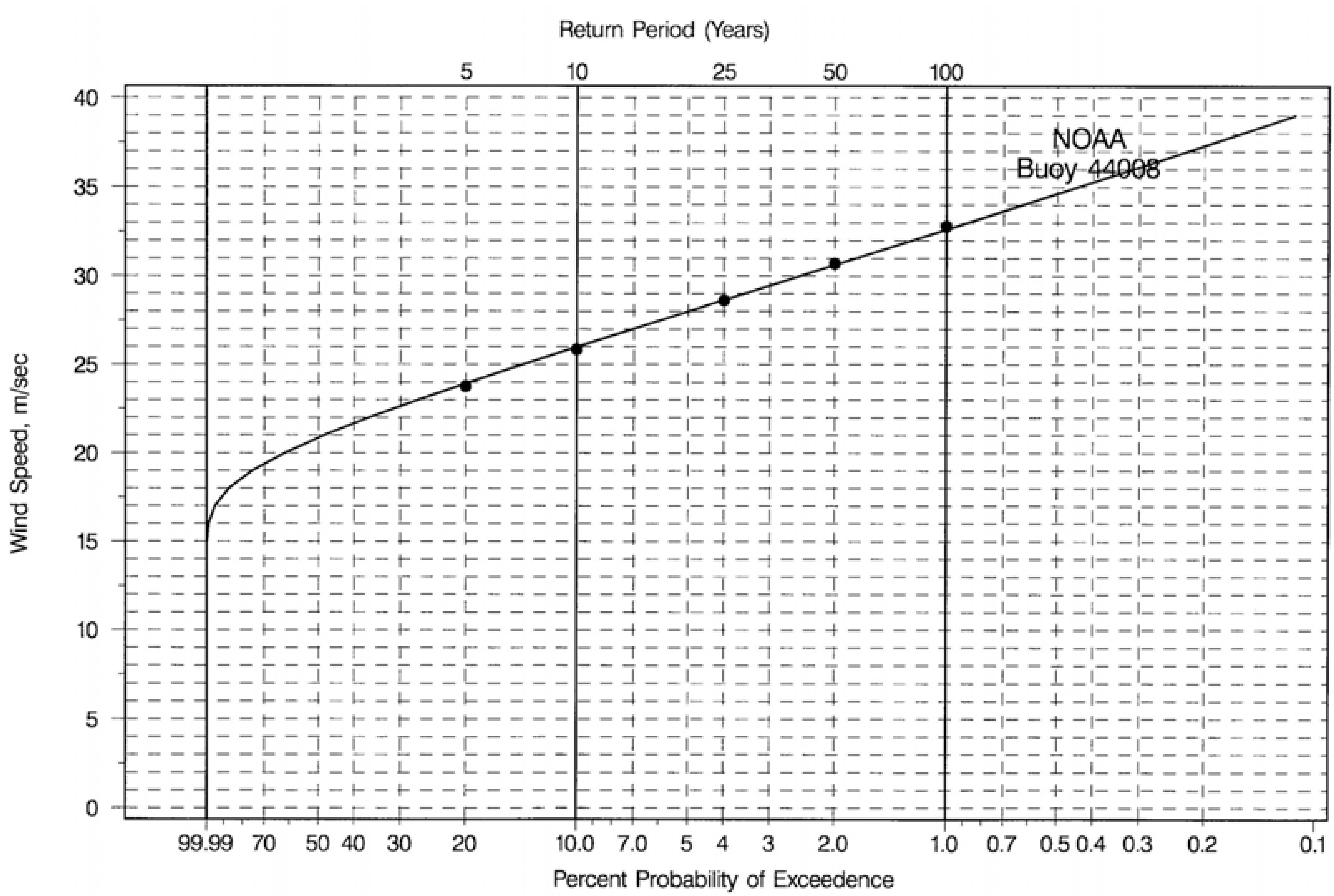


Figure C.2.5. Design wind speeds for various return periods

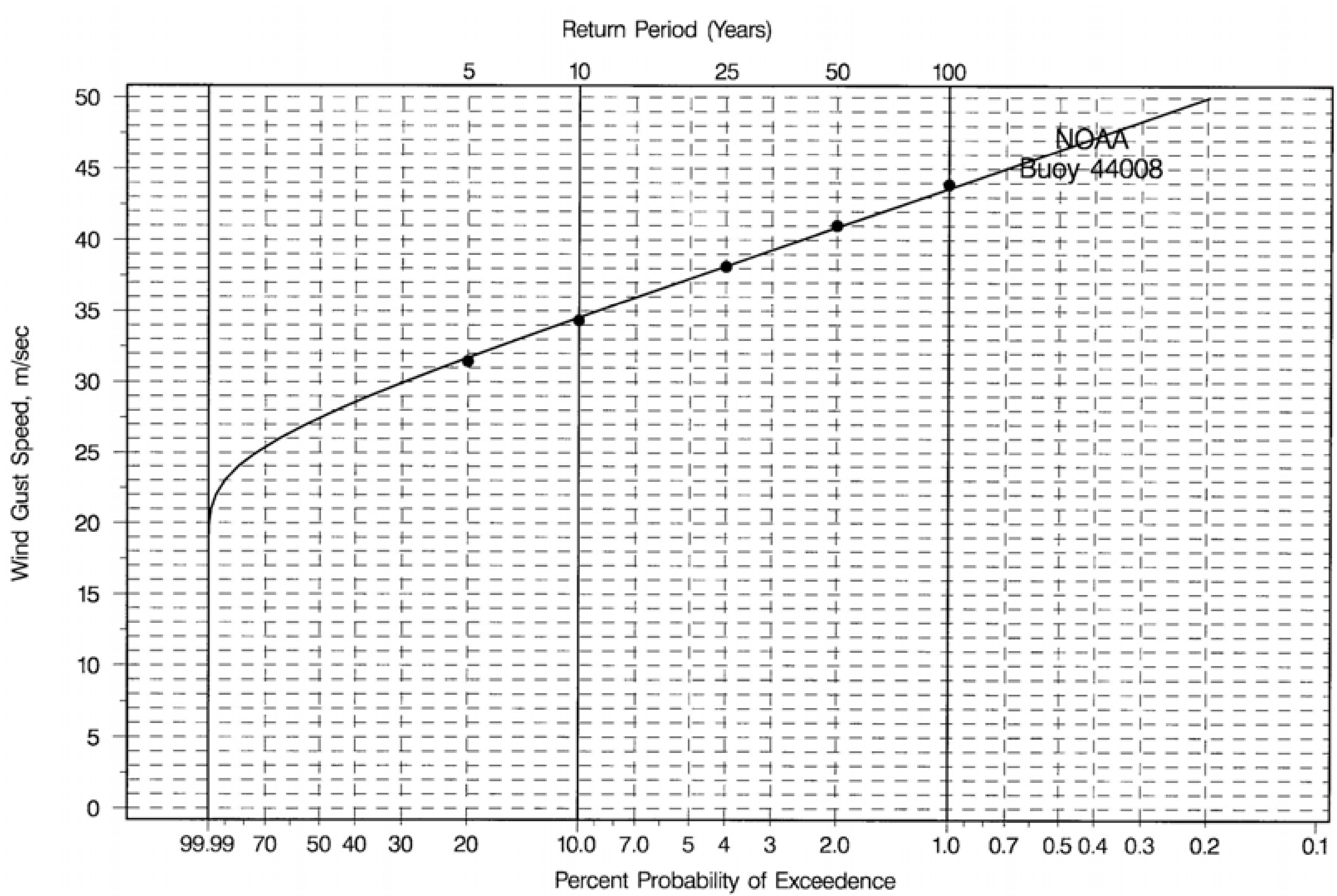


Figure C.2.6. Design wind gust speeds for various return periods

Table C.2.1. Summary of Design Wave and Wind Parameters for Various Return Periods Offshore Southeast of Nantucket

Return Period	Significant Wave Height (m)	Periods		Wind Speed (m/s)	Wind Gust (m/s)
		Average (s)	Peak (s)		
5	9.1	18.8	12.1	23.8	31.5
10	10.2	20.1	13.2	25.9	34.1
25	11.5	22.2	14.3	28.8	38.0
50	12.5	23.8	15.2	30.6	41.0
100	13.6	25.1	17.1	31.4	44.0

Table C.1.2. Table of Parameters for Wind and Waves (hourly data)

Wind Speed (m/s)	N	Significant Wave Height, Mean (m)	Significant Wave Height, Max (m)	Peak Wave Period, Mean (s)	Peak Wave Period, Max (s)	Average Wave Period, Mean (s)	Average Wave Period, Max (s)	Wind Gust, Mean (m/s)	Wind Gust, Max (m/s)
0−1	3,865	1.1	4.8	8.2	20.0	6.1	12.2	1.0	4.0
>1-2	7,921	1.1	6.0	8.2	20.0	6.1	12.0	2.1	12.9
>2-3	12,987	1.1	5.6	8.2	20.0	6.1	12.6	3.1	10.0
>3-4	16,540	1.2	6.8	8.1	20.0	6.0	12.3	4.2	11.0
>4-5	18,808	1.2	6.7	8.0	20.0	5.9	12.7	5.3	12.0
>5-6	18,964	1.3	6.7	8.0	20.0	5.8	14.5	6.5	13.0
>6-7	17,128	1.5	6.8	7.9	20.0	5.7	12.4	7.7	15.7
>7-8	14,882	1.6	6.6	7.7	16.7	5.6	12.4	8.9	16.1
>8-9	12,129	1.8	7.0	7.6	20.0	5.6	13.0	10.2	17.0
>9-10	9,904	2.1	8.7	7.7	16.7	5.7	10.6	11.5	21.1
>10-11	7,728	2.4	6.9	7.9	20.0	5.8	9.8	12.7	21.0
>11-12	5,621	2.7	8.0	8.0	16.7	6.0	10.3	14.0	91.2
>12-13	4,320	3.0	8.0	8.1	16.7	6.2	9.9	15.3	24.7
>13-14	3,046	3.3	8.1	8.4	14.3	6.4	9.6	16.5	23.5
>14-15	2,092	3.6	8.8	8.6	16.7	6.6	10.0	17.8	28.2
>15-16	1,387	4.1	9.6	8.9	14.3	6.8	10.6	19.1	25.4
>16-17	916	4.4	8.3	9.2	16.7	7.0	10.0	20.5	30.0
>17-18	596	4.9	10.8	9.6	16.7	7.3	10.5	21.7	28.5
>18-19	334	5.3	11.5	9.8	14.3	7.5	11.0	22.9	27.7
>19-20	180	5.5	9.9	10.0	16.7	7.6	10.2	24.2	30.5
>20-21	97	5.5	9.2	10.2	14.3	7.6	9.8	25.4	28.8
>21-22	49	5.9	8.2	10.2	12.5	7.7	9.1	26.3	29.0
>22-23	28	6.8	11.4	10.7	14.3	8.3	11.0	28.3	35.7
>23-24	16	6.3	9.2	10.3	16.7	7.8	10.1	29.0	30.3
>24-25	6	7.6	9.3	13.4	16.7	8.8	10.2	30.2	31.3
>25-26	2	6.0	6.0	9.1	9.1	7.6	7.6	33.5	33.5
>26-27	5	7.1	9.6	10.9	14.3	8.1	9.7	33.4	34.6
>27-28	2	9.1	9.3	11.1	11.1	9.5	9.6	33.5	34.4

References

Galbraith, N., A. Plueddemann, S. Lentz, S. Anderson, M. Baumgartner, and J. Edson, 1999. Coastal mixing and optics experiment moored array data report. Tech Report, Ref. WH01-99-15, Woods Hole Oceanographic Inst., Woods Hole, Mass.

Glenn, S., O. Schofield, C. Jones, R. Rhodes, P. Hogan, and F. Bubb, 2004. A study of the circulation of the western North Atlantic. *Papers in Physical Oceanography and Meteorology* 4: 1-101.

Shearman, R. K. and S. J. Lentz, 2003. Dynamics of mean and subtidal flow on the New England shelf. *J. Geophys. Res*. 108: 37-1 to 37-18.

U.S. Army Corps of Engineers, 1988. Historic Wave and Sea Level Data Report: San Diego Region. Ref. No. CCSTWS 88-6.

Appendix D: Load Cases

D.1. Wind Turbine Model and Load Cases

D.1.1. Bladed Model Introduction

This document presents the GH Bladed wind turbine model of the CMA proposed 5-MW wind turbine mounted on a semi-submersible platform. This model will be used to simulate the load cases that are to be considered to evaluate the lifetime fatigue and extreme loading. The turbine model has been based on information provided by David Malcolm of GEC [1-5]. Parameters that match both the natural frequencies and the magnitude of displacement for three given test cases have been selected for the semi-submersible platform. [1 & 6]

D.1.2 Model Description

This section contains a detailed description of the turbine model.

Table D-1. General Characteristics of Rotor and Turbine

Rotor diameter	126	m
Number of blades	3	
Teeter hinge	No	
Hub height	90	m
Offset of hub to side of tower center	0	m
Tower height	87.6	m
Tilt angle of rotor to horizontal	5	deg
Cone angle of rotor	−2.5	deg
Blade set angle	0	deg
Rotor overhang	5.0191	m
Rotational sense of rotor, viewed from upwind	Clockwise	
Position of rotor relative to tower	Upwind	
Transmission	Gearbox	
Aerodynamic control surfaces	Pitch	
Fixed/variable speed	Variable	
Diameter of spinner	3	m
Radial position of root station	1.5	m
Extension piece diameter	3.5	m
Extension piece drag coefficient	1	
Cut in wind speed	3	m/s
Cut out wind speed	25	m/s

Table D-2. Blade Geometry

Blade name	NREL	
Blade length	61.5	m
Pre-bend at tip	0	m
Pitch control	Full span	

Distance from Root (m)	Chord (m)	Twist (deg)	Thickness (% chord)	Pitch Axis (% chord)	Pre-bend (m)	Aerody-namic Control	Aerofoil Section Reference
0	3.542	13.308	100	50	0	Pitchable	1
1.367	3.542	13.308	100	50	0	Pitchable	1
4.1	3.854	13.308	100	50	0	Pitchable	1
6.833	4.167	13.308	100	47.3	0	Pitchable	2
10.25	4.557	13.302	40	39.2	0	Pitchable	3
14.35	4.652	11.488	35	33.9	0	Pitchable	4
18.45	4.458	10.162	35	29	0	Pitchable	4
22.55	4.249	9.009	30	29	0	Pitchable	5
26.65	4.007	7.795	25	29	0	Pitchable	6
30.75	3.748	6.549	25	29	0	Pitchable	6
34.85	3.502	5.359	21	29	0	Pitchable	7
38.95	3.256	4.189	21	29	0	Pitchable	7
43.05	3.01	3.144	18	29	0	Pitchable	8
47.15	2.764	2.319	18	29	0	Pitchable	8
51.25	2.518	1.526	18	29	0	Pitchable	8
54.667	2.313	0.863	18	29	0	Pitchable	8
57.4	2.086	0.37	18	29	0	Pitchable	8
60.133	1.419	0.106	18	29	0	Pitchable	8
61.5	0.04	0.106	18	29	0	Pitchable	8

Blade Mass Distribution

Distance from root (m)	Centre of Mass (% chord)	Mass/unit length (kg/m)
0	50	802.72
1.367	50	802.72
4.1	50	634.77
6.833	47.3	427.782
10.25	39.2	445.16
14.35	33.9	368.301
18.45	29	353.51
22.55	29	335.102
26.65	29	306.314
30.75	29	272.375
34.85	29	245.485
38.95	29	201.195
43.05	29	167.837
47.15	29	140.582
51.25	29	107.471
54.667	29	90.806
57.4	29	70.842
60.133	29	48.355
61.5	29	48

Blade Mass Integrals (No Ice)

Blade mass	17728.2	kg
First mass moment	363230	kgm
Second mass moment	1.18E+07	kgm^2
Blade inertia about shaft	1.293E+07	kgm^2

Blade Stiffness Distribution

Radial Position (m)	Stiffness about Chord Line (Nm^2)	Stiffness Perpendicular to Chord Line (Nm^2)
0	1.91E + 10	1.955E + 10
1.367	1.91E + 10	1.955E + 10
4.1	1.123E + 10	1.535E + 10
6.833	5.815E + 09	8.46E + 09
10.25	4.654E + 09	7.173E + 09
14.35	2.542E + 09	5.034E + 09
18.45	2.022E + 09	4.469E + 09
22.55	1.549E + 09	3.953E + 09
26.65	1.051E + 09	3.378E + 09
30.75	6.41E + 08	2.685E + 09
34.85	3.782E + 08	2.17E + 09
38.95	2.151E + 08	1.486E + 09
43.05	1.18E + 08	1.114E + 09
47.15	8.396E + 07	7.559E + 08
51.25	5.498E + 07	4.849E + 08
54.667	3.717E + 07	3.758E + 08
57.4	2.545E + 07	2.735E + 08
60.133	7.887E + 06	8.728E + 07
61.5	9,370	24,500

Hub Mass and Inertia

Mass of hub	56,780	kg
Mass center of hub	0	m
Hub inertia: about shaft	115,926	kgm^2
Perpendicular to shaft	0	kgm^2
Total rotor mass	109,965	kg
Total rotor inertia	3.886E + 07	kgm^2

Tower Details

Station Number	Height (m)	Diameter (m)	Wall Thickness (mm)	Material	Mass/Unit Length (kg/m)	Stiffness (Nm^2)
1	-27	1	0	-	12914	2.42E+18
2	-25.4	1	0	-	12914	2.42E+18
3	-25.4	73.152	0	-	12914	2.42E+18
4	-23	73.152	0	-	12914	2.42E+18
5	-20.5	73.152	0	-	12914	2.42E+18
6	-19.304	73.152	0	-	12914	2.42E+18
7	-19.304	5.036	0	-	12914	2.42E+18
8	-18	5.036	0	-	12914	2.42E+18
9	-10	5.036	0	-	12914	2.42E+18
10	0	5.036	0	-	12914	2.42E+18
11	7.21	5.036	0	-	12914	2.42E+18
12	7.21	4.57	0	-	8925	2.42E+18
13	11.716	4.57	0	-	8925	2.42E+18
14	11.716	9.144	0	-	17002.9	2.42E+18
15	15.716	9.144	0	-	17002.9	2.42E+18
16	15.716	5.666	33.472	steel	5034.48	4.933E+11
17	17.52	5.574	33.02	steel	4885.76	4.633E+11
18	26.28	5.361	31.98	steel	4550.87	3.991E+11
19	35.04	5.148	30.94	steel	4227.76	3.419E+11
20	43.8	4.935	29.9	steel	3916.41	2.91E+11
21	52.56	4.722	28.86	steel	3616.84	2.46E+11
22	61.32	4.509	27.82	steel	3329.05	2.065E+11
23	70.08	4.296	26.78	steel	3052.99	1.719E+11
24	78.84	4.083	25.74	steel	2788.74	1.418E+11
25	87.6	3.87	24.7	steel	2536.28	1.158E+11

steel: density	8,500	kg/m^3
steel: Young's modulus	2.1E + 11	N/m^2

Total tower mass	814,700	kg
Total turbine mass	1.165E + 06	kg

Drag coefficient for tower	0.6	
Environment	Offshore	
Mean sea depth	62	m

Station Number	Height (m)	Hydrodynamic Drag Coefficient	Hydrodynamic Inertia Coefficient
1	−27	1.15	3
2	−25.4	1.15	3
3	−25.4	1.15	3
4	−23	1.15	3
5	−20.5	1.15	3
6	−19.304	1.15	3
7	−19.304	0.8	2
8	−18	0.8	2
9	−10	0.8	2
10	0	0.8	2
11	7.21	0.8	2
12	7.21	0.8	2
13	11.716	0.8	2
14	11.716	0.8	2
15	15.716	0.8	2
16	15.716	0.8	2
17	17.52	0.8	2
18	26.28	0.8	2
19	35.04	0.8	2
20	43.8	0.8	2
21	52.56	0.8	2
22	61.32	0.8	2
23	70.08	0.8	2
24	78.84	0.8	2
25	87.6	0.8	2

Movement of Tower Foundation

Tower base translational motion?	Yes	
Foundation mass	1.E + 06	kg
Translational stiffness of foundation	3.4E + 06	N/m
Tower base rotational motion?	Yes	
Moment of inertia of foundation	7.22E + 09	kgm^2
Rotational stiffness of foundation	2.6E + 11	Nm/rad

Nacelle Geometry

Nacelle width	2.3	m
Nacelle length	14.3	m
Nacelle height	3.5	m
Nacelle drag coefficient	1	

Nacelle Mass

Nacelle mass	240,000	kg
Nacelle center of mass lateral offset	0	m
Nacelle center of mass above tower top	1.75	m
Nacelle center of mass in front of tower axis	−1.9	m
Yaw inertia (about tower axis)	2.608E + 06	kgm²
Nodding inertia (about CoG)	0	kgm²
Rolling inertia (about CoG)	0	kgm²
Total tower-head Mass	349,965	kg
Total yaw Inertia: 0° azimuth	2.481E + 07	kgm²
Total yaw Inertia: 90° azimuth	2.481E + 07	kgm²

Drive Train

Gearbox ratio	97	
Position of shaft brake	High-speed shaft	(Gearbox end)
Generator inertia	534.116	kgm²
High-speed shaft inertia:	0	kgm²
Low-speed shaft	Flexible	
Low-speed shaft torsional stiffness	8.676E + 08	Nm/rad
Low-speed shaft torsional damping	1.243E + 06	Nms/rad
High-speed shaft	Stiff	

Generator Characteristics

Generator model	Variable Speed	
Power electronics time constant	0.02	s
Maximum generator torque	45,000	Nm
Minimum generator torque	0	Nm
Phase angle	0	deg

Mechanical Loss Torque (kNm, Referred to Low-Speed Shaft)

Low-Speed Shaft Torque (kNm)	Loss Torque (kNm)
200	76.2
2,448	93.8
4,500	120.3

Electrical Losses

No load power loss	0	kW
Efficiency	94.4	%

Power Production Control

Variable-speed pitch regulated controller	Dynamic	
Minimum generator speed	350	rpm
Maximum generator speed	1350	rpm
Optimal mode quadratic speed-torque gain	2.06113	Nms²/rad²

Optimal mode maximum generator speed	1173.7	rpm
Generator torque set point	43093.6	Nm
Above-rated generator speed set point	1173.7	rpm
Minimum pitch angle	0	deg
Maximum pitch angle	90	deg
Pitch direction	to Feather	
Speed transducer time constant	0	s
Power transducer time constant	0	s
Maximum negative pitch rate	−8	deg/s
Maximum positive pitch rate	8	deg/s
Torque controller	Discrete	
Pitch controller	Discrete	

Discrete Controller

Communication interval	0.01	s
Power production control:	Pitch, Torque	

External Controller Data

LOG 1

NSTEPP 5
KPPS 0.0285
KIPS 0.0095

QKPPS 1e-8
QKIPS 1e-8
PIT1 0.05236
PIT2 0.6109
DIV2 5

W1A 5.1
D2A 0.15

CONSTPOW 1
MINTRQFAC 0.96
MAXTRQFAC 1.05

KPQS 3000
KIQS 750

QVGAIN 1893
QVFREQ 10.63
QVDAMP 0.49
QVTLAG 0.0

QVGAIN 3229
QVFREQ 22.44
QVDAMP 0.19

Pitch Actuator

Pitch actuator responds to	Position demand	
Ramp control for step changes in input:	Disabled	
Pitch position response	Passive	
First order lag time constant	0.3	s
Lower pitch limit	0	deg
Upper pitch limit	90	deg
Lower pitch rate limit	−8	deg/s
Upper pitch rate limit	8	deg/s
Pitch actuation	Individual	

Shaft Brake Characteristics

Brake Number: 1

Maximum brake torque	28116.1	Nm
Shaft brake ramp time	0.6	s

Imbalances and Failure Modes

Out of balance mass	500	kg
Radius of out of balance mass	1	m
Azimuthal position of out of balance mass	0	deg

Blade	Error in Blade Set Angle (deg)	Error in Pitch Angle (deg)	Error in Blade Azimuth (deg)
1	0.3	0	0
2	0	0	0
3	−0.3	0	0

Tower Shadow

Tower shadow model	Potential Flow
Fraction of tower diameter to use	1

Vertical Wind Shear

Wind shear model	Exponential
Wind shear exponent	0.14

Physical Constants

Air density	1.225	kg/m^3
Air viscosity	1.82E-05	kg/ms
Gravitational acceleration	9.81	m/s^2
Density of water	1030	kg/m^3

Frequency Response

The following tables present the coupled frequencies of the system at rated and cut-out wind speeds, along with an approximate description of the mode. The Orcaflex frequencies from the pluck tests showed a first tower frequency of 0.05 Hz and a second of 0.35 Hz.

Table D-3. Coupled Frequencies at Rated Wind Speed

Frequency (Hz)	Damping (-)	Description (-)
0.05	0.5%	Tower fore-aft 1
0.05	0.1%	Tower side-side 1
0.34	7.1%	Tower fore-aft 2
0.35	0.6%	Tower side-side 2
0.73	70.5%	Rotor out of plane
0.74	67.7%	Rotor out of plane
0.76	65.8%	Rotor out of plane
0.82	0.5%	Tower side-side 3
0.82	1.4%	Tower fore-aft 3
1.11	1.8%	Rotor in plane
1.12	1.8%	Rotor in plane
1.64	0.7%	Drive train torsion
1.99	17.2%	Rotor out of plane
2.00	17.0%	Rotor out of plane
2.02	16.6%	Rotor out of plane
3.50	1.0%	Rotor in plane collective
4.02	0.6%	Rotor in plane
4.05	0.7%	Rotor in plane

Table D-4. Coupled Frequencies at Cut-Out Wind Speed

Frequency (Hz)	Damping (-)	Description (-)
0.05	0.3%	Tower fore-aft 1
0.05	0.2%	Tower side-side 1
0.34	7.6%	Tower fore-aft 2
0.35	1.0%	Tower side-side 2
0.82	0.5%	Tower side-side 3
0.83	1.6%	Tower fore-aft 3
0.84	47.0%	Rotor out of plane
0.87	55.8%	Rotor out of plane
0.88	51.9%	Rotor out of plane
1.02	1.4%	Rotor in plane
1.03	1.2%	Rotor in plane
1.57	1.0%	Drive train torsion
2.62	11.9%	Rotor out of plane
2.62	11.8%	Rotor out of plane
2.65	11.5%	Rotor out of plane
3.35	1.6%	Rotor in plane collective
3.69	1.7%	Rotor in plane
3.72	1.7%	Rotor in plane

Test Cases

The following figures plot the dynamic response of the turbine to three different wave inputs, and can be compared to similar runs from the Orcaflex model.

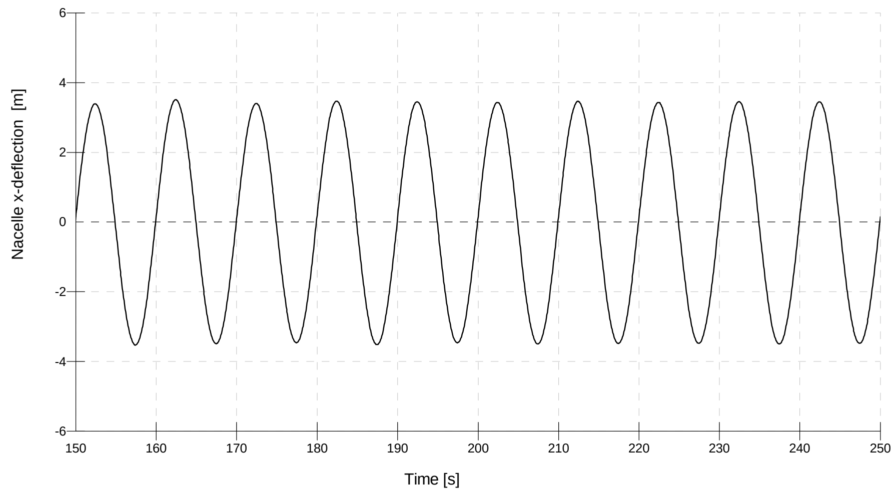


Figure D-1. Response to 5-m 10-s wave

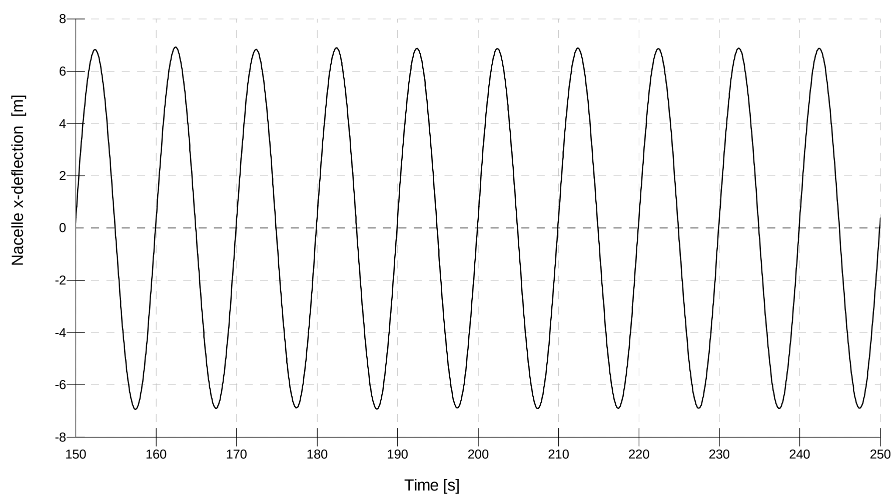


Figure D-2. Response to 10-m 10-s wave

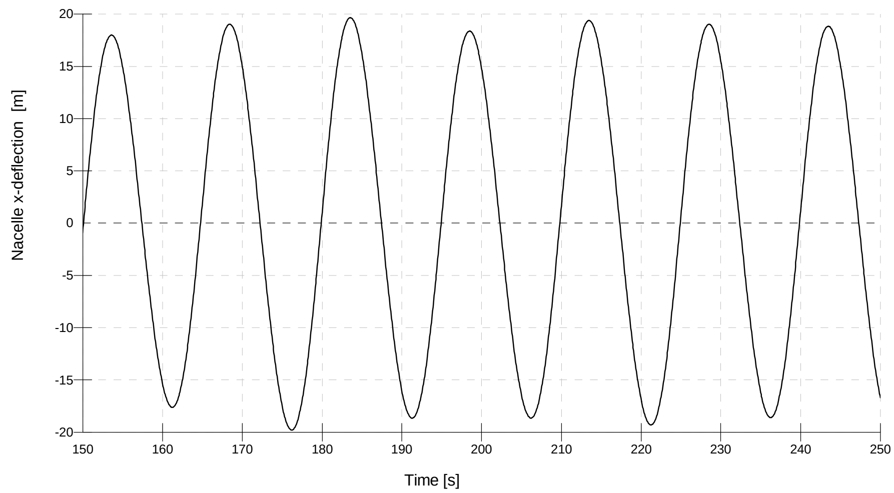


Figure D-3. Response to 18.75-m 15-s wave

Load Case Description

Input Parameters

General Notes on Wind and Sea Conditions for Extreme Load Calculations

The wind and sea conditions for the extreme load calculations were derived from [1] and [2] and are presented in Tables C.5 and C.6. Unless otherwise stated, all gusts are assumed, where appropriate, to commence at the beginning of the transient operation of the turbine, for example, loss of grid, application of brakes.

The extreme wind speeds are taken from [1], assuming IEC Class I conditions.

General Notes on Wind Conditions for Fatigue Load Calculations

Table C.6 describes the normal sea conditions for fatigue load calculations. The wind and sea conditions were derived from [1], and [3]. The turbulence intensity is taken from [1] assuming Class A conditions.

Load calculations for an offshore wind turbine require information about the correlation of wind speed, wave height and wave period. This information is presented in [3].

A three-component von Karman anisotropic wind turbulence model will be used for creating the wind files.

General Notes on the Turbine Model used for the Load Calculations

The model of the turbine used for the load calculations is to include the first six out-of-plane and first five in-plane blade modes, the first two tower fore-aft and side-side modes, drive train flexibility and the influence of the controller. Nacelle acceleration feedback will not be included in the controller for the first iteration of calculations unless it is found absolutely necessary.

Load Cases

The load cases are tabulated in Table D.7. The tables give the case name, the initial turbine state, the initial conditions (wind speed, sea state, yaw error, and pitch angle), and the details of any transient events or model of turbulence.

Overridden Cases

We have been able, while identifying which cases should be simulated, to eliminate whole groups of cases as either not requiring simulation or being obviously more benign than others. A case can then be said to be overridden if it has lower load factors and less arduous wind conditions, and can be assured to produce less extreme loads, than another case.

Safety Factor Strategy

Partial safety factors for loads have been applied externally to the results of the dynamic simulations. Table D.8 summarizes the safety factors that have been used in each load case.

General Notes on the Simulations

All simulations will take account of:

- Rotor mass imbalance of 500 kgm.
- Rotor aerodynamic imbalance, set angles of 0.3°, 0.0° and –0.3° on blades 1, 2, and 3 respectively
- Tower shadow
- Wind shear exponent $\alpha = 0.14$ for all conditions

All simulations take account of either irregular or regular wave modeling:

- Fatigue wave modeling: Pierson – Moskowitz spectra
- Linear (airy) wave theory
- Morison's equation, $C_D = 0.80$, $C_M = 2$
- C_D and C_M for the platform were chosen by tuning the model to then Orcaflex results.
- Extreme wave modeling: Stream function wave solution
- Morison's equation, $C_D = 1.05$, $C_M = 1.6$
- Slam/slap loading not modeled
- Simulations with wind turbulence also account for three-component, three-dimensional anisotropic von Karman turbulent field

Phasing Effect of Waves and Other Transient Events

In calculating extreme loads, the phasing effects of the waves with other transient events such as wind gusts and shutdown procedures will be investigated for load cases for this effect may lead to a significant loading variation.

Stop Logic

Some load cases may require the turbine to shut down. A shutdown pitch rate of 7.5°/s and a delay of 0.2 s before the pitch activation starts has been assumed.

Supervisory Control and Safety System Triggers

Appropriate supervisory control and safety system triggers would normally be needed to determine the action taken if environmental or fault conditions cause the turbine to move outside its normal operating condition. However, no modeling of overspeed faults will be considered in this analysis.

Table D-5. Design Load Case Parameters

Rated power, P_r (MW)	5.0
Rated hub-height wind speed, V_r (m/s)	12.0
Density of air (kg/m^3)	1.225
Hub-height operating wind speed range, V_{in} to V_{out} (m/s)	3−25
Mean wind speed, V_{ave} (m/s)	10
Design Turbulence Intensity at 15m/s, I_{ref} (-)	0.16
Hub-height annual extreme 10-min mean wind speed, V_1 (m/s)	40.0
Hub-height annual extreme 3-s gust wind speed , V_{e1} (m/s)	52.0
Hub-height 50-year extreme 10-min mean wind speed, V_{50} (m/s)	50.0
Hub-height 50-year extreme 3-s gust wind speed, V_{e50} (m/s)	65.0
Mean water depth (m)	62
50-yr extreme water depth (m)	Assumed at mean
50-yr significant wave height, Hs_{50} (m)	12.5
50-yr peak spectral period, Tp_{50} (s)	14.0
50-yr individual wave height (m)	18.75
50-yr individual wave period (associated with above wave height) (s)	11.3–12.7
50-yr tidal current surface velocity (m/s)	None
50-yr storm surge current surface velocity (m/s)	None
1-yr extreme water depth (m)	Assumed at mean
1-yr significant wave height, Hs_1 (m)	7.0
1-yr peak spectral period, Tp_1 (s)	10.0
1-yr individual wave height (m)	10.0
1-yr tidal current surface velocity (m/s)	None
1-yr storm surge current surface velocity (m/s)	None

Table D-6. Normal Sea Conditions*

Hub-Height Wind Speed (m/s)	Significant Wave Height Hs (m)	Peak Spectral Period Tp (s)
4	1.1	8.2
6	1.2	8.0
8	1.5	7.9
10	1.6	7.7
12	1.8	7.6
14	2.4	7.9
16	3.0	8.1
18	3.3	8.4
20	3.6	8.6
22	4.1	8.9
24	4.9	9.6
25	5.3	9.8
45.5	9.1	11.1

*Wind speed has been scaled from 6-m data to hub height using shear exponent of 0.12.

Table D-7. Definition of Load Cases

Design load case (DLC)	1.2	
Design situation	Power production	
Wind condition	Normal turbulence model	
Sea condition	Normal sea state	
Type of analysis	Fatigue	
Partial safety factors	None	
Description of simulations		
	Wind conditions	Sea conditions
1.2	$V_{hub} = V_{in}$ to V_{out} V_{hub} = 4,6,8,10,…..,24	From Table C6
Yaw errors, y (deg)	No yaw errors considered	
Comments	Wind and wave directions aligned No variation in wind and wave direction to be considered 10-min simulations Three simulations per wind speed	

<table>
<tr><td colspan="2">DLC</td><td colspan="2">1.3a</td></tr>
<tr><td colspan="2">Design situation</td><td colspan="2">Power production</td></tr>
<tr><td colspan="2">Wind condition</td><td colspan="2">Extreme turbulence model</td></tr>
<tr><td colspan="2">Sea condition</td><td colspan="2">Normal sea state</td></tr>
<tr><td colspan="2">Type of analysis</td><td colspan="2">Ultimate</td></tr>
<tr><td colspan="2">Partial safety factors</td><td colspan="2">Normal</td></tr>
<tr><td colspan="4">Description of simulations</td></tr>
<tr><td></td><td colspan="2">Wind conditions</td><td>Sea conditions</td></tr>
<tr><td>1.3a</td><td colspan="2">V_{hub} = 12, 25 m/s
TI at 12 m/s = 29.74 %
TI at 25m/s = 19.07 %</td><td>H_s, T_p From Table C 6</td></tr>
<tr><td colspan="2">Yaw errors, y (deg)</td><td colspan="2">No yaw errors considered</td></tr>
<tr><td>Comments</td><td colspan="3">Wind and wave directions aligned
ETM: $\sigma_1 = c \quad I_{ref}\left(0,072\left(\frac{V_{ave}}{c}+3\right)\left(\frac{V_{hub}}{c}-4\right)+10\right);\ c = 2 \quad m/s.$

10-min simulations</td></tr>
</table>

DLC	1.3b	
Design situation	Power production	
Wind condition	Normal turbulence model	
Sea condition	Extreme sea state	
Type of analysis	Ultimate	
Partial safety factors	Normal	
Description of simulations		
	Wind conditions	Sea conditions
1.3b	V_{hub} = 12, 25 m/s TI at 12 m/s = 17.0 % TI at 25m/s = 13.6 %	50 year significant wave height: (H_{s50}|V_{hub}) H_{s50} at 12m/s = 7.44 m H_{s50} at 25m/s = 12.22 m T_p = Selected to give worst case loading. (expected to be T_p closest to the resonant frequency of the structure) = 12.5s
Yaw errors, y (deg)	No yaw errors considered	
Comments	Wind and wave directions aligned 1-h simulations	

DLC	1.4	
Design situation	Power production	
Wind condition	Extreme coherent gust with direction change	
Sea condition	Normal wave height	
Type of analysis	Ultimate	
Partial safety factors	Normal	
Description of simulations		
	Wind conditions	Sea conditions
1.4a-b 1.4c-d 1.4e-f	V_{hub} = 10 m/s, wind direction ± 72 deg V_{hub} = 12 m/s, wind direction ± 60 deg V_{hub} = 14 m/s, wind direction ± 51.4 deg	Deterministic wave height H = H_s, T = T_p From Table C 6
Yaw errors, y (deg]	No yaw errors considered	
Comments	Start time of wind gust and wave set to give worst case loading. Wind and wave directions initially aligned	

DLC 1.6 removed on the basis of DLC1.3b

DLC	2.3		
Design situation	Fault condition (Grid loss)		
Wind condition	Extreme operating gust		
Sea condition	Normal Wave Height		
Type of analysis	Ultimate		
Partial safety factors	Abnormal		
Description of simulations			
	Wind conditions	Sea conditions	
2.3a 2.3b 2.3c 2.3d	V_{hub} = 10 m/s, 4.7 m/s gust V_{hub} = 12 m/s, 5.2 m/s gust V_{hub} = 14 m/s, 4.7 m/s gust V_{hub} = 25 m/s, 4.7 m/s gust	H_s, T_p From Table C 6	
Yaw errors, y (deg]	No yaw errors considered		
Comments	Start time of wind gust relative to wave period set to give worst case loading. Grid loss causing shutdown: −0.2-s delay and 7.5°/s pitch rate. Wind and wave directions aligned		

DLC	6.1a
Design situation	Parked or Idling
Wind condition	Extreme wind model (turbulent wind) – 50-yr return
Sea condition	Extreme sea state – 50-yr return
Type of analysis	Ultimate
Partial safety factors	Normal

Description of simulations

	Wind conditions	Sea conditions
6.1a	$V_{hub} = V_{50} = 50$ m/s	$H_s = H_{s,50}$ with H_{50} constrained wave $T_p = 14.0$ s

Yaw errors, y (deg]	No yaw errors considered

Comments 10-min simulations

Wind and wave directions aligned

Three simulations with different wind and sea state seeds

Turbulent wind model

Turbine Idling with brake off

<table>
<tr><td>DLC</td><td colspan="3">6.4</td></tr>
<tr><td>Design situation</td><td colspan="3">Parked or idling</td></tr>
<tr><td>Wind condition</td><td colspan="3">Normal turbulence model</td></tr>
<tr><td>Sea condition</td><td colspan="3">Normal sea state</td></tr>
<tr><td>Type of analysis</td><td colspan="3">Fatigue</td></tr>
<tr><td>Partial safety factors</td><td colspan="3">None</td></tr>
<tr><td colspan="4">Description of simulations</td></tr>
<tr><td></td><td colspan="2">Wind conditions</td><td>Sea conditions</td></tr>
<tr><td>6.4</td><td colspan="2">$V_{hub} = 0.7\ V_{50} = 45.5$ m/s</td><td>H_s, T_p From Table C 6</td></tr>
<tr><td>Yaw errors, y (deg]</td><td colspan="3">No yaw errors considered</td></tr>
<tr><td>Comments</td><td colspan="3">Wind and wave directions aligned
10-min simulations – three seeds considered
Number of simulations per wind speed depends on number of sea state conditions defined per wind speed.
Turbine idling with brake off</td></tr>
</table>

DLC	7.1a		
Design situation	Parked or Idling with fault		
Wind condition	Extreme wind model (turbulent wind) – 1-yr return		
Sea condition	Extreme sea state – 1-yr return		
Type of analysis	Ultimate		
Partial safety factors	Normal		
Description of simulations			
	Wind conditions	Sea conditions	
7.1a	$V_{hub} = V_1 = 40$ m/s	$H_s = H_{s,1}$ with H_1 constrained wave $T_p = 10.0$ s	
Comments	10-min simulations Wind and wave directions aligned Two faults considered independently: Yaw error and single blade pitch error: Pitch error: 0°−90° Yaw error: 0°−360° Turbine idling with brake off.		

Table C-8. Partial Safety Factors for Loads

Load Case Type	All Components
Normal	1.35
Abnormal	1.1

Appendix E
Cable Design Information

Power cables are now used to transfer captured energy from an offshore wind turbine (wind farm) to onshore facilities. Some future technologies such as hydrogen gas and battery storage may not require oceanographic cables. A typical method of cabling the energies to the shore is to run a separate cable to each wind turbine from a shallow water junction box. Relatively small cables can be installed from a shallow water junction box to each wind turbine. From the shallow water junction box to the shore, large cables can be installed. The breaking wave action in the near shore area is destructive to small cables. Large cables can be protected in the near shore environment by several methods. Oceanographic cables are often composed of metal components (copper or aluminum cable for power transmission) and fiber optic cables (for communication transmission). Rarely are metal components used for power transmission and communications because of the potential for electromagnetic interference (EMI or crosstalk). If power transmission and communications require metal cables, a separation in distance or shielding is required between them.

E.1 Oceanographic Cables in Deep Water

Small cables can be installed from a junction box in shallow water to each wind turbine. The junction box is typically installed in water that is approximately 80 to 100 ft deep. The exact location of a junction box is chosen based on the wave and bottom conditions of the site. From the junction box to the wind turbines the cables are installed with approximately 5% slack in gradual slopes and with up to 10% slack in steep slopes. A cable laying vessel is used with dynamic station keeping and a linear traction winch or cable laying winches. If repeaters or amplifiers are designed into the cable, a linear traction winch is preferred to accommodate dramatic changes in the cable diameter.

E.2 Protecting cables in the near shore

Many near shore areas consist of a rocky bottom with heavy wave action. The cables in the near shore area are typically installed with little to no slack. The best ways to protect cables in the near shore environment is to directional drill or bury the cables through the surf zone. Alternative methods are to install heavily armored cables that may be anchored to the bottom with rock bolt clamps or heavy weights such as split pipe.

Appendix F
Orcaflex Dynamic Output

F.1 Orcaflex is a software for offshore system analysis. Some Orcaflex applications are described in Figure F-1. Technical Details of Orcaflex are provided in Figure F-2.

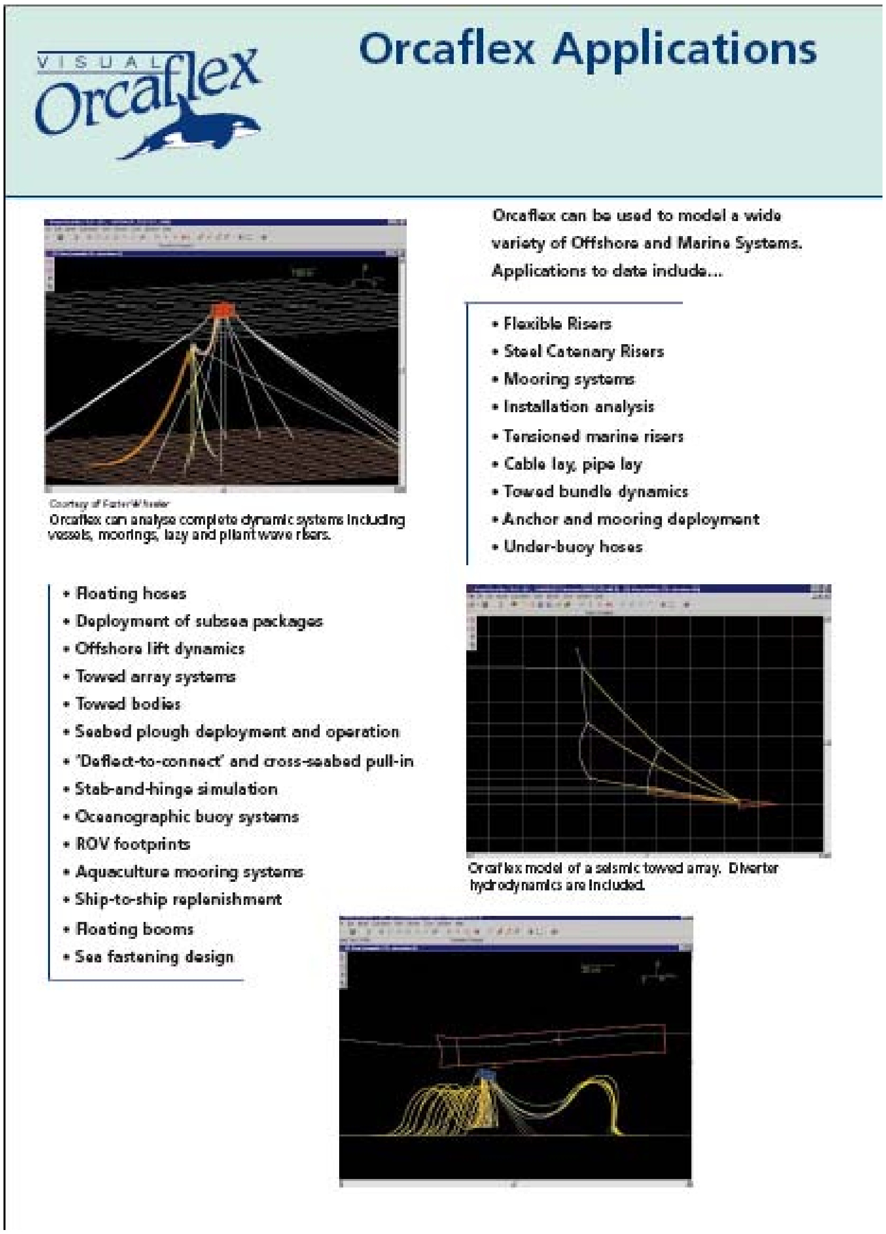


Figure F-1 – Orcaflex Software Applications

Technical Details

VISUAL Orcaflex

Data Input:

- Interactive Graphical User Interface
- Edit model using browser and pop-up data forms
- Drag and drop facilities from Library files or other sources
- Simple object replication
- Batch processing
- Batch script file facility
- Full backwards compatibility with earlier Orcaflex versions
- Comprehensive facilities for vessel RAO import, including graphical RAO realism checks
- Typical Line properties available through built-in 'wizard' facility
- Import facility for vessel motion and wave elevation time history

Modelling Elements:

- Line elements for modelling mooring chains, wire and man-made fibre ropes, homogeneous pipe, flexpipe, floating hoses, cables and umbilicals.
- Centrifugal internal flow effects included
- Lines having non-isotropic properties (bending stiffness, drag and added mass) can be modelled
- Line centre of mass may be displaced from geometric centre
- Solid shapes (boundaries and clashing forces)
- Vessels including RAOs, wind and current force coefficients
- Slow-drift modelling using QTFs, wind spectra
- Winches, including winch control and constant tension options
- Links, offering piecewise linear representation of non-linear stiffness and damping
- Clumped line attachments (buoyancy or weight)
- Full 3D and 6D modelling of buoys
- Spar buoy modelling
- Towed fish, including wings, tailfins
- Compressibility effects on Lines and Buoys

Environment:

- Choice of regular wave models (Airy, Stokes' 5th Order, Dean Stream Function, Cnoidal)
- Choice of irregular wave spectra (ISSC, JONSWAP, Ochi-Hubble)
- Combination spectra eg swell plus local waves from arbitrary directions
- Wave particle kinematics fully computed at all points in wave profile
- Preview and selection of irregular wave profile
- Horizontal, sloping or irregular seabed profiles
- 3D current profile
- Seabed friction (non-isotropic) in both static and dynamics
- Wind spectrum
- Fluid compressibility, density profile

Analysis:

- Full 3D modelling
- Complete and partial quasi-static analysis
- Time domain dynamic analysis with ramp up to minimise starting transients
- Non-linear large displacement analysis, including line compression and snatch loads
- Fully coupled tension, bending and torsion.
- Contact, clashing and clearance analyses
- Vessel manoeuvres (forward speed and turn rate)
- Surface piercing fully modelled

Numerical Procedures:

- Lumped mass model with 6 degrees of freedom at each segment end
- Explicit time integration avoids time consuming implicit integrations
- Slow varying water particle loads can be computed at a larger time step than structural displacements
- User specified number of wave components for irregular wave analyses
- Optional FFT re-construction of wave field from single point elevation time history
- Fluid forces based on industry-standard Morison and cross-flow assumptions
- No stiffness matrix to invert, therefore compression is easily handled

Data Output:

- Full Windows style presentation
- View as many multiple panes on same window as required
- Results form aids selection of results for display / output
- Selected key results can be monitored at run time and during simulation replay
- Output can be graphical (time histories, range and X-Y graphs), raw data, statistical analysis and screen snapshots
- Graphs and 3D images can be copied and pasted into other Windows applications
- AVI file export to presentation applications such as Powerpoint
- Raw data and results of statistical analyses can be exported to spreadsheets for further post processing if required
- Results spreadsheet allows selected data to be easily extracted from multiple simulation files and processed
- Cumulative fatigue damage calculations carried out by built-in facility

Figure F-2 – Technical Details of Orcaflex Software

F.2 Technical merit, feasibility, and rationale for development of the proposed concept

We had some difficulties as we tried to have the Orcaflex models and the Bladed models to converge on all the results. The Orcaflex model calculates motions and forces in six degrees of freedom per node. The Bladed model calculates motions and forces in four degrees of freedom per node. Because of the hydrodynamic actions of an at-sea TLP, the Orcaflex results appear to more reliably represent the actual predictions for the survival case (50 return period storm event). Because of constraints in the project, we present the Bladed model results for the 1-yr return period event and for the operational (energy capturing) conditions.

F.2.1 Diffraction and Froude-Krylov Forces

Vertical and horizontal pluck tests were performed on the concept design model. Results from these tests indicate that 3-D diffraction/radiation and Froude-Krylov Forces need to be investigated in a preliminary design. The model used does not fully include these forces and it is beyond the scope of this study. Figures F-3 and F-4 are provided to depict this recommendation.

The question has been posed as to why the tendon tensions vary as they do. The answer lies in the Froude-Krylov effect and in the diffraction that can also be explained partly as a dynamic subsurface pressure variation.

Broadly speaking, the increase in hydrostatic pressure beneath a still ocean surface increases linearly with depth. Beneath a wave crest there is more pressure. Beneath a wave trough there is less pressure.

At the depth of one-half of a wave length, the pressure change is negligible in most engineering applications. Thus, the pressure change varies exponentially with depth beneath the free surface, and the pressure change on a horizontal rectangular structure will be larger on the top surface than on the deeper bottom surface. When the wave crest is above the structure, the increase in pressure, being larger than the increase in pressure on the bottom surface, causes the structure to feel a downward force. When the structure is under the trough, the opposite happens.

When the structure is dynamically sensitive (with respect to wave frequency) the phasing of the forces and induced motions are difficult to understand intuitively. Hence we use numerical analyses.

Figures F-5, F-6, and F-7 show very small motions and tether tension changes in steep short waves and much larger changes in longer waves of the same height. Careful examination will yield a better understanding of what is happening.

Morison's equation cannot help with the vertical "pressure" forcing, only with the horizontal and vertical drag and inertia forces on the system. Because the plan projected area is so large in comparison to the side projected area and in proportion to the wave lengths being considered, the pure Morison force results are inadequate.

Checks on the phasing of the tendon tensions show no surprises. One cannot treat the system statically, even though it has been designed to be statically determinate. The dynamics have a strong influence, from all the terms we have previously discussed. We have the cantilever periods, the tendon axial periods, the barge sway periods, the barge pitch periods, and so on, all combined into one integrated system.

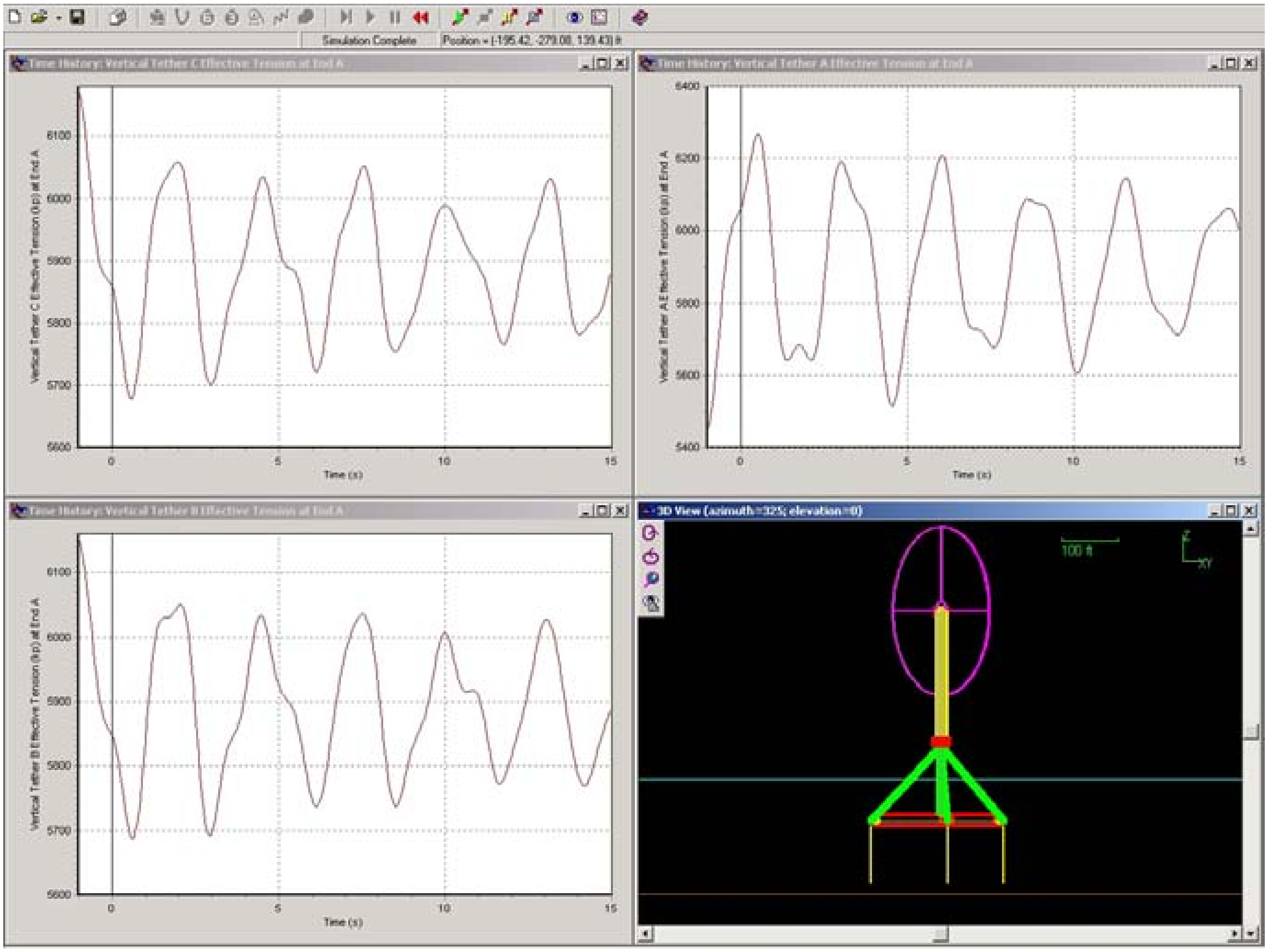


Figure F-3 – Vertical pluck test

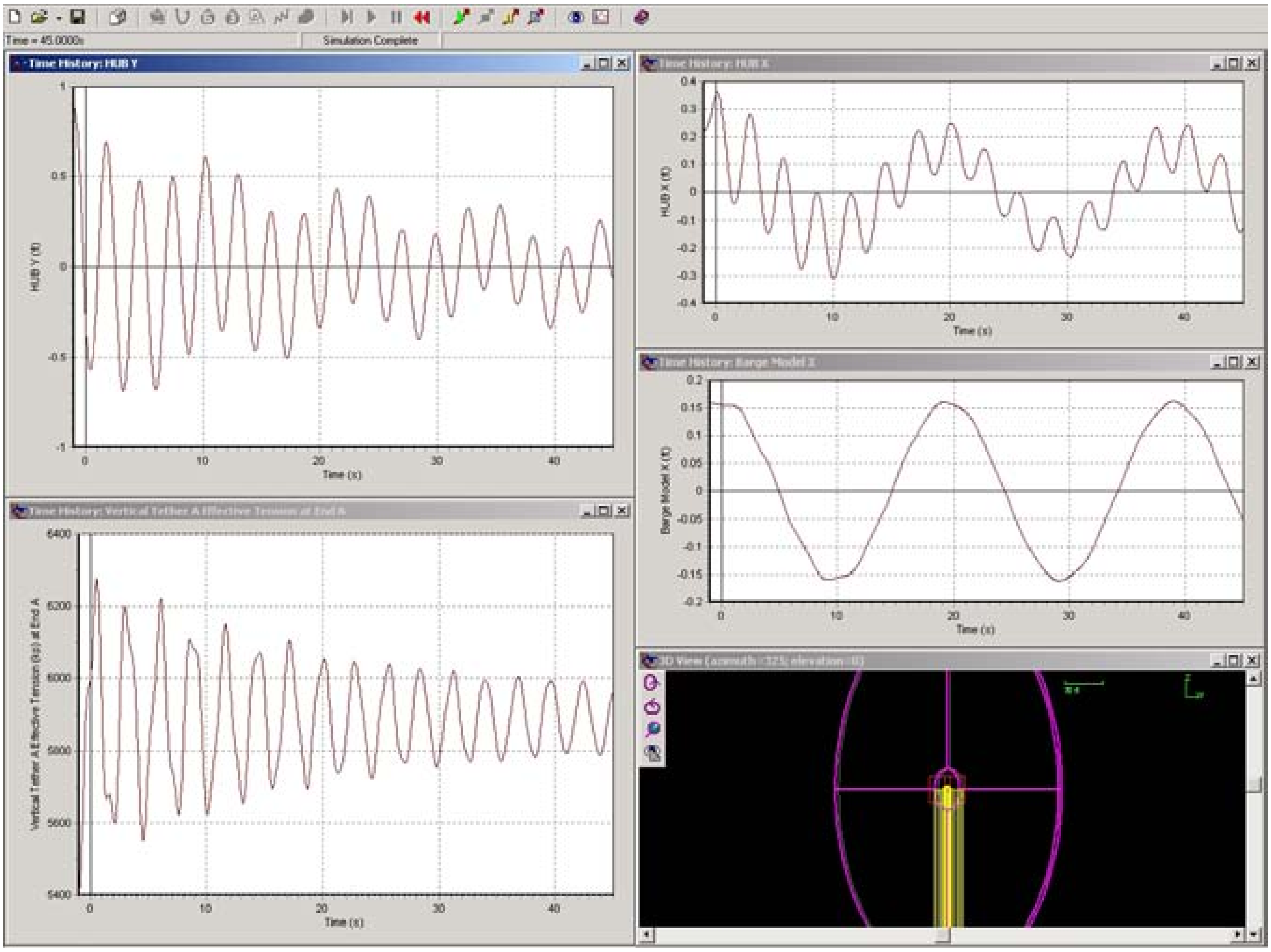


Figure F-4 – Horizontal pluck test

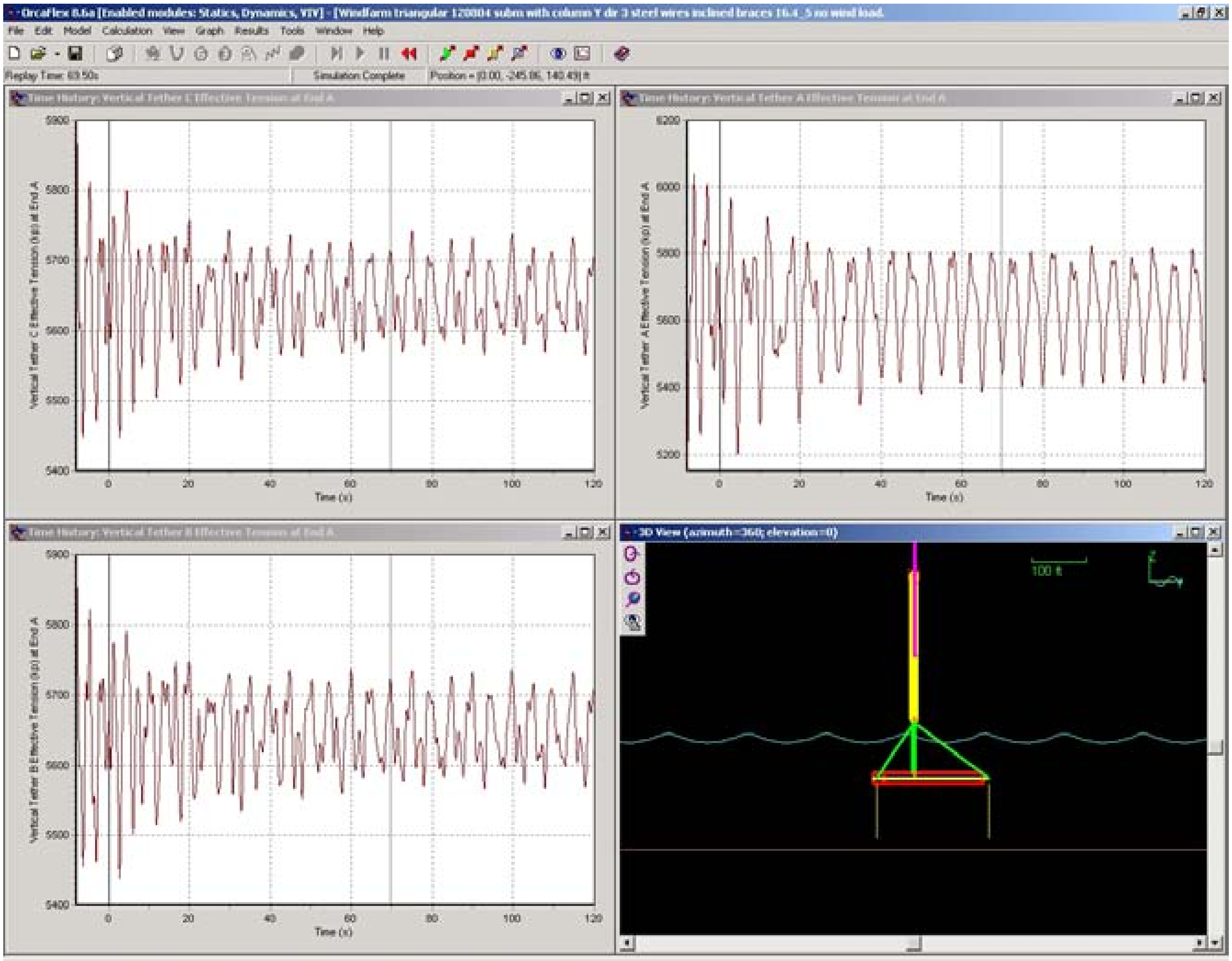


Figure F-53 – Wave 5-m height, 5-s period no wind

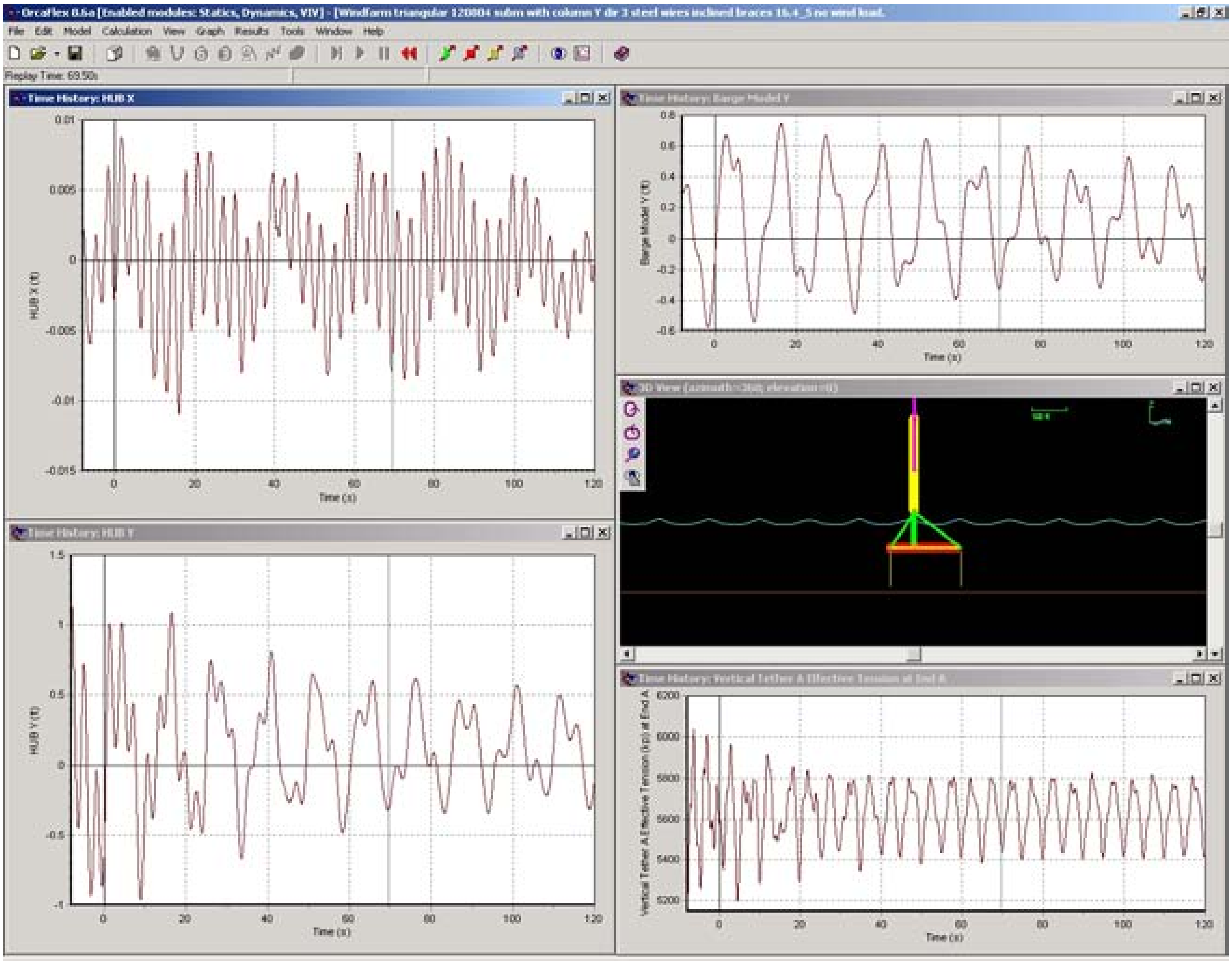


Figure F-6 – Wave 5-m height, 5-s period no wind 2nd screen

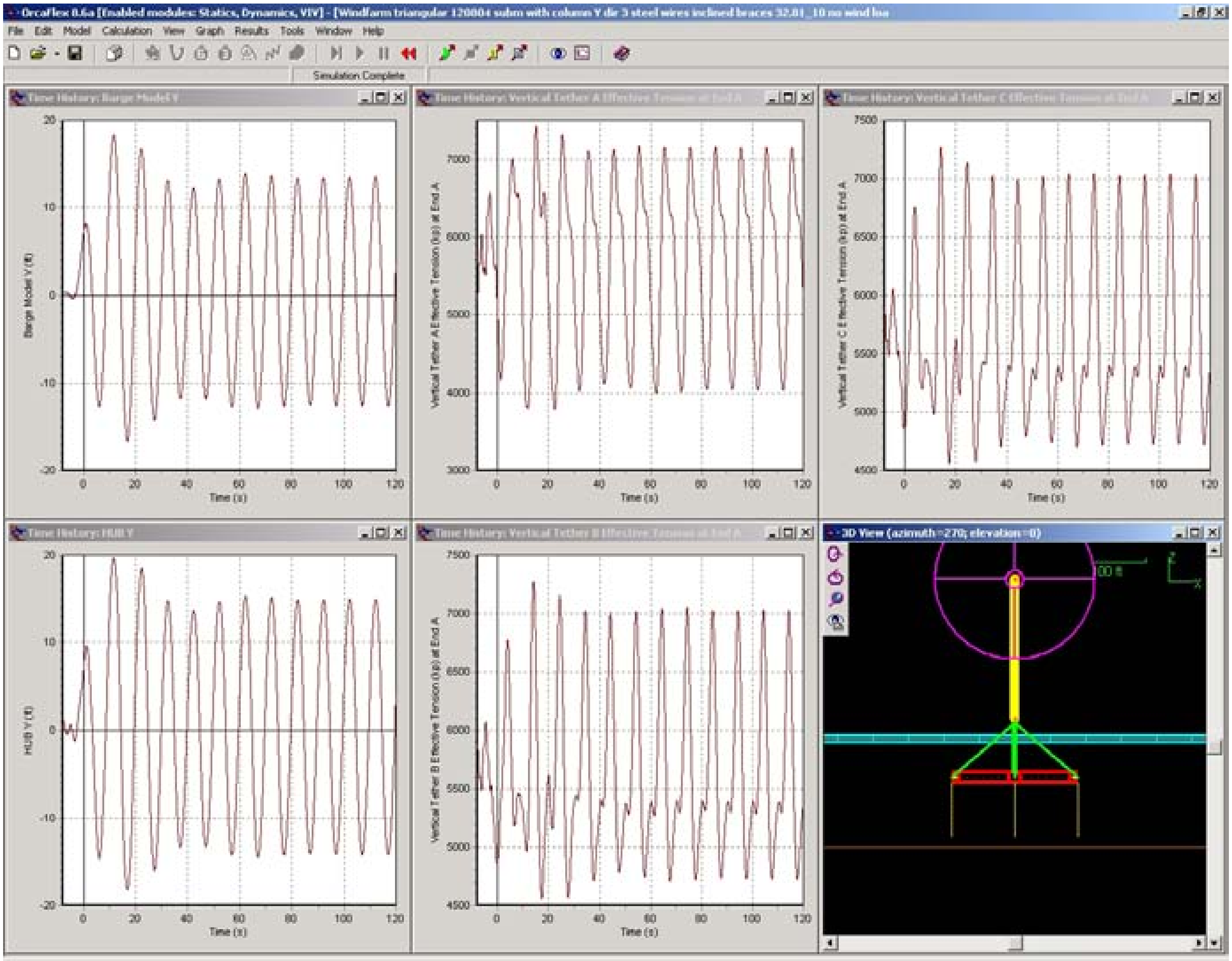


Figure F-7 – Wave 5-m height, 10-s period no wind

Appendix G
Cost Analysis for Balance of Station

Summary

Item	Description	High	Low
Item 1	Mobilization, Plant and Equipment	232,000	200,000
Item 2	Permits and Engineering	57,000	57,000
Item 3	Gravity Anchor	1,602,000	1,252,000
Item 4	Semi-Submersible Platform	1,783,000	1,343,000
Item 5	Tension Legs, Winches, and Porches	1,823,000	910,000
Item 6	Deployment	161,000	161,000
Item 7	Electrical Interface	1,475,000	1,475,000
	Balance of Station Cost	7,133,000	5,397,000

NOTE: The high estimate is based on the following detailed cost breakdown without benefit of system optimization. The low estimate is based on optimization of the system design and improvement of manufacturing techniques as described in Section 6, Cost of Energy.

Table G-1. Detailed Cost Analysis for Balance of Station

Item	Description	Assumption	Quantity	Units	Price/Unit	Extension	Total Units	Summary Unit Cost	BOS Cost
	A. Mobilization, Manufacturing Plant and Equipment								
1	Dry-dock form or multi-barge assembly	Assume 4 steel barges welded together to establish a sinkable work platform or fabricate a special dry-dock casting platform.	4	each	500,000	2,000,000	8	$16,000,000	
2	Site preparation (4 facilities)	Permanent production site may require establishing way platforms, seawall access, staging areas, assembly areas, and overall equipment access lanes.	8	acres	20,000	160,000	4	$640,000	
3	Land rental (4 facilities)	Permanent work site for full production to include 800−1000 ft of water front with vertical access and a minimum of 5−8 acres of backland.	8	Acres/ month	2,000	16,000	48	$768,000	
4	Office facility on site (4 facilities)	Permanent work site to include production office facility, 3 workmen facilities, on site utilities, and standard office equipment.	1	each/ month	3,000	3,000	48	$144,000	
5	Concrete plant on site (4 facilities)	On site concrete plant to be sufficiently sized to supply a minimum of 30−40 yd of batched concrete per hour.	1	each	500,000	500,000	4	$2,000,000	
6	On site equipment (4 facilities)	Equipment would include 1 tower crane, 1 rubber tired crane, 1 loader and 2 forklifts, 3 pickup trucks, plus misc. equipment as needed.	1	each/ month	54,000	54,000	48	$2,592,000	
7	Operational staff (4 facilities)	Including a project manager, superintendent, office engineer, clerical	1	each/ month	22,500	22,500	48	$1,080,000	
		Total Item A.						$23,224,000	$232,240
	B. Gravity Anchor Structure								

Item	Description	Assumption	Quantity	Units	Price/Unit	Extension	Total Units	Summary Unit Cost	BOS Cost
8	Steel form	All forms to be 8-in. x 3/8-in. channel prepared and set up for casting as tilt up panel sections. Forms include all interior and exterior walls.	560	tons	2,500	1,400,000	8	$11,200,000	
9	Top support forms	Form work to consist of wooden sheeting, framing, and kickers to support the final deck section pour of the top.	27,000	ft^2	5	135,000	100	$13,500,000	
10	Misc. piping	Misc. internal piping, pumps and related fittings, and casting. Components would be specific to controlling the flotation and ballast of the anchor.	1	each	15,000	15,000	100	$1,500,000	
11	Concrete placement	Includes reinforcing steel, concrete, and concrete placement of all concrete for pre-cast wall panels, closures, plus top and bottom sections.	2,540	yd^3	400	1,016,000	100	$101,600,000	
12	Set pre-cast panels	Pre-cast panels to be set in positions, reinforcing steel make-ups completed, closure forms set, and closure poured.	12	sets	5,000	60,000	100	$6,000,000	
13	Production labor (4 facilities)	Assume 3 separate crews of 15 each for set up, casting, and stripping etc.	10,800	MH/ month	50	540,000	48	$25,920,000	
14	Tug service (during casting)	Assume 20 h of support in control and positioning forms during casting operation.	20	h	250	5,000	100	$500,000	
	Total Item B.							$160,220,000	$1,602,200

Item	Description	Assumption	Quantity	Units	Price/Unit	Extension	Total Units	Summary Unit Cost	BOS Cost
	C. Semi-Submersible Platform Structure								
15	Steel forms	All forms to be 8 inch by 3/8 inch channel prepared and set up for casting as tilt up panel sections. Forms include all interior and exterior walls.	560	tons	2,500	1,400,000	8	$11,200,000	
16	Top SUPPORT Forms	Form work to consist of wooden sheeting, framing, and kickers to support the final deck section pour of the top.	27,000	ft^2	5	135,000	100	$13,500,000	
17	Misc. piping	Misc. internal piping, pumps and related fittings and casting. Components would be specific to the operation for floatation and ballast of the platform.	1	each	15,000	15,000	100	$1,500,000	
18	Winch house	Formed as part of an internal compartment to house winches, cable drums, and related operational equipment. Deployment equipment to be operated from surface support equipment vessel.	175,000	ft^2	2	350,000	100	$35,000,000	
19	Concrete placement	Includes reinforcing steel, concrete, and concrete placement of all concrete for pre-cast wall panels, closures, plus top and bottom sections.	2,117	yd^3	400	846,800	100	$84,680,000	
20	Set pre-cast panels	Pre-cast panels to be set in positions, reinforcing steel make-ups completed, closure forms set, and closure poured.	12	sets	5,000	60,000	100	$6,000,000	
21	Production labor (4 facilities)	Assume 3 separate crews of 15 each for set up, casting, and stripping etc.	10,800	MH/ mo	50	540,000	48	$25,920,000	
22	Tug service (during casting)	Assume 20 h of support in controlling and positioning forms during casting operation.	20	h	250	5,000	100	$500,000	
	Total Item C.							$178,300,000	$1,783,000
	D. Tension Leg Wire Ropes, Winches, and Porches								

Item	Description	Assumption	Quantity	Units	Price/Unit	Extension	Total Units	Summary Unit Cost	BOS Cost
23	Wire rope (6-ft diameter)	Assume 9 lengths @ 250 feet per length. Wire rope weight 65 lbs/ft	2250	ft	125	281,250	100	$28,125,000	
24	Triple drum wench system	Triple drum wench assumed to have a tensioning capacity for 10,000 kips and a braking rating of 20,000 kips. All related wench hydraulic operational gear.	3	each	450,000	1,350,000	100	$135,000,000	
25	Turbine mast supports & porch components	4-ft diameter piping, 3 sections, assumed length of 160 ft each, welded to turbine mast and secured to platform. Porch beams.	1	unit	192,000	192,000	100	$19,200,000	
		Total Item D.						$182,325,000	$1,823,250
	E. Deployment								
26	Tug service (tow and deploy)	Assume one day out for towing operation, 4 days to deploy turbine assembly, and one day return. Operation to include 2 tow tugs and one support tug. Based on 24 hr. days.	432	h	350	151,200	100	$15,120,000	
27	Equipment support vessel	Support vessel to include pumps, generators, compressors, crane, piping, fittings, personnel quarters and safety equipment needed to deploy assembly.	1	each	950,000	950,000	1	$950,000	
		Total Item E.						$16,070,000	$160,700

	F. Other								
28	Electrical interface	Transformers, cables and connections	1	lump sum	13,150,000	13,150,000	1	$13,150,000	
29	Permits and engineering	Federal and local environmental permits, engineering and management (3% of Project cost)	1	lump sum	17,198,677	17,198,677	1	$17,198,677	
	Total Item F.							$30,348,677	$303,487

Total Project Cost	$590,487,677	
Per Unit Cost	$5,904,877	$5,904,877

Appendix H
Hydrogen Production Transport and Storage System

Appendix to NREL concept study report of semi-submersible platform and anchor foundation systems for wind turbine support.

By Harry E. Dempster

G.1 SYNOPSIS

Our computer modeling study confirms that a sub-surface concrete support platform is a viable cost effective solution to the installation of wind farms in deep water far from the shoreline view shed. However, the further you move the wind farm from shore the more it cost to transport the electrical energy. We feel that the solution to this problem is to convert the electrical energy at the wind farm to liquid hydrogen and transport it by barge to where it is needed.

G.2 ADVANTAGES OF THIS SYSTEM

1. Locating the system far offshore in Federal or international waters would circumvent many of the problems of permitting and damage to the shore line view shed. If placed two hundred miles offshore a liquid hydrogen loaded transport barge could be towed to an onshore facility in one day.

2. Presently there is about a 25% loss of energy when converting electricity to hydrogen. However in the open ocean a stronger more consistent wind will produce a higher energy yield that would compensate for this loss.

3. Placing the production and storage barges below the wave action removes them from view and protects them from high sea conditions. The barges can quickly be submerged or re-floated for transport or maintenance.

4. An open ocean wind farm using the barge shipping method would be free to locate in areas of the highest and most consistent wind conditions without the concerns of cabling into a local electrical grid.

5. Storing the hydrogen in a submerged barge at a gas transfer location some distance from populated shore areas would reduce the concerns regarding onshore explosion or terrorist act.

6. The fabrication, transportation and maintenance of this type of system would provide employment for a large number of semi skilled American workers.

7. With such a system in place we could reduce our dependency on importing a polluting fuel from unreliable supply source and become an exporter of a renewable clean American energy.

8. With the proper funding, a wind energy hydrogen transport and storage system could be engineered, fabricated and placed into operation within four years.

Following is a general description of the system for the production, transport, and storage of hydrogen gas *(see attached drawings figures 1 through 12)*.

Figure 1: Illustrates a sub-surface wind turbine hydrogen production facility located at a deep water high wind area. Electrical energy produced by the wind turbine (1) is conducted by an underwater cable (2) to a sub-surface concrete production barge (3) to power a hydrogen production system. The production barge is held in place by anchoring cables (4) that extend up from the dead weight re-floatable concrete anchor (5) to surface attachment buoys (6) that hold the cables in place. The production barge (3) is equipped with a desalination (7), electrolysis (8) and gas compression system (9) that converts ocean water into liquefied hydrogen. The liquid hydrogen is transferred by a floating high pressure hose (10) to a sub-surface concrete storage / transport barge (11). When filled with liquid hydrogen the transport barge would be re-floated by filling its ballast tanks as it winches its self upwards along anchoring cables (4). When at the surface, transfer hose (10) and anchor cables (4) are disconnected and the barge is towed to a offshore gas transfer terminal.

Figure 2: Depicts the transport barge at the transfer terminal connected to floating anchoring cables (4) and land transfer hose (10). In figure 3 the barge has released air from the ballast tanks and is winched below the wave action and out of view.

Figure 4: Shows the production barge (3) being fitted with desalination (7), electrolysis (8) and gas compression (9) systems that are preassembled fully operational systems enclosed within water tight containers (12). The barge (3) has been fabricated on top of the anchor (5) that will be deployed at the installation site. The barge is equipped with attachment winching system (13) that will lock onto the buoy supported anchoring cable, (4) and allow the barge to move up and down along the cable.

Figure 5: Is an elevation of the production barge in an operational position below the wave action.

Figure 6: Shows the storage / transport barge (11) being fitted with high pressure hydrogen storage tanks (14). The fabrication sequence is to form the basic floating barge with cavities shaped to accept the storage tanks.

Figure 7: Is a center section view of the transport barge (11) having ballast tanks (15), and showing concrete incased storage tanks (14). A thick layer of concrete (15) is poured over the tanks which will add strength to and protect the storage tanks.

FIGURE 1

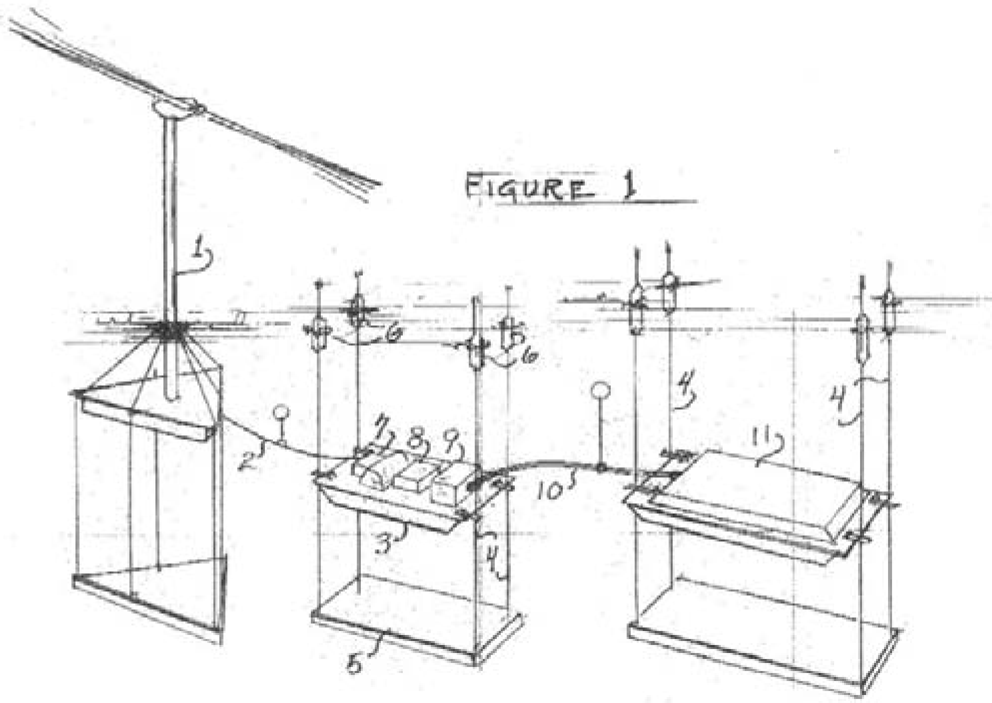
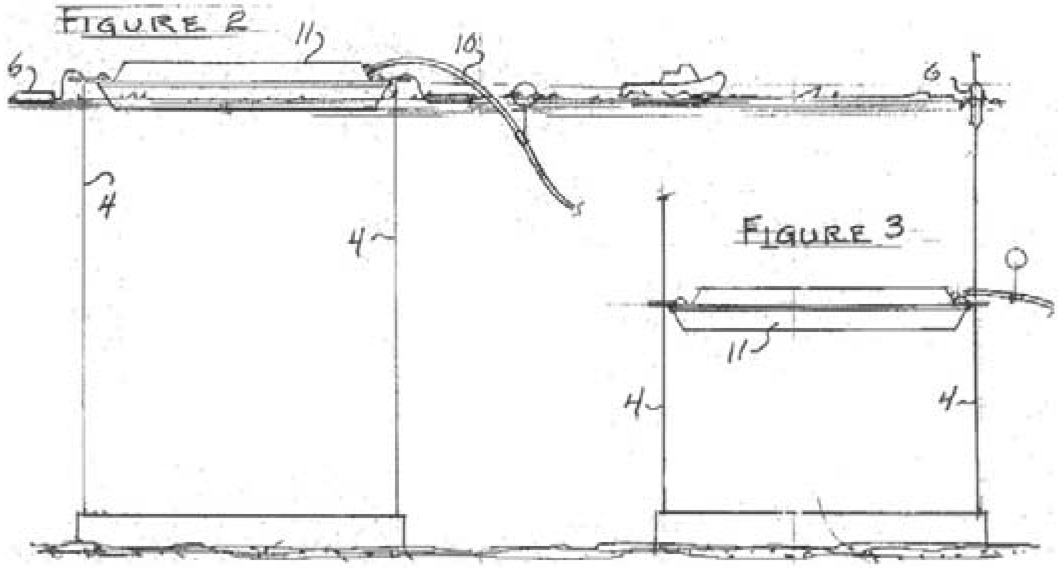


FIGURE 2

FIGURE 3



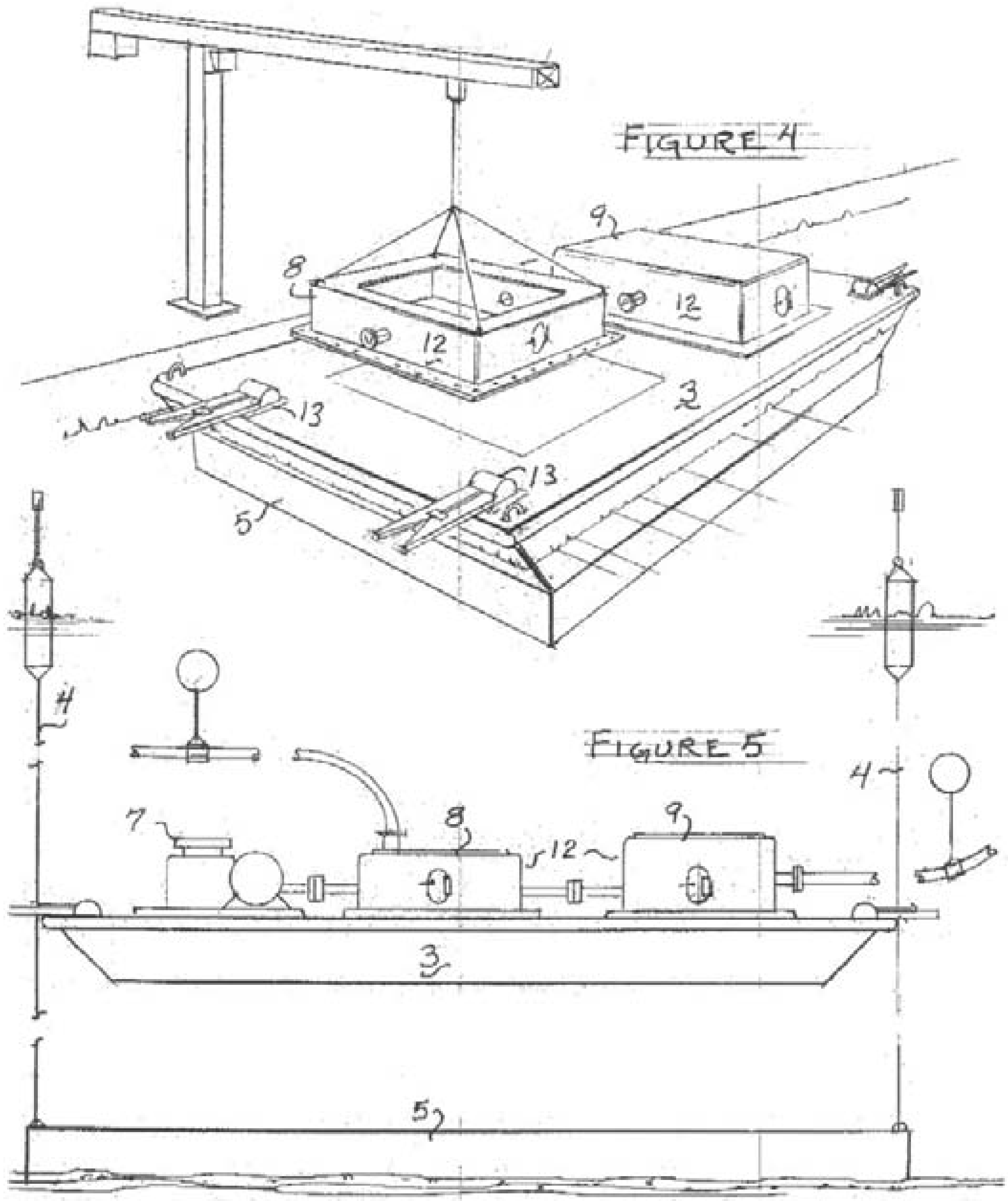


FIGURE 4
9
8
12
12
3
13
13
5
4
FIGURE 5
4
7
8
9
12
3
5

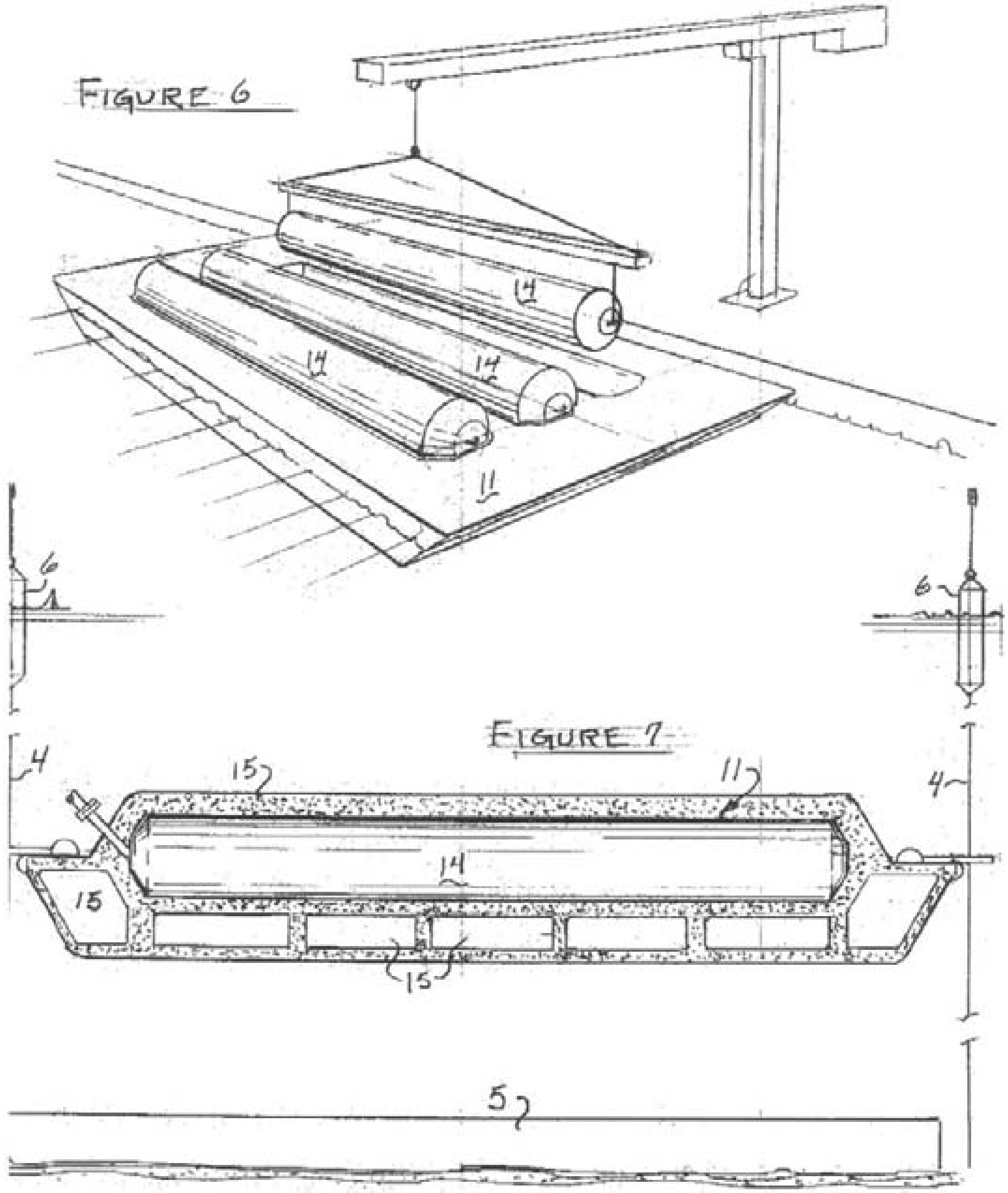


FIGURE 6

FIGURE 7

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. **REPORT DATE** *(DD-MM-YYYY)*	2. **REPORT TYPE**	3. **DATES COVERED** *(From - To)*
December 2007	Subcontract Report	8/30/2004 - 5/31/2005

4. **TITLE AND SUBTITLE** Semi-Submersible Platform and Anchor Foundation Systems for Wind Turbine Support: August 30, 2004 – May 31, 2005	5a. **CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. **GRANT NUMBER**
	5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** G.R. Fulton, D.J. Malcolm, H. Elwany, W. Stewart, E. Moroz, and H. Dempster	5d. **PROJECT NUMBER** NREL/SR-500-40282
	5e. **TASK NUMBER** WER6.0701
	5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Concept Marine Associates Inc. 6700 East Pacific Coast Highway, Suite 201 Long Beach, CA.	8. **PERFORMING ORGANIZATION REPORT NUMBER** YAM-4-33200-10
9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. **SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. **SPONSORING/MONITORING AGENCY REPORT NUMBER** NREL/SR-500-40282

12. **DISTRIBUTION AVAILABILITY STATEMENT**
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. **SUPPLEMENTARY NOTES**
NREL Technical Monitor: Walt Musial

14. **ABSTRACT** *(Maximum 200 Words)*
This report examines the feasibility of various semi-submersible platform configurations for an offshore deep water wind turbine.

15. **SUBJECT TERMS**
wind energy; wind turbine; offshore wind energy development

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT**	b. **ABSTRACT**	c. **THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18