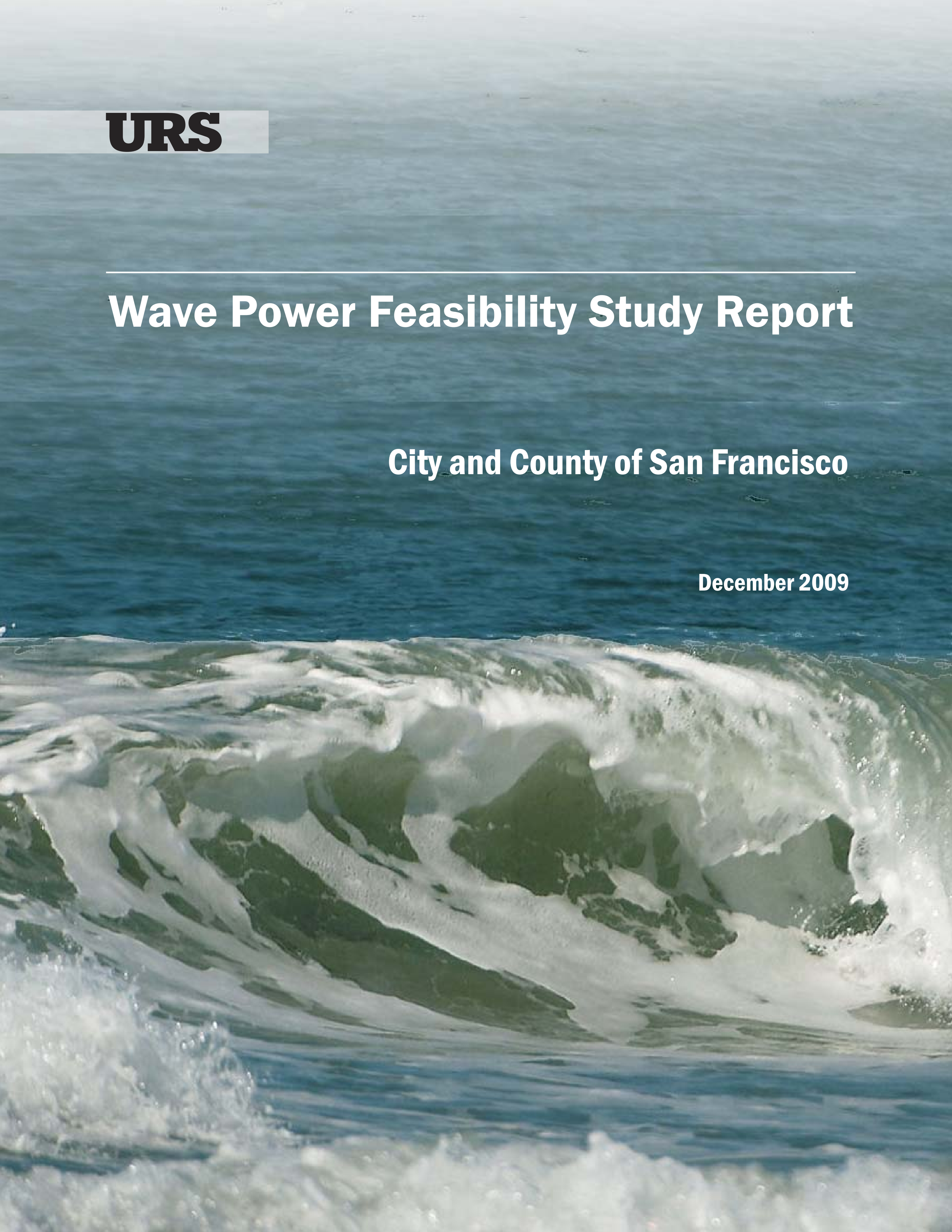

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Wave Power Feasibility Study Report

City and County of San Francisco

December 2009

WAVE POWER FEASIBILITY STUDY REPORT

PREPARED FOR
THE CITY AND COUNTY OF
SAN FRANCISCO

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EXECUTIVE SUMMARY

This report presents the results of a study addressing the feasibility of generating electrical power from waves in the Pacific Ocean west of the City and County of San Francisco (CCSF). The study included site-specific measurement of wave data at a location approximately 8 miles west of San Francisco during the fall and winter of 2008-2009 to confirm the magnitude of the wave resource. A screening-level assessment of wave energy conversion (WEC) devices identified the status of device development and applicability to a San Francisco project based on site-specific criteria, which were developed considering marine species and habitats, commercial and recreational activities, and regional planning. A limited number of promising wave energy conversion devices were further investigated to develop estimates of annual power generation, and the likely cost of power if a 30-megawatt (MW) wave farm were to be developed in the study area. The results of the study are encouraging, and suggest that over 100 gigawatt-hours (GWh) of power could be produced annually at a cost in the range of 17 to 22 cents per kilowatt-hour (¢/kWh). This cost is comparable with the cost to produce solar photovoltaic power.

WAVE DATA MEASUREMENTS

Analysis of existing wave data from deepwater buoys—including a 27-year record from a National Buoy Data Center (NBDC) buoy near Point Reyes, and two buoys operated by Scripp's Coastal Data Information Program (CDIP)—indicated a positive potential for generation of wave power offshore of San Francisco (see Figure E-1). To collect site-specific wave data that could be correlated with the long-term wave data, a wave gauge (an acoustic Doppler current profiler [or ADCP]) was deployed in September 2008 to collect late summer data, and then again in November 2008 through February 2009 to capture wave data from winter-season storms. The water depth at the deployment location approximately 8 miles offshore was 110 feet. The location was at the outer edge of the buffer zone separating the City's Oceanside Wastewater Treatment Plant ocean outfall from the surrounding Monterey Bay National Marine Sanctuary (MBNMS).

Statistical analysis comparing monthly site-specific data sets with monthly data from the long-term buoy records found the NBDC to be closely correlated with the site-specific ADCP data set. The NBDC buoy is in almost 200 feet of water, approximately twice the water depth at the outer edge of the buffer zone. Although the NBDC buoy data set does not contain direction data, direction representative data are available from a CDIP buoy west of the NBDC buoy. Transfer functions for wave height and period were developed to convert the NBDC data to that at the ADCP site to obtain an annual project-specific data set for use in estimating power production.

Monthly average significant wave heights in the annual data set range from a maximum of 2 meters in December to a minimum of 1.2 meters in August. Monthly average wave energy, measured in kilowatts (kW) per meter of wave front, ranges from a high of 34 kilowatts per meter (kW/m) in December to a low of 8 kW/meter in August, averaging 21 kW/m for the year.

Typical waves periods of between 6 and 15 seconds result in the water depths in the San Francisco study area being classified as intermediate to shallow. In shallower water depths, the motion of water particles under a wave changes from circular to a horizontal ellipse. That is, the horizontal back-and-forth surging motion is larger than vertical up-and-down heaving motion. This is one factor applied in the evaluation of the WECs most suitable for use at the San Francisco site.

WAVE ENERGY CONVERSION DEVICES

The development of the new WEC devices is at an early, but extremely dynamic, stage. More than 100 concepts have been proposed worldwide; and because of the interest in marine renewables, the number of concepts grows every month. Although many concepts have progressed to tank testing of scale models, a much smaller number have been developed to the stage of sea trials of prototypes to test the survivability and reliability of devices. The marine environment is very severe, particularly during winter storms, and prototype tests are critical to demonstrate the robustness of structural, mechanical, and electrical systems. Approximately 20 prototypes (one-quarter to full size) have been tested at wave centers in Europe and in pilot projects in the USA and Australia.

WEC devices can be sorted into six categories based on the type of wave motion from which the devices produce energy. Ocean Power Delivery's "Pelamis" is an example of *attenuators*, or *surface pitching devices*, which flex as waves pass beneath. The category with the greatest number of devices developed to date—*heave devices* or *point absorbers*—tend to look like large buoys; for example, Ocean Power Technologies' "Powerbuoy." The *oscillating surge devices*, which produce energy from the horizontal back-and-forth motion of nearshore waves, may be particularly suitable for the San Francisco project because they are fully submerged. Aquamarine Power's "Oyster," AW-Energy's "WaveRoller," and BioPower Systems' "BioWave" are examples of this type of device. Other types include *oscillating water column devices* that capture energy from air movement above large or breaking waves, and bottom-mounted pressure devices.

Submerged devices would obviously minimize any visual impacts from a San Francisco wave farm in the study area. The potential impacts of mooring systems on marine mammals are an important consideration for surface devices. These and other siting and environmental factors were evaluated to develop site-specific screening criteria for WEC devices.

SITE CONSIDERATIONS AND SCREENING CRITERIA

The study area in the buffer zone around the Southwest Ocean Outfall was selected in consideration of the MBNMS goals, which include resource protection, research, education, and public use. Because the buffer zone contains a municipal wastewater discharge, the zone is not subject to the requirements of the MBNMS management plan (MBNMS, 2008). In addition, the existing outfall right-of-way provides a logical route for a power cable alignment to the shore. Wave energy tends to increase with distance offshore; however, industrial activities are not permitted within the marine sanctuary. Because species in the adjacent protected habitat do not recognize administrative boundaries, the project will need to be protective of species, especially migrating gray whales. Prevention of marine mammal entanglement in mooring systems is therefore a project requirement.

Aesthetic impacts are also a key factor given that tourism is very important to San Francisco, and that residential and beach areas face the ocean. Other factors that have been identified during initial public outreach include commercial fishing activities in the site area, particularly Dungeness crab fishing grounds, and recreational sport fishing, among other recreational activities. Dredging operations for the Ocean Beach and Great Highway restoration program and the presence of commercial vessel traffic lanes entering and exiting San Francisco Bay have also been recognized. Other potential impacts that will be evaluated in future studies include the electromagnetic fields surrounding power generation and submarine cables, and the potential for underwater noise from device motion. A 3-year environmental study and permitting process addressing these issues has been assumed, leading to a pilot installation of one or more WEC devices.

A set of screening criteria was developed based on the site constraints, environmental factors, schedule, and financial considerations. Key criteria include:

- Prototype testing by the technology developer or others to be completed successfully by 2010 to enable pilot deployment by CCSF in 2012 or 2013;
- WEC devices must be rated for operations in 100-foot water depths and 20 kW/m wave energy climate; and
- Minimal aesthetic impact and an entanglement-proof mooring system.

Application of these criteria to WEC devices that have progressed to prototype testing indicates that fully submerged surge-type devices with single-point seabed foundations are well matched with the wave resource, water depth, and environmental considerations. However, given the world-wide interest in marine renewable power, many new devices are under development at this time, and a number of at-sea prototype tests are planned for this year. Thus, devices that are undergoing prototype testing through 2010 could be considered for a pilot installation.

COST OF POWER

The annual wave data set developed from the ADCP deployment was used to estimate the annual power production from a 30 MW wave farm in the study area. Power production was estimated at between 100 and 150 gigawatt-hours (GWh) per year. This is enough power for approximately 22,700 to 34,000 San Francisco households (or up to 10 percent of the City's 329,700 households), based on 2007 data that show average annual consumption of 4,400 kilowatts per hour (kWh) per San Francisco household (CEC, 2009).

Major project costs can be separated into capital and operation and maintenance (O&M) costs. Capital cost items for marine renewable power include the WEC devices, foundations or moorings, a subsea power hub and submarine cable, onshore grid connection and substation upgrades, federal and state leases, environmental clearances and permits, and project financing. There are large uncertainties with a number of costs, particularly subsea power hubs and O&M costs. The approach to power conditioning (stepping up voltage) for transmittal to shore is still evolving, but is expected to require bottom-mounted or surface transformers. Because there are no wave farms operating anywhere in the world, estimates for O&M costs cover a wide range. A conservative range (a combined 40 percent of initial capital for O&M and annualized equipment replacement costs) was used in the economic analysis.

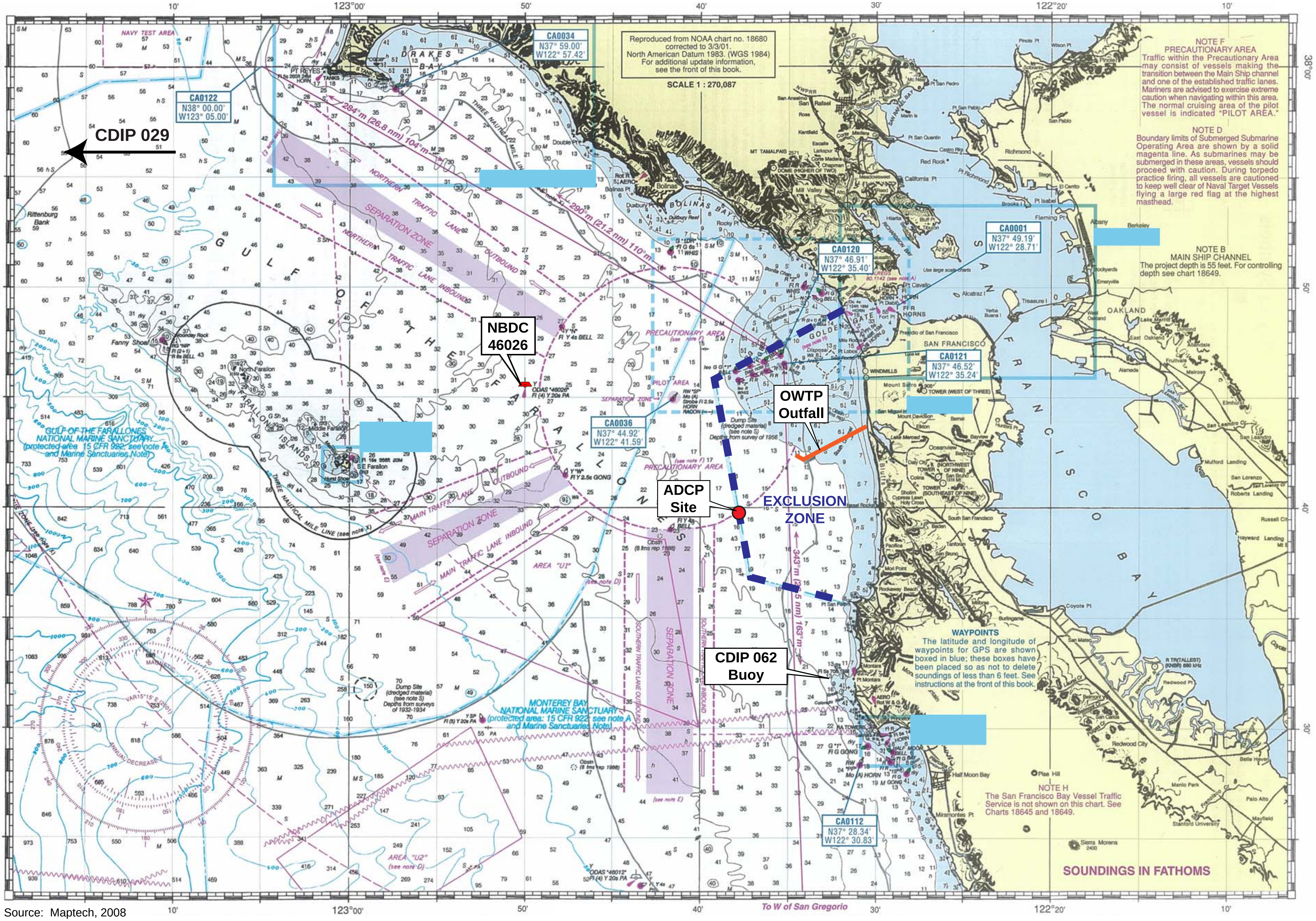
Marine renewable energy projects do not enjoy the same subsidies as wind power, which are in the form of production tax credits and double declining depreciation. The American Recovery and Reinvestment Act (ARRA) of 2009 extended the production tax credits and investment tax credits for wind and solar power, and provides a 2.1-cents-per-kWh (¢/kWh) credit for the first 10 years of a renewable energy facility's operation. For other renewable projects, including marine renewables, the ARRA provides a smaller tax credit of 1.0 ¢/kWh. By comparison, European ocean power projects enjoy government subsidies of up to 30 ¢/kWh, which helps explain Europe's lead in the development of ocean power technologies and test centers.

Equating the power production with the estimated annual project cost yields the cost of power in ¢/kWh. Making mid-range and conservative estimates for uncertainties, including power conditioning and O&M costs yields wholesale costs of wave energy for a 30-MW wave farm in the range of 17 to 22 ¢/kWh. This range is more expensive than wind power (range of 7 to 8.5 ¢/kWh, not including a 2.5 ¢/kWh tax credit) and conventional hydrocarbons (range of 10 to 12

¢/kWh), but is comparable to the cost of producing solar photovoltaic power before tax credits and other incentives are applied.

CONCLUSIONS

The analysis of the wave resource, technology, and economic feasibility indicate that there is sufficient wave energy in the buffer zone around the Southwest Ocean Outfall west of San Francisco to generate power using submerged surge technology at a cost similar to solar photovoltaic energy projects. Wave energy conversion device development is at an early stage, and with no operating wave farms to provide precedence or to base reliability and O&M assumptions, many uncertainties still exist; however, wave power appears to be much more feasible than in-stream tidal power previously studied by CCSF, with a considerably larger power generation potential at significantly lower costs.



Source: Maptech, 2008

ADCP LOCATION AND BUOY SITES

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San Francisco Public Utilities Commission
San Francisco, CA

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FIGURE E-1

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1.0 INTRODUCTION

1.1 BACKGROUND

This report presents the findings of a screening-level feasibility study addressing development of wave power in the Pacific Ocean west of San Francisco.

The scope of this study includes the following tasks:

- Assessment of the wave resource west of San Francisco using existing and site-specific data;
- Screening level assessment of WEC technologies;
- Identification of one or more technologies to carry forward for consideration for pilot studies; and
- Assessment of the economic feasibility of wave energy based on the annual generation of wave power, and the cost of a wave farm west of San Francisco.

This report presents the results of these tasks. Section 2 describes the wave resource assessment, including the deployment of a wave gauge in the project study area. Section 3 presents a description of the types of wave energy conversion devices and the devices that have advanced to the stage of sea trials. Section 4 describes site-specific considerations, identified in the study area during initial stakeholder outreach, and the resulting screening criteria. Economic considerations and the estimated cost of power are presented in Section 5.

1.2 STUDY AREA

The study area considered in this report focuses on the "buffer zone" surrounding the 4.5-mile-long Southwest Ocean Outfall from the SFPUC Oceanside Wastewater Treatment Plant in the Pacific Ocean west of the CCSF (see Figure 1-1). The buffer zone (also known as the exclusion zone) is an approximately 10.5-mile (north-south) by 8-mile (east-west) area that has been excluded from the Monterey Bay National Marine Sanctuary. The water depth at the outer western edge of the buffer zone is approximately 110 feet (33 meters). The water depths on the eastern edge of the study area, 1 to 1.5 miles from shore, range from 60 to 75 feet (18 to 23 meters).

The project study area shown in Figure 1-1 is approximately 6.5 miles wide (10.5 kilometers) in the alongshore direction (north-south); and 5.5 miles (8.9 kilometers) in the offshore direction (east-west), resulting in an area of 36 square miles (92.6 square kilometers). The study area has the following coordinates:

Point	Latitude	Longitude
1	37° 37.00'N	122° 31.50'W
2	37° 37.00'N	122° 37.25'W
3	37° 42.50'N	122° 38.25'W
4	37° 42.50'N	122° 32.50'W

1.3 PROJECT DESCRIPTION AND SCHEDULE

Initial evaluation of existing regional wave data for this study in 2008 indicated a positive potential for production of wave power. A description of a wave farm in the study area was developed for a Federal Energy Regulatory Commission (FERC) Preliminary Permit application submitted in February 2009 (named the San Francisco Oceanside Wave Energy Project). A Memorandum of Understanding between FERC and the Minerals Management Service (MMS) issued on April 9, 2009, determined that the FERC permitting process for wave power projects in federal Outer Continental Shelf (OCS) waters outside of the State 3-mile limit require a MMS Lease before a FERC permit could be considered complete. FERC therefore dismissed the San Francisco February 2009 application because, as submitted, the San Francisco wave energy project was in OCS waters and did not have a MMS lease (FERC, 2009).

Project elements for the San Francisco Oceanside Wave Energy Project include WEC devices, submarine transmission and fiber optic communication cables, and onshore interconnection to the electrical grid. A submarine transmission cable would carry power from the project area to shore (see Figure 1-1) for connection to the grid in San Francisco. To minimize the area of disturbed sea bottom, the cable alignment would follow the alignment of the existing Southwest Ocean Outfall pipeline from the Oceanside Wastewater Treatment Plant.

The study area has been delineated to allow consideration of wave energy generation inside State waters (inside the 3-mile nautical line) or on the OCS. Once the FERC Preliminary Permit is approved, a 3-year period of focused studies would lead to a pilot installation. The initial pilot deployment is expected to be comprised of one to three WEC devices, with an installed capacity of up to 3 MW. The project would then be incrementally expanded to a rated capacity of 10 to 30 MW.

2.0 WAVE RESOURCE EVALUATION

Both existing and site-specific wave data were evaluated to determine the characteristics of the wave resource offshore of San Francisco. Four months of wave data collected in the study area were compared with long-term deep-water buoy records to develop a typical data set for the site. The site data set was then used to calculate wave power in the project area, and to estimate the annual rate of power generation.

2.1 LONG-TERM WAVE BUOY DATA

Wave data have been collected at a number of locations in the vicinity of the project site, as shown on Figure 2-1. The National Buoy Data Center's (NBDC) Buoy 46026 is located approximately 20 miles west of the Golden Gate. Wave data have been collected at this location since 1982, and contain swell height and period data recorded every hour. Scripp's Coastal Data Information Program (CDIP) also has two buoys in the area: Buoy 062 to the south of the project site just offshore of the town of Montara; and Buoy 029 in deep water approximately 21 miles west of Point Reyes. The CDIP buoys collect direction data, in addition to wave height and period data collected at the NBDC sites.

The swell record from CDIP 062 extends from December 1986 to March 1992, but several months are missing. This record contains swell height, period, and direction taken every 3 hours. Based on CDIP's swell refraction model, Buoy 062 is in an area in the shadow of the Farallon Islands with regard to the predominant northwestern swells, as shown in Figure 2-2. CDIP 062 is not considered to provide a good representation of a wave buoy at the project site.

The record from CDIP 029 extends from December 1996 to the present with only one month of missing data. This record contains hourly swell height, period, and direction data. Buoy 029 is in open water and is not subject to any island effects, and therefore is representative of the deep water energy available west of San Francisco. A wave rose of the 2008 data set for Buoy 029 (Figure 2-3) shows that almost 70 percent of waves, and a higher percentage of the largest waves, originate from the northwest (315°) and west-northwest (292.5°). Figure 2-4 shows the monthly distribution of significant wave heights (H_S, the average of the highest one-third of all waves) for 2008. In 2008, the average Hs ranged from highest in February (3.3 meters) to lowest in September (1.2 meters). The largest wave events also occurred in February, with individual storm events topping 9 meters (29.5 feet).

A comparison of the histograms of significant wave height over the total periods of record at CDIP 029 and NBDC 46026 is shown in Figure 2-5. The patterns are similar; however, both the mode of the wave heights (most frequent waves) and the absolute wave heights are slightly lower at NBDC 46026, reflecting the buoy's location closer to shore and in shallower water. NBDC 46026 is also sheltered from the approximately 10 percent of storms that come from the north-northwest, as shown on Figure 2-3.

Based on its location to the northwest of the project site, the NBDC 46026 data set is considered to be most representative of the long-term wave data sets that have been collected in the project vicinity. The NBDC buoy is in almost 200 feet of water, approximately twice the water depth at the outer edge of the exclusion zone. Although the NBDC buoy data set does not contain direction data, the direction data from the CDIP 029 buoy in deeper water west of the NBDC 46026 location should be applicable, with the caveat that Point Reyes to the north and the Farallons to the southwest will moderate storms approaching from those directions.

2.2 SITE-SPECIFIC ADCP WAVE DATA COLLECTION

To obtain site-specific wave energy data at the project site, and to be able to correlate the long-term data sets with the shallower site conditions, wave data were collected at the outer edge of the exclusion zone during the late summer (September 2008) and winter (November to February 2009). As seen in the monthly distribution of wave heights at CDIP Buoy 029 (Figure 2-4), the two periods correspond to the minimum wave season and maximum wave seasons. These site-specific wave data were compared to the historic buoy data to assess for transformation or attenuation of wave energy on the edge of the San Francisco exclusion zone.

The deployment location for the Teledyne Acoustic Doppler Current Profiler (ADCP) wave data recorder used in the studies is shown in Figure 2-1. The site is approximately 9 miles offshore of San Francisco in a water depth of 110 feet. The wave data recorder collects wave period, height, and direction data via a unit mounted on the seafloor. Current speed and direction are also recorded. The data recorder was deployed and recovered by Dixon Marine Services, Inverness, California.

2.3 WAVE ENERGY AND WEIBULL DISTRIBUTIONS

This section provides a detailed mathematical assessment of wave energy, and assumes a basic understanding of wave dynamics. A simplified description of wave terminology is provided in the introduction to WEC devices, Section 3.2.

The ADCP records significant wave height and wave period. The following section presents the equations used to calculate wave energy and wave power from the raw data, and to calculate Weibull probability density distributions for statistical comparison of the ADCP and the long-term buoy data sets. Weibull distributions accurately describe natural phenomena such as long-term wind speed data and wave velocity (which is a function of wave height and period); that is, data sets that have a relatively small proportion of extreme events. Statistically, they are heavily skewed towards the right.

2.4 WAVE ENERGY AND POWER

Energy density (E) and power per unit width (P) for the waves at each wave gauge were calculated as described below. Basic parameters are:

H	(or H_S) significant wave height
T	wave period
h	mean water depth at buoy location (110 feet, or 33.5 meters)
ρ	water density (1,024 kg/m^3)
g	gravitational acceleration (9.81 m/s^2)
L	wave length
κ	wave number (kappa – angular reciprocal of wave length)

Although the ADCP records wave height and period, wave lengths are needed to calculate wave energy per wave. Wave length can be calculated in a straightforward manner in either shallow water (where wave height is a significant proportion of water depth), or in deep water (where wave height is very small relative to water depth). However, the water depth at the project site falls into the intermediate range, requiring more involved calculations.

The relationship between wave length L and wave number κ is given by the equation 2-1:

$$L = 2\pi / \kappa \qquad (2\text{-}1)$$

Dean and Dalrymple (1991), provides an approximate dispersion relation used to solve for the wave number k in intermediate water depths such as those at the project site:

$$(\kappa h)^2 = y^2 + \frac{y}{1+\sum_{n=1}^{6} d_n y^n} \qquad (2\text{-}2)$$

where d_n are empirical parameters, and y is the approximate dispersion relation given by:

$$y = \omega 2h/g \qquad (2\text{-}3)$$

and circular frequency is:

$$\omega = 2\pi/T \tag{2-4}$$

After solving equation 2-2 for wave number and then 2-1 for wavelength, phase velocity C_p and group velocity C_g can be determined by equations (2-5) and (2-6).

$$Cp=L/T \tag{2-5}$$

$$C_g = \frac{C_p}{2}\left(1+\frac{2\kappa h}{\sinh 2\kappa h}\right) \tag{2-6}$$

Total wave energy density E with units of Joules per square meter (J/m^2) is given by equation (2-7). This is the energy per unit surface area of a wave.

$$E = \tfrac{1}{8}\rho g H^2 \tag{2-7}$$

Potential or kinetic energy density (E_p or E_k) alone are each half the total energy density, so are determined by equation (2-8).

$$E_p = \tfrac{1}{16}\rho g H^2 \tag{2-8}$$

Total power per unit wave width P transmitted by a wave is the energy flux, given by equation (2-9), with units of W/m. The unit width along which P is determined is parallel to the wave crest, or in other words, normal to the direction of wave propagation.

$$P=ECg \tag{2-9}$$

The power per unit wave width due to the wave's potential or kinetic energy alone is half of the total power per unit width. This is given by equation (2-10).

$$Pp=EpCg \tag{2-10}$$

2.5 WEIBULL DISTRIBUTION

The three-parameter Weibull probability distribution is defined in terms of shape, scale, and offset parameters, which can be used to compare different data sets. The shape parameter (k) and scale parameter (λ) are both positive numbers (note that k is not the same κ or kappa used for wave number). The offset or shift parameter (μ) has a value of zero for x less than μ. The Weibull probability distribution takes the form of equation (2-11).

$$f(x) = \frac{k}{\lambda}\left(\frac{x-\mu}{\lambda}\right)^{k-1} e^{-\left(\frac{x-\mu}{\lambda}\right)^{k}} \tag{2-11}$$

Waves were characterized by calculating the histogram of significant wave height H, and then fitting that histogram to the Weibull curve (2-11). In doing this, x in equation (2-11) is the middle wave height of a bin, and f(x) is the number of occurrences in that bin divided by the total number of occurrences in the histogram. The parameters k, λ, and μ are varied to minimize the mean square error between the fit f(x) of equation (2-11) and the histogram of the data. The resulting values of k, λ, and μ characterize the wave height at that site. An analogous analysis is done to characterize the peak wave period T, the potential energy density E_p, and the potential-energy-based power per unit width P_p. Due to the form of equation (2-11), λ and μ have the same units as the quantity being fit (H, T, E_p, or P_p), but k has no units.

2.6 RESULTS

The Weibull fit of equation (2-11) was applied to data from the CDIP 062 and NBDC 46026 buoys, and to the short-term record from the site-specific ADCP wave gauge. At each site, H, T, E_p, and P_p were analyzed for each month over all years. The data for station CDIP 062 are from years 1996-2007. The data for station NBDC 46026 are for years 1982-2006. The ADCP was deployed twice: first in late September 2008 through the end of October 2008; and again in late November through February 2009. Therefore, complete monthly data were collected for October and December through February. The September and November ADCP data are included in the analysis, but are incomplete data sets.

The results of the fitted Weibull parameters are shown in Tables 2-1 through 2-4. Graphical examples of monthly fits for October (lower wave energies) and December winter conditions for the CDIP 062, NBDC 46026, and ADCP data are shown in Figures 2-6 through 2-11. Because of the partial ADCP data sets in September and November, the ADCP results for these months are not particularly meaningful.

The scale parameter (λ) gives the most accessible comparison, because it is an indication of the most frequent magnitude of the factor (H, T, E_p, and P_p) being analyzed. Table 2-1 shows wave heights increasing from lows of 1.4 meters at CDIP 062 and 0.9 meter at NBDC 46026 in September, to maximums of 2.7 meters and 1.8 meters, respectively, in December. Correspondingly, Table 2-2 shows the wave periods at CDIP 062 and NBDC 46026 increasing from short periods of 4.5 and 5.3 seconds in September, to much longer 14.3- and 14.9-second waves in December. Because wave energy is a function of the square of wave height (equation 2-8), the wave energy and wave power also increase in the winter. Table 2-4 shows the power per meter of wave front for CDIP 062 and

NBDC 46026 increases from lows of 24 and 10 kW/m, respectively, in September, to a very significant 71 and 40 kW/m, respectively, in December.

The shape (or slope) factor k indicates the type of distribution. A k value of 1 indicates an exponential distribution; 2 indicates a Rayleigh distribution; and 3 approximates a normal distribution. The offset (μ) is a measure of the lowest value (or datum) for that factor. For example, statistically speaking, wave heights at the CDIP 062 and NBDC 46026 locations are almost always greater than 0.9 meter and 0.6 meter high, respectively.

Table 2-1
Weibull Parameters Fitted to Observed Significant Wave Height

Wave height fits									
	λ (meters)			Shape factor k			μ (meters)		
Month	CDIP	46026	ADCP	CDIP	46026	ADCP	CDIP	46026	ADCP
September	1.4	0.9	0.7	2.2	1.9	1.1	0.9	0.6	0.6
October	1.6	1.1	1.1	1.8	1.8	2.1	0.9	0.6	0.7
November	2	1.5	1.2	1.9	1.9	1.7	0.9	0.6	0.8
December	2.7	1.8	1.3	2.2	1.8	2	0.6	0.6	0.6
January	2.2	1.7	1.9	2.3	1.8	3.8	0.8	0.8	0.2
February	2	1.7	3.2	1.8	2	3.7	1.1	0.7	0.7

Table 2-2
Weibull Parameters Fitted to Observed Peak Wave Period

Wave period fits									
	λ (seconds)			Shape factor k			μ (seconds)		
Month	CDIP	46026	ADCP	CDIP	46026	ADCP	CDIP	46026	ADCP
September	4.5	5.3	19.6	0.8	1.3	5.4	7.7	6.5	-6.6
October	7.5	7.5	5	2.5	2.1	1.4	5.6	5.6	6.6
November	13.8	9.2	12.7	5.5	2.8	6.2	0	4.3	0
December	14.3	14.9	13.1	6.2	5.5	5.1	0	0	0
January	14.2	18.2	12.6	5.7	6.3	5.8	0	-3.2	0
February	14.4	13.9	14.3	5.8	5.4	7.5	0	0	-1.7

Table 2-3
Weibull Parameters Fitted to Observed Potential Energy Density

Potential energy density fits									
	λ (Joules per square meter)			Shape factor k			μ (Joules per square meter)		
Month	**CDIP**	**46026**	**ADCP**	**CDIP**	**46026**	**ADCP**	**CDIP**	**46026**	**ADCP**
September	2500	1100	890	1.4	1.4	0.8	650	160	230
October	3100	1800	3200	1.3	1.5	3.7	500	0	-1600
November	4500	2500	1800	1.3	1.2	1.2	590	340	550
December	6400	3400	2100	1.3	1.1	1.5	540	440	-19
January	5300	3100	2000	1.5	1.2	2	560	500	-280
February	5000	3000	3700	1.3	1.3	1.4	1000	340	-110

Table 2-4
Weibull Parameters Fitted to Observed Potential Power Per Width

Potential power per width fits									
	λ (Watts/meter)			Shape factor k			μ (Watts/meter)		
Month	**CDIP**	**46026**	**ADCP**	**CDIP**	**46026**	**ADCP**	**CDIP**	**46026**	**ADCP**
September	24000	10000	5700	1.6	1.2	1.2	4100	2700	1200
October	32000	15000	19000	1.2	1.1	1.4	5300	2400	400
November	52000	26000	17000	1.2	1.1	0.9	5800	2600	6600
December	77000	41000	25000	1.2	1.1	1.5	5300	3100	-1500
January	65000	39000	22000	1.5	1.2	1.9	4200	3400	-2700
February	62000	36000	40000	1.2	1.3	1.4	12000	2000	-1500

Station CDIP 062 shows the greatest power per unit wave front P_p, which is logical given that buoy's location in a deep-water open ocean water environment. Table 2-4 shows that P_p at station 46026 and station ADCP are comparable to each other, although always smaller than P_p at station CDIP.

2.7 MONTHLY AVERAGE ENERGY AT PROJECT SITE

The Weibull analysis shows the site-specific ADCP data are similar to the NDBC 46026 data. Because only 4 months of complete data were collected, the two sets were further analyzed in order to develop an annual description of wave height and period distributions for use in estimating the annual recoverable wave energy (MW/year).

Figure 2-12 shows the comparison between simultaneous ADCP and NDBC 46026 measurements of significant wave height H_S and wave period Tp. A straight line was fit to the graph of H_S_ADCP versus H_S_46026, and similarly for Tp. The Hs straight line is thus a transfer function that is used to convert H_S at 46026 to H_S at the ADCP site throughout the period of record of the 46026 data. Similarly, a transfer function was developed for Tp. The functions were used to estimate H_S and Tp at the ADCP site reflective of a longer period of record.

The monthly distributions were then used to calculate average wave energy at the project site, as shown in Table 2-5. The table shows lowest wave energies in July and August (less than 10 kW/m), and over 33 kW/m from December through February.

Table 2-5
Calculated Monthly Average Wave Energies at ADCP Site

Month	Average Hs (m)	Average ECg, (W/m)
January	1.99	33,480
February	1.99	33,610
March	1.89	28,630
April	1.67	20,605
May	1.53	15,345
June	1.51	14,265
July	1.26	9,235
August	1.17	7,970
September	1.25	10,540
October	1.46	16,395
November	1.72	23,950
December	1.99	34,240
Annual	**1.62**	**20,690**

3.0 ENERGY CONVERSION TECHNOLOGIES

Development of offshore wave energy conversion devices (as opposed to shoreline installations) is at an early stage. Over 100 wave energy conversion concepts have been proposed worldwide; and, because of the interest in marine renewables, the number of concepts grows every month. A significant fraction of the concepts has progressed to tank testing of small-scale models, and a much smaller number to full-size prototypes. Approximately 20 prototypes have been tested at wave centers in Europe and in pilot projects in the U.S. and Australia.

The marine environment places extreme demands on structural, mechanical, and electrical systems, which means that survival of a season of winter storms is a prerequisite for commercial development. The fate of Finavera Renewables' "AquaBuoy" is a case in point. The prototype of this heave device sank at the end of a sea trial in Humboldt County due to buoyancy problems; subsequently, Finavera Renewables announced it would abandon WEC devices and focus on wind power. As this case illustrates, survivability is probably the most important design aspect for WEC devices, and proof of concept at sea a necessity.

At this time, winter 2009, there are no commercial WEC farms operating anywhere in the world, although at least two are under development in Portugal and Spain. The first commercial installation of three Ocean Power Delivery 750 kW P-1 devices in Portugal in fall 2008 was short lived, due to technical and financial problems. The devices developed buoyancy problems within a few months, and then project financing collapsed. A simplified 180-meter-long P-2 device is now under development.

Other devices are proving their seaworthiness and are progressing towards commercial installations. For example, 40 kW prototypes of Ocean Power Technologies' (OPT) "Powerbuoy" heave technology have survived winter weather, and OPT is developing a larger, 150 kW version for Navy applications in Hawaii, and commercial application at the WaveHub in Cornwall, England. The purpose of the above examples is to emphasize that predictions of device performance are much easier to make than to demonstrate in the 30-foot-high waves recorded during major winter storms in the San Francisco study area.

WEC devices can be divided into five or six different categories based on the component of wave motion from which the devices produce energy; for example, the roll or vertical heave of a wave as it moves past a device, or the horizontal surge in nearer-shore conditions. The oldest types of oscillating water column devices, first developed in the 1980s, capture energy from air movement induced by breaking waves at the shoreline.

Wave motion is mathematically complex, because it involves transient surface displacements and pressure fields, and the pattern of particle motions under a wave change with the depth of water. Some wave characteristics are briefly described below to provide context for the discussion of WECs.

3.1 OCEAN WAVE CHARACTERISTICS

Ocean waves develop in deep water as the result of energy transfer from sustained winds during storm events. Waves are usually described by height and period, with height measured as the difference between trough and crest, and period as the time between successive crests or troughs (Figure 3-1). As described in Section 2, wave energy is proportional to the square of wave height, which means 2-meter and 10-meter waves have, respectively, four times and 100 times the energy of a 1-meter wave. Ten-meter waves occur in winter storms near San Francisco, which means that devices designed to capture energy from the more frequent 2- or 3-meter waves will also need to be able to survive 10-meter and larger waves.

Because wave heights occur over a wide range or spectra, wave heights are defined for engineering purposes by the significant wave height (H_S), which is the average height of the largest one-third of the waves in a wave field. Individual wave heights can be greater than 1.6 times the significant wave height.

Wave periods typically range from the small 2- to 3-second wind waves seen on afternoons in San Francisco Bay to over 20 seconds in major winter storms. Almost all the site-specific data collected 8 miles west of San Francisco for this study had periods in the range of 5 to 20 seconds. In deep water, wave period can be used to directly calculate wave length, which is then used to indicate when waves will begin to “feel” the ocean bottom and lose energy. Deep water is defined as depths greater than half of the wave length. In deep water, a 6-second wave is approximately 185 feet long, a 10-second wave is approximately 510 feet long, and a 20-second wave is almost 2,050 feet long. The water depth at the outer edge of the exclusion zone is 110 feet. This means that waves with periods greater than approximately 6.5 seconds will have started to lose some energy through the effect of bottom friction, and that for most wave periods of interest, the water depth in the study area can be classified as intermediate.

In deep water, the water particles under a wave move in closed orbits that decrease in magnitude with depth. Wave energy moves across the deep ocean as a transfer of potential and kinetic energy, not from transport of water. As water depth decreases, the orbital paths become more and more compressed until they are almost horizontal in shallow water, which is defined as water depth less than 1/25 of the wave length. In nearshore shallow water, bottom friction causes waves to slow, become steeper, and finally break when the wave height is about 80 percent of water depth.

3.2 TYPES OF WAVE DEVICE TECHNOLOGIES

The European wave centers in Portugal and Britain use a common terminology to describe WECs. These centers identify six categories of WEC devices as follows:

- **Attenuator (pitching motion):** A surface device that lies parallel to the direction of wave propagation and effectively rides over the waves. The Pelamis is the best-known attenuator. It presents a very small surface area to oncoming waves, a design strategy for survival in major storms.

- **Point absorber (heave and surge):** A floating structure that absorbs energy from all directions through movement of floats near or at the water surface. Many different power take-off systems have been proposed from small water turbines through linear motors.

- **Oscillating surge (surge):** These devices extract the energy from the predominantly horizontal surge of water motion under waves in shallow to intermediate water depths. Most are mounted on pivots or hinges on the sea bottom, and a number of them pump high-pressure water to shore rather than generating power at sea.

- **Oscillating water column (air pressure):** Breaking waves and large offshore waves induce significant air movement. These devices extract energy from air trapped in columns in front of breaking or above large waves. The trapped air is forced through low-pressure bi-directional turbines that generate electricity. These were first developed in the 1980s for shoreline applications in Norway and Japan.

- **Overtopping (breaking wave run-up):** The forward momentum from a breaking wave will carry it to an elevation above sea level where it can be returned to the sea through conventional low-head turbines. This was the principal idea behind Sutro’s 1890s concept, which became the San Francisco Sutro Baths. The Wave Dragon overtopping device uses collector arms to concentrate the wave energy, which results in enormous forces on the arms during storms.

- **Submerged pressure differential (pressure):** The motion of the waves induces a pressure differential that can be used to pump fluid and generate electricity. These devices are typically bottom-mounted in a nearshore location.

Other devices have been proposed that are very conceptual or have unique designs and do not fall into the above categories. Although the devices appear to have a theoretical basis, until they are tested at sea and have demonstrated they can survive winter storm conditions, they cannot be considered to be feasible candidates for inclusion in pilot studies.

The following 19 devices, built at a scale of one-quarter full size or greater, have been tested at sea at a wave center, or as pilot projects (EMEC: European Marine Energy Center, Scotland; WEC, Wave Energy Center, Portugal).

Table 3-1
Field-Tested Wave Energy Conversion Devices

Category	Description
Attenuator	• Pelamis (Ocean Power Delivery Ltd, UK). Prototypes tested at WEC Portugal and EMEC Scotland. Three 140-meter-long 750 kW P-1 devices were installed in Portugal in 2008; the project halted in 2009 for financial and technical reasons. A larger 180-meter-long P-2 device is under development.
Point absorber	• AquaBuoy (Finavera Renewables, Canada). Prototype sank during testing in Humboldt, California in 2008. The company is no longer making WEC devices. • Archimedes WaveSwing (AWS Ocean Energy, Scotland). Submerged heave device tested in 2004 at WEC. Pre-commercial unit being developed for EMEC. • CETO (Carnegie Corporation, Australia). Submerged shallow-water device delivers high-pressure water. Two CETO-2 units were tested in Fremantle in 2008. Full-scale CETO-3 planned for testing in 2009. • FO3 (SEEWEC, Norway). A 1/3-scale wave-point converter was deployed in Norway in 2004. Plans were announced for a full-scale prototype in 2006. • Powerbuoy (OPT-Ocean Power Technologies, USA). PB-40 (40 kW) prototypes tested in Hawaii for the Navy and New Jersey. Planned commercial installation in Oregon and Spain. Planning deployment of PB-150 (150kW) at EMEC and Wave Hub. • Protean (Protean Power, Australia). A 1/3-scale proof-of-concept prototype was deployed in western Australia in 2008. • Seadog (Independent Natural Resources, Minnesota). Device pumps water to shore (pump-storage concept). A prototype was tested at sea near Freeport, Texas. • Wavebob (Wavebob Ltd, Ireland). A ¼-scale prototype was tested in Galway in 2006. Deployment of a full-scale prototype is planned. • Wavestar (Wave Star Energy, Denmark). Completed 3 years of 1/10-scale testing at sea. A 500 kW prototype is scheduled for deployment in Denmark in fall 2009.

Category	Description
Oscillating surge	• BioWave (BioPower Systems, Australia). A 250 kW 25-meter-tall pilot unit is being tested at sea in Tasmania. Grid connection planned for 2010. • Oyster (Aquamarine Power, Scotland). Shallow-water device delivers high-pressure water. Full-scale 18-meter by 12-meter 500 kW prototype was installed in 2009 at EMEC. • WaveRoller (AW-Energy, Finland). A 1/3-scale prototype was tested at EMEC in 2005. Full-scale Unit Nos. 1 and 2 (15 kW) were installed in 2008 and 2009 at what is a planned to be a 1 MW wave farm at Peniche, Portugal.
Oscillating water column	• “Mighty Whale” (Japan Marine Science and Technology Center). A 110 kW prototype, deployed off of Mie Prefecture in 1998, operates as a test platform. • OE Buoy (Ocean Energy, Ireland). A 1/4-scale prototype was deployed in Galway in fall 2006 and is generating electricity. • OWC LIMPET Plant (Voith Hydro Wavegen, Scotland). Shoreline 75 kW pilot OWC installed in 1991 on Islay, Scotland; replaced by 500 kW plant in 2000. • OWC Pico Plant (WEC, Portugal). Constructed in 1999 with Wells turbines, it operated sporadically. Testing in 2005-2006 confirmed technical limitations. Operations were suspended in 2008. • Parabolic OWC with Deniss-Auld turbine (OceanLinx, Australia). A full-scale prototype was deployed in 2005; 1/3-scale unit in 2007; and a pre-commercial in 2009.
Overtopping	• Wave Dragon (Wave Dragon ApS, Denmark). Prototype tested from 2003 to 2008 in Denmark. Plans exist to deploy a 300-meter-wide, 7 MW device in Wales.

Smaller-scale research models, such as the Oregon State University linear generator buoy, and tank-scale test devices are not included in the above list; nor are OWC devices that are built into breakwaters or seawalls.

Although each device is unique, each group of technologies tends to share some similar physical characteristics, with notable exceptions. Point absorbers tend to look like large buoys; however, the Wavestar device more closely resembles a large centipede with each leg as a point absorber. The oscillating surge devices are all submerged, with the oscillating paddle ranging in appearance and size from small plates (WaveRoller) to very large kelp (BioWave). While the earliest OWC devices were structures built into shoreline cliffs, more recent designs operate at sea.

Many of the devices cannot realistically be considered for a San Francisco project. Shoreline OWC devices (e.g., OWC Limpet and Pico plants) are not an option due to aesthetic, recreational, planning, regulatory, and other reasons. Devices with large or highly visible superstructures are not viable from an aesthetic perspective, because they would be easily visible from shore (e.g., Deniss-Auld turbine Parabolic OWC, Mighty Whale, Pelamis, Wave Dragon, Wavestar). The water depth in the study ranges to a maximum of 110 feet (33 meters), which is too shallow for the larger point absorbers (e.g., Archimedes Waveswing and the 115-foot-tall

OPT PB-150). These and other considerations led to the development of the technology screening criteria described in the next section.

A number of the surge devices tailored for shallower, nearshore environments are designed to pump high-pressure seawater ashore where it can be used for desalination or power generation purposes (e.g., CETO and Seadog). The intake of seawater for power generation purposes would invoke State 316(b) regulations designed to reduce impingement and entrainment of marine organisms, and therefore would require an intake screening device on each individual WEC device. To be consistent with the objectives of 316(b) regulations, a demonstration that use of seawater would be the optimal means of power production would likely be required, as would a new onshore turbine house and a seawater outfall. It is not clear what technology or additives would be employed to prevent growth of marine organisms on the inside of pipes. Practical constraints on cleaning and maintaining intake screens and the probable need for chlorination to prevent buildup of marine organisms suggest that the WEC devices that pump water would add several layers of permitting and construction complexity to a wave farm project.

Other surge devices designed for near-shore application (e.g., Oyster and WaveRoller) use closed-loop water systems to ameliorate the environmental impacts of seawater extraction. The devices pump high-pressure water ashore where conventional Pelton turbines can be used to generate electricity. Water is returned to the inlet side of the high-pressure pumps using a low-pressure return pipeline system. These devices have an advantage over other WECs in that electricity is generated in the onshore environment using proven technology; a characteristic that can significantly reduce O&M costs.

3.3 SAN FRANCISCO SITE ENVIRONMENTAL CONSIDERATIONS AND SCREENING CRITERIA

A preliminary set of environmental topics that would need to be addressed during environmental clearance of a wave energy project in the Oceanside study area have been identified and further explored through outreach efforts. Outreach to local agencies, organizations, and interested parties to date has included the agencies and groups shown on Table 3-2. Additional outreach to these stakeholders and others is planned. The presence of the National Marine Sanctuaries adjacent to the study area introduces a number of key considerations. Potential impacts to the Ocean Beach and Great Highway sediment transport and restoration programs, commercial and recreational fishing activities, and other recreational issues are also identified.

Table 3-2
Agencies and Groups Consulted to Date

U.S. Department of Commerce	National Oceanographic and Atmospheric Administration
National Marine Fisheries Service	National Marine Sanctuaries (NMS)
Gulf of Farallones NMS	U.S. Department of the Interior
Minerals Management Service	U.S. Fish and Wildlife Service
National Park Service	Golden Gate National Recreation Area
U.S. Coast Guard	California Coastal Commission
California Department of Fish and Game	California Energy Commission
Marin County Community Development Agency	City of Pacifica
Environmental Action Committee of West Marin	Farallones Marine Sanctuary Foundation
Natural Resources Defense Council	Ocean Conservancy
Save the Waves Coalition	Sierra Club
Surfrider Foundation	Golden Gate Fishermen’s Association
Pacific Coast Federation of Fishermen Association	Recreational Fishing Alliance
San Francisco Ocean Beach Vision Council	City of Daly City

3.4 MARINE LIFE

Considerable attention has been given to the siting of the project area, given that the Gulf of Farallones and Monterey Bay National Marine Sanctuaries occupy much of the area west of the Golden Gate (see Figure 1-1). The mission of the National Marine Sanctuary program is to conserve, protect, and enhance the biodiversity, ecological integrity, and cultural legacy of marine ecosystems. The Monterey Bay Sanctuary goals include resource protection, research, education, and public use. During initial public outreach, Sanctuary personnel indicated that construction of energy-related facilities in the Sanctuary is not permitted.

Even though a zone excluded from the National Marine Sanctuaries has been established around the Southwest Ocean Outfall of the Oceanside Wastewater Treatment Plant, the exclusion zone abuts the protected areas. Therefore, the movement of marine species resident in the Sanctuary and the seasonal movements of special-status species through the project area will need to be carefully evaluated. Of particular concern are migrating gray whales, which move northward through the study area in the spring with calves, and back southward in the fall. Gray whales are thought to migrate closer to the shore when they are protecting young calves, and further offshore during the southward journey.

The Southwest Ocean Outfall extends approximately 4.5 miles offshore, which presents an opportunity to minimize impacts by co-locating any submarine power cables along the existing alignment. The CCSF right-of-way for the outfall alignment is 1 mile wide, providing a wide corridor in which to locate submarine power cables.

3.5 OTHER ENVIRONMENTAL CONSIDERATIONS

Other topics that have been identified include:

- The presence of commercial vessel traffic lanes entering and exiting San Francisco Bay.
- Dredging operation for the Ocean Beach and Great Highway sediment transport and restoration program, and possible impacts on the regional littoral sediment transport mechanism due to changes in the wave climate.
- Impact on commercial fishing activities, particularly Dungeness crab fishing grounds, in the site area.
- Recreational flat fish and salmon sport fishing.
- Surfing, and other recreational activities.
- The impacts of electromagnetic fields surrounding power generation and submarine cables on habitat and species.
- Underwater noise that may be generated from device motion.

More detailed studies of a number of these topic areas have been proposed for funding as described below:

- Gray Whale Tracking: with the objective of understanding northward and southward whale migration pathways in the zone 3 to 15 kilometers offshore, and filling a site-specific data gap in knowledge of whale movement patterns in the area west of San Francisco.
- Wave Energy Reduction and Coastal Sediment Transport: with the objective of predicting the near-field and far-field wave patterns resulting from energy removal and the consequences for sediment transport in the Ocean Beach area.

- Crab Fishery Study: with the objective of documenting historical catch patterns, annual variability, and the likely economic loss if a zone approximately 1 kilometer long by 0.5 kilometer wide was excluded from the fishing grounds.

3.3 TECHNOLOGY SCREENING CRITERIA

The screening criteria were developed to identify the feasible technologies for San Francisco Bay. The emphasis of this feasibility study is on technologies that are suitable for large-scale commercial projects. The following screening criteria were based on the assumption that a pilot study would be required before a commercial installation could be permitted in the San Francisco Bay.

Table 3-3
Technology Screening Criteria

Category	Criteria
Stage of development (conceptual, prototype, commercial)	– Undergone ¼-scale or larger prototype testing at sea – Viable for Pilot Test in 2012 to 2013 – Commitment to optimize unit performance for SF conditions
Operations	– Capable of operating in water depths of 25 to 30 meters – Realistic O&M plan
Power Capacity (reasonable number of units capable of generating 30 MW)	– Wave Periods – 6 to 15 seconds – Wave Heights – 2 to 10 meters
Environmental Impacts	– Aesthetics – minimize visible impacts to shoreline communities – Marine Mammals – minimize mooring impacts and impediments to seals and whales – Minimize noise – Minimize EMFs
Permitability	– Significant advantages relative to other technologies
Financial	– Commitment to cooperate financially with CCSF

4.0 RECOMMENDED TECHNOLOGIES

The evaluation of WEC devices at the prototype and pre-commercial stage using the screening criteria in Section 3.3 indicate that submerged surge devices that (1) have no obtrusive surface features, (2) are bottom-mounted using single-point mounts or hinges, and (3) operate in the water depths found in the study area are suitable for further analysis. Bottom mounting has an advantage over cable mooring systems needed for surface devices in that it minimizes the potential for entanglement or entrapment of marine mammals. Submerged devices have an inherent survivability advantage in that during extreme weather they can be designed to fold down to the sea floor if wave heights exceed the maximum design wave height.

Low-profile surface-heave devices that are moored low in the water in order to have positive buoyancy—that is, use of taut cable systems—could also be considered. None of the prototype devices listed in Section 3.2 have these characteristics. However, some surface devices that have reached the small-scale prototype stage are held on taut tethers that reduce the risk of whale entanglement. These include the linear-motor device being developed at Oregon State University, and the OWC device being developed by Orecon in Cornwall, England. If larger prototypes of these devices complete sea trials by 2010, they could be considered for the San Francisco pilot program.

Submerged surge devices that pump high-pressure water to shore are not considered feasible at this time due to the reasons outlined in Section 3.2.

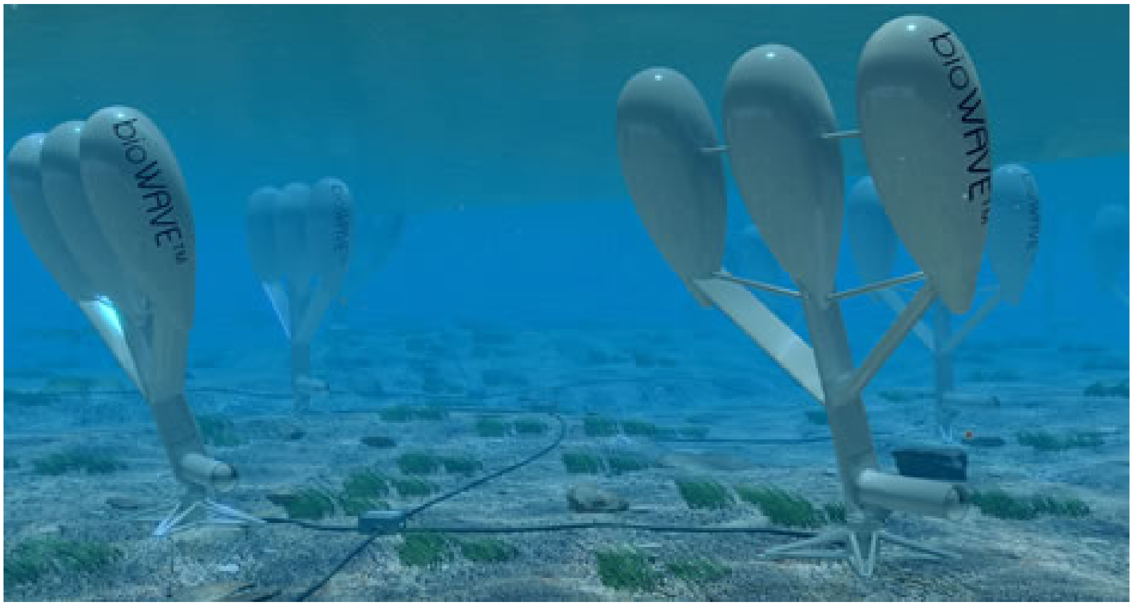
Submerged surge devices that meet the screening criteria are:

- BioWave, developed by BioPower Systems, Australia
- Oyster, developed by Aquamarine Power, Scotland
- Wave Roller, developed by AW-Energy, Finland

Illustrations of these technologies and their current status are provided below.

4.1.1 BioWave

BioWave is an oscillating surge device designed to simulate the swaying motion of the sea plants such as kelp in ocean waves. A water depth of 25 meters is ideal for the devices, which makes them well suited for the San Francisco site. The devices are designed to generate power over a range of wave heights of between 2 and 6 meters. In seas above 6 meters, the devices fold down to the bottom to ride out major storms. A hydraulic motor, rated at 250 kW in the prototype, generates power at the based pivot point.



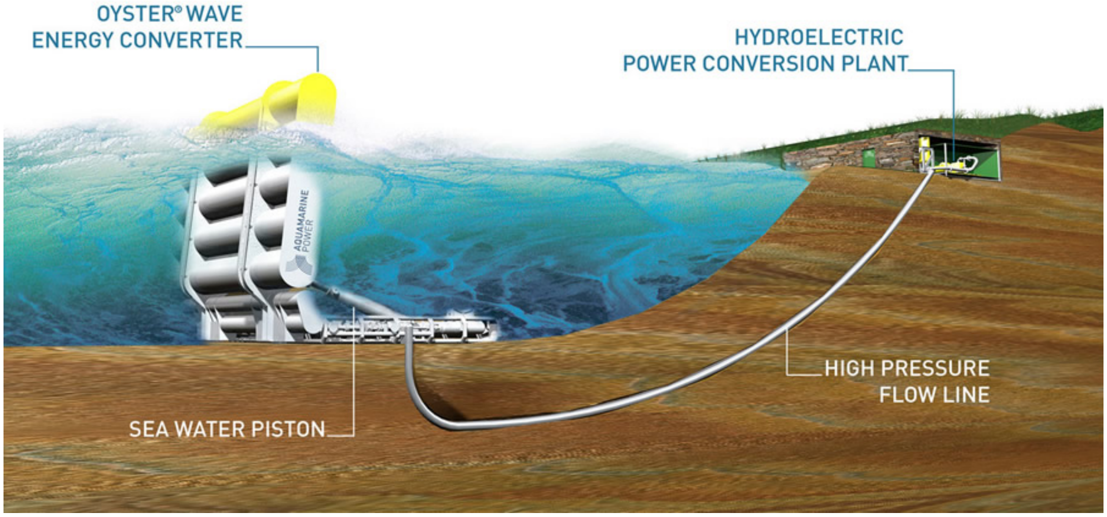
Visualization of BioWave units (www.biopowersystems.com)

A 250-kW pilot project is being developed for Hydro Tasmania at King Island, Tasmania. The 25-meter BioWave unit was installed in 2008, has been tested through 2009, and is scheduled to be connected to the island's power grid in 2010. Larger 500-kw and 750-kW units are under development.

4.1.2 Oyster

The Oyster, developed by Aquamarine Power, Scotland, is an oscillating surge technology designed to operate in 10-meter to 16-meter water depths where the average incident wave climate is greater than 17 kW/m. A pre-commercial demonstration unit measuring 18 meters by 12 meters by 2 meters installed at EMEC in Scotland in October 2009 can be configured to generate between 315 and 600 kW. Power generation starts when wave height exceeds 1 meter. Aquamarine Power is designing modifications that will enable each unit to generate 650 to 800 kW, and plans to deploy 3 to 4 units in 2.5-MW arrays.

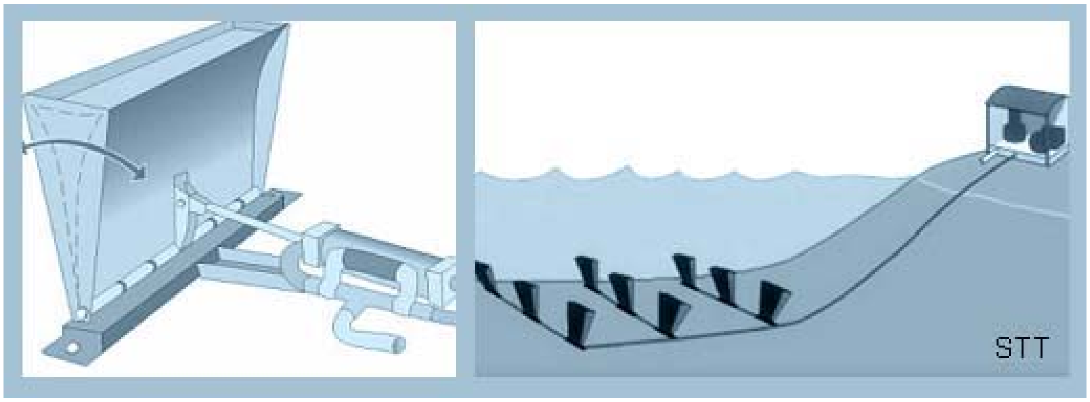
The Oyster system uses double-acting water pistons to deliver high-pressure water via sub-sea pipelines to the shore. A closed-loop system is used to minimize impacts on the environment. The high-pressure water is converted to electrical power onshore using a conventional Pelton turbine.



Schematic of Oyster Technology Installation (www.aquamarinepower.com)

4.1.3 WaveRoller

The WaveRoller is also an oscillating surge technology somewhat simpler and smaller in scale than the Oyster. A WaveRoller device is a plate hinged on its lower edge at the sea floor. The back-and-forth movement of wave surge moves the plate, which drives a closed hydraulic motor and generator system. The range of ideal water depths is 10 to 25 meters. Three to five WaveRoller units (a module) feed into a common generation system.



Visualization of WaveRoller units (www.aw-energy.com)

Smaller 1/3-scale units were tested at EMEC in 2005. Commercial prototypes measuring 3.5 meters by 4.5 meters by 6 meters, and weighing 20 tons, are being installed at a wave farm at Peniche, Portugal, targeted to generate 1 MW. Each unit contributes 10 to 15 kW. The first commercial WaveRoller unit No. 1 was deployed in 2008, and the second unit in 2009. Impacts on sediment movements and biofouling are being monitored as part of the project.

5.0 COST OF POWER

The cost of power (in cents per kWh) was calculated by equating estimated annualized plant costs with the estimated annual production of electric power (GWh per year). Costs were based on quotes provided by equipment manufacturers wherever possible. The monthly wave energies shown in Table 2-5 provided the basis for developing average monthly and annual power production. The uncertainties on both sides of the equation were addressed using sensitivity analyses assuming conservative values.

5.1 WAVE ENERGY PLANT COSTS

Major capital cost items for a marine plant (wave farm) include:

- WEC devices
- Moorings/foundations
- Power conditioning at hub and submarine cable
- Grid connection and substation upgrades
- Environmental clearance/permits/leases
- Project financing.

Low, medium, and high cost estimates were developed for each item.

Non-capital costs include:

- Annualized operations and maintenance
- Periodic unit rebuild or replacement costs
- Decommissioning.

5.1.1 Capital Costs

The cost analysis assumes that a San Francisco wave farm would be developed in the highest energy regime in the study area—that is, deep water at the outer western edge of the buffer zone around the Southwest Ocean Outfall. This area is in the federal OCS and would require obtaining a lease from MMS.

Alternatively, CCSF could develop a project within the 3-mile State jurisdiction, which negates the need for a MMS lease. Figure 2-1 shows the water depths 1 to 1.5 miles from shore are in the range of 40 to 60 feet (12 to 18 meters), the required depths for an Oyster-type WEC.

A 30-MW wave farm in the OCS would require 30 to 40 WEC devices rated at 750 kW to 1 MW. Intermediate water depths in the San Francisco study area and wave energy densities in the 20 to 25 kW/m range mean that the 2 MW and larger devices planned for 40 to 50 kW/m wave climates will not be optimum. Based on manufacturer's data, individual device costs are estimated at between $500 thousand and $1.25 million (see for example, CEC, 2008). The cost of WEC devices for a 30-MW wave farm are estimated at between $30 million and $50 million.

The cost to construct a generic 3-meter by 3-meter by 3-meter concrete foundation with deep ground anchors in the 100-foot water depth of the San Francisco site was estimated to be $250 to $350 thousand per foundation. Foundation costs are estimated in the range of $7.5 to $14 million.

One of the largest unknowns is that of at-sea power conditioning, or voltage step-up from the voltages generated at individual WEC devices to the voltage in the submarine cable used for power transmission to shore. Individual WEC devices generate power in the range of 400 to 1,000 volts. To avoid significant power loss over a 6- to 8-mile transmission distance to shore, a medium voltage submarine cable (11 to15 kV) will also be required.

OPT is developing an Underwater Substation Pod (USP) or underwater transformer to step up the low voltages generated by individual WEC devices to medium voltage for transmission to shore. The device is designed for water depths up to 150 feet. A 1.5 MW USP has been constructed to connect ten PB-150s for a wave farm project in Santona, Spain, and a 5 MW unit is under development. Six 5-MW units each connecting 6 to 7 devices would be needed for a 30-MW farm using 40 WEC devices. Procurement and installation of up to 8 miles of armored, three-phase, medium-voltage cable is estimated to cost $12 to $16 million (vendor communication). This is double the common assumption of $1 million per mile. For protection against recreational anchors, we have assumed the cable would be installed using a hydroplow to bury the cable 5 to 10 feet below the sea bottom.

As a placeholder, given the current economic climate, project financing costs are estimated at 7 percent of total capital cost.

5.1.2 Non-Capital Costs

On an annual basis, non-capital costs include:

- Annualized operations and maintenance (3 to 5 percent of total capital cost)
- Periodic unit rebuild or replacement costs (25 to 45 percent of unit costs)
- Decommissioning (3 to 5 percent of unit costs).

There is great uncertainty in the combined annual O&M and rebuild costs for WEC devices, estimated as a percentage of capital investment. All cost estimates to date are based on manufacturer estimates (e.g., EPRI, 2004b, CEC, 2008); there is a paucity of actual data against which claims can be tested. Life of power generation systems at sea is estimated to be 4 to 5 years. To date, no WEC device has demonstrated it can operate this long in the ocean. Hence, all O&M estimates are speculative, and initially will probably be closer to the high end of the estimated range, given the nascent stage of technology and challenges of operating in the marine environment.

The medium to high range of capital costs and O&M ranges are summarized below. The capital costs are equivalent to between $4,000 and $4,700 per kW of installed generation capacity.

Table 5-1
Capital Costs and O&M Ranges for an Offshore 30-MW Wave Farm

Cost Ranges for a 30-MW Wave Farm	
Capital Costs	**Likely Cost Range ($ millions)**
WEC Devices	40 – 50
Moorings/ Foundations	12 – 14
Submarine Transformers and Cables	39 – 41
Land-side Upgrades/Interconnect	12 – 15,
Permitting/Studies/Outreach	6 – 8
Construction and Financing	11 – 12
Total Capital Cost	**$120 – $140**
O&M Costs	
Annual	3 to 5% of Total Capital
Periodic Replacement	25 to 45% of WEC costs
De-commissioning	3 to 5% of WEC costs

5.2 POWER PRODUCTION

Wave energy conversion devices produce power when the wave climate exceeds the threshold wave heights needed to initiate generator or pumping action. For both the BioWave and Oyster devices, a significant wave height of 1 meter is required. The devices develop rated power with sea states of between 3.5 and 4 meters. The BioWave device will continue to operate in sea states up to a significant wave height of 8 meters. In seas larger than 8 meters, the device folds down to the sea floor to allow waves to pass over the device without causing damage. The Oyster device continues to operate in all sea states; the larger the waves, the more water will spill over the device. Power production with Oyster units does not stop in large storms, because the power turbine is onshore and protected from severe weather.

Each BioWave unit generates power at 415 volts AC using a hydraulic motor mounted at the base of the unit (see Section 4.1.1). Power from a number of units would be combined and stepped up to between 6 and 11 kV using a subsea transformer for transmission to shore. The power would then be conditioned and fed into the local grid. Power production with the Oyster units takes place onshore using a standard Pelton turbine. This allows power to be conditioned and fed into the grid as it is generated.

The annual power production for individual WEC devices in the 21-kW/m wave climate is estimated at between 1,500 kWh/year and 3,000 kWh/year (CEC 2008; manufacturer communication). The average wave monthly energy at the project site shown in Table 2-5 was applied to specific device characteristics in order to develop monthly and annual energy production rates. Power production from a 30 MW wave farm could generate between 100 and 150 GWh/year. This value is generally consistent with the 300 GWh/year estimated by EPRI in 2004 for hypothetical OPD Pelamis and Energetech OWC (now OceanLinx) wave farms rated at 100 MW offshore of San Francisco (EPRI, 2004a). In 2007, the average San Francisco household consumed 4,400 kWh/year (CEC, 2009). Assuming flat energy demand, a 30-MW wave farm could provide enough energy to power 22,700 to 34,000 San Francisco households.

The capacity factor for WEC devices operating in the study area is high; ranging from 30 to 50 percent (CEC 2008; manufacturer communication). This ratio of actual energy production compared to that theoretically produced from full-time operation at the device's rated capacity indicates both the pervasive nature of waves offshore of San Francisco, and that the supply of energy to the grid from a wave farm would be much more continuous than that from solar or in-stream tidal power.

The actual percentage of wave energy extracted from the wave field is small, similar to the small percentage of wind energy extracted wind fields. The spacing of devices to avoid physical and hydrodynamic interference is one factor. Second, much of the total energy in a wave field is associated with large waves because wave energy is proportional to the square of wave height. Therefore, major storms carry a significant portion of the total annual wave energy arriving at a given stretch of coastline. WEC devices can only produce power up to their rated capacity, and thus extract a much smaller proportion of wave energy in storm events (none, when waves are too large). Wave devices are expected to annually reduce the total energy in a wave field by 3 to 5 percent.

5.3 ESTIMATED COST OF POWER

Equating the power production with estimated cost yields the cost of power in cents per kW-hour (¢/kWh). Making mid-range and conservative estimates for uncertainties, including power conditioning and O&M costs, yields total cost of wave energy in the range of 17 to 22 ¢/kWh. This is more expensive than wind power (range of 7 to 8.5 ¢/kWh), not including a 2.5 ¢/kWh tax credit) and conventional hydrocarbons (range of 10 to 12 ¢/kWh), but is comparable with the cost of producing solar photovoltaic power before solar tax credits and other incentives are applied.

5.4 CONCLUSIONS

The estimated cost of power indicates that development of a wave farm offshore of San Francisco could generate power in the cost range of solar photovoltaics. This is an order of magnitude lower than the cost estimate developed for in-stream tidal power through the Golden Gate. Historical and site-specific wave data indicate the wave climate west of San Francisco produces wave energies averaging 21 kW/m, and that even though wave energy is higher in the winter than in summer, wave energy could generate a consistent supply of renewable energy throughout the year.

The study area is used by marine mammals, and commercial and recreational fishing, and is adjacent to the Monterey Bay National Marine Sanctuary, San Francisco Bay ship channels, and sediment dredging for Ocean Beach restoration. Studies to assess the potential impacts of a wave farm on these resources and activities will be required.

Wave energy conversion device development is at an early stage, and with no operating wave farms to provide precedence or to base reliability and O&M assumptions, there are many uncertainties. However, development of wave power appears to be much more feasible than in-stream tidal power previously studied by the CCSF, with a considerably larger power generation potential at significantly lower costs.

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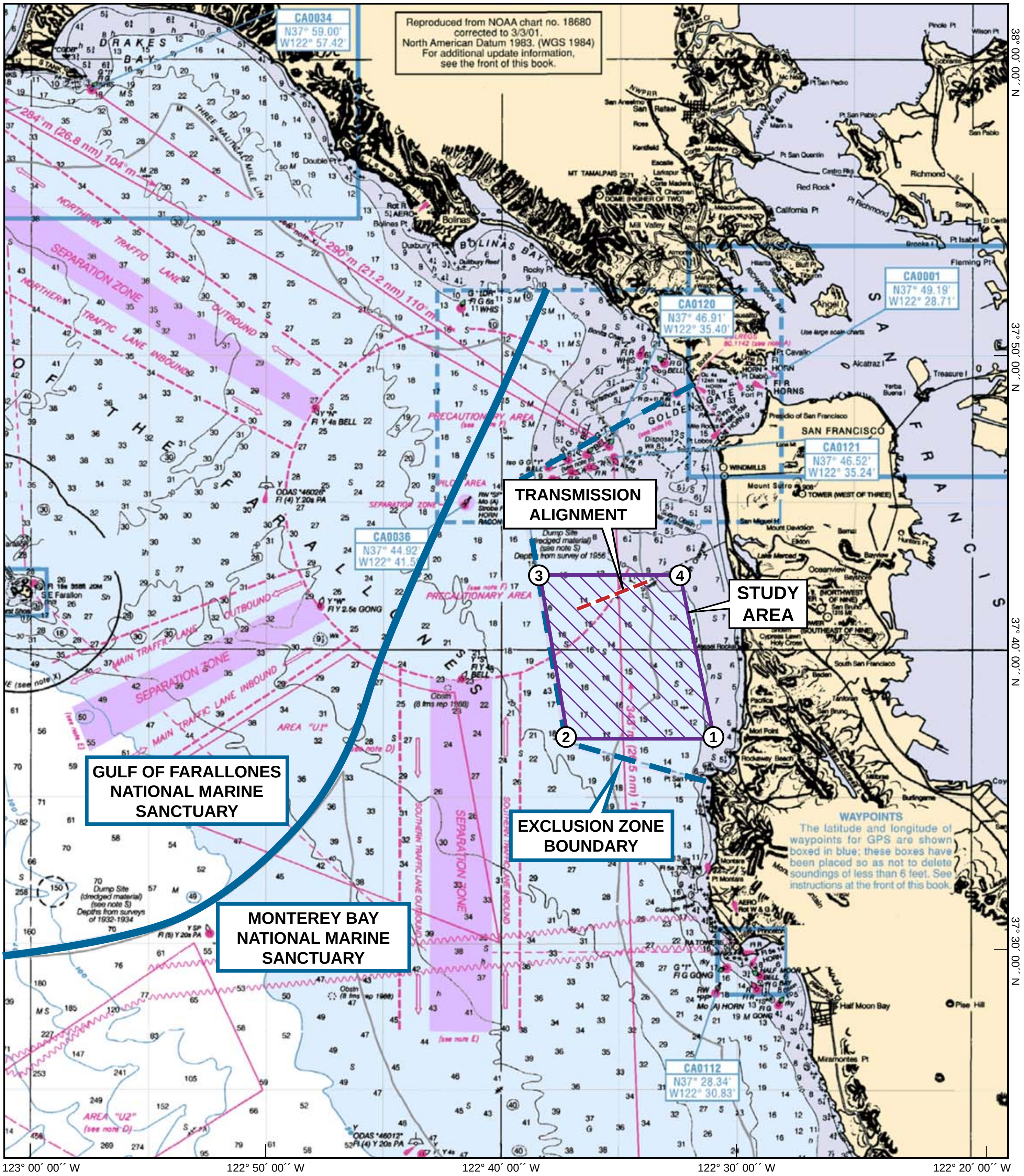

Source:
NOAA, 2001; Chart Number 1210PG02

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0 5
Scale in Miles

STUDY AREA

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FIGURE 1-1

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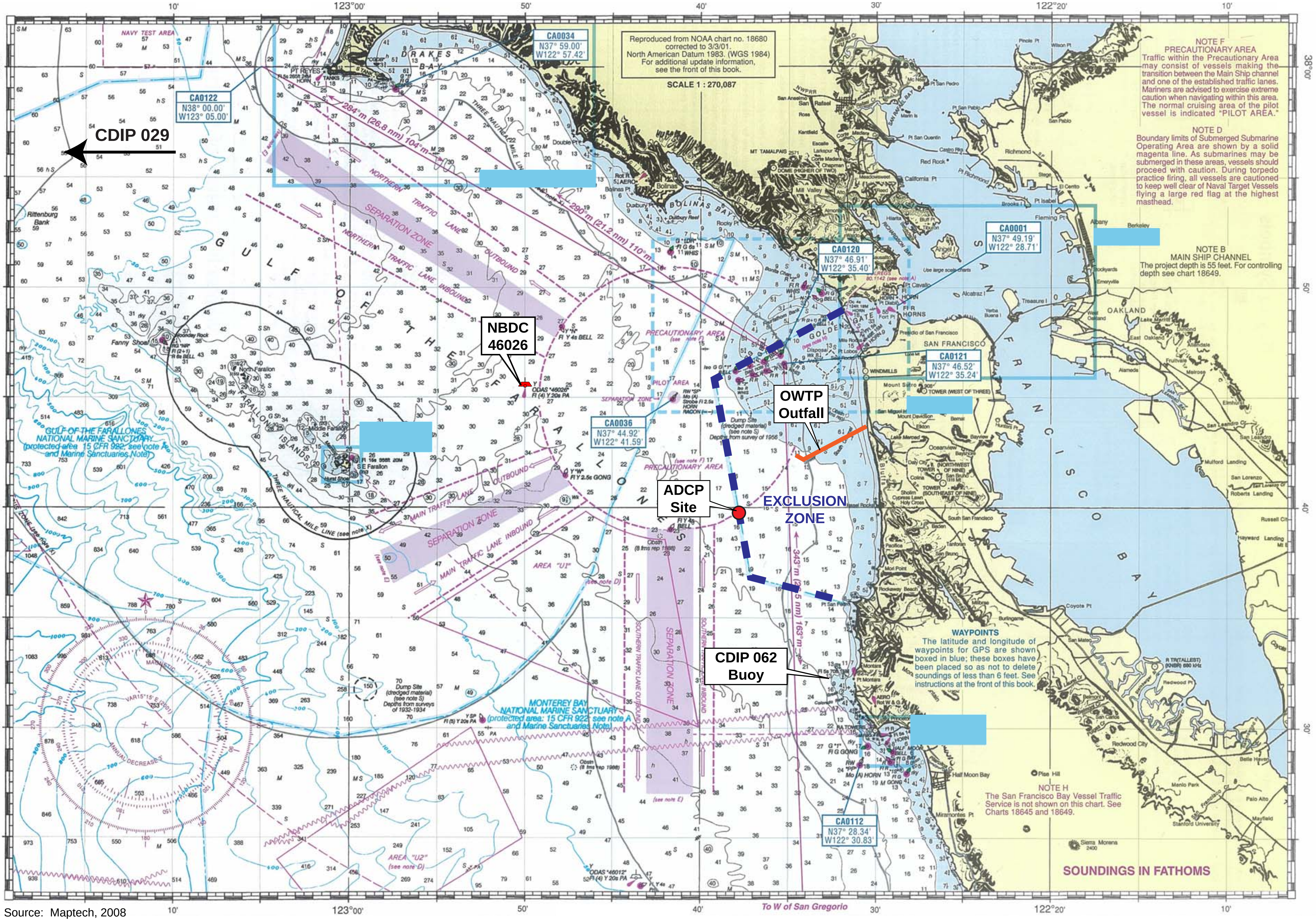

Source: Maptech, 2008

ADCP LOCATION AND BUOY SITES

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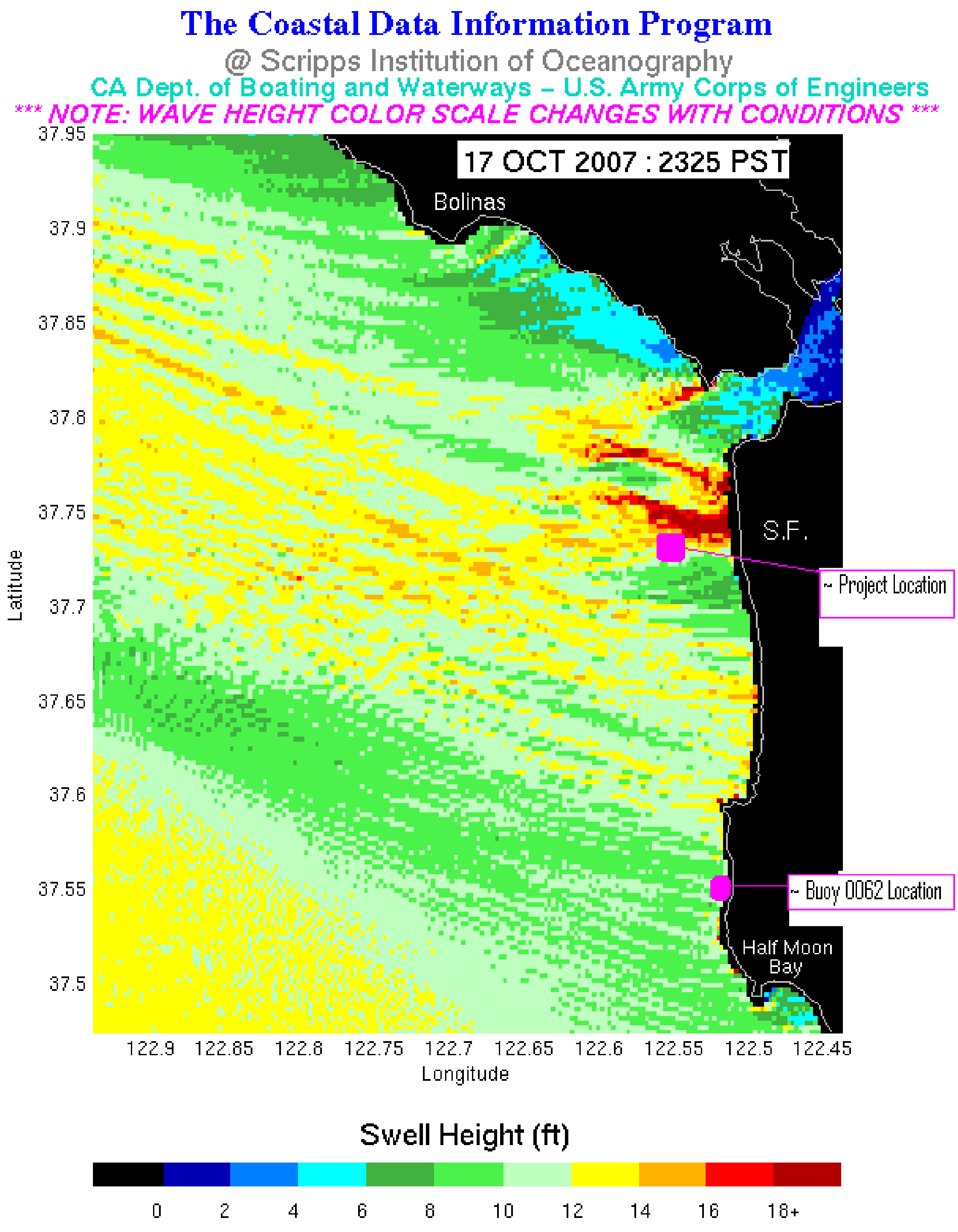
FIGURE 2-1



CDIP BUOY 062 LOCATION

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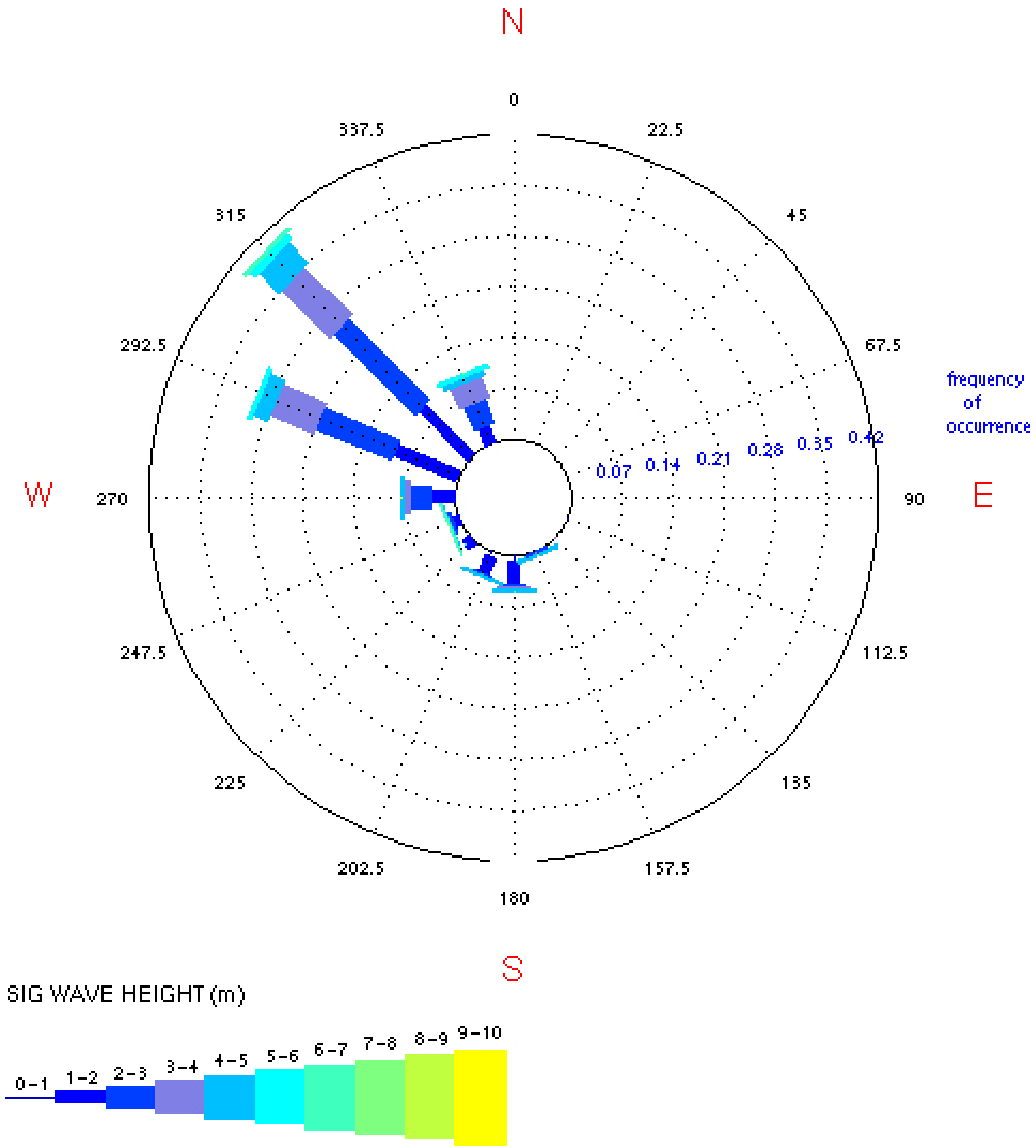
FIGURE 2-2



Source: http://cdip.ucsd.edu/

CDIP 029 WAVE ROSE

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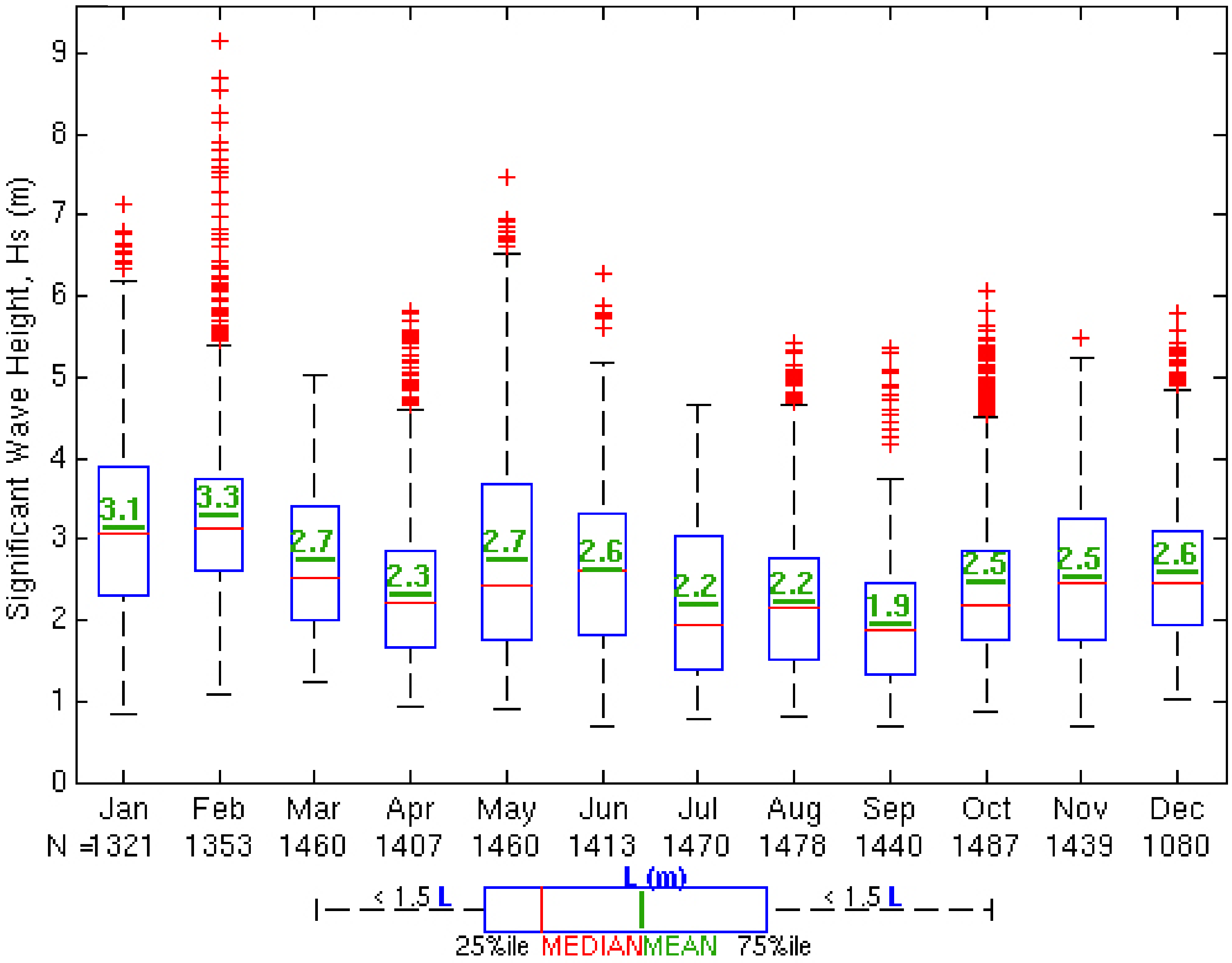
FIGURE 2-3



Source: http://cdip.ucsd.edu/

CDIP 029 SIGNIFICANT WAVE HEIGHT BY MONTH FOR 2008

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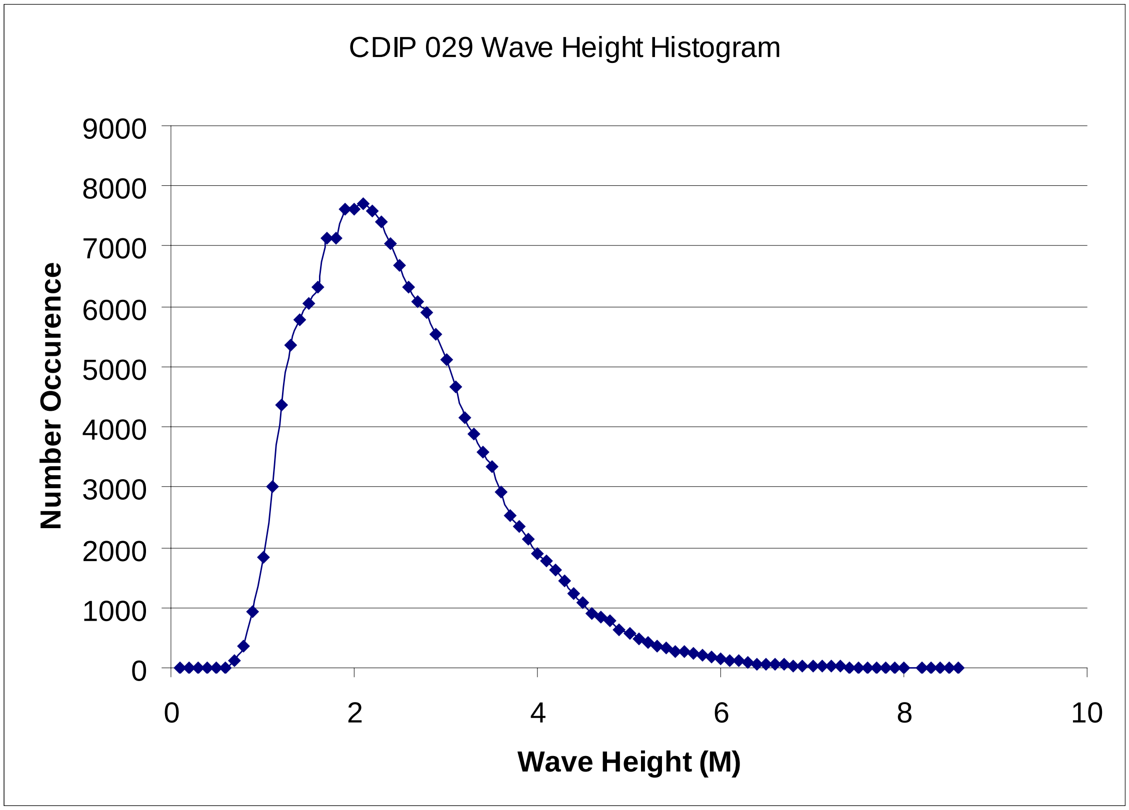
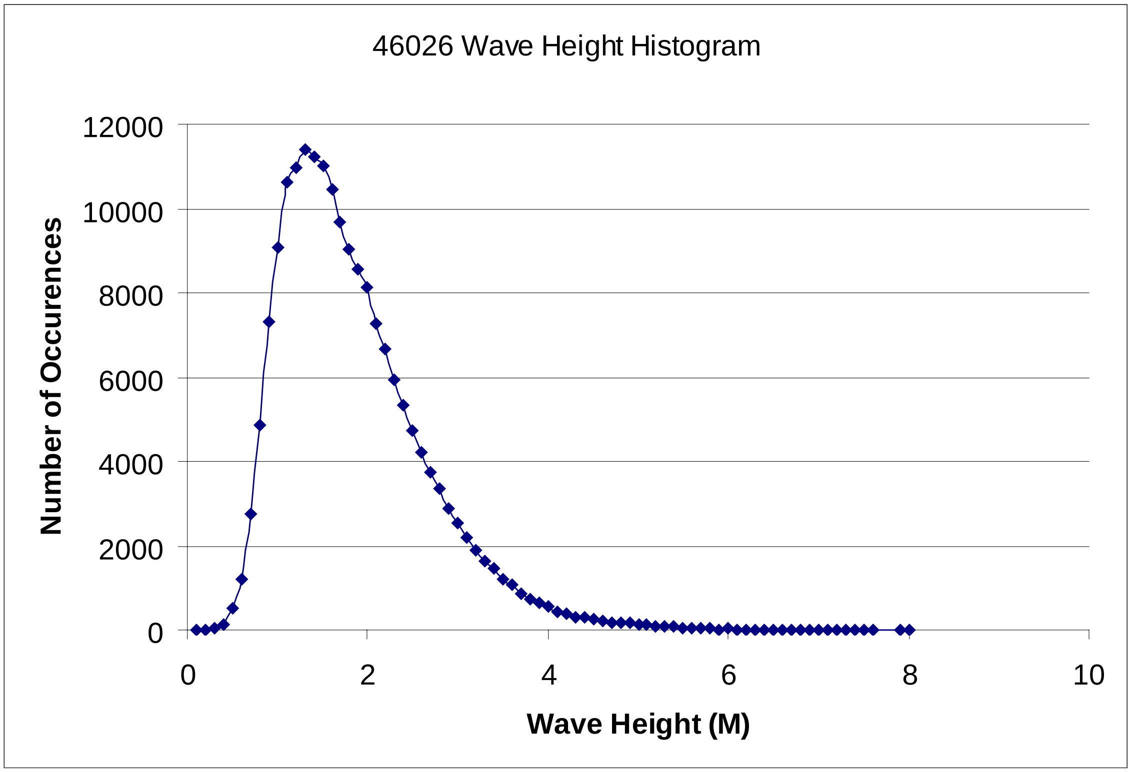
FIGURE 2-4





CDIP 029 AND NBDC 46026
WAVE HEIGHT DISTRIBUTIONS

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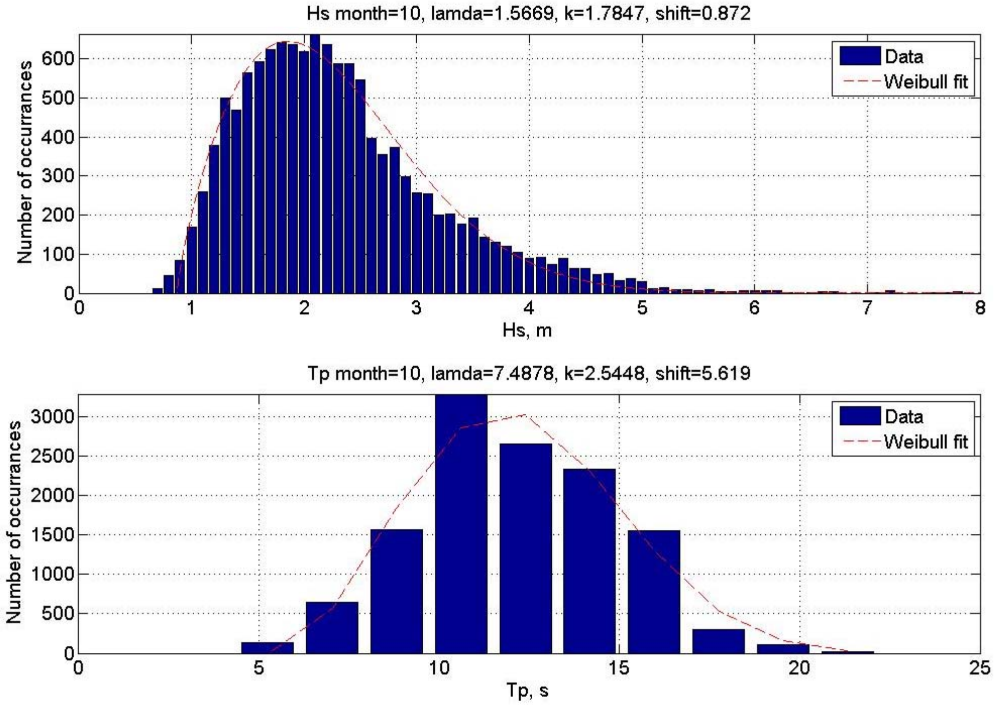
FIGURE 2-5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Tp month=10, lamda=7.4878, k=2.5448, shift=5.619

HS AND TP OF CDIP IN OCTOBER FOR DATA YEARS 1996–2007

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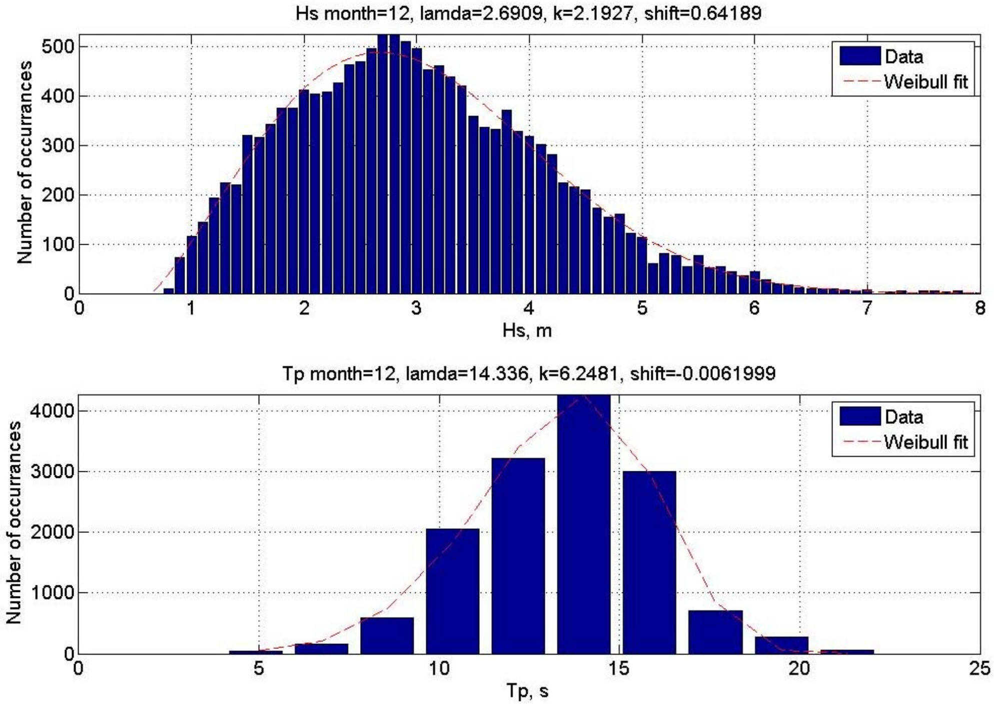
FIGURE 2-6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Tp month=12, lamda=14.336, k=6.2481, shift=-0.0061999

HS AND TP OF CDIP IN DECEMBER FOR DATA YEARS 1996–2007

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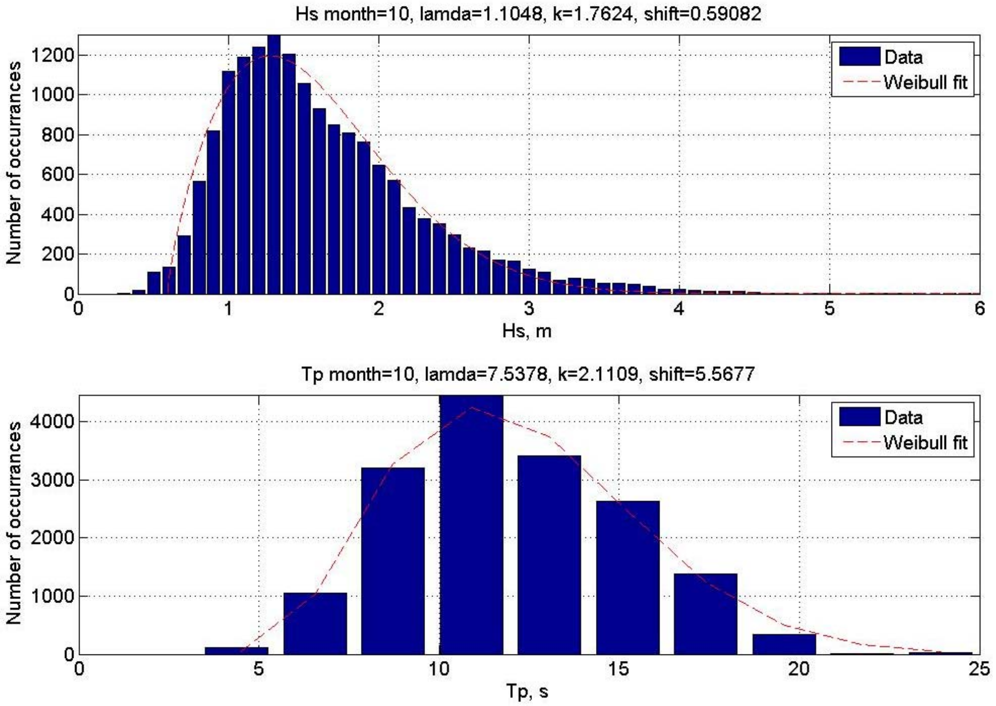
FIGURE 2-7



HS AND TP OF 46026 IN OCTOBER
FOR DATA YEARS 1982–2006

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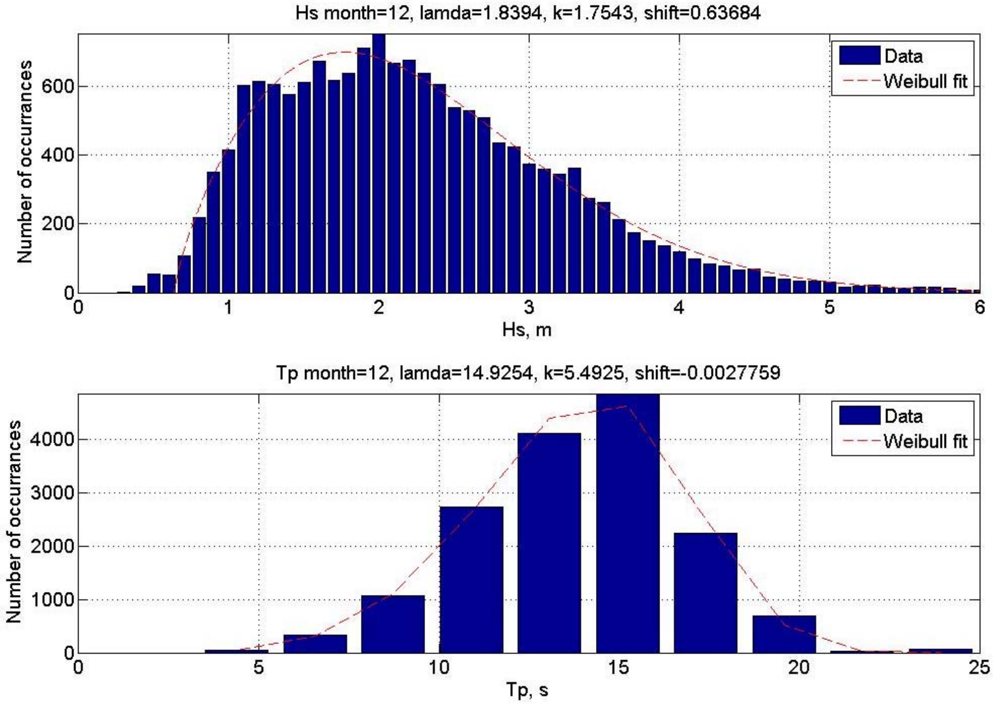
FIGURE 2-8



HS AND TP OF 46026 IN DECEMBER
FOR DATA YEARS 1982–2006

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FIGURE 2-9

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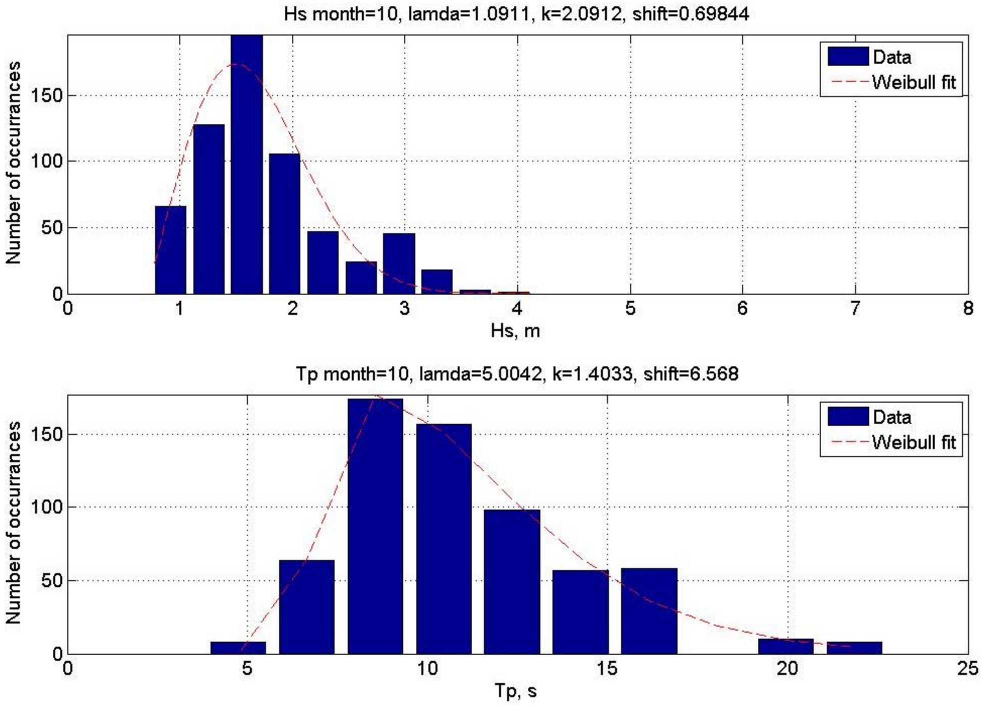

HS AND TP OF ADCP IN OCTOBER FOR WINTER 2007–2008

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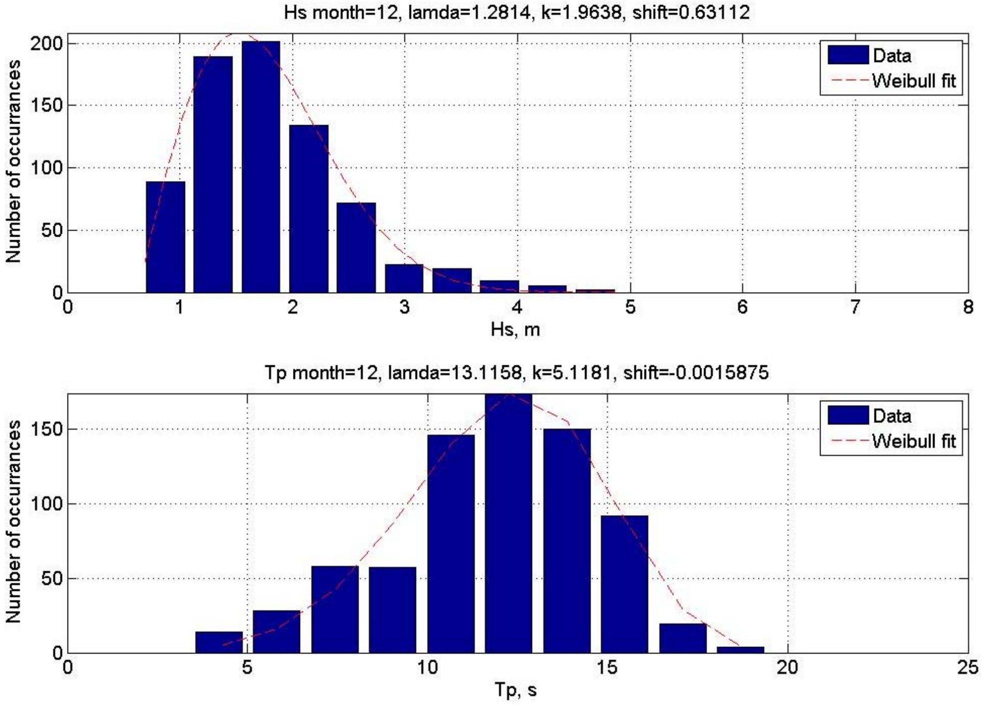
FIGURE 2-10



HS AND TP OF ADCP IN DECEMBER FOR WINTER 2007–2008

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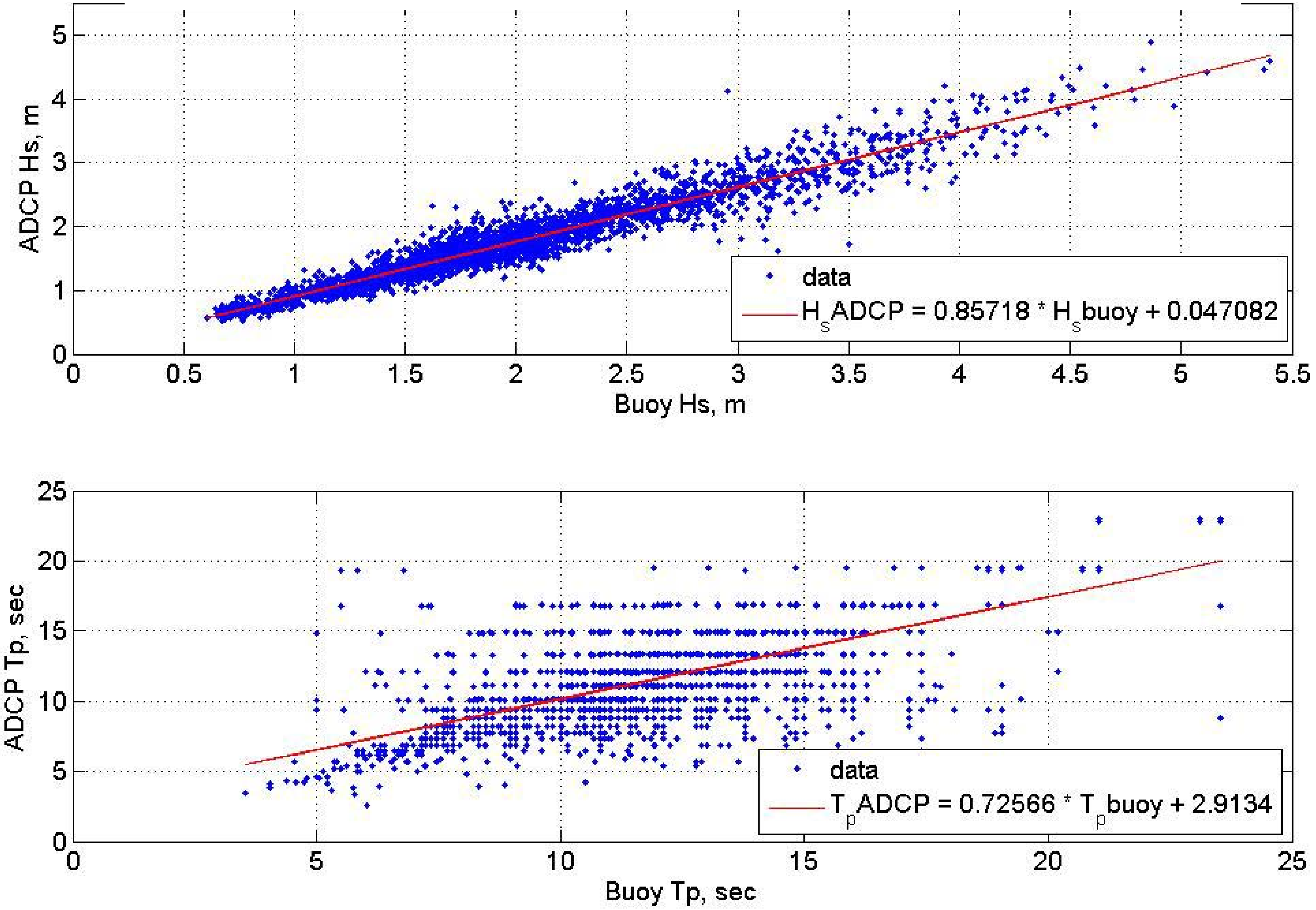
FIGURE 2-11



Source: http://cdip.ucsd.edu/

ADCP AND NBDC 46026 WAVE HEIGHT AND PERIOD TRANSFER FUNCTION

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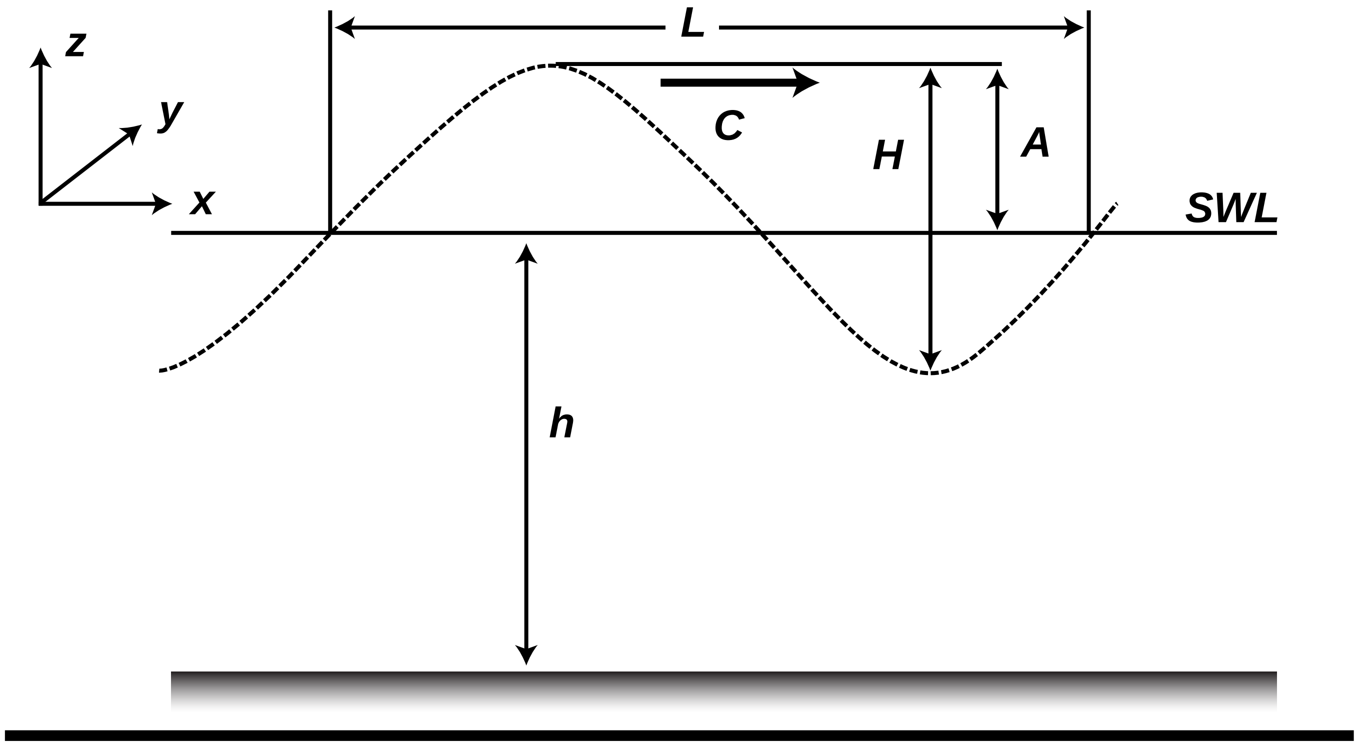
FIGURE 2-12

12/08/09 hk/vsa ..T:\SFPUC Wave Power\Dec 09\Fig 2-12_trans func.ai



Not to Scale

WAVE SCHEMATIC

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FIGURE 3-1

12/08/09 vsa/hk ..T:\SFPUC Wave Power\Dec 09\Fig 3-1_wave_schem.ai