Final Report

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I. Project Objectives

The most prudent path to a full-scale design, build and deployment involves establishment of validated numerical models using physical experiments in a methodical scaling program. This project provides the essential additional rounds of wave tank testing at ~~1:15~~1:33 [1] scale and ocean/bay testing at a ~~1:5~~1:7 [2] scale. Specific project tasks include a kickoff meeting; a hydrodynamic optimized Wave Energy Converter (WEC) shape design; if needed, an optimized ~~1:15~~1:33 scaled wave tank test; a ~~1:5~~1:7 scaled ocean/bay test and associated demonstration to Department of Energy (DOE) program managers; a full-scale design analysis of project findings; and inclusion of this analysis into the full-scale design; a final integration of test results into the WEC design, appropriately timed design reviews, and a final report.

II. Project Scope

Columbia Power will deploy an intermediate-scale wave energy converter (WEC) to demonstrate and validate the technology in preparation for a full-scale bay/ocean demonstration under Topic Area 1 of the DOE Advanced Water Power funding opportunity announcement, DE-FOA-0000069. This project furthers the development of a wave energy converter and optimizes Columbia Power's wave energy technology to improve energy capture through hydrodynamic and controls improvements, tests improvements at ~~1:15~~1:33 scale and intermediate ocean scale (~~~1:5~~1:7 scale) and integrates those findings into the full scale design.

III. Accomplishments (Task Deliverables)

A. WEC Optimization (Task 2)

In order to continue advancing the development of a low cost and reliable wave power, Columbia Power has explored optimization opportunities which improve the energy capture efficiency, reduce the capital and maintenance costs, and ensure survivability of their ocean wave energy converter.

Task 2 explores a wide variety of WEC parameters which aim to optimize: WEC shape, mass and inertia, generator control, PTO design, survivability, directionality, and to reduce mooring loads. Finding optimum operating points for each of these parameters allows Columbia Power to ultimately reduce the LCOE of their WEC systems.

The shape optimization effort explored the potential performance improvements of geometry changes to the Manta WEC. After running more than 300 unique geometries a final WEC shape was presented that could employ a simple low cost mandrel manufacturing technique. The final shape also uses a single float cross section for both the forward and aft floats allowing common tooling to further reduce costs. Conveniently, the shape optimization effort lead to large diameter cylindrical nacelle that played well with the large diameter DDR generator needs.

With a final shape selected, the optimization effort went on to explore mass and inertia optimization using a high speed neural network approach. Later, a control optimization effort looked at a variety of control strategies to increase energy capture of the device. With the benefit of the new large nacelle diameter we had the opportunity to revisit the direct drive PTO design to optimize it for cost reduction as well. This was done with a genetic algorithm approach to produce a reduced cost

[1] Scale tank testing was reduced in scale from 1:15 to 1:33 scale in order to obtain results cost effectively.

[2] WEC intermediate scale was reduced in size from 1:5 scale to 1:7 scale following full assessment of the wave climate and the most appropriate scale selection. Please see appendices H, I, and J for further details on scale selection.

design. Subsequent optimization work occurred during 33rd scale tank testing and focused on survivability, mooring load reduction, and directionality.

In the end the final design dubbed "Manta_344" was shown to absorb 230% more energy than the Baseline Manta (based on 15th scale tank test article) in a statistical annual Oregon wave climate (results based on frequency domain simulation).

For more details on Columbia Power's V3.1 optimization effort see the accompanying *Interim Optimization Report* originally submitted September 30, 2011.

B. Scaled Tank Test (Task 3)

Columbia Power and Oregon State University jointly conducted a series of tests in the Tsunami Wave Basin (TWB) at the O.H. Hinsdale Wave Research Laboratory (HWRL). These tests were run between November 2010 and February 2011. Models at 33rd scale representing Columbia Power's Ray series V3.1 WEC were moored in configurations of one, three and five WEC arrays, with both regular waves and directionally spread irregular seas generated. Task 3 focuses on characterizing the response of a single WEC in terms of power performance, range of motion and generator torque/speed statistic, and utilizing these results to validate a numerical modeling tool.

The TWB is 48.8 m long, 26.5 m wide and 2.1 m deep, with a maximum operating depth of 1.5 m. The wavemaker consists of 29 individually actuated piston-type paddles and is capable of generating regular and irregular waves. Several different wave regimes were generated for the tests, including normally incident and oblique regular waves, and irregular wave systems with various degrees of directional spreading. A total of 28 instruments (resistance wire wave gauges, an ultrasonic wave gauge and several Acoustic Doppler Velocimeters) were available for hydrodynamic observations.

Each model WEC was outfitted with a pair of model generators – one was actuated by the relative motion between the spar and the fore float, and the other by the relative motion between the spar and the aft float. The generators were modeled using oil-filled rotary dashpots, and were extensively characterized via bench testing. The mooring of each WEC was designed to have roughly the same load-displacement curve as a preliminary design of the commercial scale mooring system. This was accomplished via horizontal elastic lines running in a symmetrical three point mooring configuration. The position of each rigid body comprising the model WEC was tracked using PhaseSpace, an optical motion tracking system employing active LED markers.

The WEC performance response was characterized in terms of relative capture width (RCW) in both regular waves and irregular waves. The range of motion responses in eight degrees of freedom (DOFs) were also characterized, in terms of response amplitude operators for regular waves, and in terms of position percentiles for irregular waves. Furthermore, the ability of the WEC to weathervane, or turn into obliquely incident waves, was also characterized.

Model validation was carried out on the unidirectional (i.e. no directional spreading), normally incident (i.e. head on) dataset. A numerical model was developed using ANSYS AQWA version 14.0. The simulations were carried out in the time domain and accounted for some nonlinearity, including viscous drag. Of primary concern was estimation of mean power performance in real seas. Mean absolute error in total WEC performance over seven different sea states was used as the primary indicator of model performance. Viscous drag coefficients were modified to reduce this error metric, resulting in a reduction in error form 49% to 9.9%. The mean error of +6% (calculated without taking the absolute value) revealed a slight positive bias in the calibrated model over the range of sea states investigated. While the effects of viscous drag are not expected to be significant at utility scale, the inclusion of viscous drag in the model improved the estimations of mechanical power for the 33rd scale test considerably. Statistics of relative float motion were also compared against experimental data, showing in general excellent agreement.

Several additional items of note were observed in the WEC response. Firstly, numerical modeling had predicted yaw oscillations under wave excitation that were large enough to cause concern; this was revealed to be an error in the numerical modeling, as the model WECs were quite stable in yaw. Secondly, the model WEC did exhibit significant roll instability, particularly in off angle or spread seas, often continuing to oscillate in roll for one or more minutes after the waves subsided. This motion was not seen in the larger SeaRay prototype discussed later, and as such is assumed to be an artifact of the 33rd scale model. Thirdly, the propensity for the WEC to passively reorient itself into the incident waves was seen, although its ability to do so was restricted by the 3 point mooring system. A decision was made to investigate design changes that would allow for this weathervaning response. Finally, in the extreme seas testing a ballast change was investigated that allowed the WEC to duck under the waves to some degree, as a person might do as they swim out through the waves, presumably reducing wave induced loading. A decision was made to further investigate ballasting cases for survivability purposes.

For more details on Columbia Power's 33rd scale V3.1 tank testing and model validation effort see the accompanying *33rd Scale Experiment: Single WEC Assessment*.

C. Intermediate Scale Prototype Demonstration (Task 4)

Columbia Power Technologies deployed an intermediate scale prototype WEC in the Puget Sound in February 2011. Other than a brief period (10 days) in which the WEC was removed for repair, it was in the water for 13 months from Feb. 15, 2011 until Mar. 21, 2012. The SeaRay, as this WEC is known, consists of three rigid bodies which are constrained to allow for a relative pitch motion between the fore float and nacelle, and between the aft float and nacelle. Each of these relative pitching motions actuates a permanent magnet generator, converting the mechanical energy of the sea into electrical energy.

The SeaRay is kept on station with a spread, three-point mooring system. This prototype WEC is heavily instrumented, including but not limited to torque transducers and encoders reporting generator torque applied to and relative pitch of the floats, an inertial measurement unit reporting translational acceleration and rotational position of the spar/nacelle, a GPS sensor reporting position, load cells reporting mooring loads at the WEC connection points and a number of strain gauges embedded in the fiberglass reinforced plastic hull. Additionally, wave and current data are collected using an Acoustic Wave And Current Profiler (AWAC), allowing performance and design data to be correlated to environmental input conditions. These results will primarily be used to validate numerical models. The validated numerical models will be used to optimize commercial WEC models and inform the design process.

The SeaRay was designed as a 1:7 scale prototype of the Generation 3.1 Ray series WEC. However, due to practical limitations associated with scale and the data requirements, the mass distribution of the SeaRay differs substantially from the commercial scale design. As such, the observed performance is indicative, but does not accurately describe a scaled response of the commercial scale device. The primary use of the data is validation of numerical models, and as such the mass differences are not seen as problematic.

With the scale factor of 7, typical full scale equivalent (FSE) H_{m0} values observed in the Puget Sound range from roughly 0.5 to 3.5 m, covering the range of operational seas expected in open oceans. The maximum observed value of 1.55 m scales to 10.9 m, which is on the order of design wave height expected in open oceans. FSE energy period (T_e) was typically between 5 and 9 s, which is marginally higher frequency than what would be considered representative of expected open ocean conditions. Thus the waves on the whole tend to be steeper than expected open ocean conditions. The seas were generally much more directionally spread than would be expected in open oceans (with a spreading index typically between 1 and 2), and with stronger currents than would be typical for a candidate utility WEC location (FSE currents up to 2 m/s). All things considered, the deployment location was a good choice, offering many seas in the operational range and several in the design range. WEC and environmental data was collected for more than 25,000 trials of 512 s duration. After quality control of sea state data and WEC PTO data, roughly 16,500 trials remained for consideration.

WEC performance was characterized primarily using the Relative Capture Width (RCW). Performance was shown to correlate with six parameters characterizing either the WEC or metocean conditions: energy period, significant wave height, wave heading, PTO damping, Unidirectivity Index, and fitQ (a parameter describing the spectral shape). The strongest correlation is with the frequency content of the incident waves. In general the observed frequencies had been Doppler shifted by the pervasive tidal currents and as such the observed, rather than intrinsic, spectrum was used to calculate the energy period. Performance declined noticeably with increasing energy period. Though not as drastic, wave energy capture efficiency also declined with increasing wave heights. As expected, performance was best for head seas. This trend, however, flattened significantly with increasing energy period. The effect of PTO damping is harder to quantify, primarily because the testing of significantly different damping cases was fairly limited. That being said, performance dropped noticeably when very heavy damping was applied. Although the incident seas were in general extremely short-crested (i.e. heavily spread directionally), the positive correlation of performance with increasing Unidirectivity (i.e. long-crestedness) is clear. Finally, performance was shown to be negatively correlated with fitQ, implying that performance is generally improved when the incident wave spectrum conforms to JONSWAP shape.

The heavily instrumented SeaRAY yields not only performance data, but data that informs design as well. Design data includes mooring loads, end stop loads and structural strain. Mean mooring loads were shown to correlate with current speed, and oscillatory loads with significant wave height. Furthermore, it was found that mean loads were in general significantly greater than the oscillatory loads. Only the oscillatory strain was analyzed, as signal drift made analysis of absolute strain problematic. Oscillatory strain was seen to correlate with wave height, and was significantly greater for head seas as compared to following seas. End stop loads were found to correlate with significant wave height, and were most numerous and forceful for the aft float at the ‘top’ position where the range of motion was most restricted. The strikes were particularly forceful when the PTOs were undamped (i.e. freewheeling). WEC design has since evolved to alleviate the need for end stops.

The SeaRay was a well-conceived prototype that was well built through collaboration with several key partners. As a 1:7th scale model of the version 3.1 WEC all efforts were made to match the physical parameters as closely as possible to their FSE values. The use of fiberglass reinforced plastic (FRP) proved very valuable as it was rugged, corrosion resistant, and was easily modified. FRP will continue to be utilized in all of Columbia Powers future deployments. The commercial off the shelf PTO worked extremely well during the testing. The low cost gearbox and low speed PMG reliably converted the WEC motion into electric power. As power electronic hardware failures occurred the Electric Plant went through several design iterations. The final Electric Plant configuration proved very effective and reliable while benefiting from being readily accessible for repairs and maintenance.

The control and SCADA system aboard the SeaRay worked well but also taught us a lot about communication, accessibility, and reliability. The importance of having multiple communication paths cannot be overstated. The sensor network suite successfully gathered an enormous amount of operational data during the deployment. A few sensors experienced failure during the deployment, most due to corrosion and waterproofing failures. At times the data collection software failed to achieve high reliability, but with incremental improvements and careful operation it was able to capture tens of thousands of trials during its 13 months of operation. The Auxiliary Systems worked extremely well at supporting the WEC with station power, navigational aid, bilge pumping, and surveillance among other responsibilities.

SeaRay's three-point mooring system worked well at keeping the WEC on station and limiting mooring loads. A serious concern still exists regarding the failure of two galvanized steel cables on recovery day which warrants further investigation. When functional the yaw control system (YCS) worked to turn the WEC into any given heading. The YCS did however encounter a number of failures that required careful attention and repair.

A subset of the extensive SeaRay data set has been used to validate numerical models. The numerical model utilized to assess performance was developed using ANSYS AQWA version 14.0; the simulations were carried out in the time domain, and accounted for some nonlinearity, such as PTO torque limiting and viscous drag. The mean error over all 18 cases for total RCW is -2%. For the fore and aft PTOs considered separately, the mean errors are 7% and 2% respectively. For total, fore and aft RCW the mean absolute errors are 17%, 26% and 22% respectively. These results are quite encouraging; while the error in total WEC performance for any one case simulated can be as extreme as ±30%, on the average the result can be expected to be less than 20% off and on the whole the results are unbiased.

For more details on Columbia Power's intermediate scale V3.1 design, at-sea testing and model validation effort see the accompanying *SeaRay Experiment: A Scaled Prototype Wave Energy Converter Deployment in the Puget Sound.*

D. Project Influence on Full Scale Design (Tasks 5 & 6)

1. 0000 Design Fundamentals

a) *0010-0040 Design Conditions and Response*

(1) Model validation

As a part of efforts involved in Tasks 3 and 4, modeling tools have been successfully validated against data from experiments conducted at two different scales. Data from small scale tank testing and intermediate scale sea trials were used by Columbia Power to validate models of the V3.1 WEC developed using ANSYS AQWA. It is understood that no numerical modeling tool will be free of error, but a validated model that is properly applied is an essential design tool. Thus far the model has been validated using data from operational seas. Ideally a robust modeling tool will also yield a reasonable estimate of the WEC's response to extreme seas as well. Columbia Power plans to collect data while conducting scaled experiments in extreme seas, allowing for validation of and quantification of error associated with modeling tools.

Additionally, data from Columbia Power's small scale tank testing has been used successfully to validate performance modeling performed by Garrad Hassan using WAMIT and WaveDyn. Garrad Hassan has been contracted by Columbia Power on a number of occasions to conduct 3rd party validation of our modeling results.

Furthermore, data from the intermediate scale sea trials have been used to validate mooring modeling developed by InterMoor using OrcaFlex. InterMoor has been contracted by Columbia Power to design a mooring system for the utility scale V3.2 WEC.

(2) Model use in design

The model validation efforts undertaken as a part of Tasks 3 and 4 have increased Columbia Power's confidence in the results of the numerical modeling tools and methodologies they and their subcontractors use in the design process. Confidence is greatest in the use of models in operational sea states, and for the purposes of estimating power performance and mooring loads. AQWA has been used extensively to estimate mean annual energy production in differing locations and with various WEC modifications, ranging from mass and geometry modifications, to mooring or PTO changes. Furthermore, modeling is used to gain an understanding of various design responses, such as PTO speed and torque or six degree of freedom forces at conveniently defined hull connection points.

Moving forward, Columbia intends to use modeling extensively for investigations into performance and survival enhancing controls, structural loading scenarios, mooring design and WEC response in extreme seas.

(3) Energy capture improvements

Numerical modeling is a powerful and essential tool for developing improvements in energy capture; relying on physical modeling alone would be difficult, time consuming, require more engineering/technical resources and too expensive. Columbia Power will continue to make extensive use of validated numerical modeling tools to drive energy capture improvements.

The as-built intermediate scale V3.1 WEC, also known as the SeaRay, did not perform as well as the optimal V3.1 WEC would be expected to perform. Due to practical limitations associated with scale and the data requirements, the mass distribution of the SeaRay differs substantially from the optimal design. Extensive numerical modeling indicates that these changes in system mass and mass distribution have a significant effect on WEC response.

Following the SeaRay experiment, a decision was made to redesign the WEC hull structure to avoid end stop collisions (more on this later). The redesign was seen as an opportunity to optimize the WEC's performance further. Significant effort went into investigating the effects of many aspects of hull geometry and mass distribution using AQWA and in house numerical code. In total, nearly 1000 simulations were run in the course of this investigation. Project Lightning, as this effort was called, resulted in a substantial improvement in the power performance. A cost function was used along with performance estimates, allowing for optimization based on LCOE. Estimated mean electrical power production on an annual basis is given in Table 1 for both the V3.1 and V3.2 as-designed WECs. In a variety of wave climates, the optimized V3.2 WEC is expected to produce roughly twice the power as the V3.1 WEC. Electrical power performance estimates in real seas for V3.1 and V3.2 are depicted as 3-D RCW surface plots in Figure 1. This figure indicates dramatic improvements in energy conversion, particular at energy periods of 10s and less. Electrical power performance estimates in regular waves for a full scale as-built SeaRay, as well as as-designed

V3.1 and V3.2 WECs, are depicted in Figure 2 in the form of RCW as a function of wave period. All three WECs are scaled such that the width of the fore float is identical. Note the poor performance of the SeaRay with respect to the as-designed V3.1 WEC; as mentioned previously, this difference is accounted for by changes in mass distribution necessitated by the scale and instrumentation needs of the SeaRay design. The results in Table 1, figure 1 and figure 2 are based on existing WEC designs using linear damping and do not speculate on longer term improvement possibilities.

Table 1. Mean annual electrical power production estimates for v3.1 and v3.2 WECs.

	StingRay Scale Annual Electrical Power [kW]	
Site location	**v3.1**	**v3.2**
Hawaii, Kaneohe Bay, CDIP098	[redacted]	[redacted]
Oregon, Stonewall Banks, NDBC 46050	[redacted]	[redacted]
California, San Nicolas Island, CDIP 067	[redacted]	[redacted]
UK, EMEC	[redacted]	[redacted]

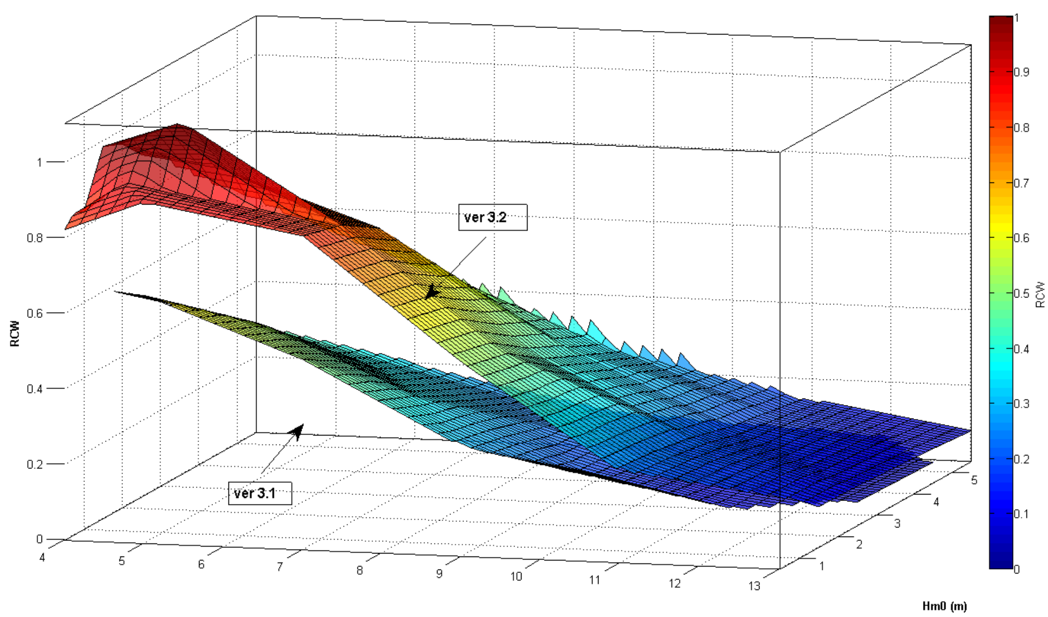


Figure 1 – Electrical power RCW matrices for as-designed v3.1 and v3.2 WECs.

[redacted]

Figure 2 – Electrical power performance in regular waves for full scale equivalent as-built SeaRay, and as-designed v3.1 and v3.2 WECs.

b) ***0050 General Requirements***

(1) 0051 Safety

The system must meet all relevant codes and recommendations regarding personnel safety, naval, structural, and electrical engineering as agreed to with certifying agency.

(2) 0052 Survivability

Perform life and repair interval estimates on all system components. The system will be capable of withstanding and surviving a 50 year storm for the given deployment location, bathymetry, bottom condition, and specified generator loading conditions. All system designs will be considered as marine applications. Design loads relating to the deployment site will be provided by Columbia Power. Best practices for minimizing risk of failure and maximizing reliability will be used. A risk assessment will be performed for all systems.

(a) *End Stops*

The SeaRay project and subsequent design efforts of end stops at utility scale taught Columbia Power that end stop collisions must be reduced or completely avoided. End stop collisions proved to be the maximum loads imparted on both the bodies and the bearings. These big spikes in force became the design requirement to which all of the bodies needed to be designed. These forces were more than ten times the nominal forces. This "no-end stop" design concept led us to our new V3.2 design which prevents any of the bodies from impacting one another.

(b) *0053 LCOE Reduction*

Proper WEC size was selected for LCOE comparison at the Kaneohe Bay wave energy test site (WETS) and optimization from the original V3.0, to shape v3.1 and finally v3.2. As seen below, LCOE with the final system design (v3.2) developed from knowledge gained during this project shows a reduction to $[redacted] /kWh projected for the first open water test, a considerable improvement over the original design (v3.0).

Table 2. Forecasted LCOE improvements of first WEC deployment.

Site location	RAY Series LCOE improvements $/kWh		
	V3.0	**v3.1**	**v3.2**
Hawaii, Kaneohe Bay, CDIP098	[redacted]	[redacted]	[redacted]
Oregon, Stonewall Banks, NDBC 46050	[redacted]	[redacted]	[redacted]

(3) 0054 Assembly, Operation, & Maintenance

System design will consider spatial integration with all other Manta systems inside the buoy. System design will consider modular installation and removal of all system components and parts. Design integration will ensure all parts are accessible, installable and removable with minimal impact to other systems.

(a) *Accessibility –*

One of the fundamental limitations of a small scaled device is accessibility to internal components. The intermediate scale buoy design left minimal accessibility to the onboard power electronics and buoy power systems. The need for access to all electronic components was known before hand and further strengthened while troubleshooting and repairing power electronic hardware failures. The need for quick access strengthened the full scale design approach for modularity with easy access and swappable components. During the immediate scale service in the Puget Sound it was more desirable to simply install an accessible module with a fully functioning unit. Then take the malfunctioning unit back to shore and do the repairs. The ability to quickly swap out malfunctioning modules reduces time at sea and down time of power production. At full scale this equates to more up time and higher capacity factor.

(b) *Modularity –*

A modular design allows for the systems to be decomposed into a number of components with standardized interfaces and can be mixed and matched as necessary to achieve the desired resulting system function. Design modularity increases the use of standardized parts and allows systems to be less tightly integrated and have a lower risk of failure.

(c) *Autonomy and Remote Operation*

As full scale WEC systems will spend decades operating in remote ocean locations with minimal on-site operations. Autonomy and remote operation will be critical.

Remote operation means having the ability to diagnose and affect an operational change to a WEC system without having personnel onsite. Many remote operation tasks can be accomplished by the SCADA and control systems with their data link to operators on shore. The sensor network will provide a host of data that can be used to interpret and diagnose the status of many WEC systems. Sensors selection must consider remote operation when chosen and placed to provide key diagnostics information for remote operation.

Autonomy will take things one step further by removing the operator from the decision making process. By carefully automating the control system we can allow it to respond to specific input conditions and take appropriate corrective actions. These events would be accompanied by alarm messages that are sent back to operators.

Autonomy may also refer to many other intrinsically automated WEC systems like battery chargers, lubrication filters, bilge pumps, generator control, breaker operation, fire alarms, and navigation beacons.

(4) 0055 Sea Keeping

(a) *Weathervane*

Numerical modeling has predicted and physical testing confirmed that the WEC performs best in head seas. The YCS tested in the SeaRay experiment presented a significant capital and maintenance cost. Furthermore, if and when the system fails the WEC is left with no ability to reorient. Moving forward, the ability for the WEC to passively orient itself to the incident wave system, or weathervane, is a key component of the full scale design.

The WEC should be able to weathervane to within 10 deg of the mean wave direction seas accounting for 95% of the annual energy. The WEC should be restrained from over rotation, to avoid winding about its own mooring lines or umbilical electrical connection.

(b) *Stability*

The WEC is generally stable while operating, with the low center of gravity and multiple bodies with reserve buoyancy at the surface dispelling any concern of the WEC upending. However, numerical modeling raised concerns regarding dynamic stability in yaw. Large yaw oscillations were observed in the simulated motion, with unrealistic amplitudes of up to ±180° in some wave conditions. Furthermore, 33rd scale tank testing had raised concerns regarding dynamic stability in roll. In spread seas or off angle waves large roll motions were excited. The roll motion appeared so problematic that Columbia Power experimented with a roll damping ‘keel’ during tank testing. These modes of motion do not generate power but do cycle mooring loads, as well as perturbing the WEC from its favorable position. Concerns regarding these extraneous motions vanished upon observing the SeaRay in heavily spread, energetic seas. The SeaRay has shown the dynamic stability of the WEC to be adequate.

In addition to the WECs stability during operation, stability during transit was also demonstrated. During decommissioning the SeaRay was towed from its deployed location to a sheltered area, where it was then crane-lifted. A line was attached to the fore float and the WEC was easily towed in its 'upright' operating position by a small craft. This successful maneuver opens the door for consideration of a variety of deployment operations at full scale.

(5) 0056 Corrosion & Biofouling

System design will take into consideration all corrosion & biofouling modes and design/specify mitigation measures to combat system degradation at all potential sites. Refer to "0640 Corrosion and Biofouling" documentation to comply with all Columbia Power standards and guidelines.

Zinc anodes will be designed to help in the prevention of corrosion for all metal surfaces external to the WEC. This will ensure an extended life and lowered maintenance on metallic components.

Biofouling coatings are currently under investigation. There are three different coatings being compared off of a dock in Newport, Oregon. Shear forces to scrape off the fouling will be measured and compared for each of the different coatings. This information will help determine an appropriate coating for any future projects to be deployed.

(6) 0057 Environmental Benign

(a) *Noise & Vibration*

System design will minimize production and susceptibility to audible noise, vibration, and electromagnetic interference (EMI). A noise study was conducted by University of Washington and submitted in August, 2011 "CPT *noisereport_final_12Aug2011*" and confirmed Columbia Power's assumption that the system is not a significant source of noise. Additionally, when the full scale device is modified to use a direct drive rather than geared PTO, the noise will be reduced even further.

(b) *EMI design minimization*

All electronic and electrical components will be manufactured to reduce specifications of EMI. EMI with be minimized in all designs.

(c) *Pinniped Protection*

Periodic sightings of pinniped haulout occurred during the thirteen month deployment. These events occurred in low-wave conditions on sunny days. Presumably, in large wave conditions, the WEC bodies pitched too much and discouraged haul-out.

(d) *Environmentally Benign Materials*

System will be non-toxic to the environment. System will strive to minimize impact on the environment where applicable.

c) ***0060 Design Process –***

The '100s' series design organization (major systems 0100-hull, 0200-PTO, 0300-Electric Plant, 0400-SCADA, 0500-Auxillary, 0600 Outfit and Furnishing, 0700-Mooring, 0800-Electrical connection) used to develop the SeaRay WEC worked extremely well and will help pave the way for its implementation in full scale design. During this project, engineering processes and systems were developed to enhance the organization of the design process. These include the organization of the design into three areas of increasing detail; concept development, front end engineering design (FEED) and system detailed design (SDD). To manage and organize design related documentation such as schematics, drawings and bill of materials with revision tracking and appropriate levels of vaulting we have acquired and implemented the use of the Enterprise Project Data Management (EPDM) software from SolidWorks. Interface control documentation (ICD) are used to define all system and sub system interfaces and. Internal and subcontracted projects are defined using scope of work (SOW) and requirements documentation.

d) ***0070 Interface Control***

The Interface Control Document (ICD) defines the requirements related to the interface between WEC Systems 0100 Hull, 0200 Power Take-Off, 0300 Electrical Plant, 0400 SCADA, 0500 Auxiliary Systems, 0600 Outfit & Furnishing, 0700 Mooring, and 0800 Electrical Collection. The ICD documents are intended to facilitate the complete design and construction of the full scale WEC by providing accurate definitions of mechanical and electrical interfaces between major systems components. Each System may include system specific ICD having more detailed interface requirements for all subsystem and components within the major system. The objective is to define the interface requirements concisely using definitions, existing specifications, and/or drawings to show specific details about the interfaces of all systems and subsystems.

The integrated design of the full scale WEC requires each system to include spatial planning of size and placement of system components. Interface design considerations will include spatial orientation of system parts and components with regards to all other systems component locations, specifications and regulations. Spatial planning will consider manufacturing, assembly, operation, and maintenance of the entire WEC. System design will consider modular installation and removal of all system components and parts and design integration will ensure all parts are accessible, installable and removable with minimal impact to other systems. The following design requirements will be considered during the detailed system design integration.

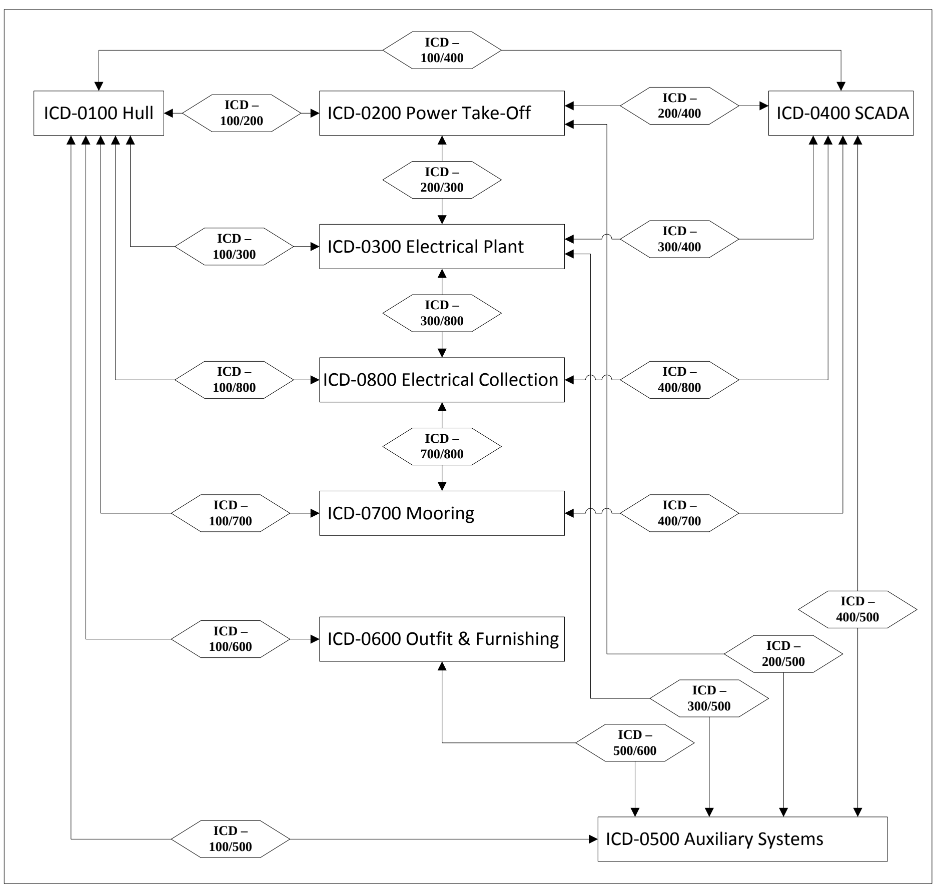


Figure 3 – Top level ICD Diagram for complete full scale WEC

(1) Size of Component, Modules, and/or Part
  (a) *All Components and Parts will fit through the service access at the top of the WEC.*
    i. *Minimal space for access between system component, module, and/or part should be 5" or less.*
    ii. *100" total allowable size (diameter)*
  (b) *All Components and Parts will fit into design access space inside of WEC*
    i. *Fit through bulkhead doors, passage ways, and hatches.*
    ii. *Fit through between other equipment*
    iii. *Pipes, modules, and assemblies should be designed to be installed and removed with minimal impact to other systems*
    iv.

(2) Placement of Components and Parts
  (a) *Distance from wall/bulkheads and other system components will be optimized for accessibility for installation, removal, operation and maintenance.*
  (b) *Heavy system components should be design integrated as low as possible in the buoy to preserve the designed center of gravity (CG).*
  (c) *Routing of cable will minimize cable length while allowing ease of access to all cable trays or buses.*
  (d) *Distance between system components will be optimized for performance and accessibility.*
  (e) *Design will allow for thermal expansion/contraction of system components and buoy components.*
  (f) *Thermal conduction between adjacent systems will be minimized to avoid adverse affects or damage to system components.*
  (g) *Vibration and electromagnetic interference (EMI) will be considered to minimize adverse affects on nearby system components.*
  (h) *All components that contain large amounts of fluid will be below all electronic equipment. Design placement will consider fluid leak contingencies to avoid cascading electrical failures or electrical fires.*
  (i) *Items that could start a fire will be contained as to not allow the fire to spread.*

(3) Personnel and Equipment Access Zones:
  (a) *Access zone will be drawn as a part into all system component installations.*
  (b) *Personnel Access will be included with reference to the 0650 Workspace Specifications and ICD 100-600 for Workspace Outfit & Furnishings.*
  (c) *Doors and Hatches will have designated space for the swing range of operation. Swing range will be drawn in SolidWorks as a part that prevents unintended spatial interference. For example: swinging door space and the space for operator to open and close it.*

(4) Design Integration:

New components and equipment will be test fitted in 3D CAD for installation and removal. Test fit will include space for equipment translations, rotations, lifting/handling equipment and personnel.

2. 0100 Hull

a) *Shape modifications*

Following the intermediate scale at-sea test, a lengthy investigation into practical end stop design was undertaken. Aside from the capital cost of the various end stop systems considered, the impact loading induced massive radial loads on the PTO bearings. A decision was made to redesign the WEC hull structure to avoid end stop collisions, and this redesign was seen as an opportunity to further optimize the WEC's power performance. The optimization effort and performance gains are discussed in section III.D.1.a)(3), while the shape modifications are covered here. Simplified depictions of V3.1 and V3.2 WECs are shown in figure 4; the widths of the fore floats are the same for both WECs.

Modifications include but are not limited to:

- Two spars rather than one so that both floats can pass through without collision
- Spars were extended past the damper tank to lower the center of gravity, which has the effect of improving performance
- Nacelle diameter was increased, which allows for larger diameter generators and improves the hydrodynamic performance significantly
- Float shapes were modified slightly from V3.1 to improve performance
- Aft float was widened and aft float arms extended, allowing both floats to rotate arbitrarily without the possibility of collision
- Damper was shaped as an oval to span spars without increasing the damper surface area in the same manner as a circular form. This significantly reduces total draft when the WEC is horizontal for transit in shallow water and addresses transit concerns.

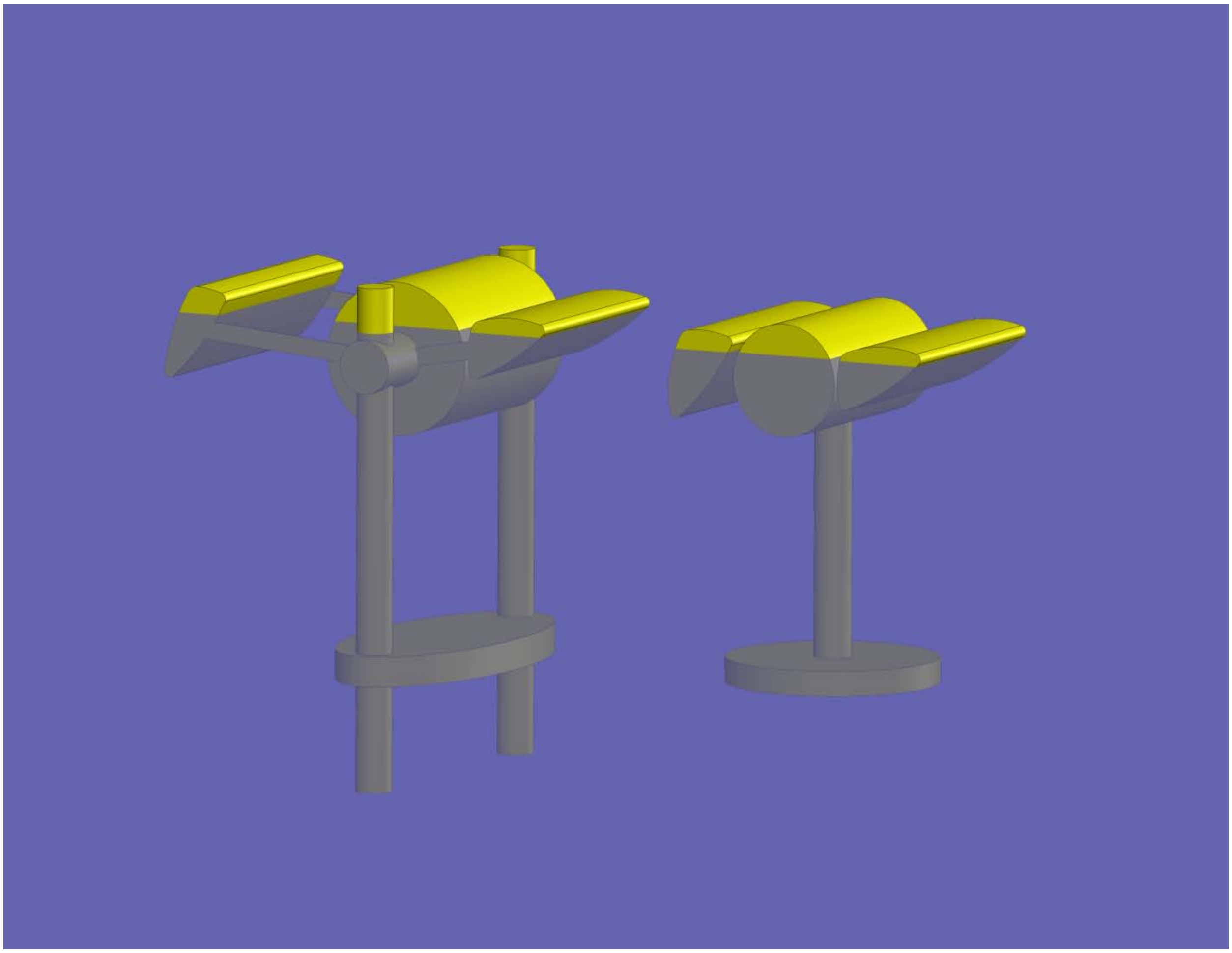


Figure 4 – Simplified depictions of StingRay V3.1 (right) and V3.2 (left) WECs, showing shape modifications.

b) ***Quality Control***

Quality control will be implemented to ensure there are no leaks through the FRP that could penetrate into the hull. This will also check the structural integrity of the manufactured FRP components. Additionally, hull components will be verified to be dimensionally accurate in accordance with build drawings.

3. **0200 Power Take-Off (PTO)**

Full scale power production is 900 times higher than the intermediate scale PTO in this project and torque is 2400 times more, which fundamentally puts the full scale engineering in a much different category. The performance and operational regions of the WEC will contribute to the full scale analysis and development of PTO performance specifications. The intermediate scale PTO demonstrated the use of an intermediate stage gear. The geared PTO system allowed generator to have a lower torque rating and a higher speed rating. For full scale, the geared solution was investigated as a possible solution. A geared PTO design would require additional maintenance costs with no capitol cost advantage. Both the full scale and intermediate scale geared PTO mass are too high and create a higher WEC center of gravity that adversely affects performance. The full scale design will use a direct drive generator.

4. **0300 Electric Plant**

The Electric Plant used during the SeaRay deployment worked very well to control the PTO load and provide energy to the Station Power system. The Electric Plant did evolve as failures were encountered and experience was gained. An unavoidable aspect of all power electronic hardware is eventual component failure. This has taught us an invaluable lesson in redundancy and accessibility. If high risk components are made redundant the system could continue operating successfully while notifying operators of the required repair work. Critical systems should be made modular so that replacements can be quickly changed out at sea and time consuming troubleshooting work can be followed up on shore. Having quick and convenient access to these high risk components will reduce the time, equipment, and ultimate cost of such failure events.

SeaRay had a lot of instrumentation within the Electric Plant capturing voltage, currents, and control status. This information was highly valuable for troubleshooting issues from on shore and made us better prepared for repair actions. The full scale design should continue this level of instrumentation and look for ways to expand on it.

5. **0400 SCADA**

A number of SCADA related design aspects of the SeaRay experiment were identified during construction, deployment, operation, recovery, and final inspection which will influence full scale.

After several iterations a reliable wireless communication arrangement was achieved using a dedicated 3G/4G network router, which also conveniently allowed for Wi-Fi connection as well. This experience has demonstrated the importance of long term hardware verification of all critical systems prior to deployment. Additionally, for a full scale deployment multiple communication options should be used to prevent interruptions and allow troubleshooting of one link from another.

An increased emphasis toward autonomy must be considered early in the design phase. Systems must be designed to automatically recover from common faults and continue operation. Software updates should be disabled as they can cause unexpected interrupts to occur. Software needs to be selected which can reliable run for months without human intervention. All critical hardware and software system MUST be verified in long duration tests prior to deployment.

A master remote power controller should be used to isolate problem hardware and allow operators restart systems. This controller would have a dedicated communication link to shore that would allow an operator to control power to all systems regardless of current status.

All onboard PC’s used in a WEC need to be setup to automatically power up when power is applied, preventing a PC from being unavailable when off or stalled. Redundant systems should be considered on critical systems to increase ‘up’ time in the event of hardware failure.

Heading sensors based on solid state compasses or “fluxgate” technologies failed to provide reliable and accurate heading information. Dual differential GPS heading sensors proved to be highly reliable and even provided additional motion data.

Corrosion to enclosures and cable connections became an issue late in SeaRay testing. Enclosure materials must be carefully selected and ideally tested prior to long term deployment. Electrical connectors should be avoided in favor of hardwired or soldered connections where practical.

6. 0500 Auxiliary Systems

a) *0510 Ballast System*

The intermediate scale was designed to have fixed ballast. The full scale will have variable ballast controls for deployment operations. It has been demonstrated that having the ability to control the ballast in the floats could increase performance the benefit survivability in extreme wave conditions.

The ballast system will need to measure the water level in each of the ballast chambers. This will detect leaks in the ballast chambers and when appropriate turn on ballast pumps to fill the chambers to the desired point. These measurements will allow operators to detect issues with the ballast chambers such as leaks or failed valves.

b) *0520 Emergency Systems*

There are multiple emergency systems for various system and sub-system level components tied to the control system for the WEC with redundant features to insure survivability. For water ingress due to accidental vessel impact both the bilge and ballast systems are capable of pumping water from the hold to maintain a positively buoyant WEC.

c) *0530 Climate Control*

Climate control on larger scale WECs would help to dehumidify the air if there is water inside the nacelle. When salt water penetrates the enclosed body of the WEC and evaporates it then condenses on components and causes them to corrode. A dehumidifier would reduce the opportunity for internal parts to corrode.

d) *0540 Station Power*

The SeaRay test experienced low station power conditions for two primary reasons. First, the 1:7th scale nature of the test meant the available energy was 900x less than an equivalent full scale case. Secondly, the Puget Sound is a sheltered water body with no significant wind and wave resources during the summer months leading to negligible energy harvest. Neither of these factors will be relevant to a full scale device in open water and station power is expected to have high availability.

The station power system will be powered from both generator electric plants as well as the shore power cable maximizing availability. The station power system will also have battery backup for critical systems in the case of Main bus power loss. All power supplies connected to the backup system must be rated to handle the voltage fluctuations of the battery bus as it is discharged and recharged.

A master remote power controller should be used to allow operators to disconnect or cycle power to all onboard systems in the event of a system error and will have a dedicated communication link.

e) *0545 Solar*

The solar electric collection system proved to be highly valuable during our intermediate scale deployment, providing good base load capability during low-wave summer conditions. Solar electric systems should be considered in full scale designs to maintain power to critical systems, like communications and bilge pumps, in the event of Main bus power failure or low-wave conditions.

f) ***0550 Navigation***
The SeaRay deployment has demonstrated that it may be wise to go above and beyond the Coast Guard minimum requirements for navigational aids. This will better ensure effective notification to mariners operating in the area. At least one high intensity beacon such as the 12 nautical mile version used on SeaRay should be used. Large passive and perhaps even active radar beacons should be used to illuminate the WEC presence on ships radar at night or in adverse weather conditions. These devices should also be mounted high above the waterline to ensure good line-of-sight in large wave conditions. In spite of all these efforts on SeaRAY, we did experience a boat strike with minimal damage on December 31, 2011. Additional measures may include acoustic notification such as a fog horn or proximity alarm.

g) ***0560 Cooling System***
The intermediate scale buoy was designed to run efficiently with minimal heat production. The relatively large surface area of the nacelle was continuously cooled by the surround Puget Sound water. There was prior testing on all components to monitor heat production and calculations proved a passive cooling design approach was sufficient. The utility scale WEC will also be designed to have minimum cooling requirements allowing passive cooling systems to be used. A cooling system which does not require electrical power is more reliable and reduces risk of failure.

h) ***0570 Bilge System***
The dual redundant bilge system that was used on the SeaRay performed exceptionally and will be mimicked on a larger scale in all future projects.

To increase the reliability of the bilge power supply a separate and isolated battery bank will be used. This dedicated supply would not be depleted by other onboard station power systems ensuring the bilge supply is always topped off and will be charged by the Main power bus.

i) ***0580 Surveillance***
The external surveillance camera that was used for the SeaRay project had returns that were above expected. Similar systems will be used in the future both external and internal monitoring. Internal surveillance could be used to determine status of hardware inside the WEC.

j) ***0590 Environmental Monitoring***
Accurate and reliable assessment and characterization of the metocean conditions (primarily waves and currents) during a full scale WEC deployment will be critical. The taught-moored subsurface mounted AWAC was likely the best option for measuring the relatively high frequency wave energy of the Puget Sound. However, in an open ocean, full scale deployment the wave energy content of interest will fall into a range that is commonly investigated. As such it is likely that a floating wave measurement buoy will be employed as their use in this application is well documented.

7. 0600 Outfit & Furnishings

a) *0610 Designation & Markings*

On at least one occasion a recreational fishing vessel tied off to the SeaRay while fishing. Though not directly destructive this undoubtedly affected the motion behavior of the WEC corrupting experimental data. Large signs will be placed on the WEC to discourage the mooring to and boarding of the WEC by unauthorized people. This will help prevent people from hurting themselves and the WEC.

b) *0620 Hull Fittings*

External and internal fittings will be scaled up from the SeaRay project to accommodate the larger components and vessels that will go along with the increased size of the WEC.

c) *0630 Hull Compartmenting*

Future designs will incorporate hull compartmenting. Hull compartmenting will be realized in the design by using removable and accessible modules. These modules will house the power electronics and auxiliary systems. The pods will be easily removable at sea as to lower operation costs and improve ease of maintenance. Each PTO will also be its own module and will be a separate watertight entity apart from the rest of the WEC. This PTO module will improve survivability because of the inherent redundancy of watertight areas. This modular design will also ease manufacturing.

d) *0640 Corrosion & Biofouling Zinc anodes worked well on SeaRAY and prevented corrosion of all major steel hardware and will be designed at full scale to help in the prevention of corrosion for all metal surfaces, internal and external to the WEC. This will ensure an extended life and lowered maintenance on metallic components.*

Research will continue on marine coatings to identify ways of reducing corrosion and potentially lessen the impact of biofouling.

e) *0660 Emergency and Safety Equipment*

Future equipment should include topside safety harness and harness connection points. In Puget Sound, this need only arose in larger sea states when repairs were typically avoided, but in off shore scenarios this will be a definite requirement. Signs with emergency contact information and a stay clear notice to mariners were added to the WEC post deployment. Collision avoidance could be improved with a fog horn triggered by a proximity detector.

f) ***0680 Sea Life Protection***

Interactions with marine life included occasional birds perching on the mast and an occasion pinniped out-hauling on the floats. Seen in figure 5, a baby seal was observed during a service call. At times, bird droppings and seal visitation caused a notable reduction in solar capacity.

Larger scale WECs may also experience such visitations and qualified biologists in the region of deployment should assess the requirement for mitigation or protection. WEC specific equipment protection should be considered on a case-by-case basis by the WEC developer.

Figure 5 – Seal on WEC's solar panel

8. 0700 Mooring

SeaRay provided a valuable insight into the full-scale mooring design. The mooring load data will help validate numerical models that will influence the full-scale design. Data showing the WEC performance with changing wave direction will inform the requirements for directionality of the full-scale system.

The combination of geometric and material spring properties used in the SeaRay mooring design proved to work well at limiting the mooring loads. This combination will be carried on to full scale design efforts. Further investigation is needed to determine the reason for the considerable corrosion, which occurred on the galvanized wire rope mooring.

The yaw control system was necessary in the Puget Sound to allow the WEC to turn into widely directional waves and confirmed that to maximize power production; the WEC requires orientation into the waves. This system proved to be a significant maintenance and reliability challenge, costing both time and money. This experience has reinforced desire to accomplish WEC orientation passively through the WEC and mooring system alone.

Full scale mooring will need to operate in shallower relative water depths. This presents a challenge in maintaining a soft mooring. With shallower depths line lengths and geometric spring lengths are shortened resulting in stiffer mooring designs.

9. **0800 Electrical Collection System**
SeaRay did not have an external electrical power cable (Electrical Collection System) and therefore will not have an influence on full scale design. The SeaRay did have a station power system with battery bank waterproof enclosures below the waterline in the damper tank. The design required electrical connections with a watertight bulkhead and cables running up the center of the spar. This design provided some design understanding of integrating utility scale umbilical cables with the hull structure. Strain reliefs, flex radius, and methods of waterproofing the design were considered.

10. **0900 Logistics**
This Project required that numerous details be addressed in the preparation, permitting, build, transportation, deployment, recovery and decommissioning of the WEC, and while those plans associated with a 7-ton device differ in magnitude from an 1100-ton WEC, the necessities are the same. These experiences are detailed in the SeaRAY experiment report.

11. **1000 System Verification & Validation**

a) ***1010-1020 Verification and 1020 Validation***
Specific details on the validation of the Ray series technology are covered in both the 33rd scale and SeaRAY reports. Overall, the technology has been demonstrated at 33rd scale and 7th scale and model validation shows good correlation with the experiments.

The SeaRay data set has been used to validate numerical models. The validated models are being used to inform the performance optimization and design of the StingRAY prototype WEC. The numerical model utilized to assess performance was developed using ANSYS AQWA version 14.0. The simulations were carried out in the time domain, and accounted for some nonlinearity, such as PTO torque limiting and viscous drag.

From the two experiments, operational assumptions regarding the WEC's offshore behavior were validated. WEC response in directional waves, mooring characteristics, performance and operation in numerous wave spectrums, WEC permitting, PTO and electrical designs, deployment and recovery procedures, operational plans, observation approaches, data collection methods and survivability in extreme seas were all confirmed.

b) ***1030 Risk Reduction***
Lessons learned during this project have been identified and added to the risk reduction strategy of the full scale WEC.

12. **1100 Operations & Installations**

a) ***Operations and Maintenance Reduction***
O&M considerations are covered in the SeaRAY experiment report.

IV. Recommendations for Future Work and Funding

A. Power Take Off Demonstration

The ColPwr critical path includes a Project that completes the design, assembly and experimental validation of a commercial-scale PTO Module in realistic WEC operating conditions. The PTO Module integrates a direct-drive rotary (DDR), permanent magnet generator (PMG) with the necessary structural, operational, protective and supporting mechanical and electrical subsystems to safely and reliably demonstrate its potential for optimal energy capture, conversion and delivery to the grid. The testing and validation should take place at the National Renewable Energy Laboratory's (NREL) National Wind Testing Center (NWTC) using the new 5 MW Dynamometer and Controllable Grid Interface, where the full range of operating conditions can be assessed. ColPwr has been in communication with the NWTC Staff and has confirmed that this test is feasible and that the NWTC would be interested in the project. A multi-national corporation, with demonstrated commitment to the MHK industry and full capabilities throughout the design to manufacturing spectrum, has been contracted for the DDR PMG design.

B. System Detailed Design of Full Scale WEC

Detailed design and certification and compliance activities in this project include a WEC design, Design Basis Review, a Design Assessment, and a Development Accompanying Assessment (DAA). The Design Basis Review evaluates and confirms that definitions and assumptions for function, safety and environment are reviewed and the design baseline is assessed for the selected deployment site. The Design Assessment is a design audit looking at compliance to applicable codes, standards and recommended practice. Both will be completed by Germanischer Lloyd (GL), a leading international maritime and renewable energy certification body. Since 2008, GL Garrad Hassan has provided ColPwr with independent engineering verification of procedural and analytic integrity, as well as design certification support services.

The DAA is an integrated effort conducted during the design process between GL-Garrad Hassan, GL and ColPwr to assure that ColPwr's design approach, load analysis, design basis and design assessment reports will be in compliance with all applicable codes and standards.

ColPwr has recently completed the Design Basis for a commercial-scale WEC, using met ocean data from the WETS wave energy testing facility for environmental operating conditions. Tier one partners have been identified for the design of the key elements of the hundred series work break down.

C. Full Scale WEC Demonstration

ColPwr is currently designing a StingRAY (v3.2) commercial-scale wave energy converter for an open-water, grid-connected test. Upon completion, ColPwr's device will have attained TRL 7/8. Major objectives of the test include: planning and permitting associated with the deployment, build of the full-scale buoy, mooring installation, testing of systems and subsystems, WEC deployment, assessment of offshore behavior and survivability, measurements and validations of energy performance, assessment of power quality, optimization of performance through controls, removal of WEC and mooring, accurate modeling of the cost of energy, verification and revision of open-ocean procedures, evaluation and assessment of environmental impacts and the knowledge gained from unanticipated issues. As the DOE and NAVFAC ESC are pursuing opportunities to jointly support WEC prototype testing at the US. Navy's Wave Energy Test Site (WETS), ColPwr is designing the StingRay for the deep-water WETS berth currently under development.

V. Project Summary

A. Final TRL Assessment

The scale of the SeaRAY prototype is a relative metric that can range between 1:1 for a data buoy and 1:7 for an optimized utility-scale system off the Oregon Coast. Given the planned WETS test at the Marine Corps Base in Kaneohe Bay, Hawaii, the SeaRAY scale might also be considered 1:4.5. The device as tested is considered TRL 7/8 when used as a power source for a data buoy, as it has proven itself in relevant operational conditions. With respect to the planned WETS-scale test, the present WEC development is considered TRL 5/6, since the StingRAY scale (with limited nacelle diameter) did not allow the demonstration of a direct-drive PTO. Although there are commercial off-the-shelf direct-drive generators with large air gaps and unmanageable costs, the low-cost, small air-gap and unique operating characteristics of Columbia Power's DDR PMG design require a TRL 6 demonstration of the PTO prior to the larger WETS-scale test. Planning for a land-based test of a WETS-scale PTO is currently in progress, as discussed in IV A above.

B. New WEC Design

This project (DOE EE0002647) allowed the design, build, deployment and analysis of the SeaRAY (v3.1) device, during which, some important design variants were identified that predicted dramatic performance- and cost-of-energy improvements. The performance predictions were subsequently validated in 1:33 scale tank tests in the O.H. Hinsdale Tsunami Wave Basin at Oregon State University in November 2012. The v3.1 WEC design was developed and tested under this project and provided key knowledge and insights that helped identify future areas for improvement.

Outside the scope of this project and following assessment of results, Columbia Power spent three months revising the v3.1 design to devlope the v3.2 design. At a high level, the StingRAY (v3.2) design eliminated end-stops by allowing a nested 360 degree rotation of both floats about the nacelle, without fear of collision and incorporated a single point mooring design that further reduced costs and improved energy capture.

The StingRAY is ColPwr's third-generation WEC, representing the collective learning from the last eight years of research and development, extensive use of numerical models and validating physical experiments. The StingRAY WEC is hydrodynamically optimized with a tri-member FRP hull and two high-torque, extremely-low-speed, large-diameter DDR PMGs. The device has three moving bodies: a central body and two floats. The central body (nacelle/dual spar) is attached to the forward and aft floats through drive shafts along its central longitudinal axis. Two PTO Modules, contained within the nacelle, convert the low-speed, reciprocating rotary motion into electricity. The StingRAY WEC captures power through two absorption modes; relative pitch between the central body and forward float, as well as relative pitch between the central body and aft float. Thus, all three bodies share the same heave and surge degrees of freedom, while each body experiences its own pitch response - resulting in five degrees of freedom affecting the power absorption modes. The nested design allows for energy capture in all sea states and results in significantly more output over the course of a year.

The design integrates several novel aspects, all of which are focused on survivability, increased energy capture, reduction in capital and O&M costs, lower environmental impact, or some combination of these.

These innovations include:

* a structurally-sound, corrosion-free, tri-hull FRP composite structure, the components of which can be fabricated locally in a temporary facility at the port of deployment for lower capital, shipping and O&M costs;

* a proprietary hydrodynamically-optimized shape that represents a hybrid blend of point absorber and attenuator designs, resulting in dual-mode heave and surge energy capture and allowing for a maximum theoretical capture limit of $3\lambda/2\pi$, which is 3x the theoretical limit of a cylindrical heave-only point absorber;

* a rigid body-to-bearing design that minimizes structural loads and improves survivability;

* removal of end stops and allowance of maximum range of motion, increased prime mover speed and continuous operation in all sea states resulting in increased energy capture;

* a single-point mooring system that allows for passive heading adjustment to increase energy capture with significant reduction of component and deployment costs and less environmental impact.

In short, StingRAY design innovations collectively result in a cost of energy reduction path that ensures cost-competitiveness in the relatively early stages of commercialization.

C. Improved Energy Forecasts

This project started with improvements to the v3.0 design resulting in a v3.1 design that was tested during this project. The StingRAY v3.2 design, developed from knowledge gained at the end of this project, is forecasted to improve delivered energy by 185% to 210% over the v3.1 design.

D. Request for Future Funding

The project has been successful to date in using limited capital efficiently, but public support has been essential to securing the private capital needed to ensure the necessary funding in advance of rapidly increasing needs. This support becomes commensurately more important as the project moves to a commercial-scale test. Once outside the controlled environment of the lab, the project is at the mercy of the environment, which leads to uncertainties that drive costs higher. In the near term, ColPwr has responded to a competitive funding opportunity (DE-FOA-0000848) that provides funding support for demonstration of critical subsystems. This will be essential in order raise the private funds necessary to de-risk the PTO subsystem in a controlled environment.

VI. Products and Deliverables

Oceans 2010 — Paper and Presentation

Scaled wave energy device performance evaluation through high resolution wave tank testing

OMAE2011-50336 — Presentation

"DEVELOPMENT OF A NOVEL 1:7 SCALE WAVE ENERGY CONVERTER"

Oceans 2011 — Presentation

"Underwater noise measurements of a 1/7th scale wave energy converter"

OMAE2011-50336 — Paper and Presentation

"DEVELOPMENT OF A NOVEL 1:7 SCALE WAVE ENERGY CONVERTER"

OMAE 2011 — Journal Paper

"Numerical Analysis and Scaled High Resolution Tank Testing of a Novel Wave Energy Converter"

2011 IEEE, PowerTech — Paper and Presentation

"WEC prototype advancement with consideration of a real-time damage accumulation algorithm"

2012 IEEE, Oceanic Engineering — Journal

"Comparison of Direct-Drive Power Takeoff Systems for Ocean Wave Energy Applications"

Oceans 2012 — Paper and Presentation

"Direct drive ocean wave energy electric plant design methodology "

Patents and Provisional patents:

12/656,950; 61/438,951; 61/471,690 PCT: 2010/000505,

- PCT/US2012/23964, METHOD AND SYSTEM FOR WAVE ENERGY CONVERSION, submitted on 2 Feb, 2012.

- PCT/US2012/032120, "A MECHANICAL ASSEMBLY FOR MAINTAINING AN AIR GAP BETWEEN A STATOR AND ROTOR IN AN ELECTRO-MECHANICAL ENGERY CONVERTER, submitted on 4 April, 2012."

- US Provisional Patent Application No. 61/707,281. "METHOD AND SYSTEM FOR WAVE ENGERY CONVERSION, Sept 28, 2012"

VII. **Participants & Other Collaborating Organizations**

Name	Ken Rhinefrank
Project Role	Principal Investigator
Nearest Person Month worked	20 months
Contribution to Project	VP of Research & Development
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	Yes, but in conjunction with a separately funded project
Country(ies) of foreign collaborator	Italy, but in conjunction with a separately funded project
Traveled to foreign country	Yes, but in conjunction with a separately funded project
If traveled to foreign country, duration of stay	5 days

Name	Al Schacher
Project Role	Sr. R&D Engineer - Controls

Nearest Person Month worked	27 months
Contribution to Project	Controls design and electrical engineering
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	Yes, in conjunction with both this and a separately funded project
Country(ies) of foreign collaborator	UK
Traveled to foreign country	N/A
If traveled to foreign country, duration of stay	N/A

Name	Joe Prudell
Project Role	Sr. R&D Engineer - Electrical
Nearest Person Month worked	18 months
Contribution to Project	Power electronics design & electrical engineering
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	Yes, but in conjunction with a separately funded project
Country(ies) of foreign collaborator	Italy, but in conjunction with a separately funded project
Traveled to foreign country	Yes, but in conjunction with a separately funded project
If traveled to foreign country, duration of stay	5 days

Name	Erik Hammagren
Project Role	R&D Engineer - Mechanical
Nearest Person Month worked	15 months
Contribution to Project	Mechanical design and CAD
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	N/A
Country(ies) of foreign collaborator	N/A
Traveled to foreign country	N/A

If traveled to foreign country, duration of stay	N/A

Name	Pukha Lenee-Bluhm
Project Role	R&D Engineer - Data Analyst
Nearest Person Month worked	17 months
Contribution to Project	Process and analyze experimental data
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	Yes
Country(ies) of foreign collaborator	UK
Traveled to foreign country	N/A
If traveled to foreign country, duration of stay	N/A

Name	Zhe Zhang
Project Role	Engineering Intern
Nearest Person Month worked	2 months
Contribution to Project	Hydrodynamic modeling
Funding Support	Columbia Power
Collaborated w/ individual in foreign country	N/A
Country(ies) of foreign collaborator	N/A
Traveled to foreign country	N/A
If traveled to foreign country, duration of stay	N/A

Organizations: List of organizations that have been involved as partners:

NNMREC - Corvallis OR

Controls, Control Systems modeling and optimization

Wallace Energy Systems & Renewables Facility

Hinsdale Wave Energy Laboratory

University of Washington - Lynnwood WA

Resource assessments, acoustic monitoring

Applied Physics Laboratory

Ershigs Inc. - Vancouver WA

Hull & ballasting design & modeling

Fabrication shop

Sound & Sea Technology - Lynnwood WA

Marine Operations & mooring design

The Glosten Associates - Seattle WA

Mooring analysis

Garrad Hassan America Inc. - Portland OR

Wave data review, WEC optimization & control algorithms development

Ecology & Environment Inc. - Seattle WA

Permitting & environmental impact and monitoring guidance

Sound Ocean Systems, Inc. - Redmond WA

Yaw control

VIII. Impact

The proven success of the TRL approach to managing the evolution from concept through commercial application is unquestioned. It is a matter of systematically removing risk with scaled prototypes, utilizing the smallest and least expensive scale necessary, in the most controlled environment possible, as early in the process as possible. Wave tanks can only test to a certain scale before sea- and open-ocean trials become necessary. This project represented an excellent example of the process, transitioning between the wave tank and sea trials, demonstrating an appropriate scale increase in a reasonably protected, though clearly representative environment. The increased scale allowed for more sophisticated approximation of the commercial subsystems and exposure to marine operations that provided significant and important experience for the engineering team. The lessons learned at this scale will ensure that increased attention is paid to the relative costs of reliability, redundancy and maintenance complexity in the commercial scale design. The design modifications resulting from the challenges encountered and insights gained have accelerated reduction of the cost of energy projections.

IX. Changes / Problems

None of substance.

X. Budgetary Information

Please see final budget submission where tables have been completed in the Excel template accordingly:

Spending Summary – TAB B

Cost Share Contributions – TAB C

Spend Plan Data – TAB D

CPT Scaled Test Site Selection

Task Order number 1131

Objective:

To gather data/information on possible test locations for a 1/5 scale test of test of a novel direct-drive rotary wave energy converter (DDR WEC).

Site specifications:

Wave conditions at test site should have Hs and Tp to $1/5^{th}$ scale power of Stonewall Banks site. The average low range of Hs for this location should be 0.32 m, and the average high range Hs would be 0.76 m, thus average Hs of 0.5 m was preferred. The 1/5 scale of Tp at the Stonewall Banks site is 1.78 seconds. Hs should not exceed 2.0 m. For these reasons sites in protected bays with adequate fetch distances to produce wind waves were examined as possible test locations. The depth required for mooring the DDR WEC is 30 m or greater.

Conditions required for wind wave:

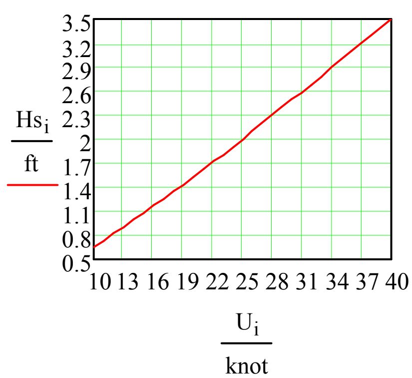
Data provided by Jim Thomson, Ph.D. a University of Washington, Applied Physics Lab study in Puget Sound, WA showed that wind speeds > 8 m/s (15 knots), with a fetch of 20 km and a duration of several hours produced wind waves with Hs = 0.5 m and Tp that varied between 2 and 4 seconds. Jim Thompson stated that Tp was not well correlated with wind speed as Tp was likely affected by currents and other features within the Puget Sound basin, and as a result ranged from 2 to 4 seconds.

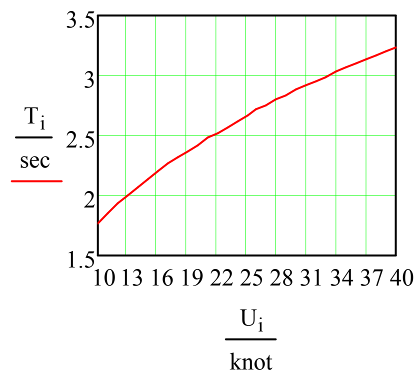
Data provided from SST engineer, Bob Taylor, from the Coastal Protection Manual provided data tables predicting the period of wind waves produced by various wind speeds (see figure below). These data are for 10 km of fetch and 100 foot water depths. They are expected to produce lower Hs and Tp than are typically found in areas of greater fetch and depth (conditions in Puget Sound).

Wind data was gathered from National Data Buoy Center (NDBC) Met station locations in the Puget Sound, WA, San Francisco Bay, CA and near Tomales Bay, CA as these were 3 bays along the US west coast that had 20 km of fetch in the direction of prevailing winds. When long-term data sets were available (10 years), analysis could be made on the average number of wind events per year that meet or exceed threshold conditions. Three threshold conditions were selected; 8 – 12 m/s, 12 – 16 m/s and >16 m/s.

From this initial analysis of wind events at possible test locations it was determined that West Point, Puget Sound, WA would be the central focus of this effort as it had a high number of wind events meeting each of the three threshold conditions listed (see Tab 3). This location also had a long-term data set on wind conditions, and satisfied other logistical considerations for the deployment of a WEC device (adequate depth, dry dock and boat yard facilities close by). A detail analysis of the average number of wind events per month from October through January was also produced for the West Point site (see Tab 2). These months were chosen as this is the expected time of the year the WEC device will be tested.

It was only possible to make estimates of Hs during wind events as there was no available wave buoy information at any of these locations. Rough estimates of Tp can be made from the table in the figure below, but it should be noted that these tables do not account for the effect of strong currents and variable bathymetry found in the Puget Sound.



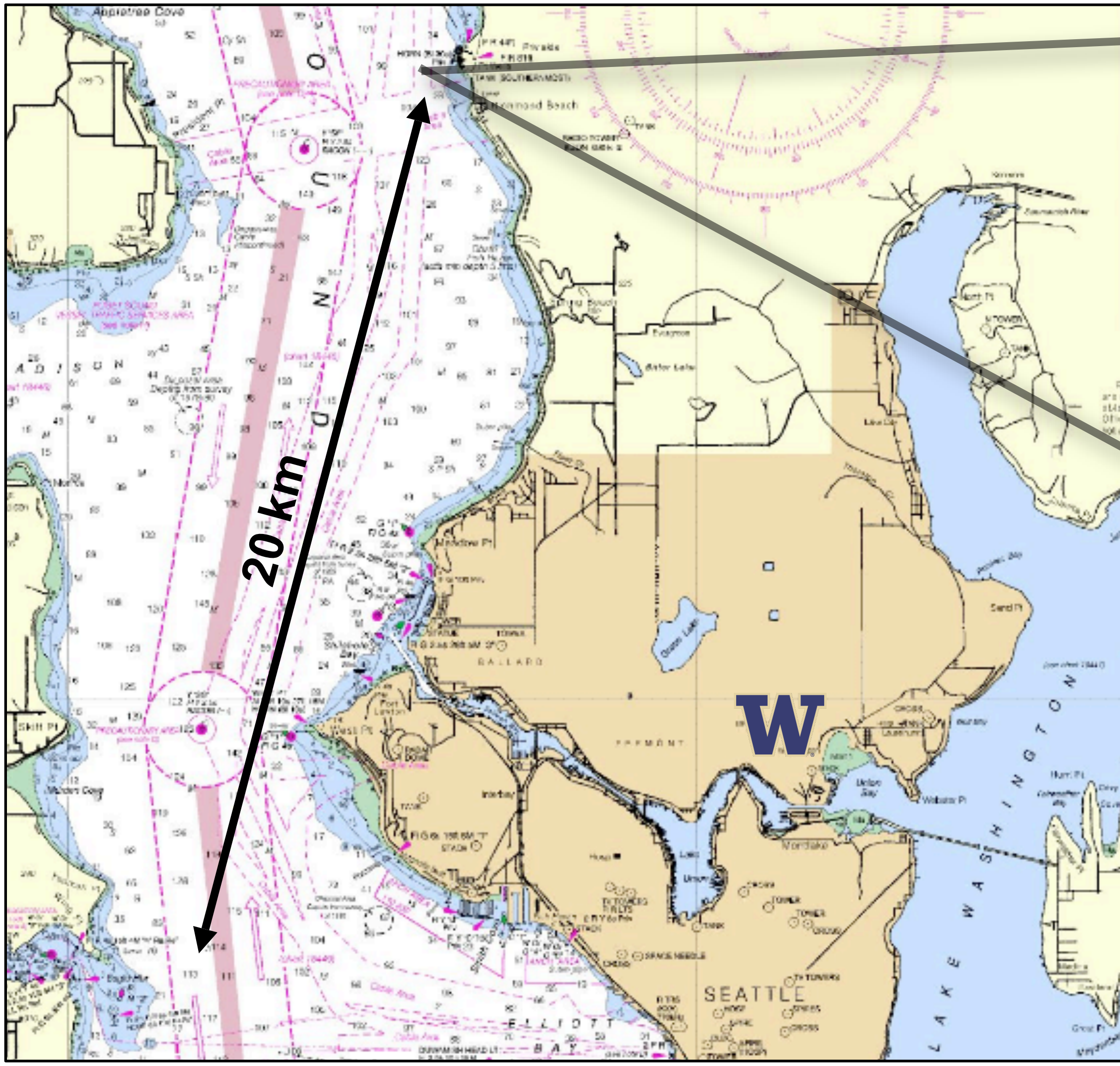


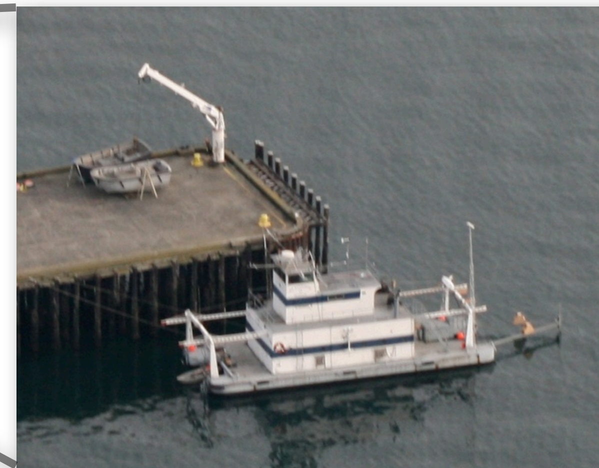
Recommendations:

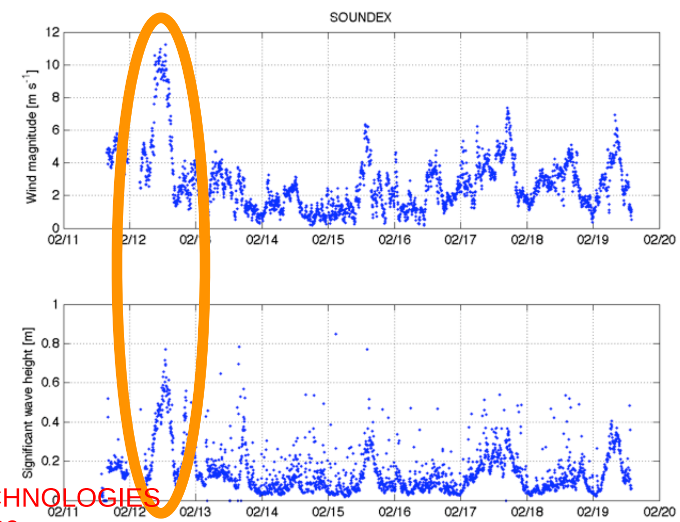
The West Point location near Seattle, WA meets many of the logistical specifications for this study. There are several marine facilities within 5 miles of this location that provide dry docks, cranes and other facilities required for the deployment of a small scale WEC device. Although the NDBC Met station location at West Point (site WPOW1) provides an excellent long-term data set on wind speeds, there is no wave buoy data available for this location. It is not likely that any site within a protected bay will have an established wave buoy as wave buoy programs are concerned with collecting data on open ocean waves. Therefore to adequately measure the Hs and Tp for wind waves near the West Point location we recommend placing a wave buoy at this location during the time of the year of the planned test (October through January) to obtain measured data of the wave spectrum at this location.

Field Experiments

Puget Sound
Feb 2008







Site Name / Description	Scale Estimates: Scale Factor Low	Scale Factor High	Scaled Power (Peak kW) Low	Scaled Power (Peak kW) High	Location: Country & State	City	Latitude / Long.	Available Facilities (DD, SY, CR, DK, PT)	Wave Spectrum & Bottom Conditions: Lowest Ave. monthly Hs (m)	Highest Ave. monthly Hs (m)	Tz (s)	Tp (s)	Max Wave (m)	Depth (m)	Sand, mud, rock	Dist. from shore (NM)	Years of data studied
Stonewall Banks, Baseline	1		400		US, OR	Newport	44.641N 124.5W		1.6	3.8	7.4	8.9	18	123	rock	20	18
West Point, Puget Sound	*	*	*	*	US, WA	Seattle	47.66N 122.44W	all	0.0	*	*	*	2	37	Sand	0.1	10
Alki Point, Puget Sound	*	*	*	*	US, WA	Seattle	47.57N 122.42W	all	0.0	*	*	*	2	37	Sand	0.1	10
Maury Point, Vashon Island	*	*	*	*	US, WA	Seattle	47.39N 122.37W	all	0.0	*	*	*	2	46	Sand	0.1	10
Dabob Bay, Hood Canal	*	*	*	*	US, WA	Seattle	47.69N 122.94W	dk	0.0	*	*	*	2	46	Sand	1.0	10
Tomales Bay, Hog Island	*	*	*	*	US, CA	Tomales	38.20N 122.94W	dk	0.0	*	*	*	1	16	Sand	0.6	10
San Pablo, S.F. Bay	*	*	*	*	US, CA	San Francisco	37.93N 122.40W	all	0.0	*	*	*	2	n/a	unk.	0.2	2
North Lummi Island	*	*	*	*	US, WA	Bellingham	48.76N 122.73W	dk, cr	0.0	*	*	*	2	37	rock	0.6	10
									*Req's wave data								wind data
									* See Tab 2								
	0	#	-	-													

DD= Dry dock
SY = shipyard
CR=Crane
DK = Dockside facilities
PT = Port or Terminal
etc, define as needed to describe facilities

http://seaboard.ndbc.noaa.gov/index.shtml
http://www.ndbc.noaa.gov/station_page.php?station=46050
http://www.marine.ie/home/aboutus/organisationstaff/researchfacilities/Ocean+Energy+Test+Site.htm

West Point N wind defined as 315 - 45 degrees T (center point 0 degrees T)
West Point S wind defined as 140 - 230 degrees T (center point 185 degrees T)
Wind conditions producing Hs: 8-12 m/s = 1.0 m, 12-16 m/s = 1.5 m, 16+ m/s = 2.0 m
(Based on Jim Thompson / UW Study)

Freq. of Hs = 1m produced by South winds

	October	November	December	January
2008	3	11	14	15
2007	15	7	11	16
2006	7	16	10	18
2005	7	10	2	5
2004	5	4	3	7
2003	9	3	12	5
2002	1	10	11	15
2001	13	11	9	7
2000	7	7	2	10
1999	7	12	11	7
Average	**7.4**	**9.1**	**8.5**	**10.5**

Freq. of Hs = 1m produced by North winds

	October	November	December	January
2008	4	3	5	1
2007	2	2	3	2
2006	3	2	0	0
2005	0	0	0	5
2004	1	2	4	3
2003	2	3	1	0
2002	3	0	3	2
2001	2	1	2	0
2000	1	0	2	1
1999	0	0	0	1
Average	**1.8**	**1.3**	**2**	**1.5**

Freq. of Hs = 1.5m produced by South winds

	October	November	December	January
2008	2	2	0	6
2007	2	3	8	6
2006	0	5	2	7
2005	2	2	1	0
2004	1	2	3	1
2003	5	1	2	2
2002	0	0	3	4
2001	2	2	6	3
2000	0	0	1	4
1999	3	0	10	9
Average	**1.7**	**1.7**	**3.6**	**4.2**

Freq. of Hs = 1.5m produced by North winds

	October	November	December	January
2008	0	0	0	0
2007	0	0	0	0
2006	0	1	0	0
2005	0	0	0	0
2004	0	0	0	1
2003	0	0	0	0
2002	0	0	0	0
2001	0	0	0	0
2000	0	0	0	0
1999	0	0	0	0
Average	**0**	**0.1**	**0**	**0.1**

Freq. of Hs = 2m produced by South winds

	October	November	December	January
2008	0	0	0	1
2007	0	0	0	1
2006	0	0	2	0
2005	0	0	0	0
2004	0	0	0	0
2003	0	1	0	0
2002	0	0	1	0
2001	1	0	3	0
2000	0	0	1	1
1999	0	0	0	2
Average	**0.1**	**0.1**	**0.7**	**0.5**

Freq. of Hs = 2m produced by North winds

	October	November	December	January
2008	0	0	0	0
2007	0	0	0	0
2006	0	0	0	0
2005	0	0	0	0
2004	0	0	0	0
2003	0	0	0	0
2002	0	0	0	0
2001	0	0	0	0
2000	0	0	0	0
1999	0	0	0	0
Average	**0**	**0**	**0**	**0**

CPT Scaled Test sites — 10-year ave unless noted by *

Location	State	Depth at site	Wind events per year >= 8 m/s	Wind events per year >= 12 m/s	Wind events per year >= 16 m/s	Wind events per year >= 18 m/s
West Point, Puget Sound	WA	16 to 30 fathoms, Chart 18441	104	23	1.8	0.6
Alki Point, Puget Sound	WA	44+ fathoms, Chart 18441	104	23	1.8	0.6
Maury Point, Vashon Island	WA	25+ fathoms, Chart 18448	104	23	1.8	0.6
Dabob Bay, Hood Canal	WA	24+ fathoms, south end, Chart 18441	104	23	1.8	0.6
Tomales Bay, Hog Island	CA	54 feet deepest N. Hog Island, 18643	144	69	4.2	0.4
San Pablo North, S.F. Bay	CA	Chart 18642 not avail for free view	2*	0	0	0
San Pablo South, S.F. Bay	CA	depth unknown	2*	0	0	0
N. of Lummi Island*	WA	30 fathoms N. Lummi, Chart 18421	16	3	0	0

*est. from Smith Island data

CPT Scaled Test sites

Location	Wind data notes	notes
West Point, Puget Sound	N. July - Sept, SW Nov - Mar	Exposed to frieghter traffic, wind chop N and S
Alki Point, Puget Sound	"	Freighter traffic, Ferry traffic, wind chop N and S
Maury Point, Vashon Island	"	NW and SW exposure good, near shipping lanes, restricted channel
Dabob Bay, Hood Canal	"	North wind, if deployed at S end of bay at point
Tomales Bay, Hog Island	NW Apr - June	8 foot deep at bar entrance, moving buoys over a problem
San Pablo North, S.F. Bay	NW Apr - June	only 3 years of wind data, NDBC event summary seem too low
San Pablo South, S.F. Bay	"	
N. of Lummi Island*	NW-N winds May - July	N. Lummi site very close to ship lanes, N. Alden Bank more area

*est. from Smith Island data

Wave Conditions on Puget Sound During Winter

- A report for Columbia Power Technologies -

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May 27, 2010

1 Abstract

Surface-gravity waves, generated by local winds, are observed in the main basin of Puget Sound, WA, from November 2009 to April 2010. A climatology a wave conditions is assembled. Wave conditions are dominated by synoptic weather patterns, which in winter storms with southerly winds on the order of 20 m/s produce waves of 1 m significant wave height and 3 s period (nominal values). These wind waves are young, fetch-limited, and highly-forced. Waves steepness and inferred whitecap breaking rates are consistent with previous observations. In addition to the naturally generated waves, ship wakes from commercial traffic are common and are larger than all but the biggest natural waves.

2 Introduction

Puget Sound is a fjord-type estuary in the Pacific Northwest region of the United States. It is connected to the Pacific via the Strait of Juan de Fuca, however swell waves from the Pacific do not propagate to Puget Sound (a result of the complex geometry). Previous observations have shown that waves in fjords exhibit fetch-limited growth and are aligned with the wind (*Thomson et al.*, 2009; *Pettersson*, 2004; *Atakturk and Katsaros*, 1999). These waves are always young, compared with the open ocean, and cannot evolve or propagate much beyond the local wind forcing.

In the following sections, a four-month long dataset of waves on Puget Sound is described, analyzed for climatology, and compared with numerical simulations. Consistent with previous observations, winter storms produce waves that are approximately 1 m height and 3 s period. Wind climatologys show that summer months are comparatively calm, although individual events may be equally strong.

3 Observations

Water surface elevations and wind speeds were recorded from 11 December 2009 to 4 April 2010 at the southern end of the Paramount Petroleum pier off of Point Wells in the main basin of Puget Sound (N 47.7799, W 122.3991). In addition, a week of pilot data was collected from 19-24 November 2009 at the same location. The site was selected to maintain deep-water conditions (depth is 16 m ref. MLLW) for short-period waves ($<$ 20 m wavelength), and for an open fetch towards the prevailing southerly winds. At summary of the wind and wave observations is shown in Figure 1.

3.1 Sampling: waves

Water surface elevations were measured with a down-looking sonic range finder (Miltronics AirRanger SPL) cantilevered out 2 m from the south end of pier. Piling spacing under the pier is approximately 3 m and the average piling diameter is 0.4 m, resulting in a blockage ratio of 13% that is unlikely to significantly alter the incoming wave field. This is visually confirmed by a lack of standing-wave or diffraction patterns in the vicinity of the pier.

Water surface elevations were sampled at 1.4 Hz for a 20 min burst at the beginning of each hour. This sampling was limited by the serial data acquisition (Acumen SDR) and wind-generated power supply (Southwest Windpower Air-X). The resulting Nyquist frequency $f_N = 0.7$ Hz is sufficient to resolve the short-period waves, and the 20 min bursts have strict stationarity for ensemble averaging. Based on previous observations on Puget Sound (*Thomson et al.*, 2009; *Gemmrich*, 2010), the unresolved highest frequencies are expected to be small, because of the persistence of an f^{-4} equilibrium (*Banner*, 1990). The f^{-4} dependence at high frequencies is sufficiently steep that estimates of peak period T_p or energy period T_e are not expected to be biased by the unresolved portion of the spectra above $f_N = 0.7$ Hz.

Wave directions are not measured.

3.2 Sampling: winds

Wind speed and direction were measured with a tri-cup and vane anemometer (Onset S-WCA-M003) colocated with the wave gage. The anemometer height was 7.5 m ref MLLW. Wind speeds were sampled at 1 Hz, with averages and maximum gusts recorded every 5 minutes to an integrated logger (Onset U10). Winds are interpolated to hourly values for comparison with wave results. It is expected, and well-demonstrated in previous work, that wave directions would be similar to the wind directions in the absence of swell.

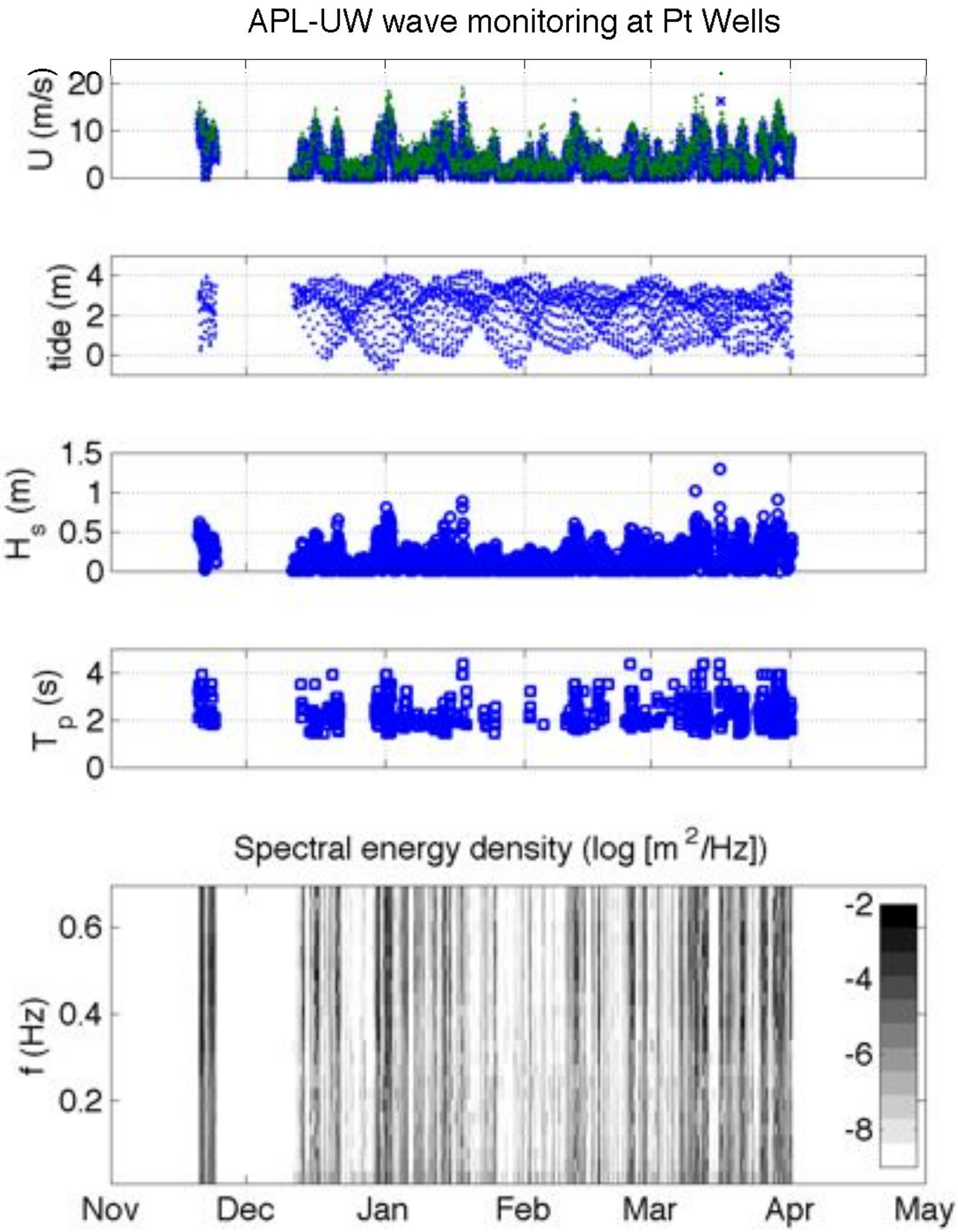

Figure 1: Summary of hourly wind speeds (blue crosses) and gusts (green dots), wave heights (blue circles), wave periods (blue squares), and wave energy spectral densities (grayscale).

4 Analysis

4.1 Spectra

Wave energy spectra are generated for each 20 min burst by first dividing into 12 windows of 50% overlap. The windows are detrended to remove the tide and tapered to reduce signal leakage. A normalized Fast Fourier Transform converts each window to frequency space, and the windows are then ensemble averaged to improved statistical confidence. In addition, each five neighboring frequency bands are merged. The resulting spectra have 60 degrees of freedom, compared with 2 degrees of freedom for raw spectra. The final frequency resolution is 0.027 Hz. Average spectral energy densities $S(f)$ are shown in Figure 2.

Peak period T_p and energy period T_e are estimated by determining the location of the peak and the centroid, respectively, in the spectral energy densities. For very small waves, the spectra are relatively flat and there are not peaks significant at 95% confidence (using 60 degrees of freedom). Thus, periods are not reported during low wave conditions. The relatively flat spectra are likely the result of low frequency motions (seiches, tides), episodic motions (ship-wakes), and aliasing of higher frequency fluctuations. The effective cutoff used is 0.2 m significant wave height, which corresponds to cases when the standard deviation of the water surface elevation is less than 0.05 m. The apparent peak around $f = 0.1$ Hz in Figure 2 during low wave conditions appears to be related to ship wakes, but a rigorous study on this effect has not been completed.

4.2 Significant wave heights

The significant wave height, corresponding to the largest 1/3 of the waves in Rayleigh distribution, is given by

$$H_s = 4 \int_{f_2}^{f_1} S(f)df \tag{1}$$

where $f_1 = 0.1$ Hz and $f_2 = 0.7$ Hz delineate the wave frequencies and the spectral estimate is approximately equivalent to four times the standard deviation of the elevation time series (assuming wave motions dominate the signal).

The average significant wave height observed is 0.13 m, but can reach 1.3 m during winter storms. A histogram of wave heights is shown in Figure 3, where significant wave heights above 0.5 m are observed only 5% of the time. In addition, ship wakes are common in the area and may include instantaneous wave heights of a few meters (*Curtiss et al.*, 2009). The significant wave heights are somewhat correlated with peak period, as shown in the joint occurrence histogram in Figure 4, presumably because of wave evolution during the longer storms that produce larger waves.

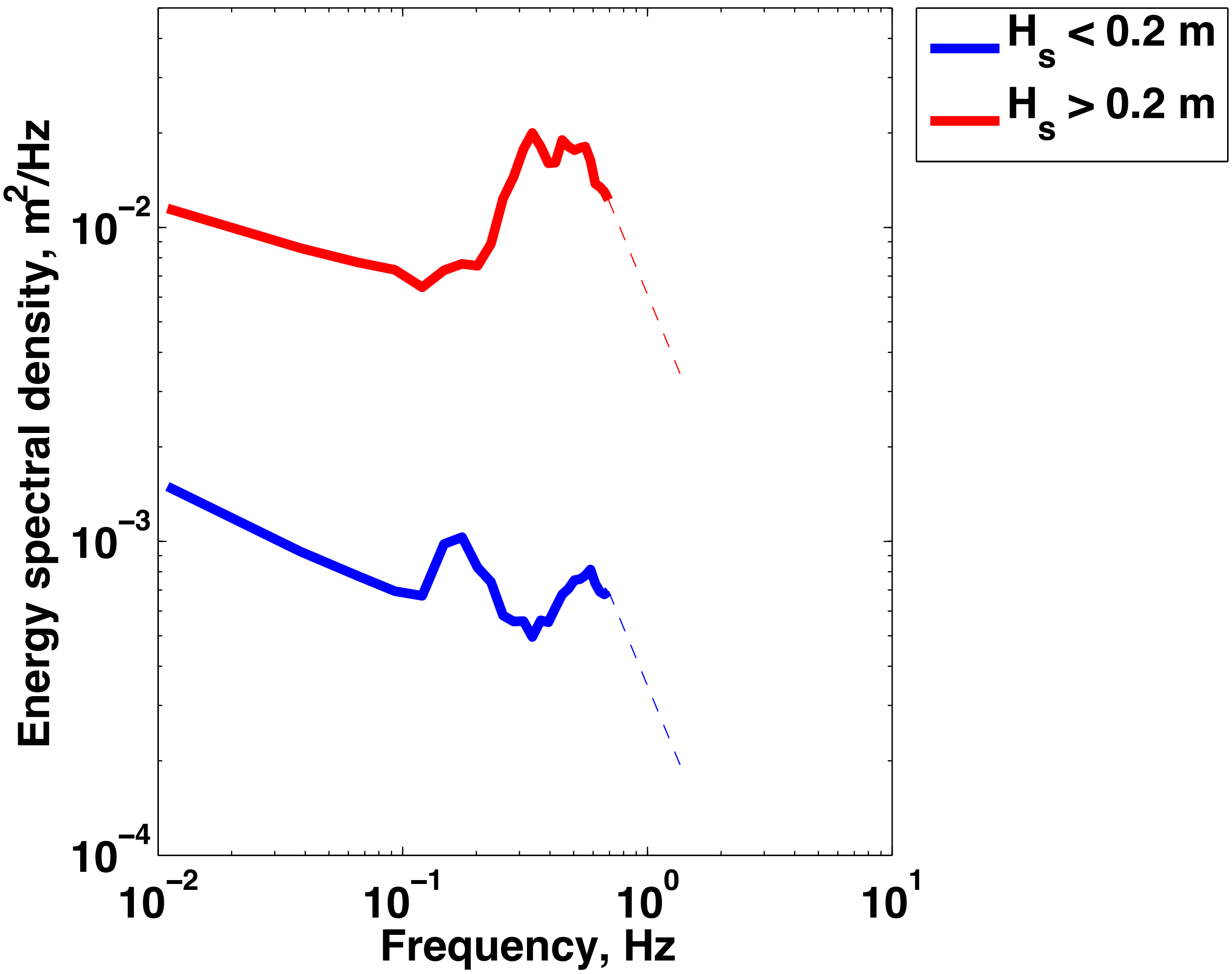

Figure 2: Mean spectral energy density versus frequency for small waves (blue) and large waves (red). The expected high frequency tail f^{-4}, determined during previous observations at the site, is shown by the dashed line.

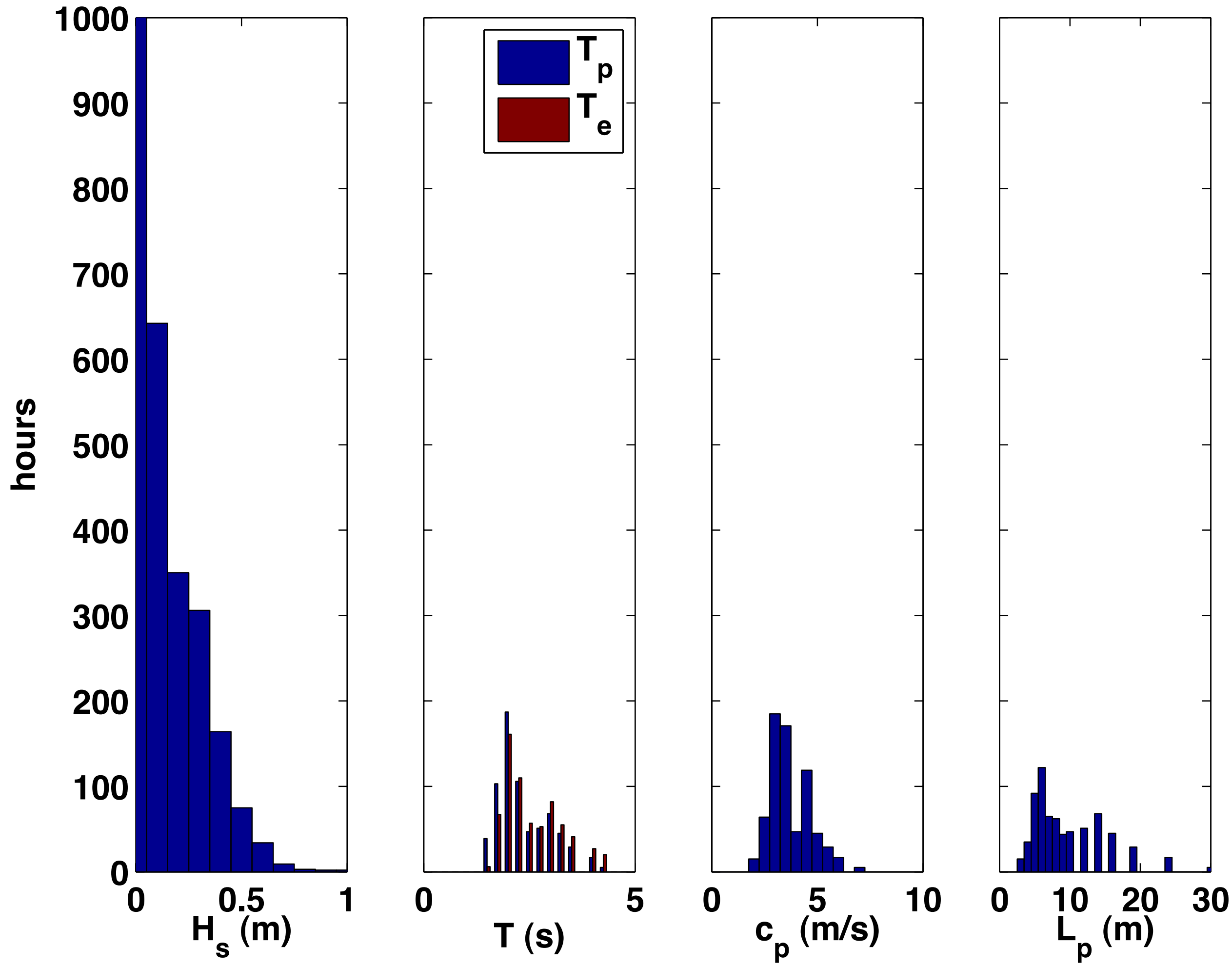

Figure 3: Histograms, by hour, of significant wave height, peak period, peak phase speed, and peak wavelength.

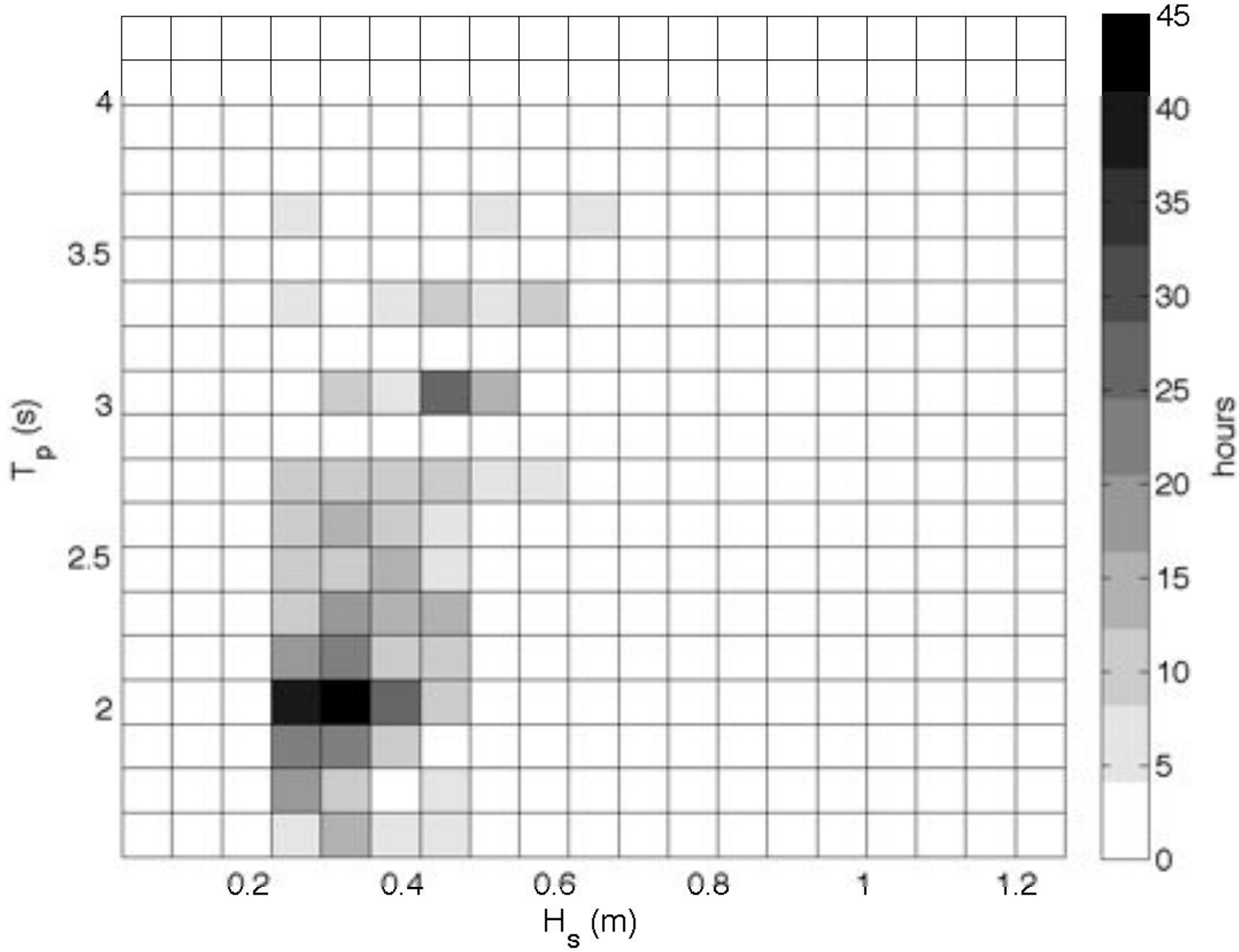

Figure 4: Joint histogram showing the hours of occurrence for wave heights at a given peak period.

4.3 Power density

The energy flux F of linear propagating waves is equivalent to the power per unit crest-length. For monochromatic waves, this is given by

$$F = \frac{1}{8}\rho g H_s^2 c_g, \tag{2}$$

where g is gravity, ρ is water density, and $c_g = \frac{g}{4\pi f}$ is the group velocity at a given frequency according to deep-water wave dispersion (*Mei*, 1989).

For natural broad-band waves, a more accurate description of the energy flux is given by

$$F = \frac{1}{8}\rho g \int_{f_2}^{f_1} S(f) c_g df, \tag{3}$$

where c_g varies with frequency inside the integral.

A shown in Figure 5, typical power densities on Puget Sound are less than 400 W/m, and the monochromatic estimate of energy flux is typically biased high by 45%.

4.4 Wave evolution

At the onset of a wind event, waves are known to form first as small capillary waves and then grow in size and extent. These waves are initially quite steep, as quantified by Ak_p, where $A = H_s/2$ and k_p is the wavenumber at the peak of the spectrum. At increased wave ages, estimated by the ratio of peak phase speed to wind speed $\frac{c_p}{U}$, wave steepness becomes limited. As shown in *Thomson et al.* (2009), this is likely a result of whitecaping, which limits the steepness of older waves to be less then $Ak_p \approx 0.12$.

A simple energy budget for the evolution of total wave energy (thus neglecting nonlinear interactions between various components) is (*Terray et al.*, 1996; *Gemmrich et al.*, 1994)

$$\rho g \int_{f_2}^{f_1} \frac{\partial S}{\partial t} df = c_e \tau - \epsilon, \tag{4}$$

where $c_e \tau / \rho$ is the energy input by the wind stress τ on a surface moving at an effective speed c_{eff} and ϵ is dissipation due to whitecaping. Using the observed dependence of ϵ on wave steepness from *Thomson et al.* (2009), this energy budget is consistent with the observations.

4.5 Climatology

Local wind forcing conditions are compared with a climatology based on 24 years of wind observations at nearby West Point (NOAA station WPOW1, N 47.662 W 122.436) during winter months (Nov, Dec, Jan, Feb, Mar). Prior to comparison with climatology, the Point Wells wind data are corrected to the standard height of 10 m, assuming neutral conditions (*Large and Pond*, 1981; *Hoffman*).

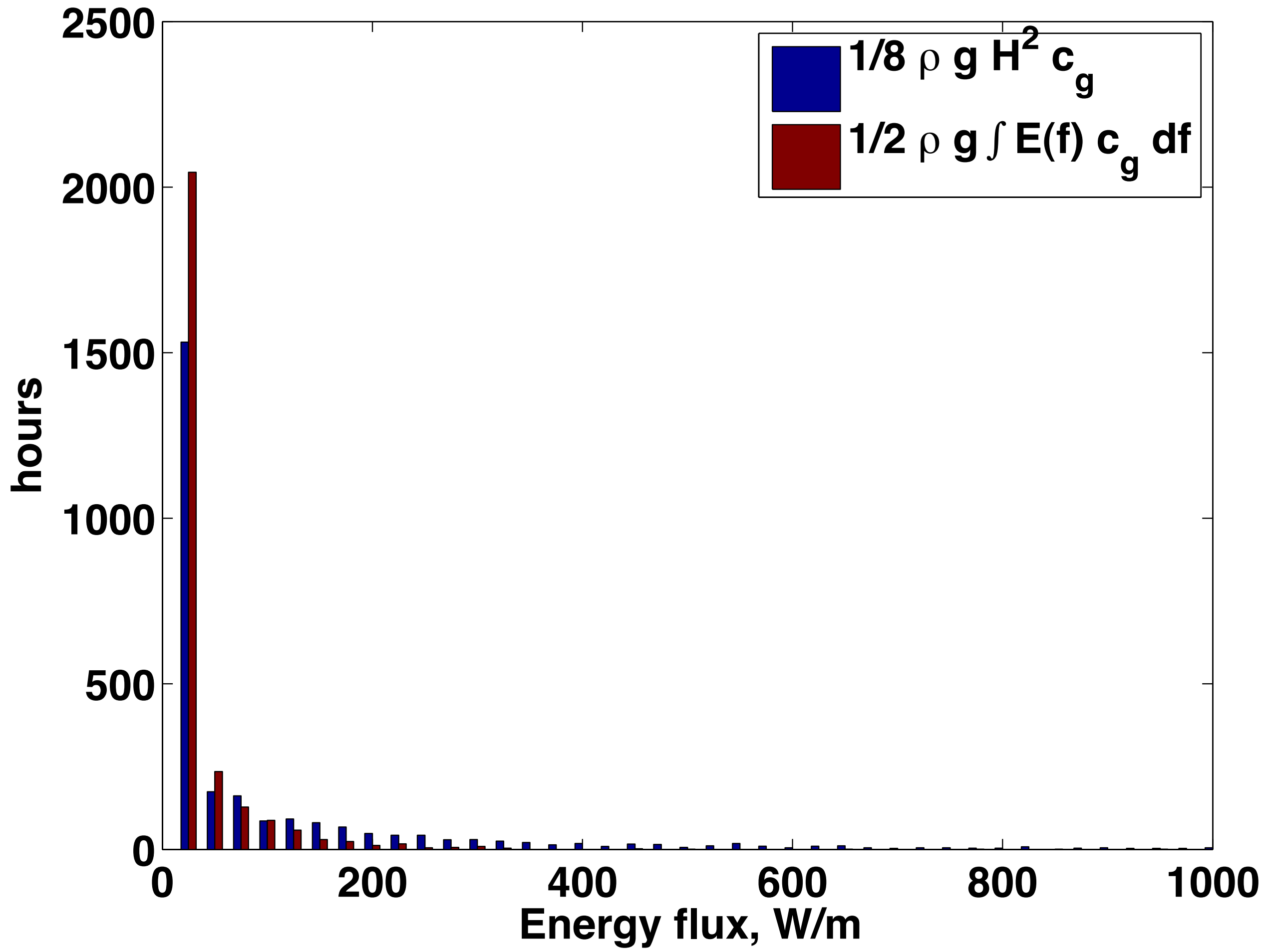

Figure 5: Histograms, by hour, of wave energy flux estimated from monochromatic values (blue) and from spectral energy densities (red).

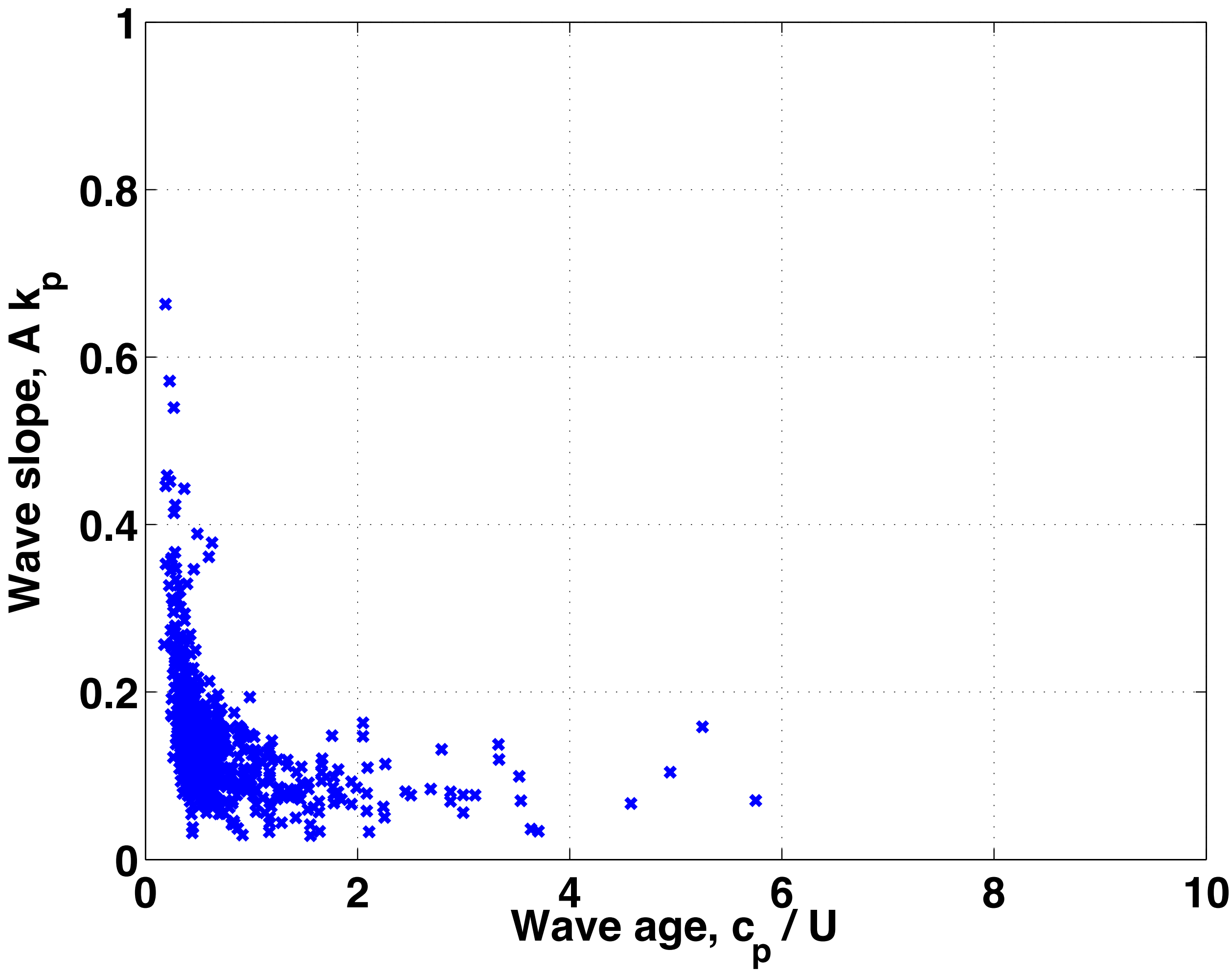

Figure 6: Hourly estimates of average wave slope versus wave age. Young waves are typically steep during strongly forced periods of growth, and then limited by whitecaping at later stages of development.

As shown in Figure 7 the 2009-2010 data from Pt Wells are consistent with climatology, especially for higher winds, suggesting that the waves observed this winter are typical of Puget Sound. The details of wind direction and storm duration are absent from this comparison, but recent work (*Pettersson*, 2004) has described significant wave directionality in fjords.

4.6 Wind-wave regression

A multi-variate linear regression is used to form an empirical relation between the wind and wave observations. This relation can be used to extrapolate historical wave conditions from previous winters when only wind observations were recorded. These extrapolated wave values are much lower quality than the actual observed values, but are useful in confirming climatology. The resulting empirical prediction for significant wave height (m) is

$$H_s = 0.04 + 0.0033U_{10}^2 + 0.024F + 0.0016D, \quad (5)$$

where U_{10} is hourly mean wind speed at 10 m height (m/s), F is fetch (km) for a given wind direction, and D is the duration of a wind event (hrs). The average residual (i.e., a measure of the error in the linear regression) in the $H-S$ regression is 0.07 m. The resulting empirical prediction for energy period (s) is

$$T_e = 1.9 + 2.1H_s, \quad (6)$$

with an average residual of 0.5 s.

5 Model-data comparison

As shown in Figure 8, numerical wave simulations provided by the US Geological Survey are consistent with the observations at Point Wells. In addition, the model output shows similar wave conditions between Point Wells (location of observations) and West Point (location of wind climatology). The model employed is SWAN (Simulating Waves Accurately Nearshore), which provides high spatial resolution wave height and period, as shown in Figure 9.

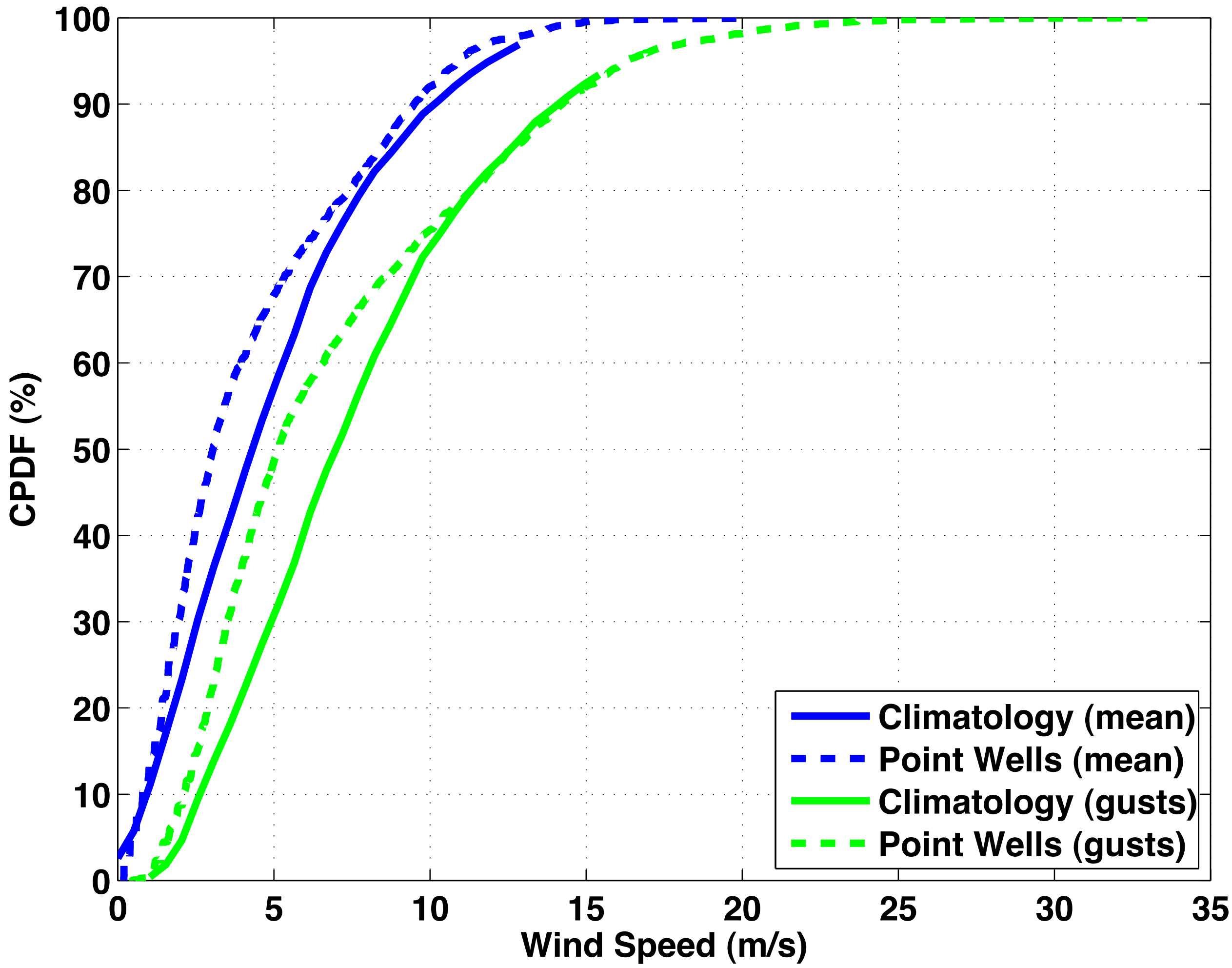

Figure 7: Cumulative probability distribution functions for hourly mean (blue) and gust (green) wind speeds during winter. Solid lines are a 24-year climatology from NOAA station WPOW1 at West Point, dashed lines are 2009-2010 data recorded a Point Wells. The distance between sites is 12 km, and both are open to the predominantly southern winds.

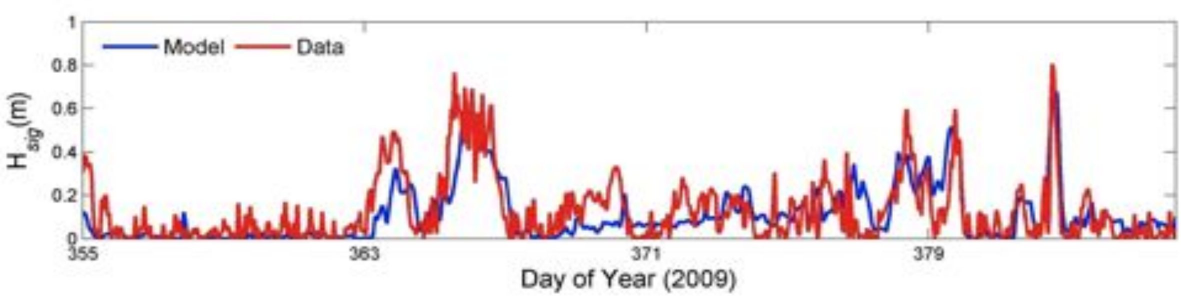

Figure 8: Comparison of modeled and observed wave heights.

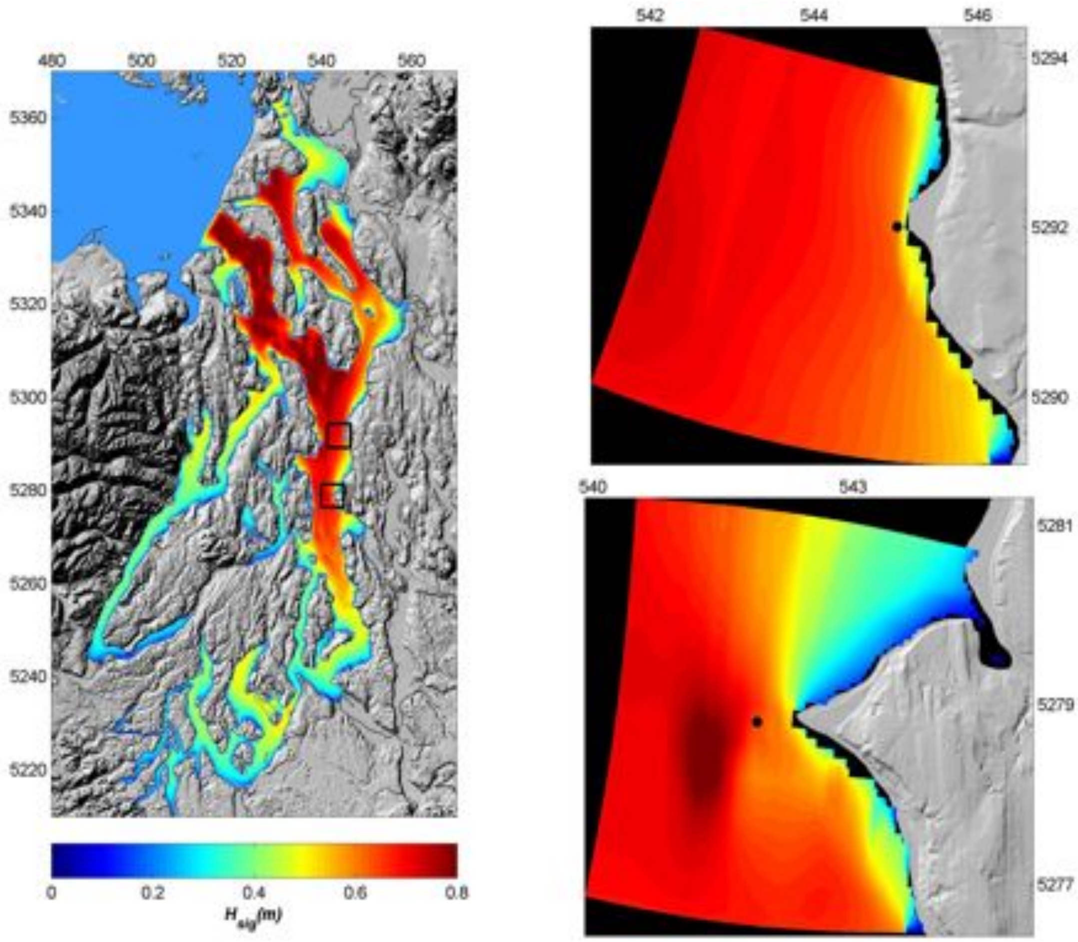

Figure 9: Spatial distribution of wave heights in Puget Sound (left) and detailed simulations for Point Wells (upper right) and West Point (lower right). Results are for an average winter storm.

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REVIEW OF SITE DATA
FOR CPT PUGET SOUND PROJECT

Client	Columbia Power Technologies LLC
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Table of Contents

1 INTRODUCTION

Columbia Power Technologies LLC (CPT) has contracted Garrad Hassan America (GH) to examine the wave climate for the West Point site in Puget Sound where a scale model wave energy converter (WEC) will be deployed. CPT has provided GH with wave measurements made at Point Wells, a site approximately 14km north of West Point. This data has been compared with wave measurements from buoys located in the North Pacific off the coast of Oregon to obtain an approximate scale factor for the site.

2 NOMENCLATURE

H	Wave height
λ	Wave length
f	Wave frequency
g	Acceleration due to gravity
$S(f)$	Variance density spectrum
$m_n = \int_0^\infty S(f)df$	n^{th} spectral moment
$H_s = 4\sqrt{m_0}$	Significant wave height
$T_e = m_{-1} / m_0$	Energy period
$T_m = m_0 / m_1$	Mean period
$T_e = \sqrt{m_0 / m_2}$	Zero-crossing period
$s = 2\pi H_s / gT_z^2$	Significant steepness
U_{10}	Wind speed at 10m above sea level
X	Fetch

3 SCALING OF WAVE CLIMATES

Scale testing of WECs is conducted according to Froude scaling laws. This ensures that scale tests are geometrically, kinematically and dynamically similar to full scale conditions. Under Froude scaling laws time scales with the square root of length. For example a full-scale sea state with H_s = 3m and T_e = 10s would be equivalent to a 5th scale sea state with H_s = 3/5 = 0.6m and $T_e = 10/\sqrt{5} = 4.47$ s.

In deep water the ratio between wave length and period is given by $\lambda = gT^2 / 2\pi$. So scaling wave period with the square root of wave length ensures that this ratio remains valid at scale, satisfying the requirement for geometric similarity, i.e. wave steepness is invariant with scale.

There are no fixed rules about how to calculate a scale factor for the wave climate at a test site. In general it is unlikely that the wave climate at a test site will be an exact scale representation of full scale conditions, due to differences in the storm characteristics over the fetches that each site is exposed to. Determining a scale factor for a site is therefore somewhat subjective and will depend on the sea states which are of interest. If the crucial criterion is the extreme wave conditions to which the scale WEC is exposed, then the scale factor for the site may be determined by the ratio of the return values at the two sites. CPT has advised that the test buoy will be designed to survive all possible wave climates at West

Point and will not be at risk of damage; therefore extreme waves are not used to limit considerations of scale in this report.

Since extreme conditions are not considered critical at this location, it may be advantageous to choose a scale factor so that the scale wave climate is marginally more energetic than the anticipated full scale site, so that there is a greater chance of higher-energy sea states occurring during testing. This will result in a greater proportion of time when tests of real interest can be conducted. In terms of device performance (as opposed to survivability) the most important tests to conduct are those which correspond to the conditions which represent the highest fraction of the available wave energy. For example if the full-scale WEC is to be deployed in an area where 90% of the available wave energy occurs in sea states with H_s in the range 2m – 6m, then it would be advisable to choose the scale factor so that there is a high likelihood of these conditions occurring during the scale model deployment.

GH recommends that the criteria which should be used to determine the scale factor for the site are the frequencies of occurrence of scaled H_s at various levels. This will inform how much data is likely to be collected for each sea state. Although the wave period also has a significant effect on the device response, it is not possible to scale the period independently of the wave height (since steepness is invariant with scaling), therefore only H_s is used to determine the scale factor.

4 ANALYSIS OF POINT WELLS WAVE MEASUREMENTS

Wave measurements have been conducted by APL at Point Wells, approximately 13km north of the proposed deployment site at West Point. The measurements cover the period 20 Nov. 2009 – 1 April 2010. The measurements were made using an acoustic wave sensor located at the end of a pontoon with the following specifications:

Resolution: 0.1 cm,
Accuracy: ±0.05 cm
Sampling frequency: 1.7 Hz,
Sample length: 20 min/hour.

Sea states with $H_s < 20$ cm are below the noise level of the sensor and have been excluded from the analysis. Figure 4.1 shows the mean spectral shape measured at Point Wells. It appears that noise is a problem for frequencies below 0.1 Hz and that the sampling frequency is too low to accurately measure the high frequency tail of the spectrum (for a sampling frequency of 1.7 Hz the Nyquist frequency is 0.85 Hz). Both these factors can cause estimates of wave periods to be biased high, especially T_z which is more sensitive to the energy in the high frequency end of the spectrum. A lower limit of 0.1Hz has been used in the calculation of the spectral moments, from which the wave parameters are derived, but no correction has been made for the high-frequency cut-off. The effect of neglecting energy at high frequencies can be gauged by considering standard spectral shapes. For a Bretschneider spectrum with peak frequency of 0.4Hz, curtailing the spectrum at 0.7Hz will result in a bias of 7% in T_e and 20% in T_z. The bias in wave steepness is even larger, since it depends on the square of T_z.

The high frequency waves which were not measured by the acoustic wave sensor are not likely to affect the response of the model. However, it is important to obtain accurate measurements of period parameters to validate machine performance. In deep water the level of non-linearity is mainly controlled by the steepness of the waves, so using biased estimates of steepness may impair the comparisons of physical and numerical models. To obtain accurate wave data when testing the scaled model at West Point, GH would recommend the following wave measurement device specifications:

- Sample Frequency: 4 Hz or above
- Range: ±3m or above
- Accuracy: <1cm
- Resolution: <1cm
- Data collection: Continuous with records analyzed in 60 minute blocks

GH attempted to mitigate for the effect of the high-frequency cut-off by fitting a high-frequency tail to the spectra. However, the individual spectra were extremely noisy and did not display standard shapes, so it was not possible to fit a reasonable looking tail. Since H_s will be the only parameter used to determine the scale factor for the site, the bias in the period parameters and wave steepness is not critical.

Figure 4.2 shows scatter plots of H_s against T_e and H_s against significant steepness (a measure of the average steepness of the waves). For offshore wave measurements a limiting significant steepness of around 0.09 is commonly observed (see Section 4). The maximum significant steepness observed in the Point Wells data is 0.11 which is high, especially considering that this is likely to be an underestimate due to the high-frequency cut-off. The tidal range at the site is almost 5m so there is a possibility of strong currents, which may be responsible for increasing the wave steepness. CPT has also noted that these high steepness events may be a result of large and steep waves generated by passing ships which have not been filtered out of the analysis.

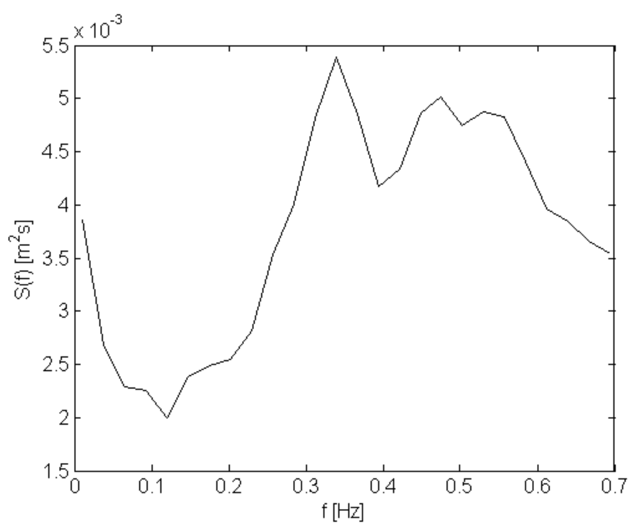

Figure 4.1. Mean spectral shape measured at Point Wells.

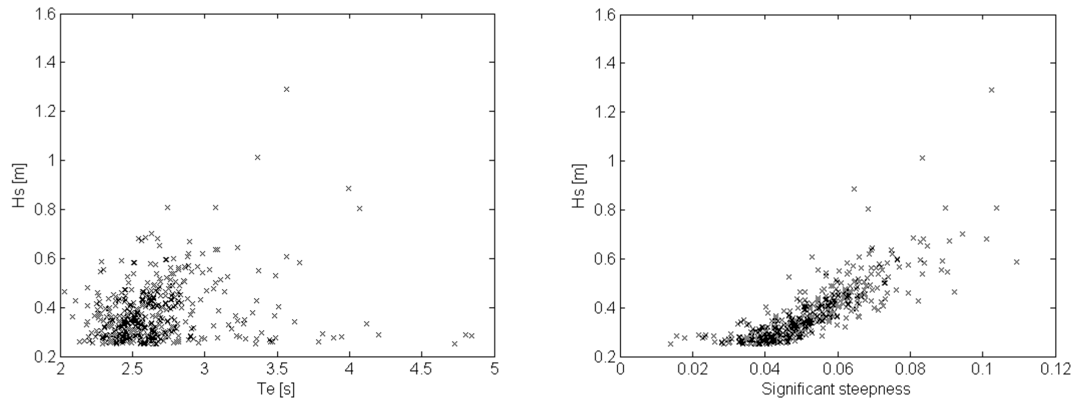

Figure 4.2. Scatter plots of H_s against T_e and H_s against significant steepness for the Point Wells wave measurements.

5 HINDCAST OF WAVE CONDITIONS AT WEST POINT

The wind and wave conditions measured at Point Wells have also been used to determine a relationship between wind speed, fetch and wave height in Puget Sound, from which the long term conditions can be estimated. The procedure has two steps:

1. Estimate relationship between wind speed, fetch and wave height at Point Wells.
2. Apply this relationship to wind data recorded at West Point to estimate long-term wave conditions.

The wind speed measurements at Point Wells and West Point were made using anemometers at different heights. To ensure the relationship between wind speed, fetch and wave height is valid for both locations, both sets of wind data have been adjusted to the same reference level. The anemometer at Point Wells is located 7.5m above mean lower low water (MLLW). APL have calculated U_{10}, the wind speed at 10m above sea level, accounting for the tide, although it is not known what formula has been used. The anemometer at West Point is located 9.8m above site elevation, and the site is 3.0m above mean water level. GH has estimated U_{10} for West Point under the assumption of neutral atmospheric stability, using the formula [1]:

$$\frac{U(z_0)}{U(z_r)} = \left(\frac{z_0}{z_r}\right)^{\alpha} \qquad (1)$$

where z_0 is the height at which the measurements are made, z_r is the reference height and α=0.11, a figure typically used for offshore conditions.

The fetches at Point Wells and West Point for various directions have been estimated using Google Earth and are displayed in Figure 5.1.

A formula which is often used to estimate H_s under fetch limited conditions is [2]:

$$H_s = 0.016 X^{0.5} U_{10} \qquad (2)$$

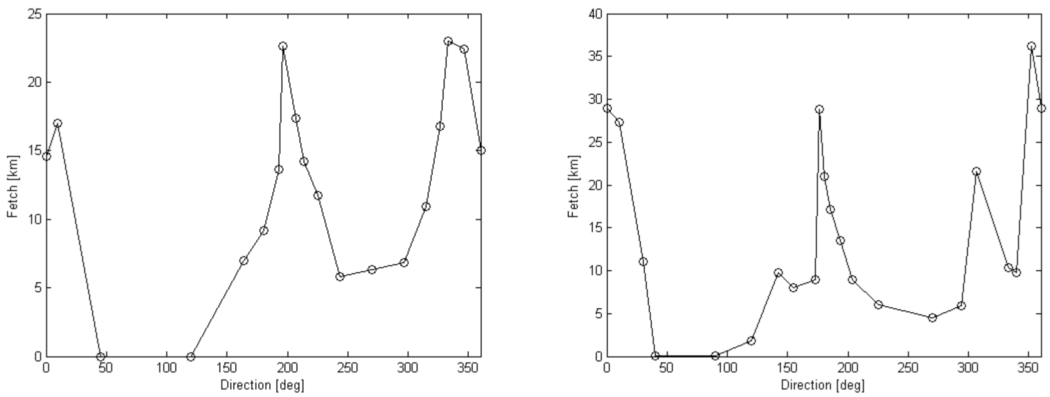

Figure 5.1 Estimated fetch against direction for Point Wells (left) and West Point (right).

The formula was derived from data obtained during the JONSWAP experiment in the North Sea. To test the applicability of the formula under the much shorter fetches in Puget Sound, a comparison of the wind and wave data recorded at Point Wells has been made. Orthogonal regression has been used to determine a linear relationship between H_s and $X^{0.5}U_{10}$ in Puget Sound. Orthogonal regression finds the line which minimises the orthogonal distances between the data points and regression line. It differs slightly from ordinary least-squares regression which minimises the vertical distances between the data points and regression line, which in effect assigns all the errors to the ordinate. In contrast, orthogonal regression accounts for errors in both data sets and gives a better approximation of the underlying relationship (for more information see e.g. [3]).

Figure 5.2 shows an orthogonal regression of H_s against $X^{0.5}U_{10}$, with the estimated parameters shown above the plot. The correspondence is reasonable, with a correlation coefficient of 0.77. The standard deviation of the residuals about the regression line is shown in the right hand plot of Figure 5.2. The standard deviation increases approximately linearly with $X^{0.5}U_{10}$ due, in part, to the increase in sampling variability in both H_s and U_{10}. The distribution of the residuals, normalised by the standard deviation, is shown in Figure 5.3. The distribution is well fitted by a Student-t distribution with 5 degrees of freedom. This gives the following model for H_s:

$$H_s = 0.03 + 0.0099X^{0.5}U_{10} + (0.075 + 0.016)X^{0.5}U_{10}\varepsilon\,, \qquad (3)$$

where ε is a random Student-t variable. The inclusion of the Student-t variable in the model accounts for the observed variability of the data about the regression line, evident in Figure 5.2.

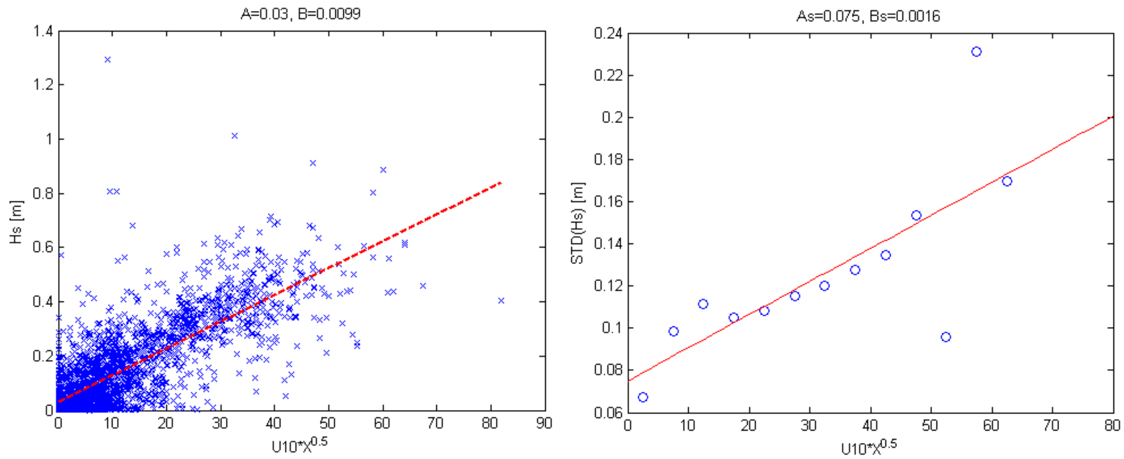

Figure 5.2. Left: Orthogonal regression of H_s against $X^{0.5}U_{10}$.
Right: Standard deviation of residuals.

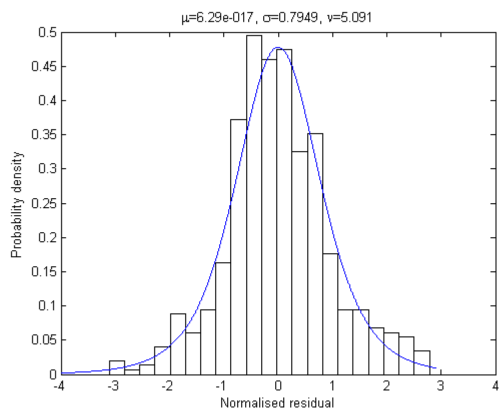

Figure 5.3. Histogram of normalised residuals and fitted Student's-t distribution.

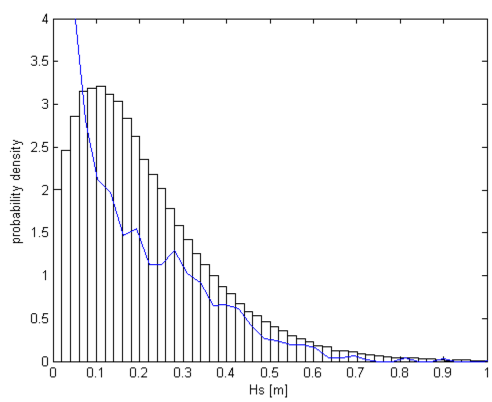

Figure 5.4. Distribution of H_s. Histogram: derived using Eq. (2). Line: Measured at Point Wells.

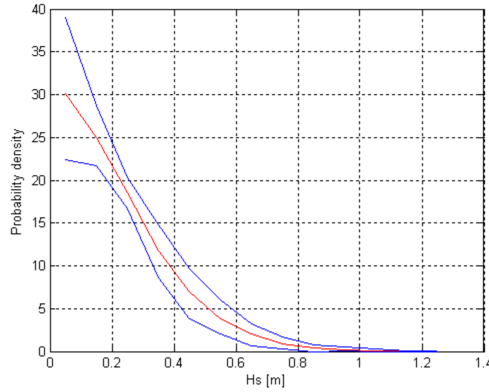

Figure 5.5. Distribution of Hs over period October-April.
Red line: mean value, blue lines: maximum and minimum values for individual years.

The relationship presented in Eq. (3) has been applied to the wind data recorded at West Point to obtain an estimate of the long-term wave conditions. Wind measurements at West Point cover the period 29 Jan. 1984 to 31 Dec 2009 at hourly intervals. H_s has been estimated using Eq. (3), with values of ε generated as random Student-t variables (records which result in $H_s<0$ are discarded). The inclusion of a random variable in the hindcast makes each realisation different, but has negligible effect on the long term statistics. Figure 5.4 shows a histogram of occurrence of H_s over the entire year, together with the distribution measured at Point Wells. It is clear that there is some discrepancy in the two distributions. This is possibly due to a difference in the wind regime at the two sites, but may also be a result of differing methods used to calculate U_{10} at the two locations.

Since the hindcast displays a different distribution to the measurements, GH would advise that the measurements are used to determine the scale factor. Since the measurements display a lower occurrence of higher sea states than the hindcast, using them to determine the scale factor will result in a lower estimate of the scale factor, but a higher frequency of occurrence of higher energy sea states.

Although the hindcast shows discrepancies with the measurements, it can still be used to estimate the level of interannual variability in the wave conditions. Figure 5.5 shows the distribution of H_s, over the period October-April together with the maximum and minimum values for individual years. There is relatively little interannual variability in the occurrence of the lower sea states with H_s<0.4m. However the occurrence of sea states with H_s>0.6m can change by as much as 50% from year to year.

6 ANALYSIS OF OFFSHORE DATA

The scale factor for the West Point test site is determined relative to the wave conditions off the coast of Oregon. There are several long datasets for this area from buoys operated by the National Data Buoy Centre (NDBC). These measurements have been downloaded from the National Oceanographic Data Centre (NODC) FTP site[1]. Details of the buoys selected for the analysis are listed in Table 6.1 and their locations are shown in Figure 6.1. The buoys selected are all located on the continental shelf and have record lengths upwards of 5 years.

Figures 6.2-6.7 show the joint distribution of H_s and T_e and the joint distribution of H_s and s for the six buoys considered in the study. Generally, the distributions display similar shapes, since each buoy has a

[1] ftp://ftp.nodc.noaa.gov/pub/f291/

similar exposure to the North Pacific. The distribution for buoy 46027 shows a reduction in the occurrence of large and steep sea states compared to the other buoys. This is most likely a consequence of being the located in a marginally more sheltered location, further south than the other buoys. The steepest waves were recorded by buoy 46010 in April 1981, but there are no concurrent measurements from nearby buoys covering this period, which can be used to validate these measurements. Visual inspection of the time series and individual spectra do not show any obvious errors.

As well as the occurrence of various sea states it is important to quantify which sea states represent the highest proportion of the available wave energy. Figures 6.8-6.11 show a comparison between the distribution of occurrence of sea states and the proportion of the total energy which they account for, using data from Buoy 46029. Figure 6.8 shows the distribution binned by both H_s and T_e, Figure 6.9 shows the distributions binned by H_s only, Figure 6.10 shows the distributions binned by T_e only, and Figure 6.11 shows the distributions binned by significant steepness only. These distributions are also presented numerically in Tables 6.2 and 6.3. It can be seen that although 90% of the sea states have $H_s < 4\,\text{m}$, this accounts for only 60% of the available energy. Approximately 75% of the total energy occurs in sea states with H_s between 2m and 6m, and 90% of the energy occurs in seas with T_e between 6s and 14s. The scale factor for the model to be deployed at West Point should be chosen so that there is a sufficient probability of occurrence of scaled equivalents of these sea states.

Buoy number	Buoy type	Latitude [°N]	Longitude [°W]	Water depth [m]	Start date	End date	Max. H_s [m]	Max. steepness
46010	10m discus	46.2	124.2	64	11/1979	04/1991	10.2	0.091
46015	3m discus	42.75	124.82	422	07/2002	11/2009	11.9	0.080
46027	3m discus	41.85	124.38	48	09/1983	11/2009	9.96	0.074
46029	3m discus	46.14	124.51	135	03/1984	11/2009	13.8	0.082
46040	3m discus	44.8	124.3	112	05/1987	06/1992	11.7	0.083
46050	3m discus	44.64	124.5	123	11/1991	11/2009	14.1	0.082

Table 6.1. Details of wave buoys shown in Figure 6.1.

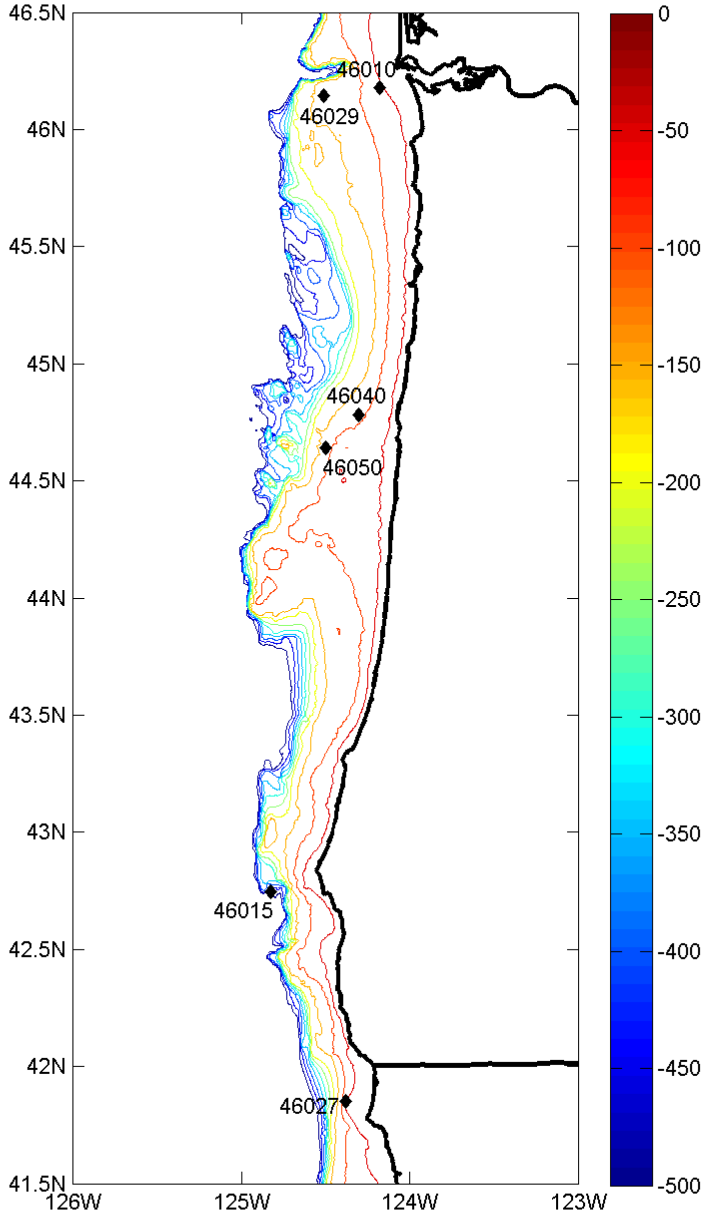

Figure 6.1. Locations of NDBC wave buoys considered in this report. Coloured contours show bathymetry at 50m intervals.

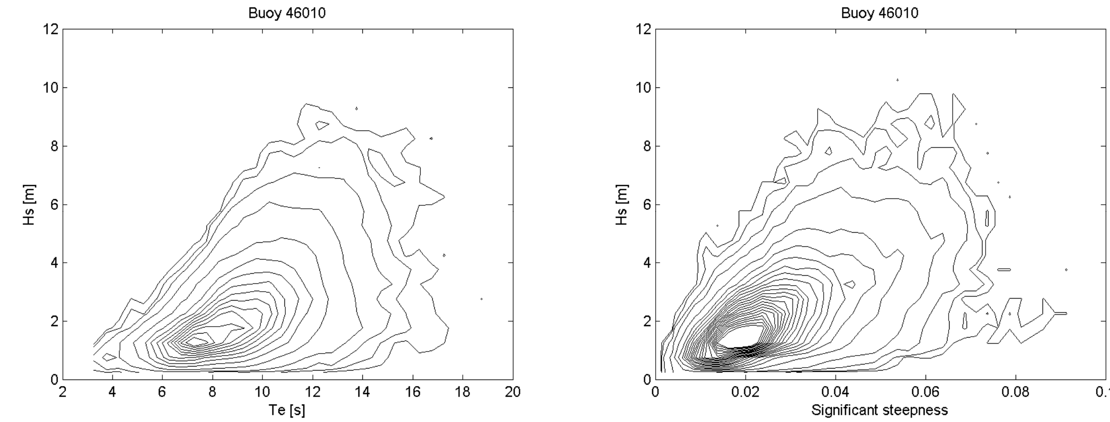

Figure 6.2. Buoy 46010: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

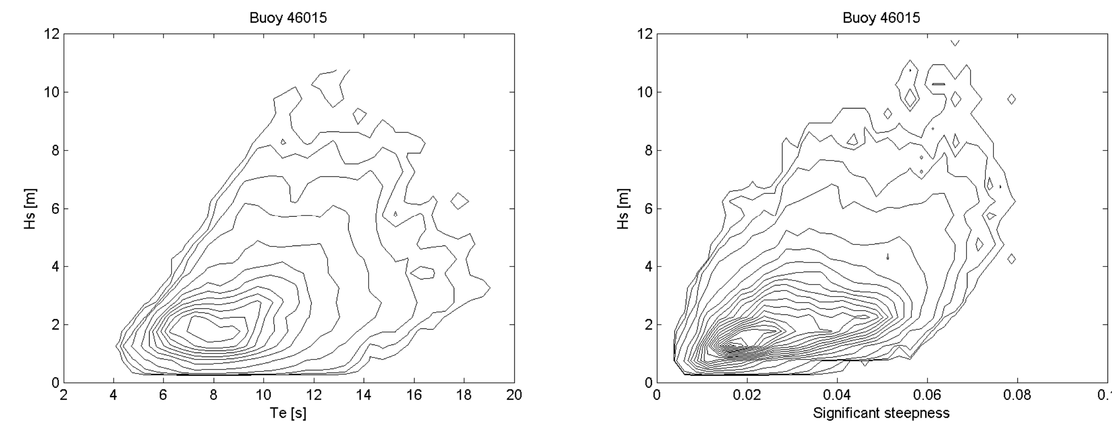

Figure 6.3. Buoy 46015: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

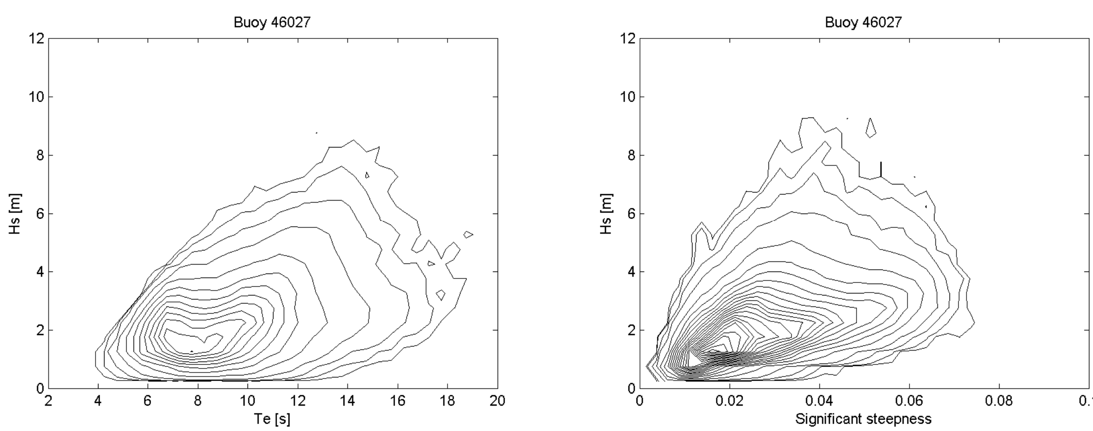

Figure 6.4. Buoy 46027: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

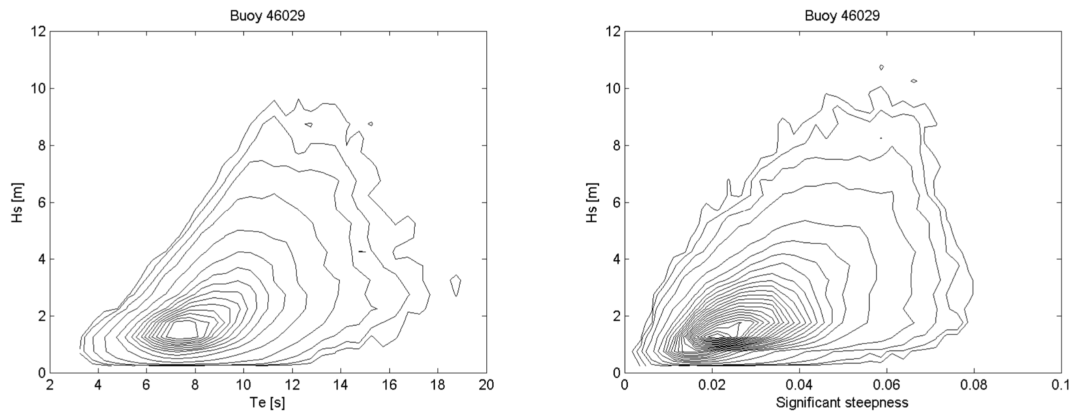

Figure 6.5. Buoy 46029: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

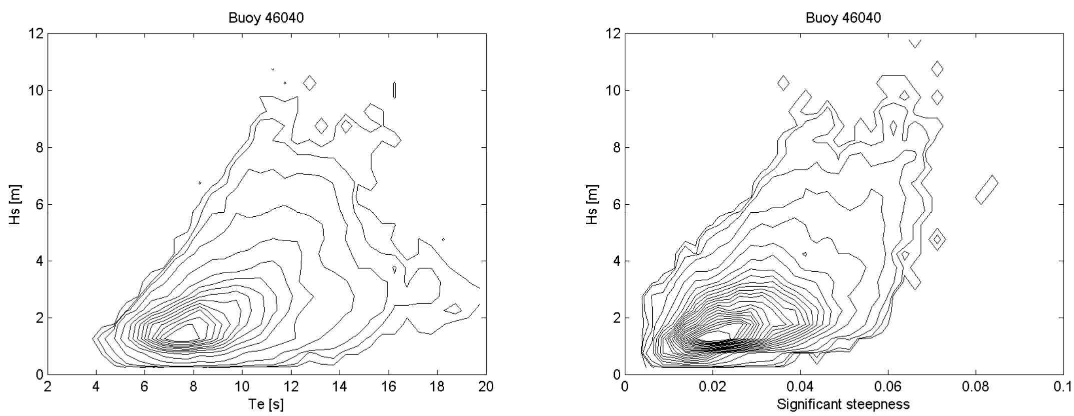

Figure 6.6. Buoy 46027: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

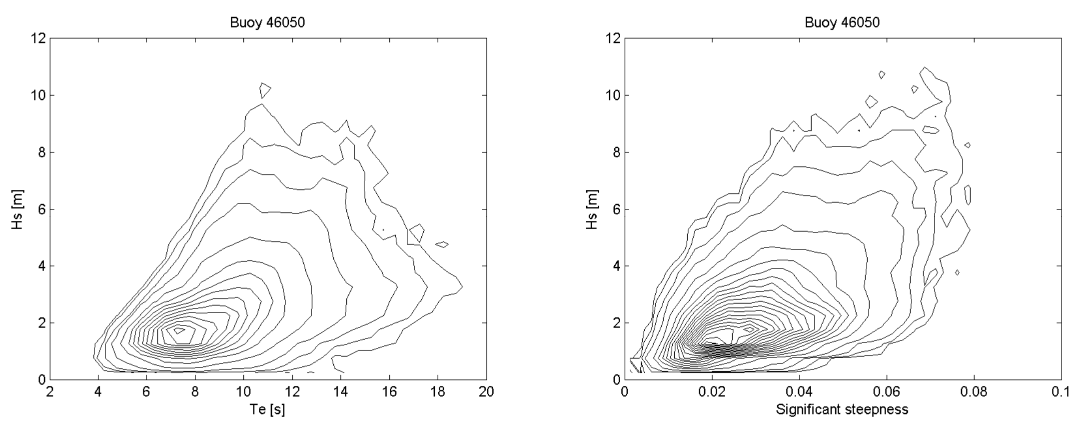

Figure 6.7. Buoy 46050: Joint distribution of H_s and T_e (left) and joint distribution of H_s and significant steepness (right).

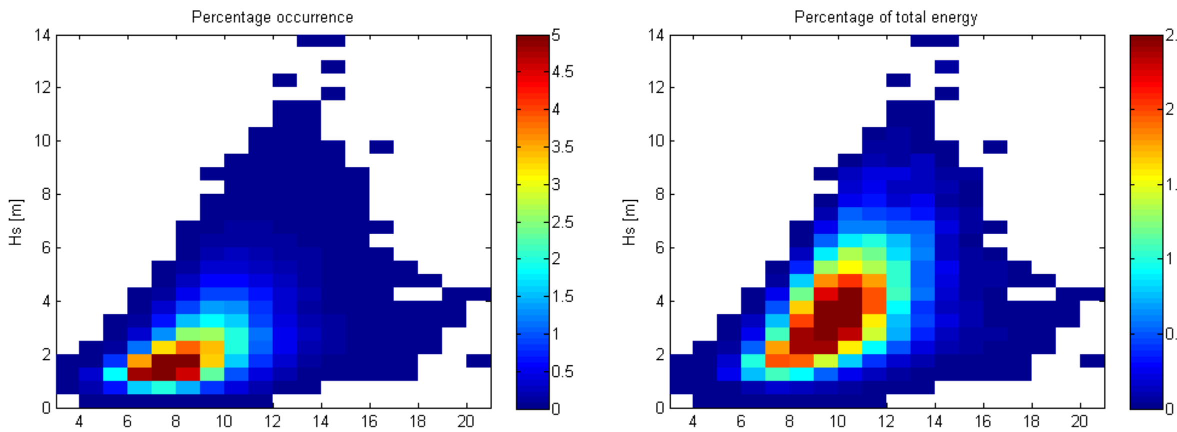

Figure 6.8. Left: Percentage occurrence of sea states, binned by H_s and T_e. Right: Percentage of total available energy, binned by H_s and T_e. Both plots for data from Buoy 46029.

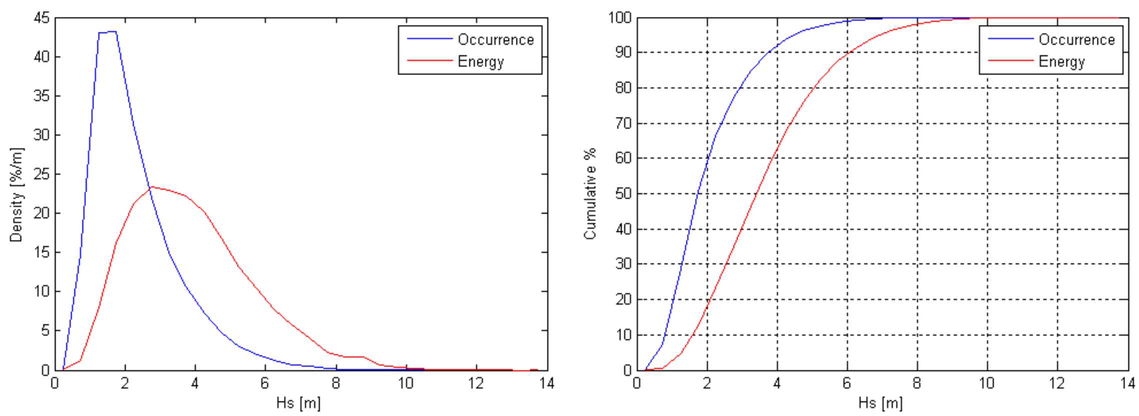

Figure 6.9. Percentage occurrence and percentage of total energy, binned by H_s (left: density; right: cumulative). Both plots for data from Buoy 46029.

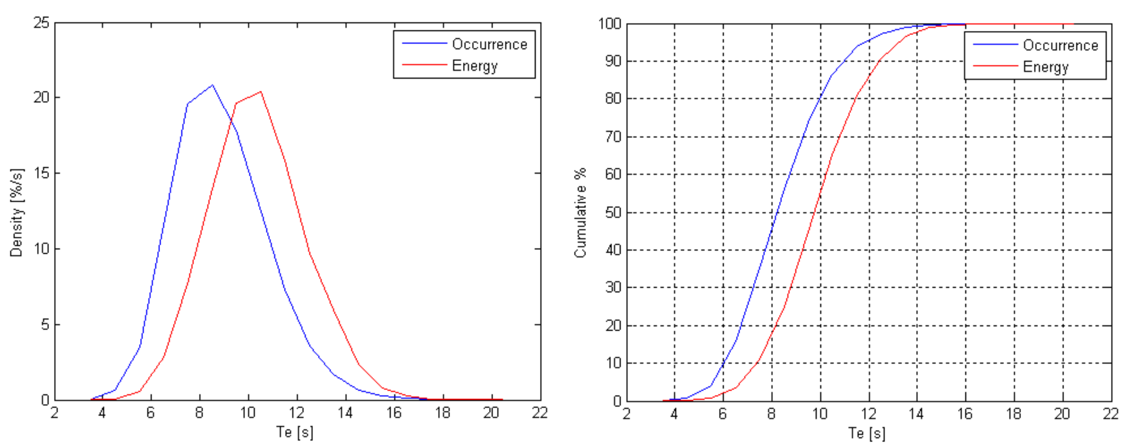

Figure 6.10. Percentage occurrence and percentage of total energy, binned by T_e (left: density; right: cumulative). Both plots for data from Buoy 46029.

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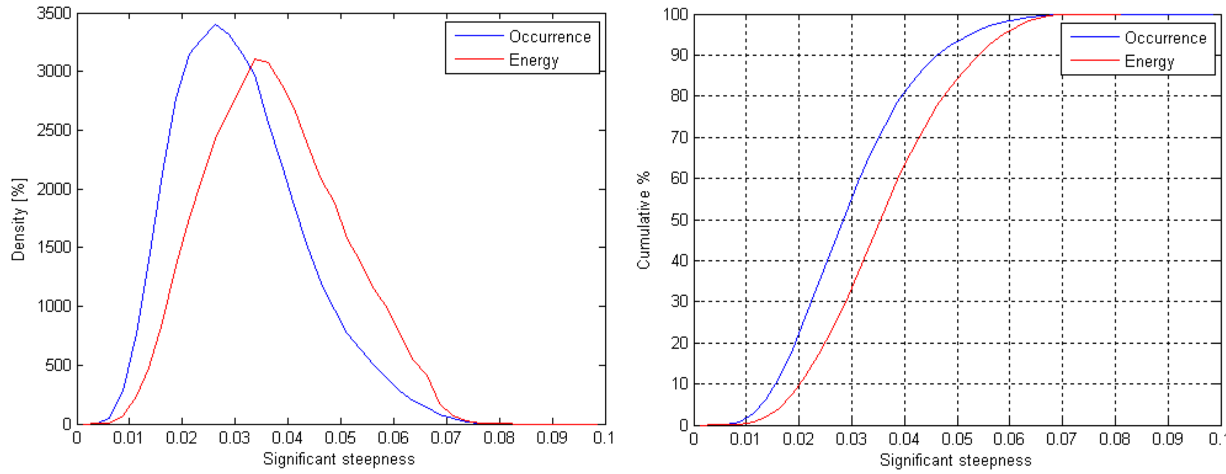

Figure 6.11. Percentage occurrence and percentage of total energy, binned by significant steepness (left: density; right: cumulative). Both plots for data from Buoy 46029.

	Te [s] → 3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	Sum	Cumu-lative
Hs [m] 0.5	0.02	0.22	0.68	1.63	2.02	1.42	0.80	0.43	0.16	0.05	0.01							7.4	7.4
1.5	0.02	0.40	2.66	8.30	11.85	9.58	5.62	2.63	1.24	0.50	0.19	0.08	0.03	0.01	*			43.1	50.6
2.5		*	0.15	1.44	4.53	6.42	6.07	4.03	2.20	1.06	0.46	0.18	0.08	0.04	0.01	*		26.7	77.3
3.5			*	0.16	0.99	2.47	3.18	2.92	1.73	0.76	0.35	0.15	0.06	0.02	0.01	0.01	*	12.8	90.1
4.5				*	0.15	0.81	1.47	1.50	1.12	0.58	0.27	0.09	0.02	0.01	*	*	*	6.0	96.1
5.5					*	0.13	0.53	0.63	0.51	0.35	0.18	0.07	0.02	0.01	*			2.4	98.5
6.5						0.01	0.13	0.23	0.23	0.17	0.13	0.04	0.01	*				1.0	99.5
7.5							0.02	0.09	0.09	0.06	0.06	0.02	0.01					0.3	99.8
8.5							*	0.03	0.04	0.03	0.02	0.01	*					0.1	100.0
9.5								*	0.01	0.01	0.01	*		*				0.0	100.0
10.5									*	*	*							0.0	100.0
11.5										*	*	*						0.0	100.0
12.5										*		*						0.0	100.0
13.5											*	*						0.0	100.0
Sum	0.0	0.6	3.5	11.5	19.5	20.8	17.8	12.5	7.3	3.6	1.7	0.6	0.2	0.1	0.0	0.0	0.0		
Cumulative	0.0	0.7	4.2	15.7	35.2	56.1	73.9	86.4	93.7	97.3	99.0	99.6	99.9	100.0	100.0	100.0	100.0		

Table 6.2. Percentage occurrence of sea states binned by H_s and T_e for buoy 46029. Cells with percentage occurrence >0% but less than 0.01% are denoted with a star.

GARRAD HASSAN

	Te [s]																		
Hs [m]	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	Sum	Cumu-lative
0.5	*	0.01	0.04	0.11	0.16	0.13	0.08	0.05	0.02	0.01	*							0.6	0.6
1.5	*	0.05	0.43	1.75	3.04	2.85	1.96	1.04	0.54	0.25	0.10	0.05	0.02	0.01	*			12.1	12.7
2.5		*	0.07	0.76	2.85	4.82	5.19	3.91	2.35	1.22	0.59	0.24	0.11	0.07	0.02	0.01		22.2	34.9
3.5			*	0.17	1.27	3.66	5.31	5.40	3.57	1.70	0.84	0.38	0.17	0.06	0.03	0.02	*	22.6	57.5
4.5				*	0.31	1.99	4.06	4.56	3.75	2.12	1.07	0.38	0.11	0.06	0.01	*	*	18.4	75.9
5.5					0.01	0.48	2.17	2.89	2.56	1.87	1.10	0.40	0.14	0.05	0.01			11.7	87.6
6.5						0.04	0.78	1.47	1.60	1.31	1.08	0.35	0.09	0.02				6.7	94.4
7.5							0.12	0.75	0.80	0.60	0.62	0.22	0.08					3.2	97.6
8.5							0.01	0.29	0.47	0.37	0.28	0.15	0.06					1.6	99.2
9.5								0.02	0.13	0.13	0.15	0.04		0.02				0.5	99.7
10.5									0.02	0.07	0.05							0.1	99.8
11.5										0.02	0.02	0.02						0.1	99.9
12.5										0.02		0.05						0.1	99.9
13.5											0.03	0.03						0.1	100.0
Sum	0.0	0.1	0.5	2.8	7.6	14.0	19.7	20.4	15.8	9.7	5.9	2.3	0.8	0.3	0.1	0.0	0.0		
Cumulative	0.0	0.1	0.6	3.4	11.0	25.0	44.7	65.1	80.9	90.6	96.5	98.8	99.6	99.9	100.0	100.0	100.0		

Table 6.3. Percentage of total available wave energy by Hs and Te for buoy 46029. Cells with percentage occurrence >0% but less than 0.01% are denoted with a star.

7 DETERMINATION OF THE SCALE FACTOR

Buoy 46029 has been chosen for comparison with the Point Wells wave data, due to the long record available. Since the wave climates at each buoy considered in the previous section were similar, the choice of a particular wave buoy is not deemed critical.

The intended deployment period for the scale model at West Point is October 2010 – April 2011. The period covered by the measurements at Point Wells covers a similar period (Nov-April). However, since the measurements are for only one year, the hindcast will be used to check whether the measurements are representative of the long term conditions.

Figures 7.1-7.6 show scatter plots of H_s against T_e and H_s against s for the Point Wells measurements, using scale factors between 5 and 10, overlaid on the distributions derived from NDBC buoy 46029. It is evident that scaled conditions only cover a limited range of the offshore conditions under scaling factors of 5 or 6. Using a scaling factor between 7 and 8 gives a reasonable coverage of the higher energy sea states with H_s between 2m and 6m. However it should be noted that the distribution of H_s and T_e is skewed towards steeper conditions than the offshore data. Since steepness is invariant with scaling it is not possible to adjust for this. Moreover, as explained in Section 4, the estimate of steepness in the Point Wells measurements may be underestimates.

The percentage occurrence of scaled H_s in bins of width 1m is shown in Table 7.1 for various scaling factors. As noted in the previous section, the conditions which account for the largest proportion of the total energy in Oregon waters have H_s in the range 2m – 6m. It is clear that using a scale factor of 5 or 6 gives a very low probability of the higher sea states occurring. Using a scale factor of 8 gives approximately 22% of the time when H_s exceeds 2m, 9% exceeding 3m, and 3% exceeding 4m. The choice of scaling factor will depend on how much time it is anticipated is needed to conduct experiments in each sea state. The percentage occurrence can be converted to hours per month, e.g. an occurrence of 3% corresponds to 0.03*24*31=22.3 hours per month. These figures can then be used to determine whether using a certain scaling factor is likely to give enough time in the required conditions for data to be gathered.

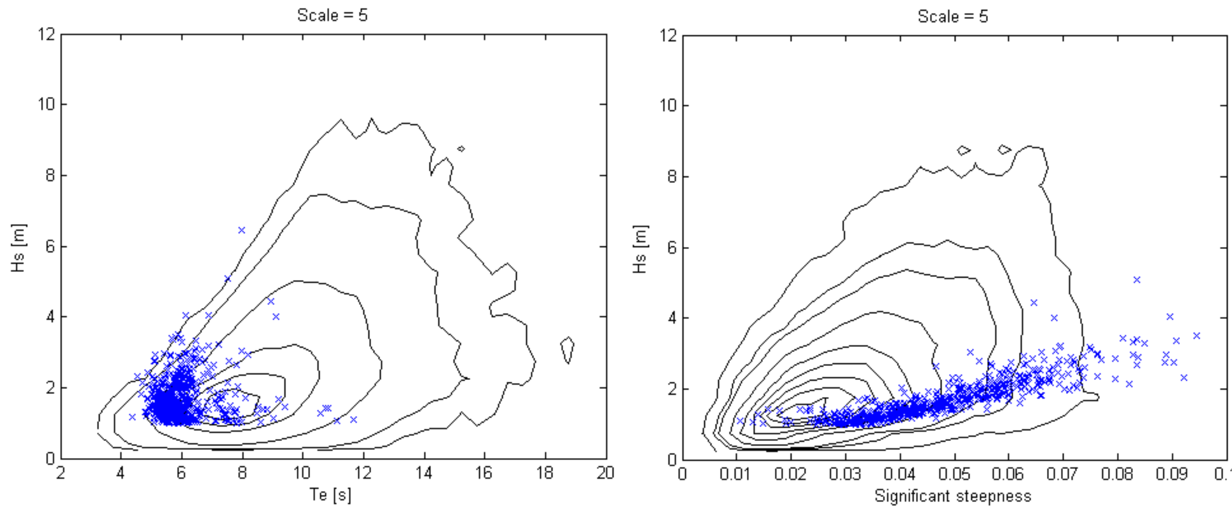

Figure 7.1. Comparison of joint distributions of H_s and T_e (left) and H_s against s (right) for offshore buoy data (contours) and Point Wells (crosses) scaled by a factor of 5.

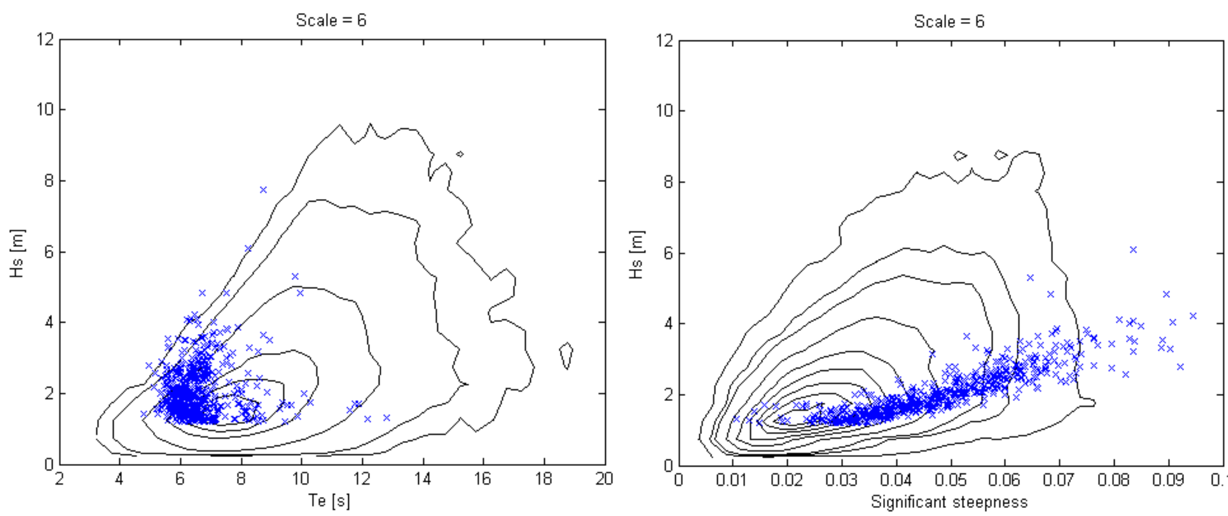

Figure 7.2. As previous figure but for a scale factor of 6.

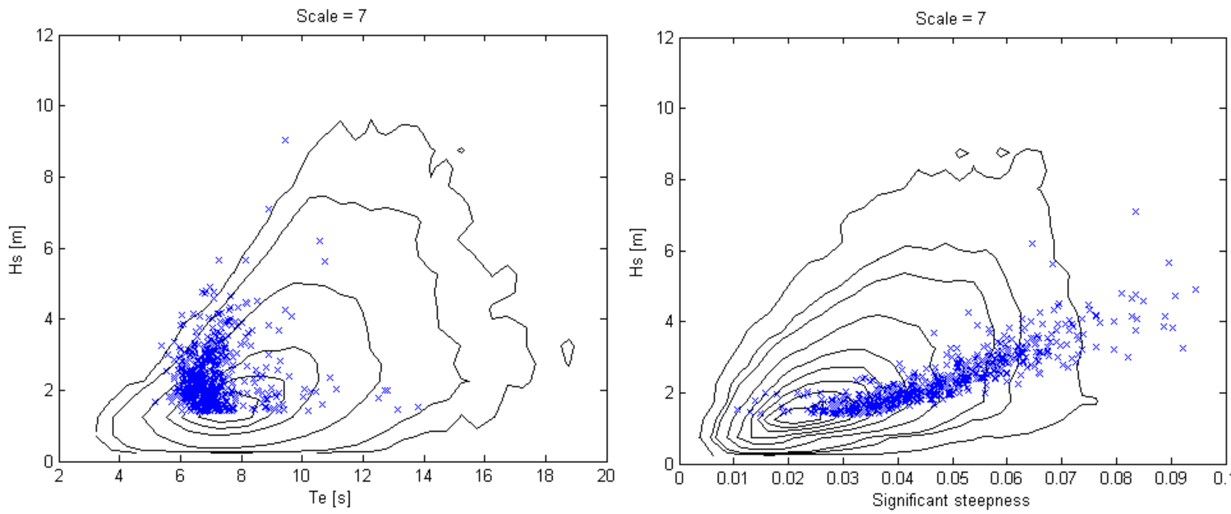

Figure 7.3. As previous figure but for a scale factor of 7.

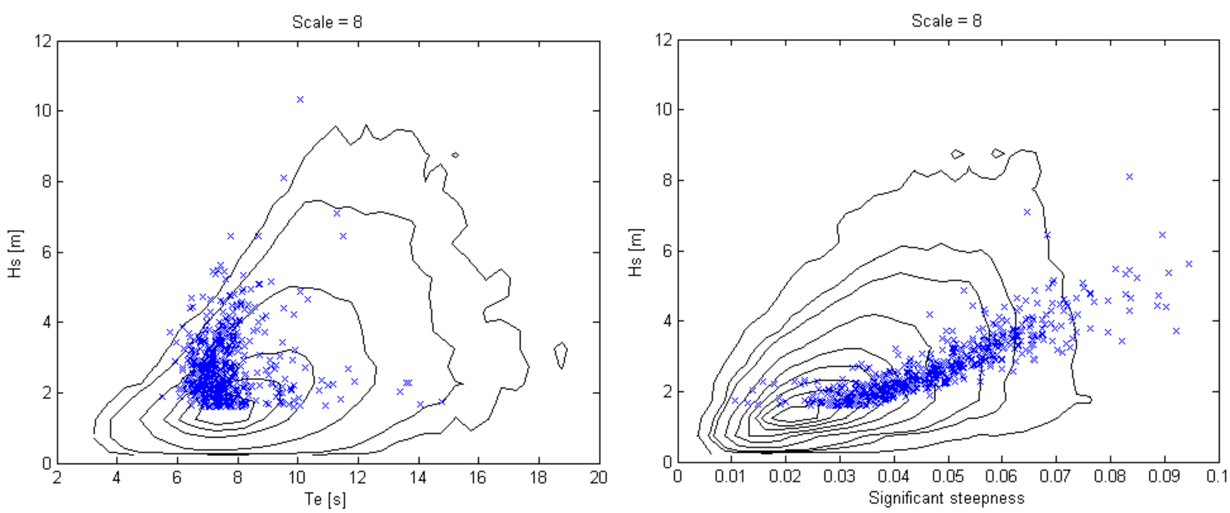

Figure 7.4. As previous figure but for a scale factor of 8.

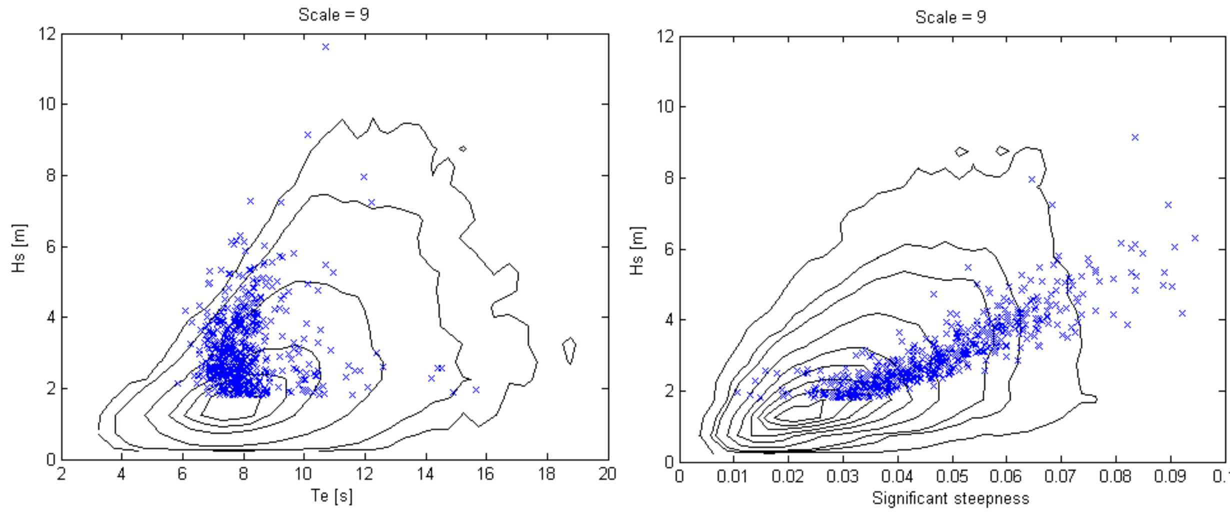

Figure 7.5. As previous figure but for a scale factor of 9.

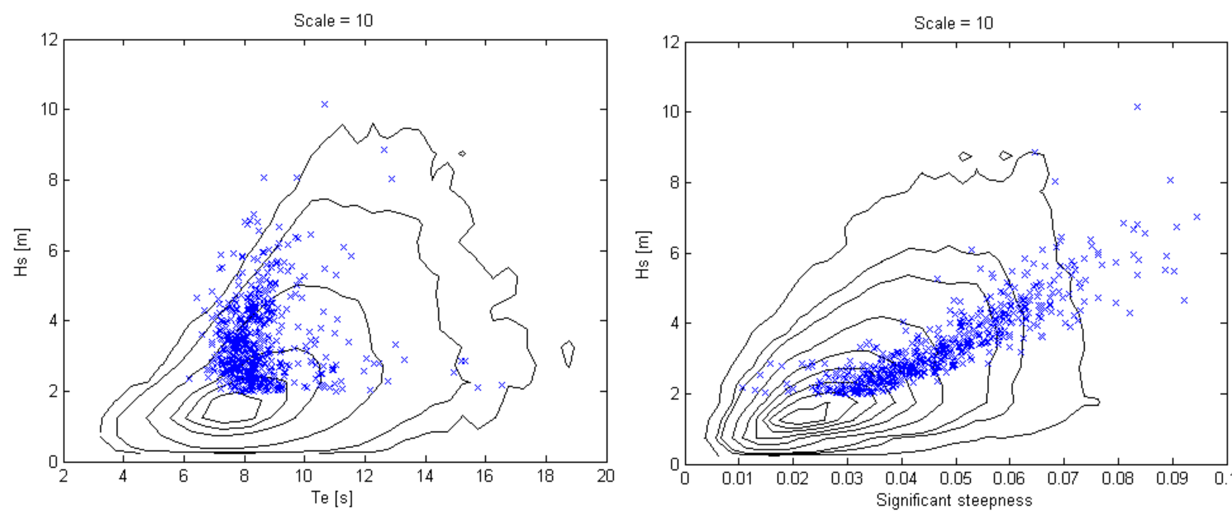

Figure 7.6. As previous figure but for a scale factor of 10.

		scale factor					
		5	**6**	**7**	**8**	**9**	**10**
Hs [m]	**0.5**	72.1	67.0	63.2	59.8	57.1	54.8
	1.5	20.1	20.3	19.4	17.9	17.9	17.3
	2.5	6.7	9.6	11.5	13.1	12.4	12.0
	3.5	0.8	2.6	4.4	6.1	7.7	8.1
	4.5	0.2	0.4	1.2	2.4	3.3	4.6
	5.5	0.0	0.1	0.1	0.4	1.2	2.1
	6.5	0.0	0.0	0.1	0.1	0.3	0.7
	7.5	0.0	0.0	0.0	0.1	0.1	0.1
	8.5	0.0	0.0	0.0	0.0	0.0	0.1
	9.5	0.0	0.0	0.0	0.0	0.0	0.0

Table 7.1. Percentage occurrence of scaled Hs for various scaling factors using Point Wells measurements.

8 FINAL RECOMMENDATIONS AND CONCLUSIONS

Wave measurements from Point Wells have been compared to buoy data recorded off the coast of Oregon. Under the assumption that the wave conditions at Point Wells are similar to West Point, a scale factor between 7 and 8 would seem appropriate for the CPT test site at West Point. The hindcast described in Section 5 indicates that the wave conditions may be slightly more energetic at West Point than at Point Wells, however this may be a result of the different methods used to estimate U_{10} at the to locations. It is recommended that the Point Wells measurements are used to determine the scale factor, since this results in more conservative estimates.

The choice of scale factor is a compromise. Using a low scale factor will enable a larger model to be tested, which is more representative of the full scale device, but a smaller range of sea states will be covered. Conversely, using a higher scale factor will mean that a greater range of sea states will be covered, but the scaled PTO and moorings may be less representative of the full scale systems. For example small scale PTO components may operate with different efficiencies to large scale components. However this may not be critical to CPT, since PTO systems can be tested on a dry rig. For the purpose of validating the hydrodynamic performance of the model a scale factor of 7 – 8 is recommended.

The marginal differences between the percentage of occurrence of the performance related sea states (H_s between 1.5 and 3.5m in Table 7.1) for the 7th scale (35.3%) and the 8th scale (37.1%) designs lead to the conclusion that a final decision regarding the scale factor, should, excluding non-technical aspects such as cost, address also the cut-in (i.e. minimum H_s to excite the model WEC) and cut-off (i.e. maximum performance related H_s) regimes. Again the differences are marginal, thus as a risk mitigation measure (i.e. to reduce the probability of exposing the scaled model to more energetic seas) the priority should be given to the cut-off regime. It is therefore recommended that the scale factor is set at 7.

This recommendation is in-line with the existing protocols (e.g. [4]) that outline the necessary steps when developing a novel WEC. Using [4], the ocean testing of a 7th scale model will be classified as a 'Process Model' (phase 3), immediately after the validation (phase 1) and design (phase 2) stages (for which CPT built and tested a 33rd and a 15th scale model, respectively). It precedes the 'prototype' and 'demonstration' stages (phases 4 and 5, respectively), which can be merged if the next selected scale is 1:1. GH recommends that the way forward (post 7th scale deployment) should include the onshore test of full-scale components, in particular critical components such as the PTO. This follows the recommendations outlined in [5]. This will allow, among other aspects, the mitigation of some of the critical risks associated with the 'prototype', the test of the SCADA system in a controlled environment and the calibration of all systems prior to deployment.

It is also recommended that additional instrumentation is deployed alongside the scaled model. Particular emphasis should be given to the wave measurements, to ensure that the measuring device meets the specifications outlined in Section 4.

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[5] Sarmento, A. and Thomas, G., EU Wave Energy Converters Generic Technical Evaluation Study, Annex Report B1: Device Fundamentals Hydrodynamics, 1993, University College Cork.

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Noise Measurements of Columbia Power Technologies 1/7 Scale Prototype (SeaRay)

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12 August 2011

Summary
Field measurements of the underwater acoustic signature of the Columbia Power Technologies (Columbia Power) SeaRay prototype indicate periodic sound generation that is correlated with the peak period of the waves. Under extremely energetic wave conditions, the received sound pressure levels attributed to the SeaRay prototype were periodic between 116 to 126 dB (re. 1 μPa, integrated from 60 Hz to 20 kHz) at distances from 10 to 1500 m. Peaks in the pressure spectral densities are identified at approximately 20, 100, 300, and 700 Hz, as well as higher harmonics. Test conditions were significant wave heights from 0.4 to 0.7 m and peak wave periods from 2.9 to 3.2 seconds, which are approximately twice the amplitude and four times the energy of typical operating conditions for the SeaRay in Puget Sound. Shipping traffic activity was typical and received as noise levels up to 132 dB (re. 1 μPa, integrated from 20 Hz to 20 kHz). In broadband terms, noise from the SeaRay accounts for only a small fraction of the total noise budget at any given range and background noise from ship traffic dominates the overall broadband (20 Hz to 20 kHz) sound pressure levels, as determined from relative distances and acoustic spectral characteristics. Fully characterizing the SeaRay noise levels was not possible due to persistent background noise produced from ship traffic and other sources. This masking by ship traffic is expected for Puget Sound, and is consistent with UW-NNMREC ambient noise data from Admiralty Inlet, Puget Sound (Bassett et al., in prep). These results should be considered in the context of the existing sound in the region. Acoustic data from a similar environment in Northern Puget Sound with comparable levels of vessel traffic show mean broadband sound pressure levels (20 Hz to 30 kHz) of 120 dB (Bassett et al., in prep). Thus, it is difficult to isolate the noise produced by the SeaRay when it is co-temporal with louder sources of similar frequency.

Methods: data collection

Hydrophone recordings were collected on 30 March 2011 from 09:08 to 13:20 PDT in the vicinity of West Point (Puget Sound, WA). Two types of hydrophone data were collected: cabled drifter and autonomous drifter. Both types of hydrophones were deployed near the SeaRay (Fig. 1) in a series of drifts.

For the cabled drifts, two Cetacean Research Technology C54XRS (-185 dB re 1V/μPa sensitivity, 16 Hz to 44 kHz) were deployed at 5 and 15 m depths from a research vessel drifting with the southerly winds. The drifts were intended to minimize flow noise over the hydrophone (as opposed to anchoring or actively holding station). In addition, cable strum was minimized using drag filaments every 20 cm along the hydrophone cables and an isolator float at the surface. Recordings were collected for 1 minute at 96 kHz continuously, except during repositioning for the drifts.

For the autonomous drifts, a Loggerhead DSG (-185 dB re 1V/μPa sensitivity, 20 Hz to 30 kHz) was deployed at 1 m depth on a free drifting buoy (APL-UW 'SWIFT'). Recordings were collected for 1 minute at 80 kHz continuously.

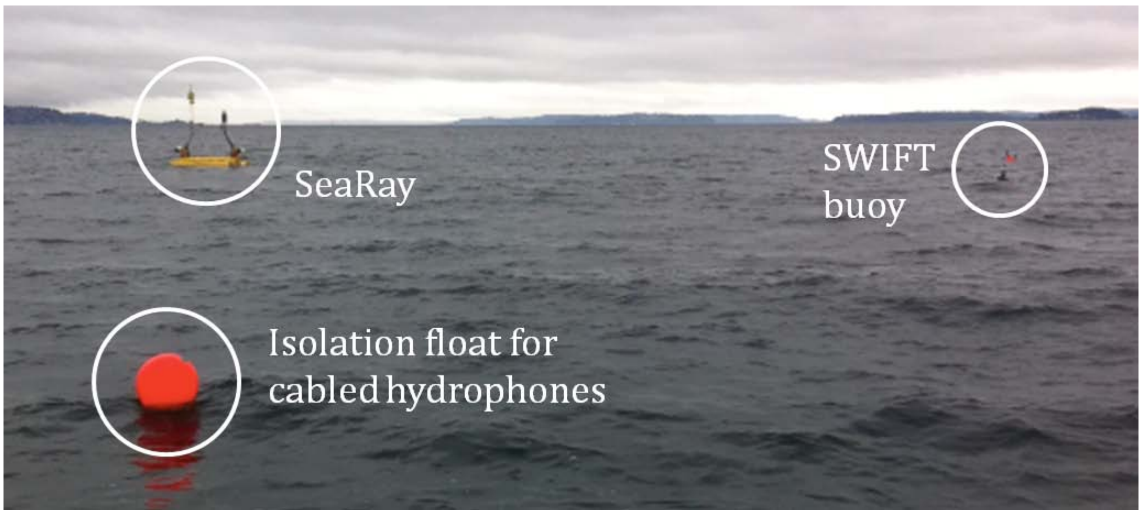


Figure 1. SeaRay (upper left), cabled hydrophone isolator float (lower left), and autonomous drifting hydrophone (upper right).

Ancillary data include GPS logs for the position and range to the SeaRay for each recording, and a ship traffic Automated Identification System (AIS) was used to quantify range to nearby vessels. Wave heights (0.4 to 0.7 m), wave periods (2.9 to 3.2 s), and winds (5-8 m/s, southerly), were measured from the APL-UW SWIFT buoy. Digital Video Recordings (DVR) of the SeaRay in operation during hydrophone recordings indicate full travel on the buoy surge mechanism.

Methods: data processing

The minute-long hydrophone recordings are divided into windows (8192 points), tapered, overlapped 50%, Fast Fourier Transformed, and normalized to preserve variance. A hydrophone calibration is applied and 700 windows are ensemble averaged to obtain pressure spectral densities (PSD) with high statistical confidence. The resulting pressure spectral densities describe the frequency content of the recordings. The minimum and maximum resolvable frequencies are dependent on the hydrophone response and data acquisition rate, respectively. The spectra are evaluated for quality control and integrated from 20 Hz to 20 kHz to determine broad-band sound pressure levels (SPL) given in dB re. 1 μPa. The broadband SPL is defined as root mean square (rms) pressure squared divided by the reference pressure squared. In addition, hydrophone recordings were reviewed audibly, and example .wav files are available upon request.

Results: spatial distribution of SPLs

Sound Pressure Levels for all measurements are shown in Fig. 2, where the drift tracks are south to north because of 5-8 m/s southerly winds during data collection. SPLs are typically around 120 dB, and only exceed this level when a ship is nearby. The max SPL observed is 132 dB and corresponds to a tugboat passing within 500 m of the site. For comparison, assuming practical 15 Log spreading losses, the max SPL attributed to the SeaRay is 126 dB and is equivalent to the same tugboat passing at 1.25 Km range.

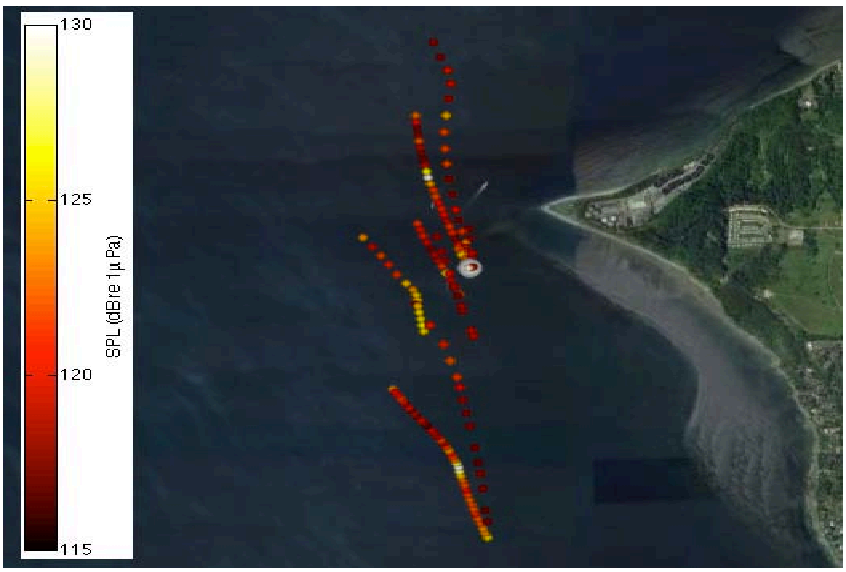


Figure 2. Spatial distribution of recorded broad-band SPLs (20 Hz – 20 kHz in dB re. 1 uPa). The white circle at the center indicates the location of the SeaRay near West Point (Puget Sound, WA), and the region shown is 3 x 3 km.

As shown in Fig. 3, which presents SPLs as function of radial distance to the buoy and recording depth, there is no trend in the spatial data. Even when screening the data for times without ships nearby, there is not a clear spatial pattern relative to the SeaRay. This is in contrast to the expectation that SPL will decrease away from the SeaRay as a result of transmission loss. It is likely that the high level of ambient noise in the region masks the expected transmission loss pattern.

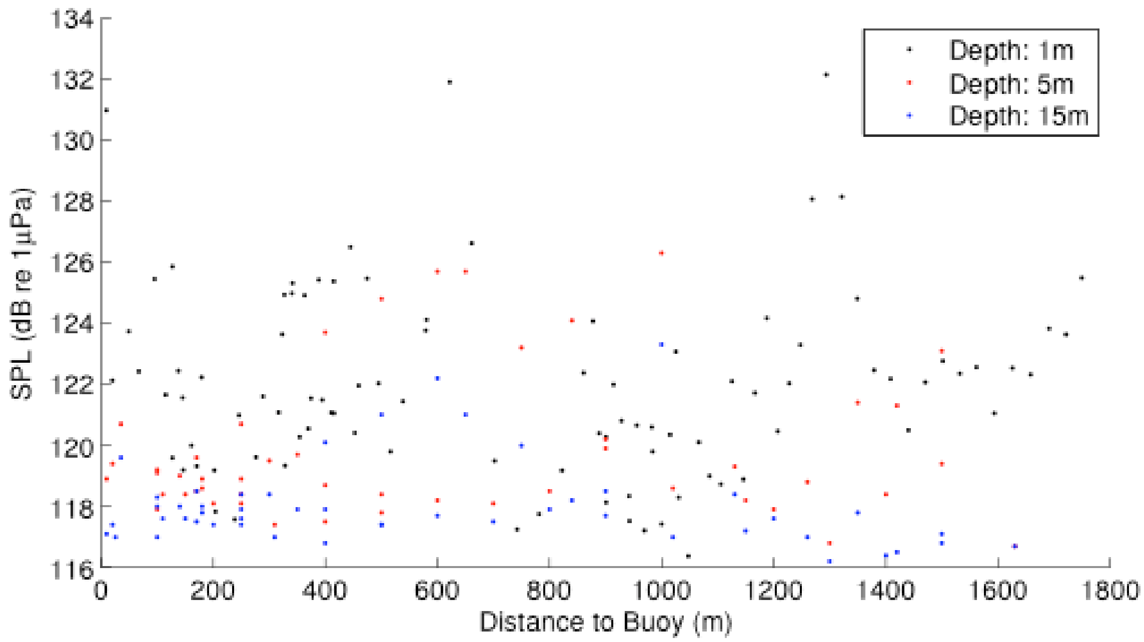


Figure 3. Broadband (20 Hz – 20 kHz) SPL as a function of range to the SeaRay. Colors indicate the different hydrophones.

Results: spectral characteristics

Although the contribution to total SPL from the SeaRay is not evident in the spatial patterns, it is possible to detect the buoy (and to hear it audibly in the recordings) at close range and in the absence of ship traffic. Pressure spectral densities, such as the examples in Fig. 4, show persistent peaks at 20, 100, 300, 700, and 1500 Hz. These peaks are most evident within 500 m of the SeaRay and during lulls in ship traffic. These noise spikes at specific frequencies may be caused by the intermittent start and stop of the drive shaft with each passing wave. The source might also be harmonics of the sound produced by the over-torque limiter or gearbox onboard the SeaRay. When a ship passes nearby (red line in Fig. 4), the peaks are obscured and the pressure spectral densities are elevated at all frequencies (note the logarithmic scale). Another source of noise is wave breaking, which typically contributes at frequencies above a few kHz (e.g., gray line in Fig. 4.). The frequency of breaking during data collection was 0.5-4 waves per minute, as measured by video onboard the SWIFT drifter.

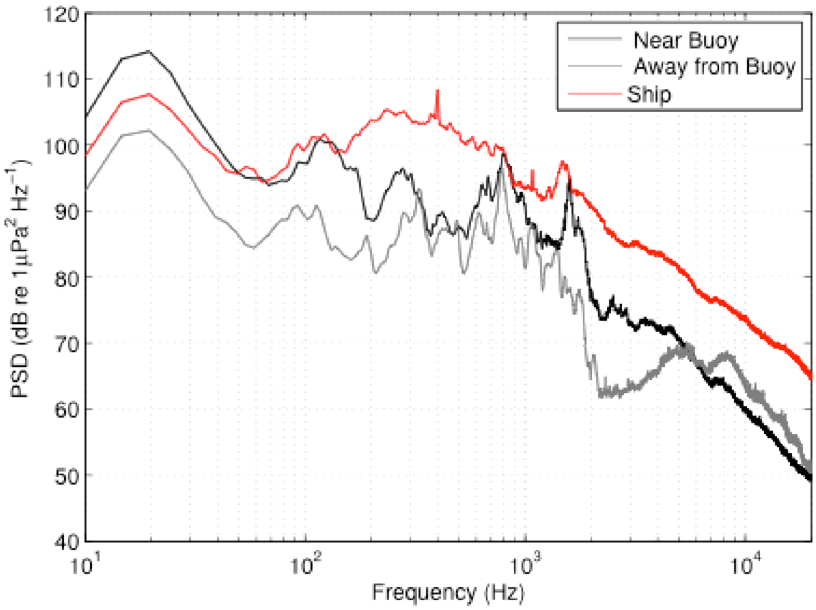


Figure 4. Example pressure spectral densities showing the source and harmonics of the SeaRay (black line and gray lines), as well as typical ship traffic (red line).

The spectral characteristics can be seen more clearly in a short times series, such as the example in Fig. 5. In the absence of ship traffic noise, the SeaRay is observed to produce distinct spectral peaks on a regular cycle with the peak wave period (approximately 3 s). Integrating the pressure spectral densities over selected frequencies ranges, the received sound pressure levels from the SeaRay are periodic pulses of approximately 120 dB (black line, lower panel of Fig. 5).

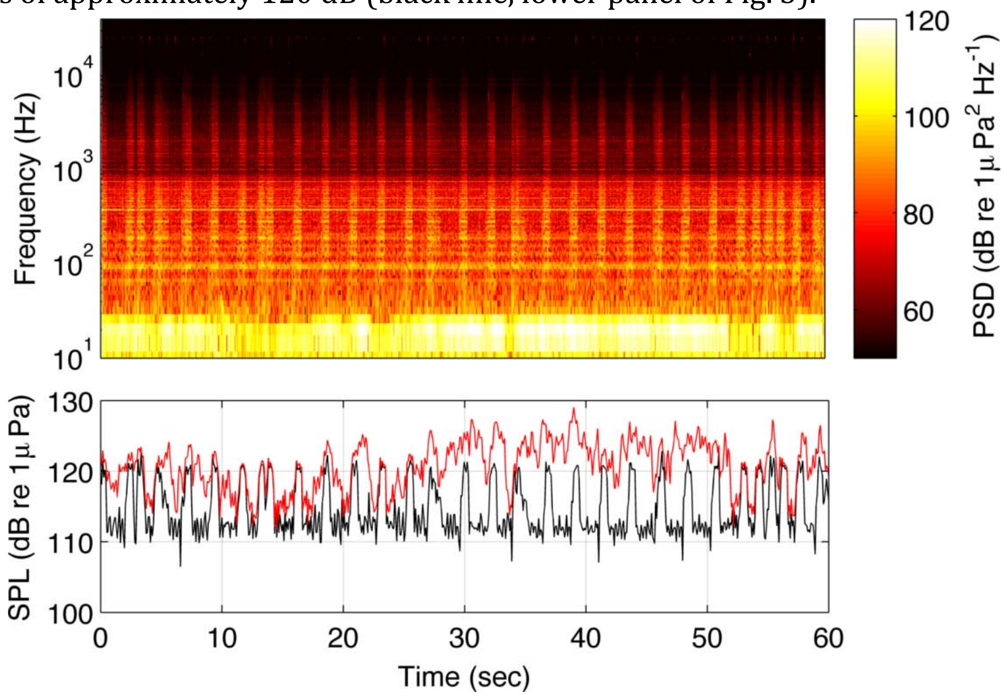


Figure 5. Example time series of pressure spectra densities (color scale, upper panel) and band-integrated sound pressure levels (lines, lower panel) showing regular sound generation at wave periods. The black line is the SPL integrated from 0.08-2 kHz, and the red line is integrated from 0.02-20 kHz. Spectra are from the cabled CRT hydrophone at 15 m depth and 1.4 km distance from the SeaRay.

Results: received levels

The large scatter in the SPL as a function of range (Fig. 3) prevents extrapolation, via the sonar equation, to estimate a source level for the SeaRay at the conventional 1 m reference. This is because, in broadband terms, noise from the SeaRay accounts for only a small fraction of the total noise budget at any given range. Measurements of received sound pressure levels, particularly integrated over the 80 Hz to 2 kHz range associated with the SeaRay, can be used to quantify the effect of the SeaRay on the acoustic environment. As shown in Fig. 5 (black line), with each passage of a wave (approximately 3 s), the SeaRay produces regular signals approximately 10 dB over the background levels in frequency bands from 0.08 Hz to 20 kHz. Note, however, that when the frequency range of analysis is increased to 0.02 Hz to 20 kHz (red line), the periodic acoustic emission from the SeaRay cannot always be discerned from the background, even very close to the SeaRay. This occurs at all distances from the SeaRay.

These results point to a general challenge in characterizing the acoustic emissions from wave energy converters. Because acoustic emissions are periodic with wave frequencies, sound pressure level is sensitive to the analysis window. For example, sound pressure level for an analysis window restricted to the time of maximum power output from the buoy will be significantly higher (at least a few dB) than one in which the analysis window contains several periodic signals. Applying a precautionary principal, the received level discussed here is for the period of maximum power output. For the SeaRay, this received level is typically 120 dB, and varies from 116 to 126 dB.

Conclusions

In general, noise from the SeaRay accounts for only a small fraction of the total noise at any given range. SeaRay noise is produced on regular intervals, corresponding to wave periods, at multiple harmonic frequencies spanning from 80 Hz to 2 kHz. The integrated sound pressure levels showed background levels of approximately 116 dB and SeaRay levels intermittently peaking to approximately 126 dB. By contrast, received sound pressure levels from ship traffic are up to 132 dB. The ship noise causes significant masking, such that the signal from the SeaRay is only detectable during times when there are no vessels within approximately 1 km of the site. Observations do not support trends with depth or distance (i.e. transmission loss), which likely is a result of masking by high levels of ambient shipping noise in the urban waterway of Puget Sound.

The inability to observe a decrease in SPL as the distance increased from the SeaRay prototype is likely caused by the high level of ambient noise in the region, which masks the expected transmission loss pattern. The wide spectral range of frequencies sampled is dominated by noise created by other human and natural sources at frequencies other than the SeaRay. While the SeaRay itself exhibits broadband levels up to 126 dB levels periodically (it is unlikely that source levels are close to 126 dB at any particular frequency), the frequency spectrum is dominated by other noise sources. This is consistent with recent UW-NNMREC propagation tests with a 120 dB re 1 μPa at 1 m source in northern Admiralty Inlet in Puget Sound, an area also dominated by shipping traffic. During those experiments, the tonal source is difficult to detect at ranges greater than 500 m (Bassett et al., in prep). The acoustic signature of the SeaRay, which is a broadband source, is even more subject to masking by stronger sources in its vicinity.

CPT 1/7th Scale Buoy Deployment Plan

Sound and Sea Technology

2-2-2011

Prepared By:

Sam Gooch

CPT 1/7th Scale Buoy Deployment Plan Revisions

Version	Date	Reason for Changes
1.0		Original DRAFT
2.0		1st Revision
3.0		2nd Revision
4.0		3rd Revision
5.0		4th Revision
6.0		5th Revision
7.0		6th Revision
8.0	10 January 2011	7th Revision
9.0	18 January 2011	8th Revision
10.0	24 January 2011	9th Revision
11.0	2 February 2011	10th Revision

Contents

1.0 Overview

This plan covers the deployment of CPT's 1/7th scale wave energy converter (WEC), slated for installation beginning 27 January 2011. The deployment will occur off West Point, Puget Sound at approximately 66 ft MLLW. The buoy will be deployed using a crane barge and held in a 3-point moor. The buoy deployment is scheduled to last for approximately four months, and is intended to collect data to be used for the design of CPT's full scale WEC.

2.0 Equipment, Vessels and Personnel

2.1 Vessels

2.1.1 SEAHORSE

Figure 1. *SEAHORSE* and one of the provided skiffs.

MV *SEAHORSE*

- **Northern Marine Salvage Co. (Seattle)**
- **Length Overall** **107.6'**
- **Main Engines:** **Twin CATD343 T/A 415 HP**
- **Breadth Over Guards** **42'**
- **Depth Molded** **7'**
- **Deck:** **3/8" Steel with 4" X 12" Plank, 40' X 60'**
- **4 - 1,000 lb Danforth Anchors**
- **1 - 6,000 lb Danforth Anchor**
- **4 - Gearmatic Winches (25,000 lb) with 1000' of 3/4" cable capacity**
- **1 - stern towing winch (150,000 lb)**
- **90,000 lb. "D" Rings every 10' on Deck**

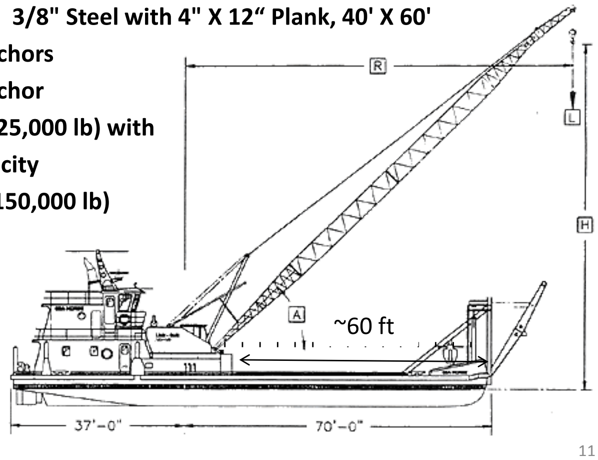


Figure 2.

MV *SEAHORSE* Crane Capacity

R (ft)	L (#)	H (ft)	A (')
30	52,300	137	78.1
35	44,800	135	75.8
40	38,200	133	73.5
50	29,000	130	68.9
60	23,100	125	64.1
70	18,800	120	59.1
80	15,700	113	53.8
90	13,200	104	48.1
100	11,300	93	41.8
100	9,700	80	34.7
120	8,400	60	26
130	7,200	10	12.7

Note: Seahorse Maximum Crane Extension (R) and Height (H) will be limited to 100 feet (Extension arm is removed). Allowable max load will be higher, although not necessary for this installation.

Figure 3.

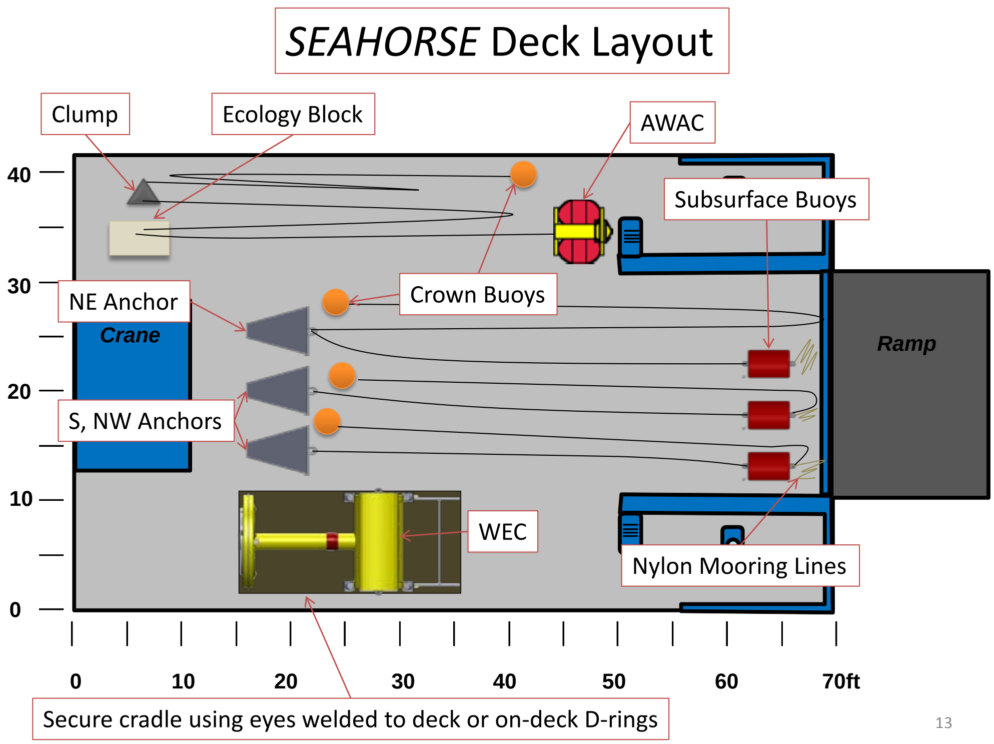


Figure 4.

2.1.2 Maintenance Vessel: *RV Neper*

Sound Support Marine will provide the *RV Neper* (Figure 5) for maintenance and charging operations. The *RV Neper* is 22.5 ft in length and is powered by a 5L gasoline engine. Gordon Roberts is the captain and will be present for all operations involving the vessel. The Sound Support Research Vessel *RV Neper* will be made available to perform the tasks defined in the maintenance section of this deployment plan. The Research Vessel *RV Neper* and vessel operator will be available on-call 24 hours a day 7 days a week during scheduled the periods of operation. Although not anticipated, the Research Vessel *RV Neper* could experience equipment malfunction that results in it not being fully available. Sound Support will provide at no extra cost to the Charterer a backup vessel Figment Too to support WEC Buoy operations until *RV Neper* is returned to service. Carl Gowler (SST) is a licensed captain and will be available to drive the *RV Neper* in the event that Gordon is not able.

The *RV Neper* will be stored at Brichard-Agee dry storage near the Ballard Locks. It will be trailered to the Shilshole Guest Launch for maintenance and inspection trips.

Figure 5. *RV Neper* Maintenance Vessel.

2.1.3 Skiffs

The *SEAHORSE* will provide 18' and 15' aluminum skiffs to be used during the WEC deployment.

2.2 Equipment List

2.2.1 Mooring Configuration

Figure 6 shows the WEC mooring configuration. Detailed component views are given in Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11. The AWAC mooring configuration is given in Figure 12. Detailed component specifications and a bill of materials are given in section 13.0.

Figure 6. Mooring Configuration.

2.2.2 Mooring Component Details

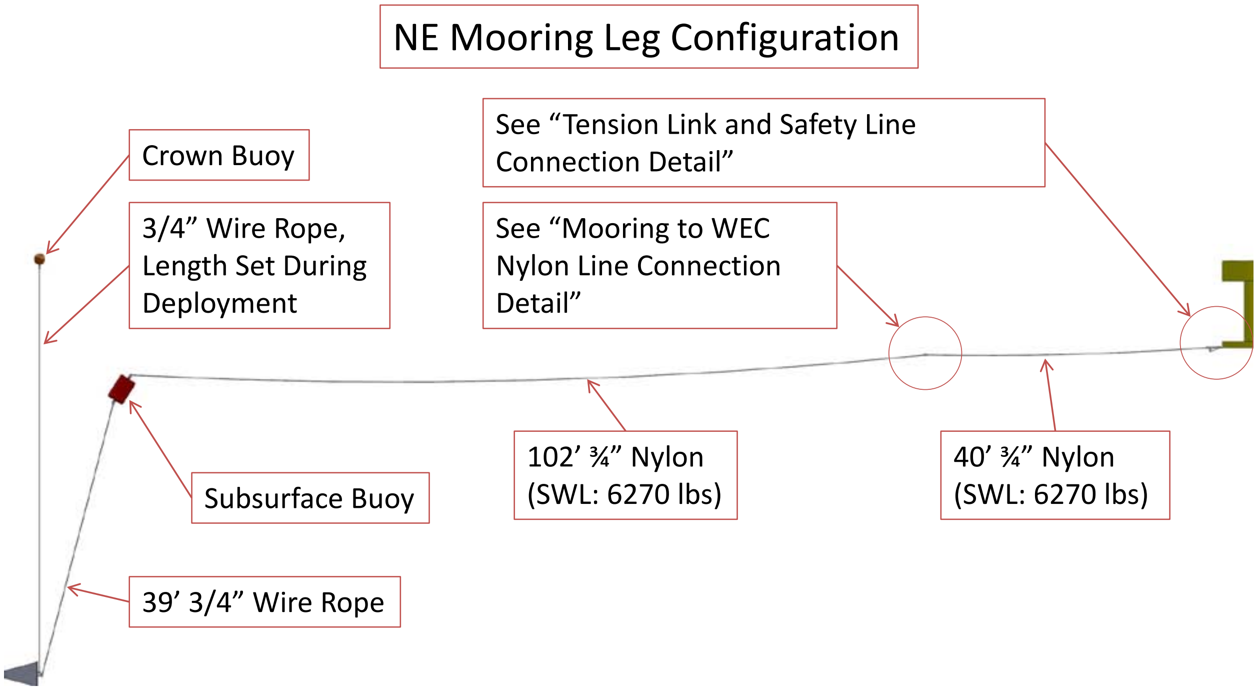


Figure 7. NE mooring leg configuration. Note that the crown buoy is attached directly to the anchor to facilitate precise placement for pretensioning.

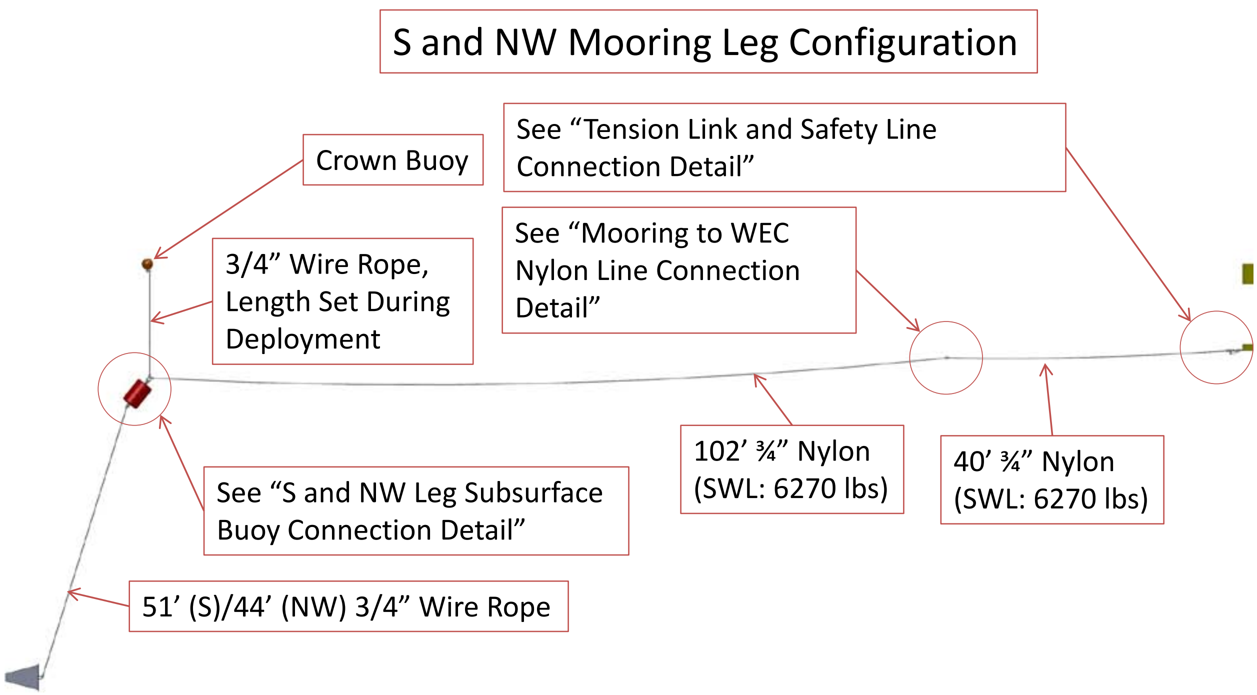


Figure 8. S and NW Mooring leg configurations. The crown buoy and retrieval line are attached directly to the subsurface buoy for easy installation and removal.

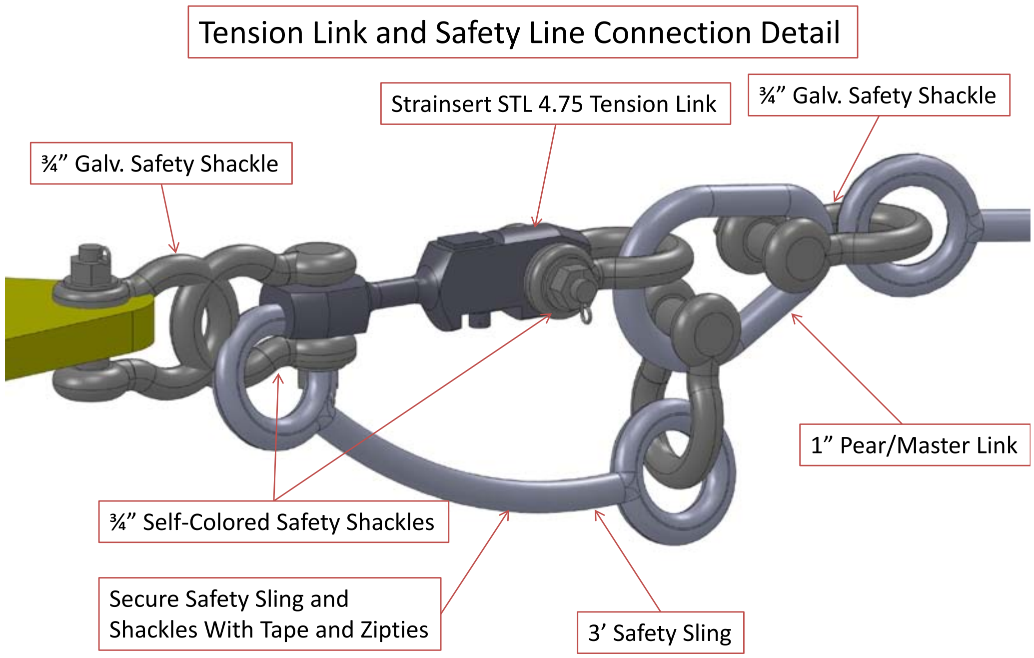


Figure 9. Tension link and Safety Line Connection Detail. Note that the safety sling will be attached to a separate padeye on the WEC (Not shown).

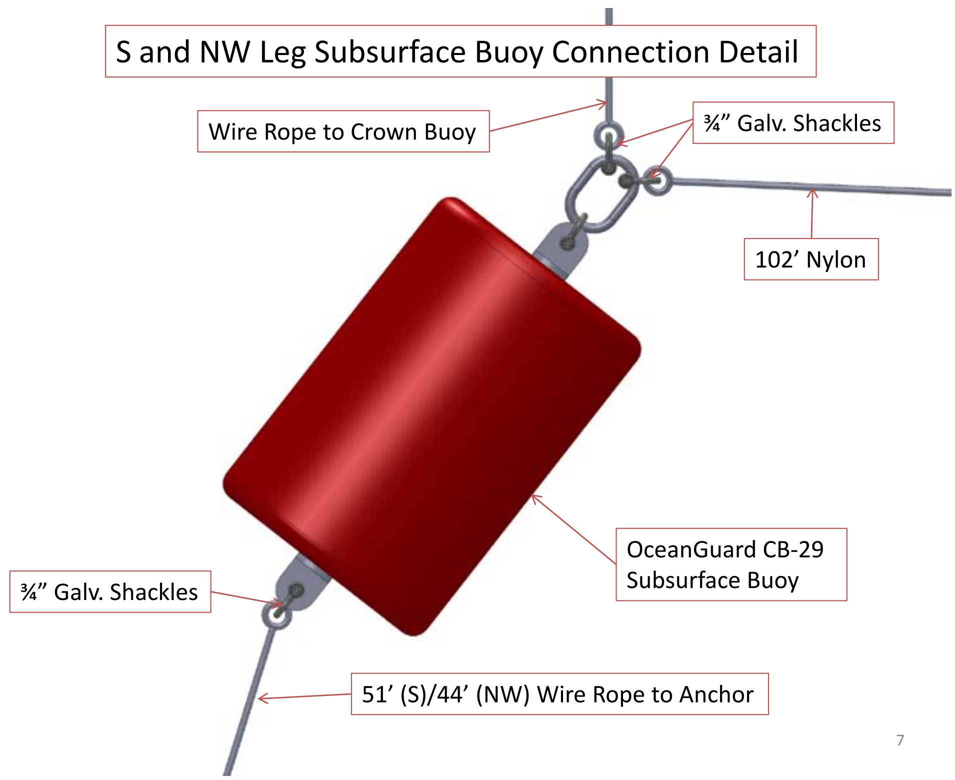


Figure 10. Subsurface buoy detail. Note that this only applies to the S and NW legs, as the recovery line is not attached to the subsurface buoy on the NE leg.

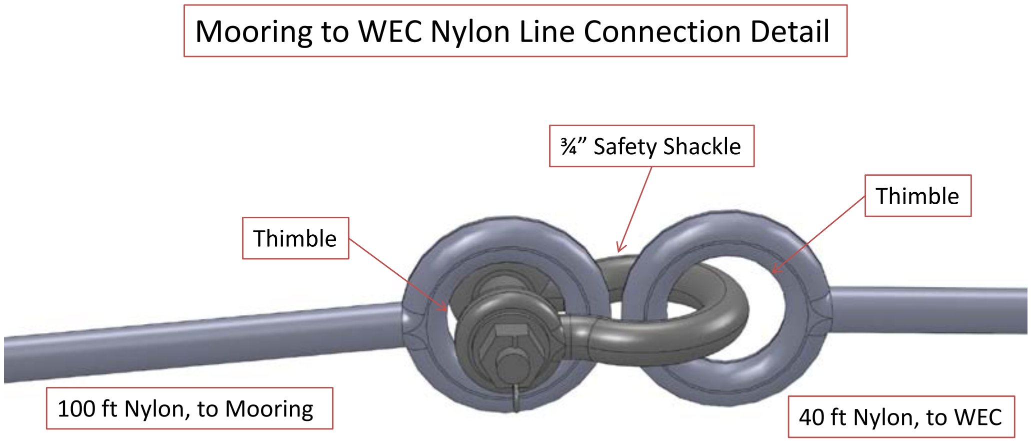


Figure 11. Connection between 40 ft nylon (initially connected to the WEC) and 100 ft nylon lines (initially connected to the subsurface buoy). The connection is made at this point because the connection point on the WEC damper plate will be submerged.

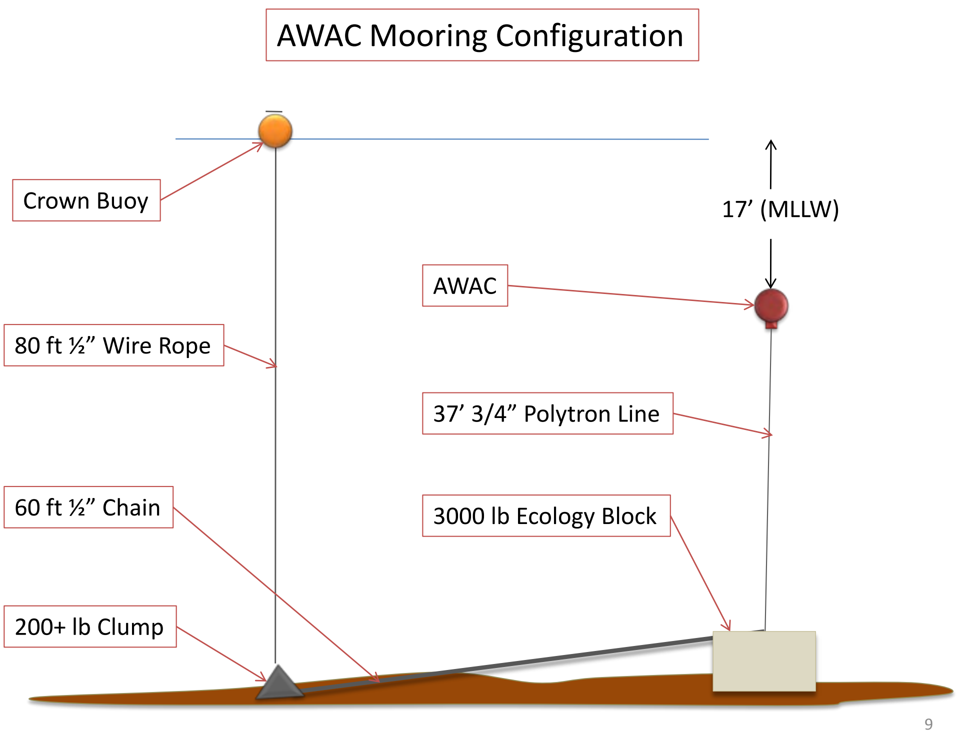


Figure 12. AWAC Mooring configuration. A separate recovery line is used to avoid having lines in the AWAC’s field of view, and to avoid the use of acoustic releases or grappling.

2.2.3 Additional Equipment

The following equipment will be required. The party responsible for providing equipment is also given.

- Northstar 951 GPS/Antenna (SST)
- PFD’s, Steel Toed Boots, Hardhats (SST/CPT)
- Lunch/Snacks (TBD)
- Shackle Mousing Wire (SST)

- Tools: Pliers, Adjustable Wrenches, Wire Cutters, etc. (SST)

2.3 Personnel

The following people will be required for the deployment:

Company	Employee	Role(s)
Columbia Power	Ken Rhinefrank	Test Director
	Joe Prudell	Rigging/Electrical
	Al Schacher	SCADA Systems
	Erik Hammagren	Rigging/Electrical
	Ted Schacher	Standby
	Mark Brown	Independent Observer
Sound and Sea	Carl Gowler	Safety Officer, Deck Supervisor
	Sam Gooch	Operations Supervisor
	Matt Ramey	Deck Operations
	Ryan Gowler	Deck Operations
Northern Marine Salvage	Brian Carlson	*SEAHORSE* Operator
	Charlie	Crane Operator
Sound Support Marine	Gordon Roberts	Maintenance Vessel Captain/Operator
Navy	Warren Bartel	Guest
	Brian Cable	Guest
	Alexandra Devisser	Guest

3.0 Mobilization

3.1 Mooring

Anchors will be brought down from the Bangor Sub Base on a flatbed truck and brought to the west wall during the deployment mobilization. Subsurface buoys (stored at the SST warehouse in Lynnwood) will be brought down using a SST furnished trailer, along with the mooring hardware.

3.2 WEC

The Wave Energy Converter (WEC) will be trucked from Ershig's to the *Seahorse*, and transferred at the west wall at Fisherman's Terminal, shown in Figure 13.

Figure 13. *Seahorse* loading location at the West Wall, Fisherman's Terminal. Deployment site shown in red.

3.3 Loading the *SEAHORSE*

Mobilization will occur at the Lake Union Dry Dock. During the mobilization day, all components requiring use of the *SEAHORSE*'s crane will be brought onboard, including the WEC/Cradle, AWAC, all anchors and subsurface buoys. Mooring hardware will be brought down from the SST warehouse; the 6000 lb anchors, ecology block and AWAC clump will be brought from Bangor Navy base on a flatbed truck. A diagram of the WEC cradle and rigging is shown in Figure 14. The WEC cradle will be secured to the deck using the D-rings available on the *SEAHORSE*.

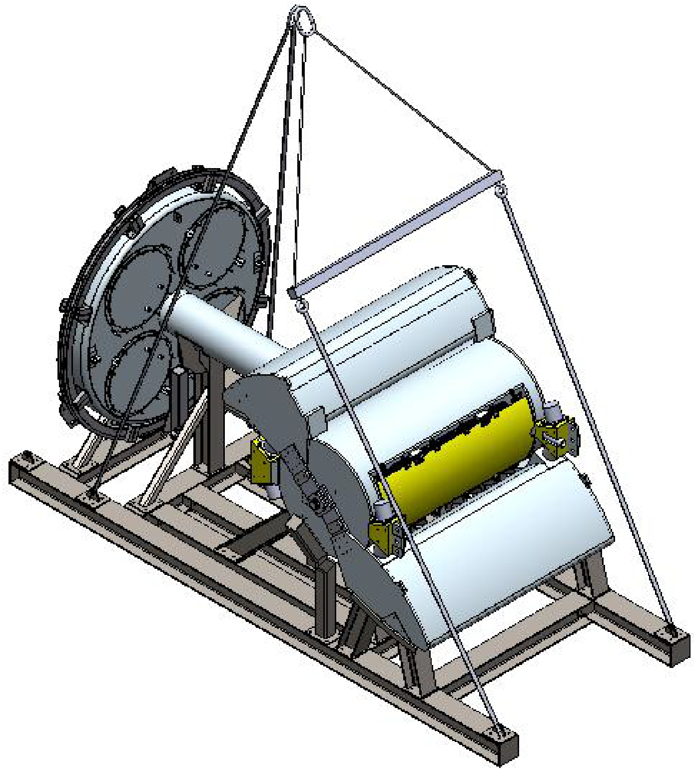


Figure 14. WEC, Crate and Rigging Hardware.

3.4 Mooring Set Up

After the mooring hardware and anchors are brought onto the *SEAHORSE*, the components must be assembled into the complete mooring leg assemblies. Drawings of these assemblies are given in section 11.0. These should be assembled so that all major components, especially the subsurface buoys, remain safely secured to the deck until they are ready to be deployed. Each mooring leg should be secured so that it may be accessed without moving the other legs.

4.0 GPS Calibration, Float Acoustic Test and Lifting Exercise

Prior to deployment, the WEC will be run through a GPS calibration, float acoustic test and lifting exercise. The GPS test consists of rotating the WEC several times to calibrate the onboard unit. The float acoustic test involves taking acoustic measurements of the WEC's floats while they are moved by the *SEAHORSE's* crane. The tests will occur at Lake Washington. The procedure will occur as follows. Prior to departure:

- Confirm all hardware & personnel on board
- Power on SCADA and confirm all IO and signals function properly. Use Columbia Power SCADA/electrical checklist.

4.1.1 Transit and Preliminary Testing

- Load WEC onto *SEAHORSE* in cradle
- *SEAHORSE* transit to Lake Washington: ~45 min
- Reconfirm SCADA Systems
- *SEAHORSE* deploys WEC, releases from crane (shown in deployment procedure)
- WEC floats unlocked (shown in deployment procedure)
- Check WEC waterline, taking fresh/saltwater density into consideration

4.1.2 GPS Test

- SEAHORSE stands off ~500 ft (to avoid interference with calibration)
- Tie small skiff (with electric motor) to float, rotate 3x. Details TBD by Carl Gowler
- Bring *SEAHORSE* back to WEC

4.1.3 Float Acoustic Test

- Attach whip to CPT-provided spreader bar, slings and pear link assembly
- Reattach crane to SST-provided spreader sling assembly, shown in Figure 15

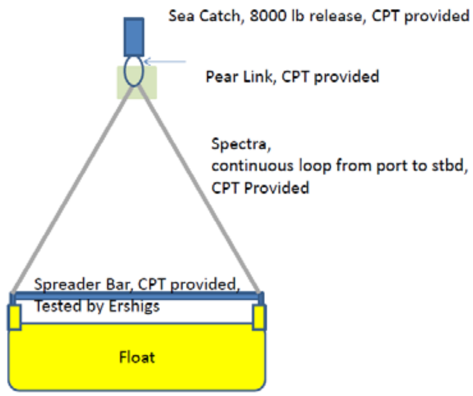


Figure 15. CPT Provided Spreader Sling Assembly.

- Move crane over WEC and attach SST spreader to WEC nacelle (shown in recovery procedure)
- Attach CPT Spreader to forward float. Float "drop" will be performed using a rigging setup shown in Figure 16. Release of the float will be initiated by pulling on the Spectra line from a skiff.
- Using the aforementioned technique, follow CPT provided test procedures:
    - This is performed with the buoy raised out of the water at the nacelle lifting points by the crane so that the floats do not touch the water when the floats are down against the lower end stops. Floats are raised and lowered using the whip, a spreader bar, 30 foot spectra lifting bridle, pear link (with floatation/padding) and Seacatch.
    - Forward float range of motion testing. Raise lower speed NTE ?? ft/sec
    - Forward float PTO power testing. Active and Passive
    - Forward float end stop testing
    - Perform float motion IO checks IAW CPT document.
    - Repeat b, c, d, e for aft float.

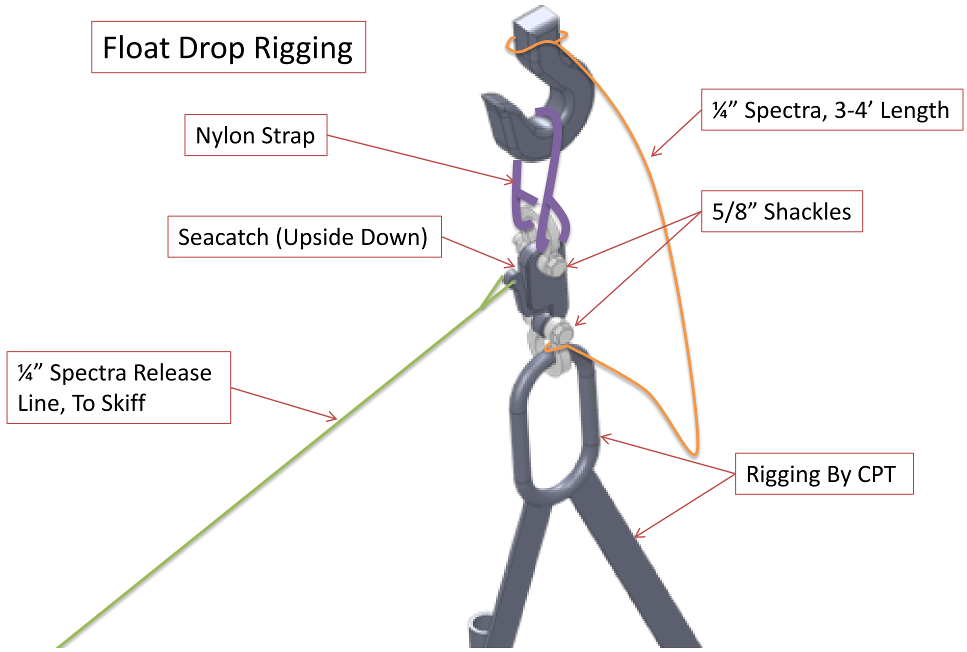


Figure 16. Float "Drop" Rigging Diagram. Pulling on the release line will cause the Seacatch to release the upper shackle. The 3-4' Spectra will catch the rigging hardware, ensuring the float is not damaged. (The Seacatch is upside down to provide the proper angle to release the squib).

4.1.4 Additional Testing and Recovery

Perform Yaw Control Test; use crane, *SEAHORSE* bow/stern and crane to create 3-point moor (if time allows)

IO and other testing per CPT recommendations

- Follow WEC recovery procedure, including forward float lockout
- *SEAHORSE* transit to deployment site or Lake Union Drydock, TBD

5.0 Deployment

After mobilization and pre-deployment testing are complete, the *SEAHORSE* will transit to the deployment site. This may occur on the same day as the pre-deployment testing, weather and time permitting. The proceeding slides detail the deployment procedure, which occurs as follows:

- Transit to deployment site
- Set NE anchor (live boat)
- Put *SEAHORSE* into two point moor
- Set S anchor (in two point moor)
- Rig S, NW anchors to WEC
- Deploy WEC
- Bring WEC to NE anchor
- Set pretension by moving NW anchor into position
- Deploy AWAC

- Transit back to Lake Union Drydock

Each diagram shows the estimated time to complete that step, along with a running estimate of the total time, and crane and whip loads.

5.1.1 Site and Transit

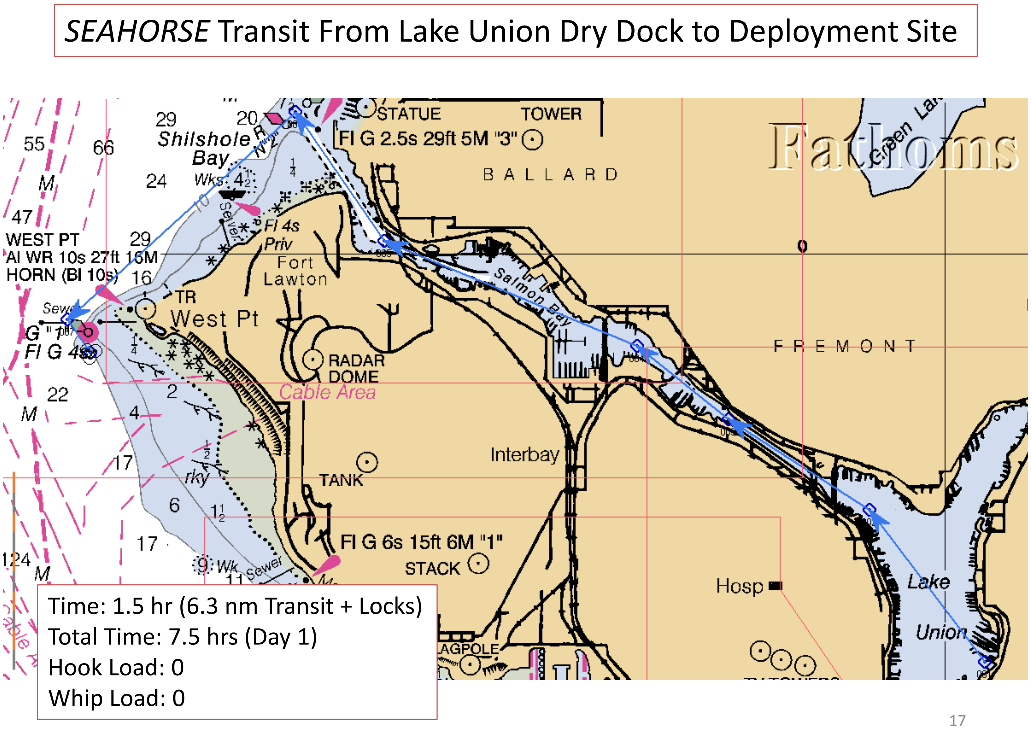


Figure 17. Transit time. Locks will take ~30 minutes to cross, in addition to travel time.

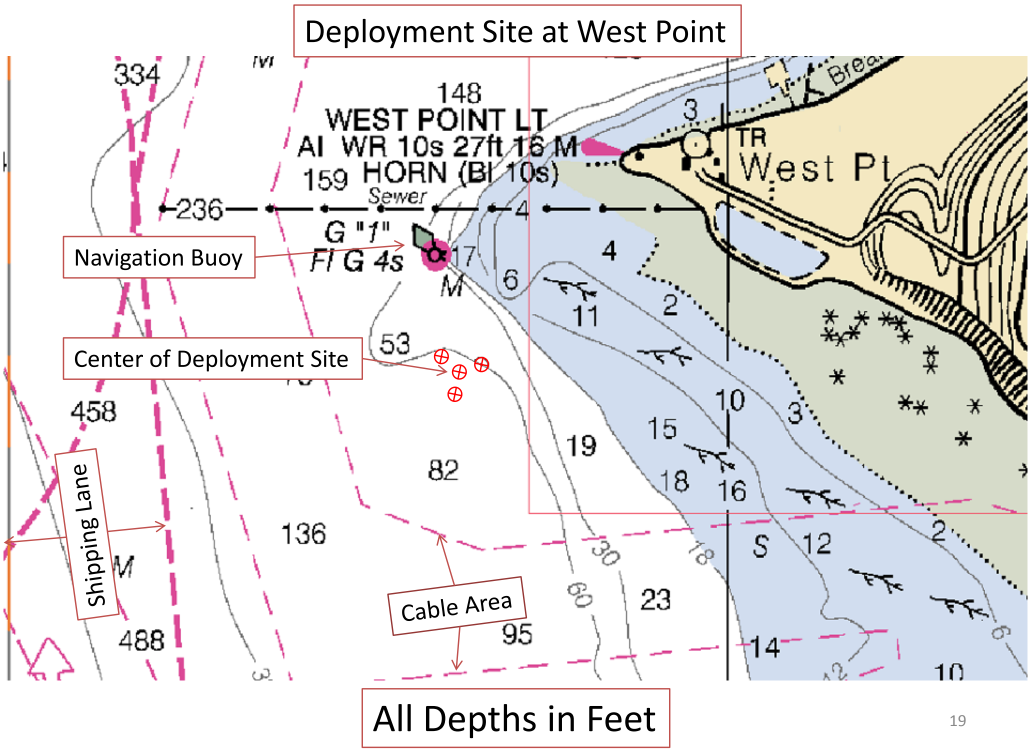


Figure 18. Close up of deployment site.

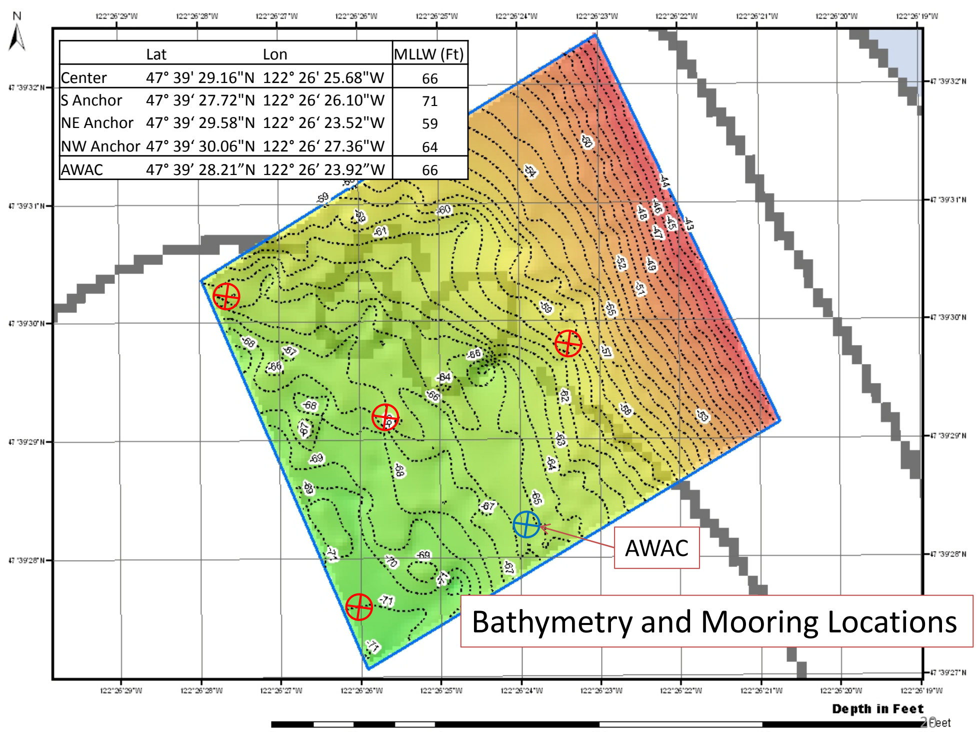


Figure 19. Bathymetry at deployment site. Accurate to within +/- 1.5 ft. Data collected by SST.

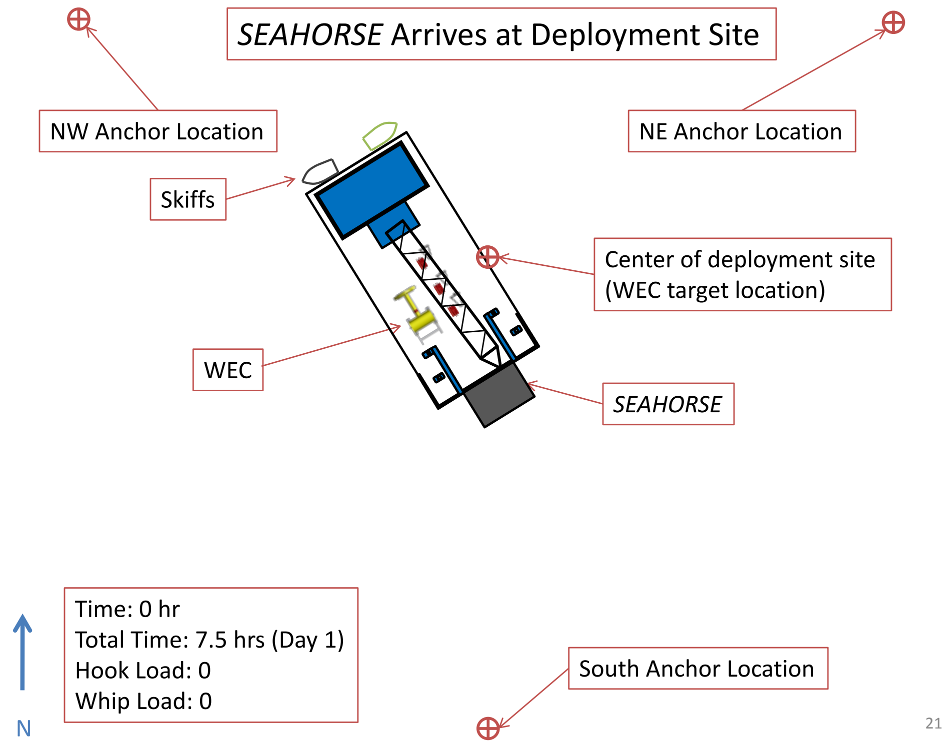


Figure 20. *SEAHORSE* arriving at deployment site. *SEAHORSE* will provide the 18' and 15' aluminum skiffs.

5.1.2 Northwest Mooring Leg Deployment

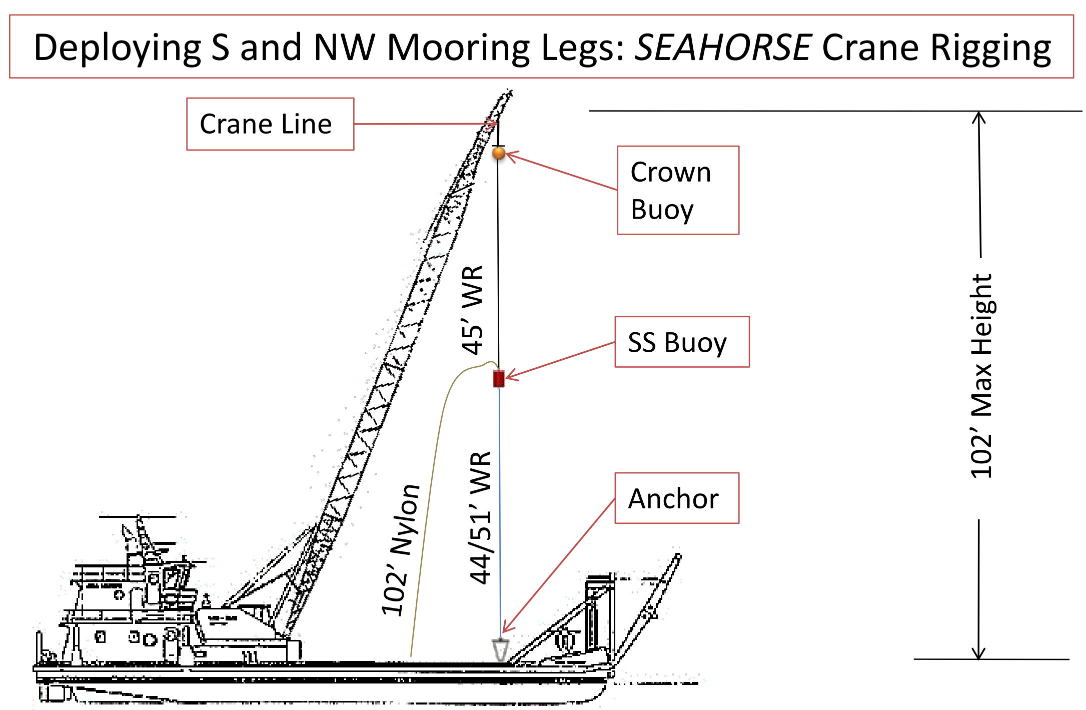


Figure 21. Rigging configuration for S, NW mooring legs. Crane is tall enough to lift entire leg in one pass.

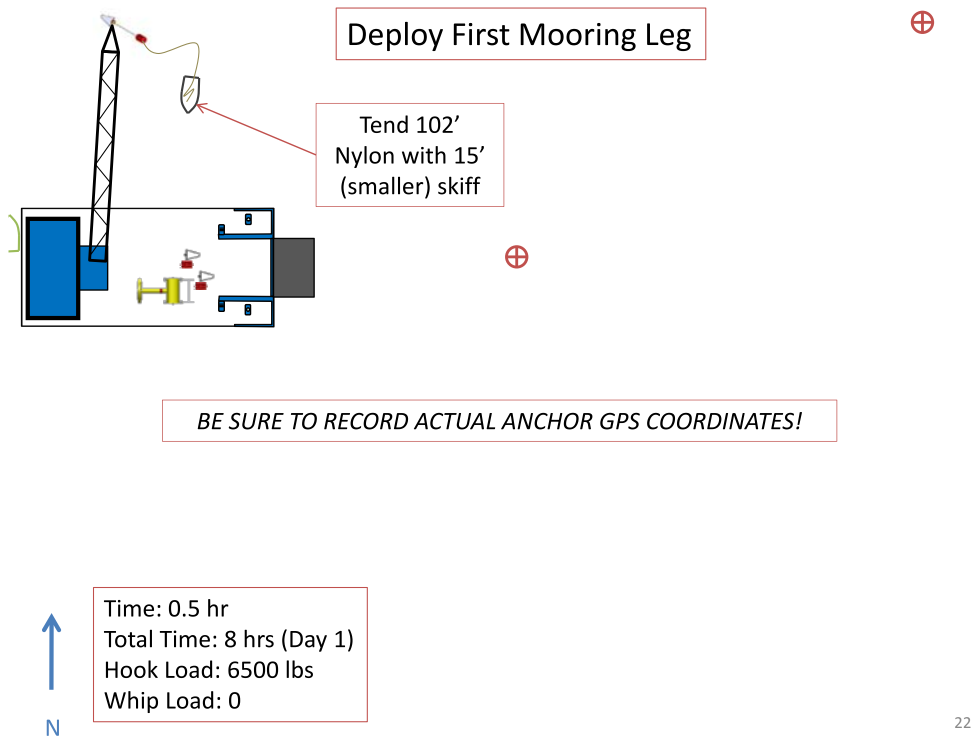


Figure 22. Deploying the first mooring leg. Orient the boat so that the mooring is in the lee. Tend the 102’ nylon section with a skiff to avoid fouling the line.

5.1.3 South Mooring Leg Deployment

The placement of the Southern mooring leg is relative to the actual placement of the NW leg, nominally given in Figure 19. Using the OpenCPN navigational program and the input from the Magellan 315 GPS (mounted at the apex of the *SEAHORSE* crane), the exact locations of the second (S) and third (NE) mooring legs can be determined using the offsets shown in Figure 23 relative to the northwest mooring leg.. This will ensure even line tensions in the mooring legs.

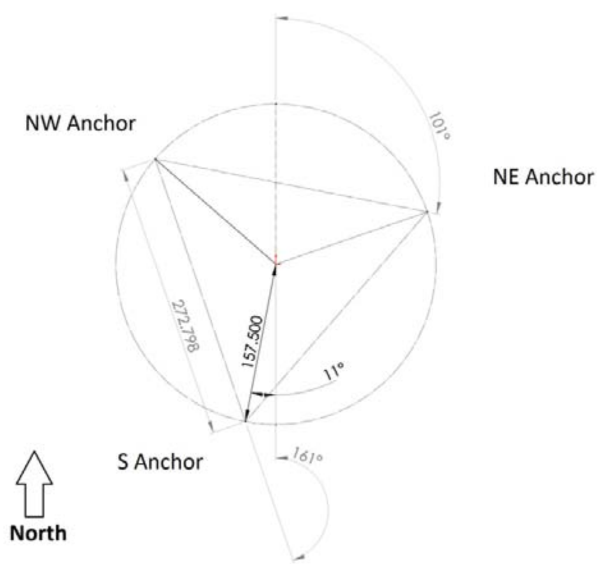


Figure 23. Angles and distances of S and NE anchors relative to NW anchor location. All lengths are in feet.

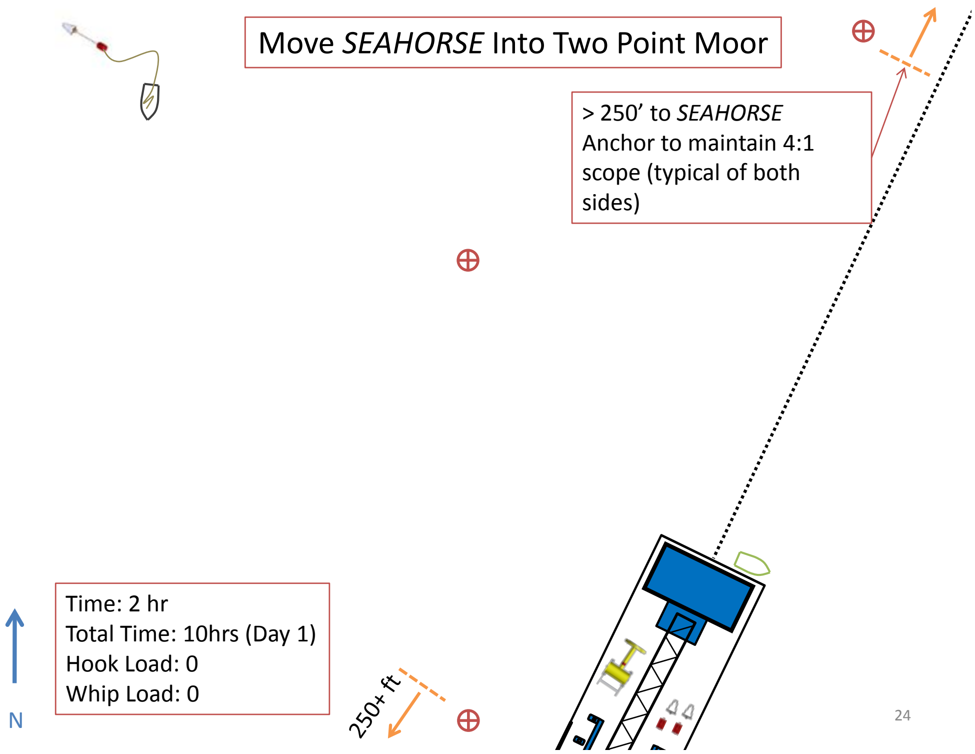


Figure 24. Putting the *SEAHORSE* into a 2-point moor. The *SEAHORSE* can set its own anchors. However, if there is a time constraint, a tug can be employed. The anchors must be placed greater than 250 feet away from the target anchor locations to maintain scope.

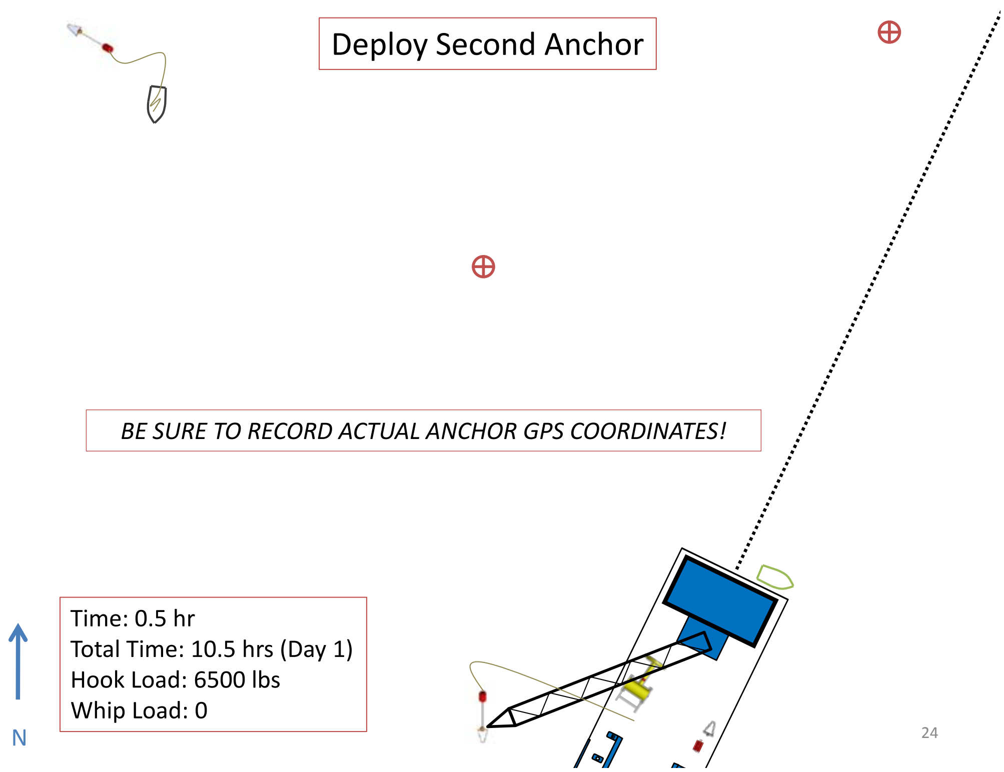


Figure 25. Setting the second anchor. Since the SEAHORSE is in a 2-point moor, this anchor can be placed very accurately. It should be placed relative to the exact position of the first anchor.

5.1.4 Optional Steps for Overnight Stopping Point

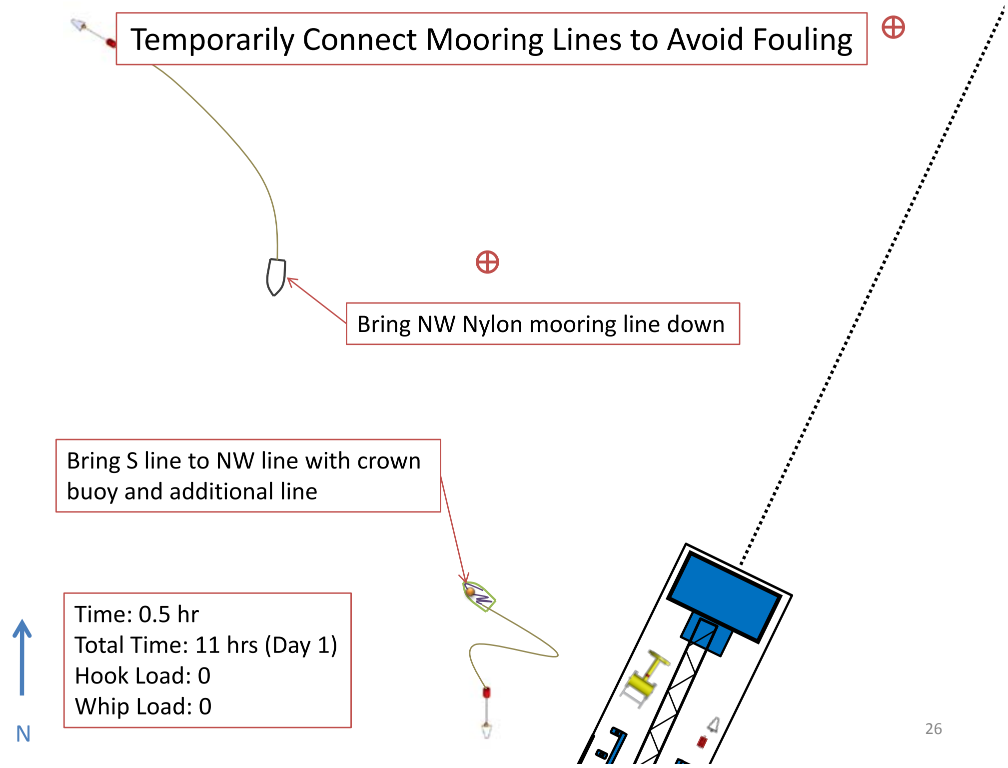


Figure 26. Connecting the mooring lines together with a crown buoy will ensure they do not become fouled.

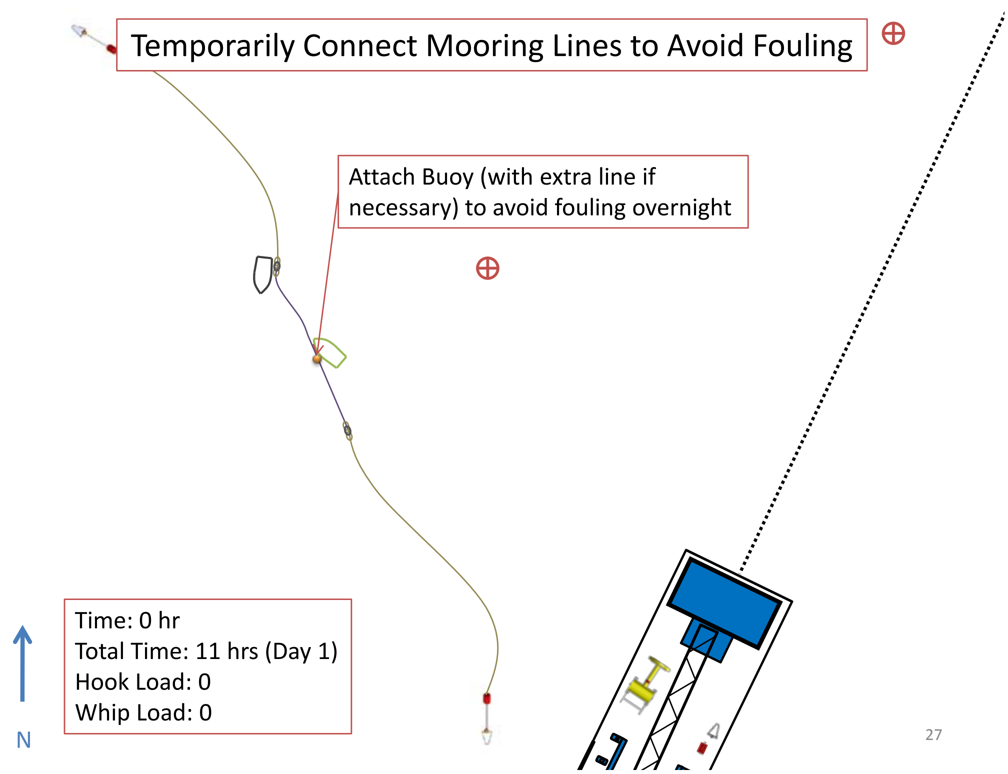


Figure 27. Note: The two mooring lines should only be connected if it is necessary to leave the moorings in place overnight; otherwise, skip to Figure 29. The crown buoy should be kept as taut as possible; however, extra line can be used if required to bring the two mooring lines together.

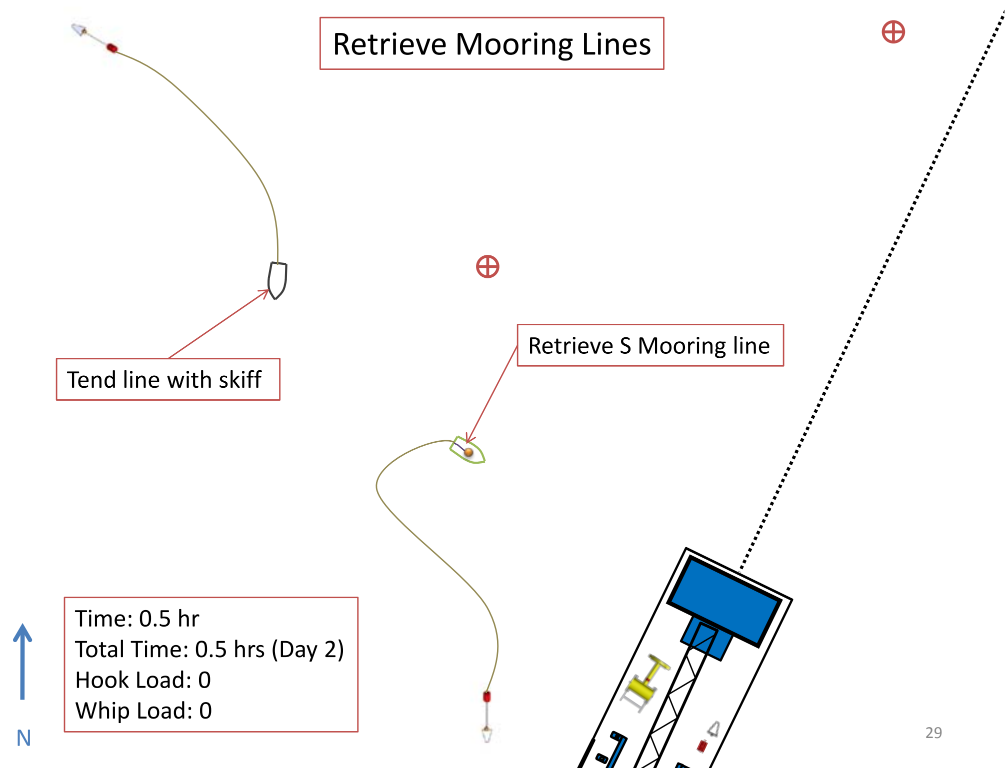


Figure 28. Again, only necessary if the moorings must be left in place overnight.

5.1.5 WEC Deployment

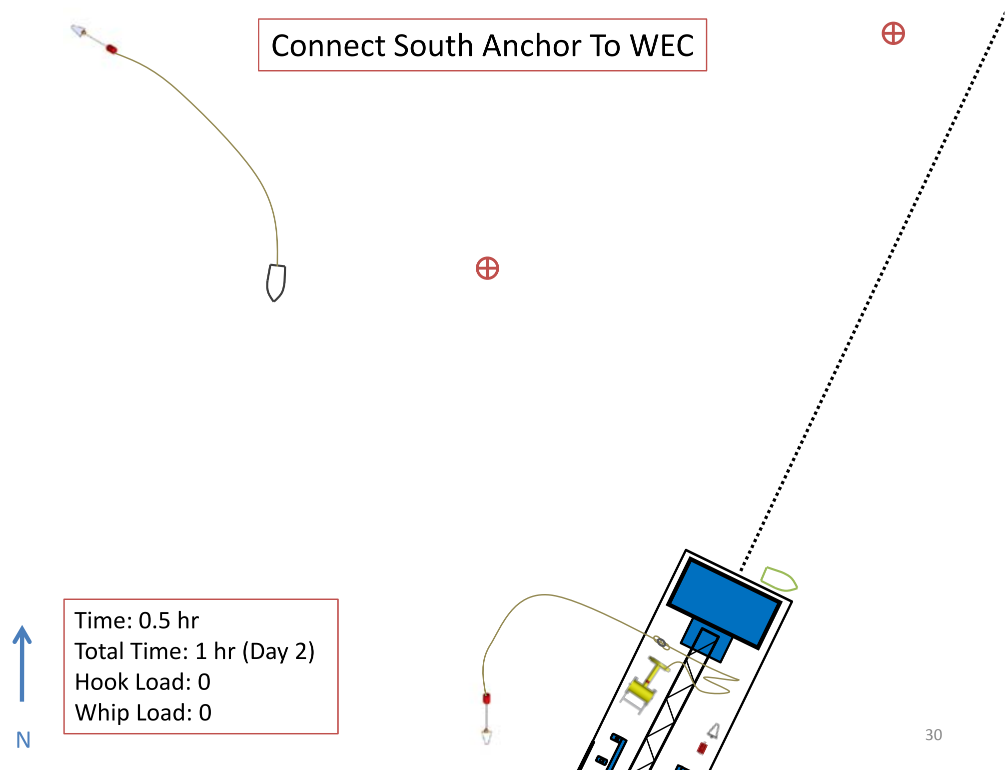


Figure 29. Connecting the S anchor allows for less skiff work and fewer lines in the water.

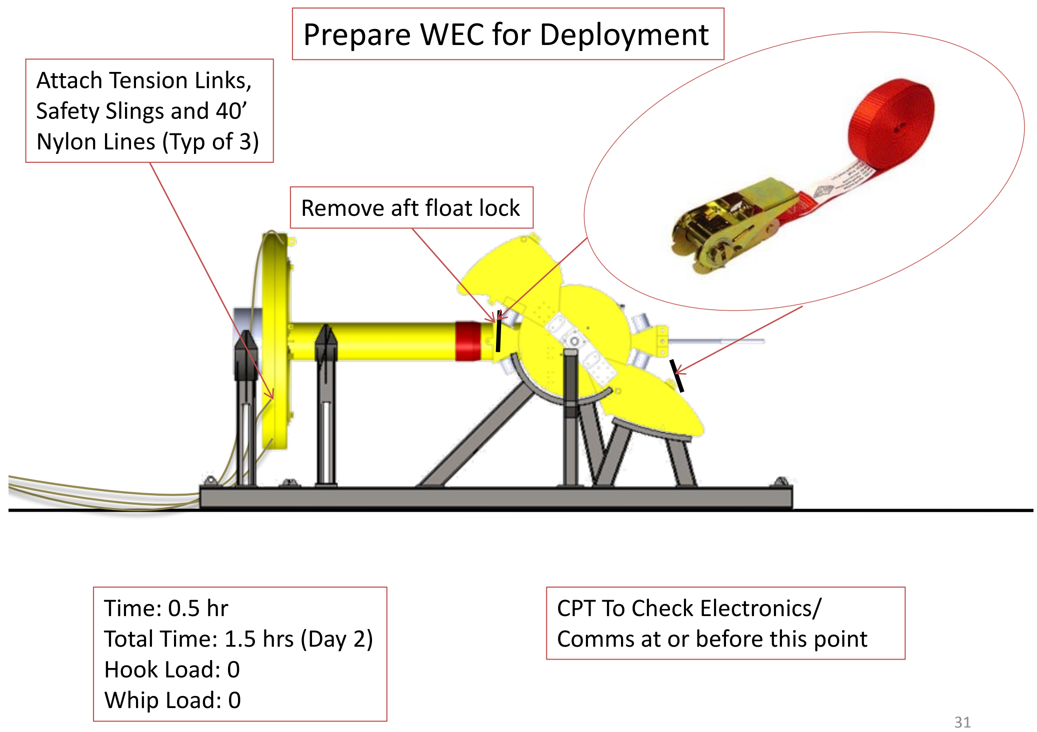


Figure 30. Preparing the WEC for deployment. Float locks will be endless nylon web ratchet straps. All systems should be verified by CPT prior to this point.

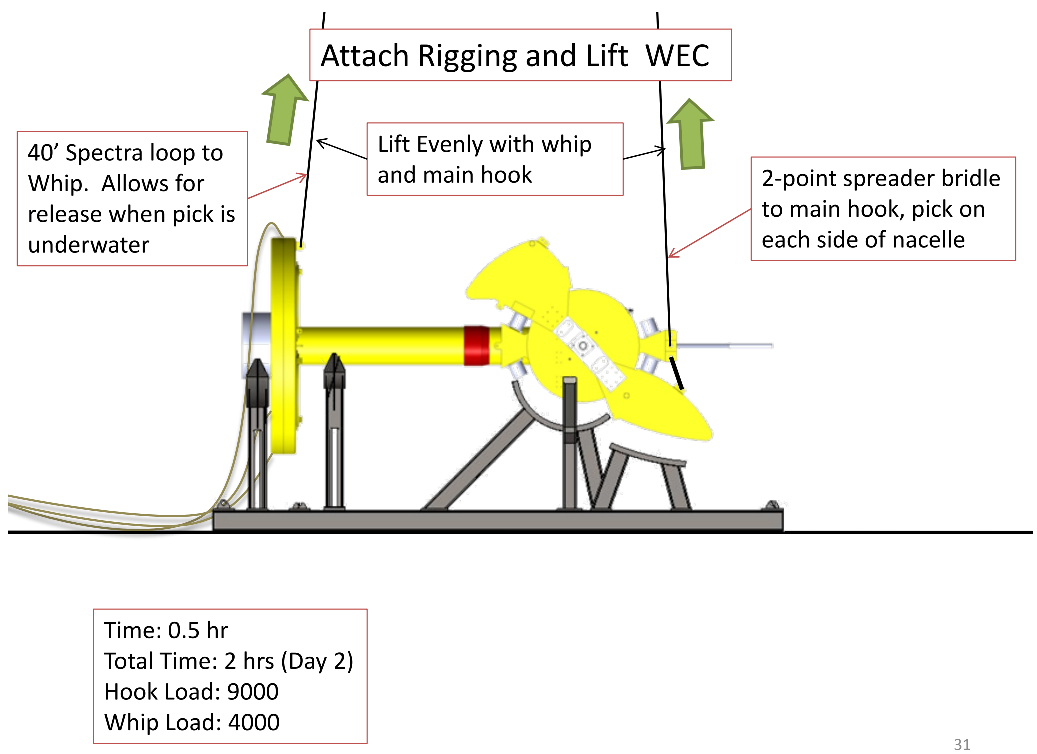


Figure 31. Whip line loop will allow for detachment while submerged. Bridle will attach to both sides of nacelle.

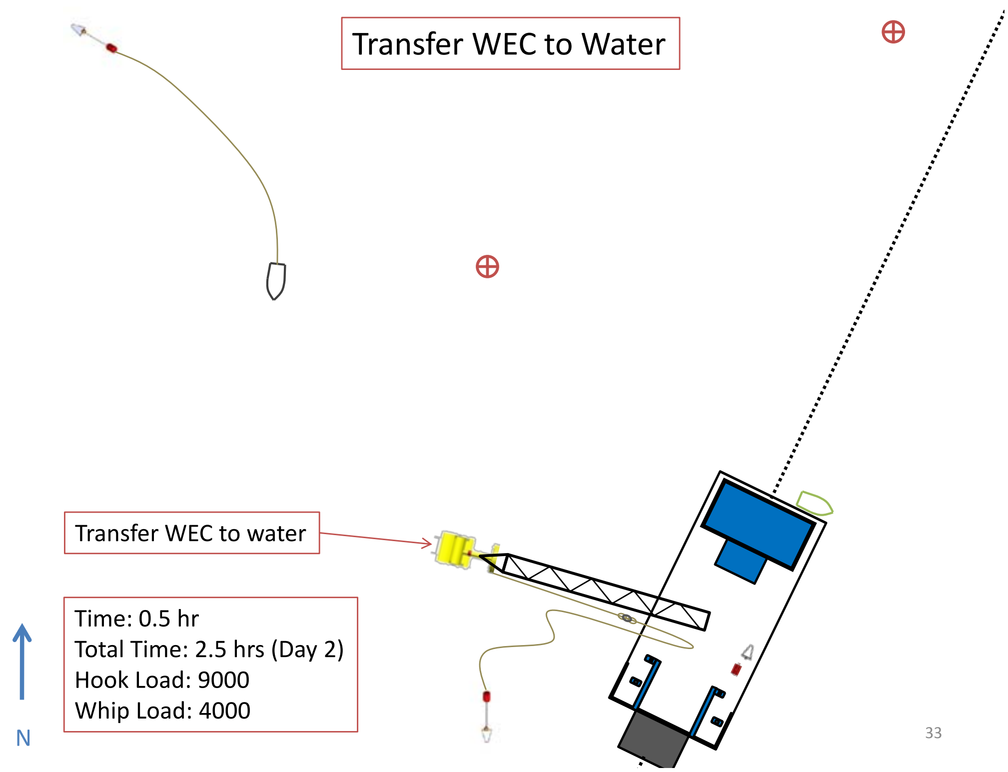


Figure 32. Transfer the WEC in the horizontal position to the water. Tend from SEAHORSE using NE and NW mooring line segments as taglines.

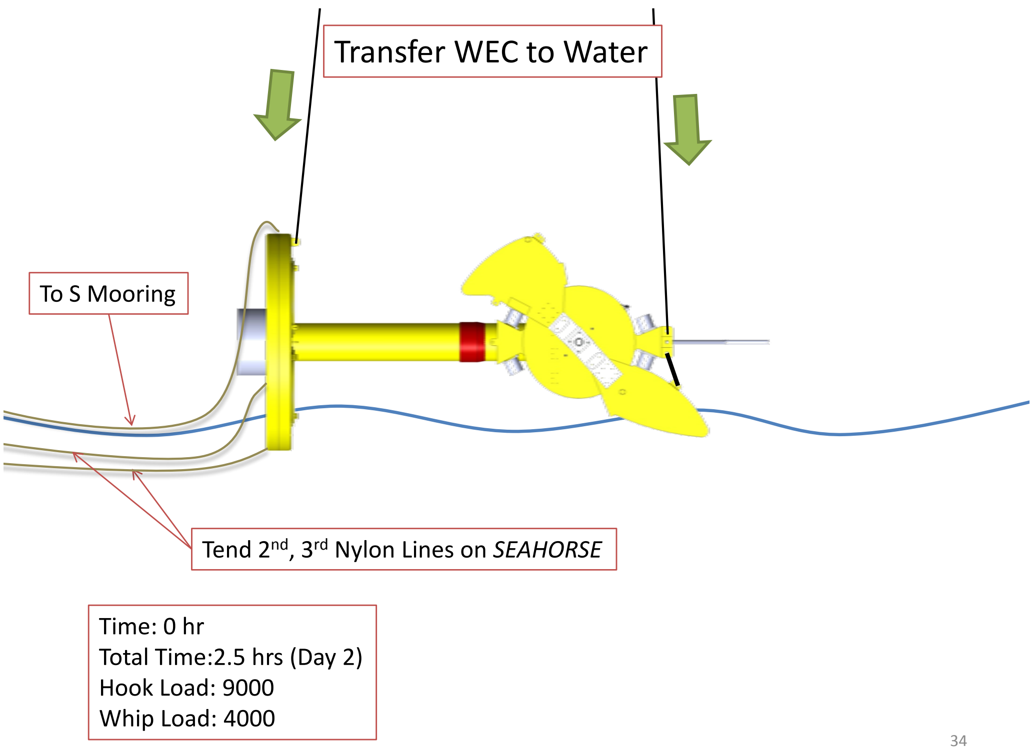


Figure 33.

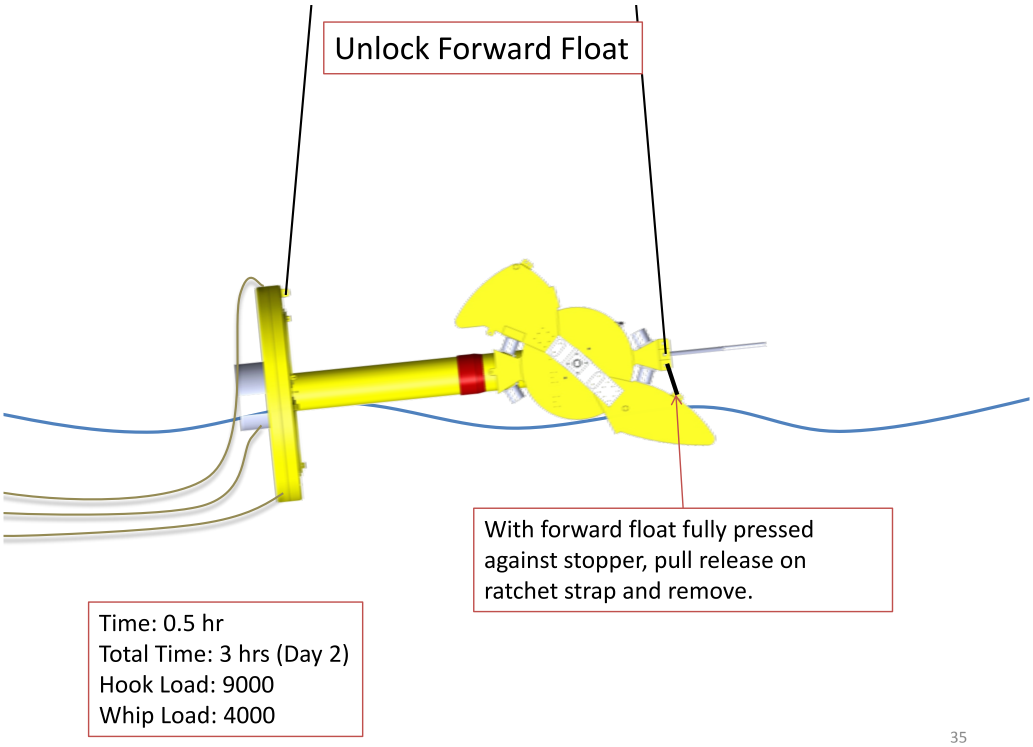


Figure 34. Unlocking the forward float. Use a skiff for this operation.

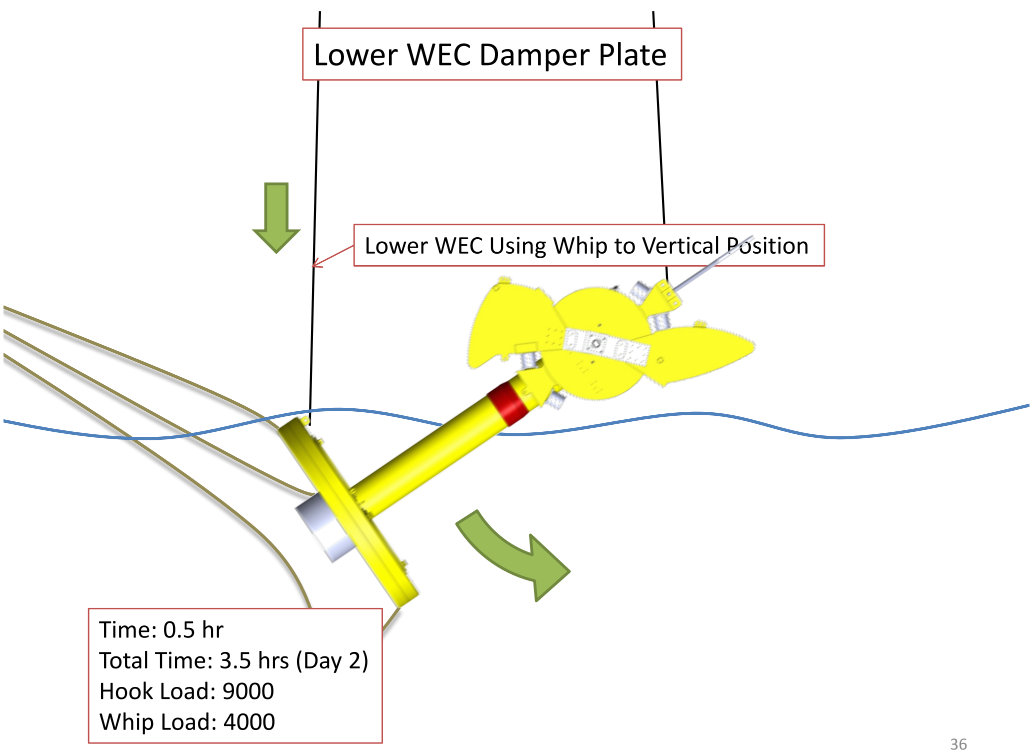


Figure 35. Begin lowering whip line.

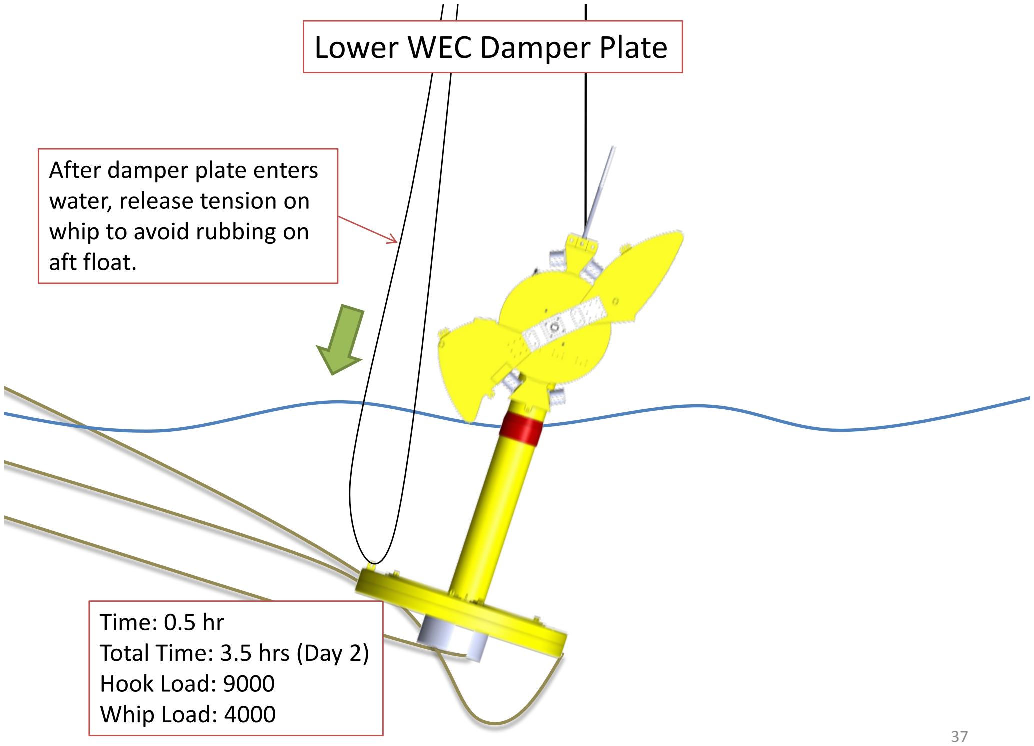


Figure 36. Relieve tension on whip line before WEC becomes vertical to avoid chafing the aft float.

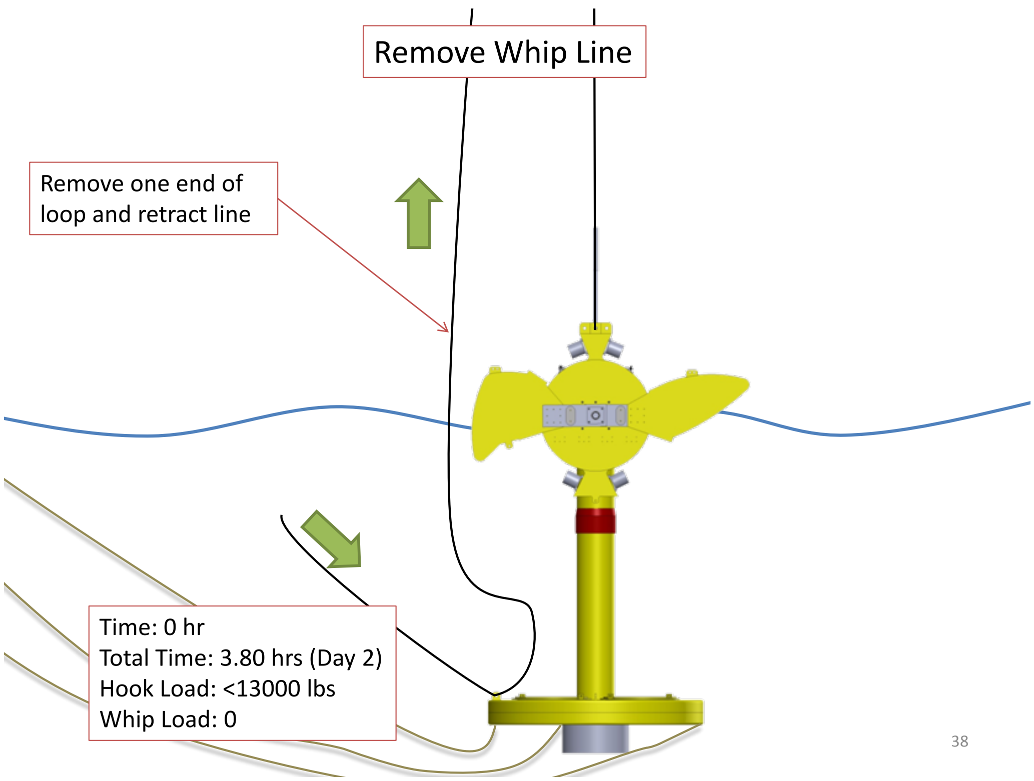


Figure 37. Remove one end of the whip loop to remove. Spectra line should allow for easy removal.

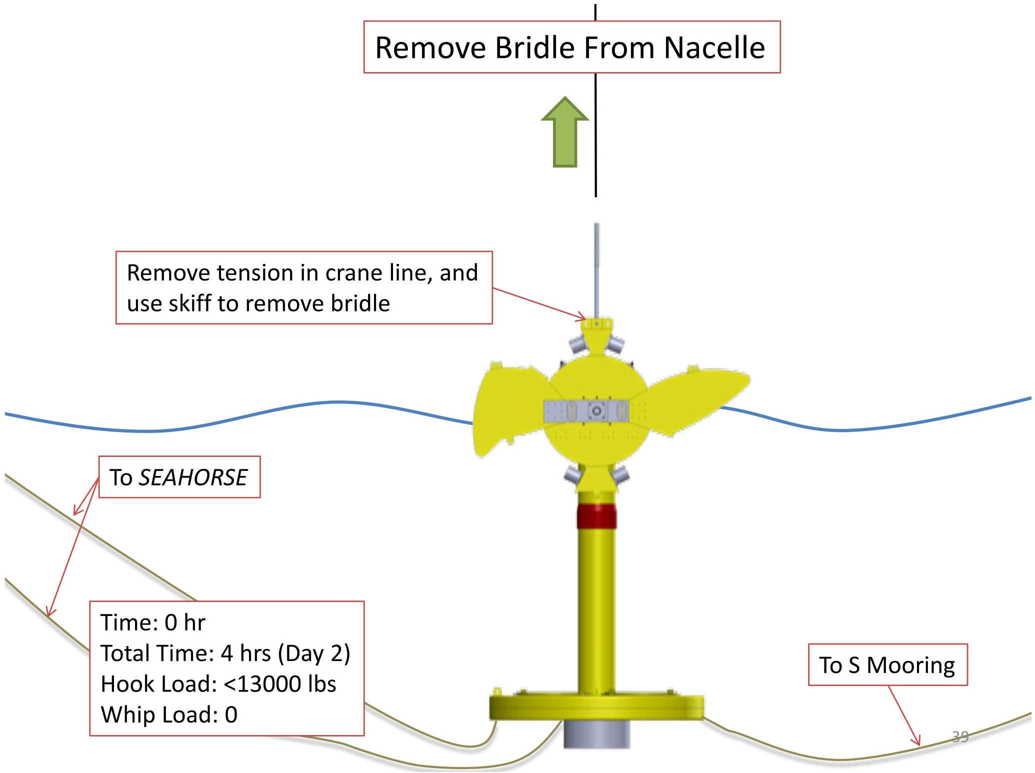


Figure 38. Use caution in the skiff to avoid tagging mooring lines or flaps, which are unlocked at this point.

5.1.6 Connecting WEC Moorings

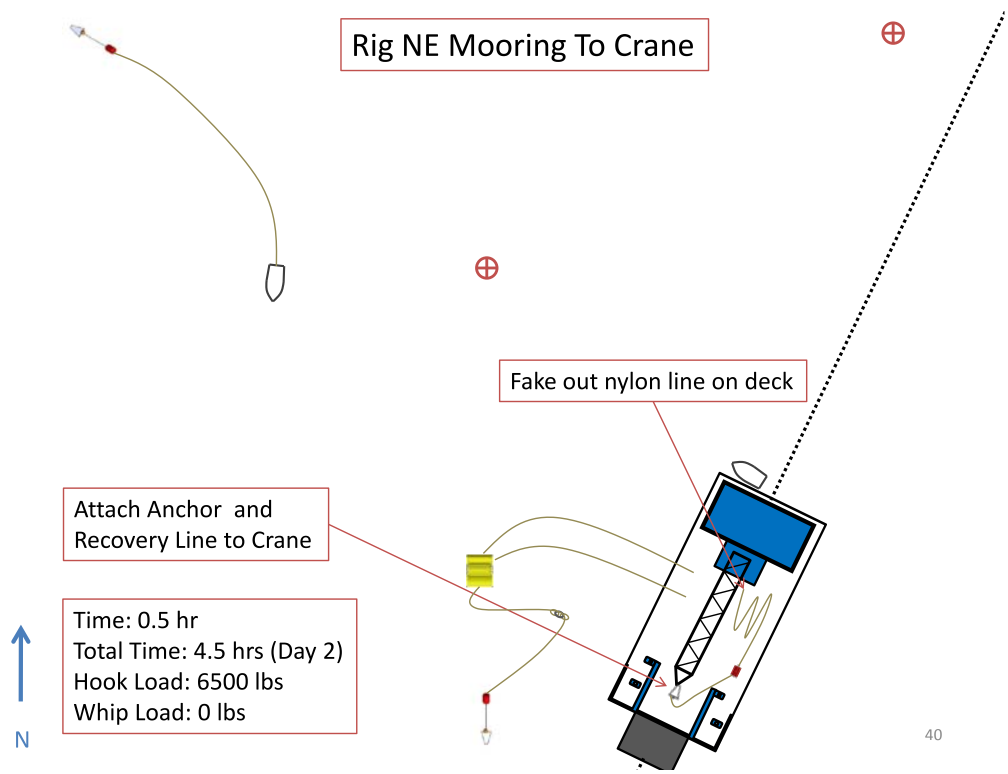


Figure 39. Rigging the NE mooring to the Crane. This step should be accomplished simultaneously with the next.

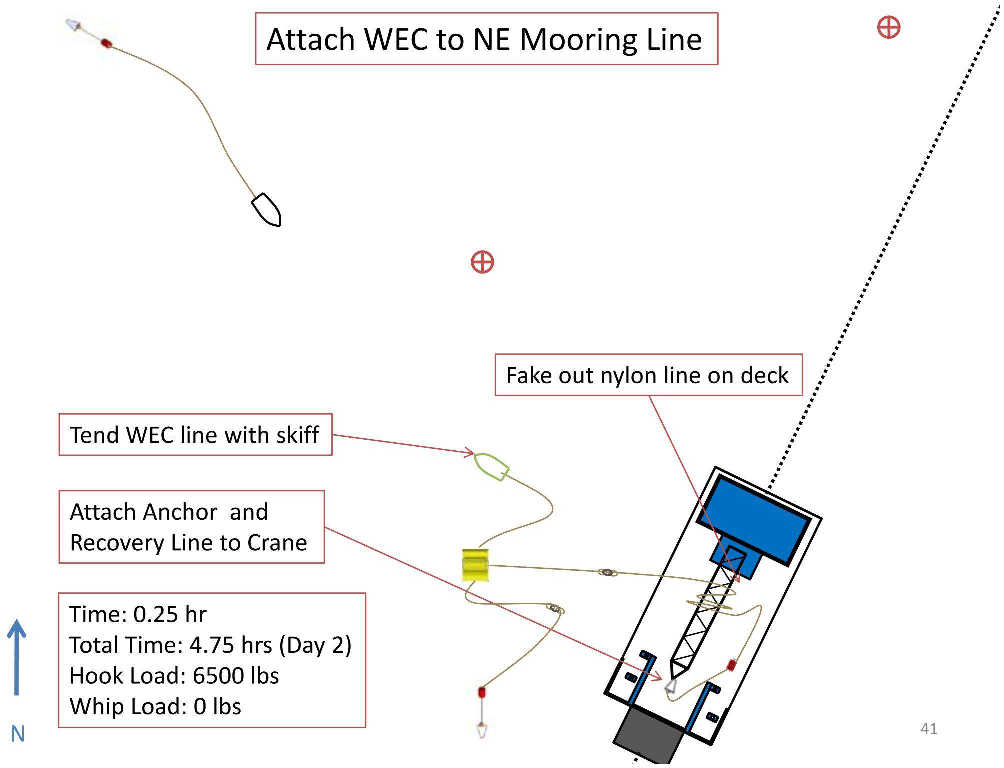


Figure 40. As soon as the NE mooring connection is accomplished on the SEAHORSE, the skiff can begin bringing the WEC towards the NW mooring.

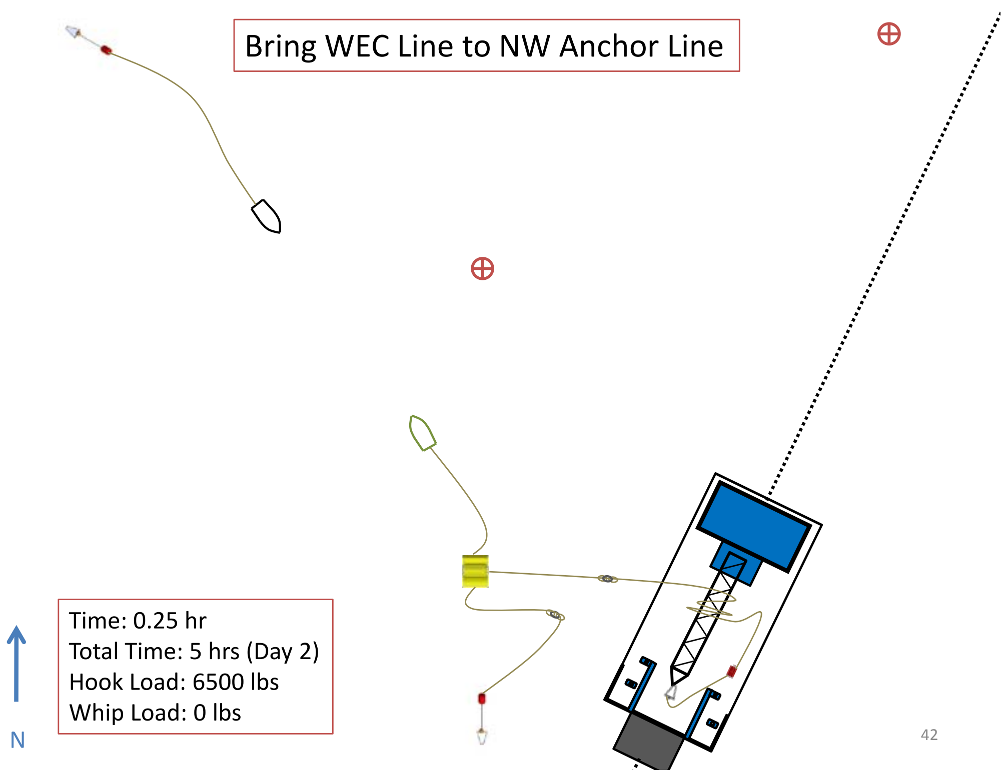


Figure 41.

5.1.7 Northeast Anchor Deployment and WEC Pretensioning

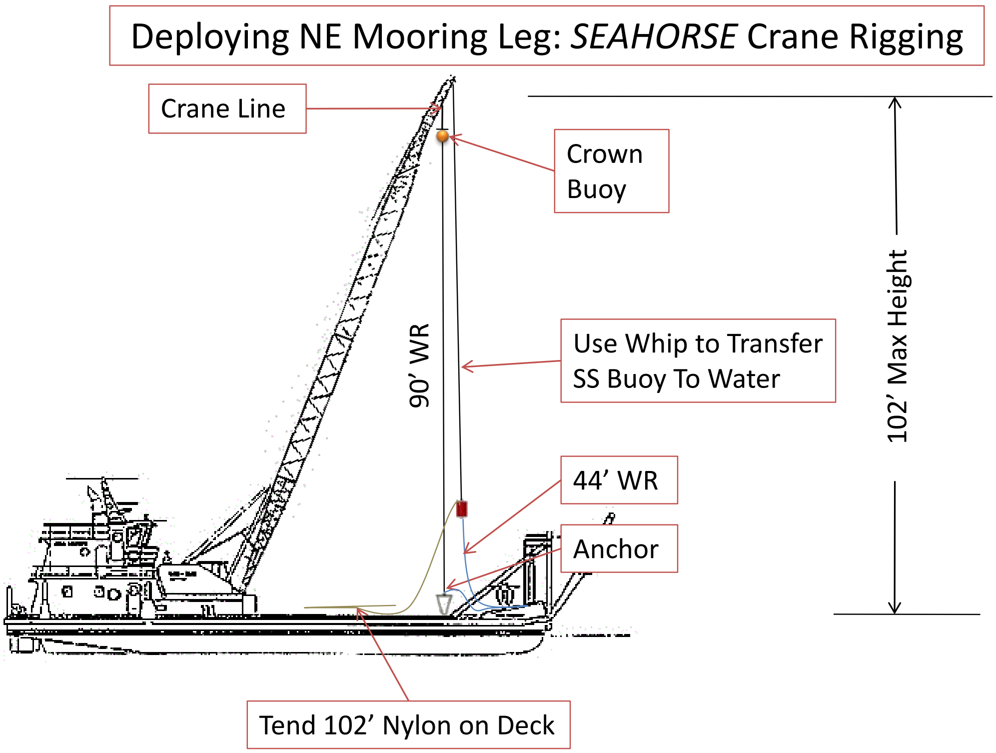


Figure 42. Rigging arrangement for NE anchor. The SS buoy can be disconnected from the whip as soon as it is over the water.

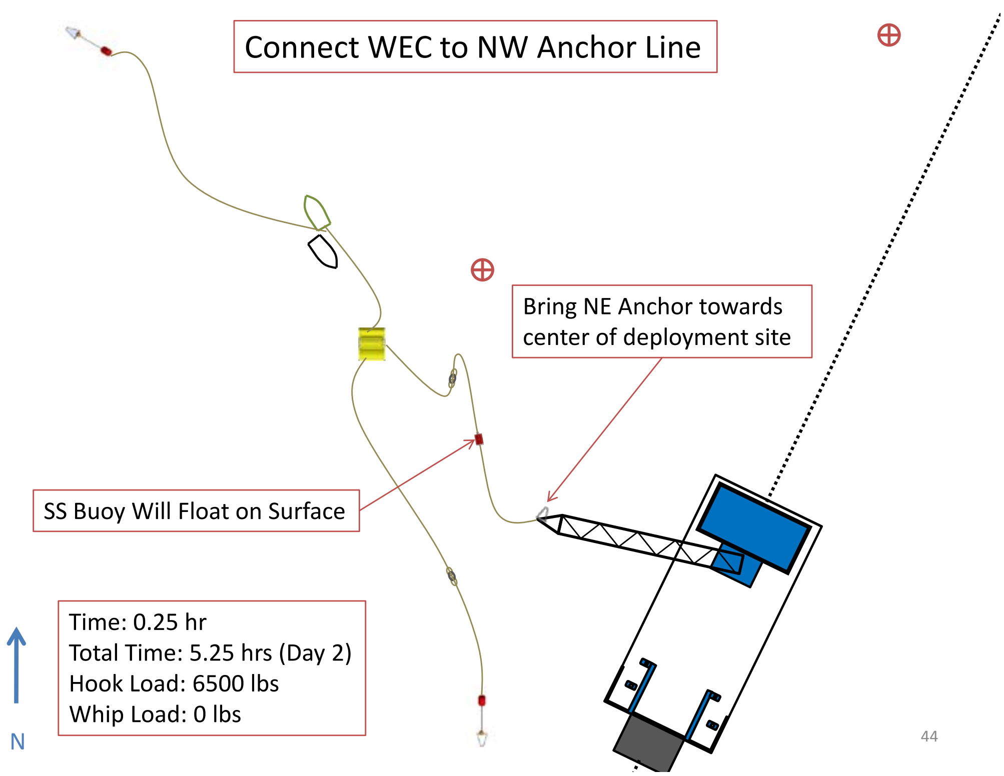


Figure 43.

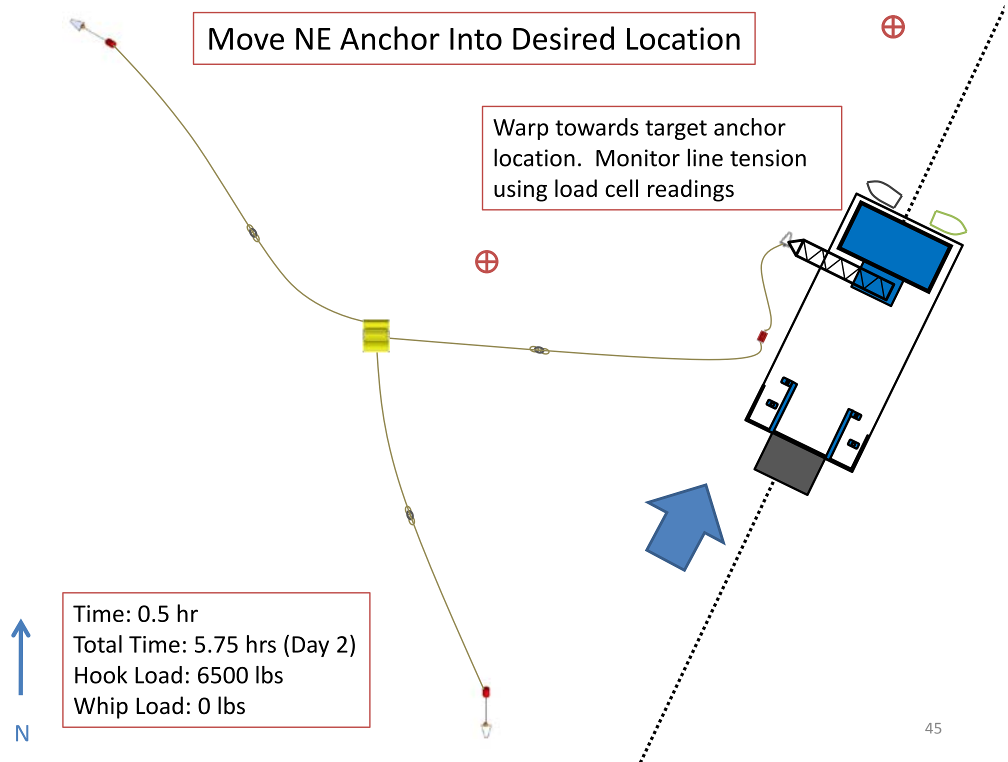


Figure 44. Note: The *SEAHORSE* crane will be at less of an angle than this to reduce side load.

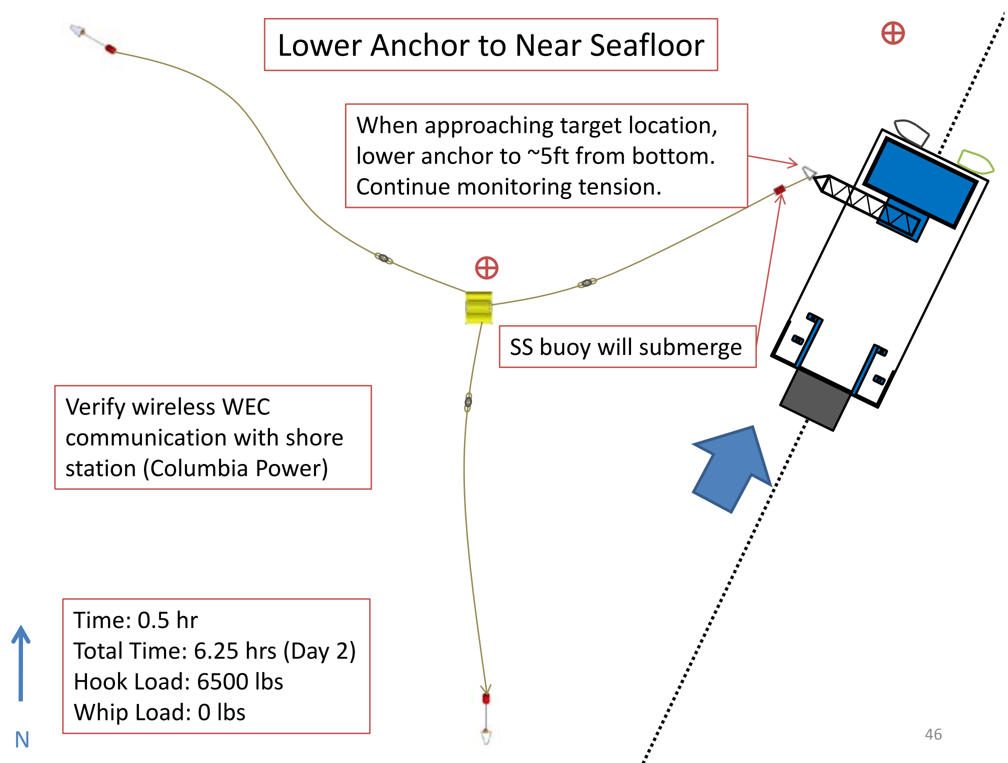


Figure 45. At this point, tension readings should begin being taken from the WEC. Keeping the anchor near the bottom will make the tension readings as realistic as possible.

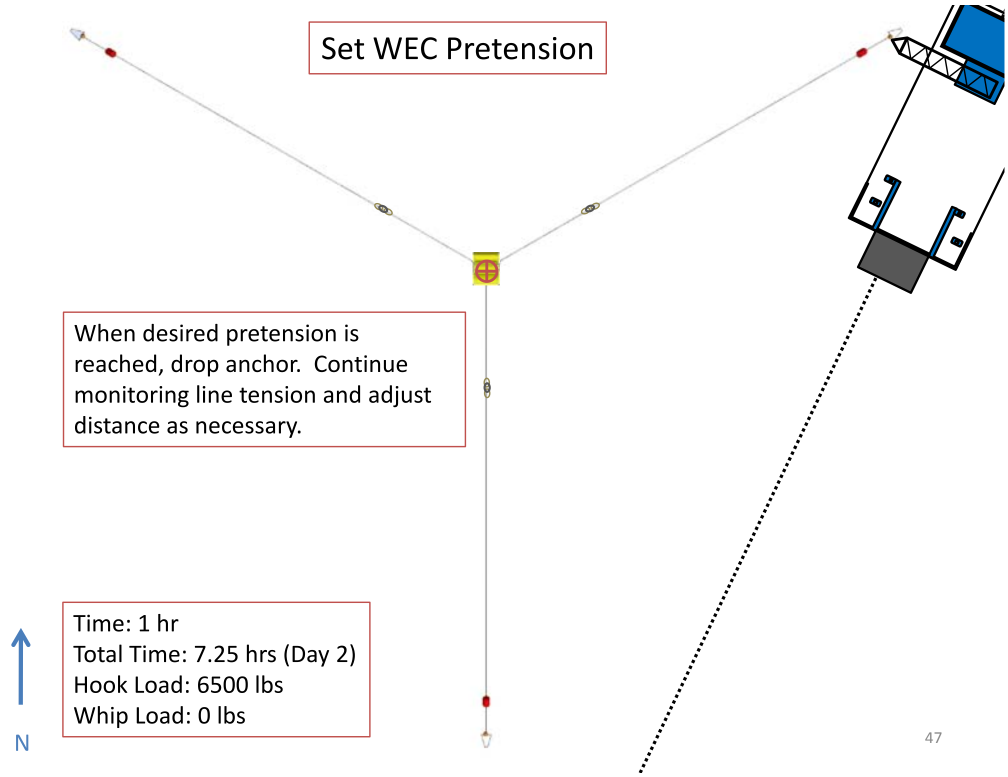


Figure 46. Set the anchor when the desired pretension is reached. (Nominally 150 lbs), refer to Glosten documentation for details.

5.1.8 Target Pretension Table

The distance in the horizontal plane from the center of the WEC to the anchor is 48.0m. If the anchor can be placed within 1.5-meter radius of the target position, then the pre-tension variation is acceptable. Pre-tension should be measured at slack tide in calm conditions (waves less than 1 foot). The following is a table of target pre-tension as a function of tide level. This allows for the measurement of pre-tension at any slack tide. Tension data will be available in real time from the WEC's tension links via a wireless 4G connection.

Table 1. Target Pretensions at Specified Tidal Conditions

Tide Level, Relative To MMLW	Target Pre Tension [Kn] For Each Line
-4	0.649
-3	0.649
-2	0.650
-1	0.651
0	0.653
1	0.655
2	0.658
3	0.660
4	0.664
5	0.667
6	0.672
7	0.676
8	0.681
9	0.686
10	0.692
11	0.698
12	0.705
13	0.711
14	0.719

5.1.9 AWAC Deployment

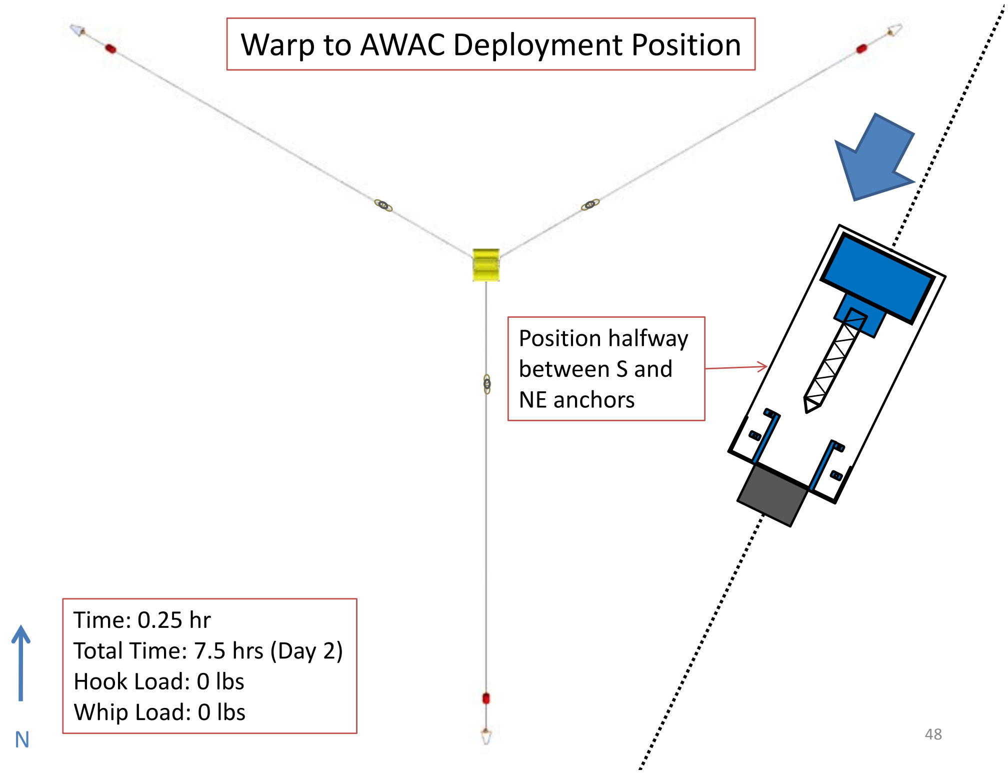


Figure 47.

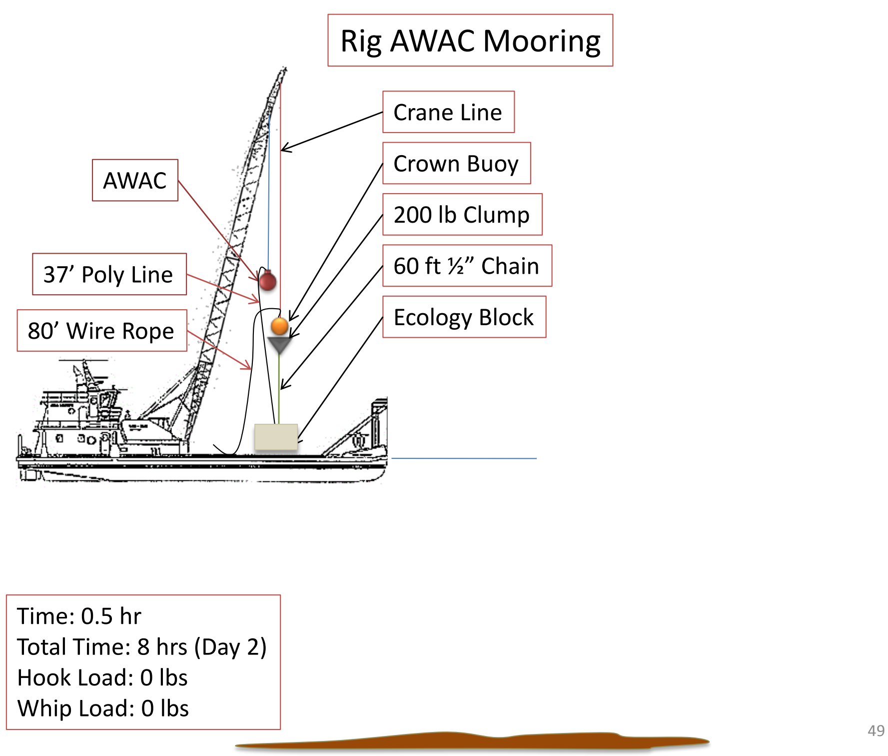


Figure 48.

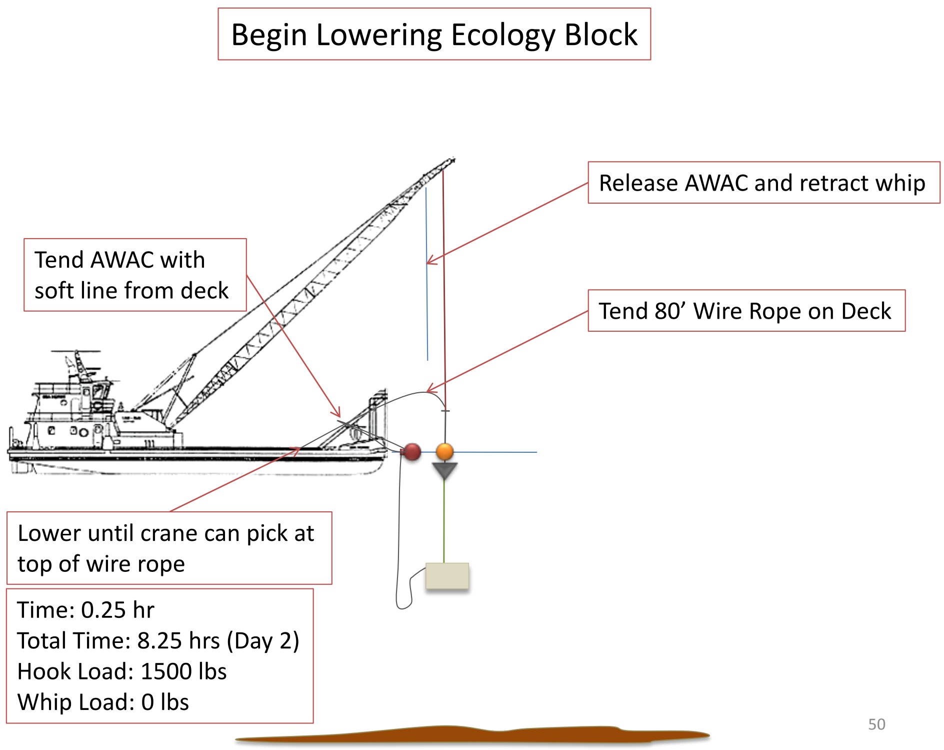


Figure 49. Release AWAC from whip and tend with soft line loop from deck.

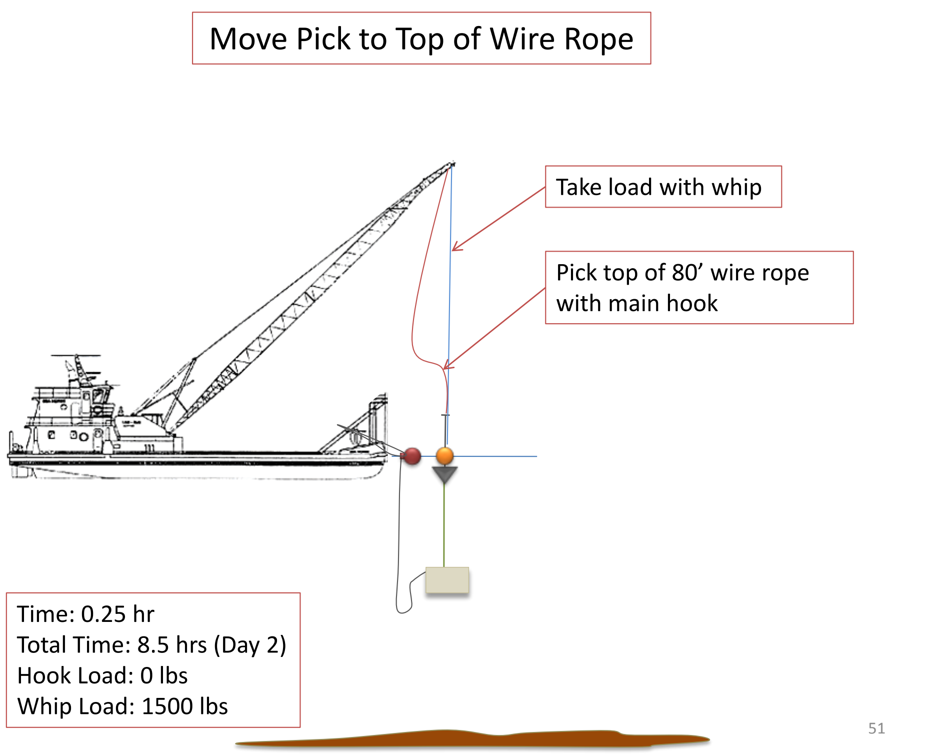


Figure 50. Since this mooring arrangement is in total longer than the SEAHORSE crane is tall, it will be necessary to “repick” it while lowering. This can be accomplished by taking the load with the whip. Since the load is small, the anchors can be lowered using the whip from that point onwards.

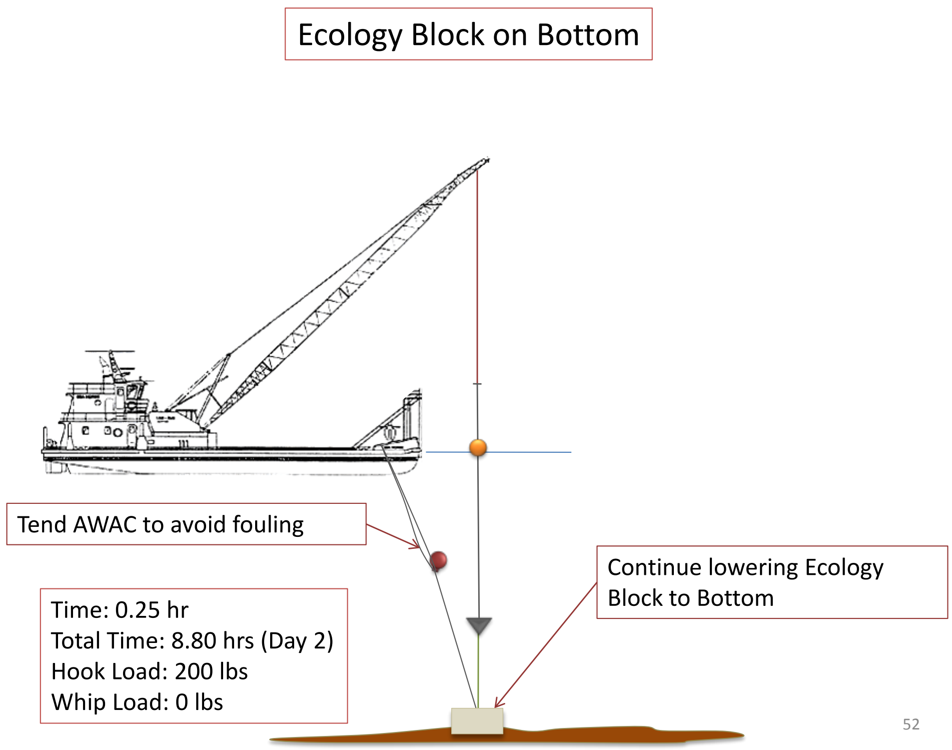


Figure 51.

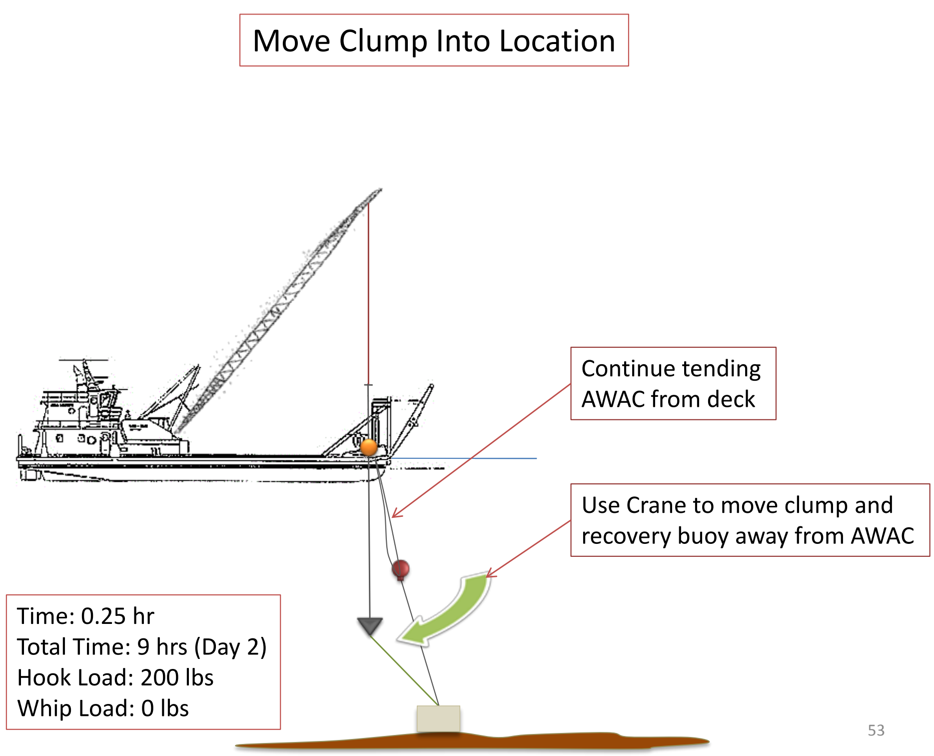


Figure 52. The clump can be moved into position by rotating the crane.

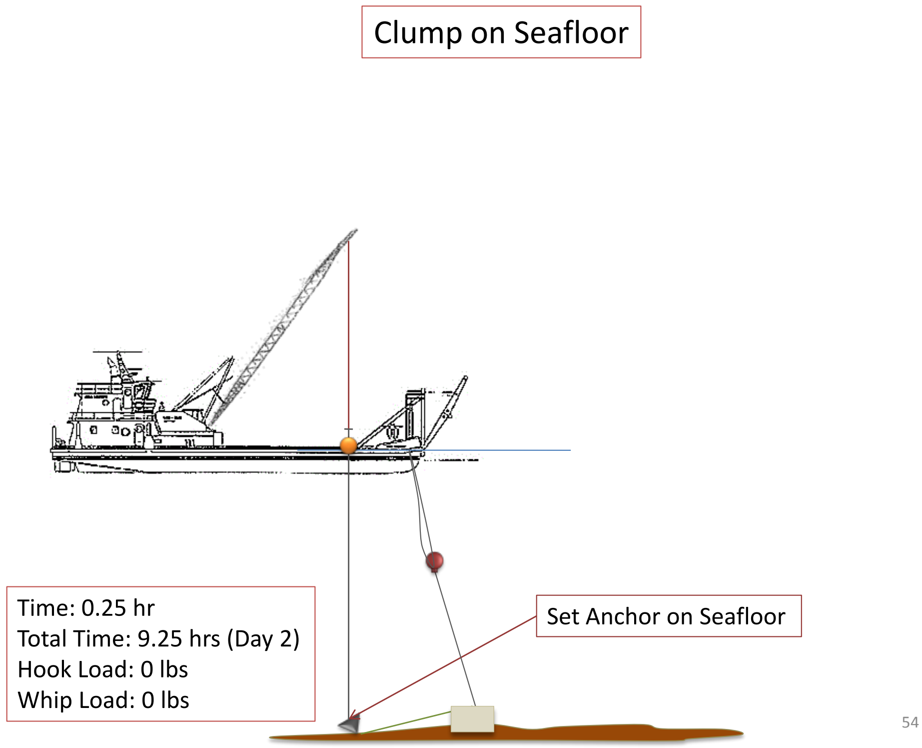


Figure 53. The clump should be lowered when the crane line starts tending off of vertical.

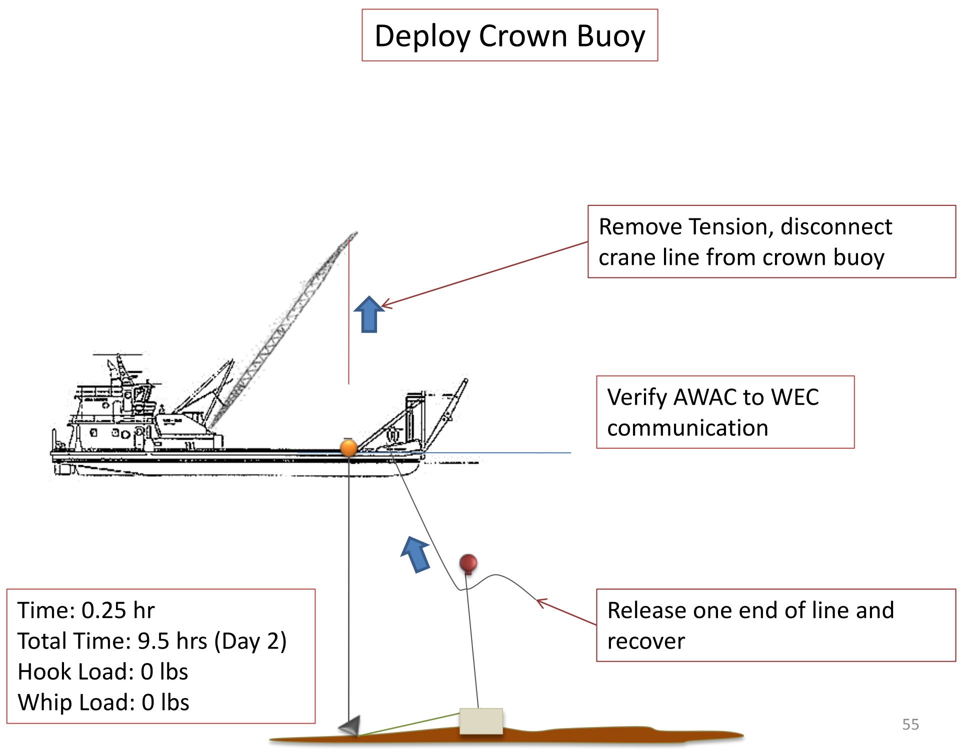


Figure 54. Crown buoy will be secured to recovery line using wire rope clamps and donut plate.

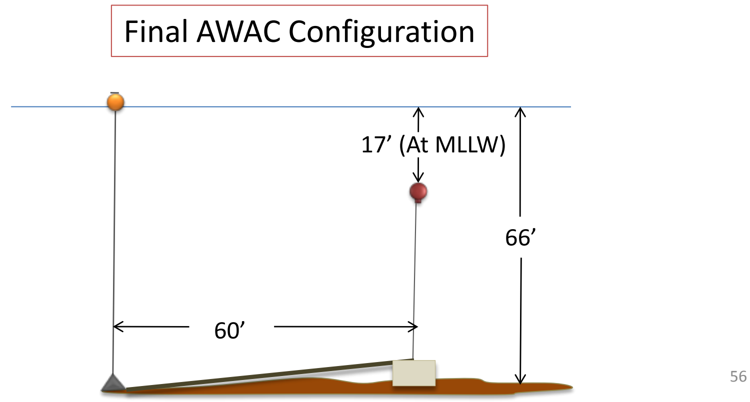


Figure 55. Final AWAC/subsurface buoy configuration. Max crown buoy watch circle: 48'.

5.1.10 Final Steps and Return Trip

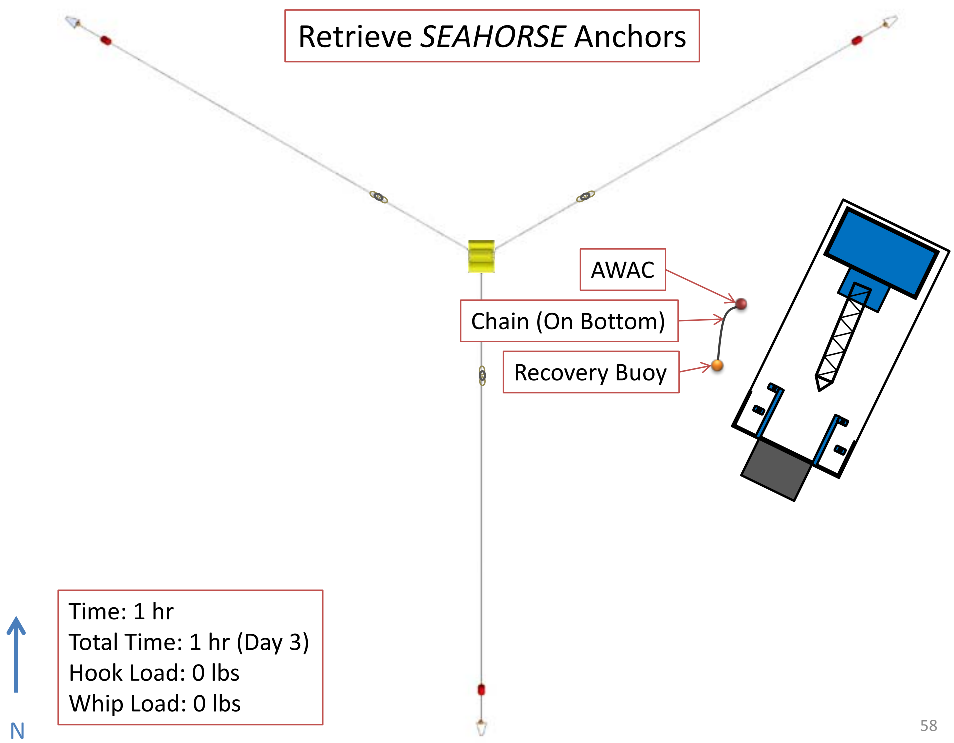
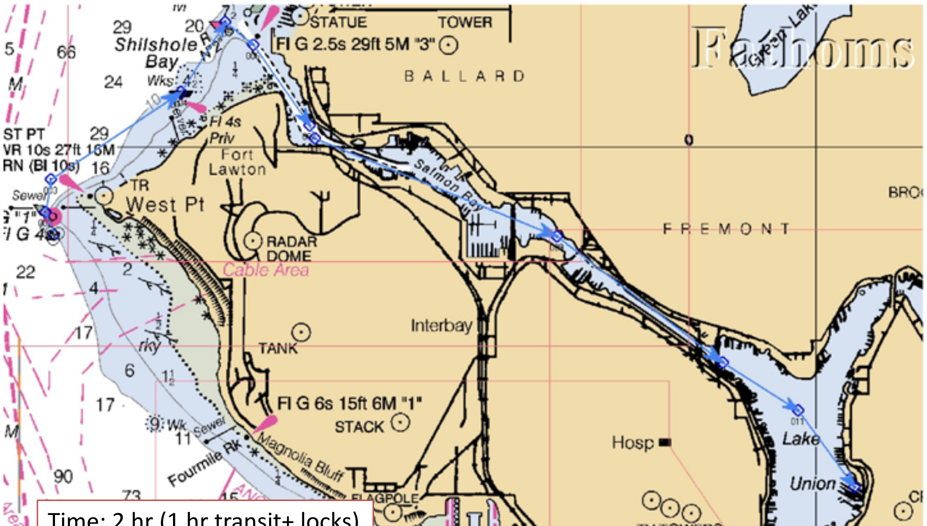


Figure 56. Remove *SEAHORSE* bow and stern anchors.

SEAHORSE Transit to Lake Union Dry Dock



Time: 2 hr (1 hr transit+ locks)
Total Time: 3 hrs (Day 3)
Hook Load: 0 lbs
Whip Load: 0 lbs

59

Figure 57. Return to Lake Union Dry Dock. (Seahorse mooring location).

6.0 Demobilization

Demobilization will occur at Lake Union Dry Dock. Arrangements will be made ahead of time to have a flatbed ready to remove the cradle and any other gear from the *SEAHORSE* and move them to a storage location, TBD.

Demobilize *SEAHORSE* At Lake Union Dry Dock

Time: 4 hrs
Total Time: 7 hrs (Day 3)
Hook Load: 0 lbs
Whip Load: 0 lbs

60

Figure 58. Lake Union Dry Dock can accommodate a truck for cradle transport.

7.0 Maintenance

7.1 Overview

For the first week of deployment, the WEC will be inspected using the *RV Neper* daily. From then on, the WEC will be inspected using the *RV Neper* every two weeks, during which charging of the WEC's batteries will take place. Maintenance trips will occur more or less frequently as is deemed necessary. Daily shore-based inspections will be performed by Sam Gooch of SST if deemed necessary. Boat operations will be provided by Gordon Roberts of Sound Support Marine, with support from Sam Gooch and/or Carl Gowler of SST.

7.2 Daily Inspection Checklist

The following points will be visually inspected from shore on a daily basis.

- WEC level: Inspect the level the WEC is floating at in the water. A change of more than 2 cm is considered abnormal and should be reported immediately.
- Damage: Check for damage from floating debris, boats, waves, etc.
- Mooring: Is the WEC in the correct position? Can all of the crown buoys still be seen, and are they in the correct positions? Changing positions could indicate anchor movement and should be reported immediately.
- Navigation Lights: Are the lights functioning? Are they being obstructed by guano or debris?
- Biofouling: Is significant biofouling present? Is it impeding the functioning of the WEC?

7.3 At Sea Maintenance

The maintenance boat will be moored at Brichard-Agee Dry Storage, near the Ballard Locks. For maintenance trips, the vessel will be trailered to the Shilshole Marina Boat Launch, shown in Figure 59. From the marina, it is <15 minutes by boat to the deployment site. TBD employees from CPT and Sam Gooch and/or Carl Gowler from SST will be present for at-sea maintenance trips.

7.3.1 Transit

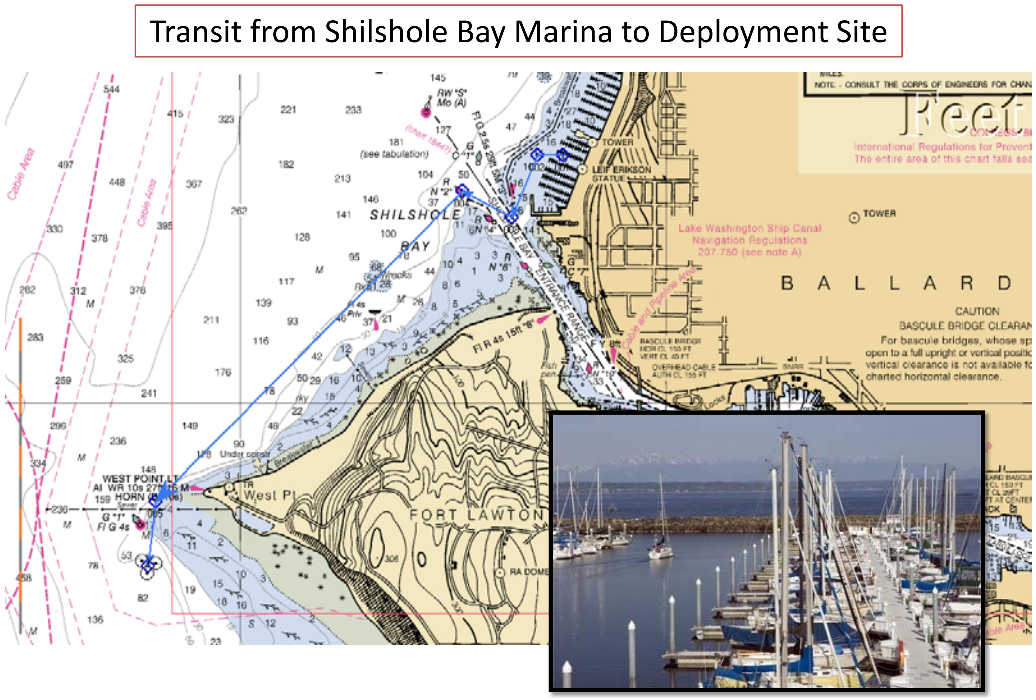


Figure 59. Transit route for maintenance.

7.3.2 Preparing for Maintenance Operations

While the exact procedure for tying off the maintenance vessel to the WEC is TBD, it will likely consist of the use of a slip line off the bow through a pad-eye on the buoy. This method allows static adjustment of the vessel to buoy separation, mooring and positioning assistance using the vessel engines, and a rapid method to break moorage in case of emergency. Some guidelines for safety and operations during the charging procedure:

- Don’t moor directly to the WEC while charging batteries. The WEC and vessel will have different responses to the wave climate which could cause collision and damage to either.
- Use the fender board arrangement in making up to the WEC during power connection/disconnection. The fender arrangement is shown in Figure 60.
- After hooking up the power cable slip the mooring, heave to using a bow line.
- Moor on the lee side of the WEC with bow into the seas.
- Plan on charging batteries during max flood or ebb currents to maximize standoff between the vessel and the WEC.
- Charge at shorter intervals vs. longer (2x4 hr vs. 1x8 hr.).
- Don’t rule out charging after dark if conditions are preferred.

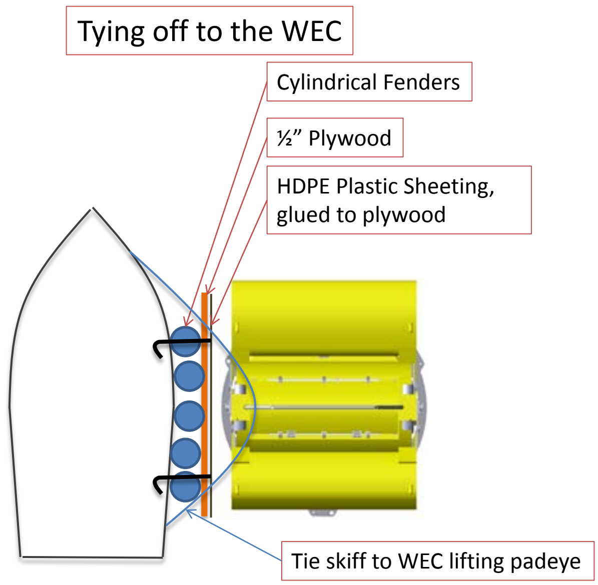


Figure 60. Vessel fendering arrangement. Only to be used for the initial connection of the WEC charging cord(s).

7.3.3 Maintenance Operations

The same points provided in the from-shore checklist will be inspected from the boat. Each maintenance trip will take approximately 8 hours, which is required to charge the WEC's batteries. Additionally, the maintenance and servicing procedures provided by CPT will be carried out.

8.0 Recovery

8.1 Mobilization

The recovery procedure is similar to the deployment procedure, with events happen in roughly the reverse order. Recovery will be a faster procedure as there is no need for precise anchor setting, pretensioning, or anchor setting on the *SEAHORSE*. It should be possible to complete all recovery operations in one working day. Mobilization for recovery will occur at the Lake Union Dry dock, where the *SEAHORSE* is moored. The cradle and will be brought down by truck from TBD storage location and loaded onto the vessel.

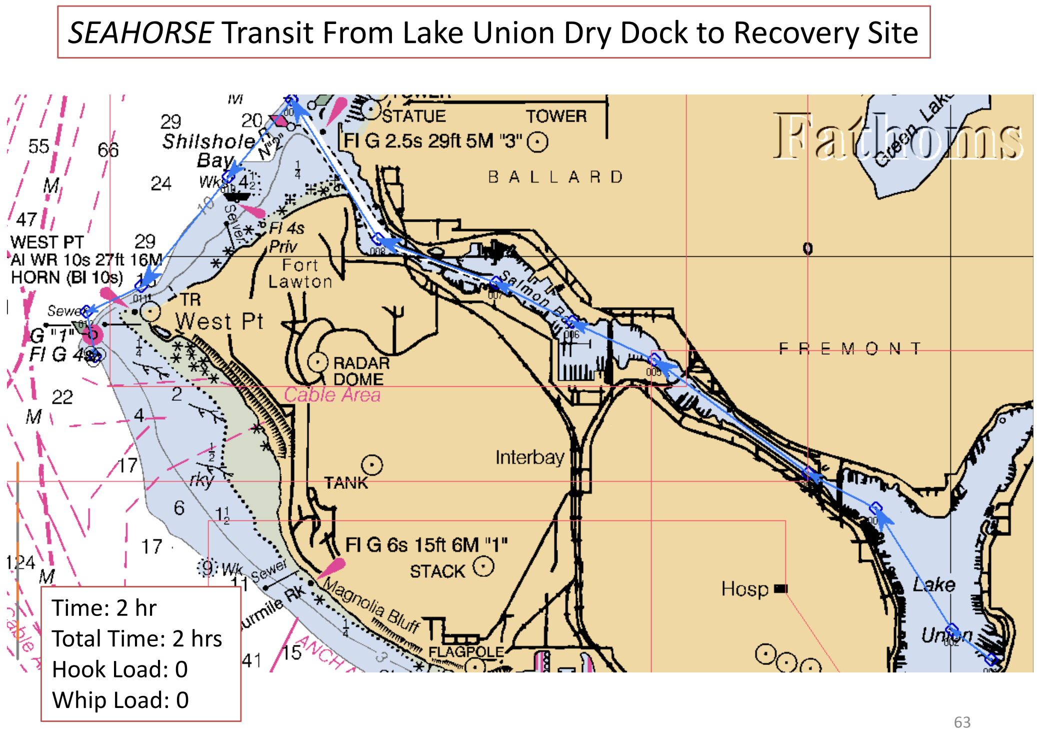


Figure 61.

8.2 AWAC Recovery

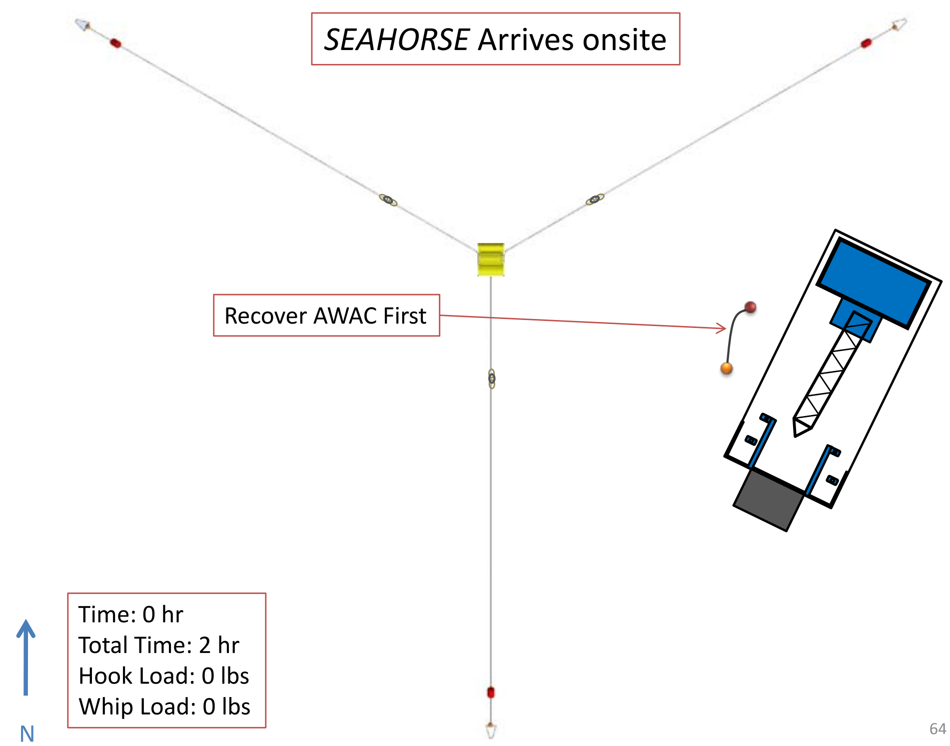


Figure 62. The first recovery step will be removing the AWAC. This will prevent the lines from getting fouled in the mooring when it is being removed.

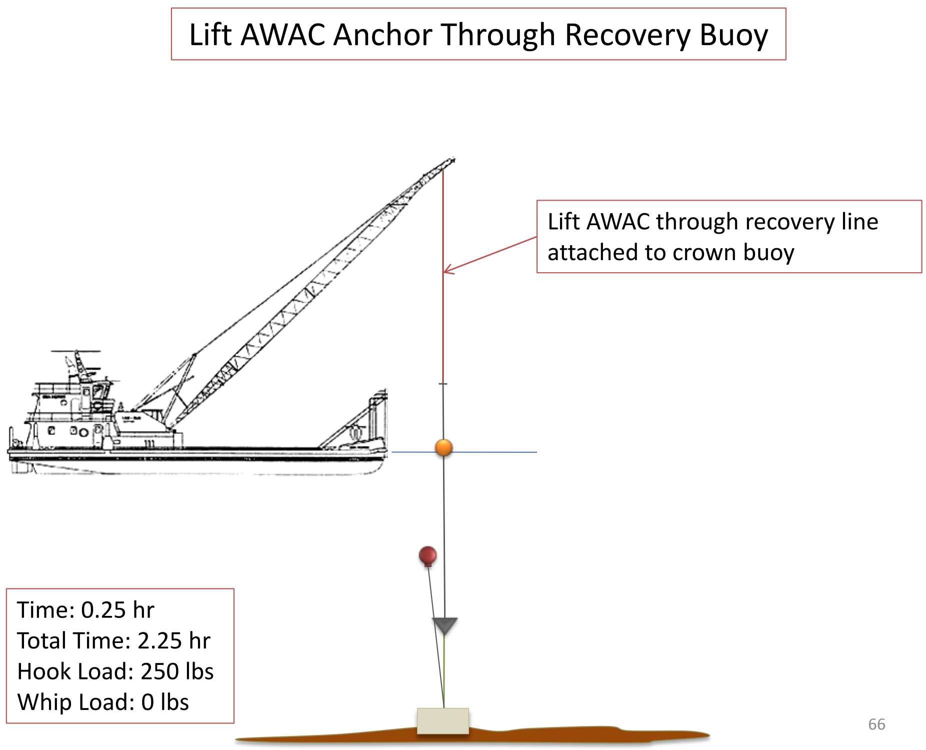


Figure 63. Lifting AWAC mooring through recovery buoy and chain (connecting clump and RR wheel anchor)

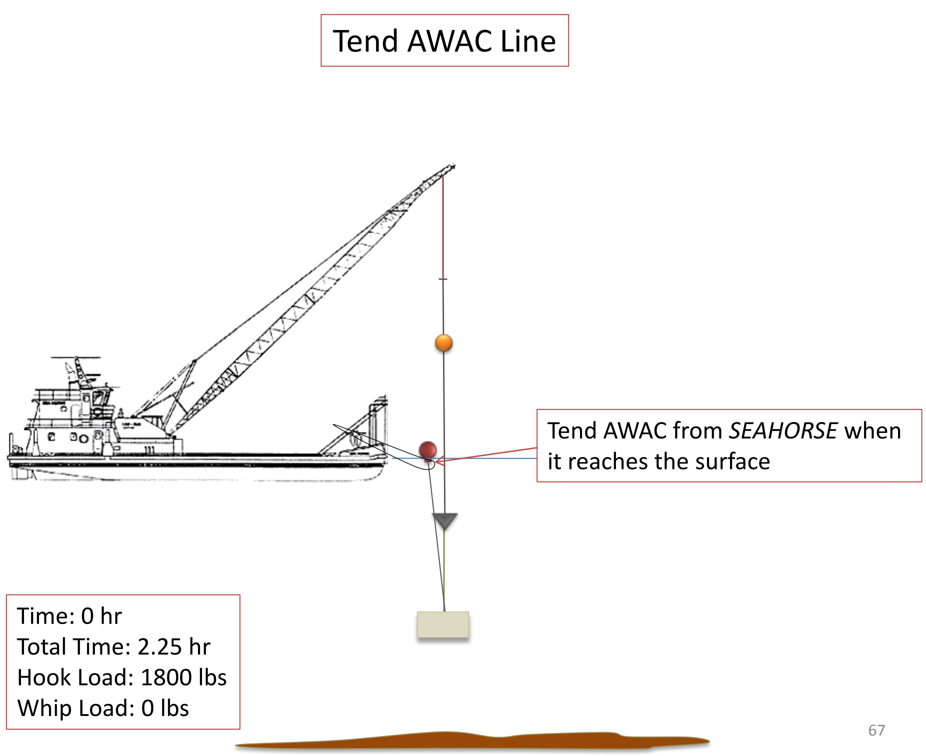


Figure 64. Tend the AWAC from the deck using a tagline. The AWAC will come onboard after the anchors.

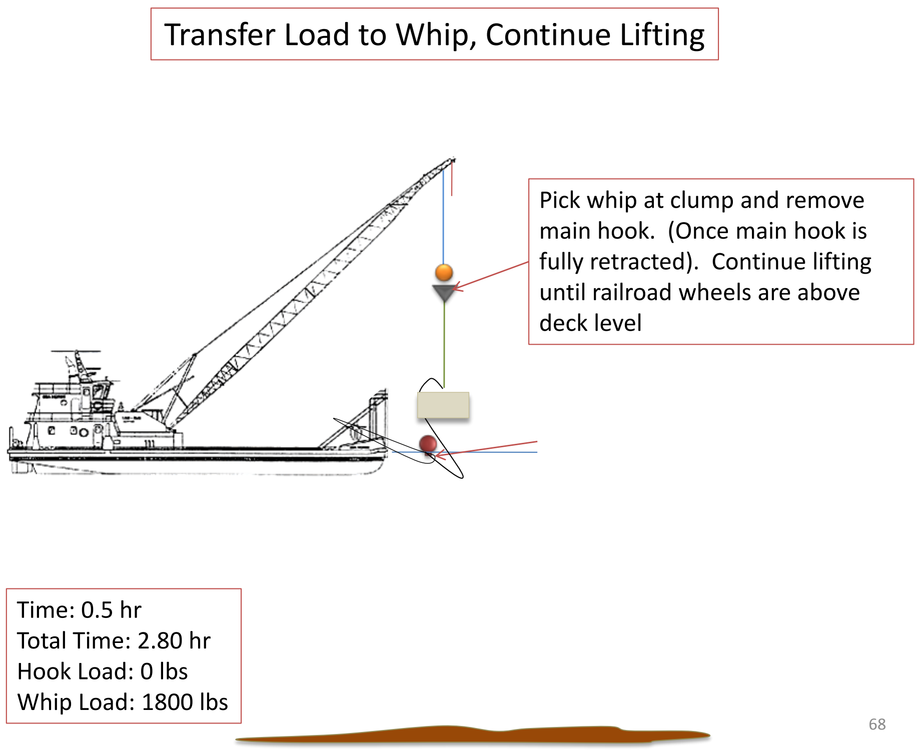


Figure 65. As in the installation, since the height of the crane is less than the length of the AWAC mooring (including the 40' chain), the load must be transferred to the whip when the crane hook reaches the top of its range of travel. The load can then continue to be lifted with the whip.

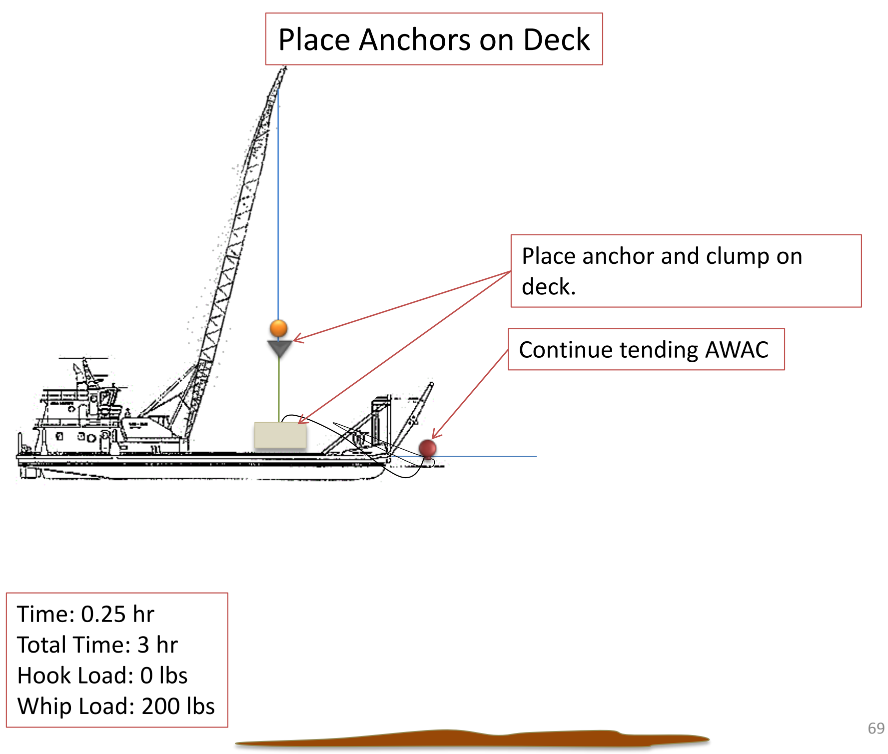


Figure 66.

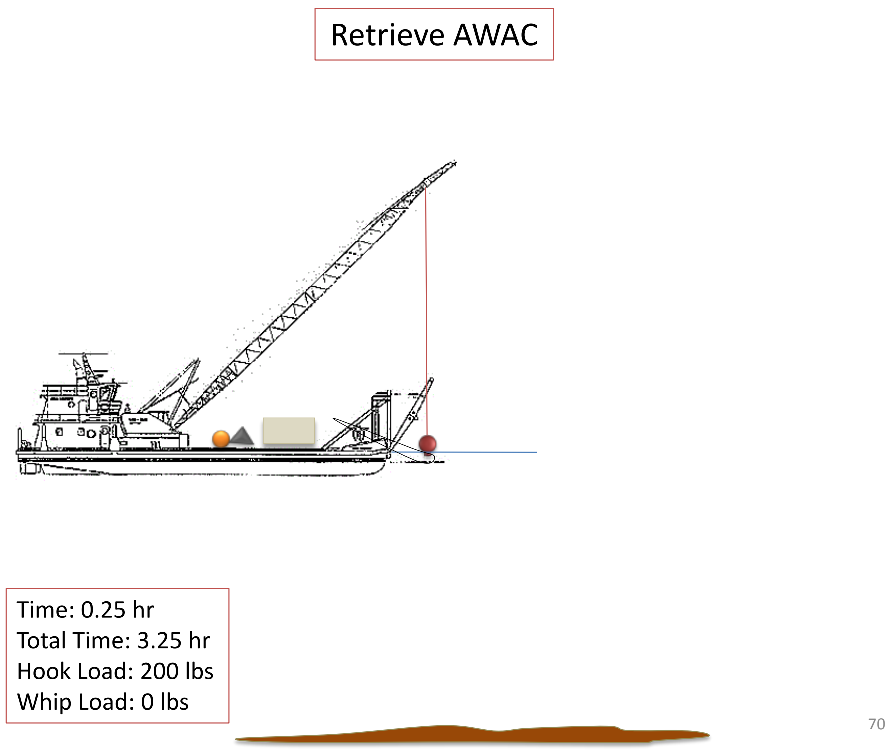


Figure 67. Use the whip or crane to lift the AWAC on deck. The existing loop can be used as a tagline.

8.3 WEC Recovery

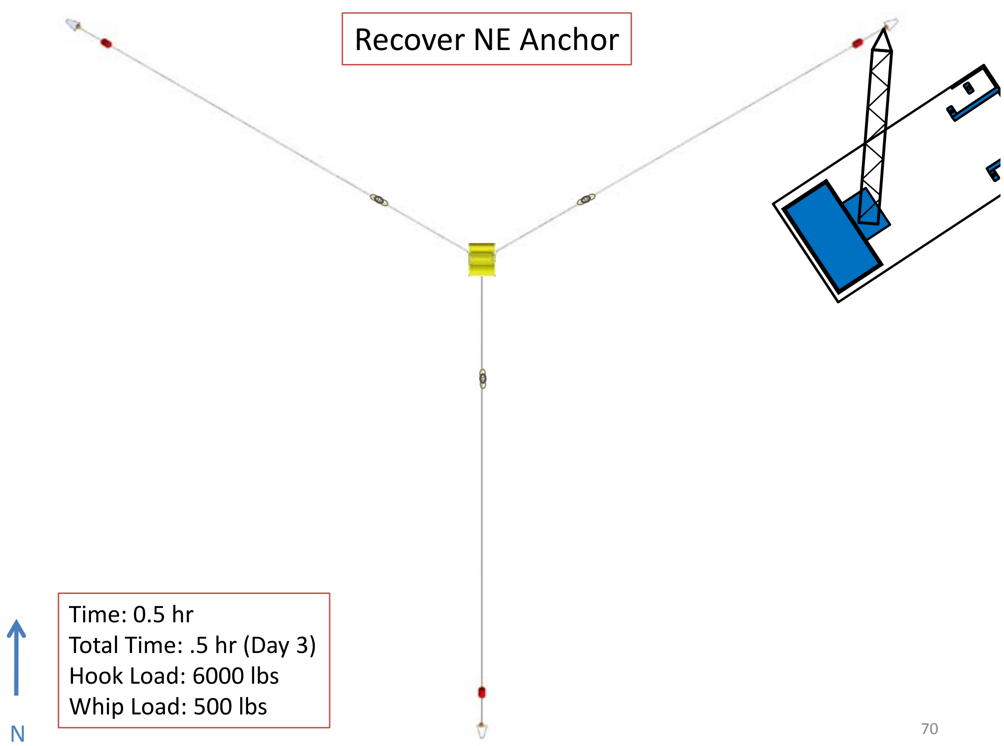


Figure 68. First step in the WEC mooring recovery process.

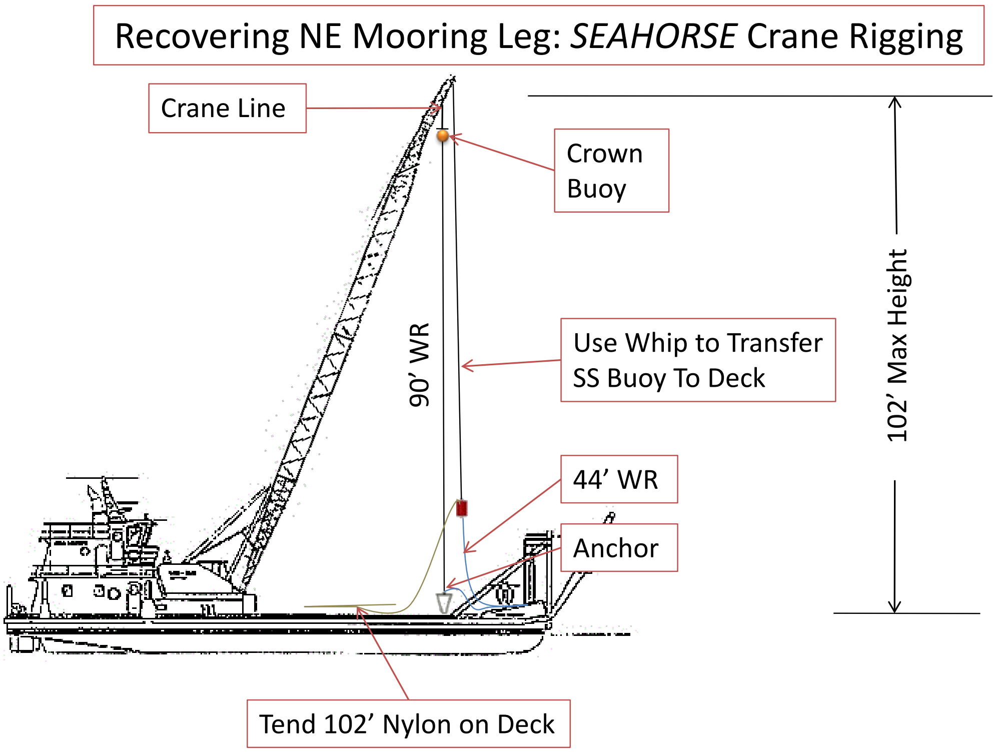


Figure 69. Note that the SS buoy can be brought onboard separately after the anchor is recovered.

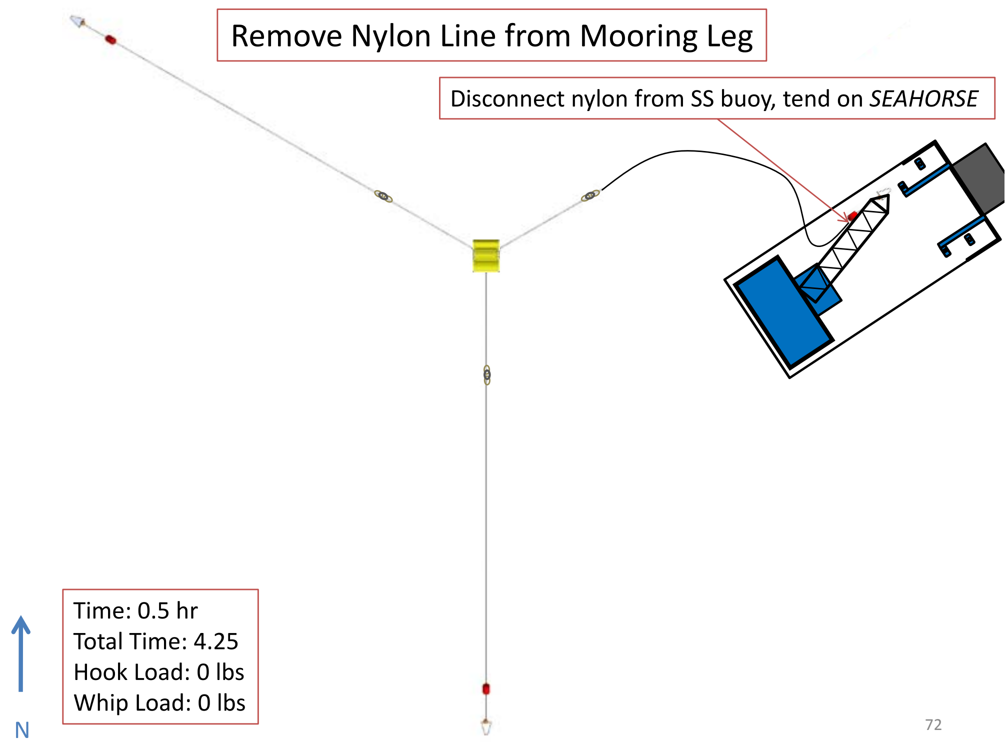


Figure 70. The nylon leading to the WEC will be used as a tagline in the next step.

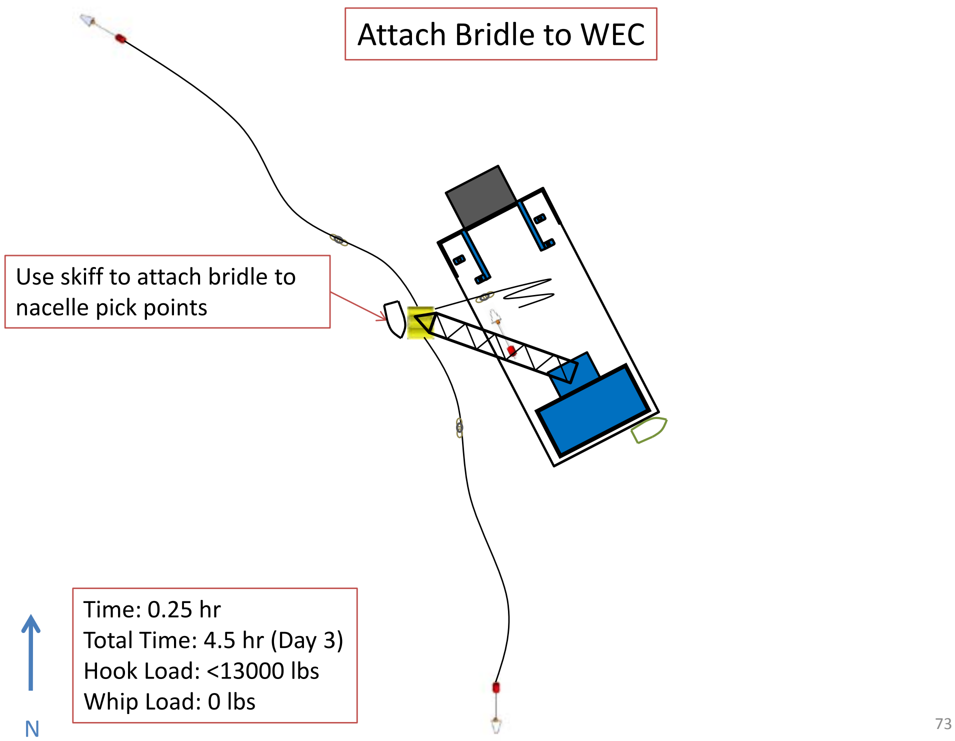


Figure 71.

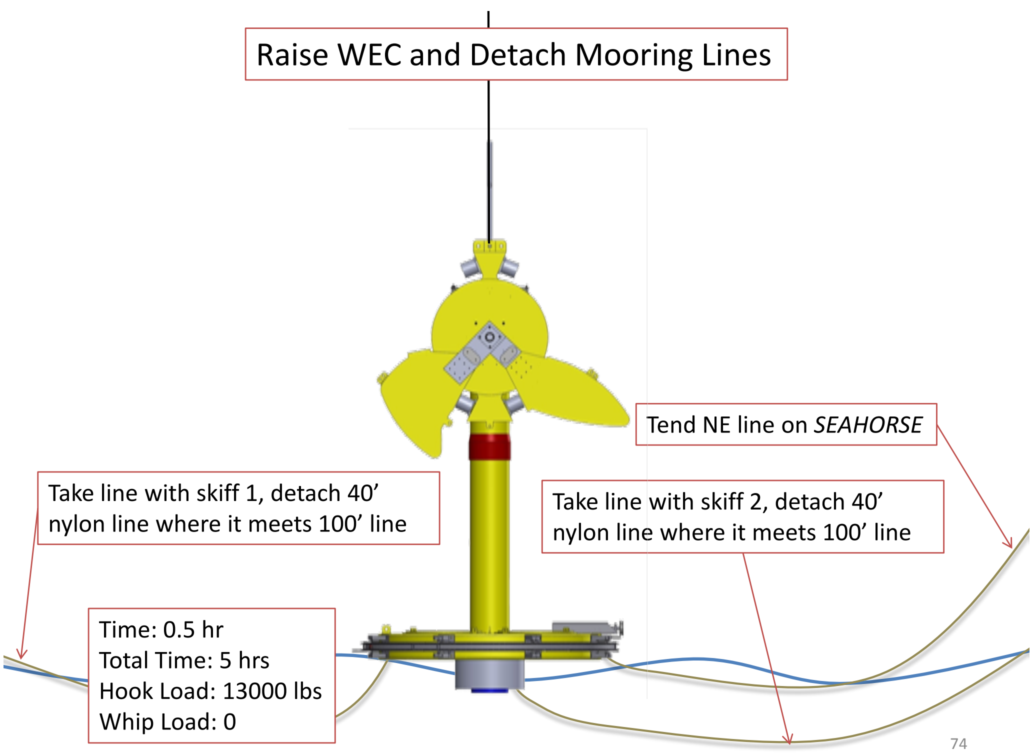


Figure 72. Disconnecting the WEC from the remaining two mooring legs.

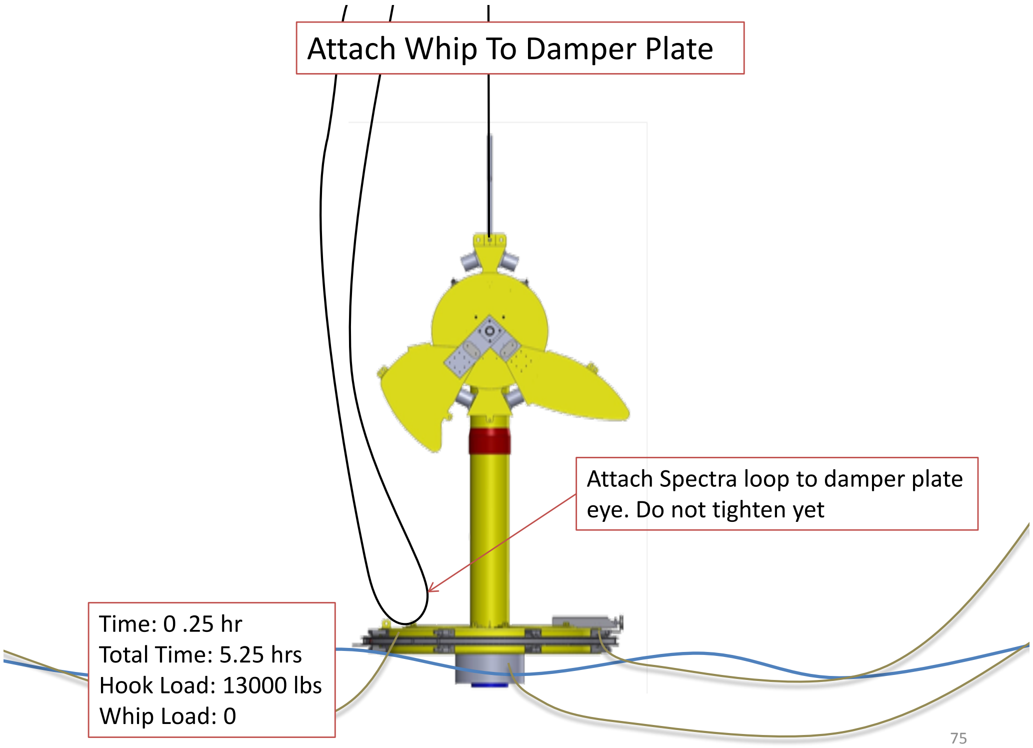


Figure 73.

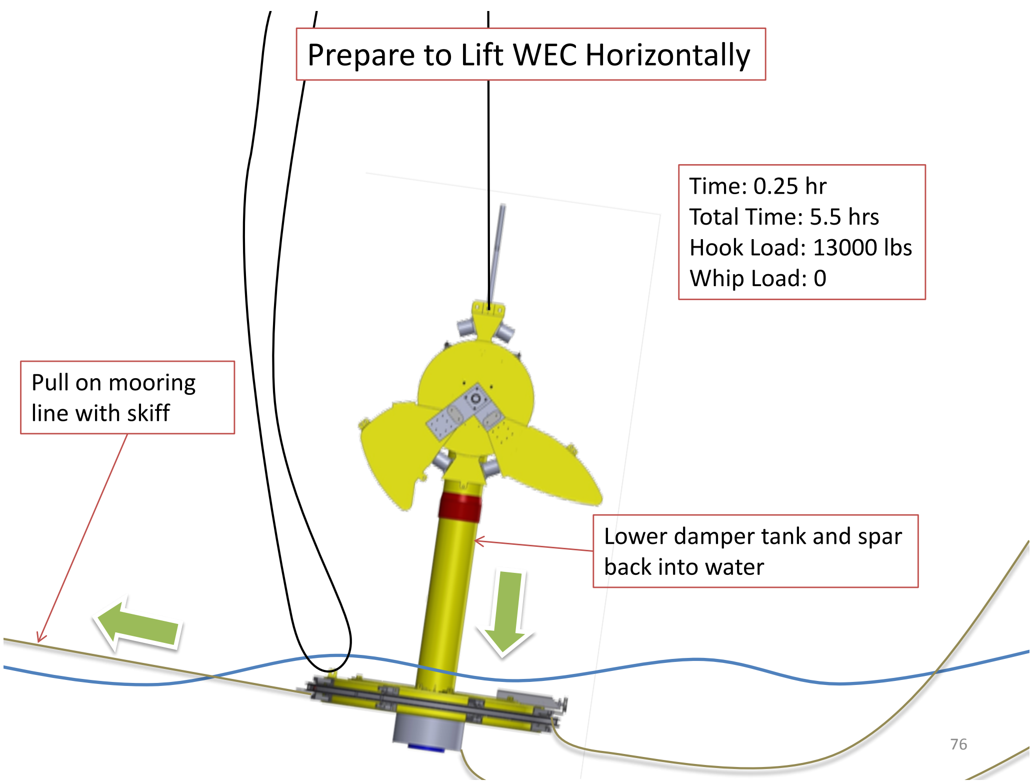


Figure 74. By lowering the WEC partially into the water and pulling on one side with the skiff, the WEC will be brought slightly off vertical. The whip (damper plate) line can then be tensioned without contacting the aft float.

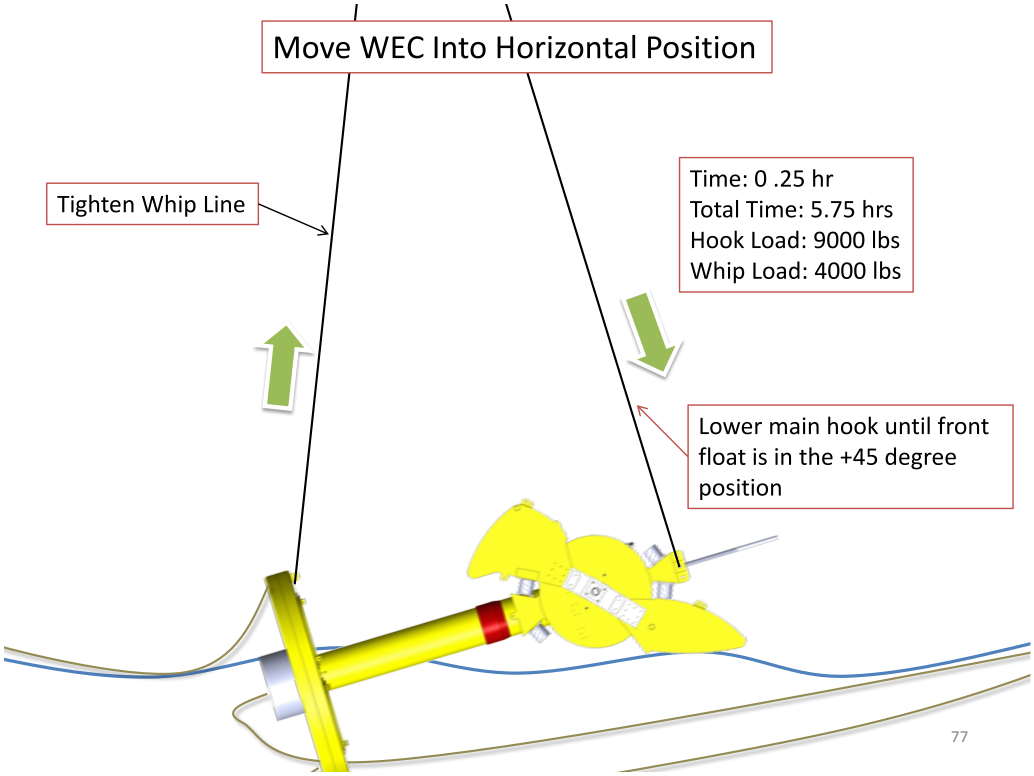


Figure 75.

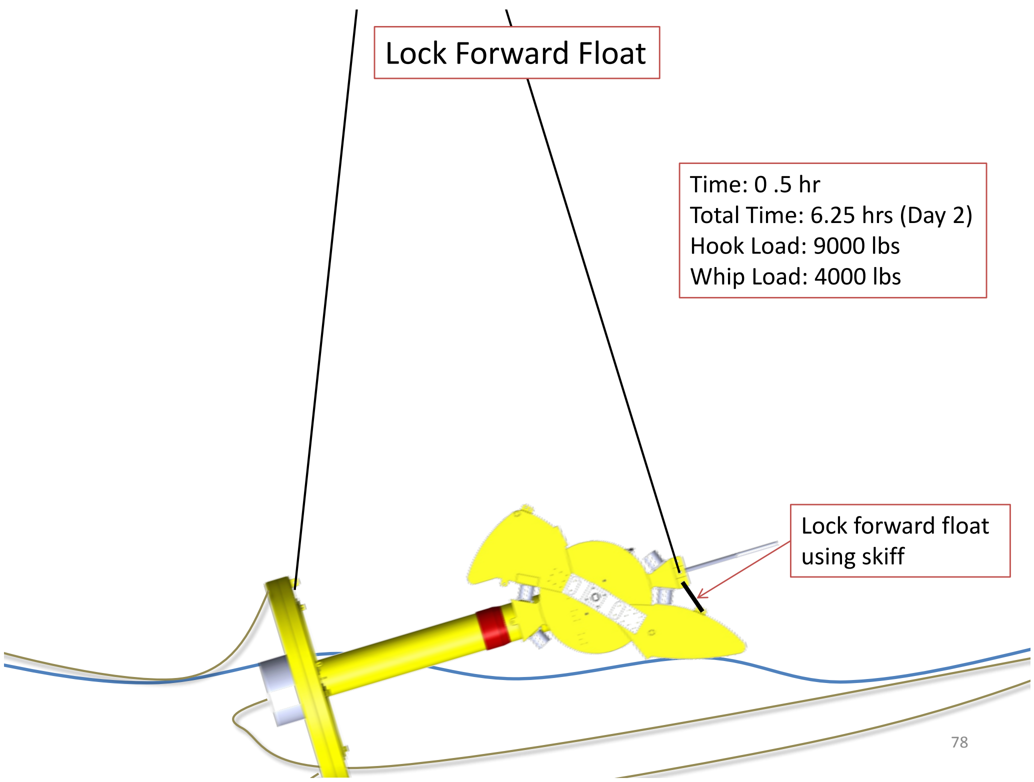


Figure 76.

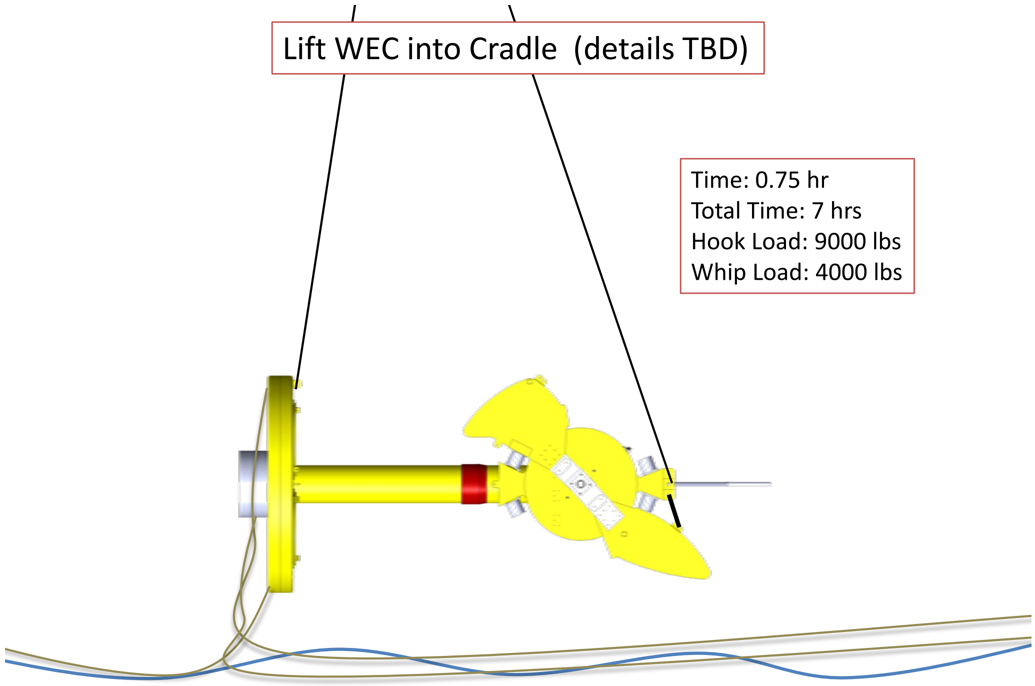


Figure 77.

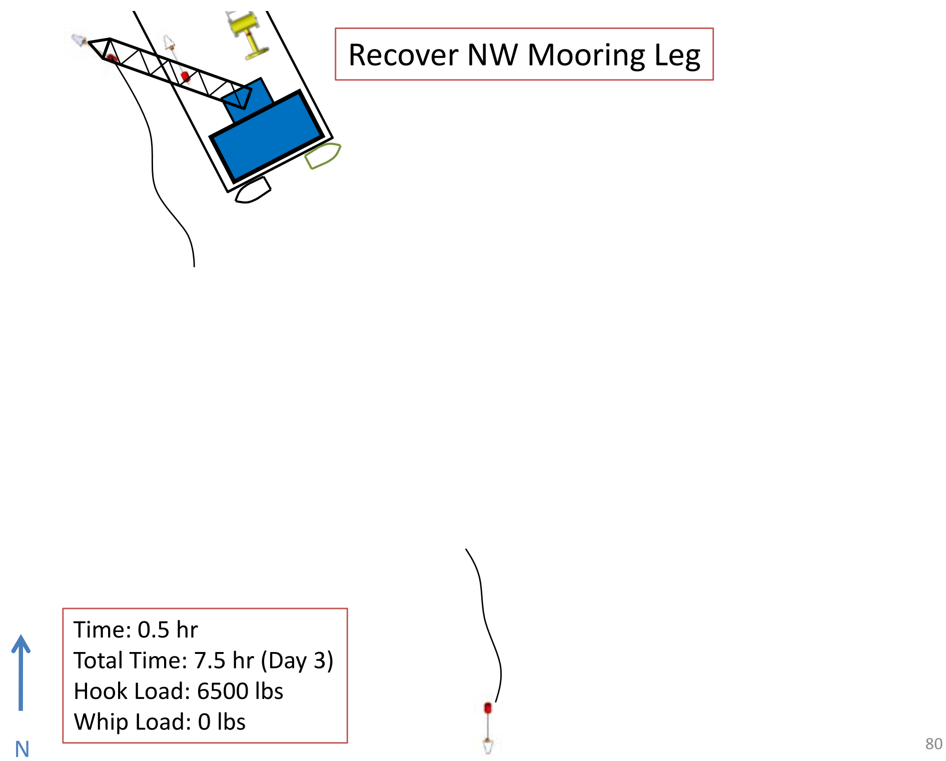


Figure 78.

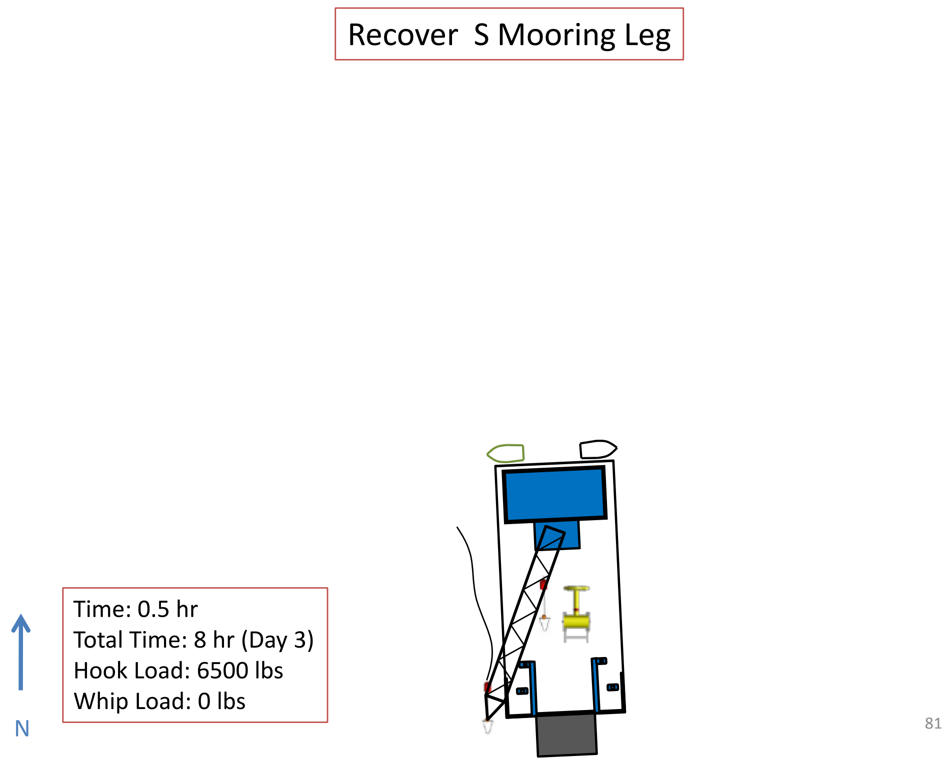


Figure 79.

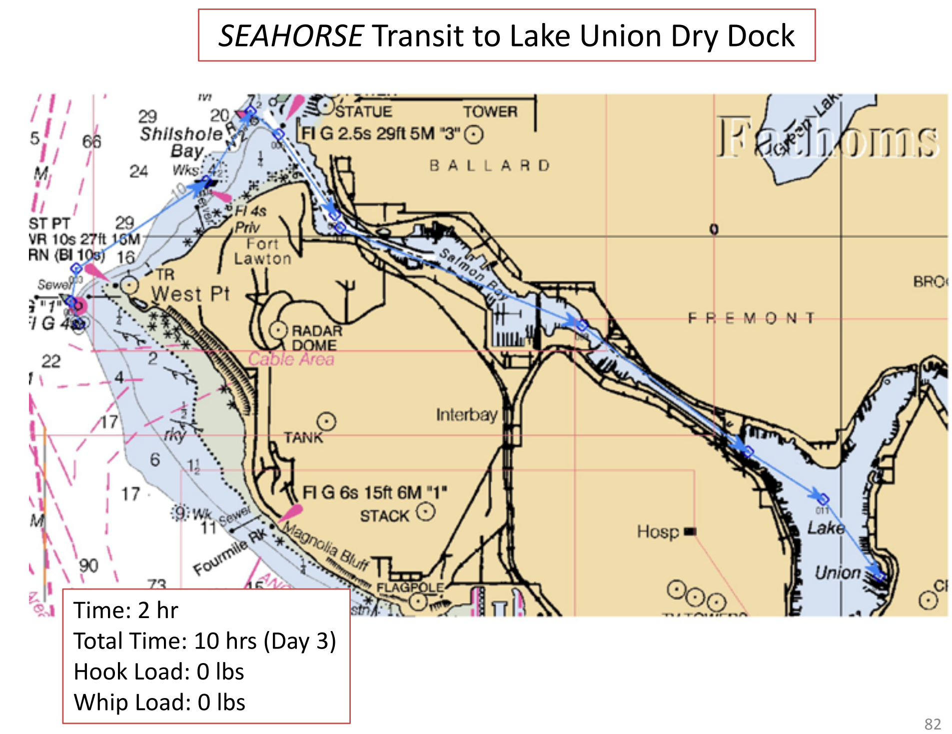


Figure 80. WEC will be unloaded onto flatbed and taken to location TBD. A separate flatbed will be brought down for anchor and SS buoy removal and mooring system disposal/recycling.

9.0 Contingencies

The following table describes several possible situations where contingency planning could be necessary, and the proposed courses of action:

Description	Resolution
***SEAHORSE* Loses Mobility**	Tugs available with <1 hr response time. Can use to move *SEAHORSE* Bow/Stern anchors or WEC Moorings
Rough Seastate	Process can be "paused" at any point. Contingency (third) day scheduled beforehand with *SEAHORSE*.
Inclement Weather	Process can be "paused" at any point. Contingency (third) day scheduled beforehand with *SEAHORSE*.

In order to facilitate stopping in case of inclement weather or equipment failure, several stopping points have been identified, where operations can be suspended indefinitely if necessary:

- After NW (first) anchor is deployed
- After *SEAHORSE* mooring is set
- After S (second) anchor is deployed
- During WEC deployment:
    - WEC can be brought back on deck until third anchor is rigged to crane
- After NE (third) anchor is deployed
- Any point in AWAC deployment

9.1 Retrieving the WEC for Service/Maintenance (If Necessary)

In the case of the WEC needing servicing or maintenance during the deployment, the WEC will be retrieved using the *SEAHORSE*. The exact procedure will vary based on the nature of the issue. A likely retrieval plan would go as follows:

- Retrieve WEC Cradle, bring to Lake Union Drydock and transfer to *SEAHORSE*
- *SEAHORSE* transit to deployment site
- Move NE anchor towards WEC to slack off mooring
- Pick WEC by Nacelle
- Detach 120' nylon mooring lines from 40' lines; attach 120' lines to central crown buoy
- Boom WEC over deck of SEAHORSE
- Attach spectra line to Damper Plate and whip
- Lift WEC horizontally using spectra line/whip, place in cradle (need to determine necessity of locking floats out)

10.0 Appendix A. Safety Plan

10.1 Introduction

It is the responsibility of Sound & Sea Technology to maintain a safe working environment for the CPT WEC deployment at West Point, Puget Sound. The USACOE Safety & Health Requirements Manual (EM385-1-1 15 Sep 2008) was used as a reference when creating this safety plan.

The Sound & Sea Technology staff shall verify through written certification that operational personnel have read and understand the Safety Plan & Safety Training. The written certification shall identify the name of each employee.

10.2 General Precautions

Safety precautions set forth in the Safety Plan will be observed during all phases of this test. Safety Officer for this program is Carl Gowler of SST. The Safety Officer will ensure that all operations are conducted in a safe and prudent manner. However, safety is the responsibility of each and every member of this team. Each person will have the obligation to halt any operation they deem unsafe. Each team member shall take their time and speak up if they have any questions. No one is to ever try to save any equipment with the use of their hand or body. Safety always comes first.

Employees are responsible for reporting all injuries or occupationally related illnesses as soon as possible to the Safety Officer.

10.2.1 Weather

Installation or maintenance will not commence until sea states are at or below Sea State 3 as determined by the Safety Officer. Additionally, installation will not commence in winds exceeding 10kts. In the event that conditions do not allow the start of operations on a particular day, install team will remain on standby. If weather conditions exceed the prescribed wind speed or seastate, the urgency of the procedure (e.g. battery charging, WEC failure) will be assessed.

10.2.2 Personal Protective and Safety Equipment

- PPE Equipment will be provided for all personnel involved in this test.
- When conducting the installation or the operations aboard vessels, all personnel shall wear full PPE (hardhats, gloves, steel-toed shoes, PFD's, etc.).
- Head Protection: Type II head protection (hardhats) will be worn by all personnel present during crane operation, or any other time when loads are moving or suspended overhead.
- Personal Flotation Device (PFD): A US Coast Guard approved Type III safety work vest shall be worn when working over the water in a small boat or on the WEC. At night, a strobe light in working order will be attached to the PFD.
- Protective Footwear: All personnel involved in crane operation or material movement aboard vessels or shore side shall wear protective footwear that meets ASTM F2412 and F2413 standards.

10.2.3 Hand and Power Tools

Hand and power tools shall be used, inspected, and maintained in accordance with the manufacturer's instructions and recommendations and shall be used only for the purpose for which designed.

Hand and power tools shall be in good repair and with all required safety devices installed and properly adjusted. Tools, including extension cords, having defects that will impair their strength or render them unsafe shall be removed from service.

10.2.4 Lifting

Assess the load to be lifted. Wherever possible, use a mechanical lifting device, i.e., dolly, gantry crane, forklift. Understand load weight, lifting points, awkward size/shape/sharp edges, hazards to personnel in the area. All are possible considerations. If in doubt, ask for help.

10.2.5 Tensioned Lines

Lines that are aboard vessels under tensioned will be monitored by the safety observer and crane director. Personnel will be directed to not stand near any lines or cables under tension. Slack lines being utilized will be monitored by the safety observer. Personnel will be directed to not stand near any working line, reef line or cable, especially in the bight of any line or cable being used.

10.2.6 SST Lifting Equipment

All equipment used in conjunction with cranes will follow the requirements of NAVFAC P-307 Section 14. SST will comply with specific activity and regulations pertaining to crane safety and operation for contractors.

Tag lines will be used in conjunction with the crane to assist in the control of the WEC during deployment and recovery.

Personnel not taking part in deployment or recovery will not be permitted aboard the contracted vessel(s).

During Lifting Operations:

- Pay attention to the job at hand
- Do not talk loudly while attending deployment or recovery
- Wear appropriate PPE
- Watch for trip hazards on deck and do not run
- Remain clear of the crane operations when not directly participating in the operation.

10.2.7 Man Overboard

Anyone observing a victim falling overboard will yell "MAN OVERBOARD" and notify the Safety Officer or anyone within ear shot.

Anyone seeing the person will continuously point to the man overboard and keep eyes on the victim's location. A USCG-approved Type IV life ring will be thrown to the victim in the water. A small boat will then be dispatched. Medical procedures are followed as appropriate.

10.2.8 Fire

If a fire breaks out, attempt to put the fire out or contain it with the Portable type 2 fire extinguisher in the galley, yelling "FIRE" and location.

10.2.9 First Aid

A First Aid Kit will be provided onboard the *Seahorse*. If a person is injured while performing project related duties the following steps will be taken in case of a medical emergency:

Call the Coast Guard (marine band channel 16).

10.2.10 Pre Existing Health Problems

Inform the Safety Officer prior to the test of any health conditions which may be adversely affected by the marine environment (heart or respiratory conditions, previous skeletal or back injuries, etc.),

10.3 Electrical safety

10.3.1 Electrical Safety Procedures

All electrical service devices, equipment, and cabling shall be in good repair. Any element that appears to be damaged or is suspected of being damaged shall be removed from operation immediately. Care will be taken during battery charging operations to avoid exposing any personnel to hazardous voltages.

All AC power equipment and cabling shall be protected from exposure to water.

Anyone witnessing a potentially dangerous electrical condition shall warn others and report it immediately to the on-site Safety Officer.

10.4 Crane Operations

Rigging will be inspected before loads are lifted. Radios will be used for blind lifts. A lift plan for installing and recovering the WEC will be in place with personnel assignments before lifting commences. SST will conduct a safety brief for the lift and associated handling operations.

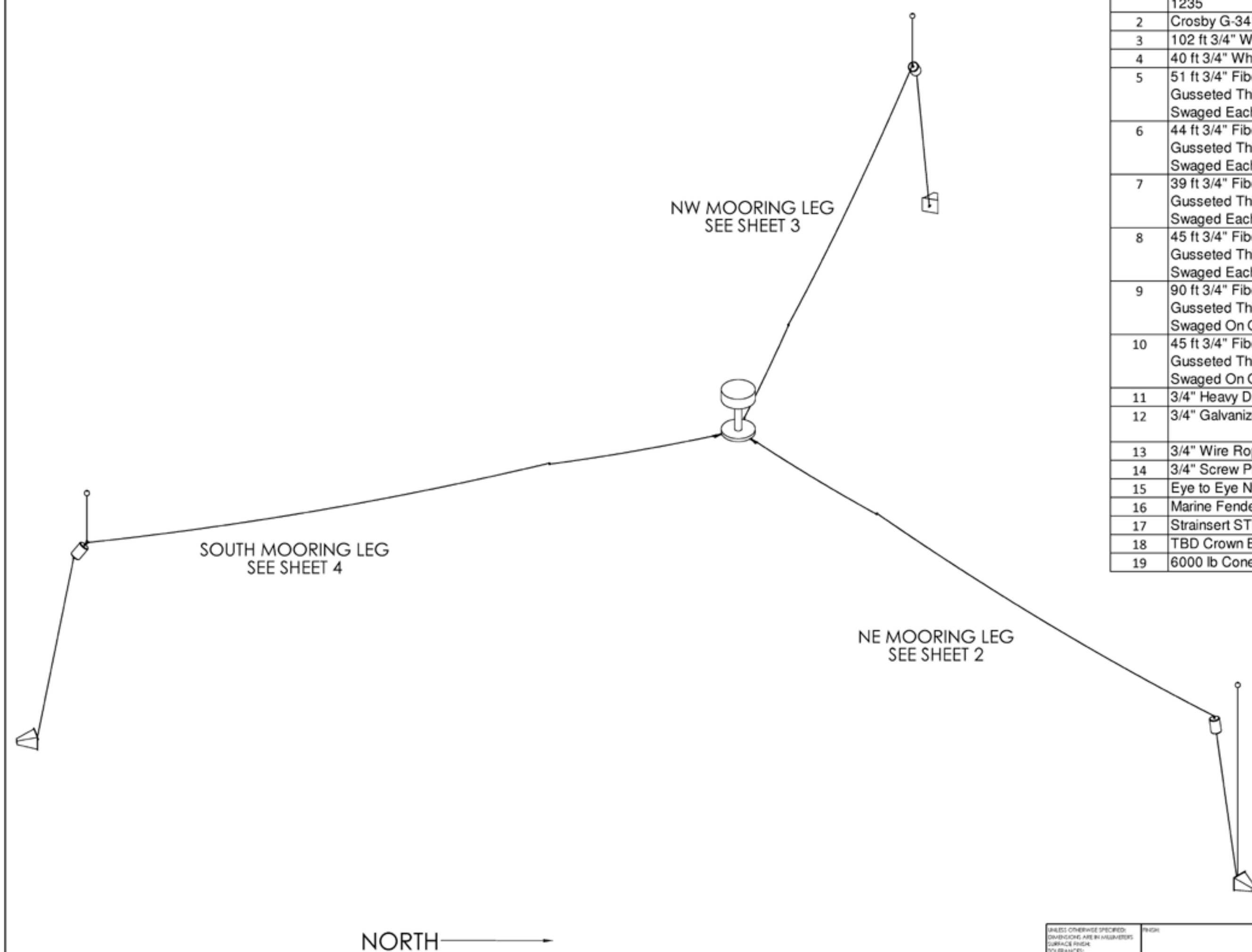
10.4.1 Lifted Equipment

The following is the majority of equipment/material that will be handled with contractor provided cranes:

Item	Weight
WEC	13,500 lbs
WEC Crate	8,000 lbs
Lead Cone Anchors	3 @ 6,000 lbs/each
AWAC	500 lbs
AWAC Anchor	2000 lbs
Subsurface Buoys	3 @ 400 lbs/each
AWAC Mooring Clump	200 lbs

11.0 Appendix B. Detailed Mooring Drawings

Item No.	Description	Qty
1	3/4" Safety Anchor Shackle, Galvanized Domestic BTC539-1235	36
2	Crosby G-341 1" Galvanized Weldless Sling Link	5
3	102 ft 3/4" Whitehill Nylon Mooring Line	3
4	40 ft 3/4" Whitehill Nylon Mooring Line	3
5	51 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
6	44 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
7	39 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
8	45 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	2
9	90 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged On One End Only	1
10	45 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged On One End Only	2
11	3/4" Heavy Duty Tube Thimbles SFEBG722	14
12	3/4" Galvanized Heavy Wire Rope Thimble BTC626-0207	10
13	3/4" Wire Rope Clips BTC699-1034	6
14	3/4" Screw Pin Shackle, Self Colored	8
15	Eye to Eye Nylon Safety Sling EEOL2 X 3'	3
16	Marine Fenders CB-29 Subsurface Buoy	3
17	Strainsert STL-4.75 Tension Link	3
18	TBD Crown Buoy	3
19	6000 lb Cone Anchor	3



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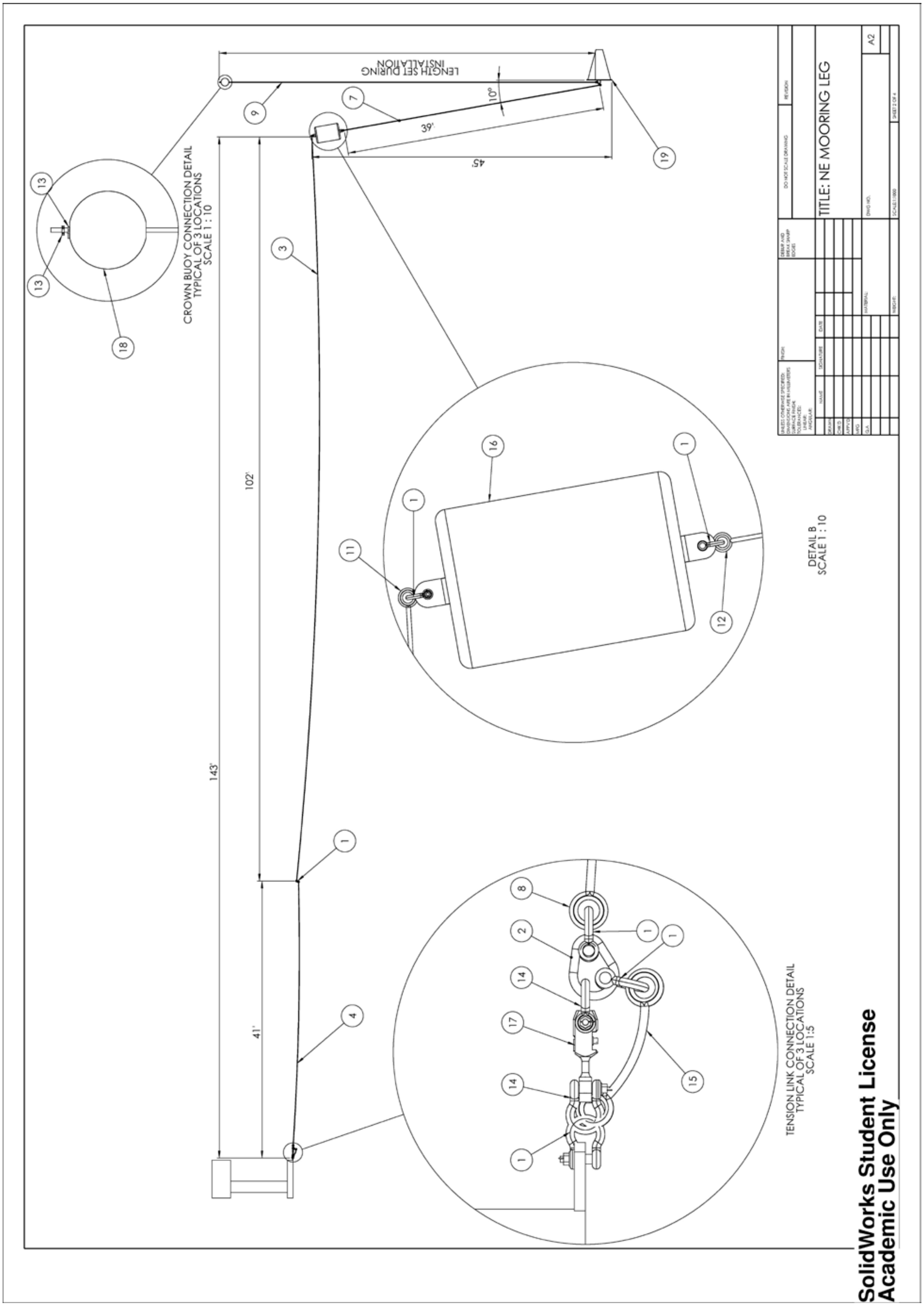
A2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LENGTH SET DURING INSTALLATION
CROWN BUOY CONNECTION DETAIL
TYPICAL OF 3 LOCATIONS
SCALE 1 : 10
DETAIL B
SCALE 1 : 10
TENSION LINK CONNECTION DETAIL
TYPICAL OF 3 LOCATIONS
SCALE 1:5
143'
102'
41'
39'
45'
10°
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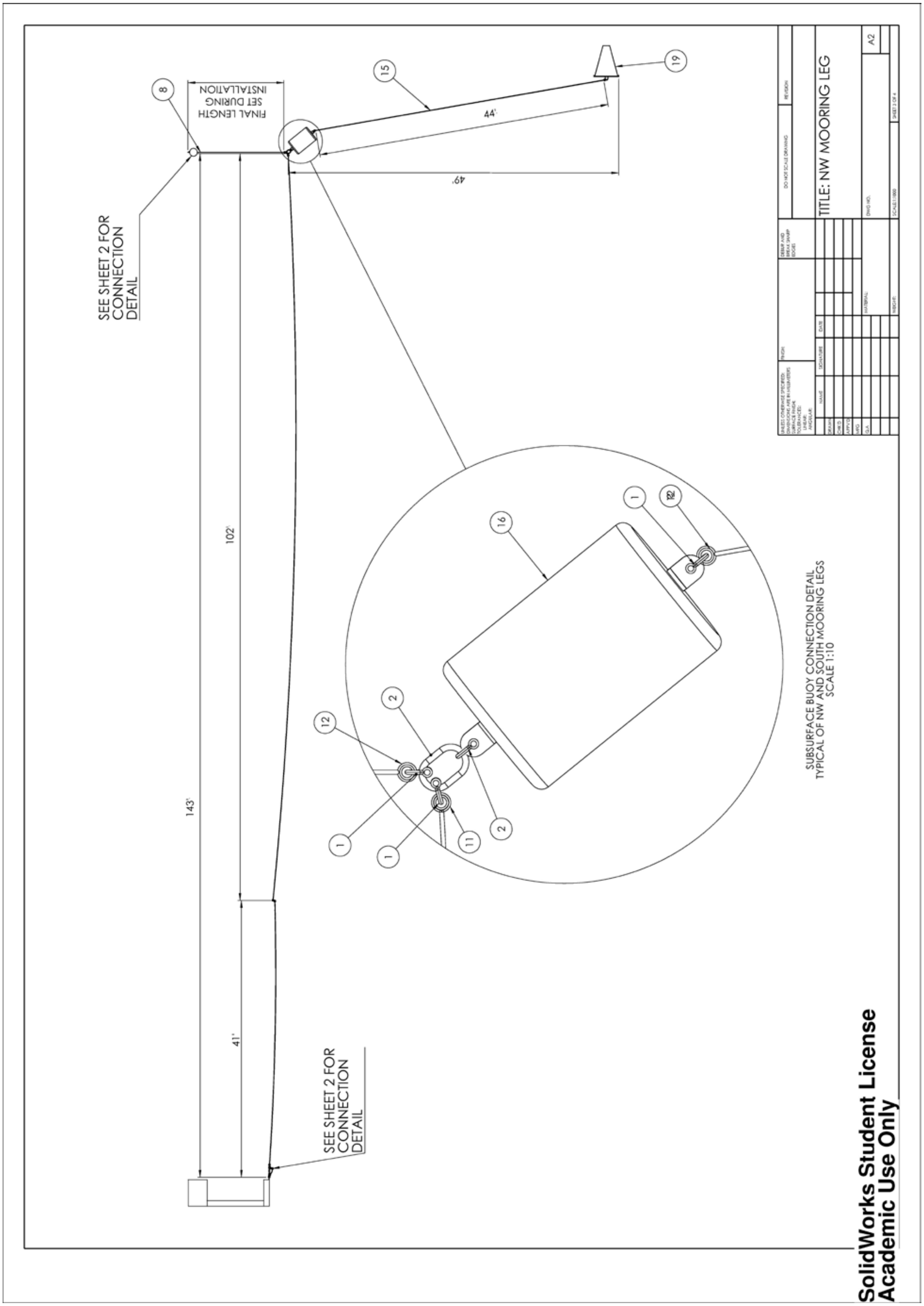
TITLE: NW MOORING LEG
A2
SUBSURFACE BUOY CONNECTION DETAIL
TYPICAL OF NW AND SOUTH MOORING LEGS
SCALE 1:10
SEE SHEET 2 FOR CONNECTION DETAIL
FINAL LENGTH SET DURING INSTALLATION
SEE SHEET 2 FOR CONNECTION DETAIL
143'
102'
41'
44'
49'
8
15
19
16
1
2
12
11
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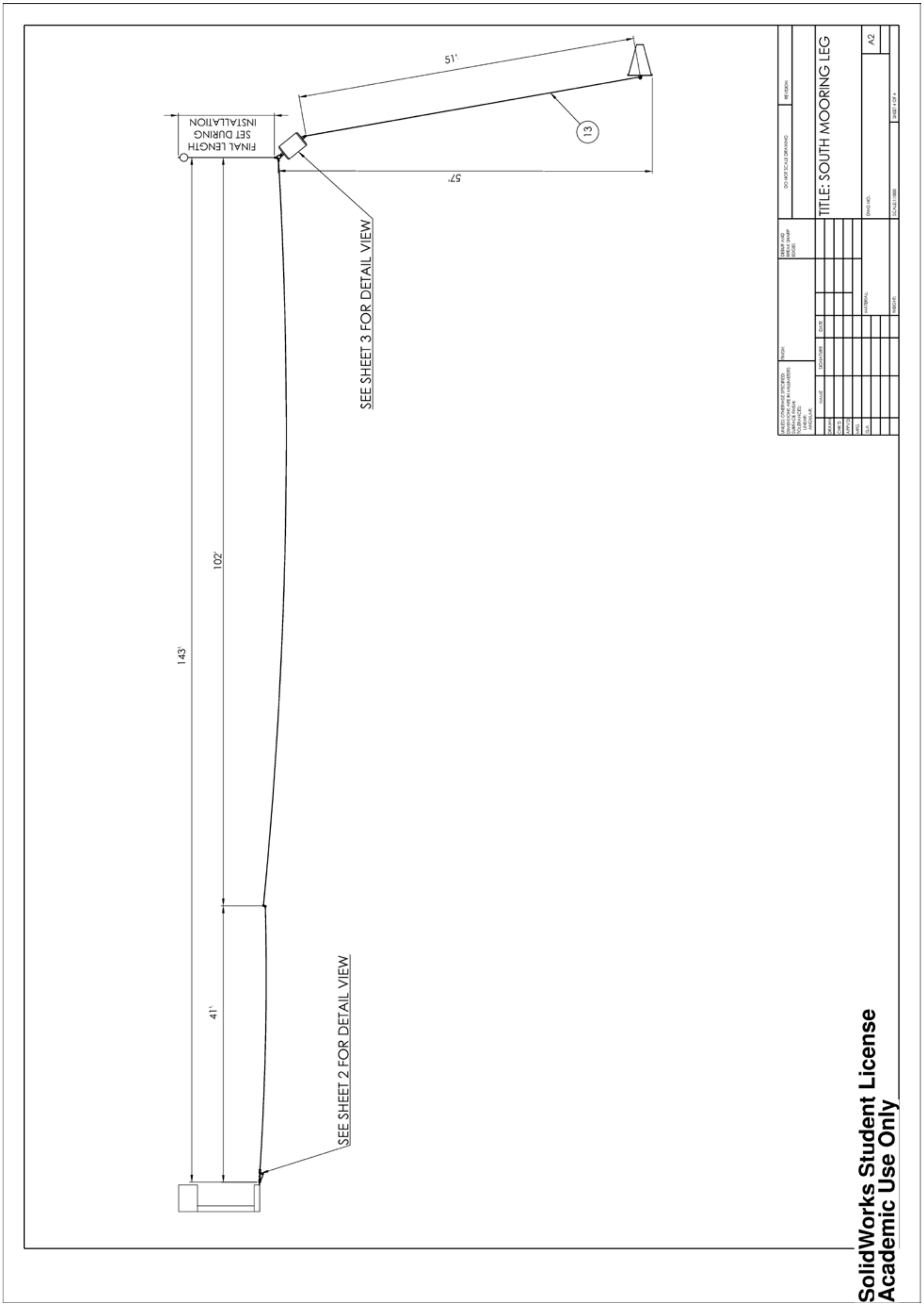
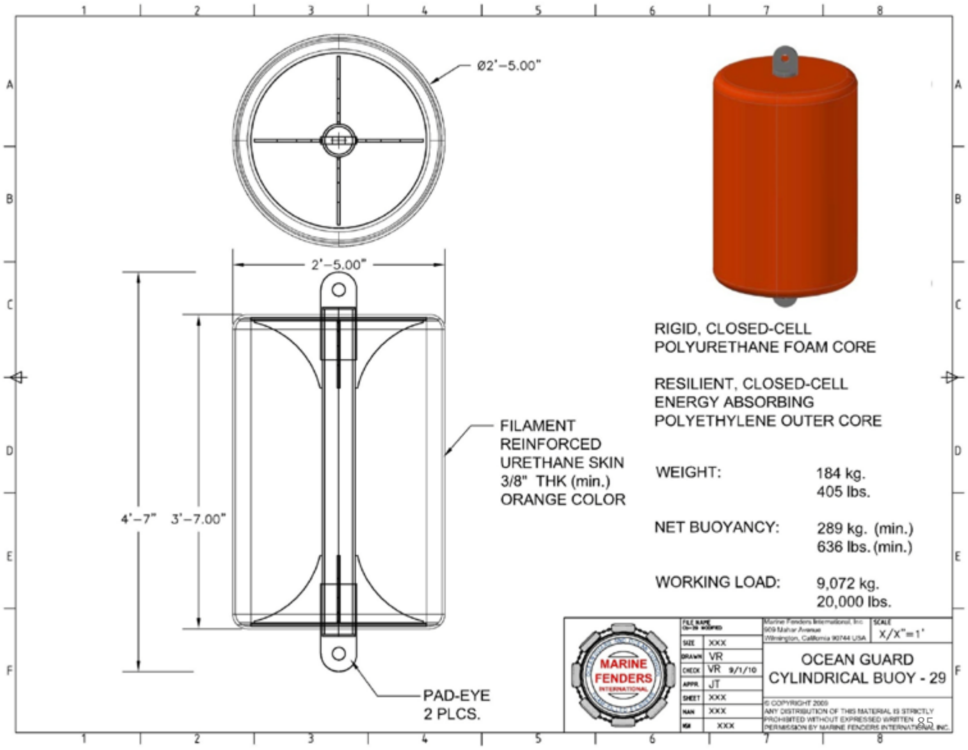
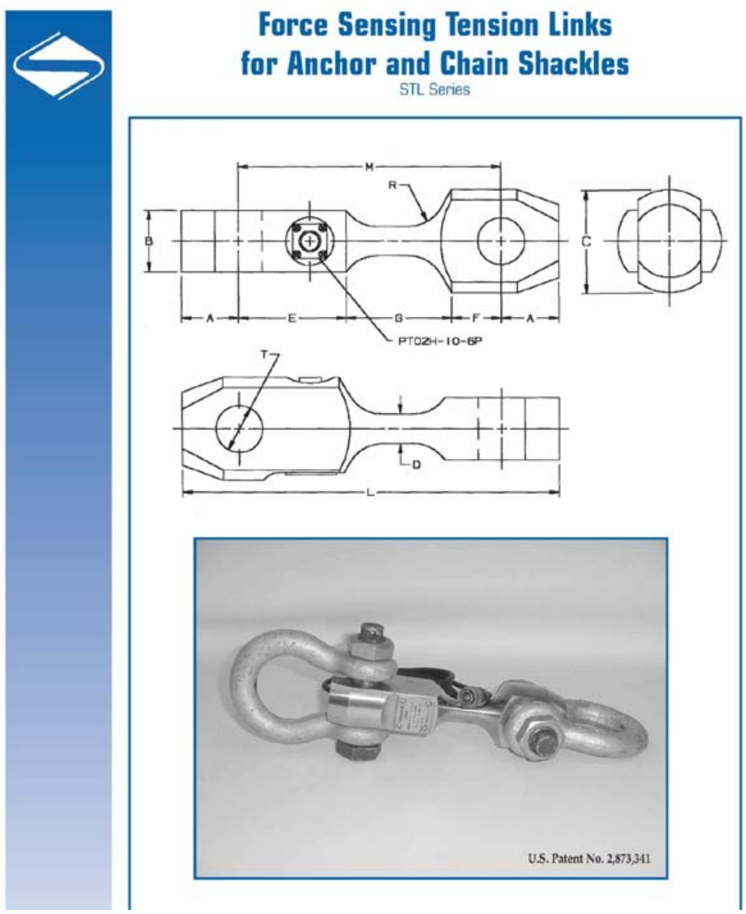

51'
FINAL LENGTH SET DURING INSTALLATION
13
57'
SEE SHEET 3 FOR DETAIL VIEW
102'
143'
41'
SEE SHEET 2 FOR DETAIL VIEW
TITLE: SOUTH MOORING LEG
A2
SolidWorks Student License
Academic Use Only

12.0 Appendix C. Mooring Materials List

Item No.	Purpose	Description	Qty
1	WEC Mooring	3/4" Safety Anchor Shackle, Galvanized Domestic BTC539-1235	36
2	WEC Mooring	Crosby G-341 1" Galvanized Weldless Sling Link	5
3	WEC Mooring	102 ft 3/4" Whitehill Nylon Mooring Line	3
4	WEC Mooring	40 ft 3/4" Whitehill Nylon Mooring Line	3
5	WEC Mooring	51 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
6	WEC Mooring	44 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
7	WEC Mooring	39 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	1
8	WEC Mooring	45 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged Each	2
9	WEC Mooring	90 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged On One End Only	1
10	WEC Mooring	45 ft 3/4" Fiber Core 6x36 EIPS (Bright) With 3/4" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged On One End Only	2
11	WEC Mooring	3/4" Heavy Duty Tube Thimbles SFEBG722	14
12	WEC Mooring	3/4" Galvanized Heavy Wire Rope Thimble BTC626-0207	10
13	WEC Mooring	3/4" Wire Rope Clips BTC699-1034	6
14	WEC Mooring	3/4" Screw Pin Shackle, Self Colored	8
15	WEC Mooring	Eye to Eye Nylon Safety Sling EEOL2 X 3'	3
16	WEC Mooring	Marine Fenders CB-29 Subsurface Buoy	3
17	WEC Mooring	Strainsert STL-4.75 Tension Link	3
18	WEC Mooring	TBD Crown Buoy	3
19	WEC Mooring	6000 lb Cone Anchor	3
20	AWAC Mooring	37 ft 3/4" Quick Splice Polytron SAM335048	1
21	AWAC Mooring	60 ft 1/2" Open Link Mooring Chain	1
22	AWAC Mooring (Crown Buoy Line)	90 ft 1/2" Fiber Core 6x36 EIPS (Bright) With 1/2" HD Galv Gusseted Thimble and Carbon Steel Flemished Sleeve Swaged On One End Only	1
23	WEC Lifting (Damper Plate Strap)	40 ft 5/8" Spectra (8" eye to 8" eye, inside eye), SAM870040	1
24	WEC Lifting (Bridle)	7/8" screw Pin Anchor Shackle, Galvanized Domestic BTC539-1435	3
25	WEC Lifting (Bridle)	2x 20 ft Nylon Strap EE-4-903 sewn to 1-1/4" Alloy Pear Link at apex	1

13.0 Appendix D. Component Specifications





86

Force Sensing Tension Links for Anchor and Chain Shackles

FORCE SENSING TENSION LINKS

Tension Link Model No.	Shackle Size	CAP. Lbs.	A	B	C Dia.	D Dia.	E	F	G	L	M	R Rad.	T Dia.	Safety Factor	Weight Lbs.
STL-0.75*	5/16	1,500	1/2	7/16	1	0.384	2-1/8	1/4	1-5/8	5	4	1/2	0.406	4.2	1
STL-1*	3/8	2,000	9/16	9/16	1-1/8	0.427	2-3/16	5/16	1-3/4	5-3/8	4-1/4	1/2	0.469	4.2	1
STL-1.5*	7/16	3,000	5/8	5/8	1-7/16	0.505	2-1/4	5/16	1-15/16	5-3/4	4-1/2	1/2	0.531	4.2	1
STL-2*	1/2	4,000	3/4	11/16	1-9/16	0.572	2-5/16	3/8	2-1/16	6-1/4	4-3/4	1/2	0.656	4.2	1
STL-3.25*	5/8	6,500	15/16	15/16	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5-1/2	1/2	[illegible]	[illegible]	1
STL-4.75	3/4	9,500	1-1/8	1-1/8	2-3/16	0.635	2-5/8	3/4	2-5/8	8-1/4	6	1/2	0.906	3.0	4
STL-6.5	7/8	13,000	1-1/4	1-5/16	2-7/16	0.695	2-3/4	7/8	2-7/8	9	6-1/2	1	1.031	3.0	6
STL-8.5	1	17,000	1-3/8	1-9/16	2-11/16	0.764	2-11/16	1-1/16	3	9-1/2	6-3/4	1	1.156	3.0	8
STL-9.5	1-1/8	19,000	1-9/16	1-11/16	2-13/16	0.797	2-3/4	1-1/4	3-1/8	10-1/4	7-1/8	1	1.281	3.0	9
STL-12	1-1/4	24,000	1-3/4	1-7/8	3-1/16	0.873	2-11/16	1-7/16	3-3/8	11	7-1/2	1	1.438	3.0	12
STL-13.5	1-3/8	27,000	1-7/8	2-1/16	3-5/16	0.916	2-7/8	1-1/2	3-1/2	11-5/8	7-7/8	1	1.563	3.0	14
STL-30	1-1/2	60,000	1-13/16	2-3/16	3-7/16	1.274	2-15/16	1-7/16	4	12	8-3/8	1	1.688	3.0	16
STL-40	1-3/4	80,000	2-1/4	2-11/16	4-1/16	1.479	3-1/8	1-7/8	4-5/8	14-1/8	9-5/8	1	2.063	3.0	25
STL-50	2	100,000	2-1/2	3-1/16	4-1/2	1.614	3-1/4	2-1/16	5-1/16	15-3/8	10-3/8	1	2.313	3.0	32
STL-80	2-1/2	160,000	3-1/8	3-3/4	5-3/8	2.054	3-1/2	2-5/8	6-1/8	18-1/2	12-1/4	1	2.875	3.0	56
STL-110	3	220,000	3-11/16	4-5/8	6-3/8	2.397	3-3/4	3-1/2	6-5/8	21-1/4	13-7/8	1-1/2	3.375	3.0	95
STL-140	3-1/2	280,000	4-1/4	4-7/8	6-7/8	2.696	4-1/16	4	7-5/16	23-7/8	15-3/8	1-1/2	3.875	3.0	120
STL-175	4	350,000	4-3/4	5-1/8	7-7/16	3.003	4-7/16	4-7/16	7-7/8	26-1/4	16-3/4	1-1/2	4.375	3.0	190

* Aluminum Alloy: 7075-T6; Hard Coat Finish: Rockwell C-60. All others 17-4 Stainless Steel, H-1025
All dimensions in inches.

ORDERING INFORMATION

STL -110 (SS) X

- *X = Axial Connector*
  W = Permanently Attached Axial Cable
- *(SS) - Stainless Steel 17-4 PH, H-1025 Standard*
  (AL) - Aluminum Alloy 7075-T6
- *Load Capacity, Tons (pounds X 2000)*
- *Model Designation*

87

Mooring Anchors

- **4’ Anchor Height**
- **6000 lb Lead Mass**
- **¾” Steel Drag Plate**
- **Steel Pick Point**

SUPER STRONG SPOOLS

Product Code: 472

Super Strong is a firm but flexible double braid of high-tenacity nylon fiber treated with Pro-Gard marine finish, which maxmizes wet wear life and strength.

FEATURES

- Fiber: nylon core, nylon cover
- Standard Color: white with blue and red ID
- Excellent shock mitigaion
- Excellent wet wear
- Remains flexible and won't shrink harden
- Class 1 Double Braid splice
- High energy absorption/shock mitigation
- Excellent wear resistance
- Highly flexible-easy to handle
- High strength to weight ratio

APPLICATIONS

- Dock Lines
- Anchor Lines
- Trawl and Bridle Lines
- Gillnet Lead and Cork Lines
- Purse Seine Lines
- Secondary Mooring Lines
- Halters/Headgear
- Leads/Longelines/Mecates
- Rodeo/Rigging/Utility
- Heavy Lift Slings
- Winch Working Lines

TECHNICAL SPECIFICATIONS

• Specific Gravity...
1.14

• Elastic Elongation...		
At % break strength		
10%	20%	30%
3%	5.3%	6.7%

Rope stabilized from 200D2. Ropes cycled 50 times at each percent of average break strength.

INCH	MM	LBS/100 FT	KG/100M	SAMSON AVERAGE STRENGTH LBS	SAMSON AVG STRENGTH KG	SAMSON MIN STRENGTH LBS	SAMSON MIN STRENGTH KG	ISO/BS EN919 STRENGTH
1/4	6.0	1.6	2.4	2,300	1,000	2,000	890	0.99
5/16	8.0	2.6	3.9	3,400	1,500	2,900	1,300	1.5
3/8	9.0	3.7	5.5	4,900	2,200	4,200	1,900	2.1
7/16	11.0	5.1	7.6	6,600	3,000	5,600	2,500	2.8
1/2	12.0	6.6	9.8	8,600	3,900	7,300	3,300	3.7
9/16	14.0	9.3	13.8	11,900	5,400	10,100	4,600	5.1
5/8	16.0	12.0	17.9	15,200	6,900	12,900	5,900	6.5
3/4	18.0	15.0	22.3	18,800	8,500	16,000	7,200	8.1
7/8	22.0	22.0	32.7	29,000	13,200	24,700	11,200	12.4

89

6X36 CLASS EIPS IWRC, FIBER CORE

Next: GALVANIZED 6X19 CLASS EIPS IWRC, FIBER CORE

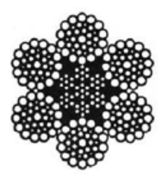
WIRE ROPE

GENERAL PURPOSE

BRIGHT 6X37 CLASS (6X29,6X31,6X36,6X37,6x41)

6 x 36 FIBER CORE
WARRINGTON SEALE

Read important warnings and information on pages 6 7 and 12 preceding wire rope section.



6 X 36 IWRC
WARRINGTON SEALE

According to Federal Specification RR W 410D, preformed, right regular lay.

	FIBER CORE (EIPS)		IWRC (EIPS)	
Diameter In Inches	Approx. weight per foot in pounds	Breaking strength in Tons*	Approx. weight per foot in pounds	Breaking strength in Tons *
1/4	0.105	3.02	0.116	3.4
5/16	0.164	4.69	0.18	5.27
3/8	0.236	6.71	0.26	7.55
7/16	0.32	9.09	0.35	10.2
1/2	0.42	11.8	0.46	13.3
9/16	0.53	14.09	0.59	16.8
5/8	0.66	18.3	0.72	20.6
3/4	0.95	26.2	1.04	29.4
7/8	1.29	35.4	1.42	39.8
1	1.68	46	1.85	51.7
1 1/8	2.13	57.9	2.34	65
1 1/4	2.63	71	2.89	79.9
1 3/8	3.18	85.4	3.5	96
1 1/2	3.78	101	4.16	114

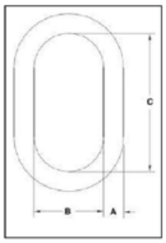
90

Alloy Master Links

QUIC-CHECK®

A-342

- Alloy Steel — Quenched and Tempered.
- Individually Proof Tested to values shown, with certification.
- Proof Tested with fixture sized to prevent localized point loading per ASTM A952. Consult Crosby for appropriate fixture size.
- Crosby A-342 products meet or exceed all requirements of ASME B30.26 including identification, ductility, design factor, proof load and temperature requirements. Importantly, Crosby products meet other critical performance requirements including fatigue life, impact properties and material traceability, not addressed by ASME B30.26.
- Sizes from 1/2" to 2" are drop forged and have a Product Identification Code (PIC) for material traceability, along with the size, the name Crosby and USA in raised lettering.
- Selected sizes designated with "W" in the size column have enlarged inside dimensions to allow additional room for sling hardware and crane hook.
- Incorporates patented **QUIC-CHECK®** deformation indicators.



A-342 Alloy Master Links

Size (in.)	Size (mm)	A-342 Stock No.	Weight Each (lbs.)	Working Load Limit (lbs.)*	Proof Load (lbs.)**	Dimensions (in.) A	B	C	Deformation Indicator
1/2W	13W	1014266	1.3	7400	17200	.62	2.80	5.00	3.50
5/8	16	1014280	1.5	9000	18000	.62	3.00	6.00	3.50
3/4W	19W	1014285	2.0	12300	28400	.73	3.20	6.00	4.00
7/8W	22W	1014319	3.3	15200	35200	.88	3.75	6.38	4.50
1W	26W	1014331	6.1	26000	60000	1.10	4.30	7.50	5.50
1-1/4W	32W	1014348	12.0	39100	90400	1.33	5.30	9.50	7.00
1-1/2W	38W	1014365	18.5	61100	141200	1.61	5.90	10.50	7.50
1-3/4	44	1014388	25.2	84900	169800	1.75	6.00	12.00	7.50
2	51	1014404	37.0	102600	205200	2.00	7.00	14.00	9.00
†† 2-1/4	†† 57	1014422	54.1	143100	289200	2.25	8.00	16.00	-
†† 2-1/2	†† 63	1014468	67.8	160000	320000	2.50	8.00	16.00	-
†† 2-3/4	†† 70	1014449	87.7	216900	433800	2.75	9.50	16.00	-

Rigging Accessories

Crosby® Bolt Type Shackles

Load Rated Fatigue Rated QUIC-CHECK® MAXTOUGH®

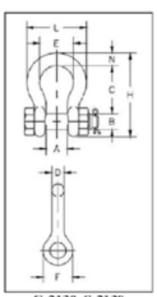
BOLT TYPE ANCHOR SHACKLES

G-2130 S-2130

Bolt Type Anchor shackles with thin head bolt - nut with cotter pin. Meets the performance requirements of Federal Specification RR-C-271D Type IVA, Grade A, Class 3, except for those provisions required of the contractor. For additional information, see page 391.

- Capacities 1/3 thru 150 metric tons.
- Working Load Limit permanently shown on every shackle.
- Forged — Quenched and Tempered, with alloy pins.
- Hot Dip galvanized or Self Colored.
- Fatigue rated (1/3t - 55t).
- Shackles 25t and larger are RFID EQUIPPED.
- Crosby products meet or exceed all requirements of ASME B30.26 including identification, ductility, design factor, proof load and temperature requirements. Importantly, Crosby products meet other critical performance requirements including fatigue life, impact properties and material traceability, not addressed by ASME B30.26.
- Shackles 55 metric tons and smaller can be furnished proof tested with certificates to designated standards, such as ABS, DNV, Lloyds, or other certification when requested at time of order.
- Shackles 85 metric tons and larger can be provided as follows.
  - Non Destructive Tested
  - Serialized Pin and Bow
  - Material Certification (Chemical) Certification must be requested at time of order.
- Look for the Red Pin® . . . the mark of genuine Crosby quality.
- Type Approval and certification in accordance with ABS 2006 Steel Vessel Rules 1-1-17.7, and ABS Guide for Certification of Cranes.

Shackles



G-2130 S-2130

Nominal Size (in.)	Working Load Limit (t)*	Stock No. G-2130	Stock No. S-2130	Weight Each (lbs.)	Dimensions (in.) A	B	C	D	E	F	H	L	N	Tolerance +/- C	Tolerance +/- A
3/16	1/3‡	1019464	-	.06	.38	.25	.88	.19	.60	.56	1.47	.98	.19	.06	.06
1/4	1/2	1019466	-	.11	.47	.31	1.13	.25	.78	.61	1.84	1.28	.25	.06	.06
5/16	3/4	1019468	-	.22	.53	.38	1.22	.31	.84	.75	2.09	1.47	.31	.06	.06
3/8	1	1019470	-	.33	.66	.44	1.44	.38	1.03	.91	2.49	1.78	.38	.13	.06
7/16	1-1/2	1019471	-	.49	.75	.50	1.69	.44	1.16	1.06	2.91	2.03	.44	.13	.06
1/2	2	1019472	1019481	.79	.81	.64	1.88	.50	1.31	1.19	3.28	2.31	.50	.13	.06
5/8	3-1/4	1019490	1019506	1.68	1.06	.77	2.38	.63	1.69	1.60	4.19	2.84	.69	.13	.06
3/4	4-3/4	1019515	1019524	2.72	1.25	.89	2.81	.75	2.00	1.81	4.97	3.50	.81	.25	.06
7/8	6-1/2	1019533	1019542	3.95	1.44	1.02	3.31	.88	2.28	2.09	5.83	4.03	.97	.25	.06
1	8-1/2	1019551	1019560	5.86	1.69	1.15	3.75	1.00	2.69	2.38	6.56	4.69	1.06	.25	.06
1-1/8	9-1/2	1019579	1019588	8.27	1.81	1.25	4.25	1.13	2.91	2.69	7.47	5.16	1.25	.25	.06
1-1/4	12	1019597	1019604	11.71	2.03	1.40	4.69	1.29	3.25	3.00	8.25	5.75	1.38	.25	.06
1-3/8	13-1/2	1019613	1019622	15.83	2.25	1.53	5.25	1.42	3.63	3.31	9.16	6.38	1.50	.25	.13
1-1/2	17	1019631	1019640	19.00	2.38	1.66	5.75	1.53	3.88	3.63	10.00	6.88	1.62	.25	.13
1-3/4	25	1019659	1019668	33.91	2.88	2.04	7.00	1.84	5.00	4.19	12.34	8.80	2.25	.25	.13
2	35	1019677	1019686	52.25	3.25	2.30	7.75	2.08	5.75	4.81	13.68	10.15	2.40	.25	.13
2-1/2	55	1019695	1019702	98.25	4.13	2.80	10.50	2.71	7.25	5.69	17.90	12.75	3.13	.25	.25
3	† 85	1019711	-	154.00	5.00	3.30	13.00	3.12	7.88	6.50	21.50	14.62	3.62	.25	.25
3-1/2	† 120 ‡	1019739	-	265.00	5.25	3.76	14.63	3.62	9.00	8.00	24.88	17.02	4.38	.25	.25
4	† 150 ‡	1019757	-	338.00	5.50	4.26	14.50	4.00	10.00	9.00	25.68	18.00	4.56	.25	.25

May 18, 2010

Columbia Power Technologies, LLC
3079 Kelley Engineering Center
Corvallis, OR 97331

Attn: Mr. Ken Rhinefrank, VP Research & Development

Subj: Scale Site Bathymetric Survey Report

Ref: Bathymetry mapping work to determine test site for scaled wave buoy system for Columbia Power, LLC (CPT). Work performed by Sound & Sea Technology, Inc. (SST).

Work has been completed as described by our original contract for the determination and bathymetry mapping of a selected site for the Scale Site Bathymetric Survey in the area adjacent to West Point – Seattle, WA. The planned approach of the survey was successful and the resulting survey data was processed in accordance with the original description of work outlined in the original contract. The results of this survey work and subsequent data processing resulted in the production of the bathymetry maps delivered with this report.

The following is a description of the process of the work completed. The original area off West Point, Seattle, WA as described in file; *"West Point Large Grid.jpg"*, was searched with a fathometer mounted on a kayak for several hours to determine a location within these boundaries that best matched the previously determined criteria for a site. This large grid area was evaluated for slope and obstructions until an area was located that best fit the desired criteria for a site survey. Once this best-fit area was determined near the southwest portion of the larger grid area, this area was buoyed off along the perimeters, denoting a square area containing a circular area with a radius of 180 feet. Transects were performed within the buoyed area and depths were recorded in a digital voice recorder at approximately 3 meter intervals. These data were corrected for any offset to MLLW and validated against other bathymetric data of this the area. These validated data points were augmented with bathymetric data resources and interpreted using Natural Neighbors Algorithm in ARCVIEW GIS resulting in 1 meter resolution. The resulting bathymetric data of the site were overlaid against NOAA chart data, and the provided SWAN model data to provide several images delivered with this report.

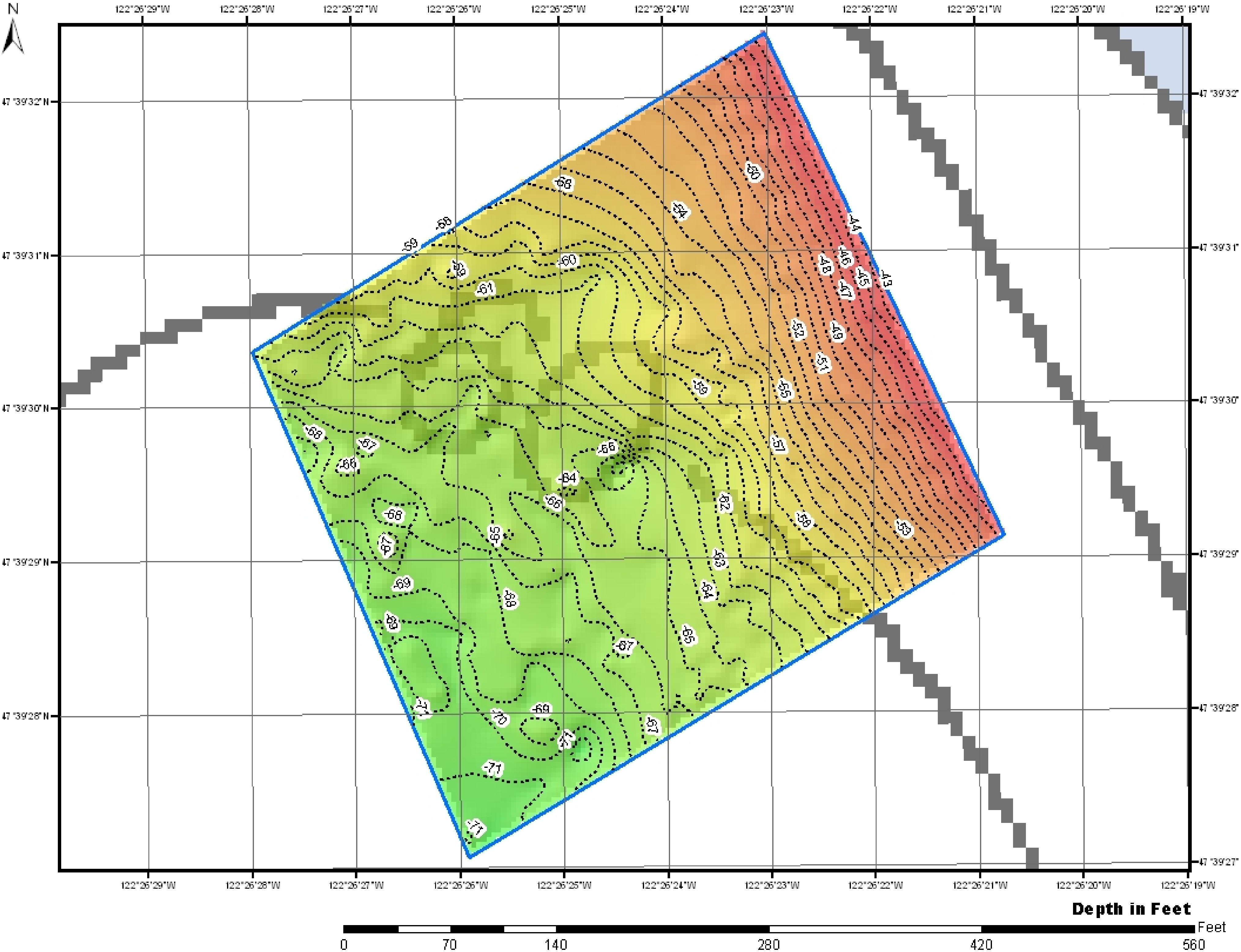
3507 Shelby Road Lynnwood, WA 98087 • Tel: +1 425-743-1282 • Fax: +1 425-742-5643
e-mail: ssquires@soundandsea.com

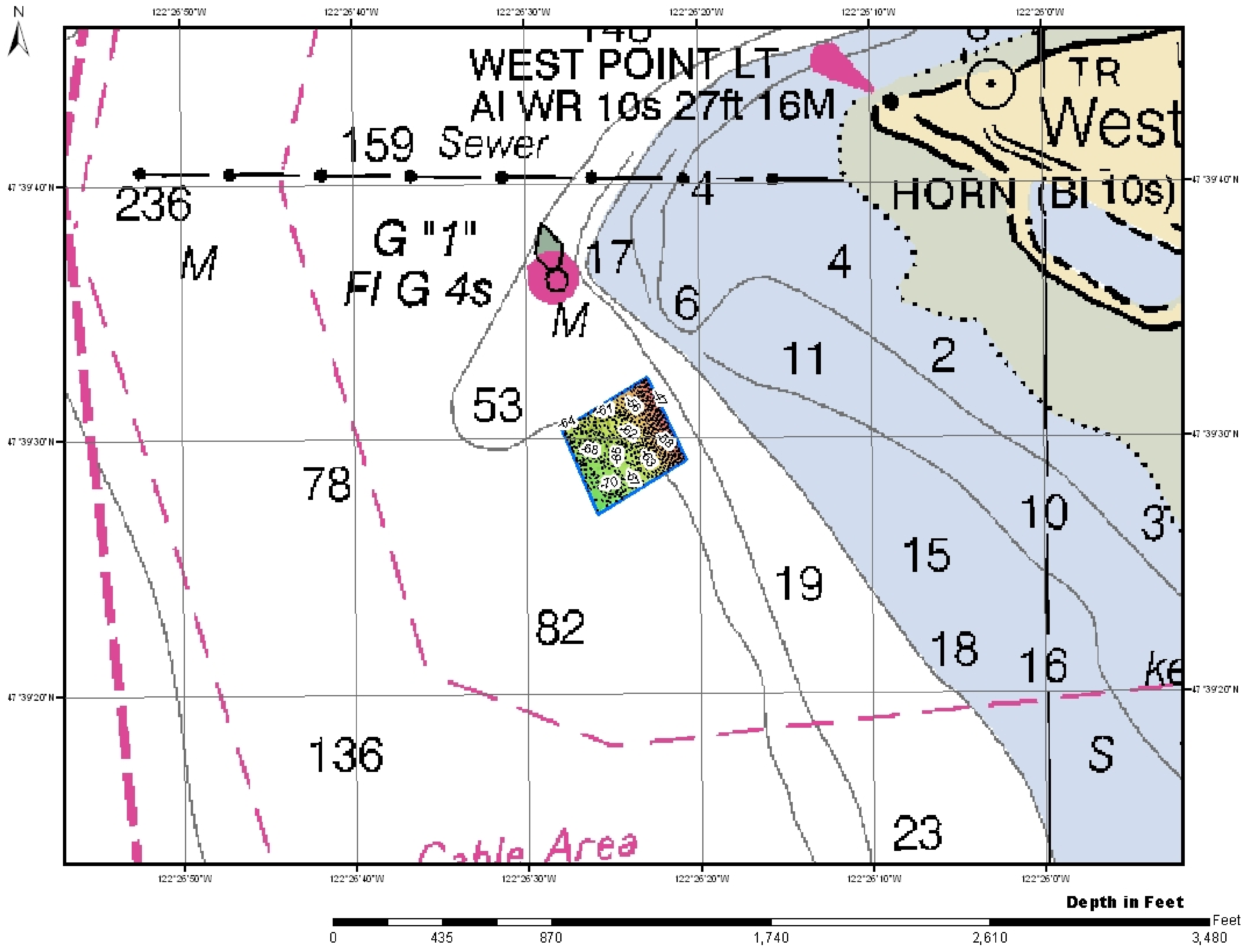
If you require additional information, please contact me at 425 248 1237.

Sincerely,
SOUND & SEA TECHNOLOGY, INC.

Todd Switzer PhD.,

3507 Shelby Road Lynnwood, WA 98087 • Tel: +1 425-743-1282 • Fax: +1 425-742-5643
e-mail: ssquires@soundandsea.com


N
122°26'29"W
122°26'28"W
122°26'27"W
122°26'26"W
122°26'25"W
122°26'24"W
122°26'23"W
122°26'22"W
122°26'21"W
122°26'20"W
122°26'19"W
47°39'32"N
47°39'31"N
47°39'30"N
47°39'29"N
47°39'28"N
47°39'27"N
Depth in Feet
Feet
0
70
140
280
420
560



N
WEST POINT LT
Al WR 10s 27ft 16M
159 Sewer
236
G "1"
Fl G 4s
M
17
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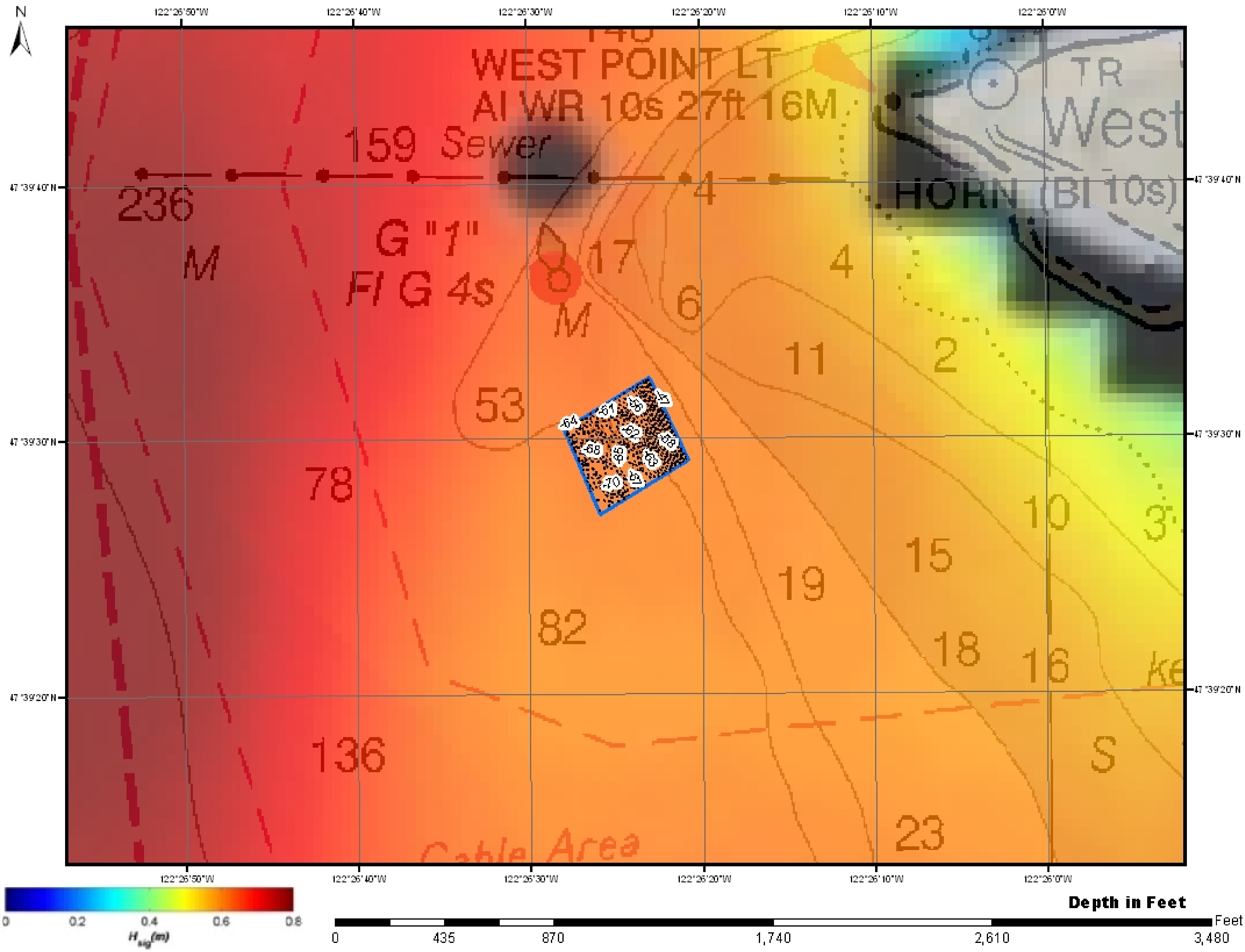
4
11
2
53
78
82
136
19
15
10
18
16
23
HORN (Bl 10s)
TR
West
S
Cable Area
-64
-61
-68
-62
-65
-63
-70
-67
122°26'50"W
122°26'40"W
122°26'30"W
122°26'20"W
122°26'10"W
122°26'0"W
47°39'40"N
47°39'30"N
47°39'20"N
Depth in Feet
0
435
870
1,740
2,610
3,480
Feet


N
122°26'50"W
122°26'40"W
122°26'30"W
122°26'20"W
122°26'10"W
122°26'0"W
47°39'40"N
47°39'30"N
47°39'20"N
WEST POINT LT
Al WR 10s 27ft 16M
159 Sewer
236
G "1"
Fl G 4s
M
HORN (Bl 10s)
TR
West
53
78
82
136
17
6
4
11
2
10
15
19
18
16
23
S
Cable Area
-64
-61
-56
-47
-62
-58
-68
-65
-63
-70
-67
0
0.2
0.4
0.6
0.8
H_{sig} (m)
Depth in Feet
0
435
870
1,740
2,610
3,480
Feet