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Biological and Existing Data Analysis to Inform Risk of Collision and Entanglement Hypotheses

Environmental Effects of Marine and Hydrokinetic Energy

RK Kropp

December 2013

Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

A literature search was conducted to identify articles that would be useful to help assess the likelihood that migrating whales, particularly gray whales, would encounter wave parks that might be proposed for off the U.S. west coast and collide with and/or become entangled in a park's underwater cables. These concerns have been mentioned in several review articles without any documentation that such encounters would be likely. Therefore, this literature search was focused on trying to obtain the necessary information to support or challenge the hypothesized concern. As an example of the potential interaction, this review focuses on a wave park placed off the coast of Oregon.

The review identified a considerable body of literature that documents the severity of entanglements involving marine mammals, particularly large baleen whales. However, these entanglements involved fixed or derelict fishing gear, such as various types of nets and the cables used to attach floats to lobster and crab traps. The review did not identify any cases of whales being entangled in mooring cables such as those planned for use in offshore wave parks. One of the key properties with fishing lines is that there is usually a considerable amount of slack in the lines. This slack enables the lines to wrap around whale body parts, which ultimately leads to entanglement. The various mooring lines and cables associated with wave parks would be taut under most circumstances and would not have enough slack to allow a whale to become entangled.

Three species of baleen whales–gray, humpback, and blue–are the most likely large species that would encounter a wave park placed about 2 to 3 nmi off Oregon. Of the three species, the gray whale is the most likely species to encounter the park because it undergoes an 18,000-km (11,185-mi) migration during which it passes through Oregon nearshore waters twice per year. Most of the more than 18,000 gray whales that pass the Oregon coast would swim within 3.5 to 6.5 km (1.9 to 3.5 nmi) of shore while migrating north to feeding areas in the Bering Sea and within 5.6 to 7.0 km (3.0 to 3.8 nmi) of shore on the return trip south to breeding areas in Mexico. Thus, it is likely that many gray whales would encounter a nearshore wave park. However, the encounter likelihood is not uniform throughout the year. Based on the timing of the migrations, the most likely encounter period would be during the northbound migration from late February through about late May when the adult males, pregnant females, and immature whales follow a migratory path through shallower Oregon waters that has strong overlap with the location of the proposed nearshore wave park. During the southbound migration most whales pass the Oregon coast in January at distances farther offshore than the location of a proposed wave park. The number of whales that might encounter a park is further reduced by the tendency of the whales to generally follow depth contours while swimming past Oregon. Thus, whales swimming at depths shallower than a nearshore wave park would tend to stay at those depths and whales swimming deeper than the park would tend to stay deeper. Humpback whales primarily use the waters off Oregon for feeding and occasionally occur relatively close to shore although most frequent offshore deeper-water banks. Blue whales do not spend much time in Oregon waters, passing through them to more northerly locations. Both species are relatively rare in Oregon waters.

Anatomical studies of whale vision and hearing allow some hypotheses about the detectability of a wave park to be made. Whale vision, especially that of gray whales, is fairly poor, and it seems unlikely that whales would be able to visually detect underwater cables and lines at a distance sufficient to allow them to avoid them. One study showed that minke whales could detect and avoid highly contrasting (black and white) lines, but whether other large whales would be able to do so is not known. The

literature suggests that baleen whales, unlike many toothed whales, do not use sound to detect underwater objects but to communicate with others of the same species.

Despite the lack of information about some aspects of large whale population density and behavior, the described features of the wave park cables and mooring lines, the relative rarity or absence of most baleen whales in nearshore Oregon waters, and the gray whale migration pattern inshore of a nearshore wave park allow the hypothesis that entanglement in wave park cables should not be a significant issue for baleen whales.

Acronyms and Abbreviations

ac	acre(s)
dB	decibel(s)
dB re 1 µ Pa	decibels relative to one micro Pascal
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ERES	Environmental Risk Evaluation System
FERC	Federal Energy Regulatory Commission
ft	foot (feet)
h	hour(s)
ha	hectare(s)
Hz	hertz
in.	inch(es)
kHz	kilohertz
km	kilometer(s)
λ_{max}	maximum absorbance wavelength
m	meter(s)
MHK	marine and hydrokinetic
mph	miles per hour
mtDNA	mitochondrial deoxyribonucleic acid
N	Newton(s)
nm	nanometer(s)
nmi	nautical mile(s)
OPT	Ocean Power Technologies, Inc.
PNNL	Pacific Northwest National Laboratory
s	second(s)
SSF	subsurface float(s)
UV	ultraviolet

Contents

Figures

1.0 Introduction

A previous literature review (Kropp 2011) identified several review articles that listed various concerns about the possible interactions between gray whales (*Eschrichtius robustus*) and offshore wave parks. The main concern expressed was that placing a wave park in coastal waters off Oregon could disrupt the annual migration of the gray whale, which swims at least 18,000 km (11,185 mi) on its round trip from breeding grounds in Baja California to feeding areas in the Bering Sea. The possible effects included increased predation risk by constricting the migration corridor to the area between the array and shore or by forcing the whales to swim into deeper waters, increased metabolic energy costs and delays in reaching the destinations, and interrupting feeding by blocking access to benthic areas under arrays. Among the review papers, Boehlert et al. (2008) and Thompson et al. (2008) also identified entanglement or collision as concerns but did not provide much information about them. Another review also mentioned that entanglement was of concern but offered little additional information other than the nature of the cable was important regarding entanglement issues (Boehlert and Gill 2010). The potential for entanglement is often raised in review articles but usually with little information other than a brief mention of the concern or a restatement of previous reviews (Brown and Simmonds 2010; Davis 2010; Dolman and Simmonds 2010; Simmonds and Brown 2010; Frid et al. 2012; Margheritini et al. 2012; Paasch et al. 2012). Two relatively recent reviews did not include marine mammal entanglement as a potential environmental concern (Bailey et al. 2011; Lin and Yu 2012). Isaacman and Daborn (2011) acknowledged that ropes and cables could be of concern for marine mammals but stated that there have not been any documented cases of a mammal being entangled in an offshore renewable energy device. URS (2009) emphasized the importance of preventing marine mammals from being entangled by offshore wave device moorings and suggested that placing a device on the seafloor bottom could reduce the potential for marine mammal entanglement. URS (2009) also suggested that taut cable moorings should be considered.

Marine mammals comprise five mammalian groups–whales (Order Cetacea), pinnipeds (Order Carnivora), sea otters (Order Carnivora), manatees (Order Sirenia), and polar bears (Order Carnivora). The whales are subdivided into two suborders–the Odontoceti (toothed whales) and the Mysteceti (baleen whales). The baleen whales are main focus of this review, although other marine mammals may occasionally be mentioned. The use of the word 'whale(s)' refers to baleen whales unless otherwise specified. Baleen whales lack teeth but have large, strong bristles of keratin that hang in plates from each upper jaw. The baleen is used to trap invertebrates or fish from the water or sediment that the whale sucks into its mouth. There are three families within the Mysteceti–the Balaenidae (right whales), Balaenopteridae (rorqual whales), and Eschrichtiidae (gray whales).

The types of information necessary to evaluate the potential for whale entanglement within a wave park off coastal Oregon include the physical features of the proposed wave park (cabling parameters and the spacing and number of units), the background ocean conditions off Oregon (ambient sound features and water clarity to understand the limits on whale sensory environment), entanglement characteristics (what factors contribute to entanglements), and whale migration patterns, population densities, sensory physiology (mainly vision and hearing), and behavior (feeding). The literature review was designed to gather this information.

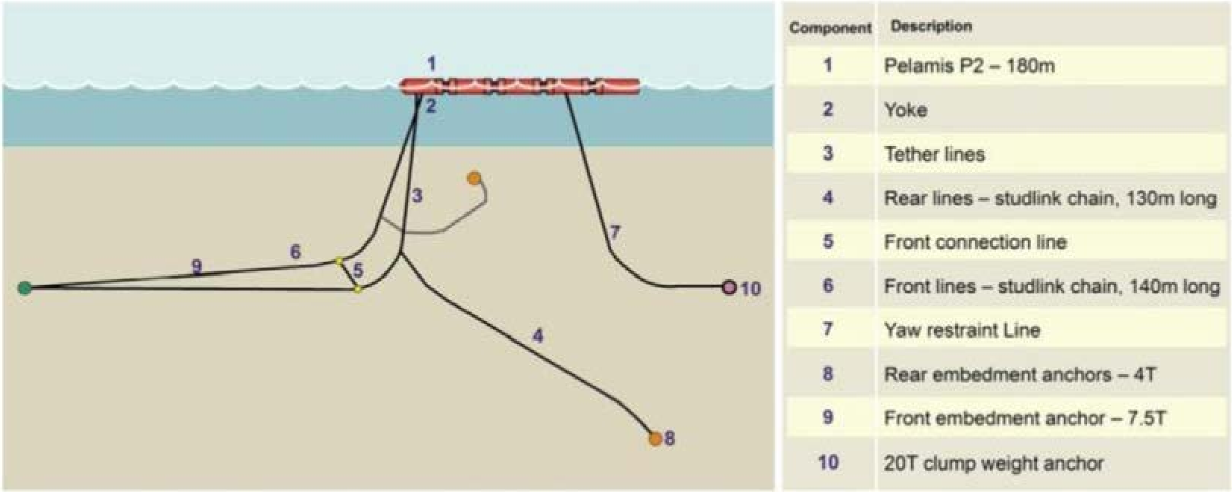
2.0 Methods and Approach

The initial literature search was conducted by using the Web of Science® databases component of the Thomson Reuters Web of Knowledge^{SM} to identify articles that would be useful to help assess the potential for gray whale entanglement in cables and/or collision with structures associated with offshore wave parks. The search was expanded to include a broader information base about whale entanglement and collisions in general, including interactions with fishing gear and ships. Additional sources were identified by cross-checking the Web of Science® databases for articles that cited the articles initially identified. Copies of relevant literature were obtained directly via the Pacific Northwest National Laboratory (PNNL) Library subscriptions or through the Library's interlibrary loan services. Some references were obtained from the Cascadia Research Collective web site (http://www.cascadiaresearch.org/). Cascadia Research is a non-profit scientific and education organization located in Olympia, Washington, that conducts research on marine mammals. The search was supplemented by using the Google™ and Google Scholar™ search engines. The latter also provided copies of some literature.

3.0 Wave Park and Ocean Conditions Background

3.1 Pacific Coast Wave Parks

This review examines three common types of wave parks that may be placed off the U.S. west coast: the Pelamis Wave Energy Converter, the Wave Dragon ApS Wave Converter, and the Ocean Power Technologies (OPT) Power Buoy. The Pelamis Wave Energy Converter is a linear surface attenuator. Each 180-m-long steel unit consists of five 4-m-diameter tubes (13-ft-diameter) that are linked via hinged joints. The moorings for the Pelamis device are designed for the specific deployment location but generally include main mooring lines and a yaw restraint line (Pelamis Wave Power 2013). Main moorings may have several anchors connected to a central location, and yaw restraints includes a single line and anchor (Figure 3.1). Several devices may be installed within a single wave farm sharing nearby anchor points. Devices in a wave farm are connected by dynamic inter-connector cables, and each device connects to a power export cable via a dynamic downfeeder cable. The interconnector cables are alternately anchored to the sea floor but are kept off the bottom by several floats. The Wave Dragon is a floating, slack-moored, overtopping wave energy converter that varies in size depending on the power generation capacity (Wave Dragon 2005). The mooring system could consist of a central buoy with four anchor lines running into the primary wave direction or a catenary anchor leg mooring system that would be anchored to the sea floor by three groups of three lines (Figure 3.2); Soerensen et al. 2000). Because Ocean Power Technologies, Inc. has received a license to construct, operate, and maintain a wave park off Reedsport, Oregon (FERC 2012), this review uses that facility as an example for the evaluation of the potential for entanglement of large whales in a facilities underwater lines and cables.



Component	Description
1	Pelamis P2 – 180m
2	Yoke
3	Tether lines
4	Rear lines – studlink chain, 130m long
5	Front connection line
6	Front lines – studlink chain, 140m long
7	Yaw restraint Line
8	Rear embedment anchors – 4T
9	Front embedment anchor – 7.5T
10	20T clump weight anchor

Figure 3.1. Mooring components of the Pelamis wave energy converter (from Sea Energy TAG 2012).

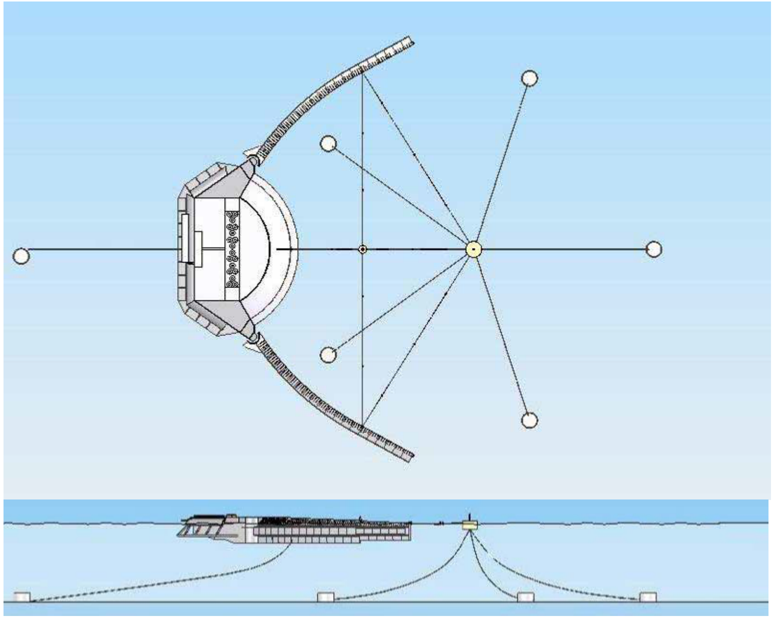


Figure 3.2. Plan view (top) and side view (bottom) of the mooring system for the Wave Dragon APS system (from Soerensen 2006).

3.2 The Proposed Reedsport, Oregon Wave Park

The Ocean Power Technologies, Inc. (OPT) wave park proposed for the Oregon coast would be located 4.6 km (2.5 nmi) off Reedsport, Oregon (FERC 2010). The park eventually would contain ten wave buoys spaced 100 m (330 ft) apart encompassing an area of 12.1 ha (30 ac; Figure 3.3). The width of the park presented to the whales migrating along the coast probably would be no more than 305 m (1000 ft). Water depths at the proposed park site range from 50 to 69 m (165 to 225 ft).

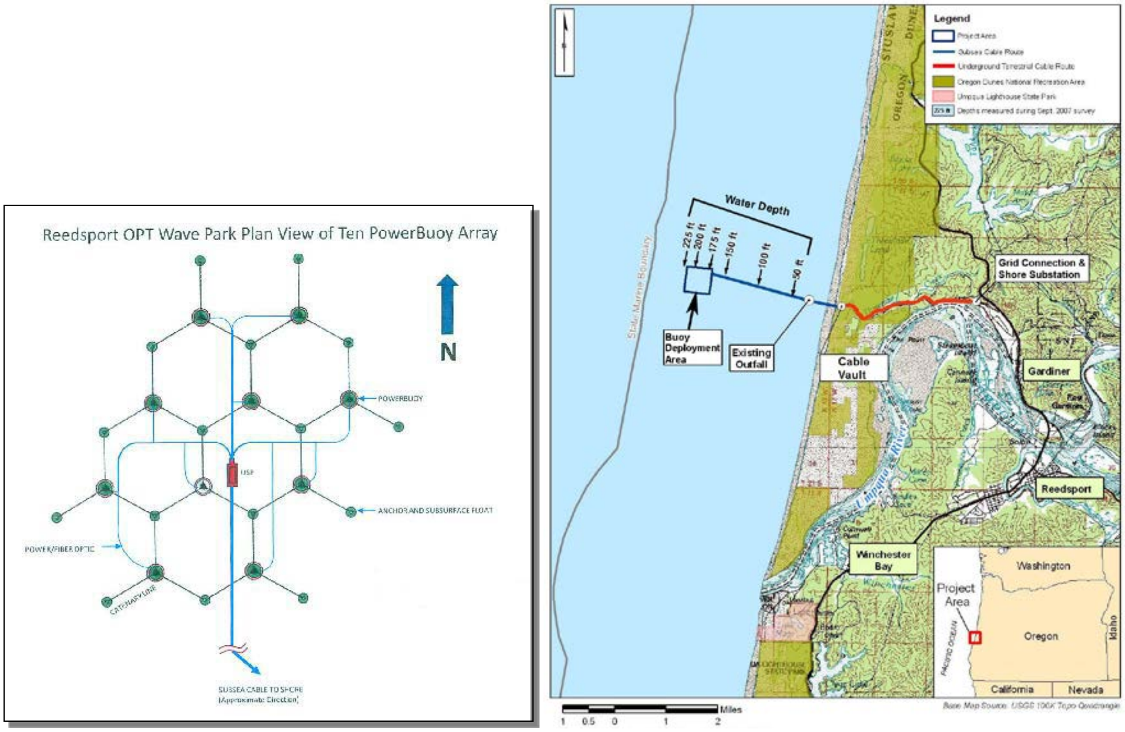


Figure 3.3.Plan view of the proposed wave park and its proposed location off Reedsport, Oregon (FERC 2010).

Each PowerBuoy would have a draft of 35 m (115 ft) and a maximum underwater width of 14 m (46 ft), which would occupy the basal 2.1 m (7 ft) of the buoy. Three 48.8-m (160-ft) catenary lines arranged symmetrically around each PowerBuoy (120-degree separation) would moor each PowerBuoy (Figure 3.4). The anchors likely would consist of steel-reinforced, pre-cured concrete blocks and would be about 10 m (33 ft) in diameter by 7.6 m (25 ft) in height (OPT, Inc. 2010). After settling, the anchors would extend about 5.5 m (18 ft) above the seabed. The mooring and anchoring system would have subsurface floats (SSFs) that would be about 3.0 m (10 ft) wide and 6.1 m (20 ft) tall. The SSFs would provide tension within the moorings, keeping the mooring lines off the seabed and holding the PowerBuoy within a specified area. Taut catenary lines would extend from the PowerBuoy to each SSF and 32-m (105-ft) tendon lines would attach the SSF to the sea-floor-mounted anchors to maintain the SSF at a depth of 9.1 to 15.2 m (30 to 50 ft). The 12.7- to 6.1-cm (5- to 6-in.) diameter mooring lines would be a commercially available synthetic polyester material, with a very high minimum breaking load (the break point was not specified). When a PowerBuoy would be removed from its mooring system for maintenance, the three catenary lines would be connected to each other centrally and supported with an additional SSF that maintains tension on the mooring system. No slack would occur within the mooring system. The wave park's proposed mooring lines and power/fiber optic cables would be more substantial than the fishing or crab pot lines that have been involved in previous entanglement incidents. OPT, Inc. (2010) stated that the mass of the PowerBuoy-anchor system would create several tons tension that would help prevent the cable from wrapping around a passing animal. Each wave buoy would be connected to an underwater substation pod by a power/fiber optic cable that would be connected to a subsurface float and would descend to the bottom in a lazy 'S' pattern (FERC 2010). The power/fiber optic cables descending from the PowerBuoys to the seabed would have a diameter of 7.1 cm (2.8 in.) and two rigid layers of armor wrapped in opposite directions around the cable core that would make it very inflexible (OPT, Inc. 2010). Several floats would be placed on the line to keep it off the bottom. This would be necessary to compensate for cable strain resulting from the up and down movement of the PowerBuoy as ocean swells pass.

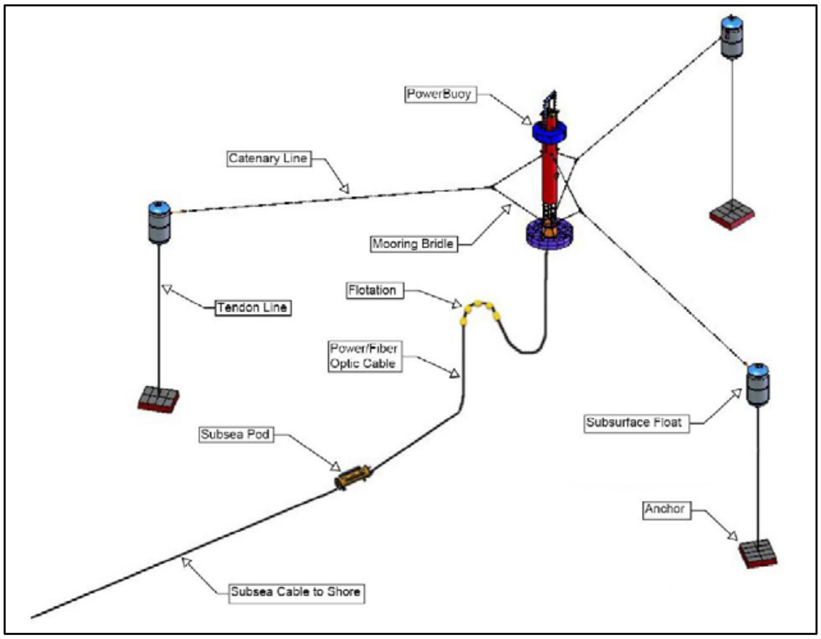


Figure 3.4. PowerBuoy and mooring schematic (from OPT, Inc. 2010).

One of the possible impacts on marine mammals that has been mentioned is the potential effects of the operational noise and vibrations produced by the wave park. It is likely that the major source of operational noise will be from waves hitting the PowerBuoy structures (OPT, Inc. 2010). Although specific noise levels were not projected, OPT, Inc. (2010) presumed that the noise for operating PowerBuoys would be similar to background noise levels in the area. Cables suspended in the sea may produce a low-frequency noise that is produced by the phenomenon of cable strumming. Strumming occurs as water flows past an underwater cable that is movable or has some degree of flexibility (Hudson 1973). The flow causes vortices to form, which cause the cable to vibrate, typically at a frequency of 2 Hz to 20 Hz (Specialty Devices, Inc. 2013). Cable strumming can be suppressed by wrapping material round the cable (i.e., “fairing”) that interrupts to vortices created by the water flow. Specific strumming effects for the Reedsport wave park cables have not been determined. These operational noises also may increase the underwater detectability of the wave park.

3.3 Ambient Conditions off Coastal Oregon

Understanding the background conditions in the coastal waters off Oregon allows an estimation of the places where some whale species are more likely to occur and contributes to evaluating whether a wave park would be detected by whales passing through the area. Oregon coastal waters are characterized by strong upwelling conditions that occur during summer when the prevailing winds are southward (Gan and Allen 2005, Spitz et al. 2005). The conditions also include a strong southward-flowing coastal current over the continental shelf. During winter, northeastward winds produce strong downwelling and surface currents that flow toward the north (Huyer et al. 2007). The upwelling brings nutrient-rich, cold water to coastal surface waters, which is linked to greater zooplankton production. Although the primary increase in nutrient and zooplankton are over the Stonewall and Heceta Bank systems, which are about 65 km (40 mi) offshore and about 60 to 70 km (37 to 43 mi) northwest of Reedsport (Tissot et al. 2008), there is a noticeably higher concentration of zooplankton extending down the coast to off Reedsport, but it is farther offshore than the 50-m (164-ft) depth contour (Spitz et al. 2005). The Stonewall and Heceta Banks have historically had relatively large numbers of humpback whales (Lagerquist and Mate 2002), most certainly because of the high productivity there resulting from the upwelling. Downwelling periods also occur in summer, during which zooplankton concentrations are closer to shore.

Haxel et al. (2011) conducted a year-long experiment to monitor underwater ambient noise in shallow [about 50-m (164-ft) depth], open water at two sites just north of Newport, Oregon. Acoustic recording packages recorded continuous (1 Hz-2 kHz) sound levels at the two offshore locations. The total sound pressure levels recorded during the experiment ranged from 95 dB re 1 μPa to 136 dB re 1 μPa. The time-averaged sound pressure level for the deployment was 113 dB re 1μPa. These data represent initial baseline recordings of shallow-water ambient noise levels in the Oregon nearshore coastal environment before wave energy conversion devices are installed and operated.

Küsel et al. (2012) used a ray-tracing model (Bellhop) to model sound propagation off the coast of Yaquina Head, near Newport, Oregon. They found that simulated sound from a 170 dB source located about 3 nmi (km) from shore at a depth of 5-m (16.4-ft) appeared to develop a surface duct that seemed to trap some sound between the surface and 10-m (32.8-ft) depth. They also observed strong sound reflection off the sea floor. Sound levels appeared to generally be less than 125 dB at about 1000 m (3281 ft) from the source. Experiments to verify the model results were not completely successful because the sound source could not be maintained in a stationary position.

The literature search did not identify scientifically collected information about general underwater visibility for nearshore Oregon waters. However, Nelson et al. (2008b) used a transmissometer attached to the CTD to measure the *in situ* light percentage of a narrow beam of light that reached a receiver with a narrow field of view at 25 cm (9.8 in.) from a light source. The mean transmissivity measured for the coastal Oregon stations was about 65 ± 10%. A 1992 NOAA diving manual characterizes underwater visibility in Oregon coastal waters as ranging from 1.5 to 7.6 m (5 to 25 ft) (NOAA 1992).

4.0 Whale Entanglement Case Study

4.1 Whale Entanglement and Collision

Entanglement in active or derelict fishing gear of many types has serious implications for marine mammal populations worldwide, especially for large whales. Entanglement occurs when fishing gear becomes wrapped around at least part of a marine mammal's body. The fishing gear that entangles mammals primarily includes longlines, traps, pots, drift nets, seines, and gillnets (Vanderlaan et al. 2011). The large-mesh gillnets that are used to reduce the risk of shark attacks at tourist beaches also may entangle large whales (Meÿer et al. 2011). In addition to many records of fishing gear entanglement in continental U.S. waters (e.g., Weinrich 1999, Johnson et al. 2005, Moore et al. 2010, Van Der Hoop et al. 2013a, b), entanglement has been documented as a potential issue in waters off Alaska (Neilsen et al.

2007, 2009), British Columbia (Baird et al. 2002, Williams et al. 2011), Newfoundland and Labrador (Benjamins et al. 2012), Korea (Song et al. 2010), and South Africa (Meÿer et al. 2011). Although the main agent of whale entanglement now is fishing gear, prior to 1959 whales occasionally were entangled in submarine telegraphic cables (Wood and Carter 2008). Wood and Carter (2008) explained that whales (primarily sperm whales, *Physeter macrocephalus*), were most often entangled at sections of the telegraph cable that had been repaired. Repairs were done onboard ships, and the cable lowered to the seabed without concern for the bottom topography and without sufficient tension to keep the cable taut. Also, the cable design itself often contributed to coiling and the formation of loops. The lack of entanglements in communication cables since 1959 is because of advances in cable design, burying techniques, and the transition to coaxial cables, which are less susceptible to forming loops, and eventually to fiber optic cables, which are typically buried beneath the sea floor. There are few records of baleen whales becoming entangled in offshore aquaculture facilities. The greater risk for entanglement appears to be for small cetaceans (e.g., dolphins) to become caught in the anti-predator nets that surround some fish farms (DuFresne 2008). There are at least two records of Eden's (often considered a form of Bryde's) whales (*Balaenoptera edeni*) becoming fatally entangled in spat collection lines in an offshore mussel farm (Lloyd 2003, as cited in DuFresne 2008).

Although baleen whales are the focus of this review, it would be remiss not to acknowledge that toothed whales also become entangled in fishing gear, typically longline gear (Gilman et al. 2006) and gillnets (Reeves et al. 2013). Among the baleen whales, entanglement in fishing gear is a very important issue for the endangered North Atlantic right (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) (Cassoff et al. 2011). Entanglement also has been documented for the minke whale (*Balaenoptera acutorostrata*; Song et al. 2010) and gray whale (Baird et al. 2002).

Several studies have reported the frequency of entanglement for various whale species, predominantly the North Atlantic right whale and the humpback whale. Myers et al. (2007) reported that about 75% of the North Atlantic right whales photographed off the U.S. and Canadian North Atlantic coasts showed evidence (scars, wounds) of being entangled at least once. Most entanglements involved lobster pot gear. Knowlton et al. (2012) evaluated photographs of 626 North Atlantic right whales taken from Nova Scotia to Florida from 1980 to 2009 and found that about 83% of the whales had been entangled at least once and 59% had been entangled more than once. About 26% of the photographed whales were entangled every year. Knowlton et al. (2012) also reported that more whales have pieces of rope still wrapped their bodies in the later years of the study period indicating that it may be becoming harder for whales to break free.

Benjamins et al. (2012) used data collected via a Newfoundland Whale Release and Strandings Program to evaluate the entanglement risk to large whales. They reported that there were 1209 recorded whale entanglements occurring from 1979 to 2008, most of which occurred in nearshore waters. Of these, about 80% (965) were humpback whales and 15% (183) were minke whales. Other whales entangled were 11 fin whales (*Balaenoptera physalus*) and one individual each of North Atlantic right whale, bowhead whale (*Balaena mysticetus*), and killer whale (*Orcinus orca*). The authors also reported a sharp decrease in the estimated annual entanglement rates that was linked to the implementation of a cod fishing moratorium in 1992. Prior to 1993, Benjamins et al. (2012) estimated that about 64 whales were entangled yearly, but from 1993 to 2008, about 19 whales were entangled every year. Neilson et al. (2007, 2009) used photographs of humpback whale tails to estimate non-lethal entanglement rates in the Glacier Bay/Icy Strait region of southeastern Alaska. They estimated that about 52 to 71% of the 180 individual whales photographed in 2003 and 2004 showed scars that were clearly a result of the whale having been entangled. Meÿer et al. (2011) documented that from 1981 to 2009, 80 whales were entangled in the shark nets that protect coastal South African beaches. Of these, 49 were humpback whales and 19 were southern right whales (*Eubalaena australis*). The number of humpback whales captured in the nets per year increased significantly from 2000 to 2009. Other whales captured by the nets were minke, sperm, and Bryde's (*Balaenoptera brydei*) whales. Rescue teams successfully released 65 of the whales from the nets. Meÿer et al. (2011) also recorded 96 entanglements in fishing gear or associated gear from 1975 to 2009 that included 58 southern right whales and 16 humpback whales. The whales were entangled in nets, longlines, anchor lines, and ropes (sometimes with traps or buoys still attached).

How whales become entangled in fishing gear is not completely understood, although there is some evidence that it occurs during feeding activities. Weinrich (1999) reported observations of a group of 30 to 40 humpback whales apparently engaged in feeding dives south of Gloucester, Massachusetts. One juvenile whale surfaced after a short dive and began unusual behavior that included a water slap, rolling 360°, slapping the water with its flukes, and trumpeting. Weinrich and the other observers noticed that the whale was entangled in gillnet gear. They later saw that the gear also was wrapped through the whale's mouth. Weinrich (1999) postulated that the whale became entangled in the gillnet while feeding just beneath the surface of the water. Kot et al. (2012) agreed that it was possible that feeding whales may be "distracted" while engulfing prey and do not detect fishing gear. Additional factors that may lead to entanglement in fishing gear include poor ability to detect objects because of their composition or shape, unfamiliarity with fishing gear, and impaired sensory perception because of poor health or poor ocean conditions (Kot et al. 2012).

Several studies have characterized the injuries to whales and the causes of death resulting from entanglement with fishing gear. Entanglement often does not result in immediate death; when it does, drowning is the most likely cause (Cassoff et al. 2001). Large whales, especially adults, that become entangled with fixed fishing gear (gear "attached" to the sea floor) may have the ability to break part of the gear free from its attachment. However, what this typically means is that the whale remains at least partially entangled in the fishing gear and is still often likely to die from long-term entanglement, which may involve almost any part of the whale's body. Cassoff et al. (2011) found that the most commonly entangled regions of the body were the mouth (67%) and the caudal peduncle ("tail") and flippers (52%). Johnson et al. (2005) reported that the mouth was the most common entanglement point for right whales (77%), but that the tail (53%) and mouth (43%) were the most frequently involved regions for humpback whales. Urbán R et al. (2004) described the complete loss of tail flukes for a gray whale that probably resulted from entanglement. They observed that the whale was still able to swim, feed, and reproduce. However, long-term entanglements often contribute to a slow, prolonged death. Moore et al. (2006) estimated that the average time to death for chronically entangled right whales was about 6 months. This drawn out process often involves reduced feeding ability with resulting slow starvation, serious infections from open wounds, bleeding, general weakness, new bone growth in flippers in response to an entangled cable, and tissue bruising or edema (Cassoff et al. 2011, Moore and van der Hoop 2012, Moore 2013). Chronically entangled whales may also be targets for attacks by large predators with the resulting injuries being fatal (Moore et al. 2013). The reality of the lingering injuries from chronic entanglement has raised substantial welfare issues concerning the potential for suffering by entangled whales (Moore and van der Hoop 2012, Moore 2013) because cetaceans are general considered among the more intelligent, sentient animals (Porter 1992), and many species are considered endangered or threatened.

During the process of disentangling about 132 m (433 ft) of 1.12-cm-diameter (0.4-in.) floating synthetic trap line from a young North Atlantic right whale, van der Hoop et al. (2013b) measured the effects of the entanglement on various dive parameters and the whale's energy requirements. The study found that the whale descended into dives and ascended from them more slowly, had shorter, shallower dives, and used fewer fluke strokes when entangled than when disentangled. Van der Hoop et al. (2013b) estimated the energy costs of entanglement by towing various configurations of the gear removed from the whale from a small boat and compared that expenditure to that of an unencumbered whale. The study estimated that a free-swimming whale swimming at about 1.5 m/s (4.9 ft/s) would take about 22 d to finish a 2900 km (1802 mi) migration and would require about 7.3×10^9 J of energy to do so. An entangled whale that was towing only fishing line would expend about 27% more energy (9.3×10^9 J) to complete the migration in the same time. Adding buoys to the entangled gear would increase the energy expenditure by about 37% versus that of a free-swimming whale.

Van der Hoop et al. (2013a) determined the cause of death for about 754 large whales in the northwest Atlantic from 1970 through 2009. Of these, 502 (67%) were attributable to human causes, with entanglement accounting for 323 deaths, the highest source of human-related fatalities. Baird et al. (2002) estimated that about 27% of gray whale deaths in British Columbia waters from the late 1960s to the mid-1990s were related to fishing operations. They estimated the annual mortality at about 2.0 to 2.4 individuals.

Two studies have examined the types of injuries caused by entanglement and the forces necessary to create them. Woodward et al. (2006) evaluated the effects of new and old, floating and sinking 9.5-mm-diameter (3.7-in.) fishing lines on a right whale fluke collected from a deceased, stranded whale. They found that the new line was much less abrasive than the older, frayed line. At the maximum force applied at 60 cycles per minute (alternating slack and taut lines) for 24 h, 267 N [9.0 kg (19.8 lbs) load], the lines did not break the skin but left furrows in the fluke that were as deep as 0.31 cm (0.12 in.). The ropes left marks on the fluke that were similar to those observed on some stranded whales. Winn et al. (2008) took the evaluation an additional step because skin penetration is typically observed on stranded whales. They found that when a load was pulled across a fluke at 5 cm/s (2 in./s), a load of about 7 to 11 kg (15 to 24 lbs) was required to break the skin of a right whale calf flipper, whereas loads of about 28 kg and 32 kg (62 and 71 lbs) were required to breaks the skin of a subadult humpback and an adult right whale, respectively. The study also found that when oscillatory (saw-like) loads were applied to the leading edge of a flipper, there was a greater occurrence of abrasive wounding when the applied load was greater than the tissue compliance, which was defined as the greatest deformation of the leading edge in response to a load before the line began slipping across the skin. The study suggested that ropes most likely would not cut into the skin until they begin to move along the skin surface.

The risk of collision with marine and hydrokinetic (MHK) energy devices is a frequently mentioned concern for marine mammals. Unfortunately, as of about 2010 there was no scientifically collected data on which an evaluation of the risk of collision could be evaluated for marine mammals (Souder et al. 2010). The present literature review did not find any recent information that is directly relevant to the issue. The potential issue has most frequently been evaluated by considering parallel issues, such as collisions with ships and interactions with fishing operations (Carter et al. 2008, Souder et al. 2010). Although it is tempting to evaluate potential collisions with MHK devices by drawing parallels with marine mammal collisions with ships, the two types of collision have little in common. Nonetheless, there is some information regarding collisions with ships that may apply, albeit indirectly, to the evaluation of the potential risks to large whales from colliding with MHK devices. Collisions with ships involve a large, relatively fast-moving object (a ship) with a much smaller, relatively slow-moving object (a whale). The risk of a fatal injury occurring from the collision between a whale and a ship has been shown to increase substantially with the speed of the vessel at the time of collision (Vanderlaan and Taggert 2007, Conn and Silber 2013). The studies estimated that at a vessel speed of about 15 knots, there was about an 80% chance that a whale colliding with the vessel would sustain fatal injuries. At slower vessel speeds, the probability of a lethal injury occurring drops to less than about 20% at speeds slower than 5 knots. Both studies were concerned with impact injuries, not those caused by strikes from propeller blades. The evaluation process has involved attempts at modeling the potential for collision. Carter et al. (2008), in a rather brief presentation, estimated the levels of sound that would be received by a marine mammal at varying distances from the sound source (a hypothetical MHK device), which would provide an estimate of the warning time for the mammal. Not surprisingly, the detection distances (10 m to >10km; 32.8 ft to >6.2 mi) and warning times (<1 s to 20 min) varied considerably with the level of the source sound, background noise, and the hearing capability of the mammal species.

4.2 Likelihood of Encounter

The potential encounter probability between a wave park and marine mammal can be estimated to evaluate the potential likelihood of an interaction. Wilson et al. (2007) developed a model to predict the encounter rate between marine animals and marine renewable energy devices. They stressed that an encounter differs from a collision. If an animal encounters a renewable energy structure, a collision may result if the animal does not avoid or evade the device after it has been detected. The collision rate, then, is a function of the encounter rate and the probabilities that an animal avoids or evades the device. Because the avoidance and evasion probabilities are not presently known for most, if not all, species, collision rates cannot be estimated. Wilson et al. (2007) based their model on predator-prey encounter models that have been commonly used to estimate predation rates. Applying such a model to the question of potential encounters between marine mammals and renewable energy devices requires knowledge of the density of the animals per km^2 near the device, the swimming speed of the animal, and the relative sizes of the animal and the device. The encounter rate can be calculated for a single device and extrapolated to the total number of devices planned for an area. The Wilson et al. (2007) model predicts that although the encounter rate decreases with increasing size of an animal because of decreased animal density in the area of a device, the encounter risk increases, such that a larger animal has a greater risk of an adverse encounter than a small animal.

Vanderlaan et al. (2009) used a Poisson model to evaluate the probability of large whale (e.g., fin, humpback, right, minke) collisions with vessels. In doing so, they asserted that the probability was not symmetrical because there are many vessels transiting whale habitats relative to the few number whales occupying those habitats. A similar approach might be applicable to the evaluation of potential whale interactions with a wave park, albeit with a reverse perspective because the number of whales is much larger than the number of wave park structures. Vanderlaan et al. (2009) calculated the Poisson parameter (μ) based on the number of whale strikes per year for a certain number of years. They then used the Poisson parameter to estimate the probability that various numbers of whale-vessel collision would occur within a region each year. Using this approach, the authors estimated that between 1999 and 2002 there was a 50% probability of 14 or more whale-vessel collisions occurring worldwide annually and a 60% chance that a northern right whale (*Eubalaena glacialis*) would be killed in the North Atlantic because of a vessel collision.

4.3 Whale Migration Patterns in the Northeastern Pacific

Of the baleen whales the may occur in coastal Oregon waters, the gray whale is the most likely to encounter an offshore wave park. Other baleen whales that are likely to swim through coastal Oregon waters are the humpback and blue whales. The range of the North Pacific right whale (*Eubalaena japonica*) historically included waters down to Baja California but is now much more restricted (North Pacific Right Whale Recovery Team 2004). There are only three record sightings occurring off the Oregon and Washington coasts since the 1950s (North Pacific Right Whale Recovery Team 2004, NMFS 2013). Fin, sei, and minke whales have not been sighted, or have only very rarely been sighted, in the nearshore waters off Oregon (Carretta et al. 2013).

Twice each year, east Pacific gray whales swim between their breeding grounds in Baja California and their main feeding areas in the Bering Sea. This round-trip swim of about 15,000 to 20,000 km (8100 to 10,800 nmi) is one of the longest known migrations by a mammal (Shelden et al. 2004). The whales' migration route is somewhat unusual because it follows very close to the shoreline. This proximity to shore allows scientists to study the migration and permits the general public to observe a large marine mammal. The southbound migration from the Bering Sea to Baja California generally begins in late fall and continues until early winter. The northbound migration occurs in two phases. Adult males, newly pregnant females, and immature whales (called Phase A) begin the northward swim from the central Baja California lagoons back to the feeding grounds in late winter. A few weeks later, mothers and newborn calves (Phase B) begin the journey. The northbound migrations generally are closer to shore than the southbound trip although there is overlap.

Green et al. (1995) found that in 1990 most southbound gray whale groups (66%) swam more than 10 km (5.4 nmi) offshore. Whales that passed Washington were farther offshore (25.2 km; 13.6 nmi) than those that passed Oregon (11.9 km; 6.4 nmi). Most northbound whale groups (76%) swam within 10 km (5.4 nmi) of the shoreline. Again, whales passing Washington were farther offshore (11.8 km; 6.4 nmi) than those passing Oregon (7.5 km; 4.0 nmi). Only 16% of the whales passing Oregon were within 5 km (2.7 nmi) of shore. When Phase A whales pass the northern tip of Vancouver Island, rather than crossing the 200 km (nmi) of open water from the island and Haida Gwaii, they enter Queen Charlotte Sound and swim through Hecate Strait, reaching southern Alaska at Dixon Entrance (Ford et al. 2013).

Ortega-Ortiz and Mate (2008), via observations at Yaquina Head, Oregon, in late 2007 and early 2008, found that most southbound gray whales passed the Oregon coast in January; the whales appeared along the coast through late February to early March (Figure 3.2). The average distance offshore that whales swam during the southbound trip was 6.6 km (3.6 nmi). The total corridor width extended from 2.5 to 12.5 km (1.3 to 6.7 nmi) offshore, and most whales swam about 5.5 to 7 km (3.0 to 3.8 nmi) offshore. Southbound whales swam in waters that averaged 52 m deep (171 ft); with most whales occupying waters 47 to 61 m deep (154 to 200 ft). The study also found that most southbound whales swam at speeds ranging from about 6 to 8 km/h (about 3.7 to 5.0 mph) with an average speed of 6.74 km/h (4.2 mph).

During the northbound swim, gray whales in Phase A appeared off Oregon from late February to about mid-April (Ortega-Ortiz and Mate 2008). Whales in this phase swam an average of 5.1 km (2.8 nmi) offshore. The total corridor width extended from 1.5 to 10.5 km (0.8 to 5.7 nmi) offshore, and most whales swam about 3.5 to 6.5 km (1.9 to 3.5 nmi) offshore. Whales in Phase A swam in waters that averaged 46 m deep (151 ft); most whales occupied waters 39 to 53 m deep (128 to 174 ft). Northbound gray whales in Phase B swam past Oregon from mid-April to late May (Ortega-Ortiz and Mate 2008). Whales in this phase swam an average of 4.1 km (2.2 nmi) offshore. The total corridor width extended from 0.25 to 10.25 km (0.1 to 5.5 nmi) offshore, and most whales swam about 2.1 to 5.7 km (1.1 to 3.1 nmi) offshore. Whales in Phase A swam in waters that averaged 38 m deep (125 ft), and most whales occupied waters 28 to 48 m deep (92 to 157 ft). Ortega-Ortiz and Mate (2008) reported that migrating whales tend to swim along a path that follows relatively constant water depth rather than swimming a relatively constant distance off the shoreline. Most northbound in Phase A swam at speeds of about 5 to 7 km/h (about 3.1 to 4.3 mph) with an average speed of 6.05 km/h (3.8 mph). Whales in Phase B swam more slowly with speeds ranging from 4.5 to 5.9 km/h (about 2.8 to 3.7 mph) with an average speed of 5.42 km/h (3.4 mph or 4.99 ft/s).

Additional evidence that gray whales usually swim close to shore is provided by Shelden et al. (2012) who analyzed data from counts of southbound migrating gray whales over the last four decades from Yankee Point and Granite Canyon near Carmel, California. Almost all (96%) of the whales were within 4.8 km (2.6 nmi) of shore, with about 94% occurring within 1.7 km (0.9 nmi) of shore. The authors estimated the median distance offshore that whales occurred ranged from 2.1 to 2.6 km (1.1 to 1.4) nmi but did not detect any time-related trends. Annual abundance fluctuations may reflect annual variation in numbers of whales that migrate as far south as Granite Canyon or variation in observer estimation of group size.

Gray whales passing through Oregon waters probably includes at least a few individuals from the endangered western Pacific population. Lang et al. (2011) used samples from eastern North Pacific gray whales feeding north of the Aleutian Islands and from whales feeding off the northeastern coast of Sakhalin Island, Russia to update previous studies of genetic differentiation between eastern and western North Pacific gray whales. Their results revealed identical genetic profiles between a whale sampled off the coast of San Diego and one taken off Chukotka, Russia and between two whales biopsied at Sakhalin and two from off the coast of southern California. The genetic results and photo identification studies suggested that some whales that summer off Sakhalin Island overwinter in the eastern North Pacific, at least during some years.

Weller et al. (2012) made photo-catalog comparisons of gray whales in the western and eastern North Pacific that identified some ‘Sakhalin Island’ whales, which belong to the endangered western North Pacific gray whale population, occurring off southern Vancouver Island, British Columbia, Canada. The study also found that some Sakhalin gray whales occurred in Laguna San Ignacio (Mexico). The photo-identification matches by Weller et al. (2012) and the genetic matches noted by Lang et al. (2011) provide evidence that gray whales move between the eastern North Pacific and the western North Pacific.

Humpback whales range worldwide and frequently occur in coastal waters (Clapham et al. 1999). They often undergo very long migrations, with round trips of about 16,000 to 17,000 km (9941 to 10,563 mi) (Stone et al. 1990, Rasmussen et al. 2007). Calambokidis et al. (2001), based on wintering populations in Japan, Hawaii, and Mexico, asserted that there are at least three distinct subpopulations in the North Pacific. Calambokidis et al. (2001) also identified eight feeding areas, all of which are located in the northeast Pacific from California to the Aleutian Islands. One area includes Washington, Oregon, and California. Mixing of whales from the overwintering or feeding areas occurs but is very infrequent. Most whales that feed off the U.S. west coast winter off mainland Mexico (Calambokidis et al. 2001) and Costa Rica (Calambokidis et al. 2000). Despite their inclusion in the west coast feeding area, Washington and Oregon appear to have relatively low humpback whale occurrences. Of the 973 humpback whales recorded in the area from 1991 to 1997, only 45 occurred off Washington and Oregon (Calambokidis and Barlow 2004). Tynan et al. (2005) found that most humpback whales occurred in waters 200 to 2000 m (656 to 6562 ft) deep and were primarily associated with the shoreward edge of the upwelling front during late spring and summer. During August the whales were seen at Heceta Bank and off Cape Blanco, which is about 129 km (80 mi) south of Reedsport. Lagerquist and Mate (2002) recorded five humpback whales during flights over the Stonewall and Heceta Banks in August 2002.

Blue whales are the largest living animals and occur in all of the world's oceans. The Northeast Pacific Ocean is home to a blue whale population that is likely distinct from populations in the central and western Pacific (Calambokidis and Barlow 2004). Although details of the migration are not known, the eastern Pacific blue whales migrate from tropical waters where they reproduce in the winter and spring to feeding areas at progressively higher latitudes in summer and fall (Burtenshaw et al. 2004). Burtenshaw et al. (2004) tracked blue whale calls from 1994 to 2000, and found that whale calls typically occurred off Oregon from about late September through late January, with peak calls recorded in late October. Blue whale density off Oregon was relatively low compared to that off California. The whales apparently do not spend much time in Oregon waters, simply passing through them toward more northerly locations. Calambokidis et al. (2009a) pointed out that blue whale migration patterns and population centers may vary with changing ocean conditions. Prior to 1980, blue whales were relatively common in the British Columbia-Alaska area and relatively uncommon off California. That situation reversed in the 1980s but may have shifted back to more frequent blue whale use of northern waters (Calambokidis et al. 2009a).

4.4 Whale Populations in the Northeastern Pacific

To estimate the likelihood that whales would encounter a wave park off the Oregon coast, it is necessary to have some information about population densities in the area of the park. Unfortunately this information is often lacking. Each year the National Marine Fisheries Service (NMFS) develops marine mammal stock estimates for each of its monitoring regions. The most recent available is the 2012 stock assessment that has updated information for the gray whale but repeats 2011 information for the humpback and blue whales (Carretta et al. 2013).

Carretta et al. (2013) used a population level calculated for southbound gray whales in 2006 (19,126 individuals) to estimate the current minimum population level for the eastern North Pacific stock as 18,017, which includes about 180 individuals that are part of the Pacific Coast Feeding Group. Punt and Wade (2010) stated that the eastern North Pacific population has been increasing since an unusual mortality event that occurred in 1999 to 2000. The Pacific Coast Feeding Group population currently is thought to be stable (Carretta et al. 2013). Ortega-Ortiz and Mate (2008) found that most of these whales passed the Oregon coast through a corridor that was about 3.5 to 6.5 km (1.9 to 3.5 nmi) offshore during the northern migration and about 5.5 to 7 km (3.0 to 3.8 nmi) offshore during the southern migration. The proposed Reedsport wave park would be located within the northern migration path but not that of the southern migration.

Carretta et al. (2013) cited several studies that provide evidence that humpback whales in the Pacific Ocean comprise at least four stocks, one of which consists of whales that feed off the U.S. west coast and overwinters off Mexico and Central America. Calambokidis et al. (2009b) used data collected in 2008 to estimate the population level of this latter California/Oregon/Washington Stock at about 2043 whales off California and Oregon and about 550 whales off Washington. This stock population represents about 10 to 11% of the estimated humpback whale total Pacific population of about 18,000 to 21,000 whales (Calambokidis et al. 2008). Calambokidis et al. (2009b) also reported that the California/Oregon/Washington Stock has been increasing at about 8% per year since 1991. Calambokidis et al. (2009b) indicated that about 163 of the 13,991 whale identifications made from 1986 to 2008 occurred of Oregon. Of the Oregon sightings, 120 were unique identifications. However, it appears that the low numbers off Oregon maybe at least partly related to relatively low sample sizes. Carretta et al. (2013) used the data from Calambokidis et al. (2009b) to estimate the minimum humpback population level as 1878 whales.

Blue whales in the North Pacific Ocean probably include at least two distinct stocks (Carretta et al. 2013). Blue whales that range from the tropical eastern Pacific to the northern Gulf of Alaska comprise the Eastern North Pacific Stock. This stock feeds off the U.S. west coast during summer and fall and migrates to overwintering areas off Baja California, off Costa Rica, and in the Gulf of California. Calambokidis et al. (2009b) used data collected in 2008 to estimate the abundance of this stock as about 2497 whales. As for humpback whales, blue whales appear to be much more abundant off California than they are off Oregon. Calambokidis et al. (2009b) reported only 14 unique blue whale identifications off Oregon from 1986 to 2008, with all occurring since 2001. They also reported 2028 unique identifications off California during the 1986 to 2008 period. Carretta et al. (2013) used the 2008 data to estimate the minimum blue whale population level at about 2046 individuals and noted that there is no evidence indicating that the population is growing.

The estimated minimum population level for fin whales in the waters off California, Oregon, and Washington is about 2624 individuals, whereas those for minke and sei whales are 202 and 83 individuals, respectively (Carretta et al. 2013).

4.5 Whale Sensory Perception

The sensory systems of marine mammals have adapted to life in a watery medium but are generally similar to those of their terrestrial kin (Wartzok and Ketten 1999). Water changes the way light and sound signals are transmitted. Water absorbs, scatters, and reflects light, with the specific amounts varying according to the amount of particulate material (e.g., suspended sediments, plankton) in the water and the wavelength of light. In coastal waters, the maximum penetration is for greenish light having a wavelength of about 510 to 540 nm (Wartzok and Ketten 1999). Bluish light (wavelength ~475 nm) penetrates best in open ocean waters. In open ocean waters, light intensity (irradiance) decreases about 90% for every 70 m (230 ft) increase in depth. Sound transmission is directly related to the density of the medium through which it is passing. Thus, sound travels faster and diminishes less moving through water than sound moving through air (Wartzok and Ketten 1999). In general, sound travels about 4.5 times faster in water than it does in air. Increases in temperature, pressure, and salinity increase sound transmission speed. In shallow coastal waters, the interaction between sound and the sea surface and sea bottom can amplify or attenuate sound transmission (Küsel et al. 2012). Sound pressure is quantified as a logarithmic measure that expresses the ratio between a measured pressure value and a standardized reference. The ratio is expressed as decibels (dB), and the reference pressure in seawater is “decibels relative to one micro Pascal” (dB re 1 µPa).

Since light levels underwater are much less than those in air, marine mammals have two main mechanisms for increasing the amount of light captured by the eyes so that they can receive visual signals

(Wartzok and Ketten 1999). Marine mammal eyes are equipped with large numbers of photoreceptors to enhance light capture. Just behind the retina is a reflective layer, the tapetum lucidum, that bounces light that was not captured by the photoreceptors back through the retina to make it available again for capture.

Light sensitive visual pigments are found in the rods and cones of a mammalian eye. The cones function in brighter light situations and detect color, whereas the rods function primarily in low light situations (Fasick et al. 2011). Most mammals have two types of color detectors, short-wavelength-sensitive (S-) cones and middle- to long-wavelength-sensitive (M/L-) cones, which detect the blue to ultraviolet (UV) and green to red part of the spectrum, respectively (Griebel 2002). However, many marine mammals (all cetaceans, seals, sea lions) lack functional S-cones, which means they cannot detect colors in the blue to UV part of the spectrum (Peichl et al. 2001, Levenson and Dizon 2003). Levenson and Dizon (2003) documented the lack of functional S-cones in six baleen whales species, including gray and humpback whales. Levenson and Dizon (2003) also indicated that the loss of the S-cone likely occurred prior to the split of the odontocete and mysticete lineages. The lack of S-cones in marine mammals is unusual considering the shift toward blue light wavelengths in the ocean, particularly in deeper waters, and its adaptive significance is not yet understood. The loss may be related to the high scattering propensity of the shorter wavelengths (Levenson and Dizon 2003).

Rods are the predominant light receptors in the retina of a cetacean, comprising about 99% of the detectors (Griebel and Peichl 2003). Rods in a whale’s eye have the same visual pigment as the rods of a terrestrial mammal, but their light sensitivity is shifted somewhat toward shorter wavelengths (McFarland 1971). The visual pigments of most mammals have a maximum absorbance (λ_{max}) of about 500 nm (Bischoff et al. 2012), which may be related to the distribution of light at dawn and dusk and at night in terrestrial habitats (McFarland 1971). For two mysticete whale species, the shift toward shorter wavelengths is very slight at most. McFarland (1971) estimated the λ_{max} for rods in the gray whale eye to be about 497 nm, and Fasick et al. (2011) estimated the λ_{max} for North Atlantic right whale rods at about 499 nm. The lack of a strong shift toward shorter wavelengths for each species is most likely related to the predominant use of shallow-water coastal habitats by the gray whale and the surface-feeding behavior used by the right whale. Other marine mammals, including some baleen whales, have stronger shifts toward shorter wavelengths. Bischoff et al. (2012) calculated the λ_{max} values for 11 baleen whale species and 3 toothed whale species. They used these values to group the various baleen whale species into three habitat groups--deep sea, pelagic, or surface. The deep-sea “group” consisted of only one species, the pygmy right whale (*Caperea marginata*), with rods whose λ_{max} is 479 nm. Little is known about the biology of the pygmy right whale, which was recently placed in a whale family (Cetotheriidae) that was thought to be extinct (Fordyce and Marx 2013), but its rods have a maximum absorbance that is similar to that of sperm whales and Sowerby’s beaked whale (*Mesoplodon bidens*), which are known to feed in the deep-sea. The pelagic baleen whale group included blue, minke, fin, sei (*Balaenoptera borealis*), and Bryde’s whales, all in the Family Balaenopteridae, and had rods whose λ_{max} is 484 nm. These whales are “lunge feeders” that feed on swarms of planktonic prey (krill, herring) removed from large volumes of water captured in single, repeated gulps or by steadily swimming through a dense prey school (Goldbogen et al. 2013). The surface whale group included the gray whale (Family Eschrichtiidae), the bowhead whale (Family Balaenidae), and the North Atlantic and southern right whales (Family Balaenidae) with rods whose λ_{max} is 493 nm. These whales often feed near the water surface (Balaenidae) or on the benthos in shallow coastal waters (gray whale). Humpback whales have rods whose λ_{max} is 492 nm, which is close to the surface group.

Mass and Supin (1997) investigated the visual acuity (i.e., the ability to see fine detail) of gray whales by examining the structure of the eye and determined that the retina contained mostly large neurons and had a mean ganglion cell density over the whole retina of 70 cells/mm^2. Cell densities were higher in the nasal and temporal areas of the retina, with averages of 130 and 183 cells/mm^2, respectively. Both high density areas are located near the equator of the retina. Mass and Supin (1997) stated that these areas are the best vision areas of the retina because the higher cell densities provide better visual resolution. The two high density areas align with the horizontally oriented slit that occurs with dilation of the pupil, which provides light to the best vision areas. The authors estimated the best visual acuity of the gray whale as about 11 and 13 arcmin for the nasal and temporal areas of the visual field, respectively. Visual acuity estimates for other cetaceans include 7 and 7.6 arcmin for minke whales (Murayama et al. 1992), 9.7 and 10.4 arcmin for killer whales (Mass et al. 2012b), 14 and 17 arcmin for belugas (*Delphinapterus lucas*; Mass and Supin 2002), and about 19 arcmin for the Florida manatee (*Trichechus manatus latirostris*; Mass et al. 2012a). These estimates indicated that gray whale visual acuity in water is slightly worse than some cetaceans (e.g., minke whales) but is better than others (e.g., beluga). For reference, 20/20 vision in humans is defined as being equal to 1 arcmin (Evans 2006).

Most of what is known about hearing in cetaceans has been derived from studies of toothed whales, and relatively little is known about hearing in baleen whales (Au 2007, Mooney et al. 2012). Au (2007) mentioned that even a basic understanding of how baleen whales hear, what frequencies they hear, and how sensitive they are to various frequencies is generally unknown. In large part, this lack of knowledge is attributable to the large size of the whales, and that they have not been trained or kept in captivity as has been done for toothed whales. What is known about baleen whale hearing has been derived from studies of anatomy, responses to sound playbacks, and recordings of the sounds baleen whales produce (Mooney et al. 2012). Au (2007) remarked that it is difficult to understand how baleen whales hear given the lower jaw anatomy and the lack of a connection between the jaw and the temporal bones. However, a recent study by Yamato et al. (2012) identified the presence of a fat body associated with the ears in a minke whale that was very similar, albeit smaller than, than acoustic fats that transmit sound in toothed whales. Mooney et al. (2012) mentioned that studies of baleen whale anatomy suggest that the whales hearing is mainly within a low frequency range. This would seem to be supported by Parks et al. (2007) who used basilar membrane thickness measurements to predict that right whales would detect sounds within a frequency range of 10 Hz to 22 kHz.

Playback responses, in which a researcher plays sounds of various types and frequencies, can provide some information about the sounds baleen whales hear. However, there are some important caveats. Playback response experiments typically are not designed to measure whale hearing but test the effects of certain sounds on whale behavior. Also, it is important to remember that the lack of a response to a stimulus does not mean that that the stimulus was not perceived (Fryer and Iles 1972, Mooney et al. 2012). Au (2007) and Mooney et al. (2012) summarized the results of some playback experiments as indicating that whales responded to sound intensities of about 85 to 120 dB and frequencies within the range of about 15 Hz and 28 kHz.

That baleen whales produce sounds is well-known, particularly because of humpback whale “songs” (Payne and McVay 1971). Although sounds are an important part of the social interaction among humpback whales (Parsons et al. 2008), they have also been thought to serve a sonar function used in particular by males to locate other individuals (Frazer and Mercado 2000). The sonar hypothesis generated considerable argument and may not yet be resolved (Au et al. 2001, Mercado and Frazer 2001, Parsons et al. 2008). Other baleen whales produce sounds. For example, blue whales (*Balaenoptera* *musculus*) produce powerful moaning sounds with a frequency range from 14 to 222 Hz and a duration of about 37 s (Cummings and Thompson 1971). Fin whales produce long bouts of 18- to 23-Hz sounds at 7- to 26-s pulses that likely are part of the species' reproductive behavior (Watkins et al. 1987). Cummings et al. (1968) recorded underwater sound produced by migrating gray whales and described moans at frequencies ranging from 20 to 200 Hz and lasting about 1.5 s as the most common sound. Gray whales also made blowing and bubble sounds that ranged from 15 to 305 Hz. The whales made knocking sounds at frequencies as high as about 375 Hz. Sounds were produced night and day and not associated with particular behaviors other than the exhalation blow sounds. Crane and Lashkari (1996) recorded gray whale sounds in deep and shallow water during migration. Sounds were characterized as pulses and bonging signals low-frequency moans, grunts, and subsurface exhalations. Crane and Lashkiri (1996) found that whales produced sounds more often when they were in lagoons than when migrating and when they were in shallow water versus deeper water. The low-frequency moans were the most common signals, supporting the earlier finding by Cummings et al. (1968). Crane and Lashkiri (1996) thought that gray whales used sounds for communication, not for echolocation, because of sound production pattern and the often long silent periods between sounds.

Despite the apparent deficiencies in baleen whale vision and hearing, there is some evidence that some baleen whales can detect and respond to the relatively fine lines that comprise fishing gear. Kot et al. (2012) deployed several rope systems in the Gulf of St. Lawrence to evaluate the ability of minke whales to detect the vertical buoy lines used with whelk and crab traps. The variably colored rope systems were made of 1.5-cm (0.6-in.) diameter polypropylene line, such as that used by trap fishers. The study showed that whales slowed as they approached the rope system and increased speed after passing it. Whales also changed direction when approaching a rope system, responding most strongly to black ropes. Underwater observations showed that the whales swam in a parabolic path around the rope systems. The study results strongly suggested that minke whales visually detected the rope systems during the day, and that white and black ropes probably were the easiest to detect. Kot et al. (2012) acknowledged that the ropes also may produce a detectable sound as water flows through the system, but that possibility has not yet been tested.

4.6 Whale Diving and Foraging Behavior

Most gray whales in the eastern Pacific migrate northward to the northwestern Bering, the Chukchi, and the Beaufort Sea to feed on benthic amphipods (Highsmith and Coyle 1992, Weller et al. 2013). Benthic feeding whales scoop up large quantities of sediment by scraping the sides of their heads along the bottom, forming pits in the sediment that are about 1.8 m (6 ft) long and 0.9 m (3 ft) wide (Frost and Karpovich 2008). Sediment passes through the baleen, which retains small benthic animals. Migrating gray whales feed somewhat sporadically, although some whales leave migratory routes to feed in shallow, coastal waters (Dunham and Duffus 2001; Newell and Cowles 2006). Whales that leave the migration route, often called summer residents in the areas where they feed, use two basic sources of food, one pelagic and one benthic. Gray whales also may feed on hyper-benthic mysids, small planktonic shrimp-like crustaceans, and porcelain crab larvae in Clayoquot Sound, British Columbia that they capture by straining seawater through the baleen (Dunham and Duffus 2001, 2002; Nelson et al. 2008a). Prime amphipod habitat was located in waters less than 20 m (66 ft) deep. Whales that leave the migration route off Oregon from about May through October, similar to those in Clayoquot Sound, feed primarily on dense swarms of mysids and porcelain crab larvae that typically occur in waters that range from 2 to 15 m (6.6 to 49 ft) deep and are within 0.6 km (0.3 nmi) of shore (Newell and Cowles 2006; Newell 2009).

These “summer residents” off Oregon and British Columbia are more formally known as the Pacific Coast Feeding Group, which was defined by the International Whaling Commission as “whales observed between 1 June to 30 November within the region between northern California and northern Vancouver Island (from 41°N to 52°N) and photo-identified within this area during two or more years” (Calambokidis et al. 2012, Weller et al. 2013). Some of these whales may venture northward to Barrow, Alaska to feed (Calambokidis et al. 2012).

Rorqual whales (humpback, blue, minke) feed on pelagic prey, such as krill (planktonic crustaceans) and small fish), by engulfing large volumes of water in a single gulp and straining it through the baleen to remove the organisms. During lunge feeding, fin whales accelerate to fast speeds and open their mouths wide to engulf large masses of prey (Potvin et al. 2009; Simon et al. 2012). Lunge feeding is not completely passive, and the volume of the water engulfed can be controlled by muscles that line the ventral part of the buccal area (Potvin et al. 2009). Simon et al. (2012) showed that lunge-feeding humpback whales begin to slow as the buccal pouch reaches its largest size, and the whales use fluke strokes throughout the lunge to avoid slowing to a near or complete stop and glide at a relatively slow speed after completing the lunge. Straining and swallowing the prey takes about 46 s. Humpback whales may make as many as 10 to 15 lunges during a single dive with lunges being targeted at the upper boundary of krill aggregations (Goldbogen et al. 2008). Goldbogen et al. (2012) found that lunge-feeding blue whales occasionally perform a 360° rolling maneuver as they approach dense krill patches. The rolling probably counters the escape response of the prey and allows whales to watch prey behavior so that the mouth can be opened in the area of highest prey density.

5.0 Putting it All Together

There is no doubt that entanglement in underwater cables or lines presents a serious injury or mortality risk to baleen whales. Although most of the evidence now points to fishing gear as the predominant entanglement factor, it is reasonable to evaluate the potential for injury that may result from adding MHK-related cabling to waters frequented by large whales. Understanding this potential requires detailed knowledge of the proposed MHK facility and of the coastal conditions where the facility would be placed. Also required is knowledge of whale use of the waters where the facility would be located, population structure in the area, and various aspects of whale biology, including migration patterns, feeding behavior, and sensory perception. Among the key questions to be evaluated are will whales encounter the facility? If so, which whales would most likely encounter the facility? Once the facility is encountered, would whales be able to detect the obstacles, especially underwater cables, in their paths? If whales cannot detect the obstacles or do not detect them with sufficient time to avoid them, what is the risk of entanglement and subsequent injury and/or mortality? Finally, are there measures that are being considered or should be considered to lessen the potential for injury to whales encountering a wave park?

The following paragraphs attempt to answer these questions to the extent allowed by the studies reviewed. It is important to note that very few of the studies have been designed and conducted with the specific intent of evaluating the potential interaction between large whales and MHK devices, in particular offshore wave parks. Therefore, the answers presented in this section represent inferences of the likelihood of an interaction based on interpretation of information collected by the reviewed studies. There is little information available that allows a direct conclusion about the potential impacts of MHK devices on large whales to be made. These inferences could serve in some form as ideas that might be tested by future studies.

The wave park proposed for the Oregon coast would be located about 4.6 km (2.5 nmi) off of Reedsport in waters about 50 to 69 m (165 to 225 ft) deep. The park would eventually include 10 PowerBuoys that would span an area of about 12.1 ha (30 ac). The width of the park presented to the migrating whales probably would be no more than about 305 m (1000 ft). The 10 PowerBuoys would be spaced about 330 ft apart, and each would be connected to three subsurface floats by 48.8-ft-(160-ft-) long catenary lines. The floats would be connected to seafloor anchors by 32-m- (105-ft-) long tendon lines. The mooring lines would be 12.7 to 152 cm (5 to 6 in.) in diameter and would have a high minimum breaking load. Each PowerBuoy would be connected to a subsea pod by a power/fiber optic cable, the middle section of which is suspended in the water column. The 7.1-cm- (2.8-in.-) diameter power/fiber optic cable would have layers of shielding that would make it inflexible.

Of the several species of baleen whales that inhabit the North Pacific Ocean, most are relatively low in abundance or do not frequent coastal waters off Oregon. Three species have some degree of likelihood of encountering the proposed Reedsport wave park. Some humpback and blue whales occur in the waters off Oregon but do so infrequently. The most likely baleen whale to encounter the proposed wave park is the gray whale, which migrates through Oregon coastal water twice each year. Most of the more than 18,000 gray whales that pass the Oregon coast would swim within 3.5 to 6.5 km (1.9 to 3.5 nmi) of shore while migrating north to feeding areas in the Bering Sea and within 5.6 to 7.0 km (3.0 to 3.8 nmi) of shore on the return trip south to breeding areas in Mexico. Recent genetic studies suggest that some of the gray whales swimming past Oregon may be part of the endangered western Pacific population. Although specific encounter probabilities remain to be calculated, it is very likely that many gray whales would encounter the Reedsport wave park. However, the encounter likelihood is not uniform throughout the year. Based on the timing of the migrations, the most likely encounter period would be during the northbound migration from late February through about late May when the adult males, pregnant females, and immature whales follow a migratory path through shallower Oregon waters that has strong overlap with the location of the proposed Reedsport wave park. During the southbound migration most whales pass the Oregon coast in January at distances farther offshore than the location of the proposed wave park. The number of whales that might encounter the park is further reduced by the tendency of the whales to generally follow depth contours while swimming past Oregon. Thus, whales swimming at depths shallower than the wave park would tend to stay at those depths and whales swimming deeper than the park would tend to stay deeper.

Information gathered about whale sensory perception, particularly that of gray whales, suggests that the wave park structures, especially the relatively small diameter cables that support the structures, would be difficult to detect. Whales have relatively poor underwater vision. They have little to no ability to distinguish colors, especially in the blue to UV range. Gray whale eyes are adapted for life in shallow coastal waters. The eyes have high densities of rods with the highest concentrations located in the two places on the retina best suited to detect light. Gray whale eyes also have a reflective layer associated with the retina that bounces light back that misses the rods through the array of rods so that it might be captured. However, gray whales have relatively poor visual acuity. That is, they have some difficulty discerning relatively small objects. Expressed in terms of human vision, gray whale visual acuity is roughly 20/240. This relatively poor vision, coupled with generally poor underwater visibility, suggests that gray whales would have little time to see wave park structures and react to avoid them. For example, at good underwater visibility conditions (for Oregon) at the slowest average swimming speed for migrating whales, a gray whale would have about 5 s to detect and react to wave park structures (7.6-m or 25-ft visibility; swim speed of 3.4 mph or 5 ft/s).

The question of whether migrating gray whales would be able to detect sounds produced by an operating wave park is difficult to answer. Hearing in baleen whales is not well understood, but some studies indicate that these whales hear mainly low frequency sounds. Baleen whales produce sounds that can travel long distances, but these sounds appear to be used primarily in social communication rather than being used as sonar to detect underwater objects. These observations, coupled with the low-level sounds projected to be produced by a wave park suggest a low likelihood that whales would be able to detect the park at a distance that would allow them to avoid the underwater structures.

Despite these vision and hearing limitations, there may be measures that can be taken to increase the "detectability" of the park to migrating whales. Minke whales have been observed to avoid lines simulating those used in trap fishing, especially when those lines were white or black, which provided relatively stronger contrast in the water column than lines having other colors. Although the study involved only one whale species, the results suggest that contrast among underwater cables, lines, and structures may be an important visual factor in increasing the detectability of wave park cables to large whales. The study also suggested that water moving through the ropes may produce sound that might be detected by the whales, but did not test the hypothesis. Sound warning systems may provide for earlier detection and avoidance of a wave park. A multi-year study determine whether sounds could alert migrating gray whales to the presence of a wave park and to induce them to avoid the park is in progress (Mate and Lagerquist 2010). Results from the study are not yet available.

Considering the information available about gray whale migration patterns and the whales relative lack of sensory capabilities to detect MHK devices, it is unreasonable to presume that all of the whales would detect the wave park and avoid it. Whales that do enter the park risk entanglement in the wave devices' supporting cables or risk colliding with the cables or other underwater structures. The evidence suggests that the risk of entanglement would be low. Entanglements occur with lines that have little tension and can be made to form some kind of loop. The cables associated with the Reedsport array would be taut and very inflexible, making the formation of loops unlikely. The lazy-s cable that connects the PowerBuoy to the subsea pod could have more potential for entanglement because it likely has less tension than mooring cables. It also is smaller in diameter (7.1 cm or 2.8 in.) than mooring lines (12.7 to 152 cm or 5 to 6 in.), but it is double armored with protective layers wrapped opposite directions, which decreases the cable's flexibility. There is some concern that derelict fishing gear might collect on the underwater structures of a wave park, and that gear might represent an entanglement risk to whales. Vigilance and a debris removal program by the wave park operators, such as that proposed by OPT (OPT, Inc. 2010), would help minimize this risk.

The probability of a whale colliding with underwater structures in the park cannot be calculated yet, but the possibility of a collision cannot be discounted. Migrating gray whales do not swim very fast, typically cruising at about 4.8 to 6.4 km/h (3 to 4 mph). Evidence from studies of whale collisions with ships suggests that a collision at such slow speeds is not likely to be life threatening, especially since the mass of the park's underwater structures would be much less than that of a ship. However, there are no data with which this hypothesis can be evaluated. Collision with underwater cables could cause injuries similar to those induced by a cable being pulled along a whale fin or other body part. In such cases, a force greater than about 6.8 kg (15 lbs) for a small whale or greater than about 27.2 kg (60 lbs) for a large whale would be necessary to cause abrasive wounds or cuts. The force with which a swimming whale would collide with a cable has not been determined.

Since interactions between migrating whales and the proposed Reedsport wave park cannot be ruled out, should mitigation measures that might be used to reduce the likelihood of a collision be considered? In its environmental assessment, OPT, Inc. did not identify any measures to proactively reduce the likelihood of migrating whales colliding with park structures. OPT, Inc. did, however plan to conduct post-installation surveys for whales and develop protective measure should whales be found to be colliding with the structures. OPT, Inc. suggested that sound might be used to deter whales from entering a wave park. As mentioned previously, NOAA recently funded a study designed to evaluate such potential use of sound, but the results are not yet available. One study suggests that using white or black cables could increase contrast with background waters and possibly enhance visibility underwater. However, the potential that this would enhance visual detection by gray whales has not been evaluated.

6.0 Information Needs

Two of the key factors that need to be determined to evaluate the potential for whales to become entangled in mooring lines and cables associated with the Reedsport wave park are the encounter probability and the detectability of the park structures. Although some information is available about the numbers of whales that may use Oregon waters, especially for gray whales, there is not sufficient information about whale densities in the specific locale of the wave park to accurately calculate encounter probabilities. Density information for two of the three species most likely to encounter the wave park is difficult to collect because of their relative rarity (humpback and blue whales) and difficulty in obtaining accurate counts. Gray whales migrate close to shore and may be more easily observed. Nonetheless, very accurate counts of whales swimming through the wave park area may be difficult to obtain visually because the whales periodically spend a good portion of their journey underwater and continue swimming at night. Most observational data on these whales, especially gray whales, has been collected from aerial, shipboard, or land-based visual sightings.

The detectability of the underwater structures of the wave park depends on the sensory capabilities of the whales and the physical design of the structures. Although much is known about whale vision and hearing, most of that information is derived from anatomical, not behavioral or physiological studies. Therefore, “conclusions” based on these studies are better considered as hypotheses about whale perception. One study did determine that minke whales could “detect” and avoid ropes placed within their paths. The study suggested that string contrast is an important part of detectability. Such behavioral studies have not been done for the larger baleen whales that may encounter the Reedsport wave park. One study to determine the effect of sound on gray whale behavior is in progress (Mate and Lagerquist 2010), but additional studies of whale vision and sound perception would be useful.

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