ELECTRIC POWER RESEARCH INSTITUTE

EPRI Workshop on EMF and Aquatic Life

2013 TECHNICAL REPORT

EPRI Workshop on EMF and Aquatic Life

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Abstract

A workshop on Electric and Magnetic Fields (EMF) and Aquatic Life was organized by the Electric Power Research Institute (EPRI) and held on November 15, 2012, at the Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. The purpose of the workshop was to help EPRI identify research needs regarding the potential impact of EMF from offshore energy generation and/or underwater transmission cables on various forms of aquatic life. The workshop participants reviewed the current state of knowledge based on field and laboratory studies on the developmental and behavioral effects of EMF on aquatic animals, and EMF marine exposure assessment studies.

The workshop was intended to explore how EPRI might shape a future EMF and Aquatic Effects research program to help fill knowledge gaps on the environmental impact of offshore energy and underwater transmission developments. This is largely in response to the worldwide push for renewable energy development that will include, among others, wave, tidal, and offshore wind facilities. It is also in response to the growing use of undersea cables to transmit power and interconnect grids. The specific objectives of the workshop were threefold:

- Identify gaps in EMF aquatic-life knowledge
- Develop recommendations for future research
- Set priorities for the recommendations

Keywords
Aquatic
Electromagnetic
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Section 1: Introduction

A workshop on EMF and Aquatic Life, hereafter referred to as the "workshop," was organized by EPRI and held at the Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California, on November 14-15, 2012. It had an attendance of 21 individuals from various research communities around the world, as well as EPRI staff. The agenda and list of attendees are shown in Appendices A and B. The purpose of the workshop was to help EPRI identify research needs regarding the potential impact of electromagnetic (EM) fields from offshore energy generation and/or underwater transmission cables on various forms of aquatic life.

The workshop explored the current base of knowledge from field and laboratories studies on the behavioral effects of EMF on aquatic animals, as well as the evolving EMF marine exposure environment. Highlights from the technology workshop are included in this report.

The report is organized into six segments as follows:

- Section 1 – Introduction
- Section 2 – Critical Issues
- Section 3 – Field Studies
- Section 4 – Laboratory Studies
- Section 5 – Exposure Characterization
- Section 6 – Research Recommendations and Priorities

Background and Driving Forces

Power cables, transformers, ac/dc conversion devices, rotating turbines, and generators associated with ocean energy development may expose marine life to EMF levels that could, in principle, alter their behavior and/or physiology, with potentially lasting effects on migration, feeding habits, reproductive potential, population or community status. Scientific knowledge of EMF impacts on the diverse species of the marine environment remains limited and fragmented, posing growing regulatory concern as marine, hydrokinetic, and offshore wind energy development burgeons.

Offshore Wind

Offshore wind energy development is well underway in Europe, as shown in Figure 1-1, and nearing the jumping off point for large-scale development in the U.S. and China. By 2012, roughly 4 Gigawatts (GW) of offshore wind capacity was operational in Northern Europe, with an additional 16 GW likely to come online by 2015. Forecasts anticipate a level of 75 GW worldwide by 2020. Currently, the Walney Wind Farm in the UK, at 367 Megawatts (MW), is the largest offshore facility in the world, followed by the 300 MW Thanet Offshore Wind Project, also in the UK. The London Array (630 MW) is under construction and is slated to replace Walney as the largest in the world in the next few years. Nevertheless, these projects will be dwarfed by subsequent wind farms that are in the pipeline, including Dogger Bank at 9,000 MW, Norfolk Bank at 7,200 MW, and Irish Sea at 4,200 MW.

The wind and water resources off the United States' coasts offer a vast untapped energy potential. According to DOE's *20% Wind Energy by 2030* report, offshore wind alone has the potential to produce 54,000 MW by 2030. The Bureau of Ocean Energy Management (BOEM) intends to facilitate the development of these domestic energy resources by pursuing priority leasing and efficient regulatory processes for sites with high, commercial-scale potential. Director Beaudreau says BOEM has already published the regulatory framework, issued four leases for resource data collection offshore Delaware and New Jersey, and convened 10 intergovernmental task forces engaged in planning for Atlantic outer continental shelf (OCS) wind leasing and development. BOEM also recently launched task forces in Oregon and Hawaii that are leading the way for renewable energy along the Pacific Coast.

Offshore Transmission

Related ocean energy network development is also advancing. In 2011, a right-of-way grant application for the Atlantic Wind Connection (AWC) Project was submitted by Atlantic Grid Holdings LLC to BOEM for an offshore electric power grid. This project would be the first offshore backbone electrical transmission system proposed in the United States. The fully-built AWC Project would include two 320 kV high-voltage direct-current (HVDC) circuits, each installed within a separate offshore corridor to lessen the risk of a single event, such as an anchor drag, damaging both circuits. The AWC Project would enable up to 7,000 megawatts of offshore wind turbine capacity to be integrated into the regional high-voltage grid. The proposed offshore grid is intended to increase reliability and reduce congestion in the heavily congested corridor between Virginia and the metropolitan New Jersey/New York City area. This modern HVDC subsea backbone transmission system would be constructed off the coasts of New York, New Jersey, Delaware, Maryland, and Virginia. When fully built, AWC would comprise about 790 miles of offshore transmission cable constructed over approximately a 10-year timeframe (source: ROW grant application to BOEM, August 10, 2011).

The high-voltage submarine cable market is expected to see significant growth in the coming years. Submarine cables will be required for offshore renewable power generation facilities, to link remote landmasses, and to interconnect national grids. According to a recent report, more than 1,100 new submarine electricity cable systems are planned during the next 8 years. (Source: Business Wire, December 21, 2012).

Marine and Hydrokinetic Energy

There is considerable interest in the development of marine and hydrokinetic energy projects in rivers, estuaries, and coastal ocean waters of the United States. Marine and hydrokinetic (MHK) technologies convert the energy of waves or the moving water in rivers, tidal currents or ocean currents into electricity, without the impacts of dams and impoundments associated with conventional hydro-power or the extraction and combustion of fossil fuels (DOE 2009). The Federal Energy Regulatory Commission (FERC) maintains a database that displays the geographical distribution of proposed MHK projects in inland or coastal waters (FERC 2011). As of November 2011, 52 preliminary permits had been issued to private developers to study MHK projects in inland waters, the development of which would total over 6,000 MW. Most of these projects are proposed for the lower Mississippi River. In addition, another 27 preliminary permits for tidal projects (totaling 2,404 MW) and 6 wave projects (totaling 3,297 MW) had been issued by FERC.

Regulatory Concerns

Rapid development of offshore wind power, and emerging offshore wave and tidal power developments have led to an upsurge in regulatory concern and increased relevance to permitting and environmental impact assessment studies in Europe and in North America, where questions are being increasingly raised about the potential effect of EMF in the marine environment. This has taken on added importance given the integrated nature of the wind farms where large arrays require a network of cables to collect and transmit the power to shore.

There is some concern that the limited knowledge of EMF effects on marine life could slow or hobble development, creating a "catch-22" situation, where deployment of offshore wind awaits greater knowledge of the environmental impacts, but impacts can't be ascertained until facilities are in place. This is a key point for the science and the industry, and needs to be addressed.

The lingering environmental concerns surrounding terrestrial wind power in the U.S., even after 30-40 years of progressive development, strongly suggest that regulators would be well served to get ahead of the environmental issues surrounding ocean energy development. Some of the key questions being raised include:

- How important are artificial EMFs to organisms in the aquatic environment?
- What would be the effect of a large, commercial-build out scenario? Would aquatic animal populations and communities, and the species that constitute them be threatened? Would migration patterns change?
- Are the effects of large arrays likely to be significant, and if so, are they additive, multiplicative, or synergistic?
- What is the effect of adding EMF to other stressors, such as noise from turbines, and maintenance activities?

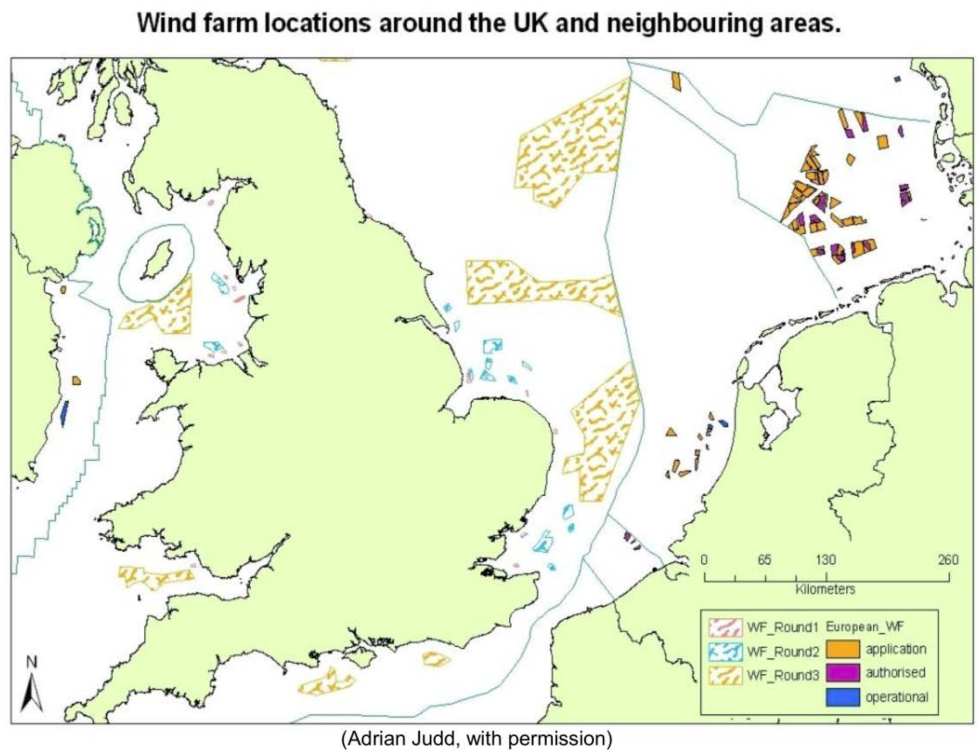

Figure 1-1
Wind Farm Locations around the UK and Neighboring Countries

Workshop Perspective

Workshop chair, Gabor Mezei, opened the meeting with background on the EPRI EMF research program, as well as an explanation of the workshop objectives, organization, and processes. The overriding goal of the workshop was to help EPRI establish priorities for future research in the area of EMF and aquatic life.

The Institute's mission statement emphasizes that the research carried out by the non-profit Electric Power Research Institute (EPRI) is done in the public interest, and is related primarily to electricity generation, delivery and use, as well a variety of environment issues associated with electricity.

EPRI's environmental program includes work in nine key areas, including EMF health assessment. The health-related research on electromagnetic fields goes back to EPRI's founding years in the early 1970's. Over the last 40 years, EPRI's environmental program has grown to encompass occupational health and safety, air quality, global climate change, land and groundwater, T&D health effects, water and ecosystems, renewables, and sustainability.

The main thrust of EPRI's health research on power frequency fields (50-60 Hz) involves epidemiological and laboratory studies, with the main focus on childhood leukemia, the end point with the most suggestive association to date. More recent research is looking at other end points, including miscarriage and neurodegenerative diseases. Extensions of the program to non-human effects now include studying the effect of EMF on animal behavior, such as bees, cows, and fish.

In 2011, EPRI contracted with Oak Ridge National Laboratory (ORNL) to review the scientific literature on EMF and aquatic life. The published EPRI Resource Paper (1024943), authored by Glen F. Cada of ORNL, entitled "Potential Effects of Electromagnetic Fields from Submerged Electrical Cables on Aquatic Life, March 2012," underscored the need for additional research. "The current state of knowledge about the EMF emitted by submarine power cables is too variable and inconclusive to make an informed assessment of the effects on aquatic organisms (CMACS 2003). The small, time-varying magnetic field (B field) emitted by a submerged three-phase AC cable may be perceived differently by sensitive aquatic organisms than the persistent, [quasi-]static, geomagnetic field generated by the Earth. Following a thorough review of the literature related to EMF and extensive contacts with the electrical cable and offshore wind industries, Gill et al. (2005) concluded that there are significant gaps in knowledge regarding sources and effects of electric and magnetic fields in the marine environment. Even less is known about effects on freshwater organisms."

Cada concludes that, "A workshop that brings together experts on the effects of EMF on aquatic animals could be a useful way to come to a consensus on the most appropriate experimental conditions, behavioral (and other) indicators of responses to EMF, methods for extrapolating observed effects on individual animals to the population and community levels, and methods for monitoring biological/ecological responses at field sites with operating cables."

Workshop Objectives

The workshop is intended to explore how EPRI might shape a future EMF and Aquatic Effects research program to help fill knowledge gaps on the environmental impact of offshore energy development. This is largely in response to the worldwide push for renewable energy development that will soon expand to include wave, tidal, and offshore wind facilities. It is also in response to the growing use of undersea cables to transmit power and to interconnect grids. The specific objectives of the workshop are threefold:

- Identify gaps in EMF aquatic-life knowledge
- Develop recommendations for future research
- Set priorities for the recommendations

A key question is whether the introduction of anthropogenic electric and magnetic fields into the ocean environment poses an ecological threat to species of concern, ranging from fish to crustaceans to marine mammals and the marine communities of which they are part.

Discussion Environment

The organizers intended the workshop environment to be a free, open and creative exchange of views and opinions from the participants, who represented diverse backgrounds and experiences. Respect for dissimilar or opposing views was encouraged to help to clarify issues, identify gaps in knowledge, and reveal the range of interpretations of the same set of ambiguous data. The ultimate objective of the discussion was to come up with a scientifically valid and useful research agenda for EPRI.

Workshop Organization and Process

The workshop was organized around three topical areas to set the stage for subsequent roundtable discussion:

- **Field studies—**A broad overview of field studies and related field observations, was presented by Andrew Gill, Environmental Science and Technology Department at Cranfield University in the UK. Field studies are covered in Section 3 of this report.
- **Laboratory studies—**Laboratory research results and perspective were provided by Andrea Copping in the Coastal Division of the Pacific Northwest National Laboratory (PNNL). Laboratory studies are covered in Section 4 of this report.

- **Exposure and measurement—**An overview of EMF exposure characterization in the marine environment was presented by Adam Schultz of the College of Earth, Ocean and Atmospheric Sciences at Oregon State University. Exposure issues are covered in Section 5 of this report.

Following the presentations and an exchange of views, the participants were asked to recommend a list of viable research projects that could form the core of a potential research program for EPRI. The recommendations were aligned with the three topical areas.

The final step was prioritization of these recommendations using a weighted voting process. Each participant was given a "virtual $100" budget to spend/allocate among the array of recommended projects. Minimum allocation was $10. Above the minimum, participants could spend any amount up to the full $100 on specific research items. The allocation scheme was devised to help bring out the strength of collective belief in the value of each project. The recommendations and priorities are shown in Section 6 of this report.

Section 2: Critical Issues

A number of critical issues arose repeatedly, threading through the discussion, and overlapping the three presentations. They ranged from the specific species of greatest concern to end points of interest and ecological impact, to what EMF parameter(s) are important. For the reader's benefit, a number of these common themes have been isolated and summarized in this Section.

Species of Concern

The aquatic species of greatest concern are invariably those that are of commercial, recreational, conservation or cultural importance, and in the case of EMF, includes those known to be electro- or magneto-sensitive. The highest priority of concern goes to species that are protected under a variety of legislation, such as the Endangered Species Act (ESA), the Marine Mammal Protection Act (MMPA), and the Marine Bird Treaty Act (MBTA). Some of the specific species/groups of concern include:

Cartilaginous fish

- **Elasmobranchs—**Sharks, skates, and rays possess functional electro-receptors that can sense the weak electric fields (E-fields) that emanate from their prey's muscles and nerves during activities such as respiration and movement, and potentially to detect the interaction of ocean currents with the geomagnetic field for navigation. Elasmobranch's E-field sensitivity may be as low as 0.02-.2 nV/m, a level smaller than the current state of the art in marine EM sensing instrumentation.
- **Sturgeon and paddlefish—**Sturgeons are slow growing, long lived fish that use a weak electroreceptor sense, in conjunction with other senses, to locate prey. Green sturgeon are listed as threatened under he ESA within their habitats along the west coast. Lake sturgeon and paddlefish are of interest in major rivers where developers may place turbines. Lake sturgeon are endangered and paddlefish populations are much depleted.

Teleosts (Bony fish)

- **Eels—**Certain teleost fish species, including eels, may use the Earth's magnetic B-field to provide orientation during large-scale migrations.
- **Cod—**These commercially and recreationally important fish are not on the US endangered species list, but some species, such as the Atlantic cod have been overfished.

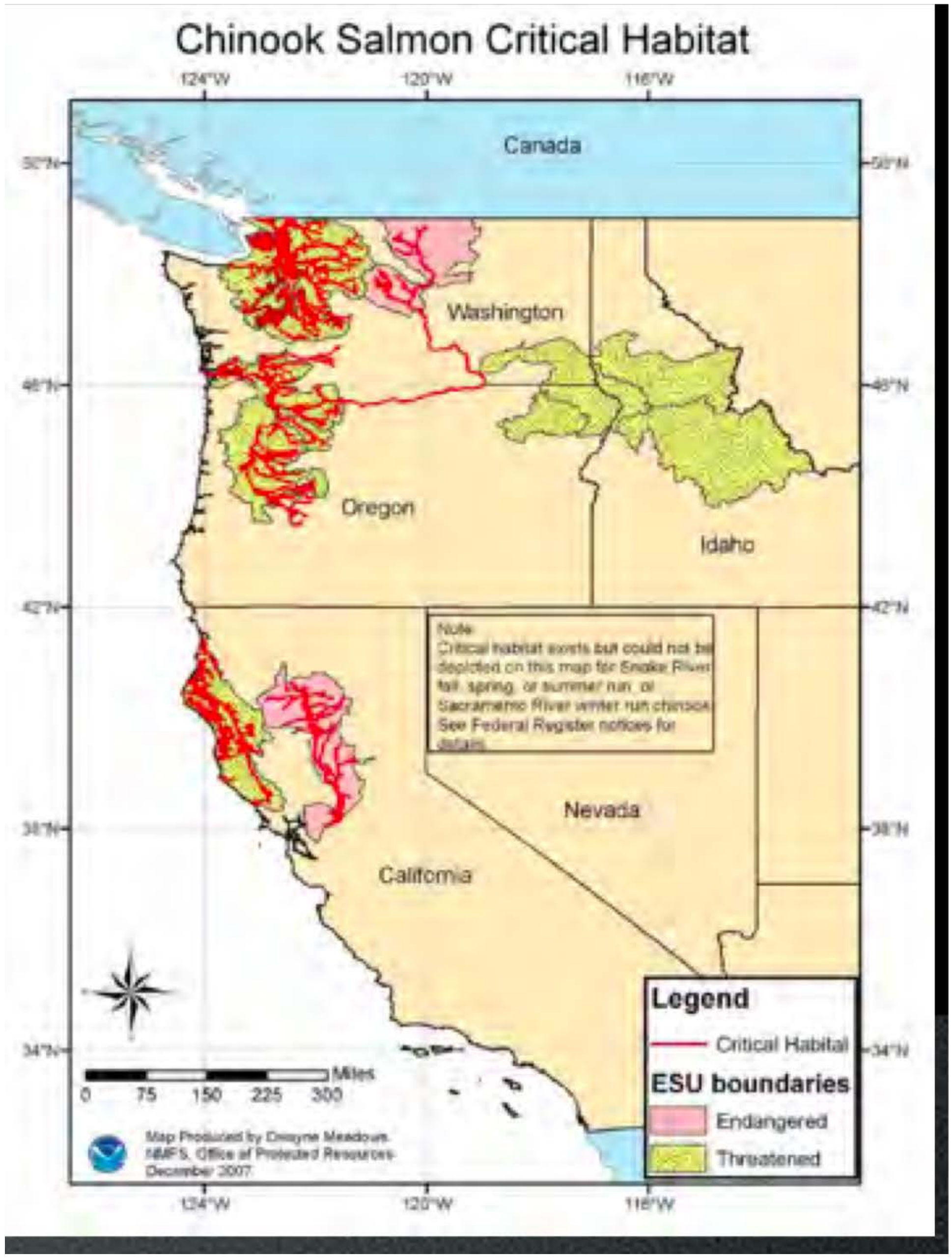

Figure 2-1
Critical Habitat of Chinook Salmon

- **Salmonids—**Salmonids possess magneto/electro-sensitivity. Threatened or endangered stocks are of particular interest and include Coho and Chinook salmon (Figure 2-1). Research suggests salmonid species may be influenced by anthropogenic E-fields, but there is limited support for the influence of the earth's magnetic B-fields. Concerns have led some utilities in the Northwest (e.g. Snohomish WA PUD) to address the EM sensitivity of salmonids and green sturgeon in EIS for proposed hydrokinetic power installations.

Crustacea

- **Crab—**Dungeness crabs are extremely important commercially on the west coast. They are not classed as endangered but are very sensitive to their ocean/chemical environment, and perhaps moderately sensitive to the EMF environment.
- **Lobster—**In addition to other signals, spiny lobsters use the earth's magnetic field to orient. In a controlled experiment, spiny lobster altered their course when subjected to a horizontal magnetic pole reversal. American lobster, while not closely related to spiny lobster are extremely important commercially in the northeast, particularly in coastal areas where offshore wind and tidal energy development are focused.

Sea Turtles

- Several species of sea turtles undergo transoceanic migration. Green sea turtles and loggerheads may utilize the earth's magnetic B-fields to assist in navigation.

Cetaceans

- **Whales and dolphins**—are able to form a useful "magnetic map" which allows them to travel along corridors of low magnetic intensity and gradient (magnetic valleys). It has been suggested that they use geomagnetic cues to navigate accurately over long-distances of open ocean that do not have geological features for orientation. Live strandings of toothed and baleen whales have also been correlated with local geomagnetic anomalies.

Sensory Mechanisms

There was general agreement among the participants that the research community has yet to accurately identify the specific biophysical mechanisms and sensory capabilities that allow aquatic species to respond to and use electric and magnetic fields. There is a considerable body of anecdotal and extrapolated ideas, but as yet nothing definitive.

There exist two main hypotheses in the literature to explain the phenomenon of magnetic field sensitivity. According to one model, cryptochrome, when exposed to blue light, becomes activated to form a pair of two radicals (molecules with a single unpaired electron) where the spins of the two unpaired electrons are correlated. Activation of cryptochrome may affect the light-sensitivity of retinal neurons, with the overall result that the animal can "see" the magnetic field. The second proposed model for reading magnetic fields relies on the animal's use of iron oxide at the cellular or molecular level to create, in effect, a magnetite-based compass.

For electric fields, the inductive sensing methods used by sharks, rays and chimaeras (cartilaginous fish) involves a unique electro-receptive organ known as Ampullae of Lorenzini which can detect a slight variation in electric potential. This in turn enables them to detect weak electric field strengths below a nanovolt per meter. These species use their sensory apparatus for detection of prey, conspecifics and predators as well as ocean navigation and orientation.

Another anecdotal mechanism might be that aquatic species use electro-sensors as a proxy for magneto-sensors, since there is an electric field set up by the cross-product of the magnetic field with the motion of the fish through the seawater. A fish in motion might be able to detect the geomagnetic field orientation simply by moving through the water and sensing the electric field.

End Points of Concern

Observable changes in animal behavior, development, or reproduction resulting from exposure to anthropogenic EMF may have larger consequences, such as potentially impacting the size and distribution of the species population, species maintenance, or even survival. The end points of greatest interest to the research community, according to Andrea Copping of PNNL, are as follows:

Overt avoidance or attraction, or aggressive behavior towards cables. A number of observations have shown elasmobranchs in particular are attracted to lower voltages while repelled by higher voltages. They are attracted, for example, to dc fields in the range of 0.005 to 1 μV/cm, and avoid dc fields of 10 μV/cm (or 1000 μV/m). Some have been recorded attacking submarine cables.

- **Changes in the ability to navigate.** Interference with the electro-magnetic mechanisms used for migration or feeding could adversely affect a number of species. This would be a clear marker for larger ecological consequences.
- **Changes in the ability to detect food, predators, or competitors** could compromise the species survival, and alter the food chain. Changes in detection capability could occur as a short term response to an energized cable, or possibly linger after exposure.
- **Changes that effect survival, development, or biophysical condition**. Exposure to anthropogenic EMF could possibly affect the viability of juveniles of a given species, or delay critical developmental stages, putting the population at risk.

EMF Stressors

Electromagnetic fields (EMF) originate from both natural and anthropogenic sources. Natural sources include the earth's magnetic field and different processes—biochemical, physiological, and neurological—within organisms themselves. Marine animals are also exposed to natural EMF caused by the magnetohydrodynamic effect of conductive sea water flowing through the geomagnetic field. The presence of magnetic fields can produce a second induced component in a fluid conductor, a weak electric field, referred to as an induced electric (iE) field. The iE- field is created by the flow of seawater or the movement of organisms through a magnetic field, as shown in Figure 2-2.

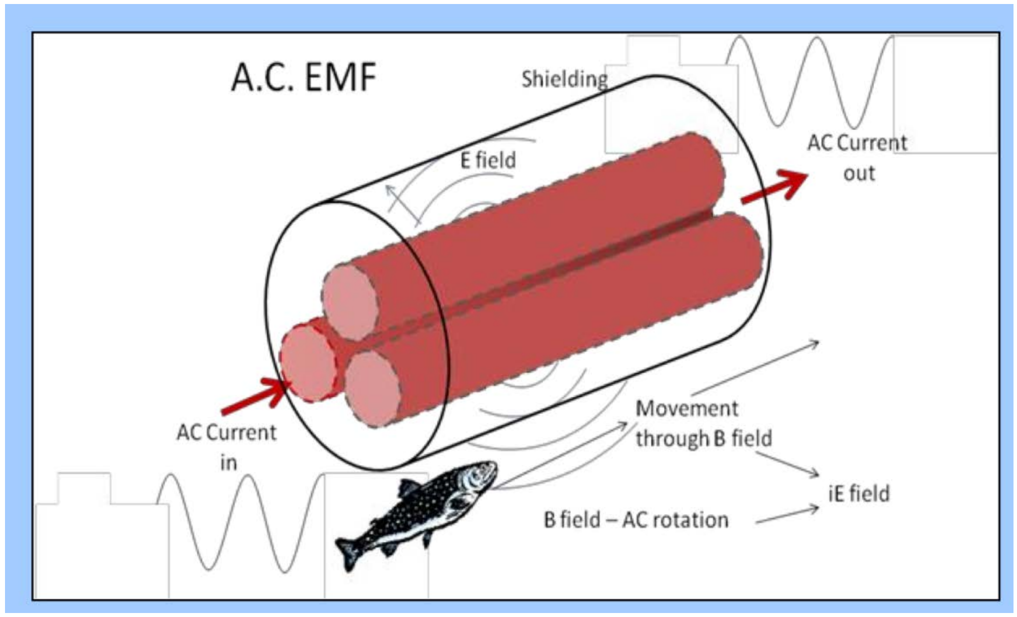

Figure 2-2
AC Cable Fields in Marine Environment

The earth's geomagnetic field can be more properly characterized as "quasi-static," in that it contains low frequency components due to currents in the earth's core and the interaction of the magnetosphere and ionosphere with the solar wind and higher frequency components due to lightning.

Anthropogenic sources of EMF in the marine environment include submarine telecommunications (fiber optic and coaxial), undersea power cables, offshore oil/gas installations, and shipping. Three components of an ocean energy project are likely sources of EMF:

- The wave or tidal energy converter,
- The subsea pod for power aggregation, control, or conversion,
- The subsea power transmission cables, including the power cable exiting the side of each turbine or hanging down from a wave energy converter (WEC) to the seabed and those cables from the subsea pod to a land-based substation.

The type and degree of observed EMF effects may depend on the source, location, and characteristics of the anthropogenic source, and the marine environment. EMF propagation in the marine environment depends on geology, water depth, source geometry and orientation. The complexity of the EMF ocean environment is exemplified by the north-south directed bands of weak and strong magnetization created at the ocean spreading centers that can locally disrupt the geomagnetic fields. Whales have been shown to strand where these magnetic lineations intersect the coastlines of North America and Great Britain due to tectonic shifts in the oceanic plates. Hammerhead sharks make highly oriented feeding migrations from their daytime aggregation sites at seamounts to their nighttime foraging grounds along these magnetic pathways. Anthropogenic EMFs that intrude into the same range of frequencies and intensities as the geomagnetic field EMFs would likely elicit a behavioral response from sensitive species. Further details on EMF in the marine environment, exposure characterization and measurement can be found in Section 5.

Environmental Framework

A six-level framework for tying together the causative linkage from energy conversion device to EMF exposure to environmental impact was developed by Boehlert and Gill (2010) and presented at the workshop by Gill, as shown in Figure 2-3.

At the first level, the energy conversion device is introduced into the marine environment, leading to a number of environmental stressors, including EMF, as depicted in level two. Level three shows the wide array of potential physical and animal receptors, including benthic (seafloor) habitats and species, and pelagic (open water) habitats and free swimming species.

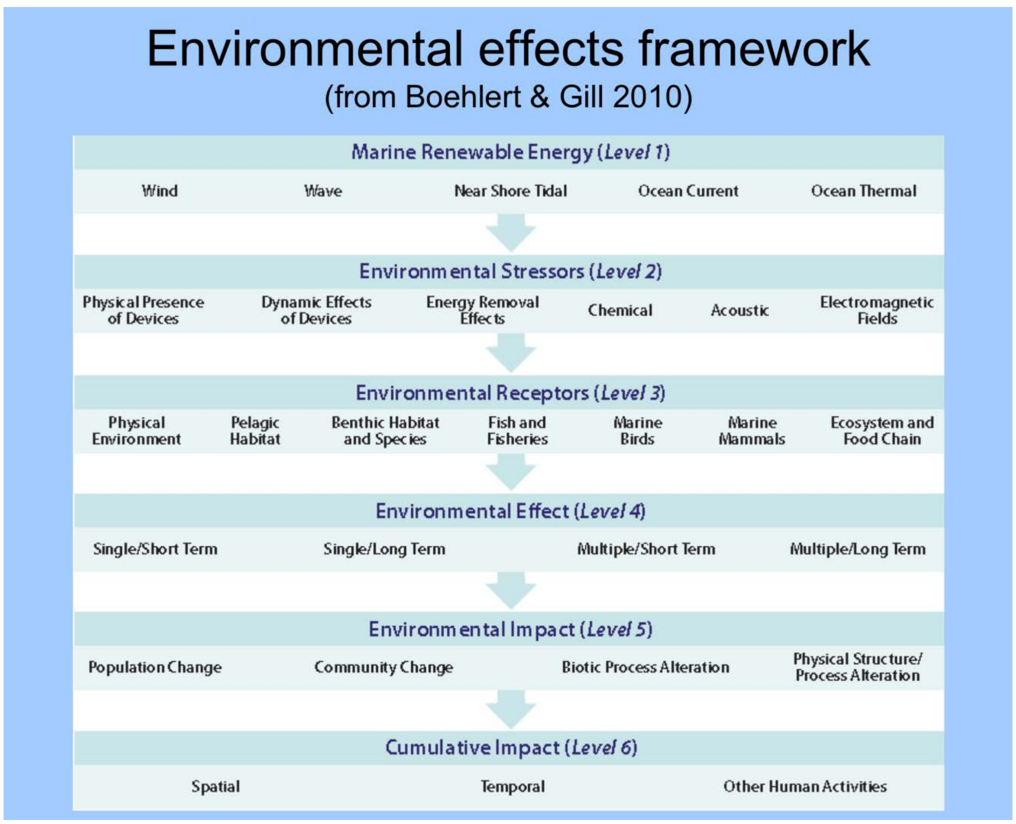

Figure 2-3
Environmental Effects Framework (Boehlert & Gill, 2010)

Level four involves the critical stage of animal response to the stressor, which triggers many of the end points listed earlier. These responses can be quite varied, and range from the singular and short term all the way up to the multiple and long term. The reaction of an animal at level four does not, however, indicate that the animal is adversely affected. Level five makes the key distinction between biological response of an animal (level four) and environmental impact, in which case the response/effect produces significant consequences impacting the animal in question. For example, they are perhaps unable to hunt as efficiently, or their migratory path has been altered sufficiently that survival rates diminish. Level six takes the impact one step further, where there are potential cumulative effects, impinging perhaps on larger elements of the ecosystem, or disrupting a complex food chain, or altering human commercial or recreational activities. Furthermore these impacts are likely over different time and spatial scales.

Gill emphasized that the critical boundary between levels four and five—between the biological response and biological impact—is often confused. A fish may hesitate to pass over a buried cable (an effect/response), for example, and then simply go on its way with no further impact on its behavior or capabilities. This distinction is one of the reasons that carefully constructed field studies and controlled laboratory studies are so important and context over the correct scales is included.

Ecological Impacts of Concern

Understanding EMF exposure and its effects on populations (level six) has the greatest ecological significance. Populations are groups of individuals of a single species that live in a particular geographic area. Effects on populations would include demonstrable changes in the numbers, individual sizes, ages and distribution of the species (i.e. the population demography), as well as changes in migratory patterns. It would also include behavioral changes that interfere with the ability to hunt, forage, navigate, recognize and deal with predators. Physiological changes that adversely affect reproduction, or alter growth patterns can have significant ecological consequences.

Communities are larger constructs that involve assemblages of populations of species living in proximity to one another and interacting within an ecosystem. Disruptions at this level would include alterations in the food chain and energy flow, enhanced competition for food or space, and changes in predator-prey relationships.

Habitats vulnerable to EM field effects would include:

- Migratory corridors
- Bays or estuaries adjacent to freshwater spawning grounds
- Nearshore or offshore spawning areas or nurseries
- Designated critical habit for threatened and endangered species
- Designated essential fish habitat

- Designated marine sanctuaries or protected areas
- Tribal fishing grounds
- Commercial or recreational fishing grounds

Copping pointed out that populations and functional habitats are the most fruitful area for research, and that communities are particularly difficult to study given the diversity, the noise in the system and the complexity of the relationships, even though the ecosystem level of mixed species is where many regulators want to concentrate. The participants largely agreed that ocean communities are well beyond today's level of scientific knowledge, and that the proper focal point at this stage is on species and populations.

Section 3: Field Studies

Andrew Gill of Cranfield University in the UK presented an overview of observations and field studies related to the exposure of marine animals to EMF. In the historical record, he found a consistent pattern of some behavioral response to the stimulus of electric and magnetic fields, but no evidence of lasting impact. The behavioral responses were found to both ac and dc high-voltage cables (HVAC and HVDC), as well as to some undersea telecommunication cables. Some of the older electric cables are open-circuit, meaning they use the sea as return. Open circuit cables are no longer recommended in part because they generate relatively large electric fields.

Field Observations and Studies

Some of the most significant studies over the last few decades include the following:

- **Baltic Sea—**Researchers found decapods aggregating around the anodes of an open circuit dc line. In another study with a closed dc circuit, anguillid eels (European eels) slowed down and diverted their migratory path over several minutes.
- **Tasmania—**The 290km, 400kV dc line linking the Tasmanian grid to the Victorian grid is the longest such line in the world. Researchers made an assessment that no pelagic species would be affected owing to the depth of the water in the Tasman Strait. They made the suggestion that benthic species of elasmobranch may interact with the cable**.**
- **Canary Islands—**Shark teeth were found embedded in a telecom cable that was subsequently shielded to avoid further attacks.
- **Russia—**In an area where high voltage overhead transmission lines crossed a shallow lake, sturgeon showed hesitation when approaching the fields but finally passed through.
- **Denmark—**Danes supported a five-year program to investigate impacts on marine life from their wind farms. Cod seemed drawn by the physical trace of the cable on the seafloor; they gathered closer to the trace whether it was energized or not. Flounder, on the other hand, gathered more abundantly around the cable when it was energized.

- **Belgium—**The Belgians found that flatfish were more abundant in the wind farm areas, although the association with EMF is not clear. There were also large increases in crustaceans and echinoderms (sea stars, urchins, sand dollars and other benthic creatures).
- **California—**Researchers at MBARI found significantly higher numbers of longnose skate around the energized Monterey Accelerated Research System (MARS) Cabled Observatory, compared to adjacent sites.

The exact cause for this heightened activity and behavioral response at or near offshore energy facilities and seafloor cables is unknown. Is it the atypical or unexpected EMF environment, or a reaction to the physical cable, or both, or to some alteration in the food supply as organisms cluster around the cable? The unanswered questions seem to be mounting as offshore wind development continues to grow. The planning activities by the Dutch, Belgians, British, Germans, and Danes indicate large-scale offshore wind projects, closely followed by wave and tidal power projects, are about to enter a new stage in Northern Europe. Behavioral responses of aquatic animals may change as the density of renewable energy devices and the interconnected cable arrays networks that go with them proliferate.

COWRIE Mesocosm Studies

Gill presented the results of the COWRIE mesocosm studies undertaken in recent years in Scotland. The studies were undertaken to answer the central question of whether electromagnetically sensitive fish respond to EM fields emitted by offshore wind farm cables.

The research was central to COWRIE's mission. The Collaborative Offshore Wind Energy Research into the Environment (COWRIE) was an unique organization that ran in the UK from 2001-2010, whose aim was to research and improve knowledge on the environmental impacts of offshore wind power. It was administered by the UK Crown Estate and funded through the planning applications of offshore wind farm developers. COWRIE focused on environmental research, data management, education, and communication. Its purpose was to facilitate collaboration and research, primarily related to the environmental impacts of offshore energy development.

Designed to meet the needs of the industry, regulators, and NGOs—who were of the opinion that laboratory studies were too restricted and field studies were too expensive—the COWRIE study effectively allowed the research team to take the "laboratory into the field". The project team built two largescale fish pens (named 'mesocosms') in the natural environment that afforded enough control to run structured experiments. They chose an isolated coastal site in Scotland, away from background EMF and noise, and selected three critical species to study. Importantly, they included a side-by-side control pen identical in all respects except that the cable running underneath the control pen was not energized. The addition of a control pen to the experimental design proved an essential requirement, serving as a reality check on the behavioral data recorded from the energized pen.

The pens were circular structures, 40 meters in diameter and 5 meters high, made of polyethylene piping, concrete and nylon fish net, and anchored to a sandy bottom, as shown in Figure 3-1. The two pens were set 20 meters apart. A standard electrical supply cable was buried underneath each pen to a depth of 0.5- 1m. As shown in Figure 3-2, one cable was energized, the other served as a dummy for control purposes.

In terms of the subjects, the research team selected two benthic species, the thornback ray and the small-spotted catshark. The free-swimming species they chose was a spurdog. The animals were acoustically tagged and their positions monitored remotely by acoustic hydrophones on the seabed attached to surface buoys with a radio link to shore. The experiments ran for 24 hours/day for 2-3 weeks, and were repeated three times with the energized mesocosm being swapped for each repeat in order to factor out mesocosm location effects. To address the likely different day/night activity levels by the fish and to reduce the potential for learning about the EMF, the power was turned on randomly for one hour and then turned off during each 12-hour period.

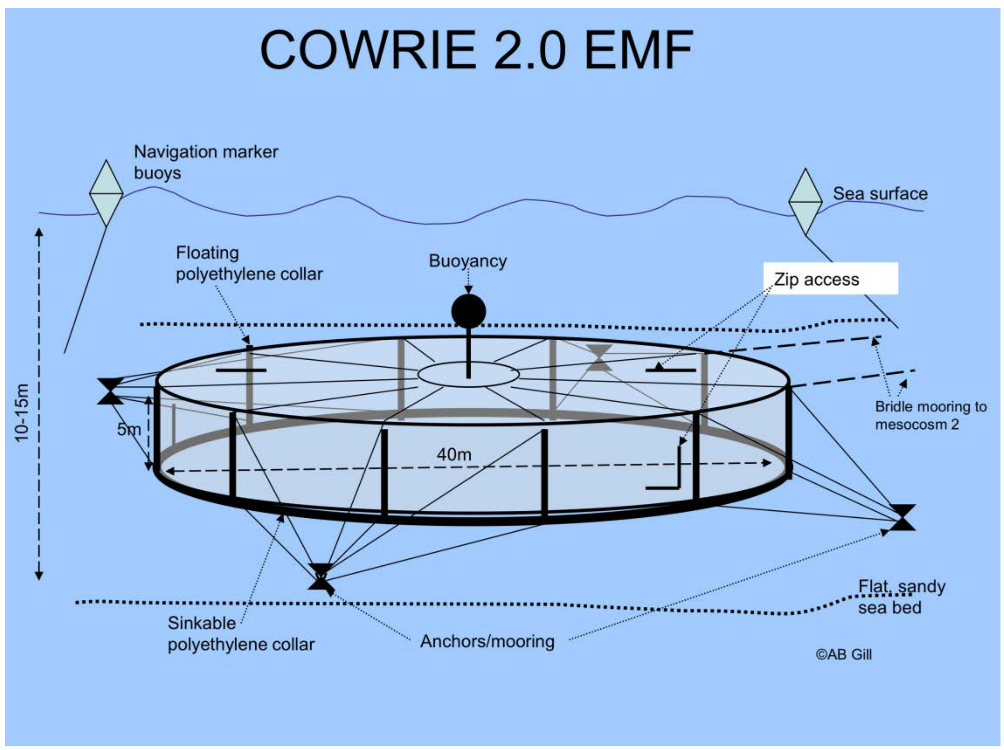

Figure 3-1
COWRIE Mesocosm Fish Pen

COWRIE Study Results

The research team determined the following:

- **Response—**The benthic elasmobranchs species did respond to the presence of EMF emitted by the sub-sea cable. This response, as expected, was variable among individuals within the species and also during times when the cable was switched on and off, day and night. The data were collected and analysed at two different scales: overall distribution and fine scale movement patterns
- **Movement—**Analysis of the movement of the fish within the mesocosms showed that all the fish species moved throughout the mesocosms regardless of whether there was any EMF present or not. Also, there was a predominance of movement towards the offshore side of the mesocosms. For thornback rays, their Step Length (i.e. the distance covered between two successive positions, based on fine scale data) was higher once the cable was switched on. There was no depth related movement during the time that the cable was on or off.
- **Spatial distribution—**Analysis of the overall spatial distribution of fish within the mesocosm was non-random and one species, the small-spotted catshark, was more likely to be found within the zone of detectable EMF emission during times when the cable was switched on. Overall, the results suggest that the catsharks were found more often near the energized cable and they moved around less than when the cable was switched off.
- **Individual differences—**The fine scale movement analysis used was limited by the technology available which meant the number of fish individuals studied was low. However, there were differences found for some individuals of thornback rays in terms of their location and rate of movement around the zone of detectable EMF when the cable was switched on.

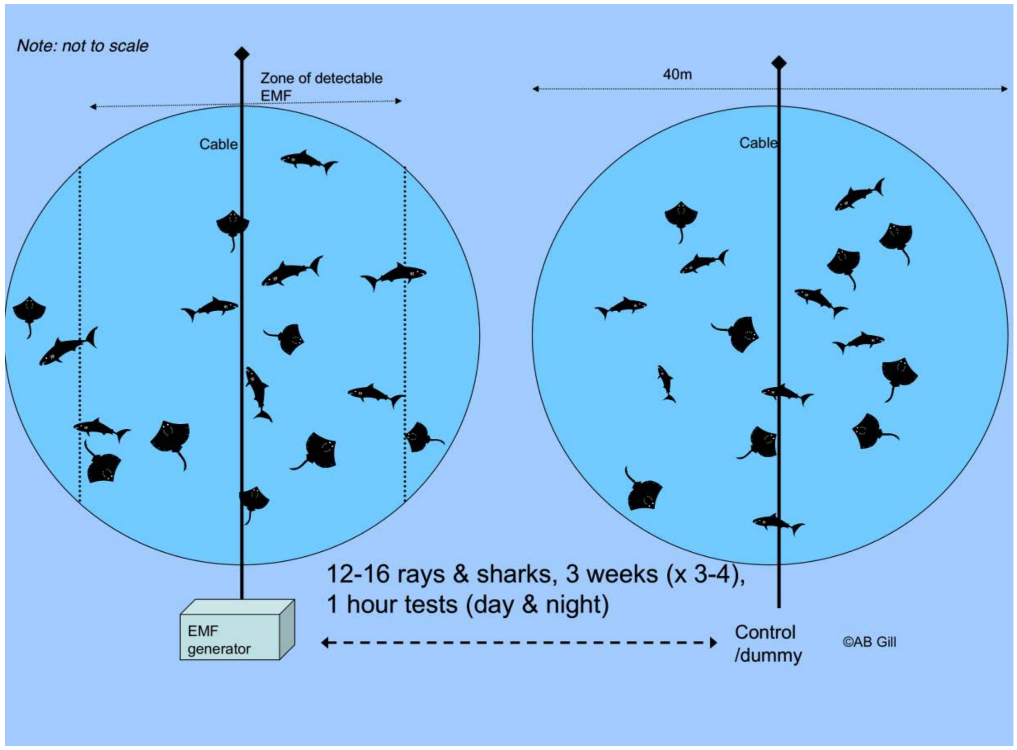

Figure 3-2
COWRIE Side by Side Operational Test and Control Pens

Importance of the control mesocosm—For one aspect (how near to the cable the individuals were on average), there appeared to be a response by the rays nearer to the cable when it was turned on; however a similar response was found in the control mesocosm. This highlights the importance of including the control in the study.

Considering its uniqueness and the enormity of the logistics involved, the field based experimental studies of the COWRIE project was ambitious; however, it met its objective by demonstrating that some electrosensitive elasmobranchs will respond to the EMF emitted. EMF influenced the overall spatial distribution of one of the species tested, as well as at the finer scale level of movement of individual fish of different species. A field survey of subsea cables from two wind farms in North Wales provided evidence that the EM field previously predicted to be emitted by the cables from offshore wind farm cables appeared to be accurate.

The amount of data collected in the mesocosm study was enormous and has not been fully analyzed. Efforts to do so have been frustrated by the switch in emphasis by the COWRIE group to underwater noise, and subsequently the disbanding of the organization. Efforts have been made to obtain funding to continue the analysis and are still ongoing.

Research Needs

Knowledge Gaps

Gill identified three knowledge gaps that need to be filled by future field research.

Variation in species response to EMF frequency—while EM sensitive animals are known to respond to both DC and AC fields, how they respond to the frequency of AC fields requires much better understanding. In the COWRIE EMF study the fish responded to 50 Hz. However, neurophysiological studies (though limited) have only looked at <0.1 to around 20 Hz. Naturally occurring fields are quasi-static, in that they have powerful AC variations from DC. The flow of ocean currents through the earth's geomagnetic fields can also create frequency variation.

Individual variability—The second knowledge gap concerns efforts to assess individual variability within a given population to determine the range of species response to EM fields. Also, if a number of individuals respond there is a need to determine emerging properties that manifest at the population level.

Effect versus impact—The third knowledge gap draws a sharp distinction between effect and impact in studies on how animals respond to a stimuli and how that translates to actual biologically significant effects (i.e. impacts, whether positive or negative). Hence, observed and recorded responses should not be confused with environmental impact that proves deleterious to the species ability to propagate, hunt, navigate, or detect prey.

Key Field Research Topics

Gill recommended a number of key research topics, outlined below, and emphasized the potential for parallel studies using different labs and field operations. He advocated the benefit of a staged approach to research by having different studies from around the world feeding into a comprehensive and coordinated program of research on the effects of EMF on aquatic life.

- **Behavioral and functional ecology—**Record and evaluate the interactions of individuals with cables and ocean energy devices. This should include life history aspects to separate response/effect from impact.
- **Spatial ecology—**Record and evaluate the spatial scale of interactions with cables and devices, including life history aspects.
- **Population and community ecology—**Isolate emergent properties that facilitate scaling up from individual response/impact to populations and even to the more complex community ecology.
- **Physiological biology and ecology—**Identify sensory abilities, determine ranges of response, and potential thresholds of dose-response.

- **Environmental assessment, risk management, and mitigation—**Characterize EM fields from various cables of different types/ratings; multiple cable arrays and geometries; various power generation devices and substations. Model cumulative effects and impacts from various cables and devices.
- **EMF environmental monitoring—**Establish methods, indicators, and protocols for monitoring EMF from underwater cables. Develop appropriate equipment to facilitate monitoring.

Section 4: Laboratory Studies

Of DOE's eighteen national laboratories, only two are engaged in biological research related to aquatic life, Oak Ridge National Laboratory (ORNL) in Tennessee, and the Pacific Northwest National Laboratory (PNNL) in the state of Washington. Andrea Copping from PNNL presented an overview of laboratory results around the world, and a summary of DOE's current research.

The impetus for PNNL's and ORNL's recent work has been the desire to get out ahead of the environmental questions surrounding ocean/river energy development in the U.S., which appears imminent and likely to follow on the surge of offshore development in Europe. Concerns in the U.S. range from the impact of wave, river, and tidal energy to offshore wind. Copping pointed out that terrestrial wind development is still hindered by environmental questions after 30-40 years.

Three years ago when Copping's team of researchers delved into the scientific literature on impacts of EMF on aquatic life they were shocked at how little there was and how inconclusive and fragmentary were the results. DOE hopes to fill some of the gaps, and PNNL is the focal point of U.S. research in this area, since it serves as DOE's only marine sciences laboratory (MSL).

Selected Laboratory and Field Results

The behavioral response of numerous species to both electric and magnetic fields is shown in Figure 4-1, which captures some of the most important laboratory and field studies in the scientific literature. Copping pointed out that in most cases the changes/responses recorded were quite minor.

She added that the PNNL laboratory experiments looked at a number of invertebrates and fish species exposed to a moderate decaying field and found limited responses, even after 5-10 trials. There was some avoidance behavior at "reasonable" field levels, which opened wide-ranging discussion among the participants about the appropriate field levels that should be used for laboratory studies.

In toxicological research, dosage is increased in controlled increments in an effort to establish the dose-response relationship, and at the lower end of the curve, to try find a threshold below which there is no meaningful biological impact. Should ordinary cable voltages be used in lab work, and if so what are they? Or should field intensities be increased to abnormal levels to try to tease out the dose-response. The question of the "rock concert" effect was discussed in this context; that is, would an exaggerated field level dull the animal's senses in a way similar to how blaring rock music can "deafen" the concert goer. In such a case, the amplified dose of EMF could void receptivity to ordinary stimuli, including EM fields.

Species	Outcome	Source
Elasmobranchs	Able to detect voltage gradients of 0.05 to 0/5 uV/m)	Kalmijn 1982
Hammerhead sharks	Attacked cable emitting 25 to 100 uT	Meyer et al. 2004
Catsharks/Dogfish sharks	Altered swimming patterns observed at 0.008mT Avoided constant electric of 1,000 uV/m	Gill et al. 2009 (COWRIE) Gill and Taylor 2002
Zebrafish	Delayed development after exposure to 1 mT	Skauli et al. 2000
Eel migration	No effect from HVDC emission of 20 to 75 uT	CMACS 2003
Mussel, prawn, isopod, crab	No mortality observed at 3.7mT	Bochert et al. 2005
Shrimp, isopod, echinoderm, polychaete, flounder	Avoidance/attraction not observed at 2.7 mT	Bochert et al. 2005
Loggerhead sea turtle	Orientation affected by exposure to 40mT pulsed EMF	Irwin and Lohmann 2005
Crab, Lobster, Halibut	No statistically significant avoidance/attraction observed at 1 mT decaying field	Woodruff et al. 2012
Halibut	Slightly delayed development at 3 mT uniform field, but not statistically significant	Woodruff et al. 2012

Figure 4-1
Laboratory and Some Field Examples for EMF Levels of Concern

Oak Ridge National Lab Experimental Results

In the Oak Ridge aquatic laboratory, several fresh-water species were tested in a large treatment aquaria (as well as in a comparable control aquaria) for short-term response to magnetic fields of various strengths. The electromagnet and camera were activated in four-second bursts, every five minutes for 48 hours, and abnormal behavior recorded. In total, there were 280 trials with lake sturgeon, and 99 with paddlefish. The sturgeon and paddlefish were initially subjected to the highest magnetic fields in the experiment, which were in the range of 50-60 thousand microtesla (50,000-60,000 μT). In subsequent trials the magnetic fields were reduced until no effect was observed.

The results were dramatically different for the two fish. While the paddlefish were unperturbed, demonstrating no response at any field strength, the sturgeon responded in a variety of ways at virtually every field strength above a threshold. According to the research team, the lake sturgeon responses were obvious, occurred frequently, and were of a varied nature, as shown in Figure 4-2. The sturgeon responses were 100% at full magnetic strength and declined to control levels at 1% of magnetic strength (500-600 μT), as shown in Figure 4-3. It is unclear whether the sturgeon were responding to the magnetic field or the induced electric field.

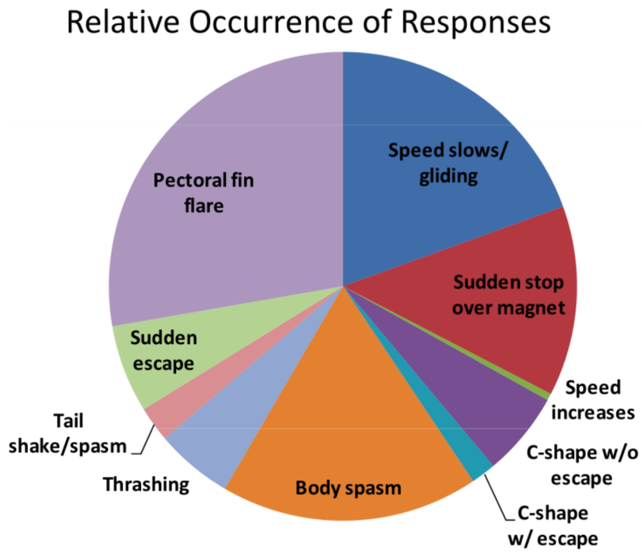

Figure 4-2
Relative Occurrence of Responses by Sturgeon in ORNL Test

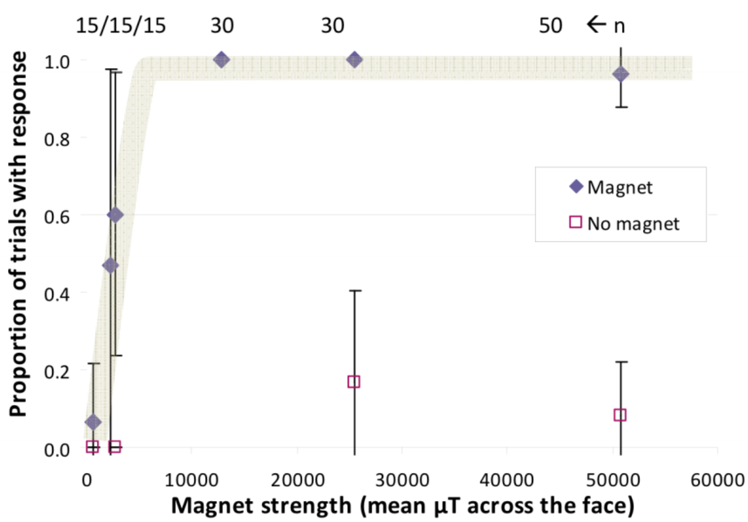

Figure 4-3
Sturgeon Response at Various Magnetic Field Strengths

To help minimize the EMF impact on migration pathways of sensitive species in rivers, cables might be buried and oriented to align with the flow of the river, as shown in Figure 4-4.

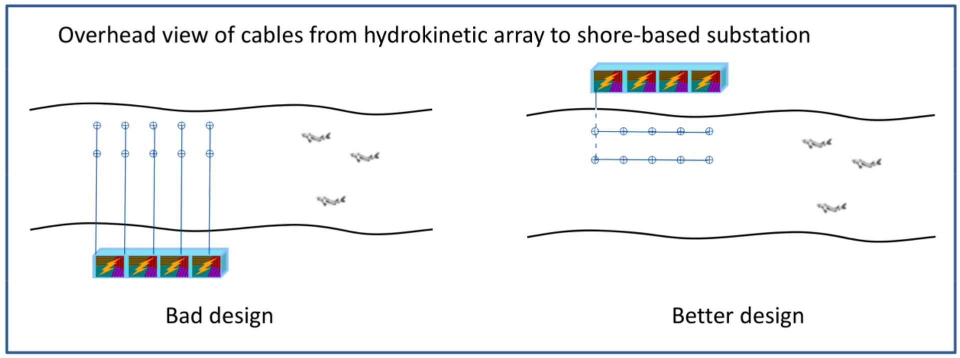

Figure 4-4
Cable Alignment to Mitigate Risk to Fresh Water Fish

Pacific Northwest Lab Experimental Results

The experimental design at PNNL involved subjecting a variety of aquatic animals at various developmental stages to relatively high field strengths. A Helmholtz coil capable of operating under ac or dc current provided magnetic fields on the order of 3mT. The results are summarized in Figure 4-5.

There was a striking difference between juvenile California and Atlantic halibut in terms of growth and development when subjected to 3mT dc fields in early and late stages of metamorphosis. Atlantic halibut demonstrated delayed development when exposed to EMF at these high field strengths, whereas the California halibut showed no impact.

Sub-adult Atlantic halibut were also exposed to a decaying EM field of 1.23 mT, allowing the animals to move towards or away from the field. Although the overall activity level of the halibut was low during the experiments with some increased activity at night, their distribution in the experimental tank was significantly different from that in the control tank. However, the changes in distribution appear to be more closely correlated with EM field orientation than field strength.

Dungeness crab were also subjected to 3mT fields, with the research team looking for changes in activity level and antennular flicking rate. The small antennules protruding from their heads are primary sensing organs, extremely sensitive to food odors, chemicals, oil, and extracts. For short-term exposures, the research team found no overt behavioral response, and no difference in their flicking rate (about 17 per minute) before and after exposure. For longer-term exposure (20 hours), the flicking rate was reduced significantly.

Dungeness crab were also exposed to the 1.23 mT decaying EM field to determine potential attraction or avoidance to the field. There was considerable variability among the experimental results, however the crabs were seen to move towards and bury themselves in the further reaches of the tank significantly more than in the areas close to the EMF source.

American lobster were exposed to the decaying EM field but the results were not clear cut. The lobster engaged in several confounding behaviors (sheltering, burrowing), resulting in no significant differences in spatial use of the habitat between the experimental and control tank. Further experimentation is needed.

Experiment	Endpoint	Result of EMF Exposure
Coho salmon exposure marker	Melatonin or cortisol production	Decrease in melatonin production No change in cortisol production @ 0.1 and 3 mT DC, 0.13 mT AC
Rainbow trout egg development	Survival and development	Evidence of delayed development @ 3 mT
Atlantic halibut	Growth and development	Slight developmental delays @ 3 mT
California halibut	Growth and development	No effects observed @ 3mT
Dungeness crab EMF detection	Antennular flicking rate	No change in flicking rate observed @ 3mT
Dungeness crab food detection	Antennular flicking in response to food extract	No change in flicking rate observed @ 3mT
Dungeness crab Avoidance/attraction	Location and position with respect to decaying field	Significant movement away from 1.23mT field
Atlantic halibut avoidance/attraction	Location and position with respect to decaying field	Significant movement away from 1.23mT field
American lobster avoidance/attraction	Location and position with respect to decaying field	No effect observed @1.23 mT decaying

Figure 4-5
Experimental Results on Aquatic Animals -- Pacific Northwest Laboratory

Research Needs Requiring Laboratory Support

Copping identified four critical areas of research that require laboratory support and leadership to understand the potential impact of EMF on aquatic life.

- **Establishing levels of EMF causing attraction or avoidance—**This is the most immediate permitting-question posed by regulators. Avoidance behavior by sensitive animals could set up barrier effects, cordoning off food supply, or restricting migration, or displacing fish from critical habitats, such as nurseries. Without answers to the attraction/avoidance issue, ocean energy development could be hampered or investment in mitigation measures misplaced.
- **Establishing dose-response relationships—**Is there a dose-response relationship between EMF and aquatic life? Does it vary from species to species? Is it linear? Is there a threshold? This is fundamental information necessary to gauge the long-term effects of EMF on populations.
- **Establishing the mode of EMF and measuring the frequency—**Will dc be the primary mode for transmitting power from offshore wind turbines? When and where is ac power likely to be used?

- **Distinguishing the differences among species—**There appear to be significant differences in the response of various species to EMF. California halibut and Atlantic halibut, for example, show striking different responses. Not all sturgeon respond the same. These differences are critical to understanding the fundamental nature of aquatic life in an environment increasingly infused with anthropogenic EMF.

Section 5: Exposure Characterization

The ocean is a highly conductive medium in constant motion through the earth's geomagnetic field, inducing electric fields as part of the ambient environment. Naturally occurring electric field potentials in the sea are extremely small. However, the motion of tides, currents, wakes, and waves creates an overlay of higher EM fields, especially in the near-shore environment where ocean energy development is likely to be the greatest. Measurements off the coast of Oregon by Schultz and others, for example, show wave-generated electric fields between 6 to 216 μV/m (at .04-0.3 Hz), tidal-generated electric fields at 33 μV/m, and those from coastal currents up to 22 μV/m. Magnetic fields are accordingly small.

Adam Schultz of Oregon State University delivered the workshop presentation on EMF exposure characterization and field measurement. Aquatic life, he pointed out, has evolved in this natural environment such that the senses of those species using electric or magnetic fields to survive have become extremely acute. Studies suggest that elasmobranchs' electric field sensitivity, for example, may be as low as 0.02-.2 nV/m (at 0.1-10 HZ), a level smaller than the current state of the art in marine EM sensing instrumentation, which has a lower bound of roughly 1 nV/m for compact survey instruments. Sharks evolved to be able to discriminate between the internally generated electric fields of prey and the weak ambient electric fields in the deep ocean. Such sensitivity poses challenges for instrumentation and complicates the job of determining the environmental impact of anthropogenic EM fields.

Anthropogenic EMFs must be viewed as perturbations to the ambient EMF spectrum, and at least close to the source, emit fields that may be orders of magnitude greater than background. A key point is that electro- and magneto-sensitive species have evolved in an environment with a rich and complex frequency-dependent spectrum of natural geomagnetic and oceanographic EMFs. Anthropogenic EMFs are superimposed on this background. Given the directional/vector property of electric and magnetic fields, anthropogenic EMFs of similar intensity but different orientation than natural EMFs may be within the sensitivity range of electro- and magneto-bioreceptors and thus may elicit a behavioral or developmental response. EMFs of substantially greater intensity may possibly elicit a toxicological response, or they may overwhelm the sensor organ and elicit no behavioral response at all. The relative lack of EMF studies on aquatic life with field intensity, direction and frequency content controlled so that behavioral, developmental and toxicity effects can be de-convolved leaves this issue an open question.

EM Field Propagation

Adding to the complexity of the ambient environment, electromagnetic field propagation depends on geology, water depth, and source geometry, and in terms of computation requires solving a 3-D problem involving the air/ocean/seafloor waveguide. Sources generating horizontal or vertical electric or magnetic dipoles all couple differently to the seafloor. Vertical magnetic dipole (VMD) induces only horizontal electric fields and thus are relatively insensitive to the presence of resistance zones beneath the seafloor. Horizontal electric dipole (HED) and horizontal magnetic dipole (HMD) sources induce both horizontal and vertical electric fields, which can be sensitive to resistive seafloor zones. As shown in Figure 5-1, an HED is used for geologic exploration below the seafloor, where an electrically resistive formation, such as crystalline rock or an oil/gas reservoir, is revealed by the waveguide.

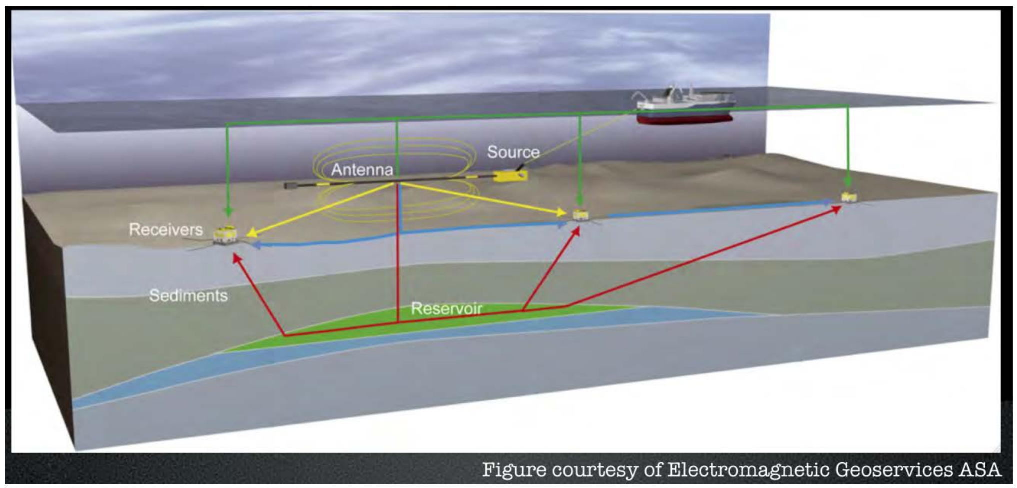

Figure 5-1
Waveguides from a Horizontal Electric Dipole Used to Explore Subsea Formations

Calculations of EMF propagation based on assumptions typically made on land are misleading in the ocean environment. In this highly conductive marine environment, Maxwell's equations reduce to quasi-static form, better characterized as a "diffusive wave equation." In the quasi-static diffusive state, the dielectric properties become insignificant, leaving only the electrical conductivity of the medium relevant to the propagation.

Cable shielding is effective in preventing radio frequency (RF) energy from leaking out of the marine power cable. Effective shielding against low frequency magnetic fields, however, requires multiple layers of highly permeable material, and possibly the addition of an active field bucking/nulling system using solenoids/Helmholtz coils. In practical terms, shielding against low frequency magnetic fields is ineffective.

Marine telecomm cables that straddle the ocean, as shown in Figure 5-2, employ a constant current power supply, with high and opposing voltages on opposite ends of the cable, with a null voltage point in mid-ocean. These cables often use a sea ground return to minimize copper conductors. One consequence of this is that it sets up a large dipole moment, with the potential for electromagnetic emissions over a large region.

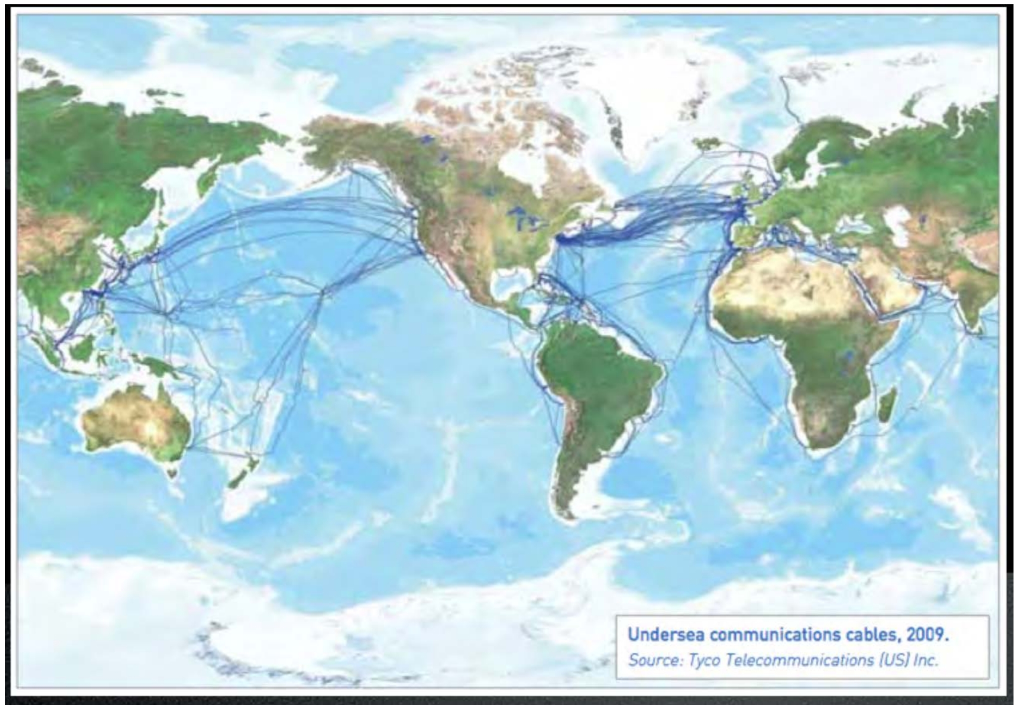

Figure 5-2
Undersea Telecommunication Cables, 2009

Measurements and Instrumentation

The fields to be measured can span nine orders of magnitude (more than 160 dB in terms of a logarithmic scale). Similarly, the measurement of magnetic fields, from the "quietest" natural fields to those from power generation facilities can require a dynamic range of over 180 dB. To acquire data sets that represent the entire dynamic range of the signal, the general measurement approach involves multiple gain stages with multiple channels.

As a rule of thumb for instrumentation, protocols, and detection limits:

- Minimum sensitivity for near-shore measurement should be 1nV/m or less in the regime greater than 1 Hz. At lower frequencies, instrumentation should have a sensitivity of 10-100 nV/m.
- DC magnetic field instruments should be capable of measuring levels of 10 nT.
- AC magnetic field instruments should have a noise ceiling of order picoT/Sqrt(Hz) at 1 Hz.

Because of the localized nature of anthropogenic EMF, the dynamic range requirements for instruments might be reduced. Wave energy converters, wind turbines, cables, and sub-sea pods represent limited spatial range; that is, they occupy discrete locations and do not exist "everywhere" as do more generalized ambient fields caused by distributed EMF sources within the water column, such as ocean waves, tidal action, and the earth's magnetic field. Since electric fields dissipate away from the source quickly in the sea, locations and sensing distances can be controlled.

Electric fields in the sea are substantially more difficult to detect than equivalent electric fields observed in the earth's atmosphere. Marine electric-field sensors are essentially highly sensitive voltmeters that measure the voltage potential between two probes separated by some distance. Several companies provide turnkey electric field sensors, and several offer multi-dimensional (3-D) marine electric field sensors.

In terms of magnetic field measurements, two types of magnetometers dominate the commercial marketplace: induction coils and fluxgates. Use of induction coil magnetometers is commonplace due to their simplicity in manufacture, calibration, and operation, and outstanding noise floor specifications for ultra-low noise measurements, particularly for frequencies > 1 Hz. Fluxgate sensors are somewhat more complex, but commercial products offer a high degree of integration, and excellent noise floor specifications for DC and low frequency (< 1 Hz) AC magnetic fields.

Induction coils are the preferred sensor for AC through powerline harmonics, although fluxgates are good choices for lower frequency oceanographic induction effects, as well as quasi-dc fields. High gain, short-span electric dipole receivers are recommended. High definition digitizers can be used to extract subtle signals, and care must be taken to avoid or filter out instrument induced or ship-related noise.

An orientation sensor mounted to the instrumentation package would help provide sensor pitch and roll information plus magnetic compass direction with respect to the earth, and provide a tool to aid data analysis and interpretation of results. Further, adding an accurate pressure sensor would also be useful. Wave action and ocean currents can play a significant role in the generation of naturally occurring electric fields, and water velocity due to wave motion is a function of the water depth. The pressure sensor would provide independent validation of wave heights and provide insight to electric field generation during periods of high waves. Acoustic Doppler current-profilers are another useful tool for monitoring the motions of the water column.

Oregon Wave Energy Trust Prototype

To build a low-cost test bed instrument capable of detecting ocean wave/swell frequencies, as well as powerline frequencies and harmonics, Oregon State University teamed up with SAIC to build a first-generation prototype of a wideband EM receiver, as shown in Figure 5-3. Development was done under the auspices of the Oregon Wave Energy Trust (OWET). In terms of engineering, they adapted for marine use the Zonge ZEN geophysical EM receiver originally designed for terrestrial use by Zonge International and Oregon State University. It uses a Zonge ANT2 induction coil magnetic field sensor, with a frequency band from <0.1 Hz to > 1 kHz. The first field test was to help the city of Newport, Oregon locate a water treatment pipeline buried under 50 feet of sediment, and beneath 50 feet of seawater.

Schultz also described a highly versatile instrument package called the OSU Multiphysics Bottom Lander, shown in Figure 5-4. It is a 1.8 meter, trawl resistant, hydrodynamically stable bottom lander equipped with wideband seismometers, magnetometers, electrometers, temperature sensors, pressure sensors, hydrophone, and a chip-scale atomic clock. It is made of composite materials to prevent EM interactions, and uses acoustic telemetry of data to ship or buoy. It can operate autonomously, or tethered to a ship or buoy. It is designed for widespread use in EMF research.

Figure 5-3
OSU/Zonge High Definition Wideband EM Receiver for Electric and Magnetic Fields

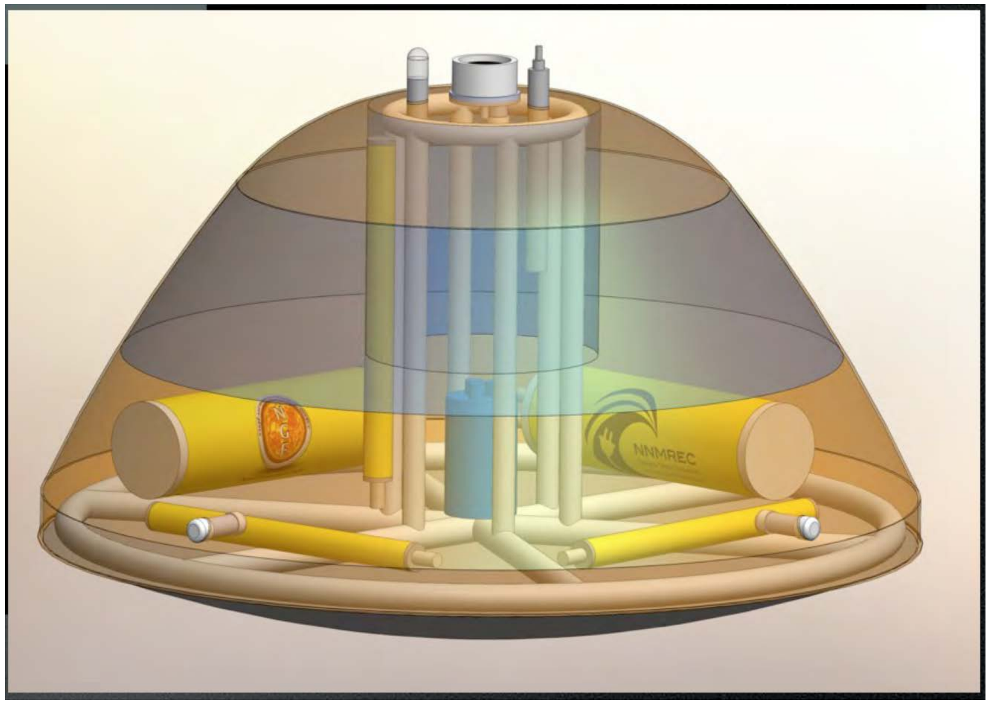

Figure 5-4
OSU Multi-physics Bottom Lander Equipped with Instrumentation to Measure Electromagnetic Fields

Research Needs and Priorities

The workshop discussion focused on a number of research needs in the area of exposure characterization and measurement used to support future field and laboratory studies.

- **Establish sensitivity floors—**Identify sensitivity floors for various species of fish, cetaceans, and pinnipeds. These should be established not only for DC fields but also AC fields at oceanographic frequencies, as well as power frequencies.
- **Enhance computational capabilities—**As the most tractable approach, recommend using frequency domain or equivalent time domain. Fine-scale model discretization is required.
- **Eliminate extraneous signals from baseline measurements—**Develop tools to avoid or digitally filter out extraneous anthropogenic signals, including instrument-induced or ship-related noise from baseline and WEC-related EMF measurements.
- **Identify relevant exposure parameters**—What aspects of exposure are the most significant with respect to animal behavior, or the most deleterious with respect to animal development, growth, procreation, feeding, hunting, migration, and survival? Can thresholds be discerned?
- **Improved instrumentation—**Can marine EMF instrumentation sensitivity be enhanced, to read E-fields comparable to those sensed by elasmobranchs?

Section 6: Research Recommendations and Priorities

The workshop participants were asked to provide recommendations to assist EPRI in its efforts to frame a research portfolio in the area of EMF and Aquatic Life. Following the discussion of research needs, participants were asked to identify and recommend specific projects appropriate for EPRI, and then, in a second stage to vote for priorities among the recommendations. The results are summarized in this Section. Recommendations for 17 potential projects are listed below in the order in which they were proposed during a free-wheeling discussion. The research recommendations were driven more by scientific need than regulatory perspective. The anticipation is that the proposed research agenda will assist EPRI members and others attempting to develop offshore energy facilities, and/or improve grid efficiency by the use of undersea cables. The priorities are shown in the next section.

Research Recommendations

Field Studies

- **Observe marine life in the vicinity of existing cables—**Undertake observational studies of assemblages of marine life near existing, energized cables around the world. Studies would include measurements, observational data, and video recording of the behavior, distribution, and movement of critical species. Researchers would look for attraction/withdrawal behavior, and patterns of response affecting food, reproduction, competition, migration, etc. Integrated databases from studies around the world would inform the research community, as well as developers, regulators, and the public, and possibly serve as guidance for future mitigation strategies. It is important to know whether and how the cables are actually energized; that is for researchers to have data available on the transmission details so that any responses by marine life can be properly correlated with the EMF. It is important that the cables in question carry the levels of EMF expected from ocean energy development.
- **Analyze existing data and develop testable hypotheses—**Integrate and analyze existing field and laboratory data on EMF effects on marine life, and use the data to develop testable hypotheses for laboratory and mesocosm research. Efforts should be made to open existing, underutilized data troves, such as the UK COWRIE mesocosm work, to further analysis. There are

substantial datasets that have not been fully analyzed for lack of funding. This a quick win study and relatively inexpensive.

- **Apply new technology to determine fine-scale behavior—**Exploit the capabilities of new technology, such as miniaturized accelerometers, to monitor fine-scale behavior of aquatic animals to an applied EMF stimulus.
- **Develop methods to scale from laboratory responses to mesocom to field work—**Methodology is needed to help the research community scale results from laboratory research to the mesocosm level to studies in the ocean and river systems. Scaling is needed in several dimensions: behavior, temporal, and spatial given the range of possible responses, from short-term, localized attraction/withdrawal to long-distance migration.
- **Establish baseline EMF measurements of the ocean environment—**Build a coherent database of EMF measurements of the natural environment that characterizes the broad distribution of EM fields in the ocean. It should include deep-ocean and near-shore ambient electric and magnetic fields, with associated frequencies, including induced AC electric fields from the motion of waves, tides, and currents.

Laboratory Studies

- **Establish baseline characterization of EMF-sensitive populations—** Beginning with representative species of different taxa, create a database of species-specific responses (including key end points listed in Section 3) to EMF stimuli of different types, field strengths, and frequencies. Screen sensitive species for further study. Differentiate responses of related species within groups (i.e. halibut, sturgeon).
- **Develop an exposure system for laboratory research—**Given likely anthropogenic sources, what kind of EMF exposures should animals be subjected to in the laboratory to emulate the real world? Exposure systems should be designed with enough versatility to handle diverse species, afford different experimental regimens, and allow for variable EMF exposure characteristics.
- **Evaluate electric versus magnetic receptors—**Efforts are needed to identify and differentiate receptors used by marine life to detect electric fields and magnetic fields, and to understand the biophysical mechanisms underlying those sensors. Animals known to detect magnetic fields have electro-receptors, but at present the mechanism of magneto-reception is unknown. Do species detect electric and magnetic fields separately or jointly? How does frequency modulation impact these sensors? What are the thresholds of detection by different species?
- **Develop dose-response relationships for model animals at different life stages and for different stimuli (e.g. AC, DC)—**Laboratory tests at graduated levels of exposure, similar to the process of toxicological research, are needed to determine if a dose-response relationship exists for EMF. Does it vary at critical development stages? Is it a linear relationship? Is there a threshold below which there is no meaningful impact? Does the dose-response relationship change and animals habituate to the stimuli?

- **Develop standardized laboratory protocols for EMF testing to characterize and categorize behavioral responses across taxa to different stimuli**—Lab studies are relatively new and there are no agreed-upon, standardized testing protocols. A standardized suite of protocols is needed to measure key end points for a wide variety of species across taxa, and to do screening studies on the most sensitive species. Standardized protocols would speed the integration of parallel studies from different laboratories around the world, accelerating scientific advance. Using standard protocols, labs could begin a comprehensive effort to characterize the responses, including epiphenomenal responses, of different species to different EMF stimuli, including AC and DC, magnetic and electric fields. The AC fields are not restricted to power line frequencies.

Exposure Assessment

- **Develop tiny magnetic field sensors**—Develop micro-electronic sensors sufficiently small and unobtrusive that they can be attached to animals in laboratory or mesocosm environments. This would allow direct readings of the magnetic field as the animal experiences them.
- **Identify relevant exposure parameters of the natural environment**—What aspects and parameters of the complex EMF marine environment have the greatest influence on aquatic life where perturbations by anthropogenic fields could make a difference? Electric field strength varies by the movement of waves, tides, and currents. EM propagation depends on the depth of the water column and geology. In the deep ocean, geomagnetic fields dominate at the surface, where many fish migrate, but seamounts magnetism can dominate near the seafloor. Which are relevant factors? This is effectively a follow up study. It is not possible to ID the relevant exposure parameters until some of the lab, mesocosm and/or field studies produce results.
- **Develop better instrumentation**—Research would be assisted by the development of simpler, less expensive instrumentation that is adapted for the complexity of the ocean environment, the task of reading fields that can vary over 10 orders of magnitude, and the challenge of achieving sensitivity levels matching those of aquatic animals.
- **Develop and validate modeling software**—Develop software that can accurately predict the electromagnetic fields emitted by undersea cables in the context of changing power flows and moving water columns. Models are now being developed to couple the motional induction into the air/ocean/seafloor induction problem.
- **Evaluate mitigation options**—Before extensive capital investment in offshore energy development, it would make sense to explore least-cost options for reducing fields from cables, wind turbines, wave generators, and the like. Shielding cables, orienting cables and cable arrays to cancel fields, avoiding seafloor as ground are possible mitigation measures, but other, more novel approaches should be evaluated.

- **Create a database of electric power cable installations—**What is the output of existing cables on the seafloor, riverbeds and lake bottoms? Obtaining such information on performance and EMF characteristics of various commercially laid power cables is not a straightforward task. Databases are available that track telecom cables but to date, not power cables. Such a database would be invaluable for researchers.
- **Create FDTD model of representative marine life—**The finite difference time domain (FDTD) method is the most commonly used numerical modeling technique to model the propagation of EM waves in biological organisms. The model can detect the dielectric properties of constituent tissues. It is used widely as a diagnostic tool but could be adapted to help laboratory researchers "see" the biological impacts of EM fields.

Research Priorities

The workshop participants used a weighted voting system to indicate their preferences for the most meaningful research that EPRI could undertake to both advance the science and provide value for its members. The combined weighted scores of the participants led to the following top ten priorities listed in order below, that together could help EPRI shape a future research program. To assist the reader, the project descriptions are repeated from those in the previous section on Research Recommendations.

The preferences centered on basics, such as taking inventory of marine life surrounding existing cable installations, building data bases of exposure environments and behavioral responses, developing protocols for testing, and undertaking experiments to ascertain dose-response. Priorities number four and five are for all practical purposes the same, focusing on characterizing the natural EMF environment to establish the world that aquatic life evolved to meet. Priority number seven goes to the heart of the scientific world's curiosity about the underlying mechanisms that aquatic life forms use to sense EM fields with such delicacy and precision. Priority number eight links closely to two, three, and five.

1. **Observe marine life in the vicinity of existing cables—**Undertake observational studies of assemblages of marine life near existing, energized cables around the world. Studies would include measurements, observational data, and video recording of the behavior, distribution, and movement of critical species. Researchers would look for attraction/withdrawal behavior, and patterns of response affecting food, reproduction, competition, migration, etc. Integrated databases from studies around the world would inform the research community, as well as developers, regulators, and the public, and possibly serve as guidance for future mitigation strategies. It is important to know whether and how the cables are actually energized; that is for researchers to have data available on the transmission details so that any responses by marine life can be properly correlated with the EMF. It is important that the cables in question carry the levels of EMF expected from ocean energy development.

2. **Develop dose-response relationships for model animals at different life stages and for different stimuli (e.g. AC, DC)—**Laboratory tests at graduated levels of different types of EMF exposure, similar to the process of toxicological research, are needed to determine if a dose-response relationship exists for EMF. Does it vary at critical development stages? Is it a linear relationship? Is there a threshold below which there is no meaningful impact? Does the dose-response relationship change as an animal habituates to the stimuli?

3. **Develop standardized laboratory protocols for EMF testing to characterize and categorize behavioral responses across taxa to different stimuli—**Lab studies are relatively new and there are no agreed-upon, standardized testing protocols. A standardized suite of protocols is needed to measure key end points for a wide variety of species across taxa, and to do screening studies on the most sensitive species. Standardized protocols would speed the integration of parallel studies from different laboratories around the world, accelerating scientific advance. Using standard protocols, labs could begin a comprehensive effort to characterize the responses, including epiphenomenal responses, of different species to different EMF stimuli, including AC and DC, magnetic and electric fields. The AC fields are not restricted to power line frequencies.

4. **Establish baseline EMF measurements of the ocean environment—**Build a coherent database of EMF measurements of the natural environment that characterizes the broad distribution of electromagnetic fields in the ocean. It should include deep-ocean and near-shore ambient electric and magnetic fields, with associated frequencies, including induced AC electric fields from the motion of waves, tides, and currents in the geomagnetic field and in man-made fields.

5. **Identify relevant exposure parameters of the natural environment—**What aspects and parameters of the complex EMF marine environment have the greatest influence on aquatic life where perturbations by anthropogenic fields could make a difference? Electric field strength varies by the movement of waves, tides, and currents. EM propagation depends on the depth of the water column and geology. In the deep ocean, geomagnetic fields dominate at the surface, where many fish migrate, but seamounts magnetism can dominate near the seafloor. Which are relevant factors? This is effectively a follow up study. It is not possible to ID the relevant exposure parameters until some of the lab, mesocosm and/or field studies produce results.

6. **Apply new technology to determine fine-scale behavior—**Exploit the capabilities of new technology, such as miniaturized accelerometers, to monitor fine-scale behavior of aquatic animals to an applied EMF stimulus.

7. **Evaluate electric versus magnetic receptors—**Efforts are needed to identify and differentiate receptors used by marine life to detect electric fields and magnetic fields, and to understand the biophysical mechanisms underlying those sensors. Animals known to detect electric fields have electro-receptors, but at present the mechanism of magneto-reception is unknown. Do species detect electric and magnetic fields separately or jointly? How does frequency

modulation impact these sensors? What are the thresholds of detection by different species?

8. **Develop an exposure system for laboratory research—**Given likely anthropogenic sources, what kind of EMF exposures should animals be subjected to in the laboratory to emulate the real world? Exposure systems should be designed with enough versatility to handle diverse species, afford different experimental regimens, and allow for variable EMF exposure characteristics.

9. **Analyze existing data and develop testable hypotheses—**Integrate and analyze existing field and laboratory data on EMF effects, and use the data to develop testable hypotheses for laboratory and mesocosm research. Efforts should be made to open existing, underutilized data troves, such as the U.K COWRIE mesocosm work, to further analysis. There are substantial data sets that have not been fully analyzed for lack of funding. This is a quick win study and relatively inexpensive.

10. **Develop and validate modeling software—**Develop software that can accurately predict the electromagnetic fields emitted by undersea cables in the context of changing power flows and moving water columns. Models are now being developed to couple the motional induction into the air/ocean/seafloor induction problem.

Appendix A: Agenda

AGENDA

EMF AND AQUATIC LIFE

November 14-15, 2012 • MBARI, Moss Landing

NOVEMBER 14, 2012	
TIME	
3:00 p.m.	Tour of MBARI
6:00 p.m.	Dinner: The Whole Enchilada *7902 California Highway 1, Moss Landing*

NOVEMBER 15, 2012		
TIME	**TOPIC**	**PRESENTER**
8:00 a.m.	Continental Breakfast	
8:30 a.m.	Welcome by MBARI	***Jim Bellingham***
8:45 a.m.	EPRI welcome, introduction of participants, why EPRI interested- main drivers, workshop overview	***Gabor Mezei***
9:00 a.m.	Field Studies: Summary of research and suggestions for future research	***Andrew Gill***
10:00 a.m.	**Break**	
10:30 a.m.	Laboratory Studies: Summary of research and suggestions for future research	***Andrea Copping***
11:30 a.m.	Exposure Characterization: Summary of research and suggestions for future research	***Adam Schultz***
12:30 p.m.	**Lunch** (possible brief luncheon presentations by BOEM and NOAA on their activities)	
1:30 p.m.	Discuss and refine proposed research and new topics	***Gabor Mezei***
3:00 p.m.	**Break**	
3:30 p.m.	Priority Setting - Virtual funding exercise	***Mike Silva***
5:00 p.m.	**Next Steps and Adjourn**	***Gabor Mezei***

Appendix B: Workshop Participants

Participant	Company
Brent Barker	Barker Communications
James Barry	Monterey Bay Aquarium Research Institute
James Bellingham	Monterey Bay Aquarium Research Institute
Mark Bevelhimer	Oak Ridge National Laboratory
Ann Bull	Department of the Interior, Bureau of Ocean Energy Management
Andrea Copping	Pacific Northwest National Laboratories
Steve Etchemendy	Monterey Bay Aquarium Research Institute
Andrew Gill	Cranfield University
Scott Hamilton	Moss Landing Marine Laboratories
Jim Harvey	Moss Landing Marine Laboratories
Pete Klimley	University of California, Davis
Christopher Lowe	California State University, Long Beach
Ana Martins	Electric Power Research Institute (EPRI)
Gabor Mezei	Electric Power Research Institute (EPRI)
Bob Olsen	Washington State University
Lynn Orr	Stanford University (MBARI Board Member)
Tom Sanford	University of Washington
Adam Schultz	Oregon State University
Mike Silva	Enertech Consultants
Michael Slater	US Navy
Tim Tricas	Institute of Marine Biology, University of Hawaii

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

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Program:

Electric and Magnetic Fields and Radio-Frequency Health Assessment and Safety

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