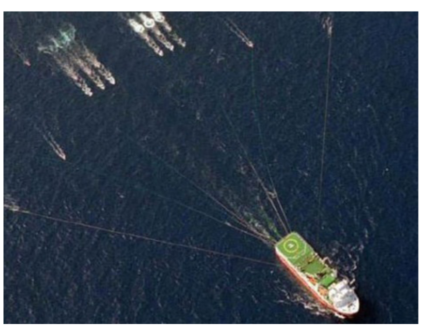
OCS Report
BOEM 2014-061

Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving Workshop

Summary Report






US Department of the Interior
Bureau of Ocean Energy Management
Headquarters

OCS Study
BOEM 2014-061

Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving Workshop

Summary Report

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ABOUT THE COVER

Cover photographs (clockwise from lower left) courtesy of the Bureau of Safety and Environmental Enforcement (offshore seismic testing) or obtained from www.shutterstock.com (offshore wind turbine, jack-up vessel, and pile installation).

CONTENTS

ABBREVIATIONS, ACRONYMS, AND SYMBOLS*

3D	three-dimensional
AIM©	Acoustic Integration Model©
AIS	Automatic Identification System
ANSI	American National Standards Institute
AQUO	Achieve Quieter Oceans
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CFD	computational fluid dynamics
cm	centimeter
CSEM	controlled-source electromagnetic
dB	decibel
DNV	Det Norske Veritas
DP	dynamic positioning
DSL	dipole source level
DTAGS	deep-towed acoustics/geophysical system
EA	Environmental Assessment
E&P	Exploration & Production
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
ESP	Environmental Studies Program
EU	European Union
FM	frequency-modulated
ft	feet
GES	Good Environmental Status
HARP	high-frequency acoustic recording package
HF	high-frequency
Hz	hertz
ICES	International Council for Exploration of the Seas
IMO	International Maritime Organization
in	inch
ISO	International Organization for Standardization
JASCO	JASCO Research
JIP	Joint Industry Programme
kHz	kilohertz
km	kilometer
kn	knots
kPa	kilopascal
LACS	low-frequency acoustic source
LISA	low-impact seismic array
m	meter
MAI	Marine Acoustics, Inc.
MEPC	Marine Environment Protection Committee
MMC	Marine Mammal Commission
MMPA	Marine Mammal Protection Act
MSL	monopole source level
MV	marine vibroseis
NEPA	National Environmental Policy Act
NGO	non-governmental organization
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
OCSLA	Outer Continental Shelf Lands Act
Pa	pascal
PAM	passive acoustic monitoring
PGS	Petroleum Geo-Services
PL	propagation loss
PRN	pseudo-random
R&D	research and development
rms	root mean square
RNL	radiated noise level
s	second
SEL	sound exposure level
SEL_{com}	cumulative sound exposure level
SILENV	Ships oriented Innovative Solutions to Reduce Noise and Vibrations
SL	source level
SNR	signal-to-noise ratio
SONIC	Suppression of Underwater Noise Induced by Cavitation
SPL	sound pressure level
SL_{rms}	source level root mean square
SPL_{peak}	sound pressure level peak
SPL_{p-p}	sound pressure level peak–to-peak
TC	Technical Committee
TEES	Texas Experimental Engineering Station
TNO	Netherlands Organisation for Applied Scientific Research
TSG	Technical Subgroup (Noise)
USD	US dollars
μPa	micropascal
WAZ	wide-azimuth

*Definitions and discussions of standard, acoustic-related terminology are presented in:

Ainslie, M.A. 2011. Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units. TNO report TNO-DV 2011 C235. Internet website: http://www.noordzeeloket.nl/images/Standard%20for%20measurement%20and%20monitoring%20of%20underwater%20noise%20Part%20I_648.pdf. Accessed January 28, 2014

EXECUTIVE SUMMARY

The focus of the Bureau of Ocean Energy Management's (BOEM's) Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving Workshop was to examine current and emerging technologies that have the potential for reducing noise generated during certain ocean activities. Specifically, the Workshop considered technologies that have potential for quieting noise from geological and geophysical exploration, pile driving, and support vessel operations.

A significant theme throughout the Workshop was the need for all regulatory agencies as well as the oil and gas industry, technology developers, and non-governmental organizations to work together to gain a better understanding of the specifics of emerging technologies. This will allow the oil and gas industry and the marine industry to better understand regulatory concerns for new technologies, follow timelines for future and pending permitting processes, and identify ways to conduct relevant environmental monitoring and field testing specific to their technology. It was noted that the coordination between industry and regulatory agencies has vastly improved over the past 10 years. This coordination is key to further improvements in technology development, establishment of the regulatory framework and mechanisms, design of environmental monitoring and field testing, and discussion of concepts and regulations to determine a path forward.

One of the important issues identified was the lack of consistent acoustic terminology and noise measurement methods/standards. Standardized measurements would allow for scientific comparisons between and among data. Without this consistency, comparing various technologies or mitigation measures and their usefulness in quieting will be extremely difficult.

For each of the three main sound-generating activities considered (airguns, pile driving, and related support vessels) the following conclusions were reached:

- At this time the primary potential but still emerging alternative to airguns (in certain settings) appears to be marine vibroseis (MV). Although there are a number of different types of MV units that are still under development, at least one system may be close to commercial use in certain applications, notably in shallow water, sensitive habitats, and near vulnerable biological resources. However, MV will not be effectively implemented on a wider scale until its economical feasibility is proven and its potential for environmental impacts is tested.
- For pile driving, there are a number of commercially available alternatives, none of which have been fully field-tested, and research into alternative pile driving methods continues. The commercially available alternatives to impact pile driving include drilling, vibratory, gravity base, and floating piles. While new pile designs have been developed (double-walled pile and lower radial expansion pile), research and development is continuing. Mitigation measures for quieting the pile driving process include bubble curtains, cofferdams, and noodle nets. None of the quieting technologies have been sufficiently tested to determine their true field performance. There is no one-type-fits-all solution to pile driving noise, especially with regards to through-sediment transmission of sound and other very site-specific issues like water depth, currents, and substrate type. For this reason, projects may require their own analysis to determine the most effective and suitable noise reduction method.
- With regards to vessel noise, there are two primary noise sources: propeller cavitation, and noise from diesel engines. Since most support vessels are typically re-purposed older vessels, retrofits and ship husbandry/maintenance are typically the means available to reduce noise. Many of the applicable quieting technology solutions are expensive because they involve retrofits for support vessels that need to serve multiple purposes. Accomplishing quieting through technology for these vessels is not straightforward, but techniques like speed reduction and regular maintenance can significantly reduce radiated noise without requiring retrofits. In addition, since there are currently no guidelines or requirements for vessel noise, there is no standardized effort focused on quieting technologies.

Workshop participants identified numerous data gaps, such as where anthropogenic noise may or may not impact marine life. Where it does, more information is needed on the type and extent of impact, the effects that need mitigation, the mitigation methods that can be used effectively to reduce adverse effects, and the benefits that would be realized from those mitigation measures. A chief concern at the Workshop was how to determine goals for reducing acoustic impacts, and subsequently how to regulate activities that result in impacts to marine life to achieve those goals. More work needs to be done to better understand noise effects in the marine environment, determine appropriate noise levels, define noise reduction, and establish standards or guidelines to assist the continued development of new methodologies.

Even before these data gaps are filled, research and development into quieting technologies should continue to proceed. Workshop participants indicated that if a new, potentially more environmentally friendly technology is developed, it should be encouraged by the regulatory agencies while research into the effects of noise on marine fauna continues.

Industry may be hesitant to utilize quieting technologies until the value of these technologies is better understood from operational, data quality, cost effectiveness, and environmental protection standpoints. Federal agencies may need to consider regulatory requirements or incentives to implement the use of new technologies as understanding of their effectiveness improves. Incentives might include proof that a particular technology is safer, more cost effective, and/or efficient; a requirement by regulations for its use; lifting some restrictions on activities; or requirements that industry achieve a particular standard for acoustic emissions within certain frequencies, as has been done in Germany for pile driving. Other examples may include, a more streamlined regulatory process, noise propagation standards that would apply at least in certain sensitive areas, or fewer restrictions on the activities, their timing, and/or location. A continued dialog between industry, non-governmental organizations, and BOEM is needed to help identify appropriate incentives or requirements. The Programmatic Environmental Impact Statements that are now in the process of being prepared for the Atlantic, Arctic, and Gulf of Mexico may be effective vehicles for establishing such incentives or requirements.

1. INTRODUCTION

1.1 BACKGROUND

The Outer Continental Shelf Lands Act (OCSLA), as amended by the Energy Policy Act of 2005, and supporting regulations necessitate studies to assess environmental impacts from activities authorized and permitted by the Bureau of Ocean Energy Management (BOEM). These activities include geological and geophysical exploration and pile driving during construction as well as associated vessel operations. Industry collects seismic data to locate hydrocarbon resources, identify potential shallow hazards and archeological avoidance areas, evaluate sites for renewable and other offshore energy infrastructure, and assess potential marine mineral resources. Pile driving can be used to install Outer Continental Shelf (OCS) structures in the seafloor (e.g., wind turbines and oil and gas platforms). Vessel traffic is associated with all of these activities.

These sound sources, together or individually, can produce noise that may be disruptive to marine life. For example, seismic exploration requires a high-energy sound source (such as an airgun) in order to penetrate deep below the seafloor. The sound source levels and propagation characteristics of airguns used in seismic surveys can potentially result in harmful injuries to marine mammals and other marine life (e.g., fishes and sea turtles) in close proximity to the sound source and can also result in behavioral disruptions. Similarly, pile driving activity generates sound at levels and frequencies that can be harmful to marine life in close proximity to pile driving operations. Both seismic surveys and pile driving require the use of support vessels (i.e., service vessels, ice breakers, vessels with dynamic positioning [DP] systems), which also add noise to the marine environment. Finding ways to minimize these impacts is of great concern to industry, governmental agencies, and environmental stakeholders.

A Scientific/Technical Review Panel (Panel) made up of leading technical experts in their respective noise-related fields was assembled to consider the issue of noise and sound reduction as a potential mitigation technique. This Panel was also instrumental in the planning and development of the Workshop. They provided technical direction for the development of the final Workshop Agenda and the key issues for discussion during the Workshop as well as lending their expertise to the selection of participants invited to make presentations at the Workshop. The Panel was chaired by Mr. John Young (CSA Ocean Sciences Inc.) and members included Dr. Michael Ainslie (Netherlands Organisation for Applied Scientific Research [TNO] – The Hague, Netherlands), Dr. William Ellison (Marine Acoustics, Inc.), Dr. Brandon Southall (Southall Environmental Associates, Inc.), Dr. Linda Weilgart (Dalhousie University), and Dr. Dietrich Wittekind (DW Shipconsult GmbH).

The focus of the Workshop was on quieting technologies. The word "quieting" implies that the starting point is something that is considered "loud" and it is desirable to make it "quieter." The word "quieting" implies some reduction of total sound, and in the context of this Workshop, this sound reduction was focused at the sound source itself. Although "quieting" was clearly the primary focus of the Workshop, it was also important to put in perspective other aspects of sound reduction that should be addressed at the same time. For example, quieting can be achieved through separation of the sound source from the affected environment in both distance and in time—shipping channels can be relocated, or seasonal restrictions on activities may separate an animal of concern from the time of the activities. Further, the spectrum of a sound source can be adjusted so that its overlap with an animal's acoustic hearing and/or communication range is lessened. These are all common sense approaches to quieting that may be (and often are) used where they are warranted, feasible, economical, or necessary for conservation purposes.

Quieting possibilities include the following:

- the source radiates less acoustic power
  - the source radiates less power in specified frequency bands, and/or
  - the source radiates less power in specified angle ranges;
- a reduction in rise time for impulsive signals;
- the source radiates lower acoustic intensity at a specified receiver position (in total intensity or in specified frequency bands);
- a reduction in total acoustic power of a source (in specified frequency bands or in specified angle ranges); and
- a reduction of the sum total of all acoustic power for the source and associated source activities (in total energy or in specified frequency bands).

Determining which of these attributes is most appropriate for assessing effectiveness of quieting for animals depends on whether there is an effect and, if so, is animal behavior or actual injury of the highest concern. The precise effects are likely to differ by source type and species, but one would expect an increase in chronic noise as offshore industry activity levels increase. Nonetheless, to address actual source quieting under any scenario, it seemed best to do so by source type (i.e., seismic surveys, pile driving, and vessel noise). Thus, the Workshop was framed around addressing the issues associated with these three primary noise sources.

1.2 PURPOSE OF THE WORKSHOP

BOEM organized the Workshop where 140 government, industry, non-governmental organizations (NGOs), and academic experts examined quieting technologies to reduce the noise generated during offshore exploratory seismic surveys, pile driving, and the operation of vessels associated with these activities. Of the 140 attendees, 21 international experts representing eight countries (Australia, Canada, France, Germany, Netherlands, Spain, United Kingdom, and the United Arab Emirates) shared the perspective from their country's regulatory standpoints and their efforts to minimize underwater noise through various programs and technologies.

The purpose of the Workshop was to examine quieting technologies. By focusing on the "technologies" themselves rather than the associated impacts, industry experts impartially examined and discussed the methods and design of equipment that resulted in lower sound output. By separating technical discussions from any particular environmental impacts, more objective discussions of the technical issues surrounding reduction of underwater noise generation emerged. The Workshop format encouraged interactive listening to allow for information sharing across disciplines and areas of expertise.

The Workshop examined current and emerging technologies that have the potential to reduce the impacts of noise generated during offshore exploratory seismic surveys, pile driving, and vessels associated with these activities. Specifically, the goals of the Workshop included the following:

1. Review and evaluate recent developments (current, emerging/potential) in quieting technologies for
   - seismic surveying, whether proposed or in development;
   - pile driving during offshore renewable energy activities; and
   - vessel noise associated with OCS energy development activities.
2. Identify the spatial, spectral, and temporal features of the acoustic characteristics of new technologies in varying environments compared to that from existing technologies.
3. Identify the system and site-specific requirements for operation of these new technologies and limitations in their use.

4. Discuss potential impacts, both positive and/or negative, in using these technologies:
   - Operational and cost effectiveness; and
   - Potential environmental impacts from these technologies.
5. Evaluate data quality and cost effectiveness of these technologies as compared to that from existing marine acoustic technologies.
6. Discuss what the current and emerging/potential technologies can do to reduce sound output.
7. Examine potential changes in environmental impacts from these technologies in comparison with existing technologies.
8. Identify which technologies, if any, provide the most promise for full or partial replacement of conventional technologies and specify the conditions that might warrant their use (e.g., specific limitations to water depth, use in Marine Protected Areas, etc.).
9. Identify next steps, if appropriate, for the further development of these technologies, including potential incentives for field testing.

Results from the Workshop provide a better understanding of the acoustic characteristics of the alternative technologies including sound propagation, their operational requirements and limitations to their use, and any further steps and time needed for their development. Additionally, the quality and economic value of the data collected using these alternative sources were compared to the quality and economic value of the data collected from current acoustic sources.

As mandated in the OCSLA, as amended by the Energy Policy Act of 2005, and supporting regulations, studies must be conducted to assess environmental impacts from activities authorized and permitted by BOEM, including seismic surveying, pile driving, and associated vessel operations. Ultimately, the outcome of this Workshop helps provide BOEM and other regulatory agencies with the information needed to determine the usefulness and appropriateness of quieting technologies to reduce impacts to marine life by reducing overall noise introduced into the marine environment. BOEM will incorporate this information into its compliance efforts related to various statutes, in particular the National Environmental Policy Act (NEPA), Endangered Species Act (ESA), Marine Mammal Protection Act (MMPA), and the Magnuson-Stevens Fishery Conservation and Management Act.

1.3 Information Synthesis Overview

Prior to the Workshop, the organizers compiled a synthesis of available literature and information on three main topics: (1) alternative technologies for conducting seismic surveys for offshore energy resources; (2) quieting technologies for pile driving operations; and (3) quieting technologies for support vessel noise. The Information Synthesis, provided in **Appendix A**, served as a resource for Workshop participants and provided a framework for identifying areas needing further examination at the Workshop.

Goals of the Information Synthesis included the following:

- Compile information regarding noise quieting technologies used within the last 10 years for use in waters from the coast to 200 nautical miles (nmi) offshore for the three main topics;
- Determine what quieting technologies have been proposed, developed, investigated, or are currently in development;
- Provide a tool for Workshop participants to inform them about the current state of the technologies; and
- Aid in identifying information data gaps to be examined at the Workshop.

One point identified during the preparation of the Information Synthesis report and confirmed during the Workshop was that acoustic terminology is not consistent amongst scientists, countries, or fields of study (i.e., airguns, pile driving, vessel noise). Differing terminologies inhibit the comparison of results, development of common threshold criteria, determination of actual noise reductions, and establishment of standards. Dr. Michael Ainslie discussed this issue in more detail during his presentation, "Basic Terminology for Underwater Sound," which is summarized in **Section 2.2.3**. Acoustic terminology for the Information Synthesis report was adopted from "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units, TNO-DV 2011 C235" (Ainslie, 2011).

Because the three main sound sources addressed in the Workshop have different methods for quieting the noise produced from their use or implementation, information for each source was presented differently in the Information Synthesis. Here, we focused primarily on airgun noise to represent seismic survey activities. Airgun noise was divided into three subsections: (1) alternative acoustic sources having the potential to replace airguns for some surveys; (2) complementary technologies that may reduce the need for seismic surveys; and (3) methods to reduce unwanted or unused noise from airguns. The first category included alternatives such as MV, low-frequency acoustic source (LACS), deep-towed acoustics/geophysical system (DTAGS), low-impact seismic array (LISA), and underwater tunable organ-pipe. Based on the information reviewed, MV appears to be the most promising technology, with several different systems being developed and tested. Low-frequency passive seismic methods, electromagnetic surveys, gravity and gravity gradiometry surveys, and fiber optic receivers were included in the second category of complementary technologies. The third category, reducing unwanted or unused noise, included bubble curtains, parabolic reflectors, airgun silencers and other methods to reduce high frequency noise, such as the E-source airgun. Because of the proprietary nature and stage of the E-source airgun development, no additional information is available at this time.

Measures that have been developed to reduce acoustic impacts of underwater sound from pile driving were divided into the following three categories: (1) alternative piling installation methods that produce less noise; (2) low-noise foundations (non-piling methods); and (3) mitigation methods to attenuate the transmission of underwater sound from pile driving. The first category included alternatives such as vibratory hammers, press-in systems, cast-in-place piles, and alternative pile materials and shapes. The use of wood, nylon, and micarta pile caps also would fall into this category. The second category included alternatives such as gravity base structures, suction-based foundations, drilled or excavated foundations, and floating foundations. The third category included noise-reducing methods such as cofferdams, bubble curtains, isolation casings, and others. All of the methods presented have the potential to reduce noise levels; however, due to the very different applications for piles, no one-size-fits-all solution exists. The applicability of alternative methods or mitigation measures is very dependent on a number of factors including water depth, application (e.g., size, anchoring requirements), sediment type, currents, and duration of pile driving activity. Having a standard noise reduction requirement (e.g., 20 dB) would assist in determining what methods are the most applicable. In addition, there are two noise paths from pile driving: a water path and a bottom sediment path (i.e. through the substrate). Typically, the alternative methods and mitigation measures for the third category (attenuation) block only the water path, whereas the bottom sediment path may also allow for longer distance low frequency sound propagation.

Support vessel noise quieting is very different from the other two topics in that vessel operation itself causes noise. Therefore, understanding what the noise sources are (engines, propellers, pumps, etc.) from support vessels is key to determining noise reduction methods. Support vessel noise sources include propeller cavitation, machinery noise, sea-connected systems, and hydrodynamic noise, and known methods for quieting each noise source are presented in the Information Synthesis. Propeller cavitation is the primary source of underwater noise for most vessels. It is a likely priority for action, as great gains in quieting could be made by reducing the noise output from the noisiest vessels.

2. THE WORKSHOP

The Workshop was held February 25-27, 2013, at the DoubleTree by Hilton Hotel in Silver Spring, Maryland. As stated, over 140 attendees including 21 international experts representing eight countries as well as 15 technical panel members and facilitators participated in the Workshop. The list of attendees is presented in **Appendix B**.

2.1 OVERVIEW OF WORKSHOP

The Workshop was divided into three major areas that started with Plenary Sessions to set the stage for the Breakout Sessions for each of the three topics and focus on the Workshop Goals. The Plenary Sessions on the first day of the Workshop presented an overview of the existing regulatory environment, provided knowledge obtained from previous recently held workshops, and introduced sound terminology and the three topic areas (airguns, pile driving, and support vessel noise). The concurrent groups within a Breakout Session were designed to first provide information on new technologies within each topic area and then focus the technical experts on detailed discussions regarding the nine Workshop Goals (see **Section 1.2**). The complete Agenda is included in **Appendix C**.

Plenary Sessions I-III set the stage for the Workshop framework. The opening remarks (Welcome, Workshop Goals, Agenda, and Introductions) and Plenary Session I (Overview) provided the participants with the framework to set the stage, define the Workshop Goals, provide BOEM's perspective, and provide the European Union (EU) perspective on the subjects at hand. Having international participation and presentation of the EU perspective provided a better understanding of the state of noise in the marine environment worldwide. The EU and the United States have both been working on this subject to ensure opportunities for joint study and learning. Plenary Session II (Knowledge from Other Workshops) provided information gathered from previous, related workshops to form a basis of discussion for this Workshop, avoid duplication, and identify information gaps for future research. Plenary Session III (Noise from Relevant Activities) presented background information on sound terminology and an introduction to each of the three topic areas: airguns, pile driving, and support vessel noise.

After the stage was set, three consecutive breakout groups, one for each topic area, were convened to discuss current and emerging/potential quieting technologies. After the presentations of the technologies by a number of technical experts, the breakout groups focused discussions on the nine Workshop Goals to provide a synopsis of the information presented as well as to provide opportunities for all the participants to provide their valuable input to the discussions regarding the goals identified by BOEM.

Day 2 of the Workshop closed with a Plenary Expert Panel that comprised the Scientific/Technical Review Panel as well as several industry experts. This expert panel offered perspectives on summarizing unintended consequences, alternative supplemental technologies, and mitigation techniques for seismic surveys, pile driving, and support vessel operations. This session was also an opportunity for the participants to ask relevant questions of these technical experts.

The facilitators from each Breakout Session provided summaries on Day 3 of the Workshop. Current and Emerging/Potential Technology presentations were summarized in Plenary Session V, and a summary of the nine goals for each topic area was provided in Plenary Session VI.

Although the focus of this Workshop was on the technologies, these discussions would not be complete without at least touching on the potential environmental impacts of these activities. Plenary Session VII provided a facilitated discussion with a panel of agency, industry, and NGO members. In the context of new quieting technologies, this discussion was based on what regulations should be in place and how they should be implemented.

The Workshop closed with a Panel Discussion (View to the Future) comprising the Scientific/Technical Review Panel members and BOEM, industry, and NGO participants. This session was designed to summarize the perspectives of each discussion panel member regarding their highlights of the Workshop discussions, important data gaps that need to be addressed, and lessons learned; these will assist BOEM in determining their next steps with regards to quieting technologies.

2.2 ANNOTATED AGENDA

The Workshop agenda was developed concurrently with the identification of key issues by the Workshop Chair, in conjunction with the other Scientific/Technical Review Panel members and BOEM. The key issues became the focal topics for the Workshop Breakout Sessions. The Workshop format was developed to maximize direct coordination amongst each topic's experts in various Breakout Sessions while also allowing for information sharing across each of the source types discussed during the Workshop in the Plenary Sessions.

The Workshop began with a welcome address from a representative of BOEM and an overview of the Workshop Goals. A short presentation introduced the panel members and facilitators and provided an overview of the agenda (**Appendix D, pp. D1-D2**). The Workshop Chair welcomed everyone and discussed the objectives for the Workshop (**Appendix D, pp. D3-D4**). The sections below document the proceedings of the Workshop as they were noted during participant presentations and discussions and does not signify that the contents necessarily reflect the views, opinions, and policies of BOEM.

2.2.1 Plenary Session I: Overview

BOEM Environmental Program – Robert LaBelle, BOEM (Appendix D, pp. D5-D7)

The overview presented by Mr. Robert LaBelle of BOEM provided the applicability of the topics covered by this Workshop to oil and gas exploration, renewable energy development, and sand/gravel (mineral) resource management.

BOEM is responsible for managing the mineral resources in 1.7 billion acres of the OCS of the United States. BOEM's Division of Environmental Assessment prepares program-level NEPA and OCSLA reports and documents and also provides oversight, policy guidance, and direction for NEPA and other environmental laws and regulations affecting OCS activities. There are over 25 statutes that must be complied with for large projects in conjunction with their coordinating agencies (e.g., National Marine Fisheries Service [NMFS], US Fish and Wildlife Service). BOEM uses applied science in the Environmental Studies Program (ESP) to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities and to aid in decision making.

An adaptive management feedback loop begins with the NEPA process. First data are analyzed, and then mitigation measures are developed. These mitigation measures feed back into monitoring to determine their effectiveness in order to identify research gaps to develop further study needs. One of the goals of this Workshop was to determine the research needs and data gaps specific to quieting technologies so that future studies can be developed to fill the gaps.

Between 2007-2012, 26% of the ESP budget has been expended on marine mammals and protected species, including impacts from noise. Noise is generated during numerous offshore activities, and BOEM needs to understand where and to what extent environmental impacts may occur on the various resources from noise. BOEM has been conducting numerous studies and workshops in recent years in collaboration with many partners focused on ocean noise.

BOEM recognizes that the best mitigation strategy is to reduce ocean noise, but that approach requires additional information regarding whether emerging technologies are ready for commercial use or if they need more development, and what the timelines are for development and potential implementation. BOEM also needs to understand the potential environmental impacts from the new technologies, how they compare to the impacts from current technologies, and if the data output and affordability of the new technologies meet industry needs. If the new technologies are viable, should their use be incentivized? BOEM ultimately requires specific information regarding quieting technologies to support its environmental analysis regarding these three types of activities performed under its jurisdiction. For this reason, BOEM conducted this Workshop to encourage dialog and information sharing among experts.

The EU Marine Strategy Framework Directive – René Dekeling, Netherlands Ministry of Infrastructure and the Environment (Appendix D, pp. D8-D11)

To provide perspective from the EU, René Dekeling presented the Marine Strategy Framework Directive established in 2008, which aims to achieve Good Environmental Status (GES) by 2020 in all EU waters, specifically looking at the ecosystem level.

EU Directives are addressed to member states, not to individual agencies or groups (unlike EU Regulations), to set the framework while allowing the individual states to determine procedures for implementation. Member states have been working cooperatively in the process of implementation, and in 2012 EU member states established Marine Strategies for their marine waters. Marine Strategies include assessment of the current state of the marine environment of the region (initial assessment), determination of what GES should be, and identification of targets and indicators. Through 2014, they will work on establishing monitoring programs to enable continued assessment, and in 2015, a program of specific measures will be designed to achieve or maintain GES that should be implemented in 2016. These EU Directives are available at http://ec.europa.eu/environment/marine/good-environmental-status/. This implementation strategy will continue to cycle on a 6-year basis.

GES consists of 11 descriptors; and for the first time underwater noise was explicitly described in EU legislation, which stated that underwater noise cannot be allowed to adversely affect the ecosystem. The EU has initially prioritized short duration, low and mid-frequency impulsive noise and long lasting, low frequency continuous noise as indicators of impact. An expert group, TSG (Technical Subgroup) Noise, was formed with numerous stakeholders to clarify the purpose, use, and limitations of the indicators of noise identified in the Directive to be used in describing GES. The TSG Noise is developing monitoring guidelines so that the member states can begin to understand the baseline conditions regarding underwater noise. It aims to continue collecting scientific data to address the biological impacts of anthropogenic underwater noise on sound-sensitive species, and to determine quantitative indicators for these effects.

The impulsive noise indicator metric, in use by the EU, focuses on "considerable" displacement rather than on specific physiological effects from a cumulative perspective or on a project-specific basis. "Considerable" displacement refers to the displacement of a significant proportion of individuals for a relevant time period and spatial scale. The indicator describes the temporal and geographic distribution where impulsive noise exceeds either a sound exposure level (SEL) or peak pressure threshold. A register (i.e., database) of all activities that generate impulsive sound (e.g., seismic, pile driving, sonar), with specific information regarding the sound signature, will be developed at a regional scale for assessment of the cumulative impacts and total habitat loss. This assessment of the database will be used for management to set thresholds in a regulatory context.

In the Netherlands, the Dutch Continental Shelf in the North Sea is one of the busiest areas in the world, with many of the European shipping channels traversing these waters. In addition, the Shelf is heavily utilized by fisheries, offshore exploration, dredging, cables and pipelines, wind energy, defense, and recreation. While it is clear that anthropogenic contributions to underwater noise have increased, it is unclear what the cumulative effects of this increase are at an ecosystem scale. The GES that must be achieved by 2020 must consider the ambitious wind energy plan in the region (e.g., installation of 1,000 turbines per year throughout the EU) and the impacts associated with this in relation to harbor porpoises (*Phocoena phocoena*). The Netherlands created an inventory of the priority sound sources including shipping, pile driving, seismic surveys, and detonation of World War II munitions as well as secondary sources such as dredging and sonar. The Dutch Marine Strategy has set a goal that by 2020, it will prevent negative effects from underwater noise at the ecosystem level for specific activities (e.g., seismic). They need additional information on the effects of noise-producing activities before specific regulations can be established regarding thresholds. The monitoring set to begin in 2014 can provide some of this additional knowledge for policy development, and continued monitoring will provide information for future adaptation of the regulations. Research projects are ongoing in the Netherlands to fill the knowledge gaps regarding physiological effects to marine mammals and fish, development of standards, risk assessment tools, and studies focused on the distribution of sensitive species.

Discussion of Presentations of Plenary Session I

The EU approach uses organism displacement as an important indicator for impact assessment, however other impacts such as behavioral changes are considered. Displacement can be quantified and is important because it is noticeably changing the suitability of the habitat. More scientific knowledge regarding effects to receiving organisms is necessary to develop regulations appropriate to the risks associated with an activity. To obtain additional information and data, the EU plans to establish the regional and EU current level and trend in impulsive sounds based on industry and government supplied information. The information can be used to evaluate impacts and develop appropriate regulations. Some existing regulations and standard practices are in place for certain noise-producing activities; however, the ambitious Marine Strategy Framework Directive aims to more effectively protect the resources by establishing cumulative, multi-sector limits. Ambient noise is not measured on a large regional scale throughout the EU, however smaller projects are being conducted.

In the EU, 3-5 years from now, it is expected that alternative technologies will become more prevalent than the mitigation approaches currently in place (e.g., temporal and/or spatial separation). However, the cost effectiveness and ability to reduce noise of the new technologies will determine the prevalence of their use. Looking forward 3-5 years from now, BOEM would like to see the industry using new, tangible instruments or techniques for reducing noise. In addition, field testing and monitoring should be occurring to evaluate the effectiveness of both mitigations and alternative technologies or techniques.

2.2.2 Plenary Session II: Knowledge from Other Workshops

This session sought to provide a brief synopsis of accrued knowledge from recent workshops and reports that focused on anthropogenic marine sound and possible mitigation techniques. This information holds value by forming a basis of discussion for this Workshop as well as to avoid duplications, identify common areas of needed future research, and focus this Workshop on new or updated information. Five experts in the field of marine acoustics gave presentations outlining knowledge from past conferences or research, and reports.

Alternative Technologies to Seismic Airgun Surveys Workshop – Dr. Linda Weilgart, Dalhousie University (Appendix D, pp. D12-D15)

Dr. Linda Weilgart outlined a 2009 Okeanos-sponsored conference, which examined new technologies that could at least partially replace or modify seismic airguns. Emphasis was placed on technologies that could reduce the amount of acoustic energy emitted or the geographic area ensonified. The consensus at the conference was that the low frequency component of airgun sound emission is needed to acquire seismic information.

The conference discussed a variety of alternatives to airgun technology, including controlled sources of acoustic emissions such as DTAGS, LISA, LACS, MV, and electromagnetic surveys. Controlled sources are effective because the acoustic energy being emitted is stretched over a longer time scale, with peak source levels at least 30 dB lower than comparable airgun systems. Controlled sources can also control for frequency and thereby limit acoustic output to the relatively narrow part of the frequency spectrum that industry requires. Other proposed ways to reduce peak sound levels included using more sensitive receivers such as fiber optic sensors, or employing airgun silencers. Early evidence from testing of some of these technologies has been positive, but complete testing is needed to assess any incidental environmental impacts of an alternative technology, as compared to airguns, before full adoption can be promoted. After testing is completed, regulatory incentives and engagement are necessary to accelerate further development and adoption of alternate technologies by industry.

Symposium Sound Solutions – Dr. Georg Nehls, BioConsult SH GmbH & Co (Appendix D, pp. D16-D19)

Dr. Georg Nehls recapped a Sound Solutions Workshop held in Amsterdam in 2011. The goal of the Workshop was to identify solutions for reducing underwater noise created by the installation of wind turbines. The major animal of concern in the North Sea is the harbor porpoise, a relatively abundant marine mammal whose optimal detection of sounds occurs between 10,000 and 130,000 Hz. Steel foundations of wind turbines are usually driven 30-40 m into the seabed by hydraulic hammers in water depths of 20-50 m, at distances up to 200 km offshore. Although much of the emitted noise is outside the prime hearing range of the harbor porpoise, some energy is emitted in the 10,000-130,000 Hz range.

One of the main challenges in Europe is that each country has different policies regarding noise reduction. For example, Germany is the only country that has established noise reduction standards for pile driving, but pile driving is widely occurring during the development of wind farms offshore in the UK, Belgium, Denmark, and Netherlands, among others. Noise mitigation in wind farm developments demands avoidance of delays in offshore construction, as the daily construction costs of up to €500,000 (~$660,000 USD) per day makes any delay extremely costly.

Most regulations are derived from EU and national Habitat Directives, where reserves must be established, no deliberate killing or injuring can occur, and disturbance to mammals must be restricted at a population level. Under most circumstances, seal scarers are used to encourage porpoises to vacate an area 1-2 km from the development site. However, it has been shown that noise emissions from pile driving at wind farm locations has caused displacement of porpoises at distances of up to 20 km.

The Workshop highlighted three experimental technologies for reducing harmful noise output: dewatered cofferdams, self installing wind turbines, and hydro sound dampers. Although none of these has been brought into use, early testing has shown promise: a 22-dB noise reduction is being advertised by a manufacturer of a dewatered cofferdam, and a hydro sound damper test reduced main energy noise release. The implementation of these technologies is under consideration by some EU countries, pending proof that they are effective and safe. Tests conducted in late 2012 and upcoming tests in 2013 should provide more data on their effectiveness and practicality.

Effects of Noise on Fish, Fisheries, and Invertebrates Workshop – Kimberly Skrupky, BOEM (Appendix D, pp. D20-D21)

Ms. Kimberly Skrupky briefly addressed a BOEM-sponsored workshop on the effects of noise on fish and invertebrates. The goal was to identify gaps in knowledge of the effects of anthropogenic sound on fish and invertebrates. To maintain brevity, the conference limited its focus to impacts caused by the oil and gas industry and the installation of renewable energy structures in US waters in the Atlantic and Arctic basins. The identification of priority species and fisheries affected by noise emissions was emphasized.

A preparatory literature synthesis was an important part of preparing attendees for the workshop, with the goal of all attendees having a common knowledge base prior to starting discussions at the workshop. The workshop addressed important topics such as the level of importance of fish behavioral alterations due to sound, the mechanisms of how different species hear, what species are affected by sound emissions, and what behavioral alterations and injuries can occur due to anthropogenic undersea sound. Overall, the workshop results focused on directing future research, NEPA analyses, and developing mitigation technologies and new Notices to Lessees and Operators (NTLs) for oil and gas operators.

A Summary of Existing and Future Potential Treatments for Reducing Underwater Sounds from Oil and Gas Industry Activities – Michael Bahtiarian, Noise Control Engineering, Inc. (Appendix D, pp. D22-D27)

Mr. Michael Bahtiarian summarized a 2007 Joint Industry Programme (JIP) workshop that aimed to identify existing and future technologies for reducing underwater sounds emitted by oil and gas company activities. A brief synopsis of a variety of existing technologies was presented, including seismic exploration information on MV, airgun filters, petrol-driven combustion engines, and LACS sound-producing systems. Offshore construction operations were also presented including tunable pipe organs, electromagnetic surveys, air curtain barriers, shear wave generation, suction piles, and press-in piles. Proposed alternatives for the explosives currently used by oil companies to decommission structures included shaped charges and hollow charges that were designed to more efficiently use explosive energy so there is less release of sound into the environment.

A second focus was on reducing vessel sound. It was noted that sound from vessels is from two sources: (1) the propeller and (2) everything else. Developing quiet propellers that minimize cavitation was identified as a key topic of research and implementation in the industry. All noises emitted from ships other than propeller and flow noise are a result of shipboard machinery. Different types of vibration reducers and other treatments are under study to help reduce noise emissions both into the ship and the ocean. Other sources of sound emissions worthy of consideration include dredging noise as well as noises caused by aircraft and helicopters traveling over water.

Two NOAA-Organized Technical Workshops on Shipping Noise, Marine Mammals, and Vessel-Quieting Technologies – Dr. Brandon Southall, Southall Environmental Associates, Inc. (Appendix D, pp. D28-D29)

Dr. Brandon Southall presented the last talk in this session by summarizing a series of workshops designed to promote discussion and understanding of how ship noise affects the marine environment. A 2004 National Oceanic and Atmospheric Administration (NOAA)-sponsored conference was an introduction to many people in the shipping and oil and gas industries to the issues of noise pollution in the oceans. At that relatively early date in marine sound research, noise emissions from ships were not widely viewed within industry as problematic. The goal of the workshop was to initiate dialogue and introduce the industry to the concept of problems with anthropogenic noise emissions. A session at the workshop introduced early research into quieting technologies. Keynote speeches by high-ranking officials, including US Congressman Wayne Gilchrest and the US Deputy Secretary of Commerce highlighted that noise emissions were beginning to be seen as an important and relevant issue by the US Government.

A 2007 NOAA workshop focused on the potential application of vessel quieting technology for large commercial ships. The discussion held value for ship designers, builders, and operators. The workshop focused on vessel acoustics, ambient noise levels, and cost/benefit analyses for operators. Non-regulatory incentives were identified as key requirements to encourage shipbuilders and operators to pursue quieting technologies. Overall, a “menu” was created for future consideration and action. The conclusion of the workshop implied that a multi-pronged approach is needed to address the increasing levels of noise emissions in the oceans, incorporating more efficient, quieter technologies, industry incentives and partnerships, and spatially based regulatory approaches.

Since 2004, the US has become more engaged with the International Maritime Organization (IMO) on this issue. An Okeanos-sponsored workshop held in Hamburg in 2008 was unique in that it promoted environmental groups to coordinate with the shipping industry to set a common direction and a call to action for reducing sound impacts on marine life. Following that workshop, the US government successfully proposed that the IMO place underwater noise on its agenda and develop voluntary guidelines for reducing acoustic output from commercial ships. It is a goal that within the next 2 years the IMO will adopt technical guidelines that propose a series of recommendations for reducing noise emissions in the oceans. Dr. Southall reiterated that the goal of the current Workshop should be to create specific recommendations of research directions and technology implementations to reduce sound impacts on marine life.

2.2.3 Plenary Session III: Noise from Relevant Activities

The purpose of this session was to examine noise from seismic airguns, pile driving, and support vessels, including the physical mechanisms that produce noise and the associated sound levels. Sound levels are one impacting factor, however additional factors must be considered (e.g., duration, harmonic structures, frequency sweeps, etc.) and the "quieting" of noise that can be achieved by reducing noise input to the marine environment.

Terminology for Underwater Sound – Dr. Michael Ainslie, TNO – Netherlands Organisation for Applied Scientific Research (Appendix D, pp. D30-D32)

Consistent sound terminology is important to allow the establishment of a common baseline and to ensure data can be compiled and compared. Sound pressure level (SPL), sound exposure level (SEL), and sound particle velocity represent basic terminology, while source level (SL) and propagation loss (PL) are more advanced. The challenge with this terminology is that it is difficult to apply to a non-continuous source, which does not have a consistent root mean square (rms) value. Depending on the duration of the measurement, the decibel outputs can vary, since SPL depends on averaging time. Criteria presently in use in the United States (Ainslie, 2012) require the averaging time to follow the 90% energy rule (SPL_{90}) for impulsive sounds.

National and international standard definitions exist for many relevant terms, but not all. For example, SPL can be measured in different ways (equivalent sound level [eq], 90%, peak equivalent rms). Furthermore, the definition of SPL is not agreed upon between the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO). For acoustical characterization of surface ships, three definitions are used for SL: monopole source level (MSL), dipole source level (DSL), and radiated noise level (RNL), which are inconsistently defined.

At present, there are three ISO working groups under the umbrella of ISO TC43 SC3 (underwater acoustics). One group is working on terminology, one is working on measurement standards for ship radiated noise, and one is working on measurement standards for pile driving.

In conclusion, the current use of (underwater acoustical) terminology is inconsistent and is not always appropriate, thus a common terminology needs to be developed that is useful and understandable to acousticians, biologists, and regulators.

Spatial, Spectral and Temporal Properties of Sound Sources – Dr. William Ellison, Marine Acoustics, Inc. (Appendix D, pp. D33-D35)

Dr. Ellison recommended that discussions during the Workshop should recognize the fact that there are different approaches for defining, measuring, and quieting "noise." The noise exposure assessment process must consider the spatial (e.g., size, movement, distance to marine life), spectral (e.g., frequency, bandwidth, sound type, ambient condition), and temporal (e.g., duration, cycle, exposure metrics) properties when describing a source and attempting to quiet that source. Currently, metrics for masking issues or for chronic exposure are not well-defined and new approaches are needed to measure and assess them. Evaluations currently consider single sound sources, transmission paths, and the effect on marine wildlife; however, larger scale assessments need to be considered to gauge mulitple sources moving throughout an area and the effects on all marine species.

For an array or complex source, the near-field region is defined by the source frequency and spatial configuration of the source. For mid-frequency and high-frequency (HF) sources, there are no near-field or far-field measurements; therefore, it is not easy to analytically describe, measure *in situ*, or effectively model. High-frequency systems have potentially high SLs; additionally, the propagation effects due to absorption are significant at higher frequencies, and are directly proportional to range.

Airguns – An Overview – Peter van der Sman, Shell (Appendix D, pp. D36-D40)

The oil and gas industry uses acoustic emissions (signals) during seismic surveying for exploration purposes. Dynamite was the first sound source used for exploration, but by 1960, airgun technology began to advance. The faster the energy is released during seismic surveying, the higher the sound intensity. Airgun shots result in hydrostatic pressure increases and decreases (impulses) that lessen over time. This quick oscillation results in an HF output that is reduced over time. The spectrum needed for exploration does not generally use the HF output. What is required for exploration is a specific signal-to-noise ratio (SNR) and bandwidth. Reductions in the energy output can occur by changing other variables (e.g., signal level).

Tuning airguns consists of reducing the by-product of frequencies that are not needed for exploration; however, the challenge is in effectively removing the un-needed frequencies while maintaining a reliable system. By firing two or more airguns simultaneously, the bubbles produced coalesce to effectively provide the necessary data for exploration. Optimization of airguns can reduce the output by designing them to produce only the necessary levels, by attenuating the out-of-band energy, or by altering the design of the array or survey. Cavitation will induce HF emissions and occurs as an undesirable by-product that can cause damage to the airgun, but removal of this element in the design is difficult. Past attenuation efforts include shaping of the port, throat, or shuttle, application of snubbers, and use of bubble screens, which help attenuate out-of-band energy. The engineering, design, and field applicability are difficult to ensure reliability throughout the operational life of the airgun. Overall, airguns represent advancement from the use of dynamite and provide excellent data for exploration.

Driving Offshore Wind Piles Quietly – William Ziadie, American Piledriving Equipment (Appendix D, pp. D41-D51)

Pile driving is rapidly advancing because larger offshore structures demand larger piles that require larger impact hammers; the industry is approaching the size limits for impact hammer technology. In order to overcome this limitation, the current design parameters, materials, and installation methods need to be reconsidered. The two sources of noise during pile driving are the point source, where the hammer strikes the pile, and the line source, consisting of evenly distributed individual point sources along the pile length. Waterborne noise is measured for regulatory purposes by a maximum decibel level at a specific distance, since this is the impact-producing factor when looking at effects of noise on marine life. The flexural wave produced by hammering radiates away from the pile, creating fluxes of sound pressure that can kill fishes, impair hearing, and alter behavior.

Impact hammers are the current tool of choice for installing pilings for wind turbines; however, this method exceeds the NMFS 160-dB threshold for marine mammals and requires attenuation in the form of bubble curtains or sleeves, which can be time consuming. Because the technology is reaching its size limit, changes in structure design must be considered, including multi-pile foundations, larger-diameter-but-shorter piles, and large diameter-helical piles. Changes in material choice must also be considered; concrete is less resonant than steel and would be quieter. Pre-stressed and spun concrete can be used with cushions to withstand the compression, but larger hammers are needed to provide the necessary energy transfer.

Mr. Ziadie asserted that the use of vibratory hammers for installation potentially allows for the pile to be driven with no bubble curtains or other attenuation mechanisms because decibel levels can remain under the current NMFS thresholds. Piles 72 feet (ft) in diameter and 183 ft long have been successfully driven to a depth of 82 ft using the multiple linked hydraulic vibratory hammer system. Use of a vibratory hammer would not limit the pile size, because numerous hammers can be linked together to drive any sized pile; the limitation for this method would be the crane size required to place the pile. In addition, vibratory hammers allow for pile extraction and adjustment for plumb if boulders or other obstacles are discovered during installation. Logistically, vibratory hammers have an advantage over impact hammers because they are standard production hammers available on a rental basis with short lead times, whereas there is limited availability worldwide of impact hammers.

Case studies revealed that successful installations using vibratory hammers can be done much more efficiently than traditional installations using cellular cofferdams, reducing installation time by up to 2 years. The installations completed to date have the advantages of quick installation with no limit on pile size, precise placement, being environmentally friendly, or modular design, and they can be installed in bad weather.

Introduction to Ship Radiated Noise – Dr. Chris Barber, Multipath Science and Engineering Solutions (Appendix D, pp. D52-D55)

Support vessel noise has different characteristics than noise from airguns and pile driving. Ship-radiated noise is low frequency and derived from transient, continuous sources, versus impulse sources for airguns. The sources of noise on a ship and how loud they are as well as the technologies to reduce these noises, their effectiveness, and the costs associated with their design and implementation are well known. However, it is unknown what decibel thresholds should be established to minimize acoustic harm to marine life. Noise emission criteria for support vessels have not been established.

Noise sources on a ship include the propeller, machinery noise, propulsion plant, generators, auxiliary machinery, hydraulic systems, suction/discharge systems, and bow thrusters. Noise paths transfer the sources into the water column, and include direct radiation (propeller), active transmission (instrumentation), structural (through the hull), airborne coupling (from within the hull), and fluid-coupled (pipes to suction/discharge). Cavitation is the dominant broadband ship noise emission at mid- to high frequencies and is caused by operating beyond the design criteria of the ship. Once cavitation begins, the noise increases rapidly at high frequencies. Conversely, operating below the design criteria is not always consistent with vessel use or plan. Non-propulsion noise derives from hull and appendage cavitation, bulbous bow designs with poor hydrodynamics, misaligned rudders and struts, and breaking waters (bow wave transients). Machinery noise is associated with the propulsion system (i.e., diesel engine, electric systems, gas turbines, and reduction gears) and the auxiliary machinery (i.e., service generators, cooling pumps, fire pumps). Silencing measures on a ship must be maintained and inspected on a regular basis.

Measurements can be taken to determine acoustic ranges, however measuring the moving source can be more of a challenge. Measurement standards must also be taken into account along with measurements in deep or shallow water. Quieting measures that are available to address noise problems come from naval requirements and include propeller design, hydrodynamic optimization, vibration isolation machinery mounts, modular machinery vibration isolation, and machinery health monitoring. The International Council for Exploration of the Seas (ICES) performance requirements for fisheries research vessels are the only requirements for ship noise that could be used to establish thresholds that are not Navy-driven. Vessel requirements must consider environmental impact, shipboard habitability, and logistical implementation during specific activities.

2.2.4 Breakout Sessions I and II and Plenary Session V – Presentations

The Plenary Sessions provided the attendees an overview of previously conducted workshops, the outcomes, and the information shared. In addition, overviews of the different noise-producing activities were presented by industry experts; they described the physical mechanisms that produce noise associated with seismic airguns, pile driving, and support vessels as well as the sound levels and propagation from those sources.

The information provided during the Plenary Sessions was then taken into specific Breakout Groups to further expand on the detailed analysis of current and emerging/potential quieting technologies for each noise-producing activity. Government, industry, NGO, and academic experts assembled in separate conference rooms to gain a better understanding of quieting technologies for airguns (**Section 2.2.4.1**), pile driving (**Section 2.2.4.2**), and support vessel noise (**Section 2.2.4.3**).

During Breakout Sessions I and II, presentations were given and a summary of the presentations was provided to all attendees during Plenary Session V. For readability and in order to provide concise, consolidated information, all of the information is presented in this section.

2.2.4.1 Group 1: Airguns

Breakout Session I

Review of Information Synthesis – Mike Jenkerson, ExxonMobil Exploration Co. (Appendix D, pp. D56-D57)

A review of potential and existing technologies for seismic airguns was discussed including improvements over earlier methods. Three major areas were covered for technologies including complementary technologies, methods to reduce unwanted airgun noise, and alternative airgun sources.

Complementary technologies that could be used in conjunction with seismic surveys to investigate subsurface geology were examined. Low frequency passive seismic methods that could augment existing seismic methods using natural sounds such as natural seismicity, ocean waves, and microseismic surface waves to image subsurface geology are being investigated. However, because of the low resolution of these methods they are unable to replace active seismic acquisition and can only be used to augment active seismic data. Controlled-source electromagnetic (CSEM) surveys or magnetotelluric surveys can be used to penetrate the subsurface to characterize fluids; however, because of the low resolution it does not give the structural information provided by seismic exploration. Gravity and gravity gradiometry surveys can also give broad structural information but again lack the necessary resolution for seismic exploration. Utilization of fiber optic receivers is a method that could reduce source levels of noise, as they are highly sensitive in specific frequency bands and could therefore potentially reduce required source output. However, this system is primarily used for seismic permanent reservoir monitoring and utilizes optical receivers permanently placed on the seafloor. Currently, this technology is not available for towed-streamer surveys and therefore has limited applications.

Four potential methods to reduce unwanted noise from seismic surveys were addressed: bubble curtains, parabolic reflectors, the airgun silencer, and modifications to current airguns. Bubble curtains use an acoustic impedance mismatch to block propagation, which requires a complex barrier to block specific frequencies. At this time its use is not practical because of the difficulties to operate in non-stationary systems and the added operational complexity due to weather and currents. Parabolic reflectors are designed to be towed over the array and direct the energy down vertically; however, they are too difficult to use with non-stationary systems. For a parabolic reflector system, a large reflector is required, thus weather and currents add operational complexity and are also difficult to operate in shallow water due to bottom reflection. The airgun silencer is an absorptive shell that surrounds the airgun and is designed to reduce acoustic levels above a frequency of 700 Hz. This technology has been tested only on small airguns and is able to withstand only approximately 100 shots. As a result, airgun silencers are not practical in commercial applications. Several modifications to airguns have been proposed including E-source airguns and changes to the points of airguns (port or throat shape) to reduce the energy greater than 100 Hz. A patent has been filed for the E-source airgun, though it is still in development and the efficacy of this design remains uncertain. However, with this design, only the airguns themselves would have to be changed on the vessels because all handling systems would remain the same.

Alternatives to airguns identified and discussed included MV, LACS, DTAGS, LISA, and an underwater tunable organ-pipe. In terms of their availability and ability to perform seismic acquisition, DTAGS, LISA, and the underwater tunable organ-pipe are all high frequency systems that are not useful for deepwater seismic acquisition. The LACS system may be suitable but it currently exists only as a design, and there is no known interest in further development of the system. The ability of MV units to spread its energy output over a period of time as a continuous frequency-modulated (FM) sweep or as a pseudo-random noise (PRN) sweep makes it the most promising alternative technology to airguns at this time. Due to this slower output, MV lowers rise time, lowers peak pressures, and energy above 100 Hz is significantly reduced. In data comparisons, MV is comparable to airguns with only some challenges in deepwater. One potential problem with MV is that some MV units use hydraulics, which can cause worse harmonic interference than airgun noise. Additionally, significant vessel retrofits are necessary to accommodate this new technology.

Seismic surveys require acoustic energy in the 0-100 Hz band in order to image the seafloor. The energy can be introduced quickly (as with an airgun) or slowly (as with MV units); the most efficient way to generate the energy has yet to be determined. Airguns are very effective at generating the required low frequency content, and any proposed alternative technology will have to be as effective to be considered as a replacement.

Environmental Assessment for Marine Vibroseis – Dr. William Ellison, Marine Acoustics, Inc. (Appendix D, pp. D58-D61)

The Joint Industry Programme Environmental Assessment (EA) of Marine Vibroseis was issued in April 2011 (LGL and MAI, 2011). There were four primary study objectives: (1) evaluate potential environmental impacts from seismic surveys using next-generation MV; (2) examine how MV impacts would compare with airgun impacts; (3) evaluate how an MV unit could be operated to minimize impact (e.g., optimum duty cycle, sweep type, other mitigation measures); and (4) identify data gaps and recommend studies to address them. The EA included a comparison of airgun and MV signals, consideration of biota types, and first-order modeling for numbers of marine mammals potentially injured and disturbed by each method.

Certain assumptions were made to accomplish the comparison because there were too many variables with insufficient data to consider. The first logical variable to keep constant between the two systems was the energy in the two signals (SEL). MV using a swept FM pattern creates a lower pressure but outputs the same total energy as an airgun. Assuming similar energy per shotpoint, the comparison between airguns and MV shows that MV's energy is spread out over a few seconds' time span with a frequency sweep, whereas the airgun's brief impulsive shotpoint is only tens of milliseconds. The airgun has a high peak pressure, faster rise time, and an ~1% duty cycle, while the peak pressure and rise time are not really applicable to MV, which has an estimated ~50% duty cycle and is non-impulsive. It should be noted, however, that the duty cycle for MV is not yet clearly defined because of potential engineering constraints. The size of the sweep required for MV also still needs to be defined. One of the main design advantages for MV is the more rapid decrease of frequency above 100 Hz as compared with an airgun.

Several types of biota were considered during investigation of environmental impacts, including fish, invertebrates, sea turtles, and marine mammals. Marine mammals received the most detailed consideration especially baleen and toothed whales as well as pinnipeds. The Southall et al. (2007) criteria were used to determine environmental impacts during the modeling studies examining possible behavioral disturbance, acoustic masking, auditory thresholds (temporary threshold shift, permanent threshold shift), and non-auditory impacts (i.e., resonance, behavior-induced injury). M-weighting, similar to C-weighting for human exposures (Southall et al., 2007), was used, although it was designed for injury assessment and not behavior. All curves from the M-weighting were very flat, showing very little difference between marine mammal groups. Results were compared relative to the number of marine mammals likely to be disturbed or possibly injured by seismic surveys conducted by airguns versus MV, identifying the sensitivities to mammal type, water depths, duration/duty cycle, and frequency roll-off rates of the portion of the MV signal above 100 Hz. A key project objective was to assess tradeoffs and presumed-to-be positive and negative features of MV.

The modeling effort assumed equal energy per sample: 261 dB re 1 μPa m^2 $SL_{p\text{-}p}$ for airgun shots and 235 dB re 1 μPa^2 m^2 SL_{rms} for a 2 second (s) sweep with MV. Additional MV sweep durations of 5 and 8 s with corresponding lower source levels were also considered. The airgun duty-cycle was assumed to be 1% as compared to 50% for MV. A key issue for regulators is the consideration of received rms sound pressure levels (SPL_{rms}) versus received SEL. In agreement with the standard NMFS criterion for impulsive sound sources, the study used received SPL_{rms} thresholds of 160 dB re 1 μPa and 180 dB re 1 μPa to represent marine mammal behavioral disturbance and injury, respectively. In addition, M-weighted cumulative SEL (SEL_{cum}) criteria from Southall et al. (2007) of 198 dB re 1 $\mu Pa^2 \cdot s$ and 215 dB re 1 $\mu Pa^2 \cdot s$ were also used to represent injury associated with impulsive (airgun) and non-impulsive sounds (MV), respectively. The difference between the SEL_{cum} of 198 dB and 215 dB provides an injury threshold of 17 dB higher for non-impulsive MV relative to airguns, which means the injury potential is substantially reduced for MV. The study used the Acoustic Integration Model© (AIM©) to predict acoustic exposure history based on marine mammal motion relative to the seismic source. Received levels for airguns or MV were predicted in three dimensions using the Comprehensive Acoustic Simulation System–Gaussian Ray Bundle (CASS-GRAB) model.

The main conclusions show that MV surveys have the potential to reduce auditory and perhaps disturbance effects relative to airgun surveys, though that conclusion is based mainly on indirect evidence. However, masking may be of greater concern with MV because of the potential for longer signal duration and/or higher duty cycle, though use of FM sweeps would reduce masking potential. MV design may be optimized to minimize marine mammal impact with further understanding of effects. Empirical studies are needed on masking, disturbance, auditory, and perhaps resonance effects in key species sensitive to low frequency sounds. The results of those studies can be used to help optimize MV unit design features to have minimal impacts on the marine environment. With these studies, it may be possible for MV surveys to be conducted with reduced mitigation compared to airgun surveys.

Marine Vibroseis Joint Industry Programme (JIP) – Bob Rosenbladt, Shell; Mike Jenkerson, ExxonMobil; and Henri Houllevigue, Total (Appendix D, pp. D62-D64)

ExxonMobil, Shell, and Total teamed up with the Texas Experimental Engineering Station (TEES), which is a part of Texas A&M University, to create an MV JIP. After discussions of what transducers were currently on the market, a broad advertisement was placed looking for low frequency underwater sound sources for seismic surveys, which was marketed to industries other than oil and gas companies (e.g., defense, electronics, etc). The group wanted a product different from what was currently available for transducers.

The project has four Phases. Phase I began in May of 2008 to determine the scope of the project and what specifics were required for transducers. Informally, 26 vendors were contacted and current transducers were assessed to determine if they met the specifications the JIP required. Phase II began at the end of 2009, to develop the legal framework with TEES. Upon completion, 36 vendors were contacted, with 19 confidential requests for information. This was narrowed down to seven requests for formal proposals with three applicants selected. The main goal of the JIP up to now was to ensure that all avenues had been investigated for development of new MV technologies.

At the time of this report, detailed specifications have been identified that include both required specifications as well as those that are desired. A summary list and further discussion is presented below.

- An array output for 5 s signal
  - 5-10 Hz 190 dB re 1 $\mu Pa^2/Hz$ m
  - 10-100 Hz 200 dB re 1 $\mu Pa^2/Hz$ at 1 m
- Harmonic content above 150 Hz when driven with tone in 5-100 Hz range
  - >40 dB down
- Operating temperature range
  - Better than -2°C to +50°C
- Operating depth range
  - 2-30 m required
  - Up to 0.5 m desirable for shallow water version
- Signal types
  - PRN, swept frequency, short chirps, coded sweeps

It was noted that previous MV units typically have had problems creating lower frequencies, so the requirement was set at 10 Hz for low frequencies with a preference of frequencies down to 5 Hz. The requirement for >40 dB down for harmonics is due to the difficulty in signal processing in the presence of other harmonics. The temperature range is set to allow the MV unit to be operated worldwide. The operating tow depth would be preferable as low as 0.5 m to allow for a shallow water version. The various signal type requirements allow for a range of signals usable in operations depending on the circumstances. Auditory masking should be greater with MV than airguns, with a greater effect using pseudorandom signals rather than FM signals.

The pros and cons of MV were considered by the JIP as strengths, weaknesses, opportunities, and challenges. There are several strengths with MV including the control of output frequency spectrum and sweep length, low peak output level, the type of sweep being controlled, and control of the output levels. The weaknesses of MV include the long duty cycle and the vessel motion during signal output. This can affect data quality, which is a difficult compromise because this emerging technology is competing with a very mature, established airgun technology. There are still several challenges that have to be overcome including ensuring adequate low frequencies from the systems and limited availability of devices. In addition, masking issues for marine mammals from duty cycles and possible harmonics outside of the planned frequency range need to be addressed.

Phase III has begun, with one contract currently signed with Petroleum Geo-Services (PGS) and two contracts in progress with two other vendors. In addition, the MV JIP is currently looking for three additional sponsors. Phase III will continue to move forward with the concurrent development of prototypes with a test plan. The JIP expects a first prototype MV unit to be tested and evaluated in 18 months. The PGS marine vibrator will likely be the first prototype, which will have new technology from PGS in a magnetic drive flextensional shell. This system is an all-electric system with no hydraulics, able to achieve a frequency range of 5-100 Hz, and has an overall efficiency about six times greater than that of airguns. Phase IV will include building and field testing commercial systems, and is planned to begin in late 2014 and extend through 2016.

Discussion of Presentations of Breakout Session I

With the discussion of multiple technologies for seismic exploration, MV was identified as the strongest candidate moving forward to provide another "tool in the toolbox" for seismic exploration. In the short term, this technology is unlikely to replace airguns in all applications. It will take quite some time for broad implementation industry-wide, but MV can be a resource for some areas of seismic exploration in the near future. BOEM and NMFS can accelerate the implementation process through incentives and regulation. The implementation will most likely start in shallow water and then move into deeper water as engineering challenges are met. The oil and gas industry has solved previous engineering problems for the implementation of new technologies into the industry, and it is expected that this will be the case for MV. There is a strong industry and environmental interest to develop and adopt MV technology, but there are areas of concern regarding operational and regulatory issues that need to be addressed.

Significant operational challenges identified included the retrofitting of existing vessels with new equipment and the operational downtime that would occur with this type of retrofit. Seismic contractors will have to incur capital expenditures to integrate this new equipment. Hopefully, MV will be able to use electrical systems already in place onboard vessels, with a limited amount of rewiring and expense required. In addition, training of workers in the industry to operate MV systems will take time and additional expenditures.

There were several concerns raised with regard to potential environmental impacts of MV systems. The most significant concern identified was masking by low frequency specialists such as mysticete whales. There are differing opinions regarding masking and the type of signal produced by MV, whether it is FM sweeps or PRN. It is currently perceived that FM sweeps will have the least amount of impact on these species. There are also differing opinions as to whether MV or airguns would produce greater masking effects, with some participants noting that the higher-amplitude airgun signals spread over time in any case through multi-path propagation and reverberation. There is a definite need for field studies to identify the near- and far-field masking issues related to MV. In order to perform these environmental studies, MV has to be available. It was suggested that the environmental study should be done in concert with the prototype development of MV units, and that it in their opinion it would be possible to get a research permit for these studies (as opposed to an operational permit) if tested in the United States.

Some workshop participants suggested that there should be regulations or incentives to truly advance MV so that MV has less regulatory costs and time than airguns. Some participants cited the German example for pile driving, in which establishing a standard and indicating that it would become mandatory quickly drove the industry to develop superior noise reduction and attenuation technology for commercial use. In addition, there is a need for an answer regarding whether MV would be considered a continuous sound source under NMFS criteria at a regulatory level of 120 dB re 1 μPa or an impulsive source. If MV were considered a continuous source, this would be problematic because the required mitigation would be very difficult to achieve. The Southall (2007) criteria for semi-continuous sources were discussed and it was thought that this might be an appropriate category for MV. It was concluded that there is a need for a defined regulatory pathway with associated mitigation regarding MVs in the United States.

Breakout Session II

The Geokinetics Marine Vibrator – Bill Pramik, Geokinetics (Appendix D, pp. D87-D95)

Mr. Bill Pramik's presentation provided information about airguns and seismic exploration compared to the Geokinetics marine vibrator. Reflection seismology is a method of exploration geophysics, and it requires a stable source of seismic energy; for the past 50 years, airguns have been used as that stable source of energy. Industry motives for switching to MV include the potential for improved data quality and operational efficiency, the potential for less restrictive environmental regulations, the ability to acquire data where airguns are not allowed, and being seen as a good corporate world citizen in regards to environmental stewardship.

The biggest difference between MV and airguns is the duration of the sound sources, which makes comparisons difficult; MV has a long duration source, whereas airguns are an impulsive (short duration) source. When making comparisons, there are two major parameters to quantify: the useful energy needed for seismic exploration and the SPLs produced in the environment. Both measurements are almost mutually exclusive of each other because they are not measured the same way, and therefore it is difficult to make direct comparisons. Airgun-based seismic exploration generates sound outside the useful frequency band (nominally 10-120 Hz), whereas MV generates little energy outside of that band. MV units can be designed and constructed to limit the energy outside of the band of interest – reducing environmental effects from the incidental energy. Furthermore, the duration can be adjusted to increase energy to be comparable with airgun capability without increasing the SPL.

Mr. Pramik showed a favorable comparison of seismic imaging data using airguns and MV with the same energy within the useful frequency band. Though the data set was limited, it was possible to extract seismic imaging information using MV in a manner similar to traditional airgun surveys.

The Geokinetics marine vibrator is a collaborative project with PGS and is a significant design departure from previous MV systems. The proof of concept was demonstrated offshore Texas in 1999. It follows specific design specifications of a frequency range between 6 and 100 Hz and an output level of approximately 2 bar meters (200 kPa m) peak-to-peak. The advantages of the Geokinetics marine vibrator include potentially lower environmental impacts with lower amplitude levels, capability of specialized sweeps using pseudo-noise technology, and no in-water hydraulics with a completely electric mechanical system for drivers and controls. With the efficient flextensional shell design, which minimizes water flow and maximizes pressure wave generation, this design is more efficient at generating low frequencies. Another advantage of the Geokinetics system is the two intentional resonances within the seismic bandwidth making it easier to generate the desired frequency band. By combining two phase-matched projectors with different resonant-design frequencies, Geokinetics was able to "flatten" the marine vibrator response from 6-100 Hz.

In 2007, PGS took over commercialization of the system and used it in onshore and shallow water regions. Geokinetics purchased the Onshore Division of PGS, which included the onshore and shallow water MV unit, in 2010 and have since developed a more robust vibrator to withstand the rigors of seismic operations in their commercialization of MV in water depths of up to 200 m. PGS continues to own the intellectual property for MV development for use in deep water (>200 m). This design has replaced the electromagnetic voice coil drivers with more reliable drivers and has made refinements of the springs and pressure equalization systems, as well as implementing a feedback control system that can drive the vibrator. This system went through calibration tests in 2011 and was tested in both vertical and horizontal positions. Currently, the design is awaiting sea trials to test for data quality, field ability, and endurance. Once completed, commercial deployment could potentially begin by the end of the year 2013.

A Practical Marine Vibratory Sound Source – Stephen Chelminski, Chelminski Research (Appendix D, pp. D96-D98)

Mr. Stephen Chelminski presented his prototype for a marine vibratory sound source that has been in development for the past 10 years. The first patent experienced design problems and was essentially a proof of concept. A patent for proof of concept of the current design is pending, and a prototype needs to be developed to prove it is commercially viable. The proposed construction is a modular, fully functional, marine vibratory sound source that is 20 ft long with a 20- to 22-inch (in) diameter, and would have the potential to be towed at speeds up to 12 kn.

This system will be a pressure balanced, hydrodynamic system to enable the vibratory source to be used at any water depth with no floats for depth control. Practical limitation for usage could depend on the functional limits of the hydraulic hoses. This system could use a single hydraulic hose and pump sea water as the power source. The system can also use bio-hydraulic fluids to reduce environmental impacts in the event of a spill. The source units can be towed in water depths of 30 m or shallower, including swamp areas and transition zones, and also can be dragged on the bottom or used while stationary. Multiple source units may be accurately synchronized in water and can be placed nose to nose, moving the sources in opposite directions and reducing the amount of operational noise. Modular, vibratory pistons are used to move back and forth within the shaft as water is pulsed between and out through the ports of the piston chamber housings, propagating waves out and around the marine vibratory system. The expected frequency range for the system is 2-100 Hz. Mr. Chelminski estimated that based on a conservative value of a piston stroke of 0.25 in at 20 Hz, a single radiating unit would produce a sound pressure level of 206 dB re 1 μPa m.

This design is currently ready to build a full scale unit for testing and survey, and does not require the construction of a smaller prototype. The parts have been specified and quotes have been sent out to subcontractors to identify time and delivery on certain parts. It is estimated to take 6-10 weeks to custom forge or cast the major components of this unit. After low level testing in New Hampshire, the unit could be tested at any site, on any ship capable of carrying it. The source is fully engineered and manufacturer drawings are partially finished with components specified, and applications for US and international patents have been submitted. Once financing has been secured, building for shipping and testing can occur within 1 year.

Vibroseis – Paul Novakovic, Independent Consultant (Appendix D, pp. D99-D101)

Paul Novakovic presented a review of underwater acoustics, noise reduction, and his development of an MV system. In looking at the need for low frequency sounds in seismic operations, the only way to create those frequencies is with the movement of large amounts of water. The required level of amplitude for marine survey vibrators presents a challenge for piston-type equipment. It was explained that it is important to have a basic understanding of the concept of sound propagation to understand the challenges behind generating such low frequencies.

Due to regulatory requirements, seismic land surveys moved from the use of high explosives to large hydraulic vibrators. The offshore industry should move forward with the development of new technologies before regulations prohibit the use of airguns.

Low frequency projectors have been built, and the signals are monitored in Hawaii from Japan for military reasons, showing the great distances low frequency sounds can travel. Previously, underwater speakers activated by hydraulics or electrodynamic energy were able to provide controlled signals in the frequency necessary for penetration of the ocean bottom, making them superior to impact explosive sources. Two projects were done using these projectors in Louisiana and Texas in the early 1990s.

With the need for noise reduction to minimize biological risk to marine species, the controlled signals from MV are anticipated to affect a fewer number of species than impact sources. Extensive studies should continue with a goal of better defining the impacts. With seismic operators facing stricter regulations with airguns, an option needs to be available for operators.

After looking into the specifications for the JIP group through Texas A&M University, it was decided to develop a new concept of low frequency projection, independent of that group. The technology developed thus far is covered by patent application. Mr. Novakovic claimed that a single unit would be able to meet a source level of 200-205 dB (without reference units) in the bandwidth of 5-200 Hz. This is not a piston-driven or hydraulic system and is anticipated to have minimal maintenance and simpler operating procedures than airguns. Cost for a complete installation using the new equipment is estimated to be 35% of the cost of a complete airgun installation. The development of this new piece of equipment is expected to be in operation within 1 year of this Workshop.

Discussion of Presentations of Breakout Session II

Data analysis and quality were key factors that were discussed. There are questions about whether MV will be able to produce the same data at lower frequency levels as that of airguns. Theoretically, MV should be able to do what impulse or airgun sources are capable of, with MV even being able to do some things that airguns cannot in shallower water, but this remains to be fully tested. There is a definite need for side-by-side comparisons of data from MV and airguns. There is still a concern over the harmonics found in MV data, which was a common concern that is being addressed by all the developers.

Regulatory concerns remain, including whether or not there was a recovery time for exposure to animals and what the duty cycle would be, as these factors would ultimately feed into regulatory requirements. It was suggested to review the 120 dB re 1 μPa threshold for level B harassment with continuous sound, as well as the 160 dB impulsive source threshold for airguns to determine if they are still realistic. Regulatory agencies need objective information to establish realistic thresholds; however, because this is new technology, threshold categories will need to be flexible until the impacts can be determined.

Airgun operational procedures, such as the sound source being turned off during turns, would still be followed with MV. Streamers would still be towed at roughly 4-5 kn, but line changes would be shorter. The process would likely be to run a sweep and then stop to listen, or almost continuous at a lower level, similar to airguns. In addition, the directivity of the signals from MV and airguns will be similar, allowing the array configuration to beam with the desired directivity.

Plenary Session V

Plenary Session V was a report of the information presented in Breakout Sessions I and II. See the Airgun Presentations Report in **Appendix D, pp. D129-D131**.

2.2.4.2 Group 2: Pile Driving

Breakout Session I

Impact Pile Driving: Frequency, Angle, and Range Dependence and their Implications for Current and Potential Quieting Technologies – Dr. Peter Dahl, University of Washington (Appendix D, pp. D65-D69)

The underwater sound field from impact pile driving is distributed broadly over a two-decadal frequency range (20-2,000 Hz). The primary contribution arises from the radial deformation wave, which propagates down the pile upon hammer impact at a speed that is supersonic relative to the water sound speed. The ensuing pressure field in the water is characterized by a dominant propagation angle; a contribution from the reflection from the bottom of the pile also occurs. An important implication is that sound received at distances less than about three water depths will vary greatly with depth, while at greater ranges this depth variation is reduced.

Dr. Dahl stressed that in order to understand the issues surrounding quieting technologies for impact pile driving, it is necessary to understand the sound generated by the activity. In particular, the contribution from reflection from the bottom of the pile constitutes a potential flanking pathway, which, although undergoing higher propagation loss, is not otherwise attenuated by noise control strategies based on pile-surrounding barriers or absorbing structures operating in close proximity to the pile. Overall, Dr. Dahl strongly recommended that measurements of the performance of quieting technologies should, if possible, be taken at distances at least three times the water depth from the pile. This radiation profile potentially also has implications for quieting technologies.

Underwater Noise Mitigation Measures in Offshore Wind Farm Construction – Sven Koschinski, Marine Zoology (Appendix D, pp. D70-D73)

The German approach to noise mitigation around wind farms was presented (see Koschinski and Lüdemann, 2013). The objective (universally mandatory in Germany and now included in individual offshore leases for currently approved offshore wind farms) is to ensure that received sound levels at 750 m are not above 160 dB SEL, 190 dB peak-to-peak SPL (SPL_{p-p}). Currently, many projects are exceeding the SEL or peak threshold levels. There are a number of methods for reducing sound output from pile driving. Some of these ideas have been tested, while others remain untested concepts.

The most tested offshore technology is the bubble curtain. Bubble curtains are formed from vertical streams of bubbles coming from a perforated hose that is typically laid on the seabed. However, the hoses can also be suspended vertically or in layers in the water column. Two forms of the curtain have been tried: a large radius ("Big") bubble curtain and a small radius ("Little") bubble curtain.

A Big bubble curtain is placed about 70 m from the pile, with the construction vessel located within the curtain. In a research test, this curtain reduced sound by 12 dB SEL and 14 dB SPL_{peak}. When tested around a wind farm installation, reductions were 11-15 dB SEL and 8-13 dB SPL_{peak}. Bubble curtains have also been used to reduce sound from explosive underwater disposal of munitions. A large radius (Big) bubble curtain has the potential to further reduce the noise (reductions of 17 dB SEL and 21 dB SPL_{peak}). A Big bubble curtain would also partially reduce sound coming from sediment transmission (seismic wave). Big bubble curtains allow for revolving deployment before positioning the installation vessel and thus ideally have no impact on construction time. Constraints on the large radius bubble curtain come from large compressors needed to push air through the entire length of the hose, and in handling the hoses.

Little bubble curtains closely surround the pile but do not surround the installation vessels. The performance of sound reduction is similar to that of the large radius curtain and the compressors need not be so large, but handling hoses close to the main construction vessel can be difficult. A small radius curtain can also be drifted by water currents away from the pile, thus allowing radiation of sound from the upper part of the pile; this can be mitigated by using layered pipe rings. Depending on water depth, the pipe length in a layered system can be similar to that of a Big bubble curtain, and thus the same number of compressors may be needed. Handling hoses close to the main construction vessel may cause delays in the construction.

Other techniques such as isolation casings can reduce sound absorption and reflect the sound within a casing around the pile. Different systems hold sound absorbing materials (combinations of air, foam, or active bubble screens) as the steel on its own is insufficient to decouple the sound. The casing also needs to be decoupled from the pile with guiding materials, such as rubber blocks. One particular casing is the BEKA shell, which comes in two halves that are coupled together around the pile. Another casing, the IHC Noise Mitigation Screen (developed by IHC Merwede), which is put over the pile, has already been tested during construction of a commercial offshore wind farm. Sound reduction was assumed to be 17 dB (not stated whether SEL or SPL_{peak}), but no control (without noise mitigation) was undertaken to confirm this value. Using isolation casings, there would be no reduction of sound coming through as sediment transmission.

Another form of casing is a dewatered cofferdam – essentially a steel tube with a rubber seal at the bottom that allows the gap between it and the pile to be pumped dry, and the pile is driven surrounded by an air layer. There has been one successful experiment in the Baltic Sea at a 15 m water depth. Broadband noise reduction was 23 dB SEL and 19 dB SPL_{peak}. There would be no reduction of sound coming from ground sediment transmission. A version of the cofferdam concept is pile-in-pipe piling used to install jackets. Presently, this is only in concept and would require more steel compared to a regular jacket, especially at great water depths because the cofferdam must cover the whole water column.

Another technique is the use of hydro sound dampers, which are gas-filled elastic balloons or foam fixed to nets held around the pile by a frame. The attenuation frequencies can be adjusted by the size of balloons. Proof of concept experiments have been conducted in Germany, England, and the United States. Sound reduction depends on the size of the balloons used – at the "best" frequencies (at 300, 600, and 1,200 Hz in the proof of concept) sound reductions of over 35 dB SEL were possible.

Alternatives to impact pile driving include vibratory pile driving, alternative drilling methods, gravity base foundations, floating wind turbines, and bucket foundations. For vibratory pile driving, the sound level is lower than with impact driving but the sound is continuous. Reductions of 15-20 dB rms are possible at certain frequencies. Several drilling methods are particularly suitable for very large steel or concrete piles. Continuous sound has been measured at 117 dB rms at 750 m, with sound coming mainly from the drilling machine. Another method is gravity base foundations, which are regarded as state of the art in shallow (<20 m) water depths; because of the weight and size of foundations, this method requires large installation vessels. Most floating wind turbines are at present in concept only and would use existing oil and gas technologies such as spar buoys, ballasted semi-submersibles, and tension leg platforms (particularly in deep water). Full-scale prototypes exist in Norway and Portugal. Finally, bucket foundations are sucked into the bottom in muddy or sandy seabeds and have low associated sound levels. At present, bucket foundations are concept only for wind farms.

Recent progress in reducing sound radiation has been good, and several technologies are capable of a 10-20 dB broadband SEL reduction. There is not a single best technology, as many factors affect performance. In many cases German legal requirements can be met using noise mitigation, although there may still be challenges with very large monopiles. It is better to choose a technology that avoids generating noise than to reduce it.

Bringing the Big Bubble Curtain Offshore – Noise Mitigation at the Borkum West II Offshore Wind Farm – Dr. Georg Nehls, BioConsult SH GmbH & Co. (Appendix D, pp. D74-D78)

A project using a large radius ("Big") bubble curtain to mitigate noise generated by pile driving at a wind farm off Germany was introduced. The study also investigated effects of construction on harbor porpoises in the area.

The wind farms used tripod foundations that required some pile driving. The bubble curtain used nozzles in a slurry pipe hose. This was held to the seabed by steel pipes connected to the slurry pipe by chain for weight; the chains also made it possible to pull the hose. Difficulties encountered included drilling uniform-sized holes into the hose and obtaining a large vessel to handle sizeable hose reels. Once the hose is installed (prior to construction) it can be left in place (but marked with a buoy) until construction is complete. The two aims of the project were to reduce sound output from the construction by 14 dB (SEL or peak not stated) and to not interfere with the construction process. The hose took less than 1 hour to deploy and lasted throughout deployments covering the installation of 40 foundations and 20 additional test deployments.

The amount of sound reduction varied with frequency and rate at which air was pumped through the hose (i.e., equivalent to density of bubbles). Typically at 1 kHz, sound reduction was on the order of 20 dB SEL, with lesser reductions at higher frequencies. Small nozzles more closely spaced achieved greater reduction in sound than larger nozzles further apart. A double bubble curtain with hoses spaced 80 m apart had a better performance than a double curtain with 25 m between the hoses.

Harbor porpoises are assumed to be adversely affected by received sound levels of 140 dB (peak or SEL not stated). The range that this sound level occurs around pile driving is about 6.5 km with a bubble curtain; without such a curtain, the range is 20 km.

The direct study of harbor porpoises is complicated by their seasonal migrations and movements, but it was clear that porpoises completely abandoned the area during construction. Near the piling, 100% of porpoises left the area for a duration of 1-3 days. Further away at the edge of the area affected, 10% of the porpoises left for the duration of the piling. The total displacement amounts to the equivalent of 40% of the porpoises in the area being affected.

After initiating piling, with no bubble curtain, a 3-km radius area was evacuated by the porpoises. With the bubble curtain it was difficult to observe any avoidance at all. However, statistical comparison between the two scenarios was difficult because the bubble curtain was functioning inconsistently.

In summary, when noise levels decreased, the porpoise responses decreased. If the bubble curtain is working, then it is possible to reduce sound by 12 dB (peak or SEL not stated), with equivalent reduction in porpoise disturbance. The bubble curtain did not fully meet the German noise reduction objective, but did reduce the harbor porpoise responses.

The main cost of the system is the charter of the vessel, amounting to about €100,000 ($130,000 USD) per foundation. This is less than 5% of the installation cost and less than 1% of total construction cost, but larger construction sites will need a larger hose and therefore a larger vessel. All six wind farms scheduled for construction in the near future will use the Big bubble curtains.

Discussion of Presentations in Breakout Session I

The discussion focused on the quieting methods rather than alternative foundations. There was considerable discussion on the technical aspects of the Big bubble curtain. The maximum water-current velocity for which testing has been conducted was 0.6 m/s, and it was determined that the bubbles rose at a rate of approximately 0.3 m/s. At higher current velocities and depths >40 m, the sound reduction effect would need a larger radius curtain. The vessels deploying the curtain generate some noise, but this is about 50 dB less than pile driving. The noise associated with generating the bubbles (compressors, bubble collapsing) had not been measured. The sound of bubbles collapsing had not been detected at the 750 m range (the only range where measurements had been taken).

The sound-threshold criteria applied in Germany was also discussed. The 160 dB (SEL) criteria decided upon some years ago as a "best guess" is currently considered accepted until proven incorrect. It can be justified on the basis of the knowledge of harbor porpoise hearing threshold shift but does not consider other species. At present the 160 dB (SEL) criterion is mandatory, but projects have to apply state-of-the-art mitigation technology that may not yet cause sufficient reduction in sound levels. At least half of the projects did not meet the 160 dB threshold, but this has not stopped construction to date. The studies to date have been classified as research projects and are not subjected to the same mandatory mitigation. It is not known what will happen once mitigation is strictly enforced, but mitigation measures enabling sufficient noise reduction to meet the criterion are not available. The 160 dB (SEL) level is theoretically applicable to other industries/applications producing impulsive noise. For continuous noise, a threshold must be defined using a relevant metric.

Sound also travels through the sediment as ground transmission from the pile and that sound then transmits back into the water column some distance away, and sometimes outside the bubble curtain. This effect limits the noise reduction achievable at short (though unknown) distances by quieting technologies. This issue was described and discussed further during Dr. Reinhall's presentation during Breakout Session II.

Breakout Session II

Underwater Noise Abatement Using Large Encapsulated Air Bubbles and Its Applications – Dr. Mark S. Wochner, AdBm Technologies (Appendix D, pp. D102-D108)

A new, modified technology influenced by contained bubble curtains uses static bubbles encapsulated in a compliant material (referred to as resonators) to attenuate sound rather than using active bubbling. Encapsulated bubbles are most effective at attenuating sound when the sound is near their resonant frequency, and encapsulated bubbles are specifically selected for this scenario. The resonators can be made to target a certain range of frequencies (i.e., a bubble with a radius of 6 centimeters [cm] is better for frequencies around 60 Hz and above). The resonators are fixed onto a frame and then installed underwater near the noise source. The configuration of resonator placement, size, and number are adaptable to attenuate potentially 20-50 dB SPL across a broad range of frequencies.

The advantages to this system include customizable resonance frequency by changing size and number of resonators, no hoses or air compressors are needed (lowering introduced noise), and spaces are allowable between resonators. A full-scale demonstration is planned around field pile driving. Some disadvantages include the technology is still being developed, the shell must be compliant yet strong enough to withstand resonant motion of air volume and the effects of depth, and problems of deployment around pile driving have not yet been determined, nor has the efficacy around field pile driving activities.

How Quiet is Quiet? – Dr. Michele Halvorsen, Pacific Northwest National Laboratory (Appendix D, pp. D109-D111)

Noise affects aquatic animals in many ways, but there are few modes that scientists can use to monitor and assess animal responses. The most basic mode is the behavioral reaction of animals, which is mostly unknown for fishes, but more information is available for some marine mammals. Two physiological modes are responses of the auditory system and barotrauma (tissue damage).

A component that needs consideration when making physiological assessments is the depth of the animal during the sound exposure. Most exposure studies have taken place at the water surface in laboratories and in the field. Animals acclimated to depth would experience less of an overpressure for a signal at that depth than for signals at the water surface (**Table 1**). With regards to barotrauma, it may be that aquatic animals at 10 m or deeper are somewhat protected from sound signals. Depth is probably not a factor for the auditory system; in that case, masking and threshold shift would remain constant.

Table 1. Example overpressure at various depths

Depth (m)	Atmosphere	Impulsive Signal (kPa)	Acclimation Pressure (kPa)	Ratio	Injury Risk
0	1	100	100	1:1	High-Moderate
10	2	100	200	1:2	Low?
20	3	100	300	1:3	Low?
30	4	100	400	1:4	Unlikely

What is the goal of "quieting" and how can scientists help regulators define the intent? Animals are the receivers (sensors) of the noise and they have responses. Humans can interpret those responses to determine the driving force behind the goals for quieting these activities.

Current and New Methods in Pile Driving Sound Attenuation – Dr. Per Reinhall, University of Washington (Appendix D, pp. D112-D117)

Research at University of Washington by Drs. Reinhall and Dahl and Ph.D. candidate Tim Dardis introduced a double-shield pile technique to attenuate sound in the water column by surrounding a pile with a dual shield, one layer made of a thick steel shell that is sealed to the seafloor and the other layer constructed with a sound attenuating material lining the shield, and an air gap between the shield and the pile. This configuration was tested in simulation and produced about 40 dB of peak sound attenuation. This system was tested in the field using a 36-in (0.9-m) diameter steel pile and double shield consisting of a hollow steel shield (inner diameter of 1.2 m and outer diameter of 1.5 m) lined with sound attenuating material and an air layer, which produced an 8-10 dB attenuation. The time-waveform with the shield in place was void of the initial rapid positive and negative amplitudes (of the Mach wave), however the low level of attenuation was due to sound being radiated from the sediment into the water column, where it could continue to travel for very long distances (2-3 km).

Vibratory pile driving uses centrifugal forces that generate frequencies below 1,000 Hz; using the shield on this type of driving could attenuate about 10 dB but has not yet been field tested. A few ways to achieve a higher performance included using a bubble curtain that would be installed much farther away from pile driving activity than typical installations in order to capture the sound radiating out from the sediment (ground transmission) into the water, as was described by Mr. Koschinski. Presently, none of the sound attenuation treatments in use prevent sediment noise radiation, except for the "Big" wide diameter bubble curtain.

A more practical approach would be to eliminate noise entering the substrate by using a double-walled pile that puts the shield directly into the sediment. The pile would have the outer wall that is the structural pile that would act as the shield, while inside would be a mandrel that would take the driving impacts. The two parts would have an air gap between and be tethered together such that when the mandrel was struck it would pull the shield along into the sediment. A prototype of this design has been field tested using a 6-in (15.2-cm) diameter pile and was found to provide more than 20 dB attenuation at a distance of 5 m. Further development is needed.

A final theoretical technique involves using a slit pile by cutting vertical slits into a pile while maintaining an identical bearing capability. The slits would absorb or interfere with the natural bulge (Poisson's ratio) from impact on the pile, thereby eliminating the Mach wave. Eliminating the Mach wave would greatly decrease the amount of energy entering the sediment and the water column. This technique is very early in its development phase. It is theorized that the structural integrity of the pile could be maintained by staggering the orientation of the slits on the pile.

Discussion of Presentations in Breakout Session II

Much of the discussion revolved around the resonator (static bubble) technology by Dr. Wochner (AdBm Technologies). The cost associated with building this solution arises primarily from the framework and anchoring, not in the resonators themselves. The modular frames are estimated to have a life span of 12 months and could cost as little as $30,000-$40,000; the resonators do not add much more to the cost. The apparatus has not yet been tested with actual impact pile driving, but there are plans to do so during 2013 in Texas. The broad frequency range that the resonators can capture depends on the use of different resonator sizes. The final design will be modeled to capture a broad range of frequencies. The water-borne noise is captured by the resonators, but the ground transmission will reenter the water column with a significant amount of energy, most likely beyond the resonator placement. This problem could be addressed in part by making a larger static bubble frame, which would surround more of the radiating ground.

Ground-sediment transmission was also discussed along with the issue that only one current technology addresses this avenue of sound transmission, which is the "Big" bubble curtain (see Koschinski presentation, **Appendix D**, **pp. D70-D73**). Suggestions presented by Dr. Reinhall included a pile with slits and a hollow pile tethered to the driving mandrel, which have both shown to eliminate ground transmission in pilot field studies. Dr. Wochner indicated that by 2014 his company will be ready to focus on sound-absorbing bottom treatments as another potential solution. Dr. Ainslie pointed out that the paths generated inside the sediment would not propagate long distances because their grazing angle in water exceeds the critical angle.

The other main topic of discussion was vibratory pile driving versus impact pile driving and if vibratory is a better option. When using vibratory installation, the industry practice is to proof the pile for engineering purposes with impact driving once reaching final depth in the substrate. As for barotrauma injury in any animal, the signal from impact pile driving contains the rapid positive and negative going pressure, which is the injury causing characteristic. This characteristic is not present to the same degree in vibratory driving; therefore, vibratory may be more protective due to the lack of the rapid pressure change to animals that would be affected by barotrauma. However, vibratory driving is an ongoing continuous sound, whereas impact driving has on average a strike every 1.5 s; thus, when using the SEL metric to characterize the signals, the vibratory energy will sum quicker than the impact because of the continuous nature of the signal. It is noteworthy that the vibratory driving also has a narrower frequency range than pile driving, which might be easier to capture with the resonators.

Appropriate and well defined metrics are needed for monitoring and measuring each signal type. On that same note, metrics for the field close to the pile are lacking and likely need to be different than those intended for more distant applications. Because of the increased uncertainty of possible impact in the field close to the pile, criteria in this field might need to be more conservative than those intended for use further away.

Plenary Session V

Plenary Session V was a report of the information presented in Breakout Sessions I and II. See the pile driving Presentations Report in **Appendix D, pp. D132-D135**.

2.2.4.3 Group 3: Support Vessel Noise

Breakout Session I

Introduction: Ship Noise – Michael Bahtiarian, Noise Control Engineering, Inc. (Appendix D, pp. D79-D80)

An introduction to vessel quieting was provided, which included an overview of how vessel quieting has progressed through history. The first submarines designed with consideration of noise output, including silencing treatments such as flexible couplings, vibration mounts, and electronics boxes for platform noise, were developed in the 1950s. In the 1990s, the International Council for Exploration of the Seas (ICES) established commercial underwater noise limits for civilian and commercial vessels (Mitson, 1995). In the 2000s, NOAA fishery survey vessels were the first vessels to be tested and measured for quieting. Currently, measurement standards and tools have been established for noise measurements, including the following:

- 2009: American Standards Association (ASA) Standard (S12.64) for measuring;
- 2010: Det Norske Veritas (DNV) silent class, series of underwater noise criteria, including simple measurement methodology;
- 2013: International Organization for Standardization (ISO) underwater standards for measuring;
- 2013: International Maritime Organization (IMO) underwater guidelines. On March 22, 2013, the subcommittee agreed to a draft Marine Environment Protection Committee (MEPC) circular on Guidelines for the Reduction of Underwater Noise from Commercial Shipping. The non-mandatory Guidelines are intended to provide general advice about reduction of underwater noise to designers, shipbuilders and ship operators, and consider common technologies and measures that may be relevant for most sectors of the commercial shipping industry; and
- Other standards for quiet research vessels and support vessels.

Measurements of Ship Radiated Noise – Dr. John Hildebrand, Scripps Institution of Oceanography, University of California, San Diego (Appendix D, pp. D81-D84)

Dr. Hildebrand previously worked with the International Whaling Commission examining vessel noise associated with global seismic exploration, specifically in the Gulf of Mexico, the Arctic, and along the west coast of the United States. In the Gulf of Mexico, a passive, broadband, high-frequency acoustic recording package (HARP) was deployed 8 miles northwest of the Macondo wellsite following the Deepwater Horizon incident. The HARP measured the level of ambient noise that was then used to develop hourly noise estimates as well as sounds from marine mammals and vessels that came relatively close to the sensor. Over the timeframe of these recordings, an interesting observation was made. During the Macondo response effort, a hurricane approached the area, which forced the response and support vessels back to port. While the ships were at port, the noise data recorded by the HARP indicated an ~15 dB decrease in ambient noise levels at 400 Hz, illustrating that vessel noise seems likely to be an important contributor to ambient noise in the ocean.

Due to ice cover and the absence of commercial vessel traffic, the Arctic is typically very quiet. Dr. Hildebrand measured noise radiated from the US Coast Guard *Healy* ice breaker. Noise levels while holding station were compared to those from when the vessel was in transit at 5 kn. The data indicate that due to the noise created by the thrusters used to hold position, holding station is not necessarily quieter than transiting.

To record ambient noise levels in the Santa Barbara Channel, Dr. Hildebrand and his graduate student Megan McKenna used HARPs that have been deployed since 2006. They compared the data to ship traffic using the Automatic Identification System (AIS). By measuring the sound associated with many individual passages of identified ships, they were able to create sound signatures for different types of vessels based on their design, speed, and size. The data allow the comparison of sound from the aft versus the bow of the ship and source levels across a range of speeds; the latter can help identify an optimal, moderate speed that would minimize ensonification of an area by balancing ship noise, which increases with speed, in conjunction with residence time.

Based on the sound source profiles and aggregate ship traffic patterns, realistic cumulative underwater noise scenarios for the Channel were modeled. Cumulative sound levels can be modeled using AIS data to determine the source levels of the ships, operational parameters, speed, and size. This modeling can determine the acoustic noise propagation predictions. The model predictions can then be compared with data collected by the HARP sensors. For the Santa Barbara Channel, the comparison of the model results to the recorded data indicated similar sound levels from both methods.

Design Options and Operational Considerations for Reducing Ship Radiated Noise – Dr. Chris Barber, Multipath Science and Engineering Solutions (Appendix D, pp. D85-D86)

A key point stressed by Dr. Barber was that there needs to be incentives to quiet vessels, a demonstrated reason to quiet them, and the quieting of the vessel must be given a monetary value (dollars/decibel). In addition, operators need to know when (during what operational scenarios) and where they need to be quiet so that operators, builders, as well as designers can have a target (i.e., a standard) to work towards. Further, it is not fully understood how ship noise relates to seismic sources for cumulative impact analyses (e.g., ship noise when compared to seismic survey and impulsive noise, may not be significant and not warrant noise reductions in some contexts). Ways to quiet vessels with little to no monetary investment need to be investigated.

There are two approaches to quieting vessels: mitigating noise sources and mitigating noise paths. Quieter components are available for use in ship building and design but are typically more expensive and not selected unless required. Minimizing noise transmission (paths) may be a more economical and a more feasible option than controlling source levels. Some vessel components will be extremely difficult to quiet, for example bow thrusters are loud components, but their duty cycle is limited (i.e., not used often). A “quiet” bow thruster is not currently available.

The propellers are the dominant noise source, followed by the propulsion plant. Cavitation from propellers creates the most noise on vessels; however, propellers can be designed to be cavitation-free for specific vessel use and speeds in the typical operational range of 11-14 kn. Currently, there is not a non-cavitating propeller design for speeds over 14 kn. Maintaining vessel speed within the range where the propellers do not cavitate may require changes in operations. For example, during a seismic survey, the tow speed will likely be optimized to complete the survey in the shortest time, rather than to avoid cavitation.

Noise paths (how the sound is transferred into the ocean) can be examined to reduce noise, including hull-mounted machines using isolation mounts that can reduce the transmission of vibration from the source equipment to the hull and into the water. When determining if mounts can be used to reduce the vibration, it is critical to use mounts on all of the noise-critical equipment, otherwise the un-mounted equipment that is not hard-mounted will continue to cause vibrations in the hull and transmit noise. If further quieting is required, then compound mounting can be done, where entire beds of mounted equipment are isolated on mounted platforms to obtain a double degree of isolation. It is also important to consider fluid-coupled paths (intake and discharge systems), which can be quieted by selecting quieter pumps and/or de-coupling the energy between the pump and the fluid by using flexible hoses.

Awareness among vessel operators of the acoustic operating posture is critical in quieting vessels; this comes after the design phase of selecting quieter components. This next step involves employing acoustically smart operational scenarios (e.g., run two pumps in separate locations rather than side-by-side, select a vessel speed to reduce cavitation, or minimize use of bow thrusters). The Navy is aware of ship noise and employs these types of mitigation measures; however, commercial vessels currently do not.

Discussion of Presentations of Breakout Session I

Each of the standards described in the Introduction are somewhat different from the others, but they are all useful for classifying noise levels. There are multiple working groups that work together to establish standards and guidelines relevant to vessel noise, for example by participating in the corresponding working groups of ISO Technical Committees (TCs) 8 and 43. TC8 focuses on the standardization of design, construction, structural elements, outfitting parts, equipment, methods and technology, and environmental considerations used in shipbuilding. In addition, the Committee concentrates on the operation of ships, including sea-going ships, vessels for inland navigation, offshore structures, ship-to-shore interface, and all other marine structures subject to IMO requirements. TC43 focuses on acoustics, with Subcommittee 3 (TC43/SC3) focusing specifically on underwater noise. The establishment and use of consistent measurement standards is critical to vessel quieting because there needs to be common ground for comparison of noise levels.

A significant issue is the comparison of retrofitting existing ships versus designing new ships based on efficiency and economics. There are certain mitigation measures that are permanent (e.g., propeller design); however, other mitigation measures may fail or become less effective over time. The first step to vessel quieting is to perform a sound source survey when a vessel is in port to check for various “sound shorts” (e.g., pipe hangers and other vibrations against hull) that can be reduced at a relatively low cost. If a vessel is required to reduce sound further, pumps can be changed out or isolation mounts can be installed. When planning a retrofit, it is important to first characterize and quantify the sound sources so they can be properly mitigated and quieted.

As part of vessel quieting, the decibel reduction should be estimated and considered as part of the evaluation of the cost of retrofit. For example, if the cost of retrofit is high and does not result in a great reduction in sound output, then is it really worth it? This is why conducting a noise survey is important. It will measure what the current noise levels are and identify the relative noise contributions of sources so it can be determined if a retrofit is an economical solution.

Dr. Hildebrand explained that the data collected from the HARPs, coupled with AIS data, can identify when a propeller is damaged, and this information could possibly be used to send a notification to ships to alert them if their propeller exceeds a certain underwater sound level. This information regarding propeller damage would also be beneficial to ship operators for fuel efficiency and lower maintenance costs.

It is important to consider the entire ship’s husbandry (maintenance) as a whole and not just the propeller or the noise path—it is how they all connect. If vessel-quieting measures are not maintained as specified, noise levels can rise. If the loudest source is quieted and the next loudest source is not, then the effort to quiet the first source may be insignificant in reducing the total sound output. Further, monitoring and maintenance plans can be employed to measure the noise being created onboard and transferred to the sound output into the water. In certain scenarios, it might be appropriate to require a maintenance program coupled with operational limitations as part of the impact mitigation and best management practices.

Past and current research and development (R&D) has focused on quieting Navy and cargo ships. We do not currently have detailed information or methods for quieting support vessels which are of central consideration in the Workshop. For support vessels, the greatest noise levels are going to come from propeller cavitation, thrusters, and diesel generators. Propeller and hull fouling, which can make a vessel noisier, may be less important for survey vessels because they are always on the move, allowing little time for marine growth to build up, as compared to vessels that spend a considerable amount of time in port.

There is limited emerging technology for vessel quieting; however, if support vessels are required to become quieter, then a need for quieting bow thrusters would exist since dynamic positioning is integral to oil and gas operational scenarios. BOEM has limited some activities to certain areas by using dynamic positioning systems but in doing so has resulted in increased noise impacts on those areas. BOEM encouraged the development of quieter bow thrusters to reduce associated noise impacts, and suggested quieter bow thrusters could be used as a potential mitigation measure. Mr. Bahtiarian mentioned that there is emerging technology for quieter bow thrusters such as those used by Scripps and Woods Hole Oceanographic Institution vessels. A vendor has this solution, but the technology is very expensive and proprietary. However, social, economic, and political issues may be driving the advancement of R&D for bow thrusters.

Breakout Session II

Alternatives and Mitigation of Support Ship Noise – Dr. Dietrich Wittekind, DW ShipConsult GmbH (Appendix D, pp. D118-D120)

Dr. Wittekind provided a presentation focused on support vessels and their operations. Support vessels typically undertake the following activities: tow airgun arrays, drive piles, install foundations and platform top sides, transport supply materials, tow barges and installation vessels, transfer personnel, and break ice. Based on the tasks support vessels perform, they are typically smaller, operate at slower speeds (except supply vessels), and utilize DP (except seismic survey vessels, which are almost constantly in motion). This is in contrast to merchant ships, which are larger, designed for speed, and have different propulsion requirements. Many support vessels multi-task and are not dedicated to one use as compared to merchant vessels.

Support vessel noise is derived primarily from constant noise output from propeller cavitation, diesel engines, and variable output from DP; additional noise may come from auxiliary systems. Propellers cannot be designed to operate cavitation-free for all operational scenarios, so there must be compromise in the design. For example, propeller cavitation occurs when generating high thrust at low speeds (bollard pull condition), but not generally during transit speeds. Suction side-sheet cavitation is the primary noise-generating mechanism. For diesel engines, machinery-mounted generators may reduce noise, but in general industry (shipyards) has limited knowledge of how to silence ships.

There are a variety of support vessel types, including jack-up vessels for wind farm installation, airgun and other survey equipment towing vessels, general service vessels, tugs, and multi-purpose vessels, which all have variations in noise levels based on their design and use. Quieting of diesel engines can be achieved by resiliently mounting diesel engines with soft springs and a high impedance foundation, which must be very rigid so the springs can perform a noise dampening function.

There are also various propulsion types for DP, including pods, azimuth thrusters, tunnel thrusters, the Voith-Schneider propeller, and pump jets. Most DP designs are custom, based on the intended use and function and the operating environment that they will working in, resulting in great variability. There are many advantages and disadvantages to the various DP methods, but all of them will cavitate when in use. The process of cavitation is scalable and therefore can be modeled. However, modeling is not typically considered for service vessels, although it is done for merchant vessels. The noise output and frequency are determined by blade rate and speed, leading to cavitation with an increased blade-shaft rate.

A design option available in the shipyard to reduce noise is the use of controllable pitch propellers, which have propeller blades with adjustable pitch to allow constant shaft speed and flexibility at varying resistance and towing conditions. In addition, the cavitation inception diagram can be used by naval designers in shipyards to determine and minimize the cavitation during operating scenarios by adjusting shaft speed and the pitch of blades, resulting in a cavitation-free propeller when operating at <12 kn.

Noise reduction of DP propellers can be achieved by controlling speed rather than pitch, improving the propeller by increasing the diameter to reduce thrust, using air injection, employing a rim drive design (reduces cavitation), optimizing the automation of DP to minimize noise automation (minimize duration of maximum load), and distributing the load across multiple thrusters.

The Voith-Schneider propeller is a vertical axis propeller with individually controlled blades that respond quickly. These propellers are adjustable from transit to bollard pull with very little compromise, resulting in very low or no cavitation in the bollard pull condition.

Incentives to quiet vessels should be addressed. Currently, human habitability issues provide the main incentive to quiet vessels, noting that diesel generators and thrusters are generally arranged near crew living spaces and require noise mitigation for habitability. These reductions in onboard noise will generally result in decreased noise emitted into the ocean, but that is only an indirect outcome and not the driver for quieting. In addition, support vessel noise is likely dominated by DP propulsion since activities in offshore fields rely on DP. There are potential gains in noise reduction through the optimization of the DP automation process. The technical solutions to reduce noise are known, but questions remain regarding the quantification of that reduction (i.e., How much sound reduction? How much does it cost? How much reduction will be required by regulations?). There are no requirements or recommendations regarding noise from service vessels, nor do they appear to be on the horizon.

Coordinated Management of Anthropogenic Noise from Offshore Construction – Dr. David Zeddies, JASCO Research (Appendix D, pp. D121-D124)

Dr. Zeddies presented JASCO Research's (JASCO's) work in the Sea of Okhotsk offshore Sakhalin Island focusing on the aggregate noise produced during offshore construction and development and not just that from individual ships (Racca, 2012). The Sea of Japan is undergoing large-scale, offshore development within a habitat that supports a resident population of 150 critically endangered Western gray whales (*Eschrichtius robustus*). The offshore development includes construction of large offshore platforms (as large as a city block) that require a dredged pipeline connecting to shore. The whales feed on benthic organisms in the nearshore areas where a pipeline is proposed to be installed. One challenge was to determine how to reduce impacts from all the activities and the vessels in the field. The approach was to first identify the tasks and operations that produce noise and quantify those sources. Then, a model would be developed to forecast the anticipated cumulative noise impacts, mitigate for those impacts, and monitor the noise levels during construction.

From 2004 to 2007, a study to model the acoustic source levels was undertaken. In 2004, an extensive measurement program examined the expected source levels from all ships involved under the expected operational scenarios (e.g., operating in deep or shallow water, actively dredging near critical habitat, and holding position using DP). Over 20 vessels (including pipe layers, tugs, dredgers, and support vessels) were measured while undertaking a variety of activities in different water depths and conditions. Signature sound characteristics were recorded for various operational scenarios to create an acoustic source database of third-octave spectral levels referenced to a distance of 1 m.

JASCO then modeled the acoustic received level footprint that would result from different operational scenarios in order to provide the operator with choices for where and how to lay the pipeline in order to minimize noise impacts. The numerical modeling used the source level database to propagate frequency-dependent sound attenuation with distance using a parabolic equation algorithm, which accounts for bathymetry and properties of the water column and seafloor. Radial coverage was optimized for modeling to produce the received level footprint and model output. The model was then used to determine the best pipeline route to shore and included modeling for each phase of construction at various sequences and at various sites to determine if operational changes could mitigate the effect of radiated noise. The fundamental criterion was to minimize exposure to SEL >120 dB re 1 $\mu Pa^2 \cdot s$. Each scenario was evaluated, and alterations to the vessel types, operations, and other variables were made to determine when feasible changes reduced aggregate noise "hot spots" and reduce encroachment into the whale feeding area.

After a construction plan was chosen in 2005, real-time measurements were collected for the float-in and installation of one of the platforms located in a less environmentally sensitive area to gauge actual construction noise levels. Construction operations in 2006 to 2007, which included pipeline dredging and laying and commissioning of a second platform in an area proximal to critical habitat, were then monitored using real-time acoustic information. An automatic alert system transmitted an alert to the operators if levels were too high for specific time and noise thresholds. The outcome was that the real-time indicator performed well, resulting in no exceedance of threshold criteria (an indication that the model accurately reflected what occurred during construction).

Ship Noise: Implications for the Detection of Low-Frequency Whales During E&P Operations – Dr. Michel André, University of Catalonia, Barcelona Tech (Appendix D, pp. D125-D128)

Dr. André discussed various EU-funded projects on ship noise (i.e., Ships oriented Innovative Solutions to Reduce Noise and Vibrations [SILENV], Achieve Quieter Oceans [AQUO], and Suppression of Underwater Noise Induced by Cavitation [SONIC]) conducted to measure and model ship noise. The SILENV project began in 2009 to establish a Green Label for ships that would include guidelines for noise emissions for underwater, shipboard, and airborne noise. Guidelines to insulate and dampen onboard noise were established for onboard machineries, including HVAC (heating, ventilation, and air conditioning) and air inlet and exhaust systems. In addition, guidelines were established for propellers and machines to reduce underwater noise. The project also established a standard protocol for measuring ship noise using three hydrophones configured at specific depths and distance from the ship.

A database was compiled of the measured underwater radiated noise and data outputs from different vessels, which were then run through a three-dimensional (3D) model/assimilation tool. In the model, the number of ships, types of ships, and individual use signatures can be selected. The model can predict noise levels that would result from the activities of multiple ships during a particular scenario (e.g., seismic exploration).

One challenge to mitigating noise impacts on marine mammals is that typical towed passive acoustic monitoring (PAM) sensors may be unable to detect whales because ship activities mask their calls. For example, Dr. André's model demonstrated that whale calls are completely masked from detection by a towed PAM array when an airgun fires. External sensors (i.e., drifting buoys or wave gliders) placed in the project area at some distance from the vessel could better detect whale calls and warn operators when there was a sensitive marine species in the area. Therefore, these external PAM solutions (i.e., drifting buoys or gliders) represent an efficient alternative to conventional towed PAM arrays for determining the presence of marine mammals. Modeling of the noise sources around exploration and production (E&P) and pile driving activities allows for optimizing the positioning of acoustic sensors around the ship or platform. Once the buoys or gliders are deployed in locations determined by modeling, they allow real-time data to be communicated via an internet-based alert solution during the offshore operations. This method can remove the masking effect from towed PAM systems and provides the timely monitoring for the presence of animals during the E&P or pile driving activities.

Dr. André introduced the website www.listentothedeep.com, which processes and stores the automated real-time analysis of continuous acoustic streams from underwater observatories cabled or radio-linked to shore. These data are connected with AIS data to identify individual ships and link their activities to received sound levels.

Discussion of Presentations of Breakout Session II

The discussion raised some interesting questions regarding DP systems, guidelines for thruster operations, the modeling efforts, and the EU guidelines for noise quieting. Clarification was provided regarding whether DP is always achieved with bow thrusters, and it was explained that there are multiple DP systems, but each type creates thrust. Operationally, the load placed on the propeller is what drives cavitation. In order to maintain the required power while reducing cavitation, a larger diameter propeller must be used. In general, manufacturers and designers are not conducting R&D to optimize thrusters, thus the designs being used are the existing technologies readily and economically available currently at shipyards. Each type of bow thruster has advantages and disadvantages, and design constraints depend on the intended use (e.g., the Voith-Schneider propeller has to be located at the stern to remain above the keel). Dr. Wittekind explained that while Voith-Schneider propellers have limitations, they are the most advantageous and have the greatest potential for further development of the existing technologies. DP systems often receive a greater level of scrutiny during the regulatory processes for permitting a survey or activity.

Because the thrusters on drill ships are a critical component for operations and are required to run for long durations, the question was asked whether there are guidelines on how to operationally optimize the use of thrusters. Dr. Wittekind noted that he was not aware of a specific document or guidance, but discussed that 40% power is the future operating point to evaluate onboard noise according to IMO. He also noted that the manufacturers must develop guidance on optimization through their R&D.

A discussion ensued concerning Dr. Wittekind's statement that a reduction in cavitation occurs by lowering speeds. Based on this statement, the participants questioned whether this operational change can be incorporated into a model like the one Dr. Zeddies (JASCO) presented. The group considered whether a model like JASCO's could potentially be used to determine if the influence of speed reduction results in a reduction in noise levels. Essentially, it was asked whether this modeling could be used to determine optimized operational scenarios for large-scale projects in or near sensitive areas or protected areas, e.g., determining whether it was better to go fast and get out of an area quickly or go slowly and quietly but take longer? Investigation into the application of the JASCO model has begun. Dr. Wittekind noted that while a reduction in speed by slowing the shaft speed would in fact reduce the noise, the diesel engines may then become the dominant source because the cavitation is reduced, so that overall the noise output may not be reduced.

A question arose concerning whether the SILENV guidelines are the DNV classification and who will use the SILENV guidelines. Dr. André explained that the idea is to present the project to the EU and they can take the information to IMO regarding the Green Label. Additionally, participants asked if other environmental impacts are considered in the Green Label; it was stated that noise was the only metric considered.

The practicality of the drifting buoys was questioned, and there was a concern that they may pose a danger for entanglement with airgun arrays. Dr. André clarified that because the buoys are equipped with GPS and locations are transmitted to the survey vessel, the airgun arrays are unlikely to entangle with the buoys.

It was discussed that because seismic vessels are typically retrofitted, older boats built to multi-task, optimizing vessels at the build-stage may be a limited option. A question arose concerning whether retrofits are available in port or if the retrofits must be completed at the shipyard. Taking the vessel to a shipyard is preferred because of the need for design by an engineer and evaluation by an acoustician. In port, the maintenance and acoustic monitoring assessment could be conducted, but vessels would likely need to go into the shipyard for the actual retrofit.

Plenary Session V

Plenary Session V was a report of the information presented in Breakout Sessions I and II. See the support vessel noise Presentations Report in **Appendix D, p. D136**.

2.2.5 Breakout Sessions III and IV and Plenary Session VI – Workshop Goals

The goals of the Workshop were discussed during Breakout Sessions III and IV, and the outcomes were presented to all of the attendees during Plenary Session VI. For readability and in order to provide concise, consolidated information, all of the information for the related sessions is presented in this section.

2.2.5.1 Group 1: Airguns

Breakout Session III

Goal 1: Review and Evaluate Recent Developments (Current, Emerging/Potential) in Quieting Technologies for Seismic Surveying

The most promising recent development for quieting technologies in regards to seismic surveys lies with MV developments. Multiple designs were introduced at the Workshop, and all are in various stages of development. Some are in the construction phase, while some are still in the proof of concept phase. At least one PGS MV design, from Geokinetics, is ready to begin sea trials and will potentially be commercially viable by the end of the year 2013.

The real test of the technology will take place once the equipment is tested in the water. It will be determined at that time if MVs are able to achieve the quality of data required by industry and withstand the mechanical requirements. Important information will be determined during the development phase of the various designs, and it will be determined if they can provide another useful tool to the industry. Key criteria during the tests include the data quality and the associated, required advances in engineering and data processing capabilities. During these field trials, it is important to obtain data such as horizontal propagation distances and changes in marine mammal distribution or behavior before, during, and after use that will aid environmental assessment and regulatory review.

It is still undetermined whether MV will be able to wholly replace airguns or if it is simply another tool in the seismic survey mitigation toolbox; however, it was expressed by most that MV will not be a wholesale replacement for airguns. With the development of this technology, the industry and regulatory groups are trying to satisfy a number of goals. Regulatory agencies and the environmental community are looking for new technologies to reduce environmental effects, and industry groups are looking at new technologies to enable them to work in more sensitive or more challenging environments. There is a desire to do this safely and meet the needs of both groups. Having the regulatory community and industry working together will help with these shared goals. In addition, it was emphasized that the agencies need to engage more directly in incentivizing or setting requirements to accelerate the process. Implementation of any new technology is a slow process requiring that technology to be proven effective. Implementation of some new technologies has taken years or decades; however, the industry is at the point now where rapid progress may occur in the next couple of years. A few designs are only a year from testing and potentially commercialization. Some participants noted the example of Germany in the pile driving context, showing that effective regulatory engagement can speed new designs into development and commercial use.

Goal 2: Identify the Spatial, Spectral, and Temporal Features of the Acoustic Characteristics of New Technologies in Varying Environments Compared To That from Existing Technologies

Because there are a number of different MV units in various stages of development, generalizations had to be made regarding MV technology. One challenge is how those units would be implemented into array designs. There are many steps in the development process, and as individual units are ready for commercialization, more discussions need to be held regarding the spatial consideration of array design. Another spatial issue to consider is the ability of MV technology to be used in shallower environments.

Spectral features with these MV technologies allow for more flexibility in their acoustics. There is flexibility in how the units are tuned and how the acoustics are put into the environment. This is important because the effects of how that energy is put into the environment can potentially reduce impacts and may give more flexibility in terms of the data that industry collects, benefiting all parties. Spectral tuning also holds the promise of a reduction in high frequency noise, minimizing those types of impacts. There is a question of whether MV technology will be able to achieve the lower end of the frequency requirements (5-10 Hz) needed to provide the required imaging in some contexts. In some instances, industry needs these lower frequencies to be able to examine deeper and to investigate the composition of the seafloor subsurface.

A major concern is how the source would be regulated, i.e., whether it would be considered impulsive, continuous, or semi-continuous. It was expressed by the participants that MV is not an impulsive source. Most likely it will be categorized as continuous or semi-continuous. The regulatory agencies use these sound categories to help make informed decisions and are most interested in the impacts and effects from the sound sources, not the actual categories themselves. If better information is provided and there is a need to shift, refine, and/or expand these categories, then agencies will consider the possibility. The agencies do not want to keep strict labels but rather identify the actual impacts and regulate based on those.

Goal 3: Identify the System and Site-Specific Requirements for Operation of These New Technologies and Limitations of Their Use

The seismic array configuration needs further development as individual units are tested and commercialized. These systems are applicable in shallow water, though deepwater capabilities are still in question and require further testing. There are several different types of vibratory mechanisms including those driven by hydraulics, seawater, and electromagnetic or mechanical forces. Additionally, there are some concerns regarding the ability to provide suitable power requirements on the vessels for MV operations.

Vessel reconfiguration and downtime, operational delays, and capital investments were all identified by some industry participants as major concerns arising from adoption of MV. Some seismic companies recently went through major vessel upgrades, requiring a large capital investment that will not be paid off for the next 10-15 years. Participants voiced concerns about the requirements for implementation if a need to transition to this new technology arises. This not only includes the potential reconfiguration of the vessels, but also training of industry staff to use MV. For maximum efficiency in the implementation of MV, it will have to be feasible in an economic sense.

Goal 4: Discuss Potential Impacts (Positive and/or Negative) in Using These Technologies and Identify Operational and Cost Effectiveness As Well As Potential Environmental Impacts

The biggest concern is whether these technologies produce quality data that compare well with the existing, industry-standard data obtained from airguns. Initially, implementing this technology is likely to be expensive because of development and testing. There is also the economic consideration of the potential cost of reconfiguring vessels and training of staff.

There are many concerns over regulatory aspects. BOEM, NOAA, and the Marine Mammal Commission (MMC) are exploring the regulation of these new technologies. As groups move forward with this technology, industry needs to address how the technology will be tested and what regulatory concerns there are, and then discuss this with regulatory agencies. Interactions with regulatory agencies should happen sooner rather than later because of the lengthy regulatory process.

Based on the operating parameters, there is a strong general expectation that MV will be more environmentally friendly than airguns, given the significant reductions in source levels and control of signal amplitude and frequencies that the technology offers. These expectations remain to be verified for a wide range of potential industrial configurations, environmental conditions, and vulnerable fauna. However, as in the case of other seismic technologies, there may be environmental impacts from the energy levels in addition to indirect impacts associated with power systems, electromagnetic fields, or potential hydraulic fuel spills. Ecological impacts potentially may include both direct impacts to representative marine mammal species as well as indirect impacts such as disturbance to prey species. The removal of high frequency sounds above 100-200 Hz could result in significantly lower effects on odontocetes, but effects on mysticetes remain uncertain, with particular concern about masking (although, as some participants note, airguns could produce greater masking effects than MV). The need for a robust, thoughtful approach to documenting the effects on marine life and to identify ways to mitigate sources of effects was recognized. Empirical studies are needed on masking, disturbance, auditory, and perhaps resonance effects in candidate species sensitive to low frequency sounds. However, it must be remembered that MV only needs to be less environmentally hazardous than airguns. It was noted that much additional research was needed on airguns, too, and that development and commercialization of MV should not wait while high-energy seismic exploration was being permitted.

Goal 5: Evaluate Data Quality and Cost Effectiveness of These Technologies As Compared to That from Existing Marine Acoustic Technologies

To put in perspective the data quantity and analysis capacity within the seismic industry, it was stated that this industry uses the third highest amount of computing power next to the military and weather forecasting. Enormously complex processing tasks are being utilized by this industry. Therefore, data acquisition and processing will keep improving whether it is using MV technology, airguns, or some other system. Seismic survey data collected with MV technology are expected to be comparable to airgun data, and there is some preliminary evidence of this, as shown with the Geokinetics marine vibrator. Vibrators for seismic acquisition have taken the place of explosives on land in providing quality seismic data, so quality data from MV should not be a problem. There is a pressing need for side-by-side comparisons to measure similarities and differences; this will likely take place in the development phase once these units are field tested at sea.

One area not thoroughly discussed was the shelf life of data. If a company surveys an area and gets useful information, is there a need to go back and reshoot that same area a few years later? Perhaps this is done because of improvements in how data are collected, and new information can be gleaned from the reshoot. However, if the area shot previously has useful information that would keep an area from having to be resurveyed, attention should be given to improving post-processing to extract as much additional or improved information as possible from extant data.

Breakout Session IV

Goal 6: Discuss What the Current and Emerging/Potential Technologies Can Do To Reduce Sound Output

Increasing the sample rate simply by increasing the number of receivers is not a possibility because that would require a concomitant increase in energy output. A high shot density is required to generate subsurface images that are needed by the industry. The total energy output can be achieved in several ways by either transmitting the energy to enter the seafloor quickly (impulsive), slowly (non-impulsive), or to distribute it spatially. After the data have been processed, typically, the same results are found from the different methods of energy dispersion. By increasing the shot density, the strength of the individual source point energy could be lower even though there would still be the same overall energy output. The only difference is in the way the energy is transmitted into the seafloor. This demonstrates that there are different ways to structure the assessment process in order to obtain needed information and potentially minimize impacts. The major advantages of MV, as discussed previously, are as follows:

- the ability to substantially reduce sound output at higher frequencies;
- reduction of source levels at lower frequencies; and
- it allows for greater control and tailoring of signal amplitude.

With airguns, there are some techniques available to reduce unnecessary sound output. These include controlling the sound spectrum and sound duration of the firing of shots. Staggered shots are a means to reduce high peak pressures. However, this solution poses many data processing challenges that arise when attempting to differentiate inherent variation in signal properties from actual seafloor characteristics.

Goal 7: Examine Potential Changes in Environmental Impacts from These Technologies in Comparison with Existing Technologies

Changing the delivery of sound with MV would occur by reducing peak pressure and high frequencies, potentially mitigating impacts to marine species. However, the manner in which different species may be affected by other impacts such as masking remains to be understood.

For airguns, there has been consideration of selecting key indicator species as a model for effects across other species but the transferability of findings needs substantial study, especially for species that occupy disparate geographic areas (e.g., beaked whales could differ from either bowheads in the Arctic or sperm whales in the Gulf of Mexico).

For both airguns and MV, effects on marine species, particularly those associated with the oil field exploration operations, need to be differentiated from chronic impacts associated with production operations that occur over the lifetime of an oil field. Moreover, differences in the environment over the lifetime of a project need to be examined in order to differentiate production impacts from that of a potentially shifting baseline and thus to identify any cumulative effects. Cumulative effects involve all activities in an area (fishing, shipping, etc.), not just oil and gas activities. Further inquiry is needed to identify how sound may or may not change the function of the environment and its marine fauna over the lifespan of a production area.

There are substantial data gaps in identifying impacts on other species (e.g., invertebrates and fish) and whether impacts are site-specific. Habituation of animals could be a concern while impacts are still not fully understood, e.g., are researchers collecting biased measures because the only animals assessed are ones that tolerate the disturbances? Controlled exposure experiments, whether in open ocean or artificial settings, are needed to generate defensible information quickly in order to inform the regulatory process and thus provide guidance to industry. All these points apply to airgun impact testing as well.

Goal 8: Identify Which Technologies, If Any, Provide the Most Promise for Full or Partial Replacement of Conventional Technologies and Specify the Conditions That Might Warrant Their Use (e.g., Specific Limitations to Water Depth, Use in Marine Protected Areas, etc.)

MV technology may partially, widely, or wholly replace airguns for deep-penetration seismic exploration. While the full extent is not clear, it is likely that the nearest-term applications for MV will occur in transition zone and shallow water environments. This will be possible by the advanced state of the Geokinetics marine vibrator array, which is presently designed for those environments, and industry interest in advanced seismic technology that can work directly in shallow water, without the use of nodes. There are economic costs and regulatory concerns; the speed and quality by which these costs and concerns are addressed, and the extent to which regulators engage in incentivizing or requiring the technology, will shape the industry's choices of technology. There is a need for peer reviewed, applied research in order for regulators to make more informed decisions. MV technology has the potential to be used in environmentally sensitive areas if the impacts are found to be limited. In addition, MV can be used in extremely shallow waters (less than or equal to 2 m), but shallow waters are often biologically rich and diverse environments; impact studies must be carried out expeditiously to determine the lowest cost for both the environment and industry.

Staggering shots, airgun silencers, and the E-airgun (Western Geco) were identified as promising quieting technologies for airguns, but currently none of these options are readily available. They either pose operational and/or data processing problems and as a consequence have not gone further in development, especially in light of promising alternative techniques.

Goal 9: Identify the Next Steps for the Further Development of These Technologies, Including Potential Incentives for Field Testing

Continuing the development of MV units is crucial. With seismic surveys potentially moving to frontier areas such as the Arctic and the Atlantic, there is a need for more environmentally friendly technologies such as MV. As it moves forward with design testing, agency and industry cooperation and communication are essential. A decade ago, this level of cooperation was not in place, and as this has advanced it has opened the grounds for communication between industry and regulators to discuss concepts and regulations and determine a path forward.

It has been addressed numerous times that regulatory schemes need to be adapted. In this adaptation process, industry needs to provide input regarding drivers and incentives for development of lower source levels. With the process of movement towards lower source levels and lower impacts, there would be a reduction in the cost of mitigation with time and cost savings towards permitting. Agencies need to provide both incentives and rewards to industry participants to accelerate the development and implementation process of quieting technologies ahead of, or in lieu of, additional regulations.

Regarding the biological aspect, initiating impact studies is an immediate necessity. Until field options of MV units are available, performing additional model simulations using AIM© or a similar program should be explored. Differentiating near- and far-field effects will be imperative to identifying potential impacts, and data collection should be designed to incorporate such stratification into the modeling effort. Identification of biological indicators that accurately represent potential impacts to species of concern but do not compromise ethical treatment of animals need to be developed and approved. It would be extremely beneficial if impact studies could be performed in tandem with the design and testing of MV units. With these tandem tests, there can be a better overall assessment of airguns versus MV for both industry and regulatory needs.

Plenary Session VI

Plenary Session VI was a report of the goals information presented in the Breakout Sessions III and IV. See the Airgun Goals Report in **Appendix D, pp. D137-D139.**

2.2.5.2 Group 2: Pile Driving

Breakout Session III

The five goals of the Breakout Session were addressed in turn, but the discussions of the first two goals overlapped considerably, so they have been consolidated below. It was noted that comparison of the qualities of each of the technologies depends greatly on the precise targets for noise reduction, which in turn depends on the environmental impacts that require mitigation.

Goal 1: Review and Evaluate Recent Developments (Current, Emerging/Potential) in Quieting Technologies for Pile Driving During Offshore Renewable Energy Activities

Goal 2: Identify the Spatial, Spectral, and Temporal Features of the Acoustic Characteristics of New Technologies in Varying Environments Compared To That from Existing Technologies

The various quieting technologies described in the Workshop up until this point were listed, and attendees at the Breakout Session were invited to add to this list and comment on each of the technologies. Quieting technologies for pile driving include the following:

- <u>Bubble curtains</u>: These were described earlier by Mr. Koschinski and Dr. Nehls. It was noted in discussion that bubble curtains themselves generate noise and can stir up the sediment (as the bubbles may be forced through the sediment, depending on how the hose lies on the seabed). However, as noted in the discussion following the Dr. Georg Nehls, Breakout Session I, Bringing the Big Bubble Curtain Offshore presentation, the sound of bubbles collapsing could not be detected at the 750 m range. In addition, sound can enter the sediment (ground transmission) and then re-enter the water column. Theoretically, a large radius bubble curtain has the potential to reduce these steeper paths originating from sediment. This technology has been tested at a depth of 40 m and thus may be limited to relatively shallow waters, especially when currents shift the rising bubbles.
- <u>Encapsulated air bubbles</u>: This technology was described by Dr. Wochner. This relatively new technology has undergone proof of concept testing but needs field testing. It works through resonance and could reduce noise by at least 20 dB (metric not specified), with the frequency range for reduction being controlled by the size of the encapsulated bubbles. There could be an infinite number of bubble sizes, and attenuation could be increased by adding more bubbles.
- <u>Hydro sound dampers</u>: These are nets made of air filled foam or balloons; in tests, such systems were 9 m in diameter and 28 m in height and weighed 17 tonnes.
- <u>Double-walled pile</u>: Three types of double-walled piles were described:
  - The mandrel, where driving is done using a driving pile inside the outer main pile, with an air pocket between the two piles;
  - Steel casings with bubbles in the interstitial layer, but not dewatered; and
  - Cofferdams, where encapsulated air is held around the pile by the outer layer that does not extend into the sediments. These were tested in two trials where one had failed while the other was successful.

- Seabed treatment: There may be various treatments to prevent sound propagation from ground-sediment transmission. An encapsulated bubble blanket laid on the seafloor would need to be large. Another suggestion would be to shape and mold the seabed to divert the sound upwards, possibly using ramp-shaped-features. A geostabilization process was also suggested to change sediment permeability and its ability to transmit sound, possibly also making driving easier, but this too requires further development.
- Elongation of the pulse: There may be various ways of modifying the features of the energy radiated into the water. This could occur through the use of pile caps, but their use is probably limited to smaller radius piles due to the amount of heat generated that quickly destroys caps. Another option might be to increase the strike frequency and reduce the strike force, which would decrease the generated intensity (energy) of the pile driving signals. Ultimately, this would reduce peak energy and could slow SEL accumulation, thus pile driving would likely continue for longer durations.
- Lower radial expansion pile: Such a pile has longitudinal slits that will reduce the amount of sound radiated by the pile.

Various alternative methods to pile driving were mentioned (although they technically were not "quieting technologies for pile driving") to clarify that there are additional techniques for installation of piles that have the potential to reduce noise introduced into the marine environment, although not a specific or intended goal of the Workshop. Alternatives were not exhaustively listed or considered. They include suction bucket, gravity base, and floating foundations; drilling (see Mr. Koschinski's presentation, Pile Driving, Breakout Session I) – noting that, depending on seafloor properties, a mortar filling of the annular gap or some driving towards the end of installation may be needed using drilling methods. Vibratory driving takes less time to install but requires more planning and set-up time. A combination of technologies may be a useful approach, for instance a drive-drill-drive process, or a vibratory followed by driving approach. The choice may depend on the sediment type and the "drivability analysis." However, it would not necessarily be cost effective for installers to carry both vibratory and impact hammers.

Overall it was noted in the Breakout Session that no one technology would work in all situations and that there were advantages and disadvantages to each (and that some concepts still required field testing). The contrast between confined and open water was a very important consideration in choosing technologies. There was also likely to be variation in the sensitivity of each region where pile driving was planned due to the varying sensitivity of the fauna and their distribution. Knowledge of the variation in such faunal sensitivity was essential in knowing which frequencies to target most for reduction. It was recommended to examine each component of the pile driving system and acoustically modify it to minimize noise output.

Goal 3: Identify the System and Site-Specific Requirements for Operation of These New Technologies and Limitations of Their Use

The majority of the quieting technologies for pile driving have received insufficient field testing to be able to fully identify the system and site-specific requirements for operation of the technologies and any limitations in their use.

Bubble curtains (both large and small diameter) have been field tested by Dr. Nehls, but the remainder of the systems need further empirical results derived from field testing. The feasibility of some systems can be assessed in some instances by modeling, but empirical data are still needed to confirm results and equations. Current flow is important, and there will be an upper limit on water depth. Also, is development of a very large bubble curtain to surround an entire offshore construction site feasible?

Encapsulated air technologies have been tested in lakes around ships but not around piles.

Hydro sound dampers have been tested and proven the practicability of the system, but sound elements still need to be tested. A test has been conducted in UK waters (London Array), but the test results have yet to be made available or published.

Double-walled pile. The mandrel has been tested with 3-in and 6-in piles, with a full-scale test planned for November 2013. The type and quality of sediment in which the mandrel is being used strongly affect the stability of the pile once the mandrel is withdrawn. A test was previously conducted, but the dewatering procedure failed.

Cofferdams would not be affected by water currents but will be affected by depth, so scaling their use to deeper and larger applications may be difficult. One successful test of a cofferdam has been completed resulting in an average broadband noise reduction by 23 dB (SEL) and 19 dB (peak).

Seafloor modification to deflect sound upward from the sediment is a new concept that has not been tested yet. The concept has been used for sound mitigation around airports on land. However, the dredging required to modify the seafloor could be costly and cause additional environmental impacts.

Pile caps are limited by the heat that can be generated. This can destroy the caps, causing debris and other material damage, along with the need for constant replacement.

Goal 4: Discuss Potential Impacts (Positive and/or Negative) in Using These Technologies and Identify Operational and Cost Effectiveness As Well As Potential Environmental Impacts

Cost effectiveness of the technologies is measured by whether or not the technology causes any delays in the construction process. These delays are very expensive, therefore any system needs to be independent of the construction process, or very quick to install and use. If the noise control system becomes a regulatory requirement, then the reliability of the technology and of the system will become important. It should also be noted that the permitting process can be costly if it delays construction, and permitting may take longer if the technology is unproven. The more that is understood and proven, the more readily the sound control system will be accepted by regulators.

A high manufacturing cost can be offset if the system is readily reusable under similar conditions as costs are spread across many pile driving operations. Some double-walled pile technologies have a high manufacturing cost but are easily reused. Costs will go up if the crane-handling time increases; for mandrels, only one lifting process would be required, whereas for other double-walled approaches, two lifting processes may be needed. Costs associated with bubble curtains include relatively low material costs for the bubble curtain materials and higher operating costs due to the deployment/tender vessel costs.

From an environmental perspective, bubble curtains can stir up sediments that may resuspend contaminants and cause turbidity problems if used in areas with fine (organic) sediments; however, this technology is typically used on sandy seabeds so additional turbidity does not normally occur, as compared to other methods. In addition, depending on the type of compressor used, bubble curtains can add oil-based contaminants to the water as part of the process. Additionally, vessels can cause further impacts (air emissions, noise), so this is a good incentive to use the same vessels for sound attenuation equipment deployment as for construction. Gravity bases, used for some structures, take up much more space on the seabed compared to piles. Environmental impacts from suction buckets arise due to increased turbidity, as sediments are disturbed during pump-outs of the buckets. However, suction buckets are typically used on sandy seabeds so additional turbidity does not normally occur as compared to other methods.

Goal 5: Evaluate Data Quality and Cost Effectiveness of These Technologies As Compared to That from Existing Marine Acoustic Technologies

This question was not relevant as data quality is not an issue for pile driving. It was noted though that measurements of performance need to be standardized so that the capabilities of the technologies can be compared.

Breakout Session IV

Goal 6: Discuss What the Current and Emerging/Potential Technologies Can Do To Reduce Sound Output

Two of the emerging technologies, resonators (static bubbles) and shields with air and sound absorbing material in the open space around the pile, have the potential to reduce radiated sound by as much as 40 dB, but only in the waterborne, as opposed to the ground sediment, pathway. All current solutions are severely limited in efficacy by ground sediment transmission (seismic), where sound travels through the substrate faster than the water and partly re-enters the water column some distance from the source. The signal from ground transmission lowers the maximum efficacy of most technologies to around 15-20 dB of attenuation when the sound is measured in the far field.

Two emerging technologies addressed the ground transmission route. One was presented by Drs. Reinhall and Dahl from the University of Washington. They have pilot tested in the field a hollow pile tethered to a piling mandrel. The mandrel is hit with the hammer, which pulls the shielding hollow pile into the sediment along with itself. This pilot study showed highly effective attenuation of waterborne and ground-transmitted sound. The other technology was the "Big" bubble curtain presented by Sven Koschinski (see **Section 2.2.4.2**). The ground transmission problem is solved if less noise is produced at the outset through quieter piling techniques, obviating the need for further noise damping or attenuation after the noise is produced.

Goal 7: Examine Potential Changes in Environmental Impacts from These Technologies in Comparison with Existing Technologies

Each of these technologies may be complementary and could be utilized in a combined fashion to enhance the other, applied singularly or jointly to best attenuate sound for a given environment and to mitigate potential environmental impacts.

There seems to be no investigations of the potential environmental problems from any of the attenuation devices. Therefore, a comparative analysis of new versus existing technologies is not possible.

Resonators (static bubbles) avoid the use of "nets" and instead use vertical lines that allow animals to pass through the resonator system (between the noise source and resonators) and thus avoid a potential environmental hazard. There is minimal risk of losing a resonator as they are attached at two points and secondary resonators are encased together within a fabric type of material as an added assurance against loss.

Technology such as a sound blanket laid on the seafloor to dampen ground transmission could have effects on benthic animals, vegetation, and habitats. The loss or damage to these micro-ecosystems in specific areas could affect stakeholders (e.g., tribal communities, state lands, and local fishermen). The impacts are not just from noise but include associated physical impacts from deployment, recovery, and maintenance of noise quieting technologies. Potential damage to these habitats needs to be evaluated in the context of the entire operation.

Goal 8: Identify Which Technologies, If Any, Provide the Most Promise for Full or Partial Replacement of Conventional Technologies and Specify the Conditions That Might Warrant Their Use (e.g., Specific Limitations to Water Depth, Use in Marine Protected Areas, etc.)

None of the technologies have been sufficiently tested to determine their true performance. Opportunities for field application are necessary to expedite the testing process for each of the technologies. Technologies that have been partially tested and are ready for additional field testing include use the following:

- Hollow pile with a mandrel (see Reinhall and Dahl presentation, **Appendix D**, **pp. D112-D117**) is the main emerging technology presented that addresses both the waterborne sounds and ground transmission sounds. This technology has undergone field pilot studies;
- Double-shield pile (see Reinhall and Dahl presentation, **Appendix D**, **pp. D112-D117**) appears very effective with attenuating waterborne sounds and has been used to mitigate construction activity, but this technology does not mitigate ground transmission;
- Resonators (static bubbles) (see Wochner presentation, **Appendix D**, **pp. D102-D108**) have had pilot testing, mostly in controlled environments, and need testing around full-scale pile driving activities; and
- Slit pile (see Reinhall and Dahl presentation, **Appendix D**, **pp. D112-D117**) has been modeled and investigated at a small scale. The method needs proof of concept testing.

Suggestions to advance emerging technologies and alternative technologies include the need for a testing site that is relatively uniform in all aspects that represent comparable and standardized ranges, sediments, depths, etc. This would be available for testing technologies to provide proof of concept and the possibility of a calibrated data set that would allow for comparing results under similar conditions.

Discussions also included the use and further development of other pile construction materials like composite or concrete. These materials are solid, less flexible, and have a lower Poisson's ratio (less expansion), which means less sound goes into the water and substrate. Ultimately the amount of sound generated using concrete (or potential composite) would be less than that generated using steel. Spun concrete piles are being made up to a 66-in (1.68-m) diameter in Virginia and Louisiana and can be struck harder than conventional concrete. All concrete piles need a cushioning cap and a larger hammer to protect the pile from damage, and to dampen the stress of impact.

Depth limitations for alternative pile designs (which result in less noise introduction) or in quieting technologies are determined by the depth limitations for the pile installation itself. Further testing may reveal additional limitations to their use.

Goal 9: Identify the Next Steps for the Further Development of These Technologies, Including Potential Incentives for Field Testing

The next steps to advance these technologies include standard field test sites located around the world that represent comparable and standardized ranges, sediments, depths, etc. A variety of substrates and conditions are needed to avoid improper conclusions being drawn from a single site (i.e., over rating a system for a different sediment type). In order to make reasonable predictions, many different testing sediment types and environmental conditions would be needed for comparisons. These sites could also help organize the practicality and logistics of sound abatement testing around pile driving activity.

As standardized test sites are not yet available, general field testing is required for proof of concept and detailed testing of technologies. Cooperative partnering between pile driving companies, regulatory agencies (including environmental permitting), scientists, and companies with sound abatement technologies is needed to move forward to field testing. Any field testing needs to ensure that sediment types and environmental conditions are accurately recorded. Cost is a principal consideration for pile driving companies, and testing must be planned, designed, and executed with minimal disruption to the construction operation. Open dialogue between engineers, physicists, and pile driving companies is needed. Close collaborations between the groups with different perspectives and approaches would likely allow the testing goals to be reached more efficiently and cost effectively.

For the mandrel, in its current construction, it would be left tethered to the inside the hollow pile, which doubles the cost of the materials. To advance this technology, full-scale testing is needed and a process to untether and remove the mandrel from the hollow pile for reuse must be developed.

The overall industry standard and preference is to drive piles and not drill them, yet drilling piles is a quieter option. Even if piles are drilled instead of driven, additional pile strikes may be necessary. For example, engineers still require wind farm installation piles to be proofed using pile driving after vibratory installation. Piling techniques may be mandated by geotechnical engineering for structural purposes even though other quieter methods may be preferred.

The costs associated with field testing a single pile or a whole wind farm of piles scales up with water depth, size of the pile, and distance from shore. Testing permits in the United States (e.g., those required by the ESA and MMPA Incidental Harassment Authorization) will be required and should include NOAA involvement, including where field testing can occur. Nearshore, testing might cost around $250,000 per test project, but it would be preferable and more cost effective to partner testing with an ongoing construction project. The German Ministry of the Environment has invested €25 million ($33 million USD) annually for research of underwater noise reduction. In Europe for offshore testing, it is critical to partner with a pile driving project that will allow the testing of noise attenuation on a full-scale project. In Germany, an offshore wind farm test of a single pile was around €1 million ($1.3 million USD).

Suggestions that need further development:

- Establishing preliminary future regulatory criteria can stimulate mitigation development and implementation. Additionally, this will put pressure on the industry to develop construction methods to meet the criteria before it is mandatory. Development of preliminary criteria will result in some noise reduction while verifying and modifying the criteria in order to attain further noise reduction.
- When an opportunity arises in conjunction with pile driving activities, coordinating in order to expedite field testing by forming a joint industry program, similar to what has been done for seismic, with contractors, regulators, scientists, academia, etc.
- Incentives to allow less sound attenuation during less critical times, which allows the installation to continue during times that need mitigation. Another idea is to give point credits during the design – build bids evaluations with quieting technologies integrated into the bids (i.e., instead of green credits, quiet credits).
- Is development of a very large bubble curtain to surround an entire offshore construction site feasible? Nonetheless, that solution would be limited to filtering specific frequencies.

Alternative technologies to piling installations:

- Drilling – There are a few reported noise measurements that indicate drilling has a lower frequency range and sound pressure levels (around 117 dB re 1 µPa at 750 m) that appear to be within required mitigation levels. Also, noise measurements taken during offshore drilling for oil and gas wells were dominated by support vessels and topside equipment, not the drilling itself.
- Bucket piles – These have a larger footprint than a typical pile and cause a larger loss of seabed habitat than traditional piles.

- Gravity foundations – In Germany at depths >30 m, 20,000-30,000 m^3 of sediment needs to be removed to prepare the seafloor for installation, which Germany has rated as damaging/risky pile driving. In shallow water the base is smaller and less sediment needs to be moved.
- Crane-free gravity base foundation (by SeaTower Co) – The foundation is bottle shaped and ultimately weighs around 6,000-7,000 tons. The foundation is filled with ballast and sunk into the sea bottom, and then concrete is injected between the seabed and the bottom of the base. This type of foundation can be decommissioned in an environmentally friendly aspect in that the foundation can be removed without explosives by reversing the installation process. Gravity base foundations are even larger than bucket piles and result in an even larger loss in seabed habitat.
- Floating tension leg platforms – Some pile driving would still be needed for anchors to put tension on the cables holding these platforms, but these are likely to be relatively short pin piles.

Plenary Session VI

Plenary Session VI was a report of the goals information presented in Breakout Sessions III and IV. See the pile driving Goals Report in **Appendix D, pp. D140-D142**.

2.2.5.3 Group 3: Support Vessel Noise

Breakout Session III

The Information Synthesis (**Appendix A**) revealed a data gap that the group attempted to answer, which was describing the types of support vessels associated with energy development and the need to compare and contrast these vessels with other commercial vessels in terms of the noise they generate. Various types of support vessels that should be considered include the following:

- Installation vessels (e.g., jack-up ships, lift ships);
- Seismic survey vessels;
- Tugs;
- Offshore service vessels and platform supply vessels;
- Drilling vessels;
- Multipurpose vessels;
- Anchor handling tugs;
- Icebreakers;
- Crew transport vessels; and
- Crane barges.

Determining which of the vessels might be the biggest contributors to noise was not straightforward, and no consensus regarding rank order could be established. However, it was agreed that noise is dependent on the engineering and design of the vessel as well as on how it is operated and the environment in which the vessel is working. Therefore, it was determined that it is necessary to characterize noise based on both design parameters and operational parameters. Several key points were developed:

- Collection of radiated noise data to characterize vessel and propeller noise for existing designs should be implemented.
- Data should be collected in accordance with ANSI S12.64-2009 requirements when possible. If ANSI standards cannot be met for some reason, a simpler data collection protocol with one hydrophone at a 20 m depth, 100 m from the vessel was recommended. The ANSI standard, Grade C may be comparable to this simpler protocol.
- Data collection for characterizing vessel noise can be done in two manners: opportunistically or via measurement of individual vessel source levels.

- Opportunistic monitoring could be done at ports with fixed PAM devices, perhaps in partnership with Marine Exchanges, to collect ancillary data on vessels (e.g., loads) or with PAM and AIS together.
- Individual SL measurements could be collected in a manner similar to what was presented for the study in Sakhalin Island, Russia (see **Section 2.2.4.3**, Coordinated Management of Anthropogenic Sound from Offshore Construction by Dr. Zeddies, JASCO).
- Similarly, the Arctic sound source verification process required by the NMFS Office of Protected Resources could be implemented to determine individual vessel source levels. If permitting requires monitoring and measurement of vessel noise levels, the data would be expanded even further.

Goal 1: Review and Evaluate Recent Developments (Current, Emerging/Potential) in Quieting Technologies for Support Vessel Noise Associated with OCS Energy Development

It was agreed that both the design and the operational scenarios need to be considered. It was concluded that the various design level treatments for quieting support vessels ranked in order of significance of noise reduction are as follows:

1. Non-cavitating propellers;
2. Quiet thrusters for DP;
3. Vibration isolation for diesel engines and generators;
4. Silencers for hydraulic systems; and
5. Quiet models or vibration isolation of electrical motors and auxiliary systems.

Propellers – Propeller designs include new technologies for making ships quieter, but the technology currently resides primarily in naval operations and is very expensive. There are, however, low/non-cavitating designs more readily available. In addition, propeller-hull form integration could be considered, including computational fluid dynamics (CFD) hull optimization computer modeling, which is a new technological advancement. The vessel design must also consider function and be designed for multiple conditions and tasks (e.g., pulling array, free sailing), which can be optimized by CFD modeling or scaled model testing in tow tanks.

Thrusters – Optimization of thrusters for DP should include low/non-cavitating designs and quieter systems (e.g., drop-down thrusters, Voith-Schneider propellers, rim drive, and others). The design can be optimized using scaled modeling testing. In addition, optimization of DP automation (e.g., balancing loads to minimize noise and improve performance) could help reduce noise.

Diesel Engines and Generators – Vibration isolation will reduce noise and should involve soft springs and a dynamically stiff foundation to realize noise reduction.

Hydraulic Systems – Pulsation dampers and other silencers for hydraulic piping systems will reduce noise, and vibration isolation will reduce the transfer of vibrations through the hull.

Electrical Motors and Auxiliary Systems – Vibration isolation of existing motors and design of quiet motors will reduce noise transferred through the hull.

Operationally, various vessel configurations can reduce the noise output. To accomplish this, mission planning plays an integral role in minimizing noise by decreasing peak loads (e.g., by positioning the vessel into the wind and waves when using DP). Other components to consider during mission planning include operating at optimal speed for reducing noise where possible, balancing speed (and therefore noise level), and residence time in a given area. Specific factors to consider during planning include use of anchoring over DP, use of self-noise monitoring to inform operation planning, consideration of propagation in speed/routing decisions (if possible), and accounting for sensitive areas.

Acoustic monitoring will provide an initial noise assessment of a vessel on an acoustic range partnered with subsequent onboard vessel monitoring for change detection and maintenance. Monitoring of the propulsion systems will indicate if it is necessary to dynamically redirect loads if cavitation is detected at one component. Vessel husbandry/maintenance can reduce noise and should include underwater hull cleaning, mechanical maintenance, and "sound short" surveys.

Goal 2: Identify the Spatial, Spectral, and Temporal Features of the Acoustic Characteristics of New Technologies in Varying Environments Compared To That from Existing Technologies

There is not a clear distinction between alternative and existing quieting technologies for support vessels. In general, reduction or elimination of propeller cavitation will reduce broadband noise across the full spectrum and that reduction of narrowband, tonal noise (mostly low frequency) will be achieved by quieting diesel engines, electric motors, and auxiliary machinery. These noise reductions are spatially and temporally invariant.

Goal 3: Identify the System and Site-Specific Requirements for Operation of These New Technologies and Limitations of Their Use

This goal is considered to have limited applicability for many of the support vessels described above. **Table 2** identifies the specialized components and their limitations; however, it is necessary to realize that because support vessels are often used for multiple tasks, it is not possible to retrofit the vessel each time a new task is undertaken.

Table 2. Technologies for quieting vessels and their limitations

Technology	Limitation
Icebreakers	Pod thrusters must be able to both mill ice and propel
Drop down thrusters	Susceptible to damage in shallow coastal waters; may be limited to tunnel thrusters
Large diameter propellers	May not work in coastal waters
Jet-power	May be an alternative for shallow water (for smaller vessels only)
Voith-Schneider propellers	Can only be located at the stern of the vessel, also has draft considerations

Goal 4: Discuss Potential Impacts (Positive and/or Negative) in Using These Technologies and Identify Operational and Cost Effectiveness As Well As Potential Environmental Impacts

Operations and Cost Effectiveness – Many of these solutions are expensive. For example, ship design always involves some tradeoffs, and support vessels need to serve multiple purposes, thus selecting the optimal technology for a given vessel is not straightforward. There are a number of questions that remain regarding the quieting of vessels, especially 1) who pays for the changes, and 2) how to measure the cost effectiveness (dollars/decibel). Baseline data are limited, and monitoring has not been conducted to determine the existing noise levels of most vessels.

Acoustic monitoring options can be coupled with other machinery health and maintenance monitoring to improve cost effectiveness. The benefits to the vessel owners and operators of quieting vessels include the following:

- If quieter vessels are used, more of them could potentially be used on a project and result in the same overall noise footprint in the face of regulatory demands;
- Sonar systems function more efficiently on a quiet vessel;
- Quieting underwater noise results in lower noise levels for vessels' crews, and, therefore a more comfortable, safe, and productive environment; and

- Noise reduction and fuel efficiency/maintenance costs may go hand-in-hand, but this will likely be case specific (e.g., bringing down DP activity should also cut fuel consumption).

Disadvantages also exist including that anything done design-wise that makes the vessel more complex may impact reliability, at least at first. In addition, if the vessel is more complex, it could require a more educated crew and may result in constraints on operations. Ultimately, some design options may be very expensive and time consuming to implement, resulting in lost revenue for the vessel owners/operators.

***Environmental Impact*s** – A beneficial environmental impact associated with quieting vessels may be realized if a maintenance plan includes hull and propeller cleaning, which will, in turn, decrease operating costs through lower hull drag and could minimize introduction of invasive species.

Goal 5: Evaluate Data Quality and Cost Effectiveness of These Technologies As Compared to That from Existing Marine Acoustic Technologies

This goal is not applicable for support vessels because they are not in themselves noise quieting technology. Cost effectiveness of vessel quieting technologies was discussed in Goal 4.

Breakout Session IV

Goal 6: Discuss What the Current and Emerging/Potential Technologies Can Do To Reduce Sound Output

Cavitation avoidance, quiet propulsion systems, and cavitation-free DP systems could result in 10-20 dB reductions in noise levels. In addition, CFD-based, self-optimizing design systems derived from algorithms could lead to big improvements in hull and propeller design, but quantification of that reduction is unknown. Air injection along propellers and thrusters could have benefits but would require further investigation to quantify the reduction, and it may not be economically feasible due to the potential for a strong tradeoff between noise reduction and maintenance costs/down time. Active control through vibration mounts also could be beneficial, but further investigation is warranted and is still fairly expensive. Shipboard acoustic monitoring could result in 10-20 dB of reduction if material condition failures are identified and corrected.

Goal 7: Examine Potential Changes in Environmental Impacts from These Technologies in Comparison with Existing Technologies

There are no known environmental impacts associated with existing technologies, primarily because applied studies are limited. However, this examination did not include technologies that would result in tradeoffs between frequencies, although reducing broadband noise by eliminating cavitation may reveal tonal noise from machinery. In addition, it has been hypothesized that there may be an increased risk of vessel-marine life interactions with quieter vessels; however, evidence for this appears weak.

Goal 8: Identify Which Technologies, If Any, Provide the Most Promise for Full or Partial Replacement of Conventional Technologies and Specify the Conditions That Might Warrant Their Use (e.g., Specific Limitations to Water Depth, Use in Marine Protected Areas, etc.)

Ship designers may be able to achieve a cost effective way to reduce noise output by modeling the vessel noise during the design process. In addition, hydrodynamically and acoustically optimizing propeller and thruster design combined with designing DP automation to account for noise is a viable option. Shipboard acoustic monitoring to identify and correct problems could also provide a reduction in noise. Mission planning to minimize noise impacts can also play a substantial role in noise reduction by developing an approach for the task that implements quiet operating scenarios and components. Limitations for specific treatments were investigated in Goal 3.

Goal 9: Identify the Next Steps for the Further Development of These Technologies, Including Potential Incentives for Field Testing

Incentives to invest in R&D for quieter vessels would ultimately be driven by regulations and/or permit requirements. Much of the vessel quieting strategy and technology described here is available but the incentives to develop them are not. Adoption of the forthcoming IMO recommendations would provide further incentive for implementation. It should be noted that the IMO Design & Equipment (DE) Committee agreed to present the underwater noise guideline to next year's session (March 2014) of the MEPC for final approval. The cost effectiveness of the quieting technologies must also be evaluated. The desirability of Green Certification (similar to LEED certification [US Green Building Council, 2013]) for public awareness and market-based incentives may also lead to advancements in quieting technologies.

In order to initiate further development, calls for proposals should focus on data collection for particular vessel designs, environments, and activities in order to determine the baseline description of the vessel and the noise it produces under different operational conditions. Data could originate from opportunistic noise characterization of ships (e.g., transiting in and out of ports) and combine with additional data from Marine Exchanges to gain knowledge of the noise currently produced. Potentially, a short acoustic analysis could be conducted onboard the vessel to attain comparative data. Three possible combinations of data sources to obtain data from existing vessels are:

- AIS + PAM + Lloyds Marine Intelligence Unit;
- AIS + PAM + Lloyds Marine Intelligence Unit + Marine Exchange; and
- PAM + Lloyds Marine Intelligence Unit + Marine Exchange + onboard visit.

To encourage and justify implementation of particular quieting technologies, a market study to determine the economic costs and benefits must be conducted, especially considering different support vessel types. Development of international scope initiatives and partnerships (e.g., with IMO) is also recommended.

Questions that remain unanswered include the following:

- Should the focus be on designing new, quieter vessels or quieting the existing vessels? Will the regulatory environment allow waiting for the new vessels to come online (which may be decades)?
- Should we be asking the US Navy for acoustic data? They are unlikely to provide much and probably will not have the ancillary data required.
- What should the environmentally or biologically based acoustic limits be? Perhaps these are geographically or species-specific? It is recommended that, initially, a conservative floor level be established. It is important to have target levels to provide context for technologies and to measure accomplishments.

Plenary Session VI

Plenary Session VI was a report of the Goals information presented in the Breakout Sessions III and IV. See the support vessel noise Goals Report in **Appendix D, p. D143-145**.

2.2.6 Plenary Session IV: Expert Panel Discussion

Dr. Reeder facilitated a panel discussion summarizing unintended consequences, alternative supplemental technologies, and mitigation techniques for seismic surveys, pile driving, and support vessel operations. The parameters and issues for these three noise generating activities are very different, and each needs to be individually addressed to generate effective mitigation measures.

One of the challenges of characterizing anthropogenic sound sources in the marine environment is that ambient noise levels for most ocean basins are not well-documented. To effectively plan mitigation procedures for anthropogenic sound, a better understanding of current sound sources as well as techniques to differentiate between sound types is needed. For example, the Navy has extensive data from omni-directional sound monitoring studies, but there is no known way to identify the source of the sounds. There is an extensive network of marine buoys in US waters, but the lack of a national data center to process the data into usable information is inhibiting the full potential of this resource. Some existing information on marine background noise may be available from marine mammal researchers; however, a central depository for the data does not exist. The US Navy has extensive datasets on background ambient noise, but most of the data are classified and the Navy is unwilling to release them, even in a summarized form without raw data.

Another challenge associated with data collection is that there are currently no standard procedures for measuring ambient noise, which makes comparing data extremely challenging. It is important that measurements include directional and temporal components so that the source (i.e., shipping, environmental, meteorological, etc.) of the noise can be determined. This would preclude the use of equipment such as omni-directional sensors that provide no directional information, although Dr. Hildebrand suggested that data from omni-directional arrays are still usable and certainly preferable to no data at all. One major hurdle is the ability to acquire funding to perform an ambient noise study, especially in the absence of compelling regulatory need. Almost all ambient noise studies have been conducted as an ancillary activity to another funded study.

MV will not increase lateral propagation of sound waves in water, as compared to airguns. Mr. Pramik suggested there are two processes that inhibit the propagation of sound in the water that act on both airguns and MV units. The ghost effect causes horizontally travelling waves to be cancelled out after a distance of approximately 100 m. This does not mean that there is no energy left in the water, just that the direct wave is gone and only reflected or curved waves remain. Secondly, arrays of either airguns or marine vibrators are point sources and there is no effective attenuation inside of the emitted frequency bands. Airguns emit higher frequencies and the waves can be partially attenuated, but a PRN sweep of MV may result in a masking effect at high frequencies. Overall, MV is more effective at preventing lateral propagation of sound waves.

A conventional wide-azimuth (WAZ) survey has four sources that cycle on and off. The ability to control the transmitted spectrum may allow multiple marine vibrator sources to operate without mutual interference and therefore not be required to cycle on and off as in a conventional WAZ survey. It is unlikely that coil shooting, used in WAZ, introduces unintended additional noise into the ocean because the sources are cycled one at a time in sequence: each source fires every 100 m instead of every 25 m. The streamers in coil shooting are intentionally being towed in circles, and the turn radius of 6-8 km effectively eliminates any additional water turbulence.

Of the three topics covered in this session (seismic surveys, pile driving, and vessel noise), only vessel noise is not regulated. Existing data primarily focuses on commercial shipping noise, rather than support vessel noise; however certain components are applicable to all vessels. From a planet-wide perspective, shipping noise will likely make the greatest overall contribution to aquatic low frequency ambient noise; whereas seismic surveys and pile driving have more acute, geographically constrained effects due to the localized nature of those activities. Although prioritization of mitigation efforts should occur relative to the scale of activity in the United States, shipping or support vessel noise is unlikely to be federally regulated without intervention by third parties. When considering the MMPA, seismic surveys are the biggest concern on a localized scale. Vessel noise is a concern under the MMPA, but procedures to address it have not yet been developed due to the unregulated nature of vessel noise emissions; instead, the US has focused over the last several years on promulgating guidelines at the IMO. In offshore

European waters, seismic surveys and shipping noise have been found to emit roughly equal amounts of acoustic energy, with pile driving an order of magnitude less. The same trend likely holds true for the United States because there is even less pile driving occurring than in Europe, although the ratio may shift as offshore wind development increases in the coming years. Regional variance does occur in acoustical energy emission: seismic energy is highest in oil and gas fields, while pile driving energy is higher where wind energy is being developed. It was noted that the largest source of sound from the operation of wind farms, as opposed to construction, comes from support vessels performing maintenance and gears within the turbine, not from the blade or blade rotation.

It is not currently a BOEM requirement to conduct pre-project baseline surveys with passive acoustics to obtain background noise levels prior to pile driving activities or seismic surveys. This sort of data collection would be more effective in a collaborative way where data are shared instead of performing case-by-case studies. The concept of "baseline" depends on when the measurement is started. The idea of obtaining baseline information while there are many other projects ongoing will not give an accurate depiction of "pristine" noise levels. Instead, the goal should be to characterize current conditions in order to model the aggregate noise levels. ExxonMobil was attempting to promote collecting baseline data ahead of oil field development, but the problem was that there was no way to know which fields would be successful, and therefore how much money should be spent on monitoring. Determining the minimum amount of data that would be useful in the case of an unsuccessful oil field posed problems.

With the implementation of any new system intended for quieting, the ancillary effects must be assessed. The responsibility for conducting these studies should be done in a partnership with full public transparency between industry, government, and the academic communities. If technologies are being developed to help reduce acoustic footprints of industry, businesses in that industry should contribute financially toward the development of those technologies. However, there should be encouragement in the form of government incentives for industry to participate, or participation should be required as a condition of activity permitting. BOEM hopes to emerge from a Workshop such as this one with a prioritized list of funding needs in order to help fund appropriate studies. Coordination between studies is needed to maximize the efficiency of funding to address bigger issues.

2.2.7 Plenary Session VII: Potential Environmental Impacts

Dr. Bill Streever (BP) presented a short talk on the impacts of quieting technologies on aggregated acoustic sound exposure (**Appendix D, pp. D146-D147**). He described a project aimed to better understand the effects of aggregated sound exposure to the marine environment by modeling the effects of sound on bowhead whales in the Beaufort Sea. In reality, sounds are being generated from all directions and by a multitude of sources—everything from whales, seals, ice breakers, tug boats, production platforms, etc. The summer of 2008 was used as an example to model what types of noise producing activities were present during a busy season. Small supply boats and boats with outboard motors were ignored, and the modeling focused on large seismic arrays, large barges, and ships. The model incorporated the transient nature of some of these sounds while sustaining others through the entire modeling run. Based on the daily environmental and activity parameters, a 3D prediction of the acoustic field was generated for the Beaufort Sea. Virtual whales, with variable sensitivity to sound, were programmed to swim through the acoustic field, with programmed parameters for whale location relative to shore, directional shifts in swimming, and diving frequency, depth, and duration. Every "whale" had a virtual tag that monitored all of the programmed parameters and allowed for downloadable data. Whales were initially programmed with no sound aversion, and subsequently with a low amount of sound aversion at SPL = 160 dB re 1 μPa and increasing aversion up to 180 dB re 1 μPa. It was hypothesized that if a large seismic vessel replaced its airguns with marine vibrators, the upper limit of the SPL on any individual whale would drop due to the decreased level of higher frequencies from the marine vibrators. The conclusion of this preliminary modeling is that the focus of research and mitigation techniques needs to be on reducing chronic exposure to sound rather than addressing acute, short term sound exposure and that MV may be an effective tool for making progress towards this goal.

A follow-up discussion facilitated by Dr. Mark Tasker (Joint Nature Conservation Committee) focused on the potential environmental impacts of seismic activities, pile driving, and support vessel operations. In the context of new quieting technologies, the discussion was based on what regulations should be in place and how they should be implemented. Determining what goals need to be set to prevent impacts, and subsequently how to regulate activities to achieve those goals was outlined as a chief concern. Because the most effective way to regulate activities is often on a case-by-case basis, wide knowledge is needed on how acoustic emissions affect different systems and species. An audience member, Dr. Arthur Popper (University of Maryland), suggested that if the actions needed to protect animals from anthropogenic noise are unknown due to a lack of knowledge about how sound affects those animals, then mitigation work has very little value. However, this view was disputed by Dr. Linda Weilgart (Dalhousie University), who asserted that certain actions, such as reducing unnecessary undersea noise, are undoubtedly advantageous. She argued further that there is good reason to believe that MV is less harmful than airguns, and a longer rise time in seismic sound emission is almost assuredly better than a quicker rise time. The impacts on certain animals are what are driving societal concerns and subsequently regulations. Generally speaking, the public has greater concern for charismatic megafauna such as whales than it has for crustaceans. Because many of the sound-based regulations are based on marine mammals, it is likely that anthropogenic noise will be a major issue in future MMPA and regulatory development.

Setting guidelines for allowable sound emissions based on injury thresholds would likely be an ineffective route of regulation. In most cases, effects on individuals cannot be extrapolated to entire populations unless the population is small enough that a single individual makes up a substantial portion of the entire population. There were two possible options suggested for regulation guidelines for unproven technologies: (1) a company must prove that it will not violate certain requirements such as killing, injuring, or disturbing a certain species, or (2) an arbitrary noise emission threshold can be established by regulators that companies have to obey until there are better data to refute or refine the threshold.

Regulatory agencies should take a more proactive approach when it comes to emerging technologies. For example, allotting a certain area of sea off-limits to airgun use, but allowing use of MV; or setting source-or received-level limits for frequencies above 100 or 200 Hz in areas of high importance to odontocetes, which technologies like MV (but not airguns in their current form) could satisfy. This sort of regulation would incentivize R&D as well as adoption of improved quieting technologies. Regulatory thresholds that would constrain the development of new technologies should be avoided. Although it may not always be clear where to set the regulatory bar, it is agreed upon that as a society we want to have less of an impact than we currently do. If industry develops a new technology, it should be encouraged by the regulatory agencies while research into the effects of sound on marine fauna continues. This approach will allow for new data to improve our understanding of the impacts of sound while encouraging active R&D. If new, potentially more environmentally friendly technologies are immediately regulated more stringently than present technologies, it will discourage industry from pursuing new, more effective technologies.

A second, short discussion at the end of this session talked about risk assessment and its role in preventing environmental impacts. Although cumulative impact assessments are included in Environmental Impact Assessments (EIAs), they are usually qualitative in nature. Rigorous, quantitative risk, cumulative assessments are not usually included in EIAs or Environmental Impact Statements (EISs). It was stated by Mr. John Young (CSA Ocean Sciences Inc.) that some oil companies do conduct risk assessments prior to oil and gas development. Dr. Tim Ragen (Marine Mammal Commission) offered that risk assessments should be conducted from the perspective of marine mammals. Although humans have prohibited much of the hunting that decimated marine mammal populations in the past, many of today's unintentional effects may be just as lethal over time. Problems arise when scientific data are not available to back up current standards of regulation. Areas need to be identified where scientific data can be obtained to help take the guesswork out of risk assessments and drafting of new regulations. Since it is not desirable to impose unnecessary regulations on industry nor is it advantageous to under-protect the environment, risk assessments are a key part of preventing impacts of sound emissions on the marine environment. Emphasis was placed on the fact that risk assessments are a part of the current process of preventing environmental impacts and they are conducted on a regular basis by both industry and government agencies.

2.2.8 Plenary Session VIII: Closing Panel with a View to the Future

The goal of this final session was to review Workshop highlights and lessons learned about current technology, to discuss limitations and gaps in knowledge about marine acoustics, and to identify prospective technologies that may help address some of the current limitations. It was proposed that the final session be focused on two goals: to provide feedback to BOEM regarding what they should be doing to encourage the adoption of quieting technologies, and to discuss the bigger picture of where R&D of quieting technologies should go in the coming years. Each panel member was asked to provide their view of the future. It was emphasized that it was important for everyone in attendance to take home some concrete ideas about knowledge gained or synthesized during the Workshop so new ideas and discussions do not fade after the Workshop's conclusion.

A summary of the panel discussion with regards to the view to the future and providing BOEM with suggestions and challenges for the implementation of new technologies and mitigation measures is provided. A number of new ideas and technologies have been developed in recent years, including MV and vessel and pile driving quieting technologies. There are currently commercially viable quieting technologies for pile driving, vessel noise, and seismic surveys. In addition, there are some technologies that are in the testing stage and not yet ready for wide-scale implementation, as well as some that need further study. Timely testing and implementation of new technologies will be beneficial for offshore industries and the marine environment. Information regarding potential environmental impacts caused by new technologies is needed for many of the emerging quieting devices and should be done on a regional scale if possible, rather than on a project-by-project basis. It was suggested that impact studies should be coordinated with field testing of new technologies to acquire the necessary data to accurately gauge the impacts of untested equipment. This approach will take coordination between agencies and the operators to design a program that would meet needs of both the new technology and the regional application. The design of the studies should also include some controlled effect measurements. This approach would make the assessment of new technologies in the United States consistent with the European approach. In addition, prior to the field testing, participation in a facilitated permitting and authorization process that includes industry, agencies, and discussions with NGOs could alleviate potential litigation.

Another key point was that the existing method for performing risk analysis and impacts determination needs improvement. There has been substantial work done regarding the use of M-weighting that should be updated and utilized for risk analysis and impacts. In addition, as others have done, including the Navy, it was suggested to look at Southall et al. (2007) and additional work regarding taking a severity scaling approach to risk analysis regarding marine mammal hearing and behavioral response approach that incorporates some of the recently collected behavior effects. This would also include the application of severity scaling and use a two-stage process. The first stage uses a take-based metric that quantitatively considers the species' behavioral states; the second stage would factor in the severity aspect into the formal risk analysis.

It was noted that there are a large number of federally funded oceanographic deployments that do not include passive acoustic sensing systems on them; these deployments include oceanographic and weather buoys and physical oceanography sensors on the integrated ocean observing system. This is an important missed opportunity to collect key data that could assist with the collection of ocean data to provide more complete information on current sound levels.

BOEM issued an open call for companies to discuss their needs, concerns, and ideas for streamlining the regulatory process. BOEM recognizes industry concerns regarding full disclosure of developing technologies or proprietary information, but meetings can occur with non-disclosure agreements in place, if necessary. It is extremely important that BOEM have a full understanding and open dialog with industry and technology developers regarding their regulatory concerns and ideas for streamlining or incentivizing the development and testing of new technologies. In addition, it is just as important that industry and developers understand BOEM's requirements and data needs with regards to acoustic impacts from projects. This understanding on both sides could assist in developing a regulatory process that would provide better opportunities for technology testing and obtain data provided by technology developers during that testing that could show a quantitative reduction in noise emissions and impacts of these emerging technologies. If noise mitigation by a new technology was shown, then BOEM could provide incentives to companies that adopt these technologies and the permitting process would be streamlined, or it could set acoustic emission requirements, as Germany did for pile drivers, to accelerate development. It was noted by many that regulatory incentives and requirements are the integral step in promoting use of quieting technologies by the oil and gas industry.

With regards specifically to airgun quieting technologies, the MV is currently the most viable potential option to airguns and of the systems presented. The GeoKinetics system is more mature than others still in design phases, but it still requires additional field testing and quantitative comparison with airguns for performance in seismic assessments. There are a number of alternative MV units that have been or are currently being designed, including four contractors funded by the JIP, which will require proof of concept and field testing. Though widespread implementation of MV may be years away, it is hoped that implementation may occur substantially sooner than the hypothetical 30-year timeframe, particularly with regulatory involvement. It is likely that even if wide-scale implementation of MV occurs, there would be circumstances where airguns are still needed. Modification of airguns to reduce noise emissions in unneeded frequencies should be a focus of research but only used as a stop-gap measure until MV or an equivalent can be widely implemented. However, there are certainly some challenges to widespread implementation of MV including re-training the industry workers in using MV and potentially retrofitting of vessels for both applications since both will still be needed. Regulatory policies and incentives will likely dictate how quickly MV is adopted. Based on the information presented and the additional information obtained regarding MV, the existing EA for MV (LGL and MAI, 2011) should be updated. It was also noted that a regulatory determination regarding the classification of MV noise as an intermittent or continuous sound is necessary.

Oil and gas resources are critical to our society, and the ability to create an accurate subsurface image is critical to recovering oil and gas. Technology has gradually reduced the risks of exploration, e.g., seismic imaging is now used instead of exploratory drilling to discover new oil or to determine the boundary of a reservoir. At the same time, scientific concern about the impacts of seismic activities has grown significantly. A "carrot" approach, along with the "stick" of regulation, was recommended for helping expedite adoption of MV. For example, establish a target or noise budget for industrial operators to aim for, and if they achieve the goal, provide an incentive. These noise budgets could be all-inclusive for an oil and gas project, including pre-drilling seismic operations, installation, support vessel noise, drilling-rig operations, and decommissioning. In addition to the lack of financial incentive and regulation, widespread uncertainty about data quality and cost effectiveness is inhibiting adoption of new technologies by the oil and gas industry. Industry will need assurances that the data collected by alternative technologies, such as MV, will provide them with the same level of data quality and confidence as the existing technology. This aspect may be one of the biggest challenges with industry implementation of MV because risk reduction as well as cost effectiveness are key to the decision making process.

There are viable options available for quieting pile driving in different applications or conditions; however, most of these methods are not very cost effective and thus not truly viable working solutions. In order for industry to utilize new technologies, they must be very reliable and not cause unaffordable delay in the construction process. Additional R&D is needed to create truly cost effective pile driving solutions.

One cautionary note was that it would not be prudent to adopt a new technology that may reduce an impact on one species or species group but increase impacts on another. This trade-off needs to be evaluated from the environmental data and during the impact determination of the new technologies.

The point was made that some marine mammals and some fish appear to at least attempt to adapt to noise within their hearing ranges—either by calling louder or by changing frequencies—and that it is inappropriate to only consider anthropogenic noise as a problem due to masking of communication signals. Thus, hearing should also be thought of as a way for organisms to investigate the surrounding environment. Hearing evolved as a way to investigate an acoustic soundscape, not just to communicate, and if we disrupt hearing sensory abilities, we are disrupting far more than just communication. Masking was identified as a potential concern with regards to MV; however, MV uses a much narrower frequency band than seismic, and accordingly the sounds that would be masked would be limited to those within that narrower band. With this, the issue of duty cycle could arguably be made to say that within this band the masking potential for MV would be greater than for more intermittent seismic survey sources such as airguns. However, when the lower overall peak pressures of MV and the reverberation over large areas from seismic airguns at low frequencies are taken into account, this masking from MV may not actually be worse than from airguns.

Specific pieces of advice or ideas that might help continue the flow of information and ideas after the conclusion of the Workshop were presented and included the following: BOEM could set up a depository for new information and reports so that they would be more easily located by experts in the scientific field as well as those involved in industry and the NGO community. Establishing a presence in social media, such as blogs that advertise the creation and/or updating of open data depositories with all available datasets, would be useful to keep in contact with other experts and have easy access to data. The compilation of contact list of names, information, and areas of expertise to assist in idea sharing after the conclusion of the Workshop and the continued efforts to streamline and improve the quality of data from protected species observers will help make these this data usable. It was noted that the data from protected species observers have a lot of potential, but the efforts to synthesize and make the data more user-friendly are needed before they are made available.

Perhaps the most challenging problem preventing the continued research, development, and implementation of quieting technologies is not the lack of scientific data but a lack of integration of technology development that recognizes stakeholder needs. For example, there should be no “either-or” war with airguns and MV, but a productive conversation about what can be done to minimize environmental impacts using the technologies available. Interaction and cooperation between industry, academia, NGOs, and private firms are important in achieving successful problem solving and ultimately successful development in the marine environment while protecting sound sensitive organisms.

BOEM recognizes that quieting technologies is a growing industry and is providing additional staff to address the concerns despite budget cuts. Participants in the Workshop encouraged BOEM to focus resources on this issue, and it was suggested that a mechanism to generate the best possible data was for BOEM to provide regulatory guidance both to environmental groups as well as the oil and gas industry.

3. GAP ANALYSIS

The goal of the Gap Analysis is to identify gaps in the current information presented in the Information Synthesis (**Appendix A**) and the information presented and discussed at the Workshop. The Gap Analysis also identifies potential areas of research, establishment of standards, and questions that need to be answered to better understand what may be done to reduce noise during seismic surveying and pile driving and the associated vessel noise. Identification of these knowledge gaps is not intended to suggest that development, implementation, incentivizing, or regulation of new technologies should not continue until all data gaps are answered.

3.1 Information Gaps Identified During Information Review and Workshop Discussions

Some information gaps were identified during the information review and Workshop discussions that applied to all three topic areas and thus are presented as general needs. Also, some of these gaps are presented as studies that need to be undertaken, while others call for the establishment of guidelines/standards or the evaluation of the current approach to noise quieting. In addition to the general gaps identified, additional gaps were identified that were unique for each topic area.

General

- Need to develop and implement consistent acoustic terminology and noise measurement methods/standards so that direct, quantitative comparisons can be made. Initiatives in Europe to examine this issue and work towards development of standards include the creation of an ad-hoc working group that reported in 2011 (Ainslie, 2011). The ad-hoc report has been adopted by EU’s expert advisory group “TSG Noise,” chaired by Mark Tasker and René Dekeling, and by the Draft Science Plan of the International Quiet Ocean Experiment (Boyd et al., 2012). There is an urgent need for further consolidation, for example in the form of an international standard.
- Need to determine what property of the “source” needs to be reduced in order to best achieve quieting.
- Need to establish a definition for the “Best Available Technology” requirement for seismic surveys, pile driving, and vessel noise.
- A better understanding of the potential environmental impacts of the new technologies is required, with special attention as to whether the technology is simply trading one set of impacts for another.
- Positive incentives for development and testing of new technologies need to be developed by regulatory agencies. Regulatory requirements, such as establishing propagation standards that industry would have to meet by some time period, should also be considered.
- Need regulatory agencies to consider and utilize the fact that a number of industry sound sources decrease quickly with distance below ambient levels (e.g., the 120 dB re 1 μPa SPL contour from a typical jack-up rig is very small). Determining which other industry sources exhibit this property of rapid attenuation with distance needs clarification.
- Need to examine the relevant contribution of noise from the three topic sources in comparison to the relative contributions made by other aspects of the energy industry and other industries should be evaluated.

- Need to consider the influence of local ship noise on the use of PAM systems, especially SNR based systems. The efficacy and capability of mitigation systems associated with each of the sound source topics needs to be examined.
- Need all the agencies (i.e., BOEM, BSEE, NOAA, and the MMC) to continue to focus on ways to reduce acoustic impacts in the marine environment; however, by focusing primarily on the noise issue, the regulatory process becomes extremely conservative and may result in decisions that are not desirable to all parties (e.g., agencies, operators, industry). There is a need to examine the broader picture such as:
  - Examining these issues under the actual variety of spatial, temporal, and spectral scenarios is critical. This will allow the most efficient and clearest method of eliciting potential quieting gains, as they may fall into any combination of these three "quieting filters;"
  - Developing standards/goals for reductions in sound levels and establishing a more streamlined permitting process for those that meet those goals/standards;
  - Continuing to develop baseline information which will provide data for more informed decisions;
  - Examining cumulative sound studies in the marine environment;
  - Establishing how to determine when we have been successful in reducing the environmental effects of greatest concern from noise in the marine environment and how to monitor these effects; and
  - Determining the most suitable acoustical metric for quantifying effects.

Airguns

Airguns contribute a significant source of noise into the marine environment, and scientific concern about the impacts of airgun surveys on marine mammal populations has increased significantly over the last decade. Airguns are a well-understood and reliable technology for identifying oil and gas deposits. Furthermore, the ever-increasing computing power for seismic data analysis allows for extremely accurate drilling operations, thereby saving time, money, and environmental impacts by avoiding excessive drilling activities. As with any new technology, significant testing, data analysis and comparison with airgun results, and proof of testing will be required before MV technology is accepted by the industry as a replacement. The primary information gaps identified for improving (quieting) or replacing airgun technology include the following:

- Additional development, comparative (with airguns) testing, and evaluation of MV is needed, as MV is one of the most promising alternative technologies.
- Provide additional research on MV to clearly define the capabilities and how and where it can be utilized. The EA prepared for MV (LGL and MAI, 2011) indicated that it would not replace airguns entirely but would be used for specific applications.
- Monitor the development of the E-source airgun (which is undergoing the patenting process; the current status is proprietary). Based on preliminary information, this technology could significantly reduce unwanted high frequency noise levels.
- Compare the relative environmental impacts of MV and airgun arrays as a priority.
- Support by BOEM is needed for the use of alternate technologies such as MV by providing incentives for their use. There is ongoing R&D and testing by industry (e.g., Geokinetics, JIP, etc.) that will require these incentives for successful alternate technology development and implementation.
- Additional funding and support for MV prototypes is needed because some MV unit developers were unable or unwilling to participate in the JIP but may have viable technologies that nonetheless should be pursued.
- Establish incentives and requirements for the development and use of alternative methods. These incentives and requirements could include shorter, less costly permitting; fewer or less expensive

monitoring requirements; restrictions on use of airguns in sensitive areas; or requirements or targets (which allow some delay in attainment) that industry achieve a particular noise propagation standard within certain frequencies, as has been done in Germany for pile driving; less restrictions with regards to exclusion areas and seasonal restrictions; or given priority approval over airgun surveys.
- Continue to evaluate and determine if airgun "ramp up" is effective.

Pile Driving

There are a number of different methods to potentially reduce noise from pile driving activities, including noise dampening with different devices such as various bubble technologies, cofferdams, and other noise mitigation methods; alternative installation methods including vibratory, press-in, cast-in-place, and alternative pile materials and shapes; and low-noise foundations including gravity base, suction-based, drilled, and floating. All of these methods have applicability in various scenarios and site conditions. However, criteria or limits for noise levels need to be established in order to encourage industry to use mitigation measures or examine alternatives. For example, Germany is developing a limit for noise produced by pile driving, which has helped to spur quieter alternatives there. The United States may want to examine a similar approach.

The primary information gaps identified for quieting pile driving technology include the following:

- Establish a set of noise quieting protocols that contractors can implement so that construction can still proceed during times when there are uncertainties; gain endorsement from stakeholders.
- Establish a forum for an open dialogue between engineers, physicists, and pile driving companies because these industry elements are working to improve the same issue but are approaching the problem from different angles. Therefore, close collaboration between the groups would likely allow the targets to be reached more efficiently and comprehensively.
- Establish field testing protocols and actual testing should be a high priority because the majority of the quieting technologies for pile driving have received insufficient field testing to be able to fully identify the system and site-specific requirements for operation of the technologies and any limitations in their use.
- Establish standard field test sites to advance these technologies and data sharing located around the world that represent comparable and standardized ranges, sediments, depths, etc. These sites could also help organize the practicality and logistics of sound abatement testing around pile driving activity.
- Establish preliminary regulatory criteria that can stimulate mitigation development and implementation. Additionally, this will put pressure on the industry to meet the criteria. Development of preliminary criteria will result in some noise reduction while verifying and modifying the criteria in order to attain further noise reduction.
- Establishment of a JIP with all stakeholders (e.g., contractors, regulators, scientists, academia, NGOs, etc.) would be beneficial in order to expedite the mobilization of teams when an opportunity arises to do a field test in conjunction with pile driving activities.
- Establishment of incentives that would diminish the requirements for sound attenuation during times of low environmental sensitivity should be considered.
- Establish a system that provides credits towards selection during the design-build bid evaluation for designs that integrate quieting technology (i.e., instead of “green” credits, “quiet” credits).
- Provide additional R&D funding for promising new technologies (e.g., static bubble curtains).
- Perform additional research on structural modifications of piles themselves to reduce noise radiation.

- Improved numerical models to understand the noise generation mechanisms of pile driving and the modeling of pile/bottom interaction, which is crucial for estimating the limits of mitigation solely in the water column, are needed.
- Develop a method to examine all noise variables to uniformly determine the noise levels, impacts, and mitigation methods because too much emphasis is placed only on the variable of received sound and not all of the variables, including length of exposure, unwanted frequencies, high duty cycle, and general activity level.
- Develop a "best practices" strategy for typical site scenarios in concert with industry. This would provide a risk reduction template for agencies to endorse.
- Establish appropriate and well-defined metrics for monitoring and measuring each signal type. In addition, metrics for near-field are lacking (monitoring, discussion), and likely need to be different than those used for far-field.
- Further develop double-walled piles, which would eliminate noise entering the substrate. These piles would have an outer wall, which is the structural pile that would act as the shield, while inside would be a mandrel that would take the driving impacts. The two parts would have an air gap between and be tethered together such that when the mandrel was struck it would pull the shield along into the sediment. A prototype of this design has been field tested and found to be promising.

Support Vessel Noise

Although shipping noise in general has been included in the topic of ambient noise in the marine environment for a period of time, support vessel noise is a relatively new addition to this topic. The topic of support vessel noise is a complex one since typically vessels used for support activities for seismic surveys and pile driving are often older vessels that have been replaced in their previous application by newer vessels. The ability to quiet older vessels can be more challenging. There are two approaches to quieting vessels: mitigating noise sources and mitigating noise paths. Quieter components are available for use in shipbuilding and design but are typically more expensive for retrofits and not selected unless required. Since typically support vessels are older, quieting maintenance options may be more practical than installing quieting retrofits. Minimizing noise transmission (paths) may be a more economical and more feasible option than controlling source levels, especially with support vessels.

The primary information gaps identified for quieting support vessels include the following:

- Determine what portion of the overall contribution to ambient noise is attributed to support vessels to determine if ship noise is really a significant issue. If it is determined to be a significant issue, then reducing noise from support vessels should be a priority, specifically if the sound radiated from support vessels has the potential to cause significant chronic effects.
- Develop a database of sound source levels for different types of vessels with different propulsion plants using a standard for source level measurements in consistent units. This database should contain data for different vessels at different speeds and vessel operations and emphasize cavitation noise under bollard pull conditions and diesel engine noise. This would provide a better understanding of the design features and operational conditions that contribute the most to noise at different frequencies.
- Develop an agency-endorsed, biologically relevant noise limit for vessels, which could establish a more effective target for engineers to work towards.
- Develop methods for vessels to monitor their own noise in real-time could be a good starting point for establishment of noise limits and the database. Development of these methods and establishment of noise limits could allow vessel operators to modify operations to become quieter (e.g., how DP is used).

- Require each vessel to have a noise value quantified by an independent outside body similar to truck weigh stations (e.g., US Coast Guard during inspections); provide mitigative options and incentives to the vessel owners.
- Determine what designs work best to reduce noise at the ship building stage and pursue the least expensive modifications that yield the most decibel reduction per dollar for long-term reductions. These could also result in fuel savings or increased reliability.
- Perform R&D on quieter propellers, DP systems, and overall vessel and shipboard equipment design, and optimization of operations that would be specifically applicable to the support vessels and the kinds of conditions they operate under.
- Perform case studies regarding different vessel classes to determine which designs within each class are the quietest and use this information to guide subsequent designs and retrofitting.
- Focus on identifying and quieting the noisiest vessels.
- Research design options for quiet propulsion under bollard pull conditions, preferable both in full and model scale.
- When recording noise from passing ships it is imperative to collect the parameters of the noise source (e.g., vessel size, speed, load size) because without these parameters, data are not interpretable; noise levels alone will not produce usable data.
- Develop incentives to quiet vessels.

3.2 Priorities Derived from the Gap Analysis

Based on all the information gaps identified above, the following were identified as the priorities to facilitate the advancement of the noise quieting for the three topic areas.

- Develop and implement consistent acoustic terminology and noise measurement methods/standards so that direct, quantitative comparisons can be made. In Europe, an ad-hoc working group was formed to examine this issue, whose work is now being used by the ISO Underwater Acoustical Terminology Working Group. Their progress should be monitored and their findings potentially emulated.
- Determine source properties that need to be reduced in order to achieve quieting.
- Compare the relative environmental impacts of MV and airgun arrays, as a priority.
- Provide additional research on MV to clearly define the capabilities and how and where it can be utilized. The EA prepared for MV (LGL and MAI, 2011) indicated that MV would not replace airguns entirely but would be used for specific applications.
- A better understanding of the potential environmental impacts of the new technologies is required, with special attention as to whether the technology is simply trading one set of impacts for another. However, if a new, potentially more environmentally friendly technology is developed, it should be encouraged by the regulatory agencies while research into the effects of sound on marine fauna continues.
- It is critical to examine noise issues under the actual scenarios which include spatial, temporal, and spectral context. This will allow the most efficient and clearest method of eliciting potential quieting gains, as they may fall into any combination of these three "quieting filters."
- Develop standards/goals for reductions in sound levels and establishment of a more streamlined permitting process for those that meet those goals/standards, and identification of environmentally sensitive habitat (e.g., important odontocete habitat that would benefit from reduced acoustic output above 100 or 200 Hz) in which activities would be allowed only if those goals/standards are met.
- Continue development of baseline information that will provide data for more informed decisions.
- Examine cumulative sound studies in the marine environment.

- Work with industry and other stakeholders to develop a "best practices" strategy for typical site scenarios. This would provide a risk reduction template for agencies to endorse.
- Advance pile driving technologies to include establishment of standard field test sites located around the world that represent comparable and standardized ranges, sediments, depths, etc. These sites could also help organize the practicality and logistics of sound abatement testing around pile driving activity.
- Establish preliminary interim regulatory criteria to stimulate mitigation development and implementation. In addition, this will put pressure on the industry to meet the criteria. Development of preliminary interim criteria will result in some noise reduction while verifying and modifying the criteria in order to attain further noise reduction for seismic surveying, pile driving, and vessel sources.
- Determine the overall contribution to ambient noise is attributed to support vessels to determine if ship noise from these vessels is a significant issue. If it is determined to be a significant issue, then reducing noise from support vessels should be a priority, specifically if the sound radiated from support vessels has the potential to cause significant chronic effects.
- Develop a database of sound source levels for different types of vessels with different propulsion plants using a standard for source level measurements in consistent units. This database should contain data for different vessels at different speeds and vessel operations and emphasize cavitation noise under bollard pull conditions and diesel engine noise. This would provide a better understand of the design features and operational conditions that most contribute to noise at different frequencies.
- Develop an agency-endorsed, biologically relevant noise limit for vessels, which could establish a more effective target for engineers to work towards.
- Focus on quieting the noisiest vessels.
- Examine the relevant contribution of noise from the three topic sources in comparison to the relative contributions made by other aspects of the energy industry and other industries should be evaluated.

4. SUMMARY OF HIGHLIGHTS OF THE WORKSHOP

There were a wide variety of highlights identified during the Workshop, some that applied generally to the field of sound in the marine environment and others that were very specific to one topic area. One of the key issues discussed repeatedly was the lack of consistent acoustic terminology and noise measurement methods/standards for all three topic areas so that data comparisons can be made. Without this consistency, determining what technologies or mitigation measures actually provide useful quieting will be extremely difficult since comparisons need to be made with consistent data. It is important that measurements include directional and temporal components so that the source (i.e., shipping, environmental, meteorological, etc.) of the noise can be determined.

Examining these issues under the actual variety of spatial, temporal, and spectral scenarios is critical. This will allow the most efficient and clearest method of eliciting potential quieting gains, as they may fall into any combination of these three "quieting filters." As a result of a more comprehensive evaluation of noise, the question of chronic noise effects could be determined; there is some indication that this could be more problematic than transitory noise and should be studied further. Currently, for seismic exploration, pile driving, and vessel noise, behavioral, masking, and cumulative effects seem the primary concern rather than the acute physical effects. In addition, there is still too much emphasis on the only variable being received SPL and not all of the other attendant factors such as length of exposure, rise time, unwanted frequencies, high duty cycle, and general activity level.

A significant theme throughout the Workshop was the need for different regulatory agencies as well as industry, developers, and NGOs to work together. Understanding how and when to promote the use of new technologies and to have developers present their ideas/technologies in more detail in a confidential setting will provide a means to inform the agencies so they can best understand the available information (or lack thereof). This will encourage agency/industry collaboration for identifying ways to conduct environmental monitoring and field testing specific to their particular technology. However, the agencies should strive for public transparency within these constraints. In addition, the agencies can guide the developers through the regulatory process and develop timelines for the permitting process that informs investment choices for industry.

What regulations should be in place and how they should be implemented is a challenge. Comprehensive biological impact information remains elusive. Determining what goals need to be set to prevent impacts, and subsequently how to regulate activities to achieve those goals, was outlined as a chief concern. Specific information is needed on how acoustic emissions affect different systems and species. It was expressed by many that if industry develops a new technology, it should be encouraged by the regulatory agencies while research into the effects of sound on marine fauna continues. This approach will allow for new data to improve our understanding of the impacts of sound while encouraging active R&D. If new technologies with potential environmental benefits are immediately regulated, it will discourage industry from pursuing new, more effective technologies. In either scenario, the risk of investment remains with industry. However, there were two possible options suggested for regulation guidelines for unproven technologies: (1) a company must prove that it will not violate certain requirements such as killing, injuring, or disturbing a certain species, or (2) an informed but temporary noise emission threshold can be established by regulators that companies have to obey until there is better, published information to refute or refine the threshold. Such coordination would allow informed decisions to be made with regards to the best approach to regulation and would provide incentives for further development of technologies.

There is also a need to obtain background noise levels prior to pile driving activities or seismic surveys. This sort of data collection would be more effective in a collaborative framework where data are shared and made publicly available instead of performing case-by-case studies.

The R&D that is being done is indicating that it is better in the long run to choose a technology that avoids generating noise than to try to reduce noise levels. In addition, better planning of surveys, activities, and vessel use to avoid impacts should be used more often as a mitigation tool.

Industry may be hesitant to utilize quieting technologies until the value of these technologies is better understood from operational, data quality, cost effectiveness, and environmental protection standpoints. Regulatory requirements and/or other incentives may be needed to implement and encourage use of any developed quieting technologies. Incentives might include proof that it is more cost effective and/or efficient; requirement by regulations; lifting some restrictions on activities; or requirements that industry achieve a particular standard for acoustic emissions within certain frequencies, as has been done in Germany for pile driving. Other incentives may include a more streamlined regulatory process, noise propagation standards that would apply at least in certain sensitive areas, or fewer restrictions on activities, their timing, and/or location. The Programmatic EISs now in process for the Atlantic, Arctic, and Gulf of Mexico may be effective vehicles for establishing such incentives or requirements.

4.1 AIRGUNS

The topic of airgun alternatives received a great deal of attention. The primary highlight is that MV is the most promising alternative for airguns in select settings and applications (i.e., shallow water, sensitive habitat, near biological resources). The extent to which MV will be able to replace airguns remains unclear, though it is first likely to become available for use in transition zone and relatively shallow water environments. Although there are a number of different types of MV units under development, including four that are funded by the JIP, the Geokinetics marine vibrator is the one closest to being ready for commercial use. For the most part, other alternative impulse sources are currently experimental. Information collected to date indicates that MV is less environmentally damaging than airguns, but further evaluation is needed to accurately evaluate the impacts and determine if there are tradeoffs in the types of impacts among the different technologies. Special attention needs to be given to potential unintended consequences of the control of phase spectrum of MV, which allows for the proliferation of a number of sources being fired at the same time over a large area. This approach effectively increases the size of the area impacted, and a PRN sweep of MV in this configuration may result in marine mammal masking effects at higher frequencies than currently employed, with unknown consequences.

Regulatory incentives in the form of increased opportunity, easier permitting, and more streamlined mitigation measures would help further development and testing of MV, which in turn can inform an adaptive management regulatory approach. An example might be designating a certain area of sea off-limits to airgun use but allowing use of MV. This sort of regulation would incentivize R&D and adoption of improved quieting technologies. Another option would be to establish preliminary regulatory criteria to stimulate development and implementation. Another key point was that the worldwide fleet that performs seismic surveys is currently outfitted and has crew trained for airguns; making a transition and augmenting vessels and crew to MV potentially will be an economic challenge for some operators, depending in part on the adaptability of the MV units to existing infrastructure.

4.2 PILE DRIVING

The primary highlights associated with pile driving are that there are a number of alternatives to pile driving (e.g., drilling, vibratory, gravity base, floating, suction buckets), mitigation measures for quieting including source attenuation (e.g., bubble curtains, cofferdams, hydro sound dampers), and new pile designs (e.g., double-walled pile, lower radial expansion pile). However, there is no single solution evident with regard to through-ground transmission of sound and other very site-specific issues such as water depth, currents, and substrate type. Whatever method or combination of methods is used, the key issue is that the technology must be very reliable and not cause unaffordable delays in the construction process. The development and adoption of a "best practice" strategy by industry and regulators to guide typical site scenarios would be helpful as this would form the basis of a risk reduction template (both in terms of environmental risk and financial risk in technique development). It was also suggested that measurements of the performance of quieting technologies should, if possible, be standardized and taken at distances at least three times the water depth from the pile.

4.3 SUPPORT VESSEL NOISE

Interestingly, at first, a number of Workshop participants and panel members were not completely clear why support vessel noise was also being examined as part of this Workshop. However, upon further consideration it became clear that due to its ubiquitous and chronic nature, it should be placed near the top of the priority list for impact assessment. It is likely that vessel noise makes the greatest contribution of all anthropogenic sources to ambient underwater noise. Noise is expected to vary significantly among the many support vessel configurations, and systematic assessment across these configurations under their various tasks will be needed to adequately inform quieting strategies. There are four primary sources of vessel noise: propeller cavitation, machinery noise, sea-connected systems, and hydrodynamic noise. Because most support vessels are repurposed older vessels, retrofits and ship husbandry/maintenance are typically the means available to reduce noise. Many of the retrofitting solutions are expensive, as ship design always involves tradeoffs and support vessels need to serve multiple purposes. Accomplishing quieting for these vessels is therefore not straightforward. Because there are currently no regulatory guidelines or requirements for vessel noise, work being done in regards to quieting is largely experimental. Instead, human habitability issues aboard ships provide the main incentive for quieting, noting that diesel generators and thrusters are often arranged near crew living spaces. Nonetheless, these reductions in onboard noise will generally result in decreased noise emitted into the ocean, despite their not being the driver for quieting. Minimizing noise transmission (paths) may be a more economical and more feasible option than controlling source levels, especially with support vessels. Finally, support vessel noise is likely dominated by DP propulsion because activities in offshore fields rely on DP; mitigation for DP should be investigated.

5. CONCLUSIONS

By focusing mainly on the "technologies", Workshop participants examined and discussed the methods and design of equipment meant to lower sound output. Meaningful discussions focused on providing engineering solutions and, to a lesser degree, operational strategies to mitigate underwater noise generation that can help create a quieter ocean. The Workshop format successfully facilitated interactive listening to allow for information sharing across disciplines and areas of expertise.

The Information Synthesis and Workshop illustrated that there are a number of promising new technologies and mitigation measures for quieting noise from airguns, pile driving, and support vessels. MV was identified as the primary viable alternative to airguns, with several prototypes under development through a JIP and by individual companies and designers, with at least one close to field testing for commercial use. For pile driving, a number of noise reduction and attenuation technologies are already commercially available, including alternatives to pile driving (e.g., drilling, vibratory, gravity base, floating), mitigation measures for quieting (e.g., bubble curtains, cofferdams, noodle nets), and new pile designs (e.g., double-walled pile, lower radial expansion pile), and research and development is continuing. As there is no one-fits-all solution especially with regard to sound transmission through bottom sediments and other very site-specific issues like water depth, currents, and substrate type, projects may require their own analysis to determine the most effective and suitable noise reduction method. With regards to vessel noise, many of the quiet ship design solutions are expensive, as support vessels are usually older stock and would require retrofitting; however, techniques like speed reduction and regular maintenance can significantly reduce radiated noise without requiring retrofits. Since there are currently no guidelines or requirements for vessel noise, there is not extensive R&D work being done in regards to quieting.

There are many data gaps, and more information is needed to improve decisions regarding what methods can be used effectively and what benefits will be realized. There is much work that still needs to be done in order to have a common ground for determining noise levels, what defines noise reductions, the establishment of standards or guidelines to assist the continued development of methodologies, and a better understanding of the noise in the marine environment. One of the principal issues was the development and implementation of consistent acoustic terminology and noise measurement methods/standards for all three topic areas so that data comparisons can be made. This is a key need so that all data can be compared and informed decisions can be made utilizing uniform data.

Regulatory requirements and/or other incentives may be needed to encourage use of any developed quieting technologies. As with any technology change, there must be a very good reason to make changes to proven systems and methods. Reasons to implement new technologies can include proof that it is more cost effective and/or efficient or that it provides fewer restrictions to activities. A continued dialog between industry and BOEM would be beneficial to help identify appropriate incentives that could include a more streamlined regulatory process or fewer restrictions on activity timing or location.

Additional research funding is needed to continue the development of technologies, standards, and guidelines and further the understanding of noise in the marine environment. One suggestion to address research funding was that a fund could be established similar to the Canadian Environmental Studies Research Fund (ESRF) (http://www.esrfunds.org/abopro_e.php) where ocean users pay into the fund based on their use of the resources.

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APPENDICES

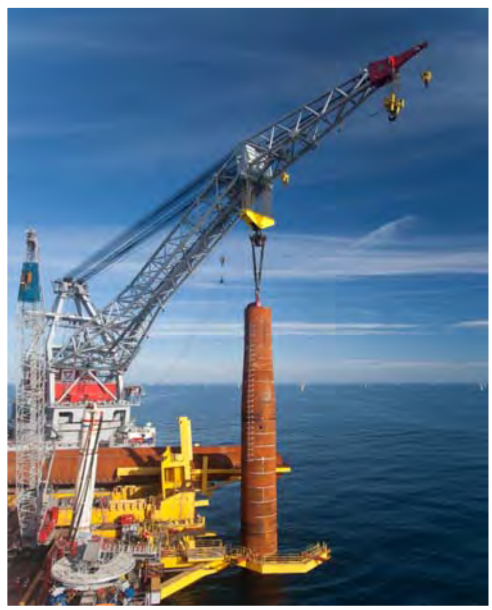
APPENDIX A

INFORMATION SYNTHESIS (UPDATED)

QUIETING TECHNOLOGIES FOR REDUCING NOISE DURING SEISMIC SURVEYING AND PILE DRIVING

INFORMATION SYNTHESIS

February 4, 2013



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ACRONYMS AND ABBREVIATIONS

µPa	micropascal
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
ASFA	Aquatic Sciences and Fisheries Abstracts
BOEM	Bureau of Ocean Energy Management
CRP	controllable reversible pitch (propellers)
CSA	CSA Ocean Sciences Inc.
CSEM	controlled source electromagnetic
dB	decibel
DP	dynamic positioning
DLI	daylight imaging
DTAGS	deep-towed acoustics/geophysical system
EC	European Commission
EM	electromagnetic
EU	European Union
ft	feet
HP	horsepower
Hz	hertz
IMO	International Maritime Organization
in.	inch
ISO	International Organization for Standardization
IVI	Industrial Vehicles International, Inc.
kg	kilogram
kHz	kilohertz
km	kilometer
kts	knots
LACS	low-frequency acoustic source
LGL	LGL Limited Environmental Research Associates
LISA	low-impact seismic array
m	meter
m^3	cubic meter
MAI	Marine Acoustics Inc.
MEPC	Marine Environment Protection Committee
MSFD	Marine Strategy Framework Directive
MT	magnetotelluric
MV	marine vibroseis
nmi	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NTIS	National Technical Information Service
OCS	Outer Continental Shelf
OGP	International Association of Oil and Gas Producers
PGS	Petroleum Geo-Services
PRN	pseudo random noise
psi	pounds per square inch
RMS	root-mean-square
RPM	revolutions per minute
SEL	sound exposure level
SPL	sound pressure level
TSG	Technical Subgroup
TWT	two-way travel time
USDOI	United States Department of the Interior

1. INTRODUCTION

The Bureau of Ocean Energy Management (BOEM) is planning a Workshop on "Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving." The Workshop is being organized by CSA Ocean Sciences Inc. (CSA) on behalf of BOEM. The goals of the Workshop include the following:

- Review and evaluate recent developments (existing, emerging, and potential) in quieting technologies for:
  - Seismic surveying, whether proposed or in development,
  - Pile driving during offshore renewable energy activities, and
  - Vessel noise associated with Outer Continental Shelf (OCS) energy development activities;
- Identify the system and site specific requirements for operation of these new technologies and limitations in their use;
- Evaluate data quality and cost-effectiveness of these technologies as compared to that from existing marine acoustic technologies;
- Identify the spatial, spectral, and temporal features of the acoustic characteristics of new technologies in varying environments compared to that from existing technologies;
- Examine potential changes in environmental impacts from these technologies in comparison with existing technologies;
- Identify which technologies, if any, provide the most promise for full or partial replacement of conventional technologies and specify the conditions that might warrant their use (e.g., specific limitations to water depth, use in Marine Protected Areas, etc.); and
- Identify next steps, if appropriate, for the further development of these technologies, including potential incentives for field testing.

This Information Synthesis Report was prepared by the CSA Team as a resource for Workshop participants. After the Workshop, it will be updated and incorporated into the Final Report for this project.

The synthesis focuses on three main topics: 1) alternative technologies for conducting seismic surveys for offshore energy resources; 2) quieting technologies for pile driving operations; and 3) quieting technologies for support vessel noise. The literature review focuses mainly on publications issued within the last 10 years and includes technologies that have been proposed, developed, investigated, or are currently in development for use in waters from the coast to 200 nmi offshore.

For acoustic terminology, this report adopts the "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units, TNO-DV 2011 C235" (Ainslie, 2011).

2. LITERATURE SEARCH METHODS

An online literature search was conducted to identify published literature, technical reports, and other relevant sources. The search included peer-reviewed publications and gray literature as well as information from websites, discussions with the Scientific/Technical Review Panel, literature provided by the Facilitators, and other information that CSA is aware of regarding ongoing developments.

Literature searches of the following online databases were run using Dialog™ (www.dialog.com):

- ASFA (Aquatic Sciences and Fisheries Abstracts) [44]
- BIOSIS Previews® (1926-present) [5]
- Ei Compendex® [8]
- FLUIDEX [96]
- GEOBASE™ [292]
- GeORef [89]
- Inside Conferences [65]
- Meteorological and Geoastrophysical Abstracts [29]
- NTIS - National Technical Information Service [6]
- Oceanic Abstracts [28]
- TULSA™ (Petroleum Abstracts) [87]

The following four sets of search terms were run in each of the databases and limited to the years 2002 to 2012. These search terms were also used in Internet searches using the Google and Bing search engines. In the following lists, "?" indicates that the term is to be truncated, "()" indicates that the terms must be adjacent, and "(s)" indicates that the terms must appear in the same sentence.

- (Noise? OR acoustic? OR sound?) AND (seismic OR air()gun? OR airgun? OR pile()driv? OR ship OR ships OR barge? OR vessel?) AND (marine OR offshore OR under()(water OR sea) OR underwater OR undersea OR seafloor OR ocean? OR aquatic?) AND (mitigat? OR reduc? OR quiet? OR minimi? OR technolog? OR silenc?)
- Bubble()(curtain? OR screen?) OR cofferdam? OR coffer()dam? OR vibratory(s)hammer? OR propeller?(s)cavitat?
- Low()frequency()acoustic()source? OR LACS OR marine(s)vibrator?
- Vibroseis AND (noise? OR sound? OR acoustic?)

Additional publications were identified by reviewing the papers and reports collected during the online search and by searching online for additional papers citing the ones already collected.

3. AIRGUN NOISE

One of the most common uses of seismic data is for the exploration, development, and production of oil and gas reserves to map potential and known hydrocarbon-bearing formations and the geologic structures that surround them. Most commercial seismic surveying is conducted for this purpose. Airguns are the most common seismic source used in oil and gas exploration surveys worldwide (International Association of Oil and Gas Producers [OGP], 2011).

An airgun is a pneumatic sound source that creates predominantly low-frequency acoustic impulses by generating bubbles of compressed air in water (OGP, 2011). The rapid release of highly-compressed air (typically at pressures of 2,000 or 2,500 psi) from the airgun chamber creates an oscillating air bubble in the water. The expansion and oscillation of this air bubble generates a strongly peaked, high-amplitude acoustic impulse that is useful for seismic profiling. Marine seismic surveys using airgun sources are capable of producing high-resolution, three-dimensional (3D) images of geological stratification penetrating down to hundreds of kilometers into the seafloor and have, thus, become an essential tool for petroleum exploration as well as for geophysicists studying the Earth's crust.

The use of airguns for seismic exploration cannot be considered in isolation because use of seismic surveys is just one of a variety of geological and geophysical techniques used by the petroleum industry to characterize the shallow and deep structure of the shelf, slope, and deepwater ocean environments. The selection of a specific technique is driven by data needs and the target of interest. Other methods include electromagnetic (EM) surveys, low-frequency passive seismic surveys, gravity and gravity gradiometry surveys, aeromagnetic surveys, deep stratigraphic and shallow test drilling, and geological and geotechnical bottom sampling. A recent Programmatic Environmental Impact Statement for the U.S.Atlantic OCS summarizes many of these techniques (U.S. Department of the Interior [USDOI], BOEM, 2012).

The use of airguns for seismic exploration has been under scrutiny for decades due to the potential for acoustic impacts on marine life (Malme et al., 1983; Turnpenny and Nedwell, 1994; Richardson et al., 1995; Goold, 1996; McCauley et al., 2000; Madsen et al., 2002; Gordon et al., 2004; Clark and Gagnon, 2006; Clark et al., 2009; Di Iorio and Clark, 2010; Ellison et al., 2011; Gedamke et al., 2011; Ellison and Frankel, 2012; Risch et al., 2012, Halvorsen et al., 2012). The transmission of low-frequency pulses into the marine environment has the potential for auditory and behavioral impacts on marine mammals, fishes, and other marine life. Baleen whales are of particular concern because they are low-frequency specialists (Southall et al., 2007) whose likely frequencies of highest hearing sensitivity overlap with the most intense frequencies produced by seismic arrays. In addition, because there is little control over spectral properties, airguns emit "wasted" sound at frequencies above 100 Hz (typically not used by geophysicists) that appears to affect other cetaceans (Goold and Fish, 1998; Stone and Tasker, 2006). Also, although airgun pulses are directed downward, lateral propagation can be extensive; Nieukirk et al. (2012) detected airgun pulses along the Mid-Atlantic Ridge at distances of 4,000 km from the seismic survey vessels. Finally, although most of the concern has focused on near-field impacts and mitigation, at greater distances the original airgun pulses may be "stretched" due to multipath propagation, resulting in an increase in background noise level (Guerra et al., 2011; Roth et al., 2012).

One of the objectives of this project is to "review and examine recent developments (existing, emerging, and potential) in alternative acoustic technologies for seismic surveying (other than traditional airgun use), whether proposed or in development." To address this objective, this summary is divided into three subsections:

- Alternative acoustic sources having the potential to replace airguns for some surveys;
- Complementary technologies that may reduce the need for seismic surveys; and
- Methods to reduce unwanted or unused noise from airguns.

We found two reports to be particularly useful for this review:

- The report from the 2009 Workshop on "Alternative Technologies to Seismic Airgun Surveys for Oil and Gas Exploration and Their Potential for Reducing Impacts on Marine Mammals" held by the Okeanos – Foundation for the Sea (Weilgart, 2010, 2012a).
- A 2007 "Review of Existing and Future Potential Treatments for Reducing Underwater Sound from Oil and Gas Industry Activities" prepared by Noise Control Engineering, Inc. for the Joint Industry Programme on E&P Sound and Marine Life (Spence et al., 2007).

3.1 ALTERNATIVE ACOUSTIC SOURCES

This section discusses alternative acoustic sources that have the potential to replace airguns for some seismic surveys.

3.1.1 Marine Vibroseis

A seismic vibrator, commonly known as vibroseis, propagates energy into the Earth over an extended period of time as opposed to the near-instantaneous energy provided by airguns (LGL Limited Environmental Research Associates [LGL] and Marine Acoustics Inc. [MAI], 2011; OGP, 2011). Vibroseis was developed by scientists at the Continental Oil Company (Conoco) during the 1950s and was a trademark name until the company's patent lapsed.

Vibroseis is used widely for seismic surveys on land, but so far has seen relatively limited use in the marine environment (OGP, 2011). According to OGP (2011), "the geophysical concept of marine vibrators is understood and offers great promise, but further investment and development will be required in order to improve operational efficiency and data imaging capability that is comparable with airgun source arrays." However, marine vibroseis (MV) has been cited as "arguably the most likely technology to eventually replace airguns" (Weilgart, 2012b). Two types of MVs have been developed: hydraulic and electromechanical. Hydraulic and electromechanical MVs can be towed in the same configuration as airgun arrays or operated in a stationary mode much like land vibrators; MV's may have fewer elements and better source characteristics, and will have lower source signal rise times, lower peak pressures, and less energy above 100 Hz (Thorson et al., 2005).

The Marine Vibroseis Joint Industry Program, sponsored by ExxonMobil, Shell, and Total, is pursuing development of new MV technologies in a phased approach. Phase I, which was completed in September 2009, consisted of scoping, casting a wide net, outside of oil/gas industry to indentify a broad range of technologies, and developing specifications. Phase Ii, which was completed in March 2013, consisted of contacting vendors, receiving and evaluating proposals, and selecting 3 proposals to fund and move forward. Phase III, which is underway, is pursuing 3 different technologies and expects that the first prototype will be tested and evaluated in 18 months. Phase IV will be to build and field test commercial systems from the technologies tested and evaluated in Phase III. Phase IV is anticipated to be complete in 2016 (Rosenbladt, Jenkerson, and Houllevigue, 2013).

Hydraulic Vibroseis

In 1981, Industrial Vehicles International, Inc. (IVI) signed an agreement with Britoil to develop a marine vibrator seismic source. In 1983, after scrapping the first design, IVI began developing a new system with the goal of producing a marine source able to emit a broad-band, high-amplitude, modulating frequency output. In 1985, the first commercial system was offered (IVI, 2003); the developed system consists of a marine vibrator, vibrator controller, and a Power Unit. The marine vibrator contains a piston within a housing with power supplied to the electrical, pneumatic, and hydraulic systems by the Power Unit. An alternator, air compressor, and two pressure-driven hydraulic pumps are driven by an air-cooled diesel engine. The source is capable of generating modulated frequencies between 10 and 250 Hz and can be used in water depths as shallow as 1 m. Signals are generated by conventional land vibrator controllers (IVI, 2010).

The system has been tested in various environments from transition zones to deepwater. Acoustic performance tests conducted at the Seneca Lake Facility of the Naval Underwater Systems Center in 1988 evaluted the system and determined that the marine vibrator was deficient in the low frequencies (Johnston, 1989; Walker et al., 1996). A comparison of marine vibrator, dynamite, and airgun sources in southern Louisiana concluded that the marine vibrator was a viable source for environmentally sensitive areas (Potter et al., 1997; Smith and Jenkerson, 1998). In transition zones, when coupled with the seafloor, marine vibrators operate like a land vibrator (Christensen, 1989).

Initial deepwater tests were conducted in the Gulf of Mexico by Geco-Prakla using a vibrator with an energy output approximately equivalent to a 1,000 $in.^3$ airgun. Despite limitations of low-frequency energy, good definition of reflectors down to 3 sec indicated that the system was viable (Haldorsen et al., 1985). In 1996, a commercial field test comparing a six marine vibrator array with a single 4,258 $in.^3$ airgun was undertaken in the North Sea by Geco-Prakla with the objective of evaluating cost, reliability, production rate, and quality of the geophysical data. After 2 weeks of data collection, a comparison between the marine vibrator and the airgun data indicated that the marine vibrator data contained more frequency content above 30 Hz and less frequency content below 10 Hz than the airgun data, but overall the data were comparable. Marine vibrator production rates were slightly lower than those of the airgun, but by the end of the survey, the technical downtime of the marine vibrator was similar to the airgun (Johnson et al., 1997).

Geco-Prakla, a subsidiary of Schlumberger, operated the marine vibrator program, conducting surveys and tests, until 2000 when the exclusive-use agreement between IVI and Schlumberger expired (Bird, 2003). IVI continued to further develop the system into the early 2000’s, but they are no longer actively marketing the product because there is no client base for the system. The significant expense to retrofit marine exploration companies’ ships to support marine vibrators is not offset by reduced operation costs or better data quality. IVI presently has marine vibrator systems that could be used for seismic data collection, but they would require renovation prior to deployment, which could take 3 months to 1 year to complete (Elmo Christensen, Vice President, IVI, pers. comm. with Jana Lage 11/09/10, 12/17/10)).

Stephen Chelminski, the inventor of the airgun and primary founder of Bolt Technology Corporation, has also developed a design for an MV prototype that he calls a “seavibe” (Weilgart, 2012b). It is 53 cm in diameter, 3.5 to 6 m in length, streamlined, and towable at any speed or depth. The signal can be pulse-coded or a swept signal or even a mix, without any high frequencies (5-100 Hz, although frequencies can range from 2 to 200 Hz). The signal duration can be changed in real-time. According to Weilgart (2012b), the prototype system is reliable, more efficient than airguns, and requires less horsepower to tow than airgun arrays. A significant amount of the engineering and design for the Chelminski Research Marine Vibratory Sound Source (the Source) has been completed on the MV prototype, patents have been applied for, but assembly and testing have not begun (Chelminski, 2013).

Electromechanical Vibroseis

Petroleum Geo-Services (PGS) began developing an electro-mechanical marine vibrator in the late 1990s. The original system consists of two transducers: the lower frequency (6 to 20 Hz) “Subtone” source and the higher frequency (20 to 100 Hz) “Triton” source (Tenghamn, 2005, 2006). Each vibrator is composed of a flextensional shell that surrounds an electrical coil, a magnetic circuit, and a spring element. The sound in the water column is generated by a current in the coil that causes the spring elements and shell to vibrate. Mechanical resonances from the shell and spring elements allow very efficient, high power generation (Spence et al., 2007; Tenghamn, 2005, 2006). The source tow-depth, generally between 5 and 25 m below the sea surface, is selected depending on the frequency and enhancement from the surface reflection that, to a certain degree, directs the acoustic signal downwards.

An electrical marine vibrator offers several advantages over hydraulic vibrators (Tenghamn, 2006, 2010). The reduction of the overall sound level and, specifically, the frequencies above 100 Hz that are beyond the useful seismic range is a major advantage of the system. Another is the reduction of acoustic power in comparison with conventional seismic sources, which occurs because the net source energy is spread over a long period of time (Tenghamn, 2005, 2006). Because highly controllable and repeatable signals can be produced, pseudo random noise (PRN) sequences can be generated, which make it possible to reduce the peak power even more (the PRN sequences not only spread the source energy over time, but also spread the frequencies over time). Finally, there is no need for heavy equipment and hydraulic systems that can cause hydraulic oil spills. As the electrical vibrator requires only an electrical power supply, it can be easily transported to different vessels.

This system was compared to a 760-in.^{3} airgun along a two-dimensional (2D) line in shallow water (water depths not specified but less than 100 m; Tenghamn 2005, 2006). A comparison of the data demonstrates that the marine vibrator equals the penetration of the airgun down to 5.5 sec two-way travel time (TWT) while spreading the source energy over a longer period than the airgun (Tenghamn, 2005, 2006). A second test comparing dynamite to the vibrators was run in water depths of 1.5 to 2 m. The transducers were mounted in a frame that was placed on the seabed. The vibrators lost the low-frequency component due to attenuation of the signal, limiting the depth of penetration to approximately 2 sec TWT. However, in the subsurface sections imaged by the vibrator, the two sources compared favorably (Tenghamn, 2005, 2006). Most of the trials have been conducted in shallow water (<100 m); deeper water tests need to be run to determine performance depth range of the system (Tenghamn, 2010).

During the early period of development, the system proved that the concept worked as a source for seismic data. However, unreliability prevented it from becoming a commercial system. PGS spent 2006 and 2007 conducting a feasibility study to improve reliability. New sources havae since then been tested fro reliability and acoustic performance during 2008 and 2009 (Rune Tenghamn, VP Innovation and Business Development, PGS, pers. comm. to Kim Olsen 6/4/13).

PGS were well positioned when a newly formed Joint Industry Project (JIP) inquired about the possibility to commercialize PGS marine vibrators. The JIP, managed by Global Petroleum Research Institute (GPRI) the Texas A&M Engineering Experiment Station (TEES), has chosen PGS to develop an electric Marine Vibrator to deliver acoustic output and frequency content comparable with a conventional impulsive source array. Oil company sponsors of the JIP are Total, ExxonMobil and Shell. The development work started in March 2013 with the objective to develop an array of sources and to have a reliable system commercialized by 2016 (Rune Tenghamn, VP Innovation and Business Development, PGS, pers. comm. to Kim Olsen 6/4/13).

According to Weilgart (2012b), a commercial electromechanical MV system, developed in 2008, could be available as early as 2014. It is being commercialized by Geokinetics, which has a license from PGS to use it for shallow-water applications. Geokinetics has been developing software and performing field tests on a commercial MV system over the past several months and is continuing with field testing. However, some mechanical design issues remain, causing unwanted harmonics (Rune Tenghamn, pers. comm. cited by Weilgart, 2012b). The Geokinetics Marine Vibrator project is the continuation of the original PGS Marine Vibrator Project which was first successfully tested in 1999 against airguns. The Geokinetics vibrators employ a more robust drive element and have refined mechanical and control systems. The vibrators and systems are continuously being tested and evaluated and additional field tests are anticipated sometime in 2013. At present, the vibrators are considered to be mechanically complete and are only awaiting refinements in the feedback control system software before the next phase of field testing takes place (Pramik, 2013).

Environmental Considerations

Potential impacts of MV have been evaluated by LGL and MAI (2011) and are also discussed briefly by Weilgart (2012b). The analysis by LGL and MAI (2011) concluded that MV surveys "should in most respects have less environmental impact than surveys using airgun arrays" in all marine habitats and environments. In general, impacts are expected to be less than for airguns, for several reasons:

- Peak pressures are lower because of the longer signal duration;
- The rapid rise time of airgun pulses is eliminated;
- The proportion of total energy emitted at frequencies above approximately 100 Hz is reduced as compared with airguns;
- Spectral properties of the signal are well controlled, allowing lower energy levels to be used; and
- MV systems may be operable at deeper depths in the water column, as compared to airguns, thus reducing potential near-surface impacts.

However, auditory "masking" is one type of biological effect that is likely to be more of a problem with MV than with airguns (LGL and MAI, 2011). MV signals are of longer duration (seconds vs. tens of milliseconds for an airgun pulse), and MV will likely have a higher duty cycle (percentage of time it is "on"). For these reasons, the MV sounds may mask faint natural sounds for more time than would occur with airguns. This would affect mainly low-frequency hearing specialists such as baleen whales and some fishes. Slight masking effects could extend to a few tens of kilometers from the MV source.

MV signals are expected to be either frequency modulated (FM) sweeps or frequency-coded signals (pseudo-random noise [PRN]) (LGL and MAI, 2011). Because of the instantaneous narrowband nature of FM sweeps, masking effects of MV should be limited if FM sweeps are used. PRN signals may provide signal-processing advantages to geophysicists and may allow an MV system to operate with a lower source level, shorter signal duration, or lower duty cycle than with FM signals, which could be advantageous from an impact perspective. However, in animals sensitive to low-frequency sound (e.g., baleen whales), masking and disturbance effects of PRN signals may be greater than corresponding effects from FM signals. LGL and MAI (2011) recommended further study of this issue to help decide which signal type to use.

3.1.2 Low-Frequency Acoustic Source (patented) (LACS)

Originally designed as a ship sound simulator for the Norwegian Navy, the low level acoustic combustion source (LACS) is an alternative acoustic source for seismic acquisition (Askeland et al., 2007, 2009). The LACS system is a combustion engine with a cylinder, spark plug, two pistons, two lids, and a shock absorber. It creates an acoustic pulse when two pistons push lids vertically in opposite directions; one wave reflects from the sea surface and combines with the downward moving wave. There is no bubble noise from this system as all air is vented and released at the surface, not into the underwater environment. The absence of bubble noise allows the system to produce long sequences of acoustic pulses at a rate of 11 shots/sec; this allows the signal energy to be built up over time with a lower amount of energy put into the water (Askeland et al., 2007, 2009). The system design also controls the output signal waveform, which can reduce the amount of non-seismic (>100 Hz) frequencies produced (Spence et al., 2007). The transmitted pulses are recorded by a near-field hydrophone, and seafloor and sediment reflections are recorded by a far-field streamer (Askeland et al., 2007, 2009).

Two LACS systems are being offered commercially. The LACS 4A has a diameter of 400 mm, a height of 600 mm, and a weight of approximately 100 kg in air. Pulse peak-to-peak pressure is 0.8 bar meter or 218 dB re 1µPa at 1 m. Field test results of the LACS 4A system demonstrate that the system is capable of accurately imaging shallow sediments (~230 m) within a fjord environment (Askeland et al., 2008, 2009). This system is suitable for shallow-penetration, towed-streamer seismic surveys or vertical seismic profiling (Askeland et al., 2008).

The second system, the LACS 8A, theoretically has the potential to compete with a conventional deep-penetration airgun seismic array. The LACS 8A system has pulse peak-to-peak pressure of 3 bar meter or 230 dB re 1µPa at 1 m. The weight is 400 kg, and the diameter is 800 mm. Several LACS units may be operated together to provide an increased pulse pressure (Bjørge Naxys AS, 2010).

This system currently does not exist, and the project is presently on hold. It would take at least 18 months to build and field test one of these systems if money became available to do so (Jens Abrahamsen, Managing Director, Bjørge Naxys, pers. comm. to Jana Lage, BOEM, 12/2/10).

3.1.3 Deep-Towed Acoustics/Geophysics System (DTAGS)

The U.S. Navy developed a deep-towed acoustics/geophysics system (DTAGS) to better characterize the geoacoustic properties of abyssal plain and other deepwater sediments. The system uses a solid state piezo-ceramic Helmholz resonator to generate a controlled broadband signal. The system was tested and modified in the early 1990's and used in various locations around the world until it was lost at sea in 1997 (Gettrust et al., 1991; Wood et al., 2003).

The second generation DTAGS is based on the original design but has more modern electronics. It uses the same Helmholtz resonator source consisting of five concentric piezoelectric ceramic rings sealed in an oil-filled rubber sleeve to generate a broadband signal greater than two octaves. The optimum frequency performance range is between 220 and 1,000 Hz, with a source level of 200 dB re 1µPa @ 1 m. The source is extremely flexible, allowing for changes in waveform and a decrease in sound level to produce a source amplitude, waveform, and frequency to suit specific requirements (Wood et al., 2003; Wood, 2010).

The DTAGS is towed behind a survey vessel, usually at a height of 100 m above the seafloor and a vessel speed of 2 kts; it can operate at full ocean depths (6,000 m). A 450-m long, 48-channel streamer array is towed behind the source to record the reflected signals. Seismic signals are digitized at each hydrophone and recorded in SEG-Y format in a top-side unit (Wood et al., 2003; Wood, 2010). DTAGS can also be configured with an aluminum landing plate that transmits the acoustic energy directly into the seafloor. With this configuration, vertical bottom-founded hydrophone arrays are used to receive reflections (Breland, 2010).

The system has a limit of 1-km penetration in most marine sediments (Wood et al., 2003). It has been used successfully to map gas hydrates in the Gulf of Mexico (Wood et al., 2008), Canadian Pacific (Wood et al., 2002; Wood and Gettrust, 2000), and Blake Ridge (Wood and Gettrust, 2000).

Two key advantages of DTAGS are proximity of the source to the seafloor and time integration over a highly controlled and repeatable source waveform (Wood, 2010). Proximity of the acoustic source to the seafloor allows the system to achieve commercially useful sound pressure-equivalent levels in the earth while minimizing the instantaneous sound levels in the ocean, particularly the shallow ocean where sound sensitive marine life is concentrated.

Wood (2010) notes several disadvantages of DTAGS, which are paraphrased below:

- Less penetration than with surface-towed airguns, mostly due to frequency content. DTAGS operates at higher frequencies than airguns (220 to 850 Hz), providing greater resolution at a cost of reduced penetration (100 to 200 m in sand, 1,000 m in soft mud).
- The deep-towed instrument limits the speed of the towing vessel. DTAGS is towed at 2.0 to 2.5 kts, whereas a surface-towed airgun system may be towed up to three times faster, covering more kilometers per day of ship time.
- With DTAGS in its present form, there is also an issue relative to navigating the source and receivers. Currently, the system is simply towed, with knowledge of its location but without having complete control over where it goes (on the sub-wavelength scale). However, technology exists to solve this problem, so this could be accomplished with adequate funding.

There is only one DTAGS in existence at this time. While it has imaged shallow sediments and gas hydrate environments extremely well, the current tool design could not replace a deep penetration airgun array for oil and gas exploration at this time; DTAGS was not designed for this purpose. However, there is no physical limitation to designing a resonant cavity source to simulate the frequency band of airguns.

According to Weilgart (2012b), DTAGS was tested in the Gulf of Mexico in the summer of 2011 and will undergo another trial off the coast of Oregon in September 2012. Though the frequency range of

DTAGS is currently 200 to 4,000 Hz, it may be extended down to about 100 Hz (Warren Wood, pers. comm. cited in Weilgart, 2012b).

3.1.4 Low-Impact Seismic Array

Nedwell (2010) briefly describes studies of a low-impact seismic array (LISA) consisting of a large array of small, but powerful, electromagnetic projectors. The projectors use a low-frequency electromagnetic transducer system. Because the signal could be well controlled, both in frequency content and in directionality, this technique offers the possibility of undertaking seismic surveys in environmentally sensitive areas with little or no collateral environmental impact.

Initial measurements were made on a small array (n=4) of existing electromagnetic transducers designed by Subacoustech. The tested system had a peak operating frequency of 25 Hz, but Nedwell stated that this could be reduced to under 10 Hz with reasonable modifications, allowing use of an array for seismic exploration. The results indicate that it would be possible to achieve an array source level of about 223 dB re 1 μPa @ 1 m, which is adequate for seismic surveying (Nedwell, 2010).

No further information about this technology was found during the literature review or during the Workshop.

3.1.5 Underwater Tunable Organ-Pipe

Morozov and Webb (2007) described a system consisting of a tunable, underwater organ-pipe driven by an electro-mechanical piston source. The pipe is used to create a tunable Helmholtz resonator capable of large acoustic amplitudes at a single frequency that is dependent on the length and other parameters of the tube. When combined with the appropriate electronic drive and control system, the system can create a high-amplitude sine sweep in the frequency range of interest.

The system as described by Morozov is capable of deployment in water depths up to 5,000 m. According to Spence et al. (2007), system efficiencies are between 40% and 90%, depending on frequency, which is very high relative to other piston-type sources. The current system was used to produce sine sweeps in the frequency range of 225 to 325 Hz, with sweep times as short at 5 sec.

As evaluated by Spence et al. (2007), this system appears to be an early prototype and has only been used with frequencies above 200 Hz.

No further information about this technology (for seismic surveys) was found during the literature review or during the Workshop.

3.2 Complementary Technologies (No Added Noise)

This section discusses methods that are used in conjunction with seismic surveys to investigate the subsurface geology. While these methods are not expected to replace seismic surveys using airguns, some may offer opportunities for reducing the amount of seismic survey activity. Fiber optic receivers are also included in this section because they may allow the use of smaller airgun arrays or some of the alternative sources discussed previously.

3.2.1 Low-Frequency Passive Seismic Methods

Low-frequency passive seismic methods use natural sounds to image the subsurface. Measurements of the Earth's passive seismic wave field are being studied by multiple academic and industry groups as a new technology for identifying and delineating hydrocarbon reservoirs (Habiger, 2010). This technology has been applied mainly on land, but warrants further investigation and development for the marine environment. An initial test has been completed in the North Sea for oil and gas applications, and the information gained can be used for planning follow-on surveys to further advance this technology (Habiger, 2010).

A typical survey consists of highly sensitive receivers (usually broadband seismometers) placed in the area of interest to collect data over a period of time. Upon survey completion, the data are analyzed and filtered to remove all non-natural sounds, which is most efficiently completed using an automated process (Hanssen and Bussat, 2008).

Passive seismic surveys cannot replace active seismic acquisition. Current passive imaging techniques offer a lower-resolution imaging suitable for frontier exploration and to rank order a list of exploration opportunities to determine which are the most likely to be successful and, therefore, pursued; however, these techniques are not sufficient for field development (Duncan, 2010). Passive acoustic data have the potential to enhance oil recovery at a better resolution than magnetic or gravimetric methods (Bussat and Kugler, 2009), especially in areas that are environmentally sensitive or where active seismic operations are difficult.

All of the current methods use one of following three sources of natural sounds: natural seismicity, ocean waves, or microseism surface waves. These categories are discussed below.

Methods Using Natural Seismicity

Natural seismicity uses the Earth's own movements as a source of energy. The most straightforward application of this passive technology is commonly referred to as Passive Seismic Transmission Tomography (PSTT) (Duncan, 2010). PSTT creates 3D images using the observed travel time of seismic signals originating from micro-earthquakes occurring below the target.

Daylight Imaging (DLI) uses the local seismicity of an area to produce reflection seismic profiles, similar to those recorded in active seismic surveys (Claerbout, 1968). As in active reflection seismic operations, geophones are deployed; the target can be imaged using a regularly spaced 2D line geometry (Hohl and Mateeva, 2006; Draganov et al., 2009). The seismicity of the area, geologic complexity, and receiver sensitivity control the record length. DLI can augment active seismic data where it is difficult to collect data.

Local Earthquake Tomography also uses local seismicity of a region to map on the reservoir scale (Kapotas et al., 2003). However, it is used to calculate the velocity structure of the subsurface in 3D by analyzing each earthquake on multiple receivers and generating ray paths instead of cross-correlating the recorded signals. This method requires a longer period of data collection than the other methods to produce results.

Methods Using Ocean Waves

Ocean waves are used as a sound source for the Sea Floor Compliance technique. The method requires that Ocean Bottom Seismometer stations with highly-sensitive, broadband seismometers and differential or absolute pressure gauges be installed in water several hundred meters deep. In the right setting, a coarse, one dimensional (1D) S-wave velocity model of the subsurface down to the Moho (the boundary between the Earth's crust and mantle) can be generated using the measured water pressure and vertical movement of the seabed caused by large passing ocean waves (Crawford and Singh, 2008).

Ambient-Noise (Surface-Wave) Tomography (AN(SW)T) uses low-frequency (between 0.1 and 1 Hz) ambient noise records to estimate shear wave velocities and structural information about the Earth. The ambient noise used mainly consists of microseism surface waves (Rayleigh and Love waves) (Bussat and Kugler, 2009). This technique requires the use of broadband seismometers to record the low-frequency surface waves that can penetrate to depths of several kilometers (Bensen et al., 2007, 2008). Because the marine environment produces abundant, high-energy surface waves, a few hours or days of acquisition can produce good quality data. AN(SW)T can be used in areas where seismic data are difficult to collect or in environmentally sensitive areas. While this technology is new and still in need of further testing, the lateral resolution at several kilometer depths may reach a few hundred meters and the resolution may be better than gravimetric or magnetic data, which is promising for oil and gas exploration (Bussat and Kugler, 2009).

Methods Using Microseismic Surface Waves

Surface-wave amplitudes is a 1D method that images the geological structure of the sub-surface by analyzing passive acoustic data that have not been geophysically processed. The transformation of incoming micro-seismic surface waves, scattered at vertical discontinuities, into body waves may produce these data, but the process is not well understood (Gorbatikov et al., 2008).

Low-Frequency Spectroscopy, which is also known as Low-Frequency Passive Seismic or Hydrocarbon Microtremor Analysis, tests for an indication of subsurface hydrocarbon accumulation using spectral signatures gathered from the ambient seismic wave field recorded by broadband seismometers. The cause of the spectral anomalies, often called Direct Hydrocarbon Indicators, is presently unknown, but the following have been proposed: standing wave resonance, selective attenuation, resonant amplification (Graf et al., 2007), and pore fluid oscillations (Frehner et al., 2006; Holzner et al., 2009). Energy anomalies in the frequency range between 1 and 6 Hz have been observed in known hydrocarbon areas, including Mexico (Saenger et al., 2009), Abu Dhabi (Birkelo, 2010), Brazil, Austria (Graf et al., 2007), and southeast Asia (West et al., 2010). However, this methodology is highly dependent on the ability to process out all anthropogenic noise and topography (Hanssen and Bussat, 2008). This method is still in the early stage of development and has not been confirmed in the field during all studies (Al-Faraj, 2007; Ali et al., 2007).

The most successful use of low-frequency passive micro-seismic data has been on land where it is easier to isolate the extraneous noise from the natural signal. The technique is promising in the marine environment. To ensure success of a marine survey: 1) it is imperative that the recording instruments are in proper contact with the substrate and 2) the increase in both anthropogenic and naturally produced noise in the marine environment is correctly filtered so that it does not mask the signal of interest.

3.2.2 Electromagnetic Surveys

EM surveys are often used in conjunction with seismic surveys to help delineate potential oil and gas reservoirs. Many geological processes in the crust and upper mantle of the seafloor involve the interaction of fluid phases with surrounding rock. The conductivities of hydrothermal phases are different from those of host rock, and collectively they offer distinct profiles of electrical conductivity/resistivity, depending on the specific geological process involved. There are two practical electromagnetic techniques applicable to oil and gas exploration: controlled source electromagnetic (CSEM) surveys and magnetotelluric (MT) surveys. Both CSEM and MT were initially developed as academic tools to study the oceanic lithosphere and mantle, but have been used as an exploration tool mainly in the last decade, with the CSEM method more widely used in deepwater environments (Constable, 2010).

Both CSEM and MT may be used in conjunction with seismic survey data to create meaningful, detailed regional geologic models and identify potential hydrocarbon traps. However, currently these methods have neither the resolution nor the penetration to replace seismic surveys in a significant range of exploration and production applications (Constable, 2010; Ridyard, 2010). In theory, broader application of these methods could reduce the level of 3D seismic surveying, but that is currently not happening (Ridyard, 2010). The technology is underutilized by many oil companies due to the widespread lack of understanding and adoption of the technology (Ridyard, 2010).

Controlled Source Electromagnetic Surveys (active source)

CSEM surveys are used in conjunction with seismic airgun surveys to help delineate potential oil and gas reservoirs (Constable, 2010; Darnet et al., 2010). In recent years, this technique has emerged as a powerful exploration tool (Ridyard, 2010).

In the CSEM technique, very low frequency (typically less than 1 Hz) EM signals are transmitted into the upper layers of the seafloor via a towed dipole. The signals are propagated laterally to an array of receivers kilometers away. The variations in the EM field relative to the geometry of the receiver arrays and distance provide a conductivity/resistivity profile of the seafloor. The measurements can be processed to create a 3D image of the subsurface resistive structures. These structures can include hydrocarbon reservoirs, but also many other resistors such as salt, volcanic rocks, carbonates, and methane hydrates. Where a resistor is observed co-located with a prospective hydrocarbon-bearing structure, the risk of drilling a dry hole is significantly reduced (Ridyard, 2010).

Environmental impacts of CSEM are expected to be negligible (Ridyard, 2010). Receivers deployed on the seabed use biodegradable anchors and have negligible environmental impact. The CSEM source uses extremely low spatial and temporal frequencies—typically wavelengths of many kilometers and frequencies of 0.1 to 1 Hz. When these low frequencies are considered in combination with the exponential decay of energy caused by highly conductive seawater, the region of potential influence on marine life resulting from EM transmissions is small (Ridyard, 2010).

Magnetotelluric Surveys (passive source)

MT surveys are used in conjunction with CSEM and seismic airgun surveys to help delineate potential oil and gas reservoirs (Constable, 2010; Darnet et al., 2010). MT surveys are passive measurement of the Earth's EM fields (Chave and Jones, 2012). This method is closely related to CSEM, as both techniques attempt to map subsurface resistivity using seafloor recordings of EM fields (Darnet et al., 2010). However, in the MT method, no electrical currents are induced into the earth, but the receiver device detects the natural electrical and magnetic fields present. Ships are used to deploy and retrieve the recording devices, which are the same as those for CSEM.

MT was initially thought to be of little use in the offshore exploration environment, but was first commercialized for use on the continental shelves as a tool for mapping geology in areas where seismic methods produced poor results (e.g., salt, basalt, and carbonate provinces) (Constable, 2010). Despite its limitations in the early days of its application to hydrocarbon exploration, the MT method has matured into a tool that works effectively in certain niche environments (Unsworth, 2005). According to Unsworth (2005), a combination of low-resolution MT and higher-resolution CSEM is becoming the preferred method for mapping the background sedimentary section and detecting discrete resistive layers. Further innovations are expected to involve better data processing, interpretation, and the integration of surface and borehole methods to improve vertical resolution (Unsworth, 2005).

Environmental impacts of MT are expected to be even less than for CSEM, since there is no active EM source. Receivers deployed on the seabed use biodegradable anchors and have negligible environmental impact.

3.2.3 Gravity and Gravity Gradiometry Surveys (passive source)

Gravity and gravity gradiometry surveys are remote-sensing methods that measure variations in the naturally occurring gravity field. These are passive surveys, with no energy emitted into the earth or water. The techniques differ in the way the field is measured, but both technologies are fairly well developed and have been used by both mining and oil and gas industries for decades (Bate, 2010).

Marine gravity data can be collected with instruments on the seafloor, in boreholes, or in helicopters, but usually on ships. In many cases, the data are collected during a seismic survey. However, the preferred method has been to use dedicated ships to acquire more precise data. With the advent of global positioning system navigation and larger, more stable seismic ships, it is now possible to achieve the same order of accuracy with meters placed in seismic ships as in dedicated ships. Helicopters also may be used to collect gravity data, but such surveys are rare because of the logistics required to keep the craft in the air for extended periods far from shore.

Gravity gradiometry involves measuring the Earth's gravity gradient, which offers an increase in resolution compared to gravity surveys. Gravity gradiometry requires more complex and expensive equipment than the traditional gravity meter. This is now possible with the release of Department of Defense technology. The instrument can be located on a survey ship or fixed-wing aircraft (DiFrancesco et al., 2009).

Gravity and gravity gradiometry are not applicable in all geological settings and cannot replace the need for seismic surveys. However, in the correct setting, working with an integrated data set of seismic and gravity gradiometry, a better picture of the subsurface can be delivered, which may also reduce the amount of seismic survey effort required (Bate, 2010).

3.2.4 Fiber Optic Receivers

Fiber optic receivers are sensors that incorporate optical fibers to transmit the received acoustic signal as light. They are most frequently used in the petroleum industry for seismic permanent reservoir monitoring, a four-dimensional (4D) reservoir evaluation application. The optical receivers are permanently placed on the seafloor, ensuring consistency and repeatability of the 4D surveys, better signal-to-noise ratios, and data quality. This technology is not currently available for towed-streamer surveys.

Nash and Strudley (2010) identify several key characteristics of fiber optic receivers that may lead to noise reduction during airgun surveys:

- Reduced amplitude. Fiber optic receivers on the seafloor have greater sensitivity and achieve a better signal-to-noise ratio than towed conventional sensors, which are subject to additional noise in the water column. This allows the use of smaller airgun sources for 4D surveys.
- Reduced airgun volume. Because fiber optic receivers have better low-frequency performance, the requirement for large airgun volumes may be reduced.
- Reduced survey duration. Because the receivers are permanently deployed, total survey time is reduced compared to towed streamer surveys because no infill is needed and weather downtime is minimized.

Fiber optic technology is likely to be of increasing importance in the future for reservoir monitoring and is particularly suited to future use with alternative seismic sources that produce less high frequency output (Nash and Strudley, 2010). The receivers are broadband sensors with a range into the tens of kilohertz, and to accommodate the output from conventional airgun sources, these sensors must have a large dynamic range at higher frequencies to avoid sensor saturation. Because sensors with a greater dynamic range are expensive, cost savings could be achieved by pairing these receivers with alternative sources that produce less high-frequency sound, such as marine vibroseis (Nash and Strudley, 2010).

3.3 Methods to Reduce Unwanted Noise from Airguns

Some of the airgun sound that has potential to impact marine mammals and other marine life comes from "waste sound" that is either too high frequency and filtered out before recording or propagates laterally away from receivers and is also never recorded. Several methods have been investigated or proposed to reduce unwanted noise from airguns. Four categories are discussed in this section:

- Bubble curtains to attenuate lateral noise propagation;
- Parabolic reflectors to focus airgun energy downward;
- Airgun silencers; and
- Other methods to reduce high-frequency sound.

3.3.1 Bubble Curtains

A bubble curtain is a sheet or "wall" of air bubbles that are produced around a sound source. The bubbles are created by forcing air through small holes drilled in metal or polyvinyl chloride (PVC) rings using air compressors. The bubbles in the bubble curtain create an acoustical impedance mismatch that is effective in blocking sound transmission (Spence et al., 2007). Reductions in peak pressure, root-mean-square (RMS) pressure, and energy are typically on the order of 5 to 20 dB or more. The effectiveness of bubble curtains depends on several factors, including the thickness of the curtain, size of the bubbles, and bubble density, among others (Spence et al., 2007).

Bubble curtains have been successfully tested and used in conjunction with pile driving and at construction sites to frighten away fish and decrease the noise level emitted into the surrounding water (Würsig et al., 2000; Sexton, 2007; Reyff, 2009). They have also been used as stand-alone units or with light and sound to deflect fish away from dams or keep them out of specific areas (Pegg, 2005; Weiser, 2010). Additional information about bubble curtains in relation to pile driving is presented in **Section 4**.

Two early reports investigated the use of a bubble curtain to block some of the laterally radiated sound from airguns (Sixma, 1996; Sixma and Stubbs, 1998). During an initial test, the sound source was flanked by two bubble screens (parallel to the direction of the vessel towing the source) to block sound in those directions. The test demonstrated that bubble curtains were capable of attenuating seismic energy up to 28 dB at 80 Hz while stationary in a lake. This two-bubble curtain configuration was field tested from a moving vessel in Venezuela and Aruba where a 12 dB suppression of low-frequency sound and a decrease in the sound level of laterally projecting sound were documented (Sixma, 1996; Sixma and Stubbs, 1998).

Spence et al. (2007) noted several limitations for the method used by Sixma (1996) and Sixma and Stubbs (1998). The reductions were measured only for locations where there was no line-of-sight with the source; locations with a direct line-of-sight path to the source showed effectively no reduction in sound. Also, the method blocks sound in only two lateral directions; it would not be practical to use a similar barrier in front of the seismic source unless the source was stationary. This may limit the practical usefulness of this approach for reducing exposure to marine animals. Furthermore, the feasibility and effectiveness in deep waters are unknown because the bubble curtain has limitations as to how deep it can be located.

A BOEM-sponsored study evaluated the use of bubble curtains to reduce lateral noise propagation from seismic exploration vessels. The study assumed that towed air bubble hoses would be used to create the bubble curtains, as evaluated by Sixma (1996) and Sixma and Stubbs (1998). A towed air bubble hose is very simple to set up and operate, and it causes only minimal fluid drag, making the support system relatively light. An initial evaluation and modeling showed that deploying an air bubble curtain to reduce lateral noise could achieve a noise reduction of 20 dB or more (Ayers et al., 2009a,b). However, a follow-up report that included more detailed 3D sound propagation and noise attenuation modeling concluded that deploying bubble curtains cannot produce the sought-after noise reduction (Ayers et al., 2010). The model results showed generally poor performance of the air bubble curtains at reducing sound levels except at short distances from the source where direct-path sound propagation was directly shielded by the curtains. In most cases, the model predicted little difference between scenarios with and without curtains in place. The authors noted that it is possible that the nozzles for bubble production could be dragged on the seafloor at the shallow water depth (50 m) in order to capture the noise within the bubble curtains, but the power to produce effective bubbles would be exorbitant and the risk of entanglement of the weighted nozzles would be high. The authors advised against further development of the bubble curtain for lateral noise attenuation because little noise, if any, would be attenuated.

A different study in the Gulf of Mexico tested an “acoustic blanket” of bubbles as a method to suppress multiple reflections in the seismic data (Ross et al., 2004, 2005). The results determined that suppression of multiples was not practical using current technology. However, the acoustic blanket measurably suppressed tube waves in boreholes and has the capability of blocking out thruster noises from a laying vessel during an Ocean Bottom Cable survey, which would allow closer proximity of the shooting vessel and increase productivity (Ross et al., 2004, 2005). However, this study did not address use of the “acoustic blanket” for environmental mitigation purposes.

3.3.2 Parabolic Reflectors

A BOEM-sponsored study also evaluated the possibility of making an airgun array more vertically directional by towing a parabolic reflector over the array (Ayers et al., 2009a). The parabolic reflector could consist of an air bubble curtain or could be constructed from solid materials such as neoprene or nitrile foams.

The report included acoustic modeling by Spence (2008), which concluded that the concept is capable of reducing lateral transmission of sound. The parabolic reflector has the potential for large reductions in sound, particularly at vertical angles greater than 70 degrees. The reflector provides an increase in output directly below the array of up to 10 dB for most frequencies, which is advantageous to seismic exploration; however, at the lowest frequencies (5 Hz and 30 Hz) there were reductions in sound of up to 17 dB depending on the specific reflector size. If the number of airguns used is held constant, a single line array can have greater directivity in the longitudinal direction (on centerline) than an array with 3 rows of guns, further improving the performance of this arrangement. Spence (2008) noted some important limitations:

- The size of the reflector may be a practical limitation, particularly for arrays positioned deeper in the water. If an air bubble curtain is used to create the parabolic reflector, the hoses used to create the air bubble curtain must be oriented laterally (transverse) and many rows of hoses must be used in order to maintain the parabolic shape over the entire array. This may prove difficult in practice. A solid material may be preferable in this case and would also provide similarly large sound level reductions. However, such a reflector would likely need to be assembled in sections to cover the entire length of the array.
- The effectiveness in shallow water is significantly compromised as a result of bottom reflections (the same is true for bubble curtains in general). If the seafloor is absorptive then this reduction in performance may not be as dramatic.

However, Ayers et al. (2009a) concluded that deploying and towing a parabolic reflector along with the airgun arrays and streamer cables might be a very risky effort, and, therefore, they did not analyze this method further or recommend pursuing it.

3.3.3 Airgun Silencer

An airgun “silencer” was tested by Nedwell and Edwards (2005). Although the report is not publicly available, the test results were summarized by Spence et al. (2007) and (briefly) by Spence (2009) and by Dr. Nedwell in the Okeanos workshop report (Weilgart, 2010).

The airgun silencer consists of acoustically absorptive foam rubber on metal plates mounted radially around the airgun. Tests demonstrated 0 to 6 dB reductions in sound pressure level at frequencies above 700 Hz. An overall increase in sound pressure level by 3 dB was measured, caused by an increase in sound near 100 Hz. Nedwell and Edwards (2005) claim that this increase in low-frequency energy in the geophysically “useful” frequency band could reduce the total number of required airguns for a given survey. Nedwell (2010) characterized the reduction achieved by the airgun silencer as modest, but well below that potentially achievable.

Spence et al. (2007) characterized the airgun silencer as a “proof-of-concept” that would require further development to become a commercial product. The main limitations are that the silencer has been tested only for small (50 bar) airguns, and the acoustically absorptive material withstood only 100 shots before needing to be replaced. During a workshop conducted for the Spence et al. (2007) report, participants suggested that placing the absorbent material farther from the airgun may increase the life of the silencer and allow it to be used for larger airguns and arrays. However, a later review by Spence (2009) characterized the airgun silencer treatment as “impractical” for the same reasons noted above.

The literature search did not identify any further studies of airgun silencers beyond the one conducted by Nedwell and Edwards (2005). This technology does not appear to be currently under development.

3.3.4 Other Methods to Reduce High Frequency Noise

A recent BOEM-sponsored study of methods to reduce lateral noise propagation briefly considered the possibility of redesigning airguns to reduce high-frequency sound while maintaining the strong low-frequency signal needed for exploration (Ayers et al., 2009a). However, the authors noted that changing the structure of airguns to add lateral noise reducers without affecting the required source signal would mean that the airgun manufacturers would have to develop and test a totally new product. This was determined to be beyond the scope of their study and was not analyzed further.

In the Okeanos workshop report (Weilgart, 2010), Peter van der Sman stated that "Improvements in reducing high frequency noise could be made in airguns by altering the port/throat design. Some work has been done in the past to illustrate this. While the ideas are published, the results are not available in the open literature. However, a patent has been filed on this concept in 2005 proposing such changes and suggesting an attendant reduction in high frequency noise." No further information is available about this method.

Weilgart (2012b) notes that "Bolt Technology Corporation and WesternGeco have attempted to design an airgun, the E-source airgun, which reduces the output of high-frequency energy while optimizing it in the seismic band of interest, in order to minimize the effects on marine animals. This approach may be too piecemeal and not comprehensive enough, however, as other potentially damaging characteristics of airgun pulses remain." The E-Source airgun is still under development and no additional information is available for the public domain at this time (Robert Laws, Schlumberger Cambridge Research Ltd., pers. comm. to Bill Streever BP 1/17/13).

4. PILE DRIVING NOISE

A driven pile is a column made of preformed material that is installed by impact hammering, vibrating, or pushing into the earth (Pile Driving Contractors Association, 2013). Driven piles are used to support various structures in the marine environment, such as docks, navigational markers, bridges, oil and gas platforms, and offshore wind turbines. Pile driving (also referred to as "ramming" in the European literature) produces underwater sound pulses that have the potential to affect marine mammals, fishes, and other marine life. In some areas, fish kills are the main concern (Laughlin, 2006; Halvorsen et al., 2011). Studies of offshore wind farms, particularly in northern Europe, have raised concerns about impacts on marine mammals (David, 2006; Madsen et al., 2006; Bailey et al., 2010; Gedamke and Schomer, 2011; Nehls, 2012).

This section discusses measures that have been developed to reduce acoustic impacts of underwater sound from pile driving. The measures are divided into three categories:

- Alternative piling installation methods that produce less noise;
- Low-noise foundations (non-piling methods); and
- Mitigation methods to attenuate the transmission of underwater sound from pile driving.

The first category includes alternatives such as vibratory hammers, press-in systems, cast-in-place piles, and alternative pile materials and shapes. The use of wood, nylon, and micarta pile caps also would fall into this category. The second category includes alternatives such as gravity-based structures, suction-based foundations, drilled or excavated foundations, and floating foundations. The third category includes noise-reducing methods such as cofferdams, bubble curtains, isolation casings, and others.

4.1 ALTERNATIVE PILING INSTALLATION METHODS

4.1.1 Vibratory Pile Driving

In vibratory pile driving, a vibratory hammer is used in place of an impact hammer. This method uses a "driver" that continuously excites the pile in the vertical direction at a specific frequency. The driving frequency is typically on the order of 10 to 60 Hz (Spence et al., 2007). The dominant underwater sound components are tones at the frequency of vibration and harmonics, although broadband sound is created at frequencies above ~500 Hz and can extend to several kilohertz (Spence et al., 2007).

Vibratory pile driving is expected to produce lower peak pressure levels than impact pile driving. Because rise times and peak over and under pressures are also significantly reduced using this method, the potential for fish mortality should be lessened (ICF Jones & Stokes, 2009). However, the total energy imparted can be comparable to impact driving because the vibratory hammer operates continuously and requires more time to install the pile (ICF Jones & Stokes, 2009).

Vibratory hammers are routinely used on smaller piles (ICF Jones & Stokes, 2009). However, the method is most effective in granular soils and in driving non-displacement piles (Spence et al., 2007). In some cases, it is difficult to drive a pile to a depth where it can reach load-bearing capacity; in these cases, impact methods must be used to set the pile (Spence et al., 2007). Matuschek and Betke (2009) indicate that the required penetration depth used for offshore wind turbines (e.g., 35 m) sometimes cannot be reached using a vibration pile driver. Furthermore, in order to verify the final stability of the installation, an impact pile driver may be needed at the end of the installation process.

PTC (2012) has developed a vibrodriver system for use in offshore piling installation. The method is suitable for large pilings up to 6.2 m in diameter, including monopile, jacket, and tripod wind farm foundation pilings. The standard vibrodriver can be used in waters up to 15 m deep without any pressurization system; in deeper water (up to 100 m), the vibrodriver is equipped with a special pressurization system. The product brochure indicates that, in some cases after the vibrodriver reaches its maximum penetration depth, a hydraulic hammer may be used to drive the pile the last meters.

4.1.2 Press-in Piles

Another alternative to conventional piling methods is "press-in piling" (Motoyama and Goh, 2007; Goh, 2010). The press-in method uses hydraulic rams to push piles into the ground and is characterized as a quieter method than conventional pile driving. Press-in piling machines are self-contained units that use static forces to install piles. The machine uses other piles that have already been installed as leverage to install new piles.

This system was originally developed for use in urban areas where human hearing impacts, vibration, and erosion are important concerns (Motoyama and Goh, 2007). This approach has been used extensively on land and in shallow water. While the conventional approach requires consecutive piles to be located adjacent to one another, the piling machine can also be located on a barge or other structure, allowing for pile installation at any location (including deepwater). Also, a "one-step approach" has been developed that synchronizes the construction process into a single sequence of events in which the bulk of temporary works can be eliminated, allowing the construction works to proceed in a narrow construction corridor without encroaching onto nearby structures or services (Motoyama and Goh, 2007).

One advantage of this method over conventional pile driving is low noise. No underwater noise measurements of press-in piling machines are available, but sound levels are expected to be very low, significantly lower than for conventional piling techniques (Spence et al., 2007). However, no applications using press-in pilings for offshore oil and gas structures or wind turbines were identified during the information synthesis effort.

4.1.3 Cast-in-Place Piles

Construction techniques have been developed where a pile casing is drilled into place and then filled with concrete (Spence et al., 2007). The approach uses no impact or vibratory hammers and, therefore, offers a potential for noise reduction. Some sound would be associated with the drilling process (including associated machinery). However, Spence et al. (2007) noted that this method has been used only on land so far. Applicability to marine environments is unknown, especially deepwater applications.

4.1.4 Pile Caps (Cushion Blocks)

Pile caps, or cushion blocks, have been used to reduce pile driving noise (Spence et al., 2007; ICF Jones & Stokes, 2009). They consist of disks of material placed atop a piling to minimize the noise generated by the hammer. Materials typically used for pile caps include wood, nylon, and micarta blocks (Laughlin, 2006). (Micarta is a high-pressure laminate material consisting of layers of linen, canvas, paper, fiberglass, carbon fiber, or other materials bonded by resin.)

Laughlin (2006) showed that pile caps can significantly reduce underwater pressure levels generated by pile driving. Wood performed the best, with measured peak pressure reductions of 11 to 26 dB, but the wood caps tended to break down quickly and were prone to catching fire. Micarta showed 7 to 8 dB reductions, and nylon had 4 to 5 dB reductions.

Although pile caps or cushion blocks may not provide sufficient noise attenuation by themselves, they may be useful in conjunction with other methods and practices, such as air bubble curtains, cofferdams, or isolation casings, to provide attenuation that is additive to the noise reduction provided by these systems (Spence et al., 2007). Because the reduction in output energy is made at the point of impact with the pile, this is one of the very few methods of reducing transmission through a ground path. However, the durability and practicality of routinely using pile caps in marine environments have not been fully evaluated.

4.1.5 Alternative Pile Materials and Shapes

There is some indication that different pile materials and shapes create different underwater sound levels (MacGillivray, 2007; Spence et al., 2007). For example, driving concrete or wood piles instead of steel piles or driving H-type piles instead of circular concrete and steel piles may produce less noise from individual pile strikes (Spence et al., 2007; ICF Jones & Stokes, 2009). Also, the use of smaller piles may reduce peak sound pressure levels from individual strikes, although they may require that more piles be driven, resulting in a larger number of pile strikes compared to use of larger piles. The appropriate materials, shapes, and sizes of pilings for a particular application depend on the engineering design.

4.2 Low-Noise Foundations (Non-Piling Methods)

4.2.1 Gravity-Based Structures

Gravity-based structures are typically constructed from steel-reinforced concrete. The principle of gravity-based structures is that the weight of the structure and ballast holds it in place, therefore, no pile driving or drilling into the seabed is needed (Lindoe Offshore Renewables Center [LORC], 2011a). However, the seabed has to be prepared with dredging, gravel, and concrete. Gravity-based structures have been used for several offshore wind facilities in Europe, beginning with the first one offshore Denmark (Vindeby) in 1991 (LORC, 2011a). Other wind farms using this technology include Nysted, Middelgrunden, Rodsand, Sprogo, and Tuno Knob in Denmark; Lillegrund in Sweden; and Thornton Bank in Belgium (Luedeke, 2012). Gravity-based structures have also been used for offshore liquefied natural gas terminals (American Bureau of Shipping, 2010).

According to LORC (2011a), gravity-based structures are affordable at shallow water depths, but in depths beyond about 10 m they generally are not competitive with other types of structures. However, the Thornton Bank wind farm offshore Belgium is located in a water depth of 27.5 m (LORC, 2011a).

4.2.2 Suction-Based Foundations (Suction Piles, Buckets, or Caissons)

Suction piling presents an opportunity to reduce construction noise while potentially increasing installation speed. Suction piles are already widely used in the oil and gas industry for mooring drilling rigs and are a potential replacement for conventional piles as well as conventional piling methods (Spence et al., 2007). A suction pile is essentially a large drum with the bottom face removed. The pile is located on the seafloor, and a pump is used to remove water and create suction to pull the pile into the ground. The weight of the supported structure can also be used to assist seabed penetration. Grout ballast can be poured into the piles once they are located in place. A detailed report on the capabilities, analysis, and limitations of suction pile anchors is given by Andersen et al. (2005).

The same principle has been used as the foundation for offshore wind turbines. The water depth range for this method is 20 to 50 m (Vattenfall, 2011). In this application, a large suction bucket is attached to a cylindrical monotower supporting the wind turbine (Ibsen et al., 2005). When installed, the suction bucket acts like a gravity-based foundation. Calculations and tests show that the soil within the bucket is trapped and behaves like a mass block (LORC, 2011b).

A fully operational offshore wind turbine was installed on a prototype of the suction bucket foundation in Frederikshavn, Denmark in October 2002 (Ibsen et al., 2005). LORC (2011b) notes that a second prototype at Wilhelmshaven failed. However, the method is currently under consideration for a wind farm offshore Scotland (Vattenfall, 2011). Also, according to Belfast (2012), Fred Olsen United (a Norwegian renewable energy company) is developing plans to partner with an international equipment manufacturer to develop an all-in-one wind turbine and foundation delivery concept within 5 years. These foundations combine monopile, gravity-based structure, and suction-anchor technology. The company hopes to have a first prototype turbine based on its suction-bucket foundation design installed offshore Denmark in 2013 and to conduct a pilot project of 5 to 10 machines in 2014 (Belfast, 2012).

Although underwater sound measurements of suction pile installations are not available, it is expected that the noise of this method would be negligible relative to existing methods because the only noise source is the suction pump (Spence et al., 2007). All impulsive type sounds are removed using this approach. Also, suction methods can be used in both deep and shallow waters.

4.2.3 Drilled or Excavated Foundations

Ballast Nedam and MT Piling have developed a foundation method for offshore wind turbines using pre-cast concrete monopiles that are installed by drilling rather than hammering (Ballast Nedam Offshore, 2009). This would eliminate the underwater noise from pile driving. Other environmental aspects are expected to be similar to those for conventional offshore drilling.

Herrenknecht AG has developed a process called Offshore Foundation Drilling (OFD) that uses a Vertical Shaft Sinking Machine to install a monopile foundation for a wind turbine without pile driving (Herrenknecht AG, 2010; Geodrilling International, 2012). A cutterhead clamped in the foundation pile cuts its way to the seabed, along with the pile. The seabed is cut out circularly by a vertical drilling machine installed in the monopile. At the same time, the monopile is inserted into the resulting cavity until the specified total depth is reached. The OFD technology supports larger diameter foundations to be used (10 m vs. the typical limit of 6 m) and makes it possible to use more cost-efficient reinforced concrete monopiles instead of steel piles (Geodrilling International, 2012).

4.2.4 Floating Foundations

Floating structures are used extensively in the oil and gas industry in deepwater areas (USDOI, Minerals Management Service, 2000; Richardson et al., 2008). Floating designs have also been developed for offshore wind facilities, although they are currently the least-used and least-proven method (LORC, 2011c). Only a few wind turbines in the world use floating support structures (e.g., Hywind in Norway and Windfloat offshore Portugal as well as a few scale models in other locations) (LORC, 2011c).

Three different types of floating foundations are recognized for wind facilities (LORC, 2011c): spar, tension leg platform, and barge floater (referred to as a moored semisubmersible in the oil and gas industry). All originated with the oil and gas industry, but modifications and hybrids are beginning to emerge in their use for wind turbines (LORC, 2011c).

4.3 Mitigation Methods to Attenuate Noise from Pile Driving

Various techniques have been developed that consist of a barrier that is placed around a pile to attenuate sound from hammering. The barrier may be drained or filled with a confined bubble layer or other absorptive material. Cofferdams and bubble curtains are the most common examples of this approach. A recent study funded by the German government (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) included several innovative methods that fall into this category (Luedeke, 2012; Verfuss, 2012; Wilke et al., 2012).

4.3.1 Cofferdams

Cofferdams are temporary structures used to isolate an area generally submerged underwater from the water column (ICF Jones & Stokes, 2009). They are most commonly fabricated from sheet piling or inflatable water bladders. Cofferdams typically are dewatered to isolate the piling from the water, which attenuates sound by providing an air space between the pile and the water column. If the cofferdam cannot be effectively dewatered, sometimes attenuation can be achieved by using a bubble curtain inside the cofferdam. Dewatered cofferdams generally can be expected to provide attenuation that is at least as great as the attenuation provided by air bubble curtains (ICF Jones & Stokes, 2009). However, the sound is not completely eliminated because some of the energy is transmitted through the ground.

Stokes et al. (2010) evaluated the potential effectiveness of a massive, dewatered cofferdam for mitigating noise from pile driving of large monopiles during construction of offshore wind farms. Modeling predicted that a massive dewatered cofferdam would reduce noise levels by approximately 20 dB. This is considered to be the upper bound on possible noise mitigation treatment performance. A second phase is currently exploring the engineering feasibility of a dewatered cofferdam (USDOI, Bureau of Safety and Environmental Enforcement, 2011).

Setup of dewatered cofferdams is likely to require more time than other similar methods, such as lined barriers and bubble curtains, because the barrier needs to be set on the seafloor such that no leaks are possible (Spence et al., 2007).

4.3.2 Bubble Curtains

A bubble curtain is a sheet or “wall” of air bubbles that is produced around the location where the pile driving will occur (Spence et al., 2007). The bubbles typically are created by forcing compressed air through small holes drilled in metal or PVC rings or hoses. Air bubbles in water create an acoustical impedance mismatch that is effective in blocking sound transmission. Additional attenuation can be achieved by taking advantage of the dispersion and attenuation of underwater sound near the bubbles' individual resonance frequency due to absorption and scattering (Leighton, 1994; Lee et al., 2012).

Air bubble curtains can be confined or unconfined (ICF Jones & Stokes, 2009). The simplest unconfined system consists of a single ring around the base of the piling. In a confined system, the bubbles are confined with a flexible material (plastic or fabric) or a metal casing. Confined bubble curtains are most often used when there is potential for high water-current velocities to sweep the bubbles away from the pile. Because many projects cannot accommodate a large cylinder around the pile, multistage bubble curtains have been developed consisting of series of rings around the pile at different depths (Reyff, 2009). Although, in this unconfined system, currents could sweep the bubbles away, the ring above would generate more bubbles, maintaining a uniform presence of air around the entire pile (Reyff, 2009).

In addition to currents, practical problems include the control of bubble size distribution and the production of a sufficient number of large bubbles (several centimeters diameter) to achieve efficacy at low frequencies (Matuschek and Betke, 2009). The design of bubble curtains must also take into account many non-acoustical factors of the local environment, such as the size and type of pile to be driven; the type of hammer (impact or vibratory); the energy produced by the hammer; water depth; tides, currents, and sea state; subsurface geotechnical considerations; forces transmitted into the contractor's template, rig, or barge; and the contractor's standard operating procedures, which may not include sound attenuation systems (Spence and Dreyer, 2012).

A further refinement of the bubble curtain concept is the use of stationary, encapsulated bubbles consisting of a volume of air within a flexible or hard shell (Elmer et al., 2012a,b; Lee et al., 2012; Spence and Dryer, 2012). These systems are discussed separately below in **Section 4.3.3**.

There are many studies of the effectiveness of bubble curtains, including for wind turbine foundations (Matuschek and Betke, 2009; Stokes et al., 2010; Lucke et al., 2011; Rustemeier et al., 2011; Nehls, 2012), docks and other coastal construction projects (Laughlin, 2006; MacGillivray and Racca, 2006; MacGillivray, 2007; Reyff, 2009; Spence and Dryer, 2012), and pile driving activities (Würsig et al., 2000; Lee et al., 2012). Reductions in peak pressure, RMS pressure, and energy have been reported in the literature to range between 5 to 20 dB (as summarized by Spence and Dreyer, 2012). Data reviewed by ICF Jones & Stokes (2009) generally indicate that an air bubble curtain used on a steel or concrete pile with a maximum cross-section dimension of 24 in. or less will provide about 5 dB of noise reduction. For a mid-sized steel pile (with a dimension greater than 24 in. but less than 48 in.), the data indicate that an air bubble curtain will provide about 10 dB of noise reduction. For larger piles (with a dimension of greater than 48 in.) about 20 dB of noise reduction is indicated.

Because the results for individual studies depend so much on the specific application being evaluated, it is difficult to generalize other than to note that bubble curtains can produce noise reductions that are sufficient to meet objectives such as avoiding fish kills (Laughlin, 2006; Reyff, 2009), reducing behavorial disturbance of marine mammals (Lucke et al., 2011; Nehls, 2012), and meeting regulatory noise criteria (Verfuss, 2012; Wilke et al., 2012).

4.3.3 Methods Using Encapsulated Bubbles

A further refinement of the bubble curtain concept is the use of stationary, encapsulated bubbles consisting of a volume of air within an flexible or hard shell (Lee et al., 2012; Elmer et al., 2012a,b; Spence and Dryer, 2012). Because freely rising bubbles tend to become unstable and break up into smaller bubbles and can be disrupted by currents and waves, Lee et al. (2012) developed a system in which large, encapsulated bubbles were created by encapsulating a predetermined volume of air within a thin elastic shell composed of latex or polyurethane. The bubble size was chosen so that the screen provided the most attenuation at frequencies near the peak frequencies emitted by the noise source. The encapsulated bubble curtain was used to partially shield a receiving area from underwater pile driving noise, and the curtain provided more than 10 dB of noise reduction in the 100- to 300-Hz frequency band coincident with the peak frequencies generated by the pile driving events.

Elmer et al. (2012a,b) describes a new, patented method using hydro sound dampers to reduce underwater noise from pile driving. The method, which was included in the German government study of mitigation methods for wind turbine foundations, uses small, thin gas-filled latex balloons and robust polyethylene foam elements fixed to a donut-shaped fishing net fixed around the piling. The resonance frequency of the air-filled latex balloons in water is adjustable, even to low-frequency ranges, in contrast to free, natural air bubbles and is inversely proportional to the diameter of the balloon. The resonance frequency also varies depending on the gas pressure inside, the water depth, and the stiffness of the encapsulating material. The size of the balloons, the effective frequency range, the damping rate, the number and distribution of the hydro sound dampers, and the influence from hydrostatic water pressure can be fully controlled. This system is independent of compressed air, not influenced by currents and tides, and easy adaptable to different applications. Modeling, laboratory experiments, and field testing in the Baltic Sea indicate that the system is a very effective noise mitigation method. The theoretical background, numerical simulations, laboratory tests, and offshore tests of the hydro sound damper system result in noise reduction of between 17 and 35 dB (sound exposure level [SEL]) (Elmer et al., 2012b).

Spence and Dreyer (2012) investigated an alternative approach where a “hard bubble” is used instead of a bubble encased with a soft membrane. The primary bubble is a 17-in. diameter ball made from high-density polyethylene with wall thicknesses ranging from 0.44 to 0.19 in. (11 to 5 mm). These balls are aligned within heavy-duty fabric sleeves that are designed to withstand very large loads. The barrier itself is buoyant and floats on the water surface; to orient the barrier vertically, ballast is suspended from the bottom of the barrier. Preliminary testing was done in a lake to evaluate the acoustical effectiveness of the design, and modeling was conducted to evaluate how a full-scale barrier would perform. The authors note that a hard bubble barrier has been installed and used to mitigate sounds from pile driving, but the results have not been officially released and cannot be reported.

4.3.4 Isolation Casings

ICF Jones & Stokes (2009) describe “isolation casings” as hollow tubes slightly larger in diameter than the piling to be driven (ICF Jones & Stokes, 2009). The casing typically consists of a larger hollow pile that is placed into the water column and the seabed. The casing then is dewatered, and the piling is driven within the dewatered isolation casing. Isolation casings are similar to cofferdams in that they isolate the work area from the water column; however, they have a smaller footprint and are suitable for individual pilings rather than multiple-piling installations. In addition, because of the smaller air space between the pile and the casing, they do not have as much attenuation value as cofferdams. The attenuation is generally at least as great as that provided by bubble curtains (ICF Jones & Stokes, 2009).

Reinhall and Dahl (2011) surrounded a piling with a double-walled steel tube, which they called a temporary noise attenuation pile (TNAP), to reduce the underwater sound caused by pile driving. The TNAP consisted of two concentric pipes with outside diameters of 60 and 48 in. and a wall thickness of 1 in. The space between the inner and outer steel tubes was partially filled with sound-absorbing material. Bubbles between the pile and the hollow tube were introduced though a bubble ring at the bottom of the TNAP. Tests and analysis showed that the noise attenuation capability of the TNAP was limited to approximately 10 dB because of the unconstrained propagation of Mach waves directly from the sediment into the water (Reinhall and Dahl, 2011). However, these measurements were limited to the immediate vicinity of the piling (e.g., within 15 m).

4.3.5 Noise Mitigation Screens

Jansen et al. (2012) described a method that uses a steel noise mitigation screen around the pile with the option of an additional confined air bubble layer. This was one of the concepts included in the German government study and was engineered by IHC Hydrohammer in the Netherlands. The noise mitigation screen is a double-walled steel cylinder and the outer cavity is usually filled with air, which provides isolation between the water inside and outside of the cylinder. When the system was tested with air inside the double-wall cavity and an air bubble screen between the pile and inner wall, the SEL at 750 m distance dropped by 10 to 11 dB (Jansen et al., 2012). The loss was frequency dependent, with a slope of about 2 dB/octave, and exceeded 20 dB in the frequency range beyond 2 kHz. The authors noted that to comply with regulatory limits, the insertion loss in the lower frequency range from 100 to 250 Hz needs to be improved. This could be achieved by increasing the bubble size, increasing the amount of bubbles, increasing the gap between inner and outer cylinder wall, and by improving the acoustical decoupling of the guidance rollers between the pile and the noise mitigation screen.

4.3.6 Ring of Fire Hoses

Another method tested in the German government study used a ring of fire hoses (Verfuss, 2012). This method developed by MENCK GmbH involves a single or double wall of fire hoses filled with compressed air. The system consists of 222 fire hoses, which are staggered so that the effective thickness of the sound-insulating wall is increased and larger air gaps are avoided. It offers several advantages, including requiring only a small air demand to inflate the system and the fact that the hoses are foldable and can be stored easily. Tests showed that the maximum efficiency in noise reduction was between 1.2 and 8 kHz (Verfuss, 2012). Wilke et al. (2012) indicate that this method reduced sound levels by about 4 to 5 dB (SEL) at a distance of 375 to 750 m from the pile.

4.3.7 BEKA Jacket

Another method tested in the German government study is a “BEKA jacket” developed by Bernhard Weyres Offshore (Verfuss, 2012). It consists of two half-shells of steel and industrial sound dampers. In addition to the double steel wall with polymer filling, it included inner and outer bubble curtains. The maximum damping efficiency was reportedly between 500 Hz and 10 kHz. Wilke et al. (2012) indicate that this method reduced sound levels by about 6 dB (SEL) at a distance of 375 to 750 m from the pile.

4.3.8 Evaluation of Systems for Ramming Noise Mitigation (ESRa)

The German government recently conducted a study comparing several noise reduction methods at an offshore wind turbine location in the North Sea (Verfuss, 2012; Wilke et al., 2012). This Evauation of Systems for Ramming Noise Mitigation study included several of the systems discussed in this section, including large and small bubble curtains, hydro sound dampers, noise mitigation screen, ring of fire hoses, and the BEKA jacket. According to Wilke et al. (2012), all systems worked well, but the achieved sound reductions were highly frequency dependent. In the frequency range of 100 to 300 Hz, where most of the energy is concentrated, the damping was between 0 and 10 dB (SEL). There was no clear “winner” among the tested systems with respect to noise reduction. Luedeke (2012) states that the mitigation measures tested in the German study have not yet achieved the high potential for sound reduction indicated by the design models for these systems and more research is required to achieve the goal.

One underestimated factor in the mitigation methods testing in the ESRa project is the propagation path along the bottom. The ESRa project showed that all of the mitigation measures tested showed approximately the same reduction in radiated noise. These values look very similar to those found in the field during “real” pile driving. All measures are limited to 10 to 15 dB noise reduction, but 20 dB are needed to meet German regulations. As all measures block only the water path, there must be a limit due to the bottom path. The bottom path may also be responsible for low frequency long distance propagation.There are ongoing systematic investigations of this issue in Germany (D. Wittekind, pers. comm.).

5. SHIP NOISE

One objective of the workshop is to "review and examine developments (existing, emerging and potential) in quieting technologies for vessel noise associated with OCS energy development activities." BOEM is specifically interested in *noise from vessels associated with activities that BOEM regulates*. These would include ships involved in conducting and supporting seismic surveys and pile driving, but also more broadly any ships involved in offshore energy exploration and development such as drillships, dynamically positioned semisubmersible drilling rigs, offshore service vessels, supply boats and crew boats, standby vessels, tugs and pushers, anchor handling vessels, crane vessels, vessels involved in platform or wind turbine installation, pipe laying and cable laying barges, and (in Alaska) ice breakers. However, most of the literature on this subject is not specific to ships involved in offshore energy exploration and development.

Ship noise from OCS energy development activities is part of a broader suite of issues that include both the noise radiated by individual ships and distant shipping noise – i.e., the contribution of multiple ships to the ambient noise. Reducing the overall level of shipping noise is an international problem that is the subject of ongoing efforts as summarized briefly here, but is not the focus of this review.

5.1 BACKGROUND

Shipping noise is ubiquitous in the world's oceans and is the dominant source of underwater noise at frequencies below 300 Hz in many areas (Wenz, 1962; Ross, 1976; Andrew et al., 2002, 2011; Hildebrand, 2009). In some areas, there is evidence that shipping noise is increasing as the level of ship traffic increases (Frisk, 2012). Measurements in the northeast Pacific Ocean suggest an average noise increase rate of 2.5 to 3 dB per decade at low frequency (ca. 10 Hz to 40 Hz) during the last 35 years of the 20th century (McDonald et al., 2006; Andrew et al., 2011).

There has been an increasing level of discussion and concern regarding the effects of anthropogenic noise on marine mammals (Richardson et al., 1995; National Research Council, 2003, 2005; Marine Mammal Commission, 2007; Southall et al., 2007, 2009). Payne and Webb (1971) first raised the possibility that noise from anthropogenic sources might affect marine mammal communication. Acoustic masking from shipping noise and other anthropogenic sources is increasingly being considered as a threat to marine mammals, particularly low-frequency specialists such as baleen whales (Clark et al., 2009; Castellote et al., 2010; Hatch et al., 2012) as well as fishes (Slabbekoorn et al., 2012).

Until recently, there was no standard way of measuring underwater noise from individual ships (Renilson, 2009). In 2006, the Acoustical Society of America formed a working group (WG-47) to develop an American National Standard for the measurement of underwater noise levels of ships using commercial technology (Acoustical Society of America, 2009). On 30 September 2009, the end product of WG-47 was published as ANSI S12.64-2009/Part 1, "Quantities and Procedures for Description and Measurement of Underwater Sound from Ships -Part 1: General Requirements." Two ISO Working Groups (TC8/SC2/JWG1 and TC43/SC3/WG1) are now working on respective international standards for radiated noise level and source level (M. Ainslie, pers. comm.).

5.2 PREVIOUS SHIP NOISE WORKSHOPS AND RELATED ACTIVITIES

The National Oceanic and Atmospheric Administration (NOAA) has held two workshops on ship noise (2004 and 2007). Another workshop was held in 2008 by the Okeanos Foundation. Related activities include the formation of a Correspondence Group on underwater noise as part of the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO).

5.2.1 2004 NOAA Workshop (Arlington)

The 2004 NOAA workshop, held in Arlington, Virginia titled “Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology,” essentially served as an introduction of the issue to industry representatives, conservation managers, and scientists. At that meeting, a number of recommendations for future action and consideration were made, including the need for a greater scientific basis for assessing the relative magnitude of the potential problem and various mitigation measures directed to reduce impacts. A summary report is provided by Southall (2005).

5.2.2 2007 NOAA Workshop (Silver Spring)

A more targeted NOAA workshop was held in Silver Spring, Maryland in May 2007, titled “Potential Application of Vessel-Quieting Technology on Large Commercial Vessels.” The workshop results are summarized by Southall and Scholik-Schlomer (2008). The symposium consisted of three technical sessions interspersed with various configurations of working groups and plenary discussions. Technical sessions focused on the acoustic, biological, and shipping-industry-specific information necessary to consider vessel-quieting technologies, the technical aspects of existing quieting options, and potential motivations (non-regulatory, not directly economic) that might lead the shipping industry to apply vessel-quieting technologies. The symposium concluded with a plenary session in which participants reached a general conclusion that initial efforts need to focus primarily on propulsion systems, whereas considerations of machinery noise and flow noise are likely secondary. Additionally, there was a general conclusion that many of these issues have not been seriously considered in the design and operation of large vessels. Consequently, a primary initial measure may simply be to inform ship designers, owners, and operators of this environmental issue. The participants concluded that a starting point in this regard could be an information paper on this subject submitted to the IMO.

5.2.3 2008 Okeanos Workshop (Hamburg)

The Okeanos Foundation hosted the “International Workshop on Shipping Noise and Marine Mammals,” which took place in April 2008 in Hamburg, Germany (Wright, 2008). Participants’ expertise covered both biology and ship technology. As a goal, the groups set a reduction in the contribution of shipping to ambient noise in the 10- to 300-Hz band by 3 dB in 10 years and by 10 dB in 30 years, relative to current levels. The group then proceeded to lay the groundwork for a submission to the IMO MEPC, which participants agreed to be the appropriate body to consider and manage the issue of noise from shipping (Paulmann, 2008). Accordingly, a summary in the form of a Statement of Participants was co-written by all participants and subsequently released (included in the workshop report by Wright, 2008). Background papers summarizing much of the information contained within the presentations were also written by the participants and included in the workshop report in the hope that these documents might spur and support a submission by a Member State to the MEPC.

5.2.4 International Maritime Organization and European Union Activity

Following the Okeanos workshop, the IMO took up the issue of shipping noise and founded a Correspondence Group as part of the MEPC (IMO, 2012). The Correspondence Group was established to develop non-mandatory draft guidelines for reducing underwater noise from commercial ships, giving special consideration to prioritize areas that should be assessed for potential underwater noise reduction (propulsion, hull design, onboard machinery, and operational modifications), and to examine the available options for ship-quieting technologies and operational practice. The Correspondence Group has collected information from experts from around the world; this information is awaiting processing in a next step toward a Working Group within one of the technical committees (Sub-Committee on Ship Design and Equipment) in IMO (Wittekind and Weilgart, 2012).

Also in 2008, the European Union (EU) issued a Marine Strategy Framework Directive (MSFD, 2008/56/EC) establishing a framework for community action in the field of marine environmental policy

(EU, 2008). The directive included anthropogenic noise as one form of pollution introduced into the environment. Annex I of the MSFD lists qualitative descriptors of good environmental status, including Descriptor 11: “Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.” A task group was formed to develop possible indicators for underwater sound (Tasker et al., 2010). In 2010, the European Commission (EC, 2010) issued a decision on criteria and methodological standards on good environmental status of marine waters, which included the following criteria for the Descriptor 11:

- Distribution in time and place of loud, low and mid frequency impulsive sounds – Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1μPa^{2}s) or as peak sound pressure level (in dB re 1μPa peak) at one meter, measured over the frequency band 10 Hz to 10 kHz (criterion 11.1.1).
- Continuous, low frequency sound – Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (center frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (criterion 11.2.1).

The EC also decided that guidance was needed to help member states implement the indicators that were chosen in the 2010 EC decision. A technical subgroup on noise (TSG Noise) was formed to clarify the purpose, uses, and limitations of the indicators and describe methodology that would be unambiguous, effective, and practicable. TSG Noise issued a report in February 2012 that made significant progress towards practical implementation of the indicators for both impulsive and ambient noise, identified knowledge gaps and future work, and included recommendations on the way forward (Van der Graaf et al., 2012).

5.3 Ship Noise Sources

The main noise sources from ships include propellers and thrusters, machinery, sea-connected systems (e.g., pumps), and hydrodynamic noise caused by the movement of the hull through the water (Spence et al., 2007; Renilson, 2009; Barber, 2012a,b). Propeller cavitation is usually the dominant source for large commercial vessels (Brown, 2007).

5.3.1 Propeller Cavitation

Propeller cavitation is a phenomenon that occurs when a propeller is passing through the water at a sufficient speed to cause a low-pressure area to form on the blade surface (Renilson, 2009). When the local pressure is reduced to the vapor pressure of water, water vapor bubbles move across the propeller blade surface. The underwater noise is caused by the collapse of these bubbles.

Cavitation noise commonly arises at vessel speeds between 8 and 12 kts and grows in amplitude with increasing speed (Spence et al., 2007). The lowest speed at which cavitation occurs is known as the Cavitation Inception Speed. Surface warships are designed to operate as fast as possible without cavitation, but this advanced technology is unlikely to make any significant difference to the noise generated by the noisier merchant ships (Renilson, 2009).

Cavitation noise at slow speeds can be significant with ships that have CRP (controllable reversible pitch) props. Often such ships are diesel powered, a system that runs most efficiently at constant revolutions per minute (RPM) with the speed controlled by the pitch setting, thus high pitch produces high speed. Cavitation occurs at low pitch angles, and such ships make more noise at slow speed than at fast. Noise increases on order of 20 dB or more may result (W. Ellison, pers.comm.).

Cavitation noise, when present, typically dominates the radiated noise spectrum at higher frequencies (above a few hundred hertz) and can also have significant influence below this frequency (Spence et al., 2007). Cavitation noise occurs when vessels are underway at transit speeds (i.e., most of the time for many vessels), when vessels use controllable pitch propellers at "off-design" pitch, when vessels are operating under high load conditions, or when dynamic positioning systems (thrusters) are used.

Propeller cavitation is discussed further by Spence et al. (2007) and Renilson (2009), including extensive earlier literature citations.

Another phenomenon is propeller "singing," which can create additional tones in the radiated noise spectrum (Spence et al., 2007). This noise is created at one or more specific propeller blade resonance frequencies, which are excited by vortex shedding. The vibrating blades radiate sound into the water.

5.3.2 Machinery Noise

Shipboard machinery creates both vibration and airborne noise. Noise can be radiated into the water by means of three main paths (Spence et al., 2007):

- First structureborne – Vibrations from machinery are coupled to the ship structure through the machinery attachment points and carried throughout the ship. When the ship's hull is excited by these vibrations, underwater radiated noise is produced.
- Airborne – In this pathway, airborne noise from machinery passes through the ship's hull when the machinery is located in a compartment adjacent to the water.
- Secondary structureborne – This occurs when airborne noise from machinery impinges on the source compartment boundaries (deck, bulkheads, and deckhead), causing those structures to vibrate, and those vibrations, in turn, travel through the ship and are radiated into the water from the hull. For example, airborne noise from diesel engines impinging on the nearby hull and tank structure may become a significant factor in radiating underwater energy (Fischer et al., 2006).

Machinery noise levels for a particular vessel depend on the equipment itself, its function and duty cycle, pertinent noise paths, and the underwater noise goals for the vessel (Spence et al., 2007). A detailed analysis would be required to define this list for any specific vessel. However, the most important sources typically are propulsion machinery, such as diesel engines or turbines, as well as diesel generators (Spence et al., 2007). Other important sources include pumps (especially large pumps greater than 1,000 HP and with long duty cycles), propulsion gearboxes, and other auxiliary machinery items. Equipment located close to the ship's hull will be more significant than equipment located farther away (Spence et al., 2007).

Machinery-induced noise is generally tonal in nature, and radiated noise can span the frequency range from very low frequencies (~10 Hz or less) to several thousand hertz (Spence et al., 2007). Higher frequency tones are typically seen at slow speeds where they are not masked by propeller cavitation. Tones below a few hundred hertz can be prominent at all speeds, particularly in vessels with large, hard-mounted propulsion engines such as tankers.

5.3.3 Sea-Connected Systems

Sea-connected systems typically consist of pumps with piping that is directly connected to the ocean (Spence et al., 2007; Barber, 2012a,b). These connections are generally made through sea chests. Noise is generated in the fluid by the pump/piping system and is directly radiated into the sea. Noise from sea-connected systems is generally an issue only for otherwise quiet vessels such as a fisheries research vessel and, even then, only at low speeds. This path will likely be of little concern for commercial vessels (Spence et al., 2007).

5.3.4 Hydrodynamic Noise

Hydrodynamic noise is caused by the movement of the hull through the water (Spence et al., 2007; Renilson, 2009; Barber, 2012a,b). Also, hull appendages such as rudders, stabilizer fins, struts, fairings, bilge keels, and sonar transducers may cavitate at high vessel speeds, introducing additional noise.

5.4 Noise Reduction Methods for Individual Ships

In general, underwater noise has not been a focus for ship designers and engineers (D. Wittekind, in Southall and Scholik-Schlomer, 2008). Exceptions are Navy ships, which include quieting features for tactical reasons, and, more recently, "green" research vessels (Bahtiarian and Fischer, 2006; De Robertis et al., 2012). For commercial ships, the main focus has been on reducing shipboard noise for the crew and passengers, preventing structural fatigue due to cyclic vibration, or preventing high ship vibration from adversely affecting machinery or equipment (e.g., Boroditsky et al., 2007; Spence, 2011; Fischer et al., 2012).

In addition to the NOAA and Okeanos workshop reports cited previously, two particularly useful reports were found that discuss methods and strategies for reducing underwater noise from ships:

- A 2007 "Review of Existing and Future Potential Treatments for Reducing Underwater Sound from Oil and Gas Industry Activities" prepared by Noise Control Engineering, Inc. for the Joint Industry Programme on E&P Sound and Marine Life (Spence et al., 2007); and
- A 2009 report by Renilson Marine Consulting Pty Ltd. (Renilson) on "Reducing Underwater Noise Pollution from Large Commercial Vessels," prepared for The International Fund for Animal Welfare (Renilson, 2009).

5.4.1 Methods to Reduce Noise from Propeller Cavitation

Propeller cavitation is the primary source of underwater noise for most ships and a likely priority for action—focusing on the noisiest vessels, at least initially. Renilson (2009) notes that, although there are only limited data on the underwater noise for merchant ships, it appears that there is a difference in noise levels between the noisiest ones and the quietest ones of the order of 20 to 40 dB (Carlton and Dabbs, 2009). It is almost certain that the noisiest ships suffer from greater levels of noise generated by cavitation than other merchant ships. Therefore, great gains could be made by reducing the noise output from the noisiest vessels.

Renilson (2009) and Spence et al. (2007) discuss several methods for reducing noise from propeller cavitation, which are summarized below:

- Reduced vessel speed – Reduced speed is one simple way to reduce propeller noise (Brown, 2007; Renilson, 2009). The simplest way to reduce inception of cavitation is by having large, slowly turning propellers. However, in some cases, it may be necessary to consider a redesign of the propeller(s), particularly for ships fitted with controllable pitch propellers, which can produce more noise at slow speeds as noted previously.

- Repair minor damage and remove marine growth – Small imperfections in propeller blades, particularly in the leading edge, can reduce their efficiency and may have a significant effect on the local cavitation, thus resulting in an increased level of underwater noise (Renilson, 2009). Propeller blades can easily be repaired while the ship is in routine drydock. Spence et al. (2007) refer to this as "regular maintenance."

- Foul release coating – Applying a non-toxic, anti-fouling coating ("foul release" system) to a propeller can improve its efficiency, and there is mixed evidence that it may also reduce noise (Renilson, 2009). However, Spence et al. (2007) note that "amplification was found at some frequencies under some conditions."

- Modify propellers to match actual use – Propellers on most ships are designed for predicted operating conditions, which rarely occur in practice. With careful record keeping, once a ship has been operating for a number of years, it should be possible to better understand the actual operating conditions for the propeller (Renilson, 2009).

Then, it may be possible to reassess the propeller design and modify the existing propeller or manufacture a new one with improved cavitation characteristics.

- Specially designed propellers and thrusters – Propellers and thrusters can be designed to delay the inception of cavitation and reduce its growth. Design guidelines for low-noise propellers and thrusters are summarized by Spence et al. (2007). There are several proprietary propeller design concepts that claim increased efficiency and a reduction in cavitation/vibration, although some have not been independently verified (Renilson, 2009). Specific examples discussed by Renilson (2009) are highly skewed propellers, Contracted and Loaded Tip propellers, Kappel propellers, and New Blade Section propellers. Unconventional, forward-skew propellers have been implemented in ducted propeller designs and thrusters to significantly improve noise and thrust performance (Brown, 2007). Spence et al. (2007) also cite propellers made from composite materials.
- Wake inflow devices and ducted propellers (Kort nozzles) – Improving wake flow into the propeller can reduce cavitation (Renilson, 2009). There are a number of devices that can be fitted to the hull of a ship to improve the flow into the propeller. Specific examples discussed by Renilson (2009) are the Schneekluth duct, Mewis duct, simplified compensative nozzle, and Grothues spoilers. Spence et al. (2007) also discusses ring propellers in which there is a continuous ring attached to the blade tips of the propeller (as opposed to using a duct).
- Propeller hub caps – A propeller generates vortices from its hub, which reduce its efficiency and are prone to cavitate. Properly designed hub caps can reduce the hub vortex cavitation and, consequently, the hydroacoustic noise, as well as improving propeller efficiency, particularly for controllable pitch propellers. Specific examples discussed by Renilson (2009) are propeller boss cap fins and propeller cap turbines.
- Altering propeller/rudder interactions – The interaction between the propeller and the rudder has a significant impact on propulsive efficiency (Renilson, 2009). Various concepts have been developed to increase efficiency, such as a twisted rudder and rudder fins (Molland and Turnock, 2007). In addition, the Costa bulb (propulsion bulb) is a concept (typically limited to single screw vessels) where the propeller is integrated hydrodynamically with the rudder by fitting a bulb to the rudder in line with the propeller shaft. Spence et al. (2007) cite the PropacRudder, which is a streamlined torpedo-shaped bulb on the rudder horn that ensures a more homogeneous water flow both in front of the propeller and in the propeller slipstream.
- Propeller bubble emission and tunnel bubble emission – Air bubbles are emitted into the water through small holes in the propeller blades or the inlet and outlet of a thruster's tunnel wall (Spence et al., 2007). The air bubbles change the local acoustic impedance of the water, effectively "cushioning" the collapsing of the cavitation bubbles. These systems have been used on naval vessels, and much of the information is classified. Spence et al. (2007) note that noise reduction may be compromised due to increased cavitation effects; these systems are prone to marine growth; and holes can clog, requiring regular cleaning.
- Air bubble system – An air bubble curtain is produced that extends along some portion of the vessel's hull, creating an acoustical impedance mismatch that blocks sound transmission into the ocean (Spence et al., 2007).
- Anti-singing edge – An effective method of reducing propeller singing is to modify the propeller's trailing edge (Spence et al., 2007). The objective is to break up, alter, or

otherwise weaken the naturally occurring vortex-shedding phenomenon that leads to the singing tones. This modification can be applied to existing propellers.

Also, a background paper produced for the Okeanos workshop (Wright, 2008) noted that twin-screw ships may have smaller propeller loading and a more homogeneous wake field and, therefore, better working conditions for the propellers. As a result, propeller cavitation and the resulting underwater noise is reduced compared to single-screw ships (Wright, 2008).

Alternatives to conventional propulsion systems also offer opportunities for reducing noise. While these are not a solution for most existing vessels, they are a consideration in the design of new, quieter ships for some uses. Several examples discussed by Spence et al. (2007) are summarized below:

- Drop thrusters – These are thrusters that can be lowered below the vessel. Because they are separated from the vessel and supporting structures that can cause flow non-uniformities, drop thrusters have better inflow and outflow characteristics and lower underwater noise (Spence et al., 2007).
- Z-drives and podded propulsion systems (azipods) – These systems use special gearing and machinery arrangements to locate the propeller farther from the vessel in an area with improved flow characteristics. They are expected to be quieter for the same reason as drop thrusters (Spence et al., 2007).
- Waterjets – Waterjets are an alternative to conventional propeller systems for high-speed vessels; they have been used increasingly for ferries and other commercial ships. They operate by sucking water from the ocean and accelerating it out of the aft of the vessel, thereby creating thrust. Studies of underwater noise are limited (Spence et al., 2007).
- Rim drive propulsion – This is a new, unique thruster design in which the blades are driven from the perimeter rather than the center. This system does not require shafting, gears, or a separate electric motor or diesel engine (Spence et al., 2007).
- Voith-Schneider systems – These are alternative systems consisting of several long blades that extend vertically downwards from the vessel and can generate thrust in any direction (Spence et al., 2007).

5.4.2 Methods to Reduce Machinery Noise

As noted previously, the pathways for machinery noise are primary structureborne, secondary structureborne, and airborne. Spence et al. (2007) listed and evaluated the following treatments for primary structureborne noise (machinery vibration):

- Resilient isolation of equipment – Resilient mounts are effectively springs that react to the motions of the mounted machinery; they reduce vibration by mechanically isolating machinery from the supporting structure.
- Isolated deck/larger structure – In this arrangement, many equipment items are resiliently mounted on one “floating” deck.
- Damping tiles – These are used on stiffened plating near machinery sources, plating adjacent to water, and locations in between to reduce vibration energy in structures.
- Spray-on damping – This method reduces vibration energy in structures and is used on stiffened plating near machinery sources, plating adjacent to water, and locations in between.
- Ballast-Crete – This is a pre-blended commercial ballast material used in place of conventional liquid ballast to provide additional damping of structures in contact with the material.

- Air bubble system – An air bubble curtain is produced that extends along some portion of the vessel's hull, creating an acoustical impedance mismatch that blocks sound transmission into the ocean.
- Decoupling materials – A decoupling material (typically foam rubber, polyethylene foam, or similar material) is applied to the exterior of the hull to reduce its radiation efficiency.

Other methods are applicable to reducing airborne and secondary structureborne noise are discussed by Spence et al. (2007) and listed below:

- Exhaust silencers – These devices reduce airborne noise from exhaust stacks.
- Fiberglass/mineral wool/"HTL" cladding – Materials are applied to boundaries of machinery spaces to block and absorb noise from airborne and secondary structureborne paths.
- Machinery enclosures – A sealed enclosure is used to surround the machinery item to block and absorb airborne noise.
- Barriers – A barrier is essentially a wall or other solid surface that blocks noise traveling in a direct path from a source to receiver. This method applies only to equipment located outdoors with a direct line-of-sight path to the water.

Also, for machinery noise in general, selection of low-noise equipment is another method of reducing the levels of underwater noise radiated into the ocean (regardless of the pathway). Spence et al. (2007) notes that differences of 5 dB are common for machinery of the same type developed by different manufacturers.

5.4.3 Methods to Reduce Noise from Sea-Connected Systems

Spence et al. (2007) discussed two general treatments for reducing fluid-borne levels inside piping attached to pumps: flexible pipe connections and pulsation dampers.

Flexible pipe connections reduce sound pressure levels by creating an impedance mismatch for fluid-borne (and structureborne) energy. Noise attenuation is broadband, with increasing effectiveness at higher frequencies.

Pulsation dampers are acoustical absorbers that are either located in-line or in-parallel with the pipe. Parallel dampers are "tuned" to have a resonant frequency (e.g., the rotation rate or blade rate of a pump) and work only at that frequency, but their effectiveness can be dramatic. In-line dampers typically use an air-filled bladder that reacts to pulsations in the fluid. Their effectiveness covers a larger frequency range than parallel dampers, but their effectiveness is smaller.

5.4.4 Methods to Reduce Hydrodynamic Noise

The hull form has a considerable influence on the power required to propel a vessel and the underwater noise propagated from its propeller (Renilson, 2009). A well-designed hull will require less power for a given speed, which is likely to result in less noise being transmitted into the water. In addition, a well-designed hull form will provide a more uniform inflow to the propeller, thereby increasing the propeller's efficiency and reducing noise and vibration caused by the uneven wake flow. Optimizing of the propeller with the hull can also create a more uniform wake field.

Renilson (2009) notes that only about 5% of new-build projects have the benefit of resistance and propulsion and propeller cavitation model testing during their design (Carlton, 2009). In general, minimizing underwater noise has not been a focus for ship designers (D. Wittekind, in Southall and Scholik-Schlomer, 2008).

For existing ships, there is some potential to improve the wake flow into the propeller by fitting appropriately designed appendages, such as wake equalizing ducts, vortex generators, or spoilers (Renilson, 2009). The technology exists to do this, but little is known about how they would affect underwater noise.

5.5 OPERATIONAL AND PLANNING METHODS

The preceding section focused on noise reduction for individual ships. At a broader level, reductions might be achieved by operational and planning methods that involve regulating vessel speed, routing, and scheduling (Southall and Scholik-Schlomer, 2008). The goal would be to reduce the level of shipping noise by requiring individual ships to reduce speed (making most of them quieter, with the exception of some ships with CRP propellers as noted in Section 5.4.1) or by reducing the density of ship traffic in certain geographic areas and/or at certain times.

Speed reductions have been discussed previously in Section 5.4.1. The other approaches would involve planning vessel routes and schedules to reduce exposure of sensitive receptors to ship noise. For example, vessels could be routed to avoid sensitive areas such as marine mammal breeding, calving, or nursery areas during all times or certain seasons. Also, in theory, ships could be routed to avoid operating in environments that favor long-range transmission (Southall and Scholik-Schlomer, 2008).

The usefulness of these planning methods for seismic exploration and development surveys is likely to be limited. For these surveys, speed reductions are probably not feasible because the vessel speed is dictated by the data acquisition requirements and the logistics of towing source and receiver arrays. The typical towing speed is already slow – about 4.5 to 5 kts (OGP, 2011). The geographic scope of these surveys is determined by the geophysical objectives and can encompass hundreds of square miles over a period of many months. Seismic surveys require BOEM authorization and may be subject to geographic and temporal restrictions in sensitive areas, primarily because of airgun arrays rather than ship noise.

Similarly, placing geographic or temporal restrictions on service vessel activities probably is not practicable if the OCS development activity that the vessels are supporting is permitted in a particular area. Most service and support vessels operate at specific sites (such as rigs, platforms, or wind turbine sites) or travel regularly between rigs/platforms and onshore support bases. In transit, these ships usually follow the most direct route between the shore base and the offshore activity site. Because the geographic location and frequency of travel is determined by the nature of the activity that the service vessels are supporting, there is little opportunity for substantially changing routes or restricting ship traffic during certain times.

Speed reduction for OCS service vessels is a possibility that would need to be evaluated further. Typically, service vessels travel regularly between an offshore site (such as a platform) and an onshore support base several times per week, and a reduction in speed would have to be weighed against the possibility of increasing the duration and frequency of trips or the possibility of needing larger service vessels to provide the same support with fewer trips. It should be noted that all ships are subject to existing restrictions such as speed limits in channels and seasonal speed limits mandated by NOAA's Right Whale Ship Strike Reduction Rule (50 CFR 224.105) in the Mid-Atlantic and Southeast U.S. seasonal management areas for North Atlantic right whales.

Another aspect of planning would be to explicitly consider underwater noise during the selection of vessels for a particular project or for all projects in certain areas or seasons. Vessels involved in OCS energy development differ in the level of noise generated (Richardson et al., 1995). For example, dynamically positioned (DP) vessels, which are often used for drilling and construction activities in deepwater environments, are expected to produce more noise than conventionally moored vessels because DP thrusters operate more or less continuously while the ships are on station. However, selection of drilling rigs and support vessels depends on several factors such as water depth, vessel size and capacity, expected weather and sea state conditions, fuel consumption, and vessel day rate and availability. Also, environmental issues other than noise may also be important considerations (e.g., air pollutant emissions, benthic impacts of anchoring for moored vessels).

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8. GLOSSARY

The following glossary provides definitions for terms used in this report. For detailed technical definitions of acoustic quantities and terms, the reader is referred to "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units, TNO-DV 2011 C235" (Ainslie, 2011).

Acoustics: The scientific study of sound, especially of its generation, transmission, and reception.

Acoustic energy: Energy in an acoustic wave, measured in joules or watt-seconds; proportional to the product of pressure squared and time.

Acoustic intensity: The work done per unit area and per unit time by a sound wave on the medium as it propagates. The units of acoustic energy flux are Joules per square meter per second (J/m^2-s) or watts per square meter (W/m^2). The acoustic energy flux is also called the acoustic intensity.

Acoustic power: Energy per unit time in watts, proportional acoustic pressure squared.

Airgun: A pneumatic device used as an acoustic source to acquire marine seismic data. It is submerged below the water surface and towed behind a ship, usually as part of an array consisting of a number of airguns (i.e., airgun array).

Ambient noise: The typical or persistent environmental background noise present in the ocean, with contributions from natural sources (wind, waves, rain, animal sounds, earthquakes, etc.) and, often, from distant and indistinguishable anthropogenic sources such as shipping. Sound from specific nearby anthropogenic activities is usually not considered to be part of the ambient noise.

Amplitude: The maximum absolute value of a periodic curve measured along its vertical axis. For sound waves, it is the maximum amount that the wave's pressure differs from ambient pressure in the medium through which the sound wave is propagating.

Attenuation: Reduction of the level of sound pressure. Sound attenuation occurs naturally as a wave travels in a fluid or solid through dissipative processes (e.g., friction) that convert mechanical energy into thermal energy and chemical energy.

Bandwidth: The range of frequencies over which a sound is produced or received. The difference between the upper and lower limits of any frequency band.

Bar meter: Unit used in seismic survey industry for peak-to-peak source level of acoustic sources. For a sinusoidal source, 1 bar-meter = 220 dB re 1 µPa-m_{p-p} or 211 dB re 1 µPa-m_{RMS}.

Continuous sound: A sound for which the mean square sound pressure is approximately independent of averaging time.

Decibel (dB): A relative unit used to describe sound levels relative to a fixed reference level, calculated as 20 $\log_{10}$ (P/P_{ref}), where P is sound pressure and P_{ref} is the reference pressure. The reference for sound pressure in water is 1 micropascal (µPa).

Drilling rig: A structure used for drilling an oil or gas well.

Drillship: A self-propelled, self-contained vessel equipped with a derrick amidships for drilling wells in deep water.

Duty cycle: The percent of time a given periodic event or activity occurs.

Electromagnetic field: The field of energy resulting from the movement of alternating electric current along the path of a conductor, composed of both electrical and magnetic components and existing in the immediate vicinity of, and surrounding, the electric conductor.

Far field: A receiver is in the far field of a spatially extended source when the source appears to have point source properties.

FM sweep: A type of acoustic transmission for geophysical exploration in which a source generates frequency-modulated (FM) signals that sweep over a frequency band consisting typically of 3 to 6 octaves during a time period of 5 to 20 seconds. The sweep is usually repeated as the boat deploying the acoustic transmitting system progresses along a survey line. The low frequencies in the transmission are important for deep penetration of the acoustic waves in the earth, while the high frequencies are important for resolution of the interfaces between strata having different signal propagation characteristics.

Frequency: The rate of vibration, measured in cycles per second. Frequency is expressed in units of Hertz (Hz), where 1 Hz is equal to one vibration cycle per second. Frequency is perceived by humans as pitch.

Helmholtz resonator: A device that produces sound by generating oscillations in a container of gas with an open hole (or neck or port).

Hertz (Hz): The units of frequency where 1 hertz = 1 cycle per second.

Impulsive sound: Transient sound produced by a rapid release of energy. Impulse sound has short duration and high peak pressure relative to a continuous sound of comparable mean level.

Insertion loss: The reduction of noise level at a given location due to placement of a noise control device in the sound path between the sound source and that location. Usually rated in octave bands or 1/3-octave bands.

Intensity: For sound, intensity is the measure of the amount of energy that is transported over a given area per unit of time, expressed in units of W/m^2.

Lay barge: A shallow-draft, barge-like vessel used in the construction and laying of underwater pipelines.

Mach wave: A pressure wave traveling with the speed of sound caused by a slight change of pressure added to a compressible flow.

Masking: The obscuring of sounds of interest by interfering sounds, generally at the same or similar frequencies.

Micropascal (µPa): Reference level for underwater sounds; 1 µPa = 10^{-5} bar.

Near field: A region close to a sound source that has either irregular sound pressure or exponentially increasing sound pressure towards the source, and a high level of acoustic particle velocity because of kinetic energy added directly to the fluid by motion of the source. A receiver is in the near field of a spatially extended source when sound from different parts of the source can be resolved spatially.

Noise: Unwanted sound; a subjective term.

Octave or octave band: A frequency band whose upper limit in Hertz is twice its lower limit.

Outer Continental Shelf (OCS): All submerged lands constituting the continental margin adjacent to the U.S. and lying seaward of State offshore lands.

Pascal (Pa): A unit of pressure equivalent to 1 newton of force per square meter.

Peak pressure: This is the maximum instantaneous sound pressure measureable in the water at a specified distance from the source airgun.

Peak-to-peak pressure: This is the algebraic difference between the peak positive and peak negative sound pressures. Units are the same as for peak pressure. When expressed in dB, peak-to- peak pressure is typically ~6 dB higher than peak pressure for a source near the sea surface.

Pseudo-random noise (PRN): A periodic signal where one period is a segment of a random signal. For geophysical exploration, the mathematical properties of the PRN can allow analysts to separate weak signals from background noise.

Pulse: A brief, broadband, atonal, transient sound; e.g., an explosion, gun shot, airgun pulse, or pile driving strike. Pulses are characterized by a rapid rise from ambient pressure to maximal pressure, and (at least near the source) by short duration.

Received level: The level of sound that arrives at the receiver (e.g., a marine mammal) or listening device (hydrophone). The received level is the source level minus the transmission losses from the sound traveling through the water.

Resonance frequency: The frequency at which a system or structure will have maximum motion when excited by sound or an oscillatory force.

Root-mean-square (RMS) sound pressure: Average sound pressure over some specified time interval. For airgun pulses, the averaging time is commonly taken to be the approximate duration of one pulse, which in turn is commonly assumed to be the time interval within which 90 percent of the pulse energy arrives. The RMS sound pressure level (in dB) is typically ~10 dB less than the peak level, and ~16 dB less than the peak-to-peak level.

Seismic: Of, subject to, or caused by an earthquake or earth vibration.

Sound exposure level (SEL): The total noise energy produced from a single noise event; the SEL is the integration of all the acoustic energy contained within the event. The SEL takes into account both the intensity and the duration of a noise event. The SEL is stated in dB re 1 μPa^2 s for underwater sound.

Sound pressure: Pressure associated with a sound wave; difference between instantaneous total pressure and static pressure (the pressure that would exist in the absence of sound waves).

Sound pressure level (SPL): A measure of sound pressure expressed in dB re 1 μPa for underwater sound.

Source level: The received sound pressure level measured or estimated at a nominal distance of 1 m from the source. It is often expressed as dB re 1 μPa at 1 m. For a distributed source, such as an airgun array, the nominal overall source level, as used in predicting received levels at long distances, exceeds the level measurable at any one point in the water near the sources.

Supply boat: A boat that ferries food, water, fuel, supplies, and equipment between an onshore base and an offshore activity location such as a drilling rig, platform, or construction site.

Third octave band (1/3 octave band): Frequency band whose width is one-third of an octave.

Transmission loss: Pressure or energy losses that occur as the sound travels through the water. Losses occur because the wavefront spreads over an increasingly large volume as the sound propagates, and because of additional processes including scattering and the absorption of some of the energy by water.

Two-way travel time: The time for an acoustic signal to travel from a source to a reflector and return to the source/receiver location.

Watt: An International System unit of power equal to 1 joule per second.

Wavelength: Length of a single cycle of a periodic waveform.

APPENDIX B

LIST OF ATTENDEES

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APPENDIX C

PROGRAM (AGENDA AND BIO-SKETCHES)

WELCOME TO THE
QUIETING TECHNOLOGIES FOR REDUCING NOISE
DURING SEISMIC SURVEYING AND PILE DRIVING
WORKSHOP

25-27 February 2013
DoubleTree by Hilton Hotel
8727 Colesville Road
Silver Spring, Maryland 20910

Workshop Objective:

The workshop will examine current and emerging technologies that have the potential to reduce the impacts of noise generated during offshore exploratory seismic surveys, pile driving, and vessels associated with these activities.

Workshop Goals:

1. Review and evaluate recent developments (current, emerging/potential) in quieting technologies for:
   - Seismic surveying, whether proposed or in development;
   - Pile driving during offshore renewable energy activities; and
   - Vessel noise associated with Outer Continental Shelf (OCS) energy development activities.
2. Identify the spatial, spectral, and temporal features of the acoustic characteristics of new technologies in varying environments compared to that from existing technologies.
3. Identify the system and site specific requirements for operation of these new technologies and limitations in their use.
4. Discuss potential impacts, both positive and/or negative, in using these technologies:
   - Operational and cost effectiveness; and
   - Potential environmental impacts from these technologies.
5. Evaluate data quality and cost-effectiveness of these technologies as compared to that from existing marine acoustic technologies.
6. Discuss what the current, emerging/potential technologies can do to reduce sound output
7. Examine potential changes in environmental impacts from these technologies in comparison with existing technologies.
8. Identify which technologies, if any, provide the most promise for full or partial replacement of conventional technologies and specify the conditions that might warrant their use (e.g., specific limitations to water depth, use in Marine Protected Areas, etc.).
9. Identify next steps, if appropriate, for the further development of these technologies, including potential incentives for field testing.

Monday, 25 February 2013

7:30 a.m. **Registration**

8:30 a.m. **Welcome, Workshop Goals, Agenda, and Introductions** [Maryland Ballroom]

Welcome and Workshop Goals – *Megan Butterworth, BOEM* (5 min)

Agenda, Ground Rules, and Housekeeping – *Kim Olsen, CSA Ocean Sciences Inc.* (15 min)

Introduction to Workshop – *John Young, CSA Ocean Sciences Inc.* (25 min)

9:15 a.m. **Plenary Session I: Overview** [Maryland Ballroom]

(Facilitator: *James Theriault, Defense Research and Development Canada*)

Goals: 1) Regulatory requirement and BOEM Information Needs.
2) Provide opportunity to gain input from the European Union.

BOEM Environmental Program; Applied Science for Informed Decisions on Ocean Energy – *Robert LaBelle, BOEM Science Advisor to the Director* (20 min)

EU Marine Strategy Framework Directive – *René Dekeling, Netherlands Ministry of Infrastructure and the Environment* (20 min)

Questions and Discussion (15 min)

10:10 a.m. BREAK

10:25 a.m. **Plenary Session II: Knowledge from Other Workshops** [Maryland Ballroom]

(Facilitator: *Dr. Carrie Kappel, National Center for Ecological Analysis and Synthesis*)

Alternative Technologies to Seismic Airgun Surveys Workshop – *Dr. Linda Weilgart, Dalhousie University* (20 min)

Symposium Sound Solutions – *Dr. Georg Nehls, BioConsult SH GmbH & Co.* (20 min)

Effects of Noise on Fish, Fisheries, and Invertebrates Workshop – *Kimberly Skrupky, BOEM* (15 min)

A Summary of Existing and Future Potential Treatments for Reducing Underwater Sounds from Oil and Gas Industry Activities – *Michael Bahtiarian, Noise Control Engineering Inc.* (20 min)

Two NOAA-Organized technical workshops on shipping niose, marine mammals, and vessel-quieting technologies– Dr. *Brandon Southall, Southall Environmental Associates, Inc.* (20 min)

12:00 p.m. LUNCH

1:30 p.m. **Plenary Session III: Noise from Relevant Activities** [Maryland Ballroom]

(Facilitator: *Dr. Roger Gentry, ProScience Consulting, LLC*)

Goals: Examine noise from seismic airguns, pile driving, and support vessels (i.e., what is the scope of the problem?)

1) Discuss the physical mechanisms that produce noise associated with seismic airguns, pile driving, and support vessels.
2) Discuss associated sound levels from these activities and sound propagation in various environments (i.e., deep water, shallow water, etc.)

Terminology for Underwater Sound – *Dr. Michael Ainslie, TNO – Netherlands Organization for Applied Scientific Research* (15 min)

Spatial, Spectral and Temporal Properties of Sound Sources – *Dr. William Ellison, Marine Acoustics, Inc.* (15 min)

Airguns-An Overview – *Peter van der Sman, Shell* (25 min)

Driving Off Shore Wind Piles Quietly – *William Ziadie, American Piledriving Equipment* (25min)

Introduction to Ship Radiated Noise – *Dr. Chris Barber,* ***Multipath*** *Science and Engineering Solutions* (25 min)

Questions and Discussion (15 min)

3:30 p.m. BREAK

3:45 p.m. **Breakout Session I: Current, Emerging/Potential Quieting Technologies**

Goals: Gain a better understanding of existing quieting technologies for airguns and pile driving operations and the associated support vessels

Group 1 [Maryland Ballroom]

Airguns – Current, Emerging/Potential Quieting Technologies (Facilitator: *Mike Jenkerson, ExxonMobil*)

- Discuss existing technologies for quieting seismic airguns.
- Discuss all aspects with respect to improvements over earlier methods (i.e., control over amplitude, frequency, and propagation).

Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving – *Mike Jenkerson, ExxonMobil* (10 min)

Environmental Assessment for Marine Vibroseis (SAML JIP) – *Dr. William Ellison, Marine Acoustics Inc.* (15 min)

Marine Vibroseis JIP – *Mike Jenkerson ExxonMobil; Bob Rosenbladt, Shell; and Henri Houllevigue, Total* (20 min)

Questions and Discussion (30 min)

Group 2 [Capitol Room]

Pile Driving – Current, Emerging/Potential Quieting Technologies (Facilitator: *Dr. Michele Halvorsen, Pacific Northwest National Laboratory*)

- Discuss existing technologies for quieting pile driving.
- Discuss all aspects with respect to improvements over earlier methods (i.e., control over amplitude, frequency, and propagation).

Impact Pile Driving: Frequency, Angle, and Range Dependence and their Implications for Current and Potential Quieting Technologies – *Peter Dahl, University of Washington* (20 min)

Underwater Noise Mitigation Measures in Offshore Wind Farm Construction – *Sven Koschinski*, *Marine Zoology* (20 min)

Bringing the Bubble Curtain Offshore – Noise Mitigation at the Borkum West II Offshore Windfarm – *Dr. Georg Nehls, BioConsult SH GmbH & Co.* (20 min)

Questions and Discussion (15 min)

Group 3 [Potomac Room]

Introduction: Ship Noise – Current, Emerging/Potential Quieting Technologies (Facilitator: *Dr. D. Benjamin Reeder, Naval Postgraduate School*)

- Understand the existing technologies for quieting support vessels used during airgun and pile driving operations.
- Discuss previous noise levels versus current noise levels relevant to ship design.

Introduction – *Michael Bahtiarian, Noise Control Engineering Inc.* (10 min)

Measurements of Ship Radiated Noise – *Dr. John Hildebrand, Scripps Institution of Oceanography, UCSD,* (25 min)

Design Options and Operational Considerations for Reducing Ship Radiated Noise – *Dr. Chris Barber*, *Multipath Science and Engineering Solutions* (25 min)

Questions and Discussion (15 min)

5:00 p.m. ADJOURN

Tuesday, 26 February 2013

8:00 a.m. Coffee/Tea and Informal Conversation

8:30 a.m. Open Day 2 – *John Young, CSA Ocean Sciences Inc.*

8:45 a.m. **Breakout Session II: Current, Emerging/Potential Quieting Technologies (Cont.)**

Goals: Gain a better understanding for emerging/potential quieting technologies and operational methods used for airgun and pile driving operations.

Group 1 [Maryland Ballroom]

Airguns – Current, Emerging/Potential Quieting Technologies (Facilitator: *Mike Jenkerson, ExxonMobil*)

Quieting Technologies for Reducing Noise during Seismic Survey and Pile Driving – *Bill Pramik, Geokinetics* (20 min)

A Practical Marine Vibratory Sound Source – *Stephen Chelminski, Chelminski Research* (20 min)

Vibroseis – *Paul Novakovic, Independent Consultant* (20 min)

Questions and Discussion (30 min)

Group 2 [Capitol Room]

Pile Driving – Current, Emerging/Potential Quieting Technologies (Facilitator: *Dr. Michele Halvorsen, Pacific Northwest National Laboratory*)

Underwater Noise Abatement Using Large Encapsulated Air Bubbles and its Applications – *Dr. Mark S. Wochner, AdBm Technologies* (20 min)

How Quiet is Quiet? – *Dr. Michele Halvorsen, Pacific Northwest National Laboratory* (20 min)

Current and New Methods in Pile Driving Sound Attenuation– *Per Reinhall, University of Washington* (20 min)

Questions and Discussion (30 min)

Group 3 [Potomac Room]

Support Vessel Noise – Current, Emerging/Potential Quieting Technologies (Facilitator: *Michael Bahtiarian, Noise Control Engineering Inc.*)

Alternatives and Mitigation of Support Ship Noise – *Dietrich Wittekind, DW Shipconsult GmbH* (20 min)

Coordinated Management of Anthropogenic Sound from Offshore Construction – *Dr. David Zeddies, JASCO* (20 min)

Ship Noise: Implications for the detection of low-frequency whales during E&P operations – *Dr. Michel André, Universitat Politècnica de Catalunya* (20 min)

Questions and Discussion (30 min)

10:15 a.m. BREAK

Tuesday, 26 February 2013 *Continued*

10:30 a.m. **Breakout Session III: BOEM Workshop Goals**

Obtain Input on the Following Goals:

1. Review and evaluate recent developments (current, emerging/potential) in quieting technologies for:
   - Seismic surveying, whether proposed or in development;
   - Pile driving during offshore renewable energy activities; and
   - Vessel noise associated with Outer Continental Shelf (OCS) energy development activities.
2. Identify the spatial, spectral, and temporal features of the acoustic characteristics of new technologies in varying environments compared to that from existing technologies.

10:30 a.m. **Breakout Session III: BOEM Workshop Goals (*Continued)***

3. Identify the system and site specific requirements for operation of these new technologies and limitations in their use.
4. Discuss potential impacts, both positive and/or negative, in using these technologies:
   - Operational and cost effectiveness; and
   - Potential environmental impacts from these technologies.
5. Evaluate data quality and cost-effectiveness of these technologies as compared to that from existing marine acoustic technologies.

Group 1 [Maryland Ballroom]

Airguns (Facilitators: *Dr. Roger Gentry, ProScience Consulting, LLC and Dr. Timothy Ragen, Marine Mammal Commission*)

Group 2 [Capitol Room]

Pile Driving (Facilitators: *Dr. Michele Halvorsen, Pacific Northwest National Laboratory and Mark Tasker, Joint Nature Conservation Committee*)

Group 3 [Potomac Room]

Support Vessel Noise (Facilitators: *Dr. Carrie Kappel, National Center for Ecological Analysis and Synthesis; Michael Bahtiarian, Noise Control Engineering Inc.*)

12:00 p.m. LUNCH

1:30 p.m. **Breakout Session IV: BOEM Workshop Goals**

Obtain Input on the Following Goals:

6. Discuss what the current, emerging/potential technologies can do to reduce sound output.
7. Examine potential changes in environmental impacts from these technologies in comparison with existing technologies.
8. Identify which technologies, if any, provide the most promise for full or partial replacement of conventional technologies and specify the conditions that might warrant their use (e.g., specific limitations to water depth, use in Marine Protected Areas, etc.).

9. Identify next steps, if appropriate, for the further development of these technologies, including potential incentives for field testing.

Group 1 [Maryland Ballroom]

Airguns (Facilitators: *Dr. Roger Gentry, ProScience Consulting, LLC and Dr. Timothy Ragen, Marine Mammal Commission*)

Group 2 [Capitol Room]

Pile Driving (Facilitators: *Dr. Michele Halvorsen, Pacific Northwest National Laboratory and Mark Tasker, Joint Nature Conservation Committee*)

Group 3 [Potomac Room]

Support Vessel Noise (Facilitators: *Dr. Carrie Kappel, National Center for Ecological Analysis and Synthesis and Michael Bahtiarian, Noise Control Engineering Inc.*)

3:00 p.m. BREAK

3:15 p.m. **Plenary Session IV: Expert Panel Discussion** [Maryland Ballroom]

(Facilitator: *Dr. D. Benjamin Reeder, Naval Postgraduate School*)

1. Discuss new operational methods or activities related to seismic surveys, pile driving, and support vessel operations that could introduce additional noise going into the oceans or quiet noise (e.g., dual source, shooting with air guns, lower frequency seismic acquisition).
2. Discuss alternative/supplemental technologies (e.g., passive acoustics, gravity magnetometers).
3. Discuss potential mitigation for the above activities.

Facilitated Discussion (with response panel)

John Young, CSA Ocean Sciences Inc.
Dr. Michael Ainslie, TNO - Netherlands Organization for Applied Scientific Research
Dr. William Ellison, Marine Acoustics, Inc.
Dr. Brandon Southall, Southall Environmental Associates, Inc.
Dr. Linda Weilgart, Dalhousie University
Dr. Dietrich Wittekind, DW Shipconsult GmbH
Paul Bidmead, WesternGeco
Danielle Buonantony, Navy
William Ziadie, American Piledriving Equipment

5:00 p.m. ADJOURN

Wednesday, 27 February 2013

8:00 a.m. Coffee/Tea and Informal Conversation

8:30 a.m. Open Day 3 – *John Young, CSA Ocean Sciences Inc.*

8:45 a.m. **Plenary Session V: Current, Emerging/Potential Technology Presentation Break Out Groups Report Out** [Maryland Ballroom]

(Facilitator: *James Theriault, Defense Research and Development Canada*)

Goals: Report findings from Current, Emerging/Potential Technology breakout groups.

Group 1: Air guns – Update on Current, Emerging/Potential Technologies (20 min)

Group 2: Pile Driving – Update on Current, Emerging/Potential Technologies (20 min)

Group 3: Support Vessel Noise – Update on Current, Emerging/Potential Technologies (20 min)

Questions and Discussion (30 min)

10:15 a.m. BREAK

10:30 a.m. **Plenary Session VI: BOEM Workshop Goals Break Out Groups Report Out** [Maryland Ballroom]

(Facilitator: *Dr. Roger Gentry, ProScience Consulting, LLC*)

Goals: Report findings from BOEM Workshop Goals breakout groups.

Group 1: Airguns (20 min)

Group 2: Pile Driving (20 min)

Group 3: Support Vessel Noise (20 min)

Questions and Discussion (30 min)

12:00 p.m. LUNCH

1:30 p.m. **Plenary Session VII: Potential Environmental Impacts** [Maryland Ballroom]

(Facilitator: *Mark Tasker, Joint Nature Conservation Committee*)

Goals: Contrast the potential environmental impacts from current seismic and pile driving operations with that of emerging technologies and methodologies.

The Impact of Quieting Technologies on Aggregated Acoustic Footprints and Cumulative Effects – *Bill Streever, BP* (15 min)

Facilitated Discussion (with Agencies, Industries, and NGO's)

Ron Brinkman, BOEM
Louis Brzuzy, Shell
René Dekeling, Netherlands Ministry of Infrastructure and the Environment
Rune Tenghamn, Petroleum Geo-Services (PGS)
G.C. "Chip" Gill, International Association Of Geophysical Contractors
Mardi Hastings, Georgia Tech
Paul Holthus, World Ocean Council
Michael Jasny, NRDC
Mike Jenkerson, ExxonMobil
Bill Streever, BP

2:30 p.m. BREAK

2:45 p.m. **Plenary Session VIII: Closing Panel with a View to the Future** [Maryland Ballroom] (Facilitator: *Dr. Timothy Ragen, Marine Mammal Commission*)

Goals: Summarize and provide perspectives on the highlights of the workshop, including lessons learned about capabilities of currently available technology, limitations and/or important gaps that could potentially be addressed in the next three to five years. Identify technology and/or advances that are on the near horizon to meet these needs.

Interactive "Listening Panel"(60 min)

Jill Lewandowski, BOEM
John Young, CSA Ocean Sciences Inc.
Dr. Michael Ainslie, TNO - Netherlands Organization for Applied Scientific Research
Dr. William Ellison, Marine Acoustics, Inc.
Dr. Brandon Southall, Southall Environmental Associates, Inc.
Dr. Linda Weilgart, Dalhousie University
Dr. Dietrich Wittekind, DW Shipconsult GmbH
G.C. "Chip" Gill, International Association of Geophysical Contractors
Michael Jasny, NRDC
Mike Jenkerson, ExxonMobil
Bill Streever, BP

General Discussion and Path Forward (60 min)

4:45 p.m. **Closing Remarks –** *James Bennett, BOEM* (15 min)

5:00 p.m. ADJOURN

SCIENTIFIC REVIEW PANEL MEMBERS

Dr. Michael Ainslie (TNO- The Hague, Netherlands). Dr. Ainslie is a Senior Scientist at TNO in The Hague, The Netherlands. He has 25 years of experience in underwater acoustics with applications to sonar performance modeling and the impact of underwater sound on marine life. He is convenor of a working group developing an ISO Standard for underwater sound terminology, a leading member of the working group set up by the European Commission to advise on the implementation of its Marine Strategy in the context of underwater noise, and he supervises a bioacoustics Ph.D. project at the University of Leiden. He has published 30 full-length peer reviewed journal articles on sonar and underwater sound, and is sole author of the book *Principles of Sonar Performance Modeling* (Springer, 2010). Dr. Ainslie has been an invited speaker at numerous conferences and workshops, including the BOEM-sponsored workshop Effects of Underwater Sound on Fish and Invertebrates in San Diego, and is a member of the Advisory Committee for the forthcoming “Aquatic Noise 2013” meeting in Budapest.

Dr. William Ellison (Marine Acoustics Inc.). Recognized as a leading expert in theoretical modeling of acoustic processes, he has developed numerous computer-based models in active use by the U.S. Navy including the Naval Undersea Warfare Center (NUWC) high frequency target strength model and the first elastic resonance model for mines. Based on his extensive field experience in the high Arctic, he developed the NUWC high frequency under-ice acoustic scattering model. Most recently, he has authored the Acoustic Integration Model (AIM), a state of the art real-time virtual model for assessing the net impact of sound from a variety of sources (moving or stationary) on a dynamic population of marine wildlife. This model can be adapted to any sound source, but was originally designed for high-powered low frequency sound sources with the potential to transmit over long distances. AIM is recognized by NOAA/NMFS as an acceptable methodology for environmental assessments, and is the primary analysis tool for numerous environmental investigations as well as two National Oceanographic Partnership Program (NOPP) awards in 2007 and 2008 where MAI is teamed with Cornell University and the University South Florida respectively.

Dr. Brandon Southall (Southall Environmental Associates, Inc.). Dr. Southall is President and Senior Scientist for Southall Environmental Associates (SEA), Inc. based in Santa Cruz, California, a Research Associate with the University of California, Santa Cruz (UCSC), and an Adjunct Assistant Professor at Duke University. Dr. Southall has an extensive technical background in laboratory and field research as well as in the application of science in national and international policies and collaborations. In 2009, Dr. Southall founded SEA, a research and consulting business focusing primarily, but not exclusively, on noise impacts on marine life. In addition to leading a variety of ongoing field and laboratory research projects (e.g., www.socal-brs.org), he also serves as a technical advisor and scientific partner to international organizations regarding environmental impacts of commercial shipping and conventional and alternative offshore energy development.

Dr. Linda S. Weilgart (Dalhousie University, Canada). Dr. Weilgart has specialized in underwater noise pollution and its effects on whales and other marine life since 1994. She has studied whales since 1982, primarily sperm whales, and her M.Sc., Ph.D., and post-doctoral studies were all in the field of whale acoustic communication in the wild. Lindy has served as invited expert on several panels, workshops, and committees on underwater noise impacts and published numerous peer-reviewed papers. She is currently a research associate in the Biology Department, Dalhousie University, Canada, as well as scientific advisor for the private Okeanos Foundation and the International Ocean Noise Coalition. She co-organized five Okeanos-sponsored scientific workshops on noise: 1) Alternative Technologies to Seismic Airgun Surveys for Oil and Gas Exploration and their Potential for Reducing Impacts on Marine Mammals; 2) Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals; 3) Noise from Shipping Operations and Marine Life: Technical, Operational and Economic Aspects of Noise Reduction; 4) Noise-Related Stress in Marine Mammals; and 5) Spatio-Temporal Management of Noise.

SCIENTIFIC REVIEW PANEL MEMBERS *Continued*

Dr. Dietrich Wittekind (DW Shipconsult GmbH). Dr. Wittekind is a naval architect with 25 years of experience in ship acoustics, including underwater irradiated noise from shipping and, since 2007, from pile driving and seismic surveys with emphasis on mitigation measures. He works for worldwide industry and government agencies and is a close observer of recent developments in technologies relevant to the Workshop. In addition, Dr. Wittekind is the Chairman of the Advisory Board for Noise Reduction on Ships of the German Navy and a member of the German Society for Maritime Technology serving as a member of the Noise and Vibration Expert and the Hydrodynamics Expert Groups. Dr. Wittekind has also been an invited participant in numerous working groups and workshops dealing with similar subject matters.

Mr. John Young (CSA Ocean Sciences Inc.). Mr. Young is a seismic expert having spent over 33 years in the research, design, testing, and application of seismic imaging technology. He also served as the International Association of Oil and Gas Producers (OGP) Sound and Marine Life Programme Chairman for the executive committee and the chair for the OGP Sound and Marine Life Task Force. Mr. Young was also instrumental in obtaining ExxonMobil financial support to help establish the World Ocean Council (WOC), the only cross-sectoral industry forum bringing together the diverse ocean business community to collaborate on stewardship of the seas. He is currently serving as co-chair, along with Dr. Brandon Southall, on WOC's workgroup on marine noise. Mr. Young is also a member on the European Union's workgroup on marine noise and served as Chairman of the OGP Marine Sound Joint Industry Program (JIP) from 2006-2011.

FACILITATORS AND INVITED SPEAKERS

Dr. Michel André (Technical University of Catalonia, Barcelona Tech, UPC and the Laboratory of Applied Bioacoustics). Dr. Michel André is a full Research Professor at the Technical University of Catalonia, BarcelonaTech (UPC) and the Director of the Laboratory of Applied Bioacoustics (LAB). Dr. André is an Engineer in Biotechnologies (Institut National des Sciences Appliquées, INSA, Toulouse, France) and holds a Master's degree in Bioquemistry and Animal Physiology (Université Paul Sabatier de Toulouse, France). His Ph.D. dissertation focused on sperm whale acoustics and noise pollution. Over the course of his career, he was a research assistant at the San Francisco State University, California; an intern scientist at The Marine Mammal Centre, California; and an associate professor at the Universidad de Las Palmas de Gran Canaria, España. His research involves the development of acoustic technologies for the control of noise pollution in the marine environment; the study of the biological and pathological impact of noise pollution on cetacean acoustic pathways; the mathematical, physical, morpho- and electro-fisiological mechanisms of the cetacean bio-sonar as well as the extraction of the information from their acoustic signals. In 2002, Dr. André was awarded the Rolex Awards for Enterprise for his work with shipping noise and marine mammals. This award is described as "supporting individuals whose courage and creativity advance human knowledge and well-being."

Michael Bahtiarian (Noise Control Engineering Inc.). Mr. Bahtiarian is currently the vice president of Noise Control Engineering in Billerica, MA, which specializes in shipboard noise and vibration control. He is a Board Certified member of the Institute of Noise Control Engineering (INCE). He holds a B.S. in Mechanical Engineering from Penn State University and a M.S. in Mechanical Engineering from RPI. Mr. Bahtiarian is the currently the convener (chair) of the ISO Technical Committee 43, Sub Committee 3, Working Group 1 which is developing international standards for the measurement of underwater noise from vessels. He was formally the chair of ASA/ANSI working group that produced the first non-military standard for the measurement of underwater noise from ships, ASA/ANSI S12.64-2009. Mr. Bahtiarian has participated in the design of ships that achieved low underwater noise including: the NOAA Fishery Research Vessels, *R/V HUGH R. SHARP* for the University of Delaware, Regional Class Research Vessel (RCRV), Arctic Region Research Vessel (ARRV) and Ocean AGOR. Mr. Bahtiarian has also developed noise controls for passengers of vessels such as the *ISLAND HOME* Ferries for Mass Steamship Authority and Washington State Ferrys, *M/V KENNECOTT* for the Alaska Marine Highway System (AMHS) Ferry and the San Francisco Bar Pilots Station Boat among many others.

Dr. Chris Barber **(*Multipath Science and Engineering Solutions)***. Dr. Chris Barber is an acoustical engineer and researcher with experience in acoustic testing and applied acoustics research including underwater noise measurement, ship acoustic signatures, sonar self-noise and ship noise reduction. He has been a Principle Investigator for sponsored research on underwater radiated noise in the nearfield and in shallow water, on improved estimation methods combining analytical models with empirical measurements, and on the radiated noise of maneuvering ships. His experience in acoustic testing ranges from underwater field experiments and testing in hydroacoustic flow facilities to room acoustic measurements and characterization of professional audio systems. He has served as staff scientist and program manager for the Signature Characterization and Analysis Division at the Naval Surface Warfare Center and has participated in 40+ sea trials of naval and research vessels. Dr. Barber has taught courses and advised students in acoustics and architectural, audio and electrical engineering at the undergraduate, graduate and professional continuing education levels. He is currently engaged in consulting projects in acoustic product development and underwater noise measurement as well as providing on-site and web-based training courses in acoustics, audio engineering and noise control.

Jim Bennett (Bureau of Ocean Energy Management). Jim Bennett has over 30 years of Federal service and experience dealing with environmental issues with the Department of the Interior focusing on NEPA, Natural Resource Damage Assessment, and GIS applications. He has two Master's degrees--one in Environmental Planning and the other in Computer Systems Management. He is with the Headquarters office of the new Bureau of Ocean Energy Management (formerly the Minerals Management Service) and serves as the Chief of the Division of Environmental Assessment. He currently oversees BOEM's compliance with NEPA and other environmental laws focusing on Federal Outer Continental Shelf programs including oil and gas, sand and gravel, and alternative energy.

Ron Brinkman (Bureau of Ocean Energy Management). Ron Brinkman earned his degree in Mathematics from University of New Orleans with a minor in Geology. He has been employed for 35 years with USGS (Conservation Division), Minerals Management Service (MMS) and Bureau of Ocean Energy Management (BOEM) as geophysical interpreter, G&G permit specialist, and environmental compliance geophysicist.

Danielle Buonantony (Navy). Ms. Buonantony is a Marine Resources and Acoustics Specialist with the U.S. Navy in the Office of the Chief of Naval Operations (OPNAV) - Energy and Environmental Readiness Division. She earned her Bachelor of Science degree in Zoology from the University of Maryland – College Park, and her Master's degree in Coastal Environmental Management from Duke University. Ms. Buonantony is the lead staff person within OPNAV who handles all Marine Mammal Protection Act (MMPA) permitting for the Navy, including pile driving and removal activities. Over the past couple of years Ms. Buonantony has been heavily involved in the Navy's compliance efforts with respect to pile driving and has assisted in developing protected resource and acoustic monitoring and mitigation plans for several pile driving projects in the Northwest and Southeast regions. Ms. Buonantony was also the Navy's technical expert on two scientific panels examining the effects of sound on protected resources and developing criteria to define the onset of injurious and non-injurious acoustic effects from impact pile driving sounds on the ESA-listed marbled murrelet, a diving seabird.

Megan Butterworth (Bureau of Ocean Energy Management). Megan Butterworth has worked as a Biological Oceanographer with the Division of Environmental Assessment at BOEM for the last three years. Her current work focuses on the effects of OCS development on lower trophic levels, fish, sea turtles, and marine mammals. Prior to BOEM, Megan worked at the Smithsonian Environmental Research Center and the University of Maryland studying the optical properties and bioavailability of dissolved organic matter as well as lignin oxidation products in Chesapeake Bay estuarine tidal marshes. Megan received her B.S. in Marine Science, B.S. in Biology and minor in Chemistry from Coastal Carolina University, and she earned a M.S. in Marine Science (emphasis in Biological Oceanography) from the University of Southern Mississippi.

Stephen Chelminski (Chelminski Research). Prior to founding Bolt Technology Corporation, Stephen Chelminski was employed by Lamont-Doherty Earth Observatory in the development of underwater exploration equipment. In 1961 Mr. Chelminski invented the marine air gun, for which he was subsequently awarded the Virgil Kauffman Medal by the SEG. He has received more than 50 U.S. patents, primarily in the field of seismic exploration equipment, as well as quite pile drivers for construction and off shore uses. More recently he has worked with an aerospace company in the design and prototype construction of GPS guided cargo parachutes, small flyable tactical vehicles and UAVs. His present work has focused on improved marine vibrator design.

Peter H. Dahl (University of Washington). Peter received his Ph.D. degree in Ocean Engineering from the Massachusetts Institute of Technology, Cambridge and Woods Hole Oceanographic Institution, Woods Hole, MA, Joint Program in Oceanography and Oceanographic Engineering in 1989. He is a Principal Engineer at the Applied Physics Laboratory, University of Washington, Seattle, where he has been since 1989, and conducts experimental and theoretical research in underwater acoustics. He is also a Professor with the Mechanical Engineering Department of the University of Washington, where he teaches graduate courses in acoustics, and advises graduate students. He has been a member of the Alaskan North Slope Borough Science Advisory Committee related to oil spills in offshore arctic areas (2008-09), and the Washington State Dept. of Transportation/NOAA working group on protocols for ESA consultations related to pile driving (2011-12). Peter has been a principal investigator for multiple experiments in underwater acoustics staged throughout the world's oceans sponsored by the Office of Naval Research, and was the chief scientist for the Asian Seas International Experiment in the East China Sea involving China, Korea, and the U.S. He has served as an Associate Editor for the IEEE *J. Oceanic Engineering* from 1997-2003, and was Guest Editor for its Special Issue on Asian Marginal Seas. He is a Fellow of the Acoustical Society of America (ASA), has served as the Chair of the ASA Technical Committee on Underwater Acoustics, on the ASA Executive Council, and was recently elected ASA Vice President.

René Dekeling (Netherlands Ministry of Infrastructure and the Environment). René Dekeling has served as a naval officer in several operational and staff functions in the Netherlands Navy and the Naval Air Service, both shore- and sea- based. He holds a degree in environmental sciences and over the last 15 years has worked on environmental issues for the Netherlands (NL) Ministry of Defence, ensuring that the NL Navy was able to operate both effectively and responsibly. He is the coordinator of the NL Ministry of Defence research programme on the effects of underwater sound on marine life. He participates in studies at sea to investigate the effect of naval sonar on cetaceans within the international 3S-programme, which is funded by the navies of the United States, Norway and the Netherlands. In the NL Ministry of Infrastructure and the Environment he is responsible for policy and research programming related to underwater noise in the national implementation of the European Marine Strategy Framework Directive. International activities include co-chairing the expert working group TSG Noise that was tasked by the European Commission to assist European member states in making the step from legislation to operational monitoring and management.

Roger Gentry (ProScience Consulting, LLC). Mr. Gentry is the retired as head of the NOAA acoustics program, which he founded in 1995. He opened ProScience Consulting, LLC, a firm that consults on underwater noise and its effects on marine life. From 2006 to 2009, he was the Program Manager for one of the Joint Industry Program (JIP) that provided $8M annually in support of original research on the effects of industry sound on marine mammals and fish. During that time, he was involved in 63 contracts dealing with measuring industry sound output (airgun arrays and single guns), the physiological and behavioral effects of sound exposure on animals, and mitigation measures.

G. C. "Chip" Gill (International Association of Geophysical Contractors). Chip Gill is President of the International Association of Geophysical Contractors. IAGC is the international trade association representing the industry that provides geophysical data, services and equipment to the oil and gas industry. Gill is a 30 year veteran of the oil and gas exploration and production (E&P) industry. In addition to his strong operational background, he has extensive experience working with governments on behalf of oil and gas interests around the world. Before joining IAGC in 2001, Gill served as Vice-President of Membership and Strategic Planning at IPAA - the Independent Petroleum Association of America. Prior to his decade of leadership in E&P industry trade associations, Gill managed government relations for Vastar Resources and ARCO for 11 years. He first worked in the oil and gas industry as a Rig Hand for Ard Drilling Company while on summer break from University. Upon graduation, he spent the first decade of his career with ARCO working on the land and contract side of their upstream oil and gas business based in the U.S. Gill holds a Bachelor of Business Administration in Petroleum Land Management from the University of Texas at Austin with an emphasis in Geology. Gill is the author of numerous articles and professional papers, and has previously served as a Senate appointee to the Oklahoma Energy Resources Board and as an appointee to a U.S. Marine Mammal Commission Federal Advisory Committee.

Dr. Michele Halvorsen (Pacific Northwest National Laboratory). Dr. Halvorsen's work is currently focused on the effects of anthropogenic sound on the physiology and behavior of freshwater and marine fish. Recent research includes barotrauma (tissue damage) response assessment of fish to simulated impulsive sounds from pile driving generated by a High Intensity Controlled Impedance-Fluid Filled Wave Tube, HICI-FT, which is capable of simulating impulsive sounds (pile driving and airguns) as well as other sound sources (shipping; tidal, wind, and wave turbines; and naval sonar). Current research addresses the barotrauma/tissue damage and hearing response of marine fish species to noise generated by tidal power generators. Dr. Halvorsen was co-principal investigator and project manager of field studies that examined the effect of the U.S. Navy's low- and mid-frequency sonar on the hearing of several fish species and is co-principal investigator for an ongoing study involving pile driving.

Mardi Hastings (Georgia Institute of Technology). Mardi Hastings is a Professor at the Georgia Institute of Technology. She has B.S., M.S. and Ph.D. degrees in mechanical engineering. Her career includes 11 years in industry, 20 years in academia, and four years at the Office of Naval Research where she developed international research programs in biosonar and the biological impacts of underwater sound. She has advised 30 graduate students, authored over 50 journal and proceedings articles, and co-authored the book, *Principles of Marine Bioacoustics* (2008). She served on the NAS Study Panel on the Potential Impacts of Ambient Noise on Marine Mammals (2001-2002) and the Barotrauma Blue Ribbon Panel for California (2007), and has received numerous awards including a 2005 FHA Environmental Excellence Award for work with Caltrans on pile driving, and the 2011 Per Bruel Gold Medal for Noise Control and Acoustics from the American Society of Mechanical Engineers (ASME). Dr. Hastings is a licensed professional engineer, and Fellow and Past-President of the Acoustical Society of America (ASA). She is a former chair of the ASA Animal Bioacoustics Technical Committee and of the ASME Noise Control and Acoustics Division, and a past member of the Board of Directors of the Institute of Noise Control Engineering.

Dr. John A. Hildebrand (Scripps Institution of Oceanography). Dr. Hildebrand is a professor at the University of California at San Diego is a Professor at the Scripps Institution of Oceanography at the University of California at San Diego. He obtained a B. S. degree in Physics and Electrical Engineering at the University of California San Diego, and a Ph.D. degree in Applied Physics from Stanford University. He has been on the research staff of the Scripps Institution of Oceanography since 1983. During this time he has chaired fourteen graduate Ph.D. thesis committees, and regularly teaches classes on bioacoustics, and experimental laboratory acoustics. He has contributed to more than 150 referred publications, on topics ranging from underwater noise, to sound production by marine mammals. His recent research has focused on ambient noise, acoustic techniques for marine mammal population census, and the effects of high intensity sound on marine mammals.

Paul Holthus (World Ocean Council). Paul Holthus is the founding Executive Director of the World Ocean Council (WOC) - the international business leadership alliance on Corporate Ocean Responsibility. The WOC brings together oil and gas, shipping, fisheries, aquaculture, tourism, offshore renewables and other ocean industries - creating unprecedented ocean business community leadership and collaboration in addressing marine sustainability challenges. Mr. Holthus has held senior positions with the United Nations Environment Programme (UNEP) and international environmental organisations, including as Deputy Director for the IUCN Global Marine Programme. Since 1998, Mr. Holthus has worked primarily with the private sector to develop practical solutions for the sustainable use of the marine environment. He has worked in over 30 countries with companies, communities, industry associations, UN agencies, international non-governmental organisations and foundations.

***Michael Jasny (NRDC*)**.** Mr. Jasny is Director of the Marine Mammal Protection Project and a Senior Policy Analyst at the Natural Resources Defense Council (NRDC). He is a leading expert in the law and policy of ocean noise pollution, and has worked domestically and internationally for more than ten years through high-profile litigation, lobbying, science-based policy development, and public advocacy to improve regulation of this emergent global problem. Michael is also engaged in securing protection for endangered marine mammal populations and critical habitat, opposing development projects that threaten marine mammals off the U.S. and Canada, and improving management of fisheries, whale-watching, and other sectors under the Marine Mammal Protection Act, the nation’s leading instrument for the conservation of these species. Michael is the author of several NRDC reports and author or co-author of various publications in legal, policy, and scientific journals. He holds a bachelor’s degree from Yale College and J.D. from Harvard Law School. Contact: mjasny@nrdc.org; w. 604-736-9386, c. 310-560-5536.

Mike Jenkerson (ExxonMobil). Mr. Jenkerson is a geophysical advisor for ExxonMobil Exploration Company. In this role, he is a science advisor on marine sound issues, including as the ExxonMobil representative on the Marine Vibroseis JIP; issues relating to seismic sources and sound source characterization; marine sound mitigation issues; active and passive acoustic monitoring issues; research category chair – OGP Sound and marine life JIP, sound source characterization and propagation; and Western Gray Whale research program (Acoustics, logistics and safety).

Dr. Carrie Kappel (National Center for Ecological Analysis and Synthesis). Dr. Kappel is an Associate Project Scientist at the National Center for Ecological Analysis and Synthesis at the University of California Santa Barbara. She is an expert in marine spatial planning and ecosystem management that has been involved in numerous working groups and workshops such as the 2010 Southern California Marine Mammal Workshop, Chair of “Collaboration and data integration” panel; the NCEAS Working Group: “Towards understanding marine biological impacts of climate change;” and an invited participant at the Okeanos Workshop and presented “Cumulative impacts/effects of anthropogenic stressors on marine mammals: From ideas to action.” In addition, she is a member of the NOAA Underwater Sound Field Mapping Working Group. Dr. Kappel also has done work on cumulative impacts of human activities on marine ecosystems and assessing the tradeoffs and impacts associated with offshore wind energy development.

Sven Koschinski (Marine Zoology). Sven Koschinski earned his degree in biology at Christian Albrechts University in Kiel (Germany) in 1996 with his diploma thesis: *Reactions of small cetaceans to fishing nets: behavioural experiments to mitigate harbour porpoise by-catch*. In his own consultancy *Marine Zoology* he is specialised on marine mammals and various aspects of underwater sound such as pile driving and underwater blasting. Further, he is specialized in by-catch mitigation of small cetaceans and seabirds. With his co-author Karin Lüdemann he prepared a report for the German Federal Agency for Nature Conservation (BfN) in 2011: *Offshore Wind Farm Construction - Development Status of Underwater Noise Mitigation Measures*. An actualized version will be available soon.

Robert P. LaBelle (Bureau of Ocean Energy Management). Robert LaBelle is Science Advisor to the Director, BOEM. He is also serving as the acting Chief Environmental Officer for the Bureau and previously as the Associate Director for Offshore Energy at the Department of the Interior. Mr. LaBelle contributes to management of key facets of the U.S. offshore oil and gas and renewable energy programs, including development and regulation of offshore wind, wave, and marine current energy in all U.S. Federal waters. He has received the Citation for Distinguished Service (2008) from the Department in recognition of his career scientific and management accomplishments. Mr. LaBelle is also the current Federal Co-Chair of the Northeast Regional Ocean Council, a state/federal partnership to advance ocean planning and related science in New England. Since 2004, he has participated in policy development and implementation and in numerous forums on offshore renewable energy issues, including environmental assessments, ocean planning and permitting. Previously with DOI as Environmental Division Chief, Mr. LaBelle managed large environmental and technology research programs and oversaw the preparation of Environmental Impact Statements and other decision documents used for U.S. offshore energy permitting. Mr. LaBelle is a graduate of the University of Massachusetts, Dartmouth (BS Biology), the University of Maryland (MS Biology), and Loyola College, MD (MBA).

Jill Lewandowski (Bureau of Ocean Energy Management). Jill Lewandowski has worked on protected species and anthropogenic noise issues with the Bureau of Ocean Energy Management’s Environmental Program for the last eight years and, prior to that, with the National Marine Fisheries Service’s (NMFS) Office of Protected Resources for five years. She received her B.A. in Biology from the University of Virginia and her M.S. in Environmental Science and Policy at George Mason University (GMU). She is currently a Ph.D. student in Environmental Science and Policy at GMU where her research interests focus on collaborative methods to improve Federal decisions on complex environmental issues, such as management and regulation of anthropogenic noise.

Dr. Georg Nehls (BioConsult SH GmbH & Co. Dr. Nehls has more than 20 years of environmental research in the marine environment. Since 1998, he has been the head of BioConsult SH. For the last 10 years, he and his team have been engaged in many offshore wind energy projects in Germany, Denmark, and the UK. Apart from Environmental Impact Assessments (EIAs) and monitoring existing offshore windfarms, Dr. Nehls has been responsible for research projects concerning specific questions related to offshore windfarms and strategic studies on windfarm development and assessment. As such, he has a comprehensive understanding of biological matters as well as the legal regulations and planning and assessment procedures required in the EU in relation to offshore wind energy and marine conservation. Notably, Dr. Nehls developed and directed the first EIA for an offshore windfarm project in Germany and regularly provides advice to government institutions and industry. Over the last few years, he and his team have been engaged in developing noise mitigation measures during pile driving and are currently assisting in bringing noise mitigation into practice at several windfarms offshore Germany.

Paul V. Novakovic (Independent Consultant). Rensselaer Polytechnic Institute – Class of 1955; Commissioned in the United States Navy 1957; President of several Ingersoll-Rand Co. international subsidiaries ending with Director of International Oil and Gas Business; Founder of several companies in the fields of military equipment, environmental projects, Oil and Gas product trading and exploration equipment, mining; Management, financial, and technical consultant to Fortune 500 companies and government agencies.

Bill Pramik (Geokinetics). Bill Pramik is the Vice President of Acquisition Technology at Geokinetics, Inc. where he oversees research and development of new seismic acquisition hardware and methods including recording technology, seismic sources and seismic receivers. Mr. Pramik was employed by PGS for 15 years, and served 3 years as their Vice President of Geophysics and Quality before moving to Geokinetics 2010. Prior to that, he worked for Amoco Production Company for 16 years, including a 6-year assignment to their Research Center. Mr. Pramik has authored and co-authored articles appearing in *The Leading Edge*, the *CSEG Recorder*, *PESA News* and other industry publications. He holds several geophysical patents and has made numerous technical presentations at the SEG, the ASEG, the INGEPET and the Simposio Bolivariano in addition to many local geological and geophysical professional societies. He was an invited speaker at the IAGC Brazil Seismic Activity and Marine Environment Seminar in 2006. Mr. Pramik received his degree in Geophysics with a minor in Mathematics in 1979 from Virginia Polytechnic Institute where he was awarded a 2 year Amoco Foundation Scholarship.

Tim Ragen (MMC). Tim's main responsibilities include providing support for three Commissioners; coordinating nine members of the Commission's Committee of Scientific Advisors on Marine Mammals; supervising a staff of 14 to conduct the Commission's business; fulfilling the Commission's responsibilities under the Marine Mammal Protection Act, Endangered Species, National Environmental Policy Act, and related legislation; developing and achieving the Commission's high priority performance goals; organizing annual meetings for Commission; completing an annual report to Congress; managing special projects assigned by Congress or initiated by Commission; overseeing all federal activities that may affect marine mammals; serving as the Commission's primary contact for Congress and Administrative agencies; developing the Commission's budget and assuming responsibility for all administrative tasks; overseeing preparation for about 130 letters per year to federal agencies providing recommendations to protect marine mammals and marine ecosystems.

Dr. D. Benjamin Reeder (Naval Postgraduate School). Dr. Reeder is a Research Associate Professor at the Naval Postgraduate School in the Ocean Acoustics Laboratory. Dr. Reeder's area of expertise is ocean acoustic propagation; the interaction of sound with marine organisms, water column, and seabed structure; and ocean noise characterization and prediction. In addition, he was the U.S. National Liaison Officer to the Science Committee for the NATO Undersea Research Centre (NURC) in La Spezia, Italy; the Assistant to the Designated Federal Officer Ocean Research and Resources Advisory Panel in Washington, DC; and on the SPAWAR PMW-120 Advisory Panel that dealt with the Assessment and Exploitation of Marine Biologic Effects on Reverberation and Sonar Performance (AEMBERS).

Per Reinhall (University of Washington, Seattle). Per Reinhall is Professor and Chair of Mechanical Engineering and Adjunct Professor of Industrial and Systems Engineering at the University of Washington, Seattle. He obtained his PhD in Applied Mechanics from Caltech with specialization in nonlinear dynamics, acoustics and solid mechanics. Professor Reinhall's main research interest include nonlinear dynamical systems, acoustics, mechanics, and computing with focus on the development of biomedical devices and instrumentation, noise and vibration control, fluid-structure interaction and sensors and actuators. Research in the biomedical area emphasize advances and innovation that result in enhanced or new clinical applications in diabetes, prosthetics, cardiac arrhythmias and disease and early detection of cancer. Research in non-biomedical areas include noise control of fluid loaded structures, vibration control of structures, and the behavior of coupled oscillator systems. Professor Reinhall have been conducting research on attenuation of pile driving noise since 2008.

Bob Rosenbladt (Shell – Upstream Americas). Bob Rosenbladt joined Shell in 1982 after completing a Ph.D. in Physics at the University of Washington (1981) and a Post Doc at Fermilab. He has had a variety of assignments in R&D, Acquisition, Processing and Interpretation. Bob currently is head of Geophysical Operations for Shell – Upstream Americas.

Kimberly Skrupky (Bureau of Ocean Energy Management). Ms. Skrupky holds a Bachelor of Science degree in Environmental Science with a concentration in Wildlife Conservation and Resource Management from the University of Maryland. She has been working on issues involving protected species and acoustics for 14 years- working at NOAA for over 5 years, Marine Acoustics, Inc. for over 4 years, and the last 4 years spent at the Bureau of Ocean Energy Management.

Dr. Bill Streever (BP). Dr. Streever works as BP's Senior Environmental Studies Advisor in Alaska. He edited the technical journal *Wetlands Ecology and Management* for 5 years and edited the compendium *An International Perspective on Wetland Rehabilitation*. He has authored or coauthored more than fifty technical publications. He is frequently called upon to sit on scientific advisory committees and panels related wetland restoration, marine life and sound, and the Arctic, including the North Slope Science Initiative's Science and Technical Advisory Panel. His book *Cold* (Little Brown, 2009), reached the *New York Times* bestseller list and was critically acclaimed as a new contribution to the literature of the north. His new book, *Heat*, released in January 2013, has been selected as a top ten science release by *Publisher's Weekly*. He lives with his son, wife, and dog in Anchorage, Alaska, where he hikes, camps, scuba dives, and cross country skis as often as conditions allow.

Mark Tasker (JNCC). Mark is Head of Marine Advice at the Joint Nature Conservation Committee (JNCC), based in Aberdeen and has held this position since 1996. JNCC is responsible for nature conservation for UK as a whole, and for UK's interests outside the UK. Mark's role is to advise on the nature conservation of the UK's offshore seas and oceans, and of those organisms that use these areas. Advice is provided to all who ask, including:

- Government departments and governmental inquiries
- Parliamentary commissions
- Energy companies and other marine industries
- International conservation organisations

Mark has been employed by JNCC or its predecessor UK statutory nature conservation bodies since 1979 – nearly all of this time dealing with science or advice in the marine environment. In relation to underwater noise, he was the originator of the "JNCC guidelines" for seismic surveys, used in UK waters and adapted for use in many other places on the planet. Mark has chaired two European level groups on underwater sound, and currently co-chairs a group providing advice on the implementation of underwater sound parts of EU's Marine Strategy Framework Directive. Mark is also employed part-time by the International Council for the Exploration of the Seas (ICES) based in Copenhagen.

Rune Tenghamn (PGS). Rune Tenghamn is Vice President Innovation and Business Development in the Geoscience & Engineering group of PGS. He has worked with R&D and business development for more nearly 30 years. He has spent his entire career in the E&P industry both International and National. Rune has been with PGS for about 20 years. He has been in various management positions and until 2007 he was Vice President Marine Technology in charge of all R&D activities on the marine side of PGS. Rune holds more than thirty-five patents in various fields. In 2007 he was appointed Vice President Innovation and Business Development. His main task is to improve innovation processes in PGS and to use his long experience in R&D and Business Development to create opportunities for new emerging technologies. Rune holds a Master of Science in Engineering Physics from Chalmers University of Technology, Gothenburg, Sweden.***James Theriault (Defense Research and Development Canada).*** Mr. Theriault is a Senior Scientist with the Defense Research and Development Canada (DRDC) Atlantic, with over 27 years of experience studying the noise effects on marine mammals, environmental effects on sound propagation, and acoustic forecasting. Mr. Theriault is currently conducting research on detection, classification, and localization of marine mammals. He leads or has led collaborative projects with Canadian Government agencies (Fisheries and Oceans Canada, Environment Canada), universities (Dalhousie University, St. Mary's University, Queens University, and University of St. Andrews [Scotland]), and international research laboratories in Italy, the UK, U.S., and Australia.

Peter van der Sman (Shell). Although my background is in EE and IT, I have been working as 'Geophysicist' for over 30 years doing research on data acquisition in general and sources for exploration activities in particular. It all started with a spell of about 12 years in marine seismic data acquisition (various acoustic sources, but largely airguns), followed by 5 years on land (mainly vibroseis) and 5 years in drilling research (using a downhole source or the bit generated noise). My current assignment is on electromagnetic methods with 5 years in marine EM and lately land EM. Since 1991, I have been looking into environmental aspects of our work, starting out with making broadband measurements on arrays of airguns. I am also participating in various committees and joint industry projects on the subject.

Dr. Mark Wochner (AdBm Technologies). Dr. Wochner grew up in Webster, New York, studied physics at Vassar College, and attained a PhD in acoustics from Penn State in 2006 studying computational nonlinear jet noise propagation with a focus on molecular relaxation phenomena. Afterward he accepted a post-doctoral fellowship at The Applied Research Laboratories at The University of Texas. There he studied human bioresponse to underwater noise and later underwater noise abatement, leading to the development of the technology commercialized by his new company, AdBm Technologies, where he serves as President and CEO.

Dr. David G. Zeddies (JASCO). Dr. Zeddies is a senior scientist with JASCO Applied Sciences. His academic and professional work includes methods of acoustic measurement and assessment of risk to marine life due to anthropogenic sounds. He has published refereed articles in the fields of auditory neurophysiology, sound source localization by fish, and the impacts of intense sounds on fish hearing. David is involved with field operations for ocean acoustic measurements, acoustic modeling, and environmental assessment reporting. Dr. Zeddies has a Bachelor's of Science in Mechanical Engineering (BSME) from the University of Illinois in Urbana-Champaign, and a Doctor of Philosophy (Ph.D.) in Neuroscience from the Department of Neurobiology and Physiology at Northwestern University in Evanston, Illinois.

William Ziadie (American Piledriving Equipment). Bill Ziadie works in sales out of the New Jersey branch of American Piledriving Equipment (APE), a Kent WA based manufacturer of pile driving equipment. After being honorably discharged from the US Army in 1986, Mr. Ziadie found entry level work at a pile driving equipment supplier and moved into the sales end of the business after mastering the mechanical aspects of the equipment. Routinely tasked by his employer with the most difficult technical and application problems that arise, Mr. Ziadie has developed a reputation within the pile driving industry as an expert in regards to vibratory hammers. Mr. Ziadie has been the point of contact for APE working with several emerging offshore wind construction projects in the northeastern US. Mr. Ziadie resides in New Jersey with his wife and 3 children.

APPENDIX D

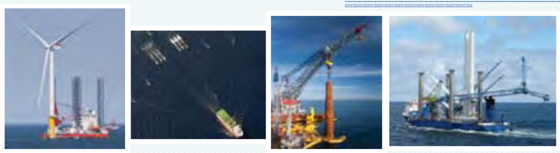
PRESENTATIONS

Presentation Title **Page**

WELCOME TO THE QUIETING TECHNOLOGIES FOR REDUCING NOISE DURING SEISMIC SURVEYING AND PILE DRIVING WORKSHOP

25-27 February 2013

DoubleTree by Hilton Hotel
8727 Colesville Road
Silver Spring, Maryland 20910



Scientific Review Panel Members

- ***Dr. Michael Ainslie (TNO- The Hague, Netherlands).***
- ***Dr. William Ellison (Marine Acoustics Inc.).***
- ***Dr. Brandon Southall (Southall Environmental Associates, Inc.).***
- ***Dr. Linda S. Weilgart (Dalhousie University, Canada).***
- ***Dr. Dietrich Wittekind (DW Shipconsult GmbH).***
- ***Mr. John Young (CSA Ocean Sciences Inc.).***

Facilitators

- *Michael Bahtiarian (Noise Control Engineering Inc.)*
- *Roger Gentry (ProScience Consulting, LLC)*
- *Dr. Michele Halvorsen (Pacific Northwest National Laboratory)*
- *Mike Jenkerson (ExxonMobil)*
- *Dr. Carrie Kappel (National Center for Ecological Analysis and Synthesis)*
- *Dr. Timothy Ragen (Marine Mammal Commission)*
- *Dr. D. Benjamin Reeder (Naval Postgraduate School)*
- *Mark Tasker (Joint Nature Conservation Committee)*
- *James Theriault (Defense Research and Development Canada)*

Agenda Overview

- Plenary Introduction Sessions
- Break-Out Groups
  - Airguns
  - Pile Driving
  - Support Vessel Noise
- Break-Out Sessions
  - Presentations
  - Goal Sessions
- Breakout Report Outs
- Panel Discussions

Workshop Goals

Workshop Objective:

The workshop will examine current and emerging technologies that have the potential to reduce the impacts of noise generated during offshore exploratory seismic surveys, pile driving, and vessels associated with these activities.

Workshop Goals:

1. Review and evaluate recent developments (current, emerging/potential) in quieting technologies for:
   - Seismic surveying, whether proposed or in development,
   - Pile driving during offshore renewable energy activities, and
   - Vessel noise associated with Outer Continental Shelf (OCS) energy development activities
2. Identify the spatial, spectral, and temporal features of the acoustic characteristics of new technologies in varying environments compared to that from existing technologies
3. Identify the system and site specific requirements for operation of these new technologies and limitations in their use

Workshop Goals cont.

4. Discuss potential impacts, both positive and/or negative, in using these technologies
   - operational and cost effectiveness
   - potential environmental impacts from these technologies
5. Evaluate data quality and cost-effectiveness of these technologies as compared to that from existing marine acoustic technologies
6. Discuss what the current, emerging/potential technologies can do to reduce sound output
7. Examine potential changes in environmental impacts from these technologies in comparison with existing technologies
8. Identify which technologies, if any, provide the most promise for full or partial replacement of conventional technologies and specify the conditions that might warrant their use (e.g., specific limitations to water depth, use in Marine Protected Areas, etc.)
9. Identify next steps, if appropriate, for the further development of these technologies, including potential incentives for field testing

D1

Ground rules and Housekeeping

Ground Rules

- Diverse group of experts
- Encourage participation by all members
- Keep focused on BOEM goals

Housekeeping

- Refreshments available during Breaks
- Lunch on your own – List at Registration Desk
- Break-out room locations
  - Airguns – Maryland Room
  - Pile Driving – Capitol Room
  - Support Vessel Noise – Potomac Room

Welcome to the Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving Workshop

25-27 February 2013

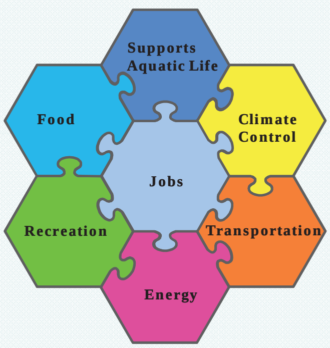
DoubleTree by Hilton Hotel
8727 Colesville Road
Silver Spring, Maryland 20910

BOEM

Slips Trips and Falls

- According to the U. S. Department of Labor, slips, trips, and falls make up the majority of general industry accidents.
- 25% of reported claims per fiscal year are due to STF.
- Over 17% of all disabling work injuries are the result of falls.

Ocean Resources



Workshop Objective

Objective:
The workshop will examine current and emerging technologies that have the potential to reduce the impacts of noise generated during offshore exploratory seismic surveys, pile driving, and vessels associated with these activities.

Things to remember:

- BOEM has specific workshop goals which we will address through the workshop...please try to stay focused; seek solutions
- Primary goal is to discuss technology
- Noise is a relative term - A quieter ocean is better for aquatic life
- Interactive listening - ask questions
- Respect others opinions

Pile Driving Activity

- Pile driving occurs in several offshore activities but of primary concern is the increased activity around offshore wind generation platforms
- Wind energy generation is increasing:
  - In the UK, wind power contributes 1.5 per cent of the UK's electric supply and is expected to increase significantly by 2020 to achieve renewable energy targets
    - RenewableUK, 2012
  - Off the shores of the United States and the Great Lakes is a power source with four times the energy potential of the entire U.S. electric power system
    - U.S. Department of Energy, 2012
  - The first report, U.S. Offshore Wind Market and Economic Analysis, looks at growth scenarios for the industry, which could potentially support up to 200,000 manufacturing, construction, operation and supply chain jobs and drive more than $70 billion in annual investments by 2030
    - U.S. Department of Energy, 2012
  - U.S. Secretary Chu Announces $45 Million to Support Next Generation of Wind Turbine Designs
    - U.S. Department of Energy, 2012

E & P Activity

- Global energy demand grows by more than one-third over the period to 2035
  - International Energy Agency, 2012
- Despite the growth in low carbon sources of energy, fossil fuels remain dominant in the global energy mix
  - International Energy Agency, 2012
- Increased offshore seismic data acquisition will be required to fulfill the need of locating hydrocarbons
- For example, according to PGS investor-relations presentations, from 2006 to end of 2012 demand for seismic has grown by approximately 120% measured by square kilometer
  - Expected capacity increases measured in number of streamers:
    - 6% increase in 2012
    - 5% increase in 2013
    - 2% increase in 2014
    - 7% increase in 2015

Dr Edward Lu, PhD

- Former Astronaut
  - Dr. Lu logged 206 days in space
  - Dr. Lu earned the distinction of being the First American to launch as the Flight Engineer on a Russian Soyuz spacecraft
  - NASA's highest honor; the Distinguished Service Medal
- Formerly with Google and now serves as Chief of Innovative Applications with Liquid Robotics
- Founder of B612 Foundation whose goal is to be able to significantly alter the orbit of an asteroid

BOEM Environmental Program

Applied science for informed decisions on ocean energy

Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving
February 25, 2013

Bob LaBelle
Acting Chief Environmental Officer
Senior Science Advisor to the Director
Bureau of Ocean Energy Management
robert.labelle@boem.gov

Overview

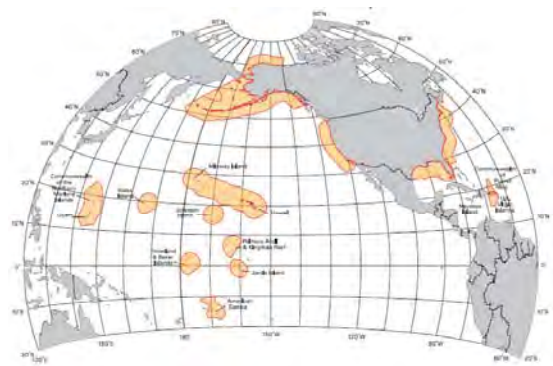
- Overview of BOEM's Environmental Program
- Why we care about noise
- Goals for this workshop

2

Outer Continental Shelf Lands Act

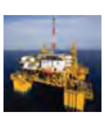
- Created on August 7, 1953
- Secretary of the Interior is responsible for the administration of mineral exploration and development of the OCS
- Provides guidelines for implementing an OCS oil and gas exploration and development program

3



4

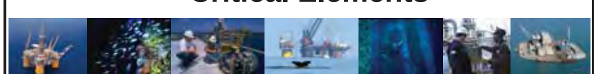
BOEM Program Areas



- Traditional Oil and Gas Program
- Offshore Renewable Energy Program
- Marine Minerals Program (e.g. sand for beach restoration)

5

Environmental Programs – Critical Elements



Applied science for informed decisions on ocean energy

BOEM
- Environmental Assessment Program
- Environmental Studies Program

BSEE
- Environmental Enforcement Program

6

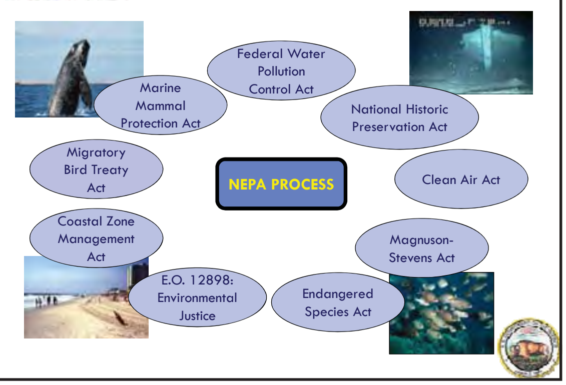
D5

Environmental Assessment

- Public Disclosure and Involvement
- Accurate Scientific Analysis
- Foster Better Decisions
- Focus on What is Affected
- Consider Cumulative Effects
- Consider Alternatives
- Identify and Assess Mitigation
- Adaptive Management

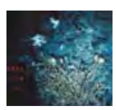
7

Environmental Assessment

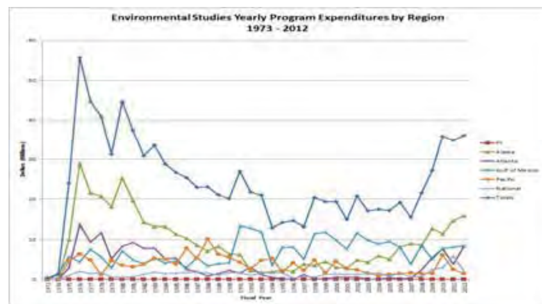


Environmental Studies

Provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.

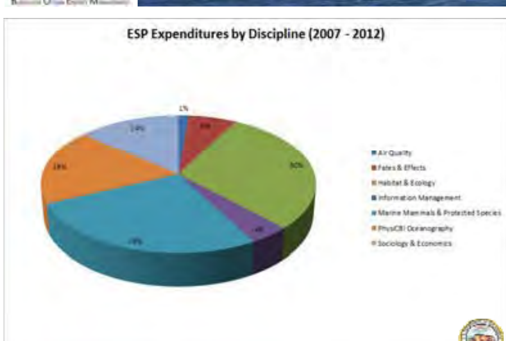


Environmental Studies



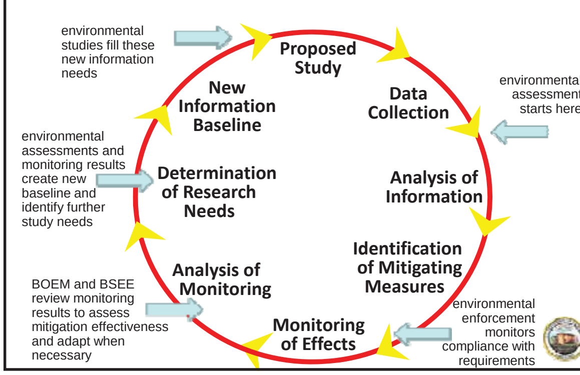
10

Science Expenditures



11

Integrating Assessment, Studies, Enforcement



Why do we care about noise?

Exploration, Construction, Development, Operations, Maintenance, Decommissioning – all make noise!

- Looking for conventional energy reservoirs (seismic surveys)
- Surveying for sand sources (multi-beam sonar surveys)
- Surveying for wind turbine site selection
- Surveying for marine archeological sites
- Dredging noise
- Pile-driving
- Explosive removal of platforms

We need to understand the potential impacts of all of this on various taxa and the systems.

13

Highlights of Past/Current Research

- Sperm Whale Seismic Study (multi-partners)
- Sperm Whale Acoustic Prey Study (NOAA)
- Analysis of Protected Species Observer data (GeoCet)
- Effects of pile driving on fish tissues (UMD)
- Construction noise and offshore wind (JASCO)
- Humpback Whale Seismic Behavioral Response Study (JIP)
- Underwater Hearing Sensitivity of Leatherback Sea Turtles
- Sound Source Characterization (air guns, pile driving, high resolution geophysical sources and explosives (during decommissioning of offshore structures))

14

Collaboration

- Example Workshops
  - Acoustic Monitoring (November 2009)
  - Marine Mammals and Sound: Science and Applications (July 2010)
  - Effects of Noise on Fish, Fisheries, and Invertebrates (March 2012)
  - Seismic Mitigation and Monitoring Meeting (November 2012)
- Example Partnerships
  - National Oceanographic Partnership Program
  - Joint Industry Programme on Sound and Marine Life
  - Coastal Management Institutes

15

Workshop Goals

- Recognize that the best mitigation is to reduce potentially impactful noise but BOEM needs more information on…
  - o Are the technologies ready for commercial use?
  - o Do they need more development?
  - o If so, what is the timeline for development?
  - o What are the potential environmental impacts from new technologies?
  - o How do these impacts compare to traditional technologies?
  - o Will the new technologies meet industry data needs?
  - o Should their use be incentivized by the government?

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Workshop Goals

Overall Goal: Evaluate developments in quieting technologies for seismic surveys, pile driving, and associated vessels

- Compare spatial, spectral, and temporal features of acoustic characteristics
- Identify system and site specific requirements and limitations of use
- Discuss potential impacts (positive and negative)
  - o operational restrictions
  - o data quality
  - o cost effectiveness
  - o potential environmental impacts
- Identify next steps for further development and government consideration

17

Ministry of Infrastructure and the Environment

The EU Marine Strategy Framework Directive

Underwater noise from a European perspective

René Dekeling
Ministry of Infrastructure and the Environment, NL

Defense Materiel Organisation, NL Underwater Technology

The European perspective

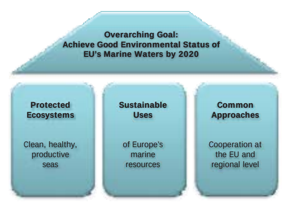
- What is happening at EU level
- What is happening in NL
- What do we need

Marine Strategy Framework Directive (2008)

Overall objective: to achieve or maintain Good Environmental Status (GES) of the EU's marine waters by 2020.

Sustainable: Ecosystem scale and integrated approach to the management of all human activities which have an impact on the marine environment

Common: Regional approach to implementation

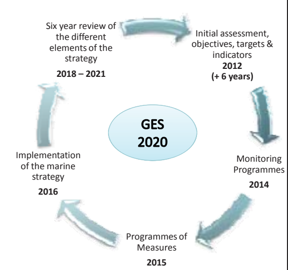


MSFD: transposition in national policy/laws

- MSFD (directive, not EU regulation) is addressed to member states
  - not on individuals
  - sets the framework for member states, but details of implementation are left for the member states to decide ("transposition": turn EU directives into national law)
- In 2012 EU member states have established national marine strategies
- Does not replace existing legislation that regulates at the scales less than MSFD (e.g. SEA, EIA and Habitats Directives)

Implementation Steps

- *Initial assessment* of environmental status of MS waters (2012)
- *Determination* of GES (2012)
- Establishment of environmental *targets* and *indicators* (2012)
- *Monitoring programme* for ongoing assessment and regular updating of targets (2014)
- *Programme of measures* designed to achieve or maintain GES (design 2015, operational 2016)



D8

11 qualitative descriptors

Descriptors for Good Environmental Status

1. Biodiversity is maintained
2. Non-indigenous species do not adversely alter the ecosystem
3. The population of commercial fish species is healthy
4. Elements of food webs ensure long term abundance and reproduction
5. Eutrophication is minimised (especially adverse effects)
6. Sea floor integrity ensures functioning of the ecosystem
7. Permanent alteration of hydrographical conditions does not adversely affect the ecosystem
8. Concentrations of contaminants give no effects
9. Contaminants in seafood are below safe levels
10. Marine litter does not cause harm
11. **Introduction of energy, including underwater noise, is at levels that do not adversely affect the ecosystem**

Indicators for energy/underwater noise

- *Descriptor 11:* Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment
- Main orientation identified for assessment and monitoring (CD on criteria and methodological standards for GES, Sep 2010)
  - short duration: low and mid-frequency impulsive* noise
    *includes sonars
  - long lasting: low frequency continuous noise
- 2 indicators described, but clarification/guidance required → Expert group formed (TSG Noise)
  - Participants from governments, research institutes, private sector, NGO's
  - Co-chaired by UK and NL

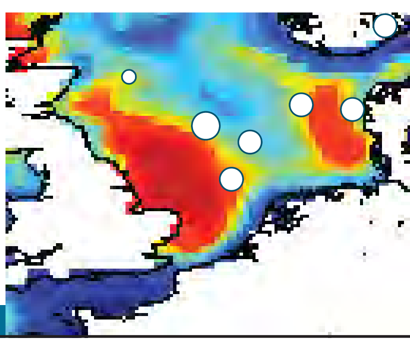
Activities of TSG Noise

- 2012 report: clarified purpose, use and limitation of the indicators and described methodology that would be unambiguous, effective and practicable
- Spring 2013: monitoring guidance (April/May)
- 27/28 May 2013: workshop monitoring in Madrid, Spain
- 2013/2014:
  - assist in future target setting
  - address the biological impacts of anthropogenic underwater noise
  - valuation of scientific data and information about sound sensitive species with the view to develop indicators for noise effects
  - assessing the need for and develop additional indicators (e.g. high-frequency impulsive sounds; EM-fields)

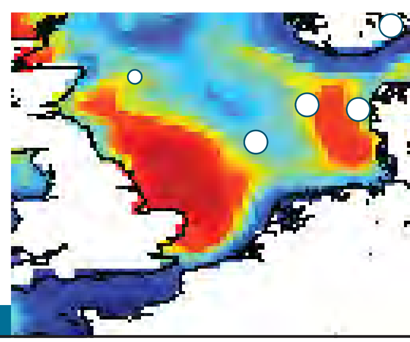
Focus: impulsive noise indicator

- *Interpretation and aim:* "considerable" displacement. Addressing the cumulative impact of activities, not individual projects.
- *GES and targets:* most MS no quantitative description of GES due to insufficient knowledge on the cumulative impacts of impulsive sound
- *The initial purpose* of this indicator will be to assess the pressure (<u>not achieved previously at this scale</u>)
  - Necessary follow-up would be to evaluate effects and set targets
- *Register:* establish the current level and trend in impulsive sounds, by setting up a register of activities generating impulsive sounds (at regional and EU level), thresholds for uptake in register, and data to be registered
- *Assessment:* the source data can (using effect thresholds, source and propagation data) e.g. be used to assess impacted area
  - 'Before' and 'After' use

Focus: displacement

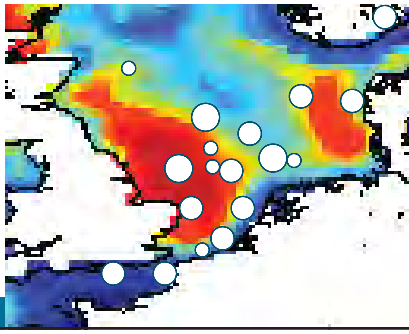


Focus: displacement



D9

Focus: displacement

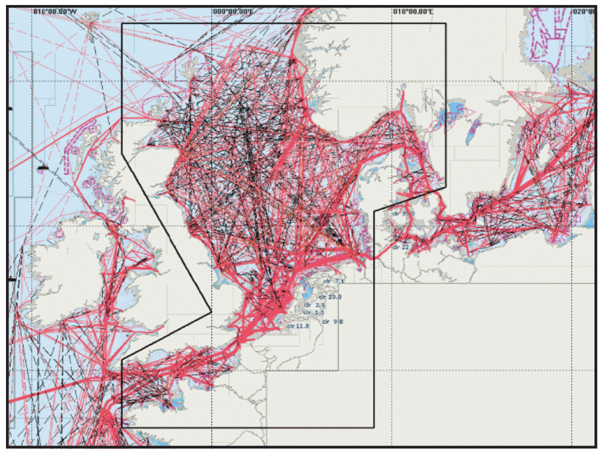


The European perspective

- What is happening at EU level
- What is happening in NL
- What do we need

North Sea

- Dutch Continental Shelf ~ 57.000 km² (1,5 times Netherlands)



North Sea

- Dutch Continental Shelf ~ 57.000 km² (1,5 times Netherlands)
- intensive shipping
- large fish-stocks
- diverse uses: nature, fisheries, shipping, offshore O&G, dredging, sand/shell mining, recreation, cables & pipelines, wind energy, defence, etc.

Main noise issues NL Marine Strategy

- Clear: that underwater noise produced by human activities has increased significantly since the mid-20th century
- Unclear: to what extent noise causes a problem, whether cumulative effects actually occur (a.o. by lack of actual data on noise sources/levels)
- But the 2020 target is: prevent negative effects at the ecosystem level → Good Environmental Status
- Increase of offshore wind energy development
- Development of Harbour porpoise protection plan (Ascobans)

D10

Inventory of sound sources in the NL North Sea

- Main
  - Shipping
  - Pile driving (windfarms, other)
  - Seismic surveys
  - Detonation of legacy munitions (WW2)
- Less importance
  - Dredging
  - Sonar

(in the NL part of North Sea)

19 25 February 2013

NL implementation of MSFD: more concrete

- Short term:
  - Prevent negative effects at the ecosystem level of specific activities
    - Update of regulation regime for seismic surveys
    - For other activities where required/new knowledge becomes available adapt present regulation regime (marine piling, explosive clearing, sonar; now all other mitigation than technology)
  - Start monitoring (2014)
- Longer term
  - Ambient noise and accumulation of effects at the ecosystem level: specific targets in 2018, if sufficient knowledge available at that time

20 25 February 2013

The European perspective

- What is happening at EU level
- What is happening in NL
- What do we need

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Knowledge needs NL

- Short term needs: effects of piling/seismic and effectivity of mitigation action
- Target setting at the ecosystem level in 2018 (next 6-yearly MSFD cycle) based on scientific progress
  - Accumulation of impulsive noise
  - Ambient (continuous) noise
  - Relation direct effects on individuals for the ecosystem/population
  - Improved knowledge to be available early 2017
- Monitoring will start 2014- will generate new knowledge of pressure on the environment; at short time will require knowledge

22 25 February 2013

Main research projects

- Knowledge on physiological effects of loud sounds on marine mammals and fish larvae (TTS/mortality)
- Equal loudness contours of harbour porpoise, seal (b/o equal latency)
- Source modelling of sound generation by piling
- Development of standards to describe acoustics (trilateral/European/ISO)
- Development of risk assessment tools (b/o RNLN operational tool)
  - Assessment of effectiveness of mitigation
  - Technical measures but also other (ramp-up, seasonal restrictions)
- Distribution of sensitive species, including trends, densities, seasonal variations- will be linked to sound mapping and increased knowledge on direct effects

23 25 February 2013

Main messages

- EU Marine Strategy introduces requirement to address noise at the national level
- Ambitious offshore wind energy targets of (mostly) NW European countries
- EU TSG Noise addressing monitoring of impulsive and ambient noise
- No overarching EU targets but this will may change
- Urgent short term: considerations mitigating action OWE
- Improved concrete knowledge of cost-effectiveness of mitigation needed
  - Other measures
  - Introduction of new technology

24 25 February 2013

D11

Alternative Technologies to Seismic Airgun Surveys Workshop

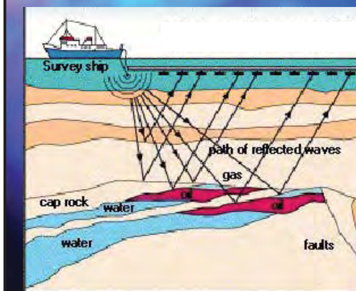
Lindy Weilgart (Ed.).

lweilgar@dal.ca

DALHOUSIE UNIVERSITY

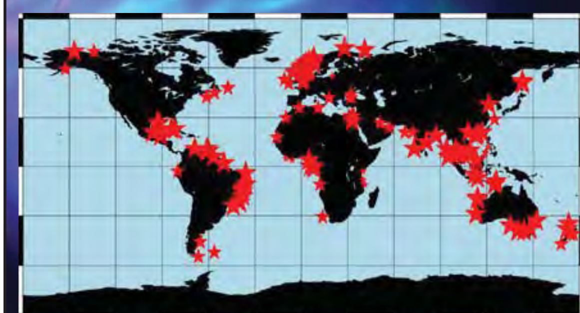
STIFTUNG FÜR DAS MEER okeanos

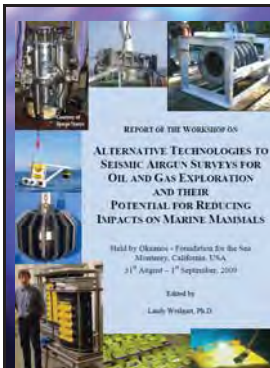
Marine Seismic (Airgun) Surveys



- Loud, sharp impulses
- Every 10 s
- Penetration: 10s-100s of km
- Surveys can last months
- Pervasive

Global Offshore Seismic Exploration





Workshop held by:

Okeanos
Foundation for the Sea

Monterey, California, USA
31 Aug. – 1 Sept., 2009

STIFTUNG FÜR DAS MEER okeanos

http://www.okeanos-foundation.org/assets/Uploads/Airgun.pdf

Workshop

- New technologies that might at least partially replace or modify airguns
  - Reduce amount or type of potentially harmful acoustic energy (i.e. peak pressure, rise time, unnecessary frequencies)
  - Reduce area ensonified
- Only participants with expertise in alternative technology invited
- Did NOT address evidence for or against biological impact of airguns
- Assumed that marine life would benefit from a quieter ocean

Participants / Co-Authors

- Ron Brinkman, MMS
- Chris Clark, Cornell University
- John Diebold, LDEO
- Peter Duncan, Microseismic
- Rob Habiger, Spectraseis
- Leila Hatch, NOAA*
- John Hildebrand, SIO
- Phil Nash, Stingray Geophysical
- Jeremy Nedwell, Subacoustech
- Dave Ridyard, EMGS
- Rune Tenghamn, PGS
- Peter van der Sman, Shell
- Lindy Weilgart, Dalhousie University & Okeanos Foundation
- Warren Wood, NRL
- John Young, ExxonMobil

* Chair

Consensus Statement

- Airguns produce "waste sound"
  - high frequency (>200 Hz), horizontal propagation
- Reducing peak levels important
- Silent or quieter technologies available or emerging
- Regulatory pressure/incentives and more funding needed to improve availability and application

Geophysical Drawbacks of Airguns

- Limited control in frequency and propagation of energy
- Source and receiver not optimal for desired bandwidth and penetration
- Potentially dangerous environment for workers

Alternative Technologies to Airguns

- Controlled sources
  - DTAGS (Deep-Towed Acoustics/Geophysics System)
  - LISA (Low Impact Seismic Array)
  - LACS (Low-frequency Acoustic Controlled Source)
  - Marine Vibrator, etc.
- Electromagnetic surveys
- Passive seismic (incl. Microseismics)
- Fiber optic sensors
- Airgun silencers, gravity gradiometry, etc.

Alternative Technologies to Airguns

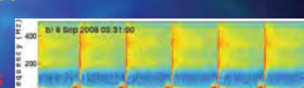
- More R&D needed to more completely replace role of airguns
- Env. aspects must be considered early in design phase of alternatives
- Good reason to believe these alternatives better for env., but must all first be tested for env. impact

Alternative Technologies to Airguns

- Controlled sources
  - Same energy spread over longer duration, thus lower peak levels (quieter)
    - 1-s pulse = airgun's 10-ms pulse
      100x quieter
      10,000x reduction in area of ensonification
  - Signals may be designed to minimize impact while still meeting geological objectives
  - Can reduce peak levels 30 dB+
  - May be more directional (vertical)

Alternative Technologies to Airguns

- Controlled sources
  - Over this 10,000-fold reduction in area of ensonification, masking (obscuring of important animal signals) may be worse due to longer pulses
  - However, also masking between airgun pulses at longer ranges due to reverberation
    - Signal is "stretched" from 10 ms to seconds
    - No recovery to ambient between shots



From:
Guerra et al. 2011, JASA,130 (5): 3046-58

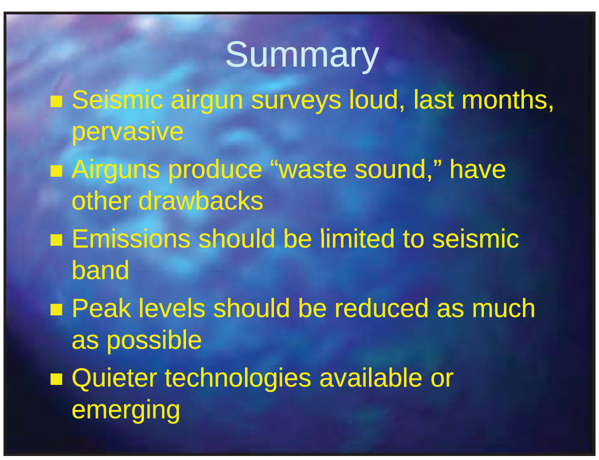
D13

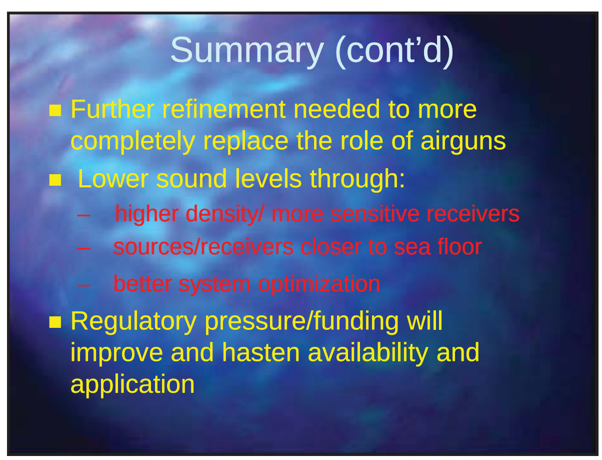

Alternative Technologies to Airguns


Alternative Technologies to Airguns
Lower sound levels achieved through:
– Higher density of more sensitive receivers
– Sound sources/receivers closer to the sea floor (in certain situations)
– Better system optimization (pairing of source and receiver characteristics)


Alternative Technologies to Airguns
Many currently in use, but cannot yet replace airguns entirely
Within 1-5+ years, these could be phased in, depending on funding and technology advancements
An increase in pressure and funding from regulators and the industry would hasten this process


Coordination/Incentives
Gov'ts should develop incentives for any alt techs with env benefits over airguns
Academic geophysicists should research quieter alts to airguns
Regulators should encourage and help fund R&D of quieter, alt sources and their EIAs
Gov'ts and regulators should produce clear, consistent domestic and int'l env compliance laws, regs, and standards and apply them consistently across different geographical areas


Summary
Seismic airgun surveys loud, last months, pervasive
Airguns produce "waste sound," have other drawbacks
Emissions should be limited to seismic band
Peak levels should be reduced as much as possible
Quieter technologies available or emerging


Summary (cont'd)
Further refinement needed to more completely replace the role of airguns
Lower sound levels through:
– higher density/ more sensitive receivers
– sources/receivers closer to sea floor
– better system optimization
Regulatory pressure/funding will improve and hasten availability and application


Acknowledgments
Thanks to:
Co-organizer Andrew Wright
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Michael Jasny
Leila Hatch
Tanja Winkler
Dieter Paulmann


Symposium Sound Solutions – Amsterdam 10.02.2012
Looking for solutions to reduce underwater noise
Symposium Sound Solutions
Georg Nehls


Symposium Sound Solutions – Amsterdam 10.02.2012
Amsterdam (Europe)
Europe from space
Nehls, BOEM, 25.02.2013

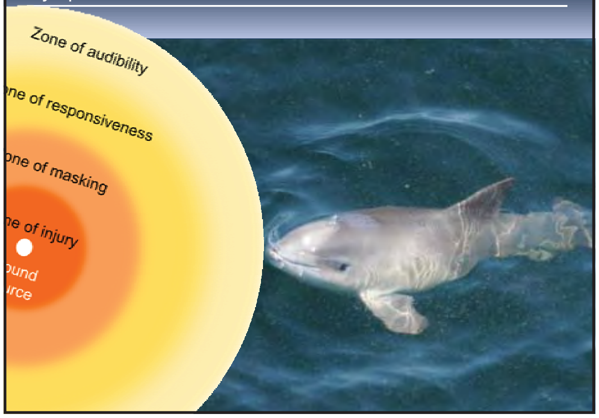

Symposium Sound Solutions – Amsterdam 10.02.2012
Old Europe
Nehls, BOEM, 25.02.2013


Symposium Sound Solutions – Amsterdam 10.02.2012
New Europe
Nehls, BOEM, 25.02.2013


Symposium Sound Solutions – Amsterdam 10.02.2012
Going offshore
Nehls, BOEM, 25.02.2013


Symposium Sound Solutions – Amsterdam 10.02.2012
Making noise
Autor, Veranstaltung, Datum

Symposium Sound Solutions – Amsterdam 10.02.2012



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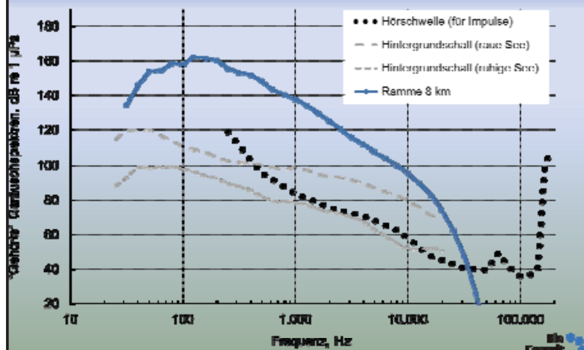
Noise immissions: 170 -180 dB$_{SEL}$ at 750 m



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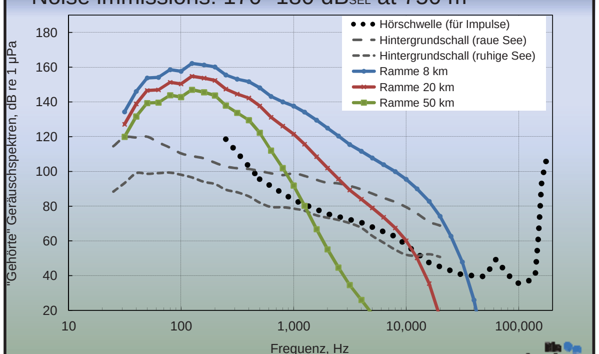
Noise immissions: 170 -180 dB$_{SEL}$ at 750 m



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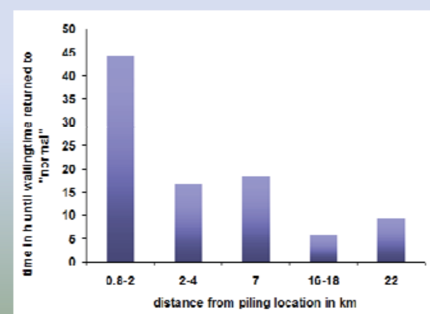
Responses of harbour porpoise



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Aim of the workshop

Overall: Looking for solutions to reduce underwater noise during the construction of future wind parks

Aim 1: limit impact on marine life

Aim 2: prevent a delay in offshore wind development

80 participants of different countries

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Regulations

Questions:

1) What are advantages and what are the disadvantages of the different national regulations?

2) How will the ideal regulations look like?

3) Which steps have to be taken to realize the ideal regulations as described under 2.

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European regulation (habitats directive):

For protected species

- Establish reserves
- No deliberate killing
- Restrict disturbance

Nehls, BOEM, 25.02.2013

Symposium Sound Solutions – Amsterdam 10.02.2012

Common practice:

- Deter marine mammals from near zone (all EU)
- Use Marine Mammal Observers (UK)
- Request noise mitigation (Germany)
- Restrict construction period (NL)

Nehls, BOEM, 25.02.2013

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Speed dating with 9 noise mitigation systems

1 IHC Noise Mitigation
2 Universal foundation-
3 Hydro Sound Dampers
4 Self-installing wind turbine
5 Large Bubble screen
6 Challenges for drilling
7 Dewatered cofferdam
8 Vibro Drilling
9 Concrete Gravity based

Nehls, BOEM, 25.02.2013

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Favourites (vote from audience)

1. Self Installing Windturbine
2. Dewatered Cofferdam
3. Hydro Sound Dampers

None of these systems has been brought to practice so far

Nehls, BOEM, 25.02.2013

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Discussion

1) What are the key advantages of this technique?
2) What are key disadvantages of this technique?
3) Could this technique be applied at a large scale in the North Sea?

Nehls, BOEM, 25.02.2013

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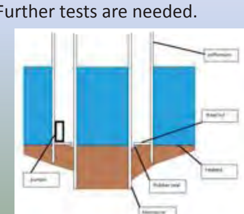
Dewatered Cofferdam

22 dB noise reduction has been communicated by manufactur.
"Speedy solution, relatively simple".
Questions on stability.
Further tests are needed.



Nehls, BOEM, 25.02.2013

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Symposium Sound Solutions – Amsterdam 10.02.2012

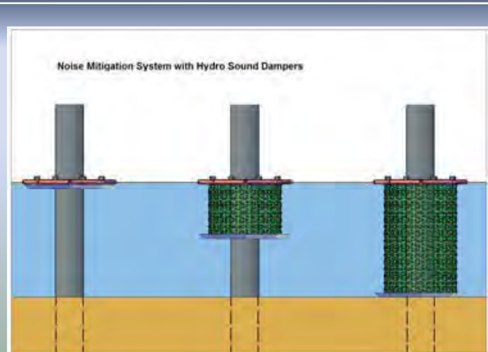
Self-installing wind turbine

Self-installing windturbines is a windturbine on an embraced monopile that is assembled inshore and towed to a site. It is installed by underpressurizing suction piles.

Symposium Sound Solutions – Amsterdam 10.02.2012

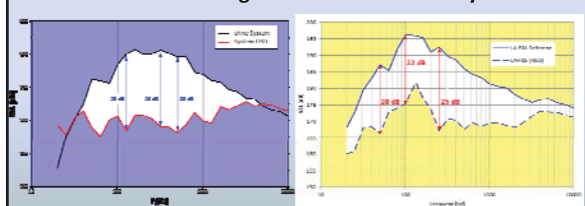
Hydro Sound Damper

Symposium Sound Solutions – Amsterdam 10.02.2012



Symposium Sound Solutions – Amsterdam 10.02.2012

Noise reduction during ESRA and London Array test



OffNoise-Solutions GmbH karl-heinz.elmer@t-online.de

Symposium Sound Solutions – Amsterdam 10.02.2012

Outlook

Noise mitigation is mandatory in Germany but in no other european country

In 2013
- One windfarm is finalizing construction without noise mitgation
- Six projects will use the Big Bubble Curtain
- For two transformer platforms a cofferdam system will be used
- A tubular system is planned to be used in 2014

Symposium Sound Solutions – Amsterdam 10.02.2012

More information: www.noordzee.nl/soundsolutions

Effects of Noise on Fish, Fisheries, and Invertebrates

A BOEM Workshop on Data Gaps and Research Needs

http://www.boemsoundworkshop.com

Kimberly Skrupky
Division of Environmental Assessment
Bureau of Ocean Energy Management
Kimberly.Skrupky@boem.gov

Purpose of the Workshop

- BOEM's Environmental Studies Program hosted the Workshop March 20-22, 2012 in San Diego California
- Focused on the effects from oil and gas, renewable energy, and marine mineral activities
- The geographic focus of the workshop was the U.S. Atlantic and Arctic OCS
- BOEM will use the results of this workshop to better inform decision-making and environmental analysis processes

Goals of the Workshop

- Identify the priority fisheries and species in the U.S. Atlantic and Arctic OCS
- Determine the feasible short-term and long-term research goals to close significant knowledge gaps
- Ascertain available means to reduce anthropogenic noise levels
- Identify mitigation options to reduce exposure risk

Literature Synthesis

- The first step in preparing for this Workshop was to write an updated Literature Synthesis on the topic
- Summarizes existing recent literature through January 2012 and picks up where previous syntheses (e.g., Popper and Hastings 2009) left off
- Provides an initial identification of information needs and data gaps for the Workshop

Main Questions in the Synthesis Part 1

- Which are the key species and fisheries likely to be affected in the areas under consideration? Does the distribution and behavior of the key species change at different times of the year? Is there sufficient information on the distribution of the animals and their use of key habitats? Are there times of the year when the animals are more vulnerable? When and where do the main fisheries take place?
- What are the current conditions in the area of interest, especially with respect to sound levels? Is the area of interest an acoustically pristine environment where the only sounds are from natural sources? What other stressors might already affect the area (e.g., chemical, electromagnetic)? Is the area likely to be subject to climatic or other changes in the future?
- What are the main energy-related developments taking place in the area? Which sound sources will be deployed—distinguishing between primary sources (i.e., airguns, pile drivers, dredgers) and secondary sources (i.e., support vessels, multi beam sonars)?
- How can sound exposure best be assessed? What metrics should be used?

Main Questions in the Synthesis Part 2

- What is known about the effects upon the species of interest at different levels of sound exposure4(e.g., intensity, duration)? Can dose response relationships be derived for different effects?
- What are the risks to individuals and populations from sound exposure? Can population level effects be determined from the data available? If not, what additional data are needed? Can cumulative or in-combination effects be integrated into the risk assessment?
- Is it possible to mitigate risk by changing the timing of sound-generating activities, reducing their spatial extent (e.g., reducing the area of a seismic survey) in relation to what is known of the biology of key species or by employing other mitigation measures to reduce the received sound levels?
- Does a response to man-made sound by an individual fish or invertebrate, or even by large numbers of these animals, really matter?

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The Workshop

- More than 150 people participated, representing several countries, Federal and State agencies, academia, non-governmental organizations, special interest groups, and the public
- Invited speakers were experts in their fields that could answer BOEM's questions

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Final Report and Gap Analysis

- Published Dec 2012
- The Gap Analysis is an integral part of this report (Section 3). It includes a full "wish" list of questions and data needs
- http://www.boemsoundworkshop.com/pages/final_report.asp

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Gaps Identified Part 1

- Assessing and Predicting Impact
- Mitigation
- Cumulative and Aggregate Effects
- Priority Habitats, Species, and Fisheries
- Priority Habitats, Species and Fisheries in the Atlantic
- Priority Habitats, Species and Fisheries in the Arctic
- Biological Mitigation
- Metrics and Terminology for Sources and Exposure
- Background Levels of Sound in the Sea
- Characterizing Man-made Sources
- Sound Propagation

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Gaps Identified Part 2

- Masking
- Source Mitigation
- Sound Measurements
- Sound Production, Sound Detection and Exposure to Man-Made Sounds by Invertebrates
- Sound Production by Fishes
- Sound Detection by Fishes
- Effects of Sound in Terms of Injuries and Effects upon Physiology
- Effects of Sounds upon Behavior
- Effects of Sounds upon Catches
- Effects of Sounds upon Populations
- Avoidance of Effects
- Forms of Behavioral Mitigation

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Use of Workshop Results

- Directing future research
- NEPA Analyses
- Developing Mitigations
- Notices to Lessees (NTLs)

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Why Talk About the Fish Workshop At the Quieting Technologies Workshop?

This workshop directly responds to some of the data gaps recognized in the Effects of Noise on Fish, Fisheries, and Invertebrates Report:

- Proposals for mitigation must be accompanied by evidence that the mitigation actually works
- Monitoring and assessing the efficacy of mitigation measures
- Exploration for minerals, oil and gas and siting for renewable energy activities is new to the Atlantic and ways must be found to deal with foreseen or potential development
- And most importantly, ***Research is needed to establish the means for reducing unwanted and damaging sound from a range of sound sources. Industry should look especially closely at alternative technologies to air guns and impact pile driving***

D21

A Summary of Existing and Future Potential Treatments for Reducing Underwater Sounds from Oil and Gas Industry Activities

Jesse H. Spence, Noise Control Engineering
799 Middlesex Turnpike
Billerica, MA 01821 USA
www.noise-control.com

Presented by Michael Bahtiarian at BOEM Workshop, March 25 2013

Overview

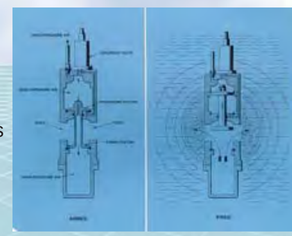
- Create awareness of research project
  - Joint Industry Programme on E&P Sound and Marine Life (www.soundandmarinelife.org)
- Purpose of work – To identify methods for reducing underwater noise from oil and gas industry activities
  - Seismic Exploration, Construction, Decommissioning, Transport (Vessels), Drilling and Production
- Literature search
  - Technical and trade journal articles
  - Contacts with manufacturers
  - Contacts with members of academia and researchers
  - Joint Industry Programme (JIP)
  - International Association of Oil and Gas Producers (OGP).
- Workshop
  - June 4-5, 2007 in Billerica, Massachusetts
  - Discuss findings so far, additional ideas
  - Attended by JIP & OGP, NOAA, MMS, USACE, and members of industry and academia

Overview

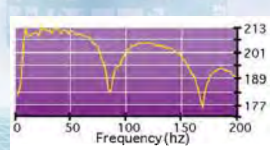
- Objective is to identify treatments that could be used to reduce underwater noise
- Ultimate goal is to reduce impacts on sea life.
  - Very limited discussions on effects of sound on marine animals
  - No discussions on the need for any particular treatment
- No source levels are provided
  - Sources ranked to focus research efforts
- Different treatments can be useful in different situations

Seismic Exploration

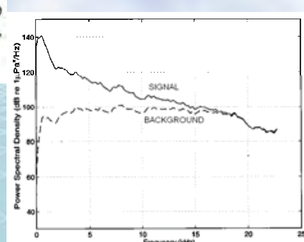
- Sources include
  - Air Guns, Boomers, Sparkers, and Explosives
- Sound generated by direct transmission
- Seismic Exploration typically uses frequencies in the 5-100 Hz range
- Sources generally produce sounds at frequencies well above this range


(Bolt Technology Corporation)

Air Gun Spectrum Examples



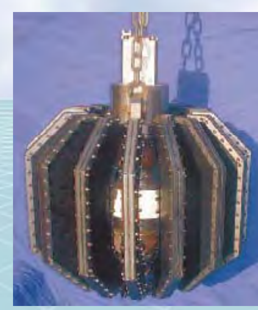
Caldwell (2000)



Goold (1998)

Air Gun Silencer

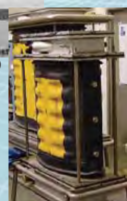
- Proof of concept design
- Reductions of 0-6 dB above 700 Hz
- 0-3 increases in level around 100 Hz
  - Provides 3 dB increase in overall level
  - Possible reduction in total number of required air guns
- Currently works only with 50 bar airguns.
  - Alternative designs possible


Nedwell (2005)

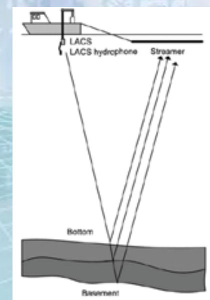
Alternative Sources

- Replacement for conventional sources
- Attempt to only create sound in useful frequency range, <100Hz
- Multiple designs
  - Petrol driven
  - Electrically driven
- 35-65 dB lower than airgun above 100 Hz
- Seismic data shows strong similarity to conventional sources

Askeland (2007)


Tenghamn (2006)

Alternative Sources

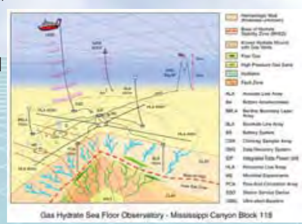


Askeland (2007)

- Cross correlation techniques
  - Shown to have ability to pull signal out of noise
  - Longer pulse
    - Increased effective rise-time, pulse length
    - Lower total energy
  - **Can reduce source level by 15 dB below 100 Hz**
- Vertical profiling currently performed with one system
- Excellent shallow water alternative to explosives

Ambient Sources

- Possible to use ship noise, wave noise, wind noise, and "micro-seisms" as sources
- Penetration depths up to 1000 meters documented
- Very large reductions in sound
- Long acquisition times required (hours, days, etc.)
  - May not be suited for new exploration
  - Possible option for Life-of-Field surveys



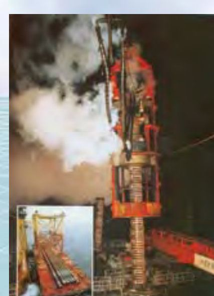
McGee (2007)

Other Options

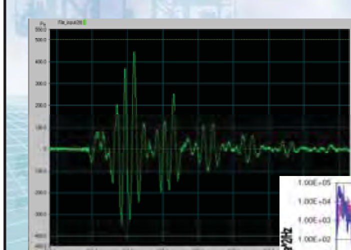
- Tunable pipe organ
  - Alternative source, deep penetration possible, currently used above 200 Hz, needs further development
- Electromagnetic surveys
  - Specific application, currently not a replacement for acoustic seismic approaches
- Air curtain barrier
  - Developed for shallow water, blocks sound in two directions
- Shear wave generators
  - More research is needed, signal may not be as useful as P-wave

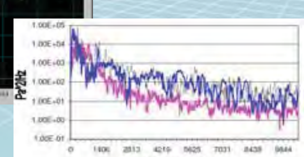
Pile Driving

- Shallow and deep water applications
  - Typical treatment for shallow applications
- Radiation primarily from pile itself
  - Flanking paths may exist through ground
- Impulsive sound
  - Quick rise-time, large peak pressures, frequency components to many kHz


Mather (2000)

Pile Driving Spectrum Examples

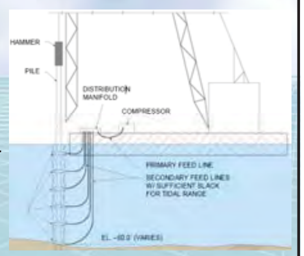

Laughlin (2007)



Laughlin (2005)

Bubble Curtains

- 'Wall' of bubbles produced around pile
  - Creates acoustical impedance mismatch,
  - Blocks sound transmission
- Bubbles are created by forcing air through ring.
  - Ring is located on the sea floor.
- Bubble 'trees' can be used in high current areas
- 5-20+ dB reduction in +\- peak, energy, and overall level
- Shallow water only



Petrie (2005)

Physical Barriers

- Metal casing located around pile
- Internal foam lining has been used by Laughlin (2007)
  - 15-23 dB reduction in peak, RMS, and energy levels
- Foam alone may also be a possibility
- Possible alternative to bubble curtains
  - Easier to implement
- Shallow water only

Laughlin (2007)

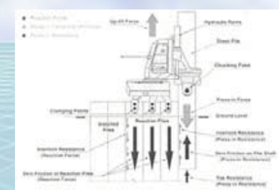
Suction Piles

- Large drum with bottom face removed
- Located on sea floor, water pumped out
- Removes all impulsive sounds, large reductions
- Can be mounted to bottom of larger structure or used for mooring
  - Applicable for deep water
- Currently used in many applications

SPT Offshore

Press-In Piles

- Piles installed using static forces
  - Reaction forces provided by previously installed piles
- Semi-automated process
- No impulse, very quiet
  - Permits approved for use on beach during turtle migration
- Sheet piles, circular piles, H-piles, etc.
- May have improved strength over impact driven piles
  - Load capacity known for each pile w/o additional testing
- Can be installed on barge for use in deep waters



Goh (2005)

Other Treatments

Pile Caps	1-20+ dB peak, RMS, energy
Vibro-piling	10-20+ dB overall level
Dewatered cofferdam	15 dB peak 3-35 dB RMS
Drilled, cast in place piles	Potentially large reductions

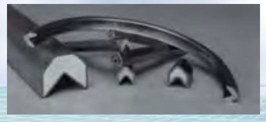
Explosives

- Uses
  - Decommissioning of offshore structures (deep water)
  - Obstacle removal (shallow and deep)
- Noise and shock wave created by direct radiation
  - Impulsive
- Spectrum is broadband

www.accessnoaa.noaa.gov/may0802/galveston.html

Shaped Charges

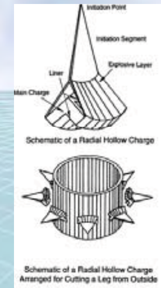
- Creates a focused explosive blast
  - Less material is needed for equivalent utility
- Used for removal of offshore structures
  - Located internally or externally around perimeter of structure
- Requires stand-off distance for maximum effectiveness
  - Possible increased engineering effort
- Effectiveness
  - ~4 dB peak pressure
  - ~13 dB Impulse
  - ~10 dB Energy Flux Density
- Produces 'clean' cut




Saint-Arnaud (2004)

Radial Hollow Charge

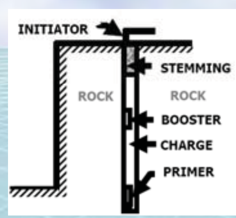
- Special application of shaped charges
- Uses less material than shaped charges
- Noise reduction expected based on reduction of required material
  - Estimates not available
- Additional cost may result due to increased complexity of design.



Committee, 1996

Borehole Stemming

- Used in applications with borehole in rock
- Top of hole is 'capped' or 'stemmed'
  - Capping material is inert
    - Rock or gravel
- Effectiveness
  - 10-19 dB +peak
  - 6-7 dB -peak
- Simple, inexpensive



Jordan, no date

Other Treatments

- Shock-wave focusing
  - 90% less material than shaped charges
- Slow burn explosives
  - Higher peak pressures
  - Much longer rise-times and impulse lengths
- Physical Barrier, Dewatered Cofferdam, Bubble Curtains
  - Previously discussed
  - Can be combined with alternative charges
  - Limited to shallow water
- Blasting Mats
  - Used extensively on land
  - Has been used underwater
    - No data
  - Could be used in deep water applications
  - Inexpensive material cost
  - Heavy
    - May require special equipment for location / installation
- Cutting tools
  - No impulse, reductions in overall level on order of 80 dB
  - Increased time on-site.

Vessels

- Includes Tankers, OSVs, PSVs, Work Boats, Crew Boats, and Icebreakers
- Sound primarily generated by
  - Propellers / thrusters
    - Cavitation
  - Machinery
    - Vibration and airborne noise
- Sound level strongly dependent on
  - Ship speed / operating condition
  - Propeller / thruster design
  - Machinery arrangement / vessel layout
- Noise control is a developed field of study

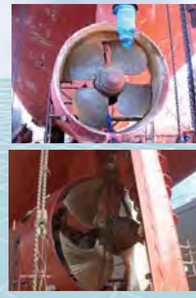

Propeller / Thruster Design

- Design Guidance
  - Large diameter, slow turning (reduced tip speed)
  - Skewed propeller designs, blade pitch modifications
  - Good inflow and outflow characteristics
- 3-10+ dB reductions in overall noise level possible
- Consult an expert
  - $50 - $200 k
- Efficiency may be a cost or benefit
  - Depending on design, increases or decreases in efficiency will result
- Decreased cavitation means less erosion, less on-board noise
- Can be applied to existing or new vessels

D25

Forward Skew Propellers and Thrusters

- Implemented for main propulsion, thrusters, waterjets, and pumps
- Reduced sensitivity to variations in inflow and vessel speed
- Large reductions possible (case study)
  - 18 dB @ 1000 Hz for thruster
  - 20 dB @12 kHz for propulsion



Provided by NAB & Associates

Drop Thrusters, Z-Drives, Azipods

- Propeller / Thruster is lowered below vessel hull
  - Better flow conditions
  - Reduced noise, est. 5-15 dB
- Some decrease in efficiency likely

www.brunvoll.no

www.uscg.mil/d9/glib/images/launch/Mack%20Launch%20010.jpg

Waterjets

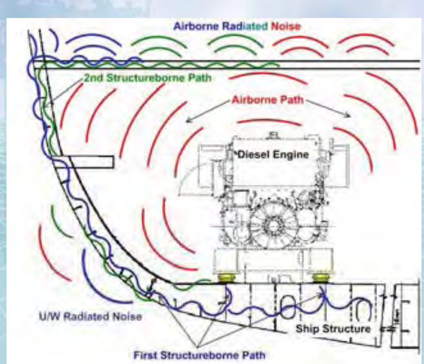
- High efficiency at high speeds (30-40 Knots)
  - Poor efficiency at lower speeds
- Lower radiated noise than equivalent open screw propellers
  - As high as 20 dB at optimal speed
- Forward skew impeller can greatly increase inception speed, tolerance to inflow non-uniformity
- Lightweight

www.rolls-royce.com

Other Treatments/Systems

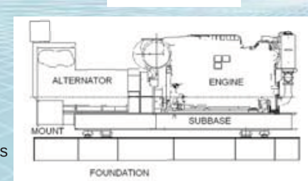
- Voith Schneider
- Rim Drive Propulsion
- Propac Rudder
- Foul Release Coatings
- Composite Blades
- Bubble Maskers
- Anti-singing Edge
- Regular Maintenance

Machinery Noise



Machinery Treatments

- Vibration
  - Resilient Mounting
  - Isolated Deck Structure
  - Damping
- Airborne
  - Cladding
  - Machinery Enclosures
  - Exhaust Silencers
- Both
  - Low noise equipment
  - Masking systems
  - Hull Decoupling materials
  - Regular Maintenance



Other Sources

- Dredges, Fixed Platforms, Floating Platforms
  - Treatments are similar to vessels
  - Application may be specialized
  - Requires case-by-case analysis
- Aircraft
  - Specialized treatments to reduce airborne noise

Summary

- Final report detailed these treatments:
  - Annotated table for quick reference
  - Discussion of sources, paths of noise, possible treatment approaches
- Final Report dated December 31, 2007
- Report posted on: **www.soundandmarinelife.org**
- E-mail jesse@noise-control.com for additional details

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Two NOAA-organized technical workshops (2004 & 2007) on shipping noise, marine mammals, and vessel-quieting technologies – progress and connections to related efforts

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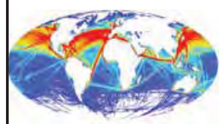
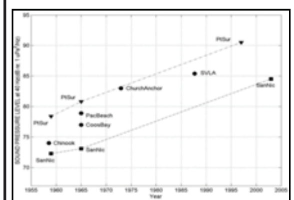
Long Marine Laboratory, Santa Cruz, CA

Duke University Marine Laboratory
Beaufort, NC

Why Shipping Noise?



Globally Distributed but Locally Dense



Significant noise footprints at LFs that propagate long ranges

Some evidence of longitudinal changes in LF noise in some areas

Masking issues (esp whales, seals, fish)

NOAA's 2004 symposium: "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology"

- *Dates*: **18-19 May 2004**
- *Location*: **Arlington, Virginia**
- *Primary Sponsor*: **NOAA's Ocean Acoustics Program**
- *Planning/Coordination*: U.S. Marine Mammal Commission, Chamber of Shipping of America, INTERTANKO, U.S. Navy, Society of Naval Architects and Marine Engineers, University of AK Marine Advisory Program, and American Bureau of Shipping
- ***Overall Objective*: Serve as a collaborative forum to initiate dialogue among various stakeholder groups on the impacts of noise from large ships on marine mammals and other marine life**

Shipping Noise and Marine Mammals (2004)

- *Issues covered*:
  - Trends in the Shipping Industry and Shipping Noise
  - Effects of Noise on Marine Life
  - National and International Response to the Marine Noise Issue
  - Developing Technologies for Monitoring Marine Noise
  - Vessel Quieting Technology: Application and Benefits
- *Notable events*:
  - Keynote address by Congressman Wayne Gilchrest; other remarks by U.S. Deputy Secretary of Commerce, NOAA's General Counsel, Director NMFS Office of Protected Resources, Director U.S. Marine Mammal Commission
  - Technical sessions on above points
  - Multi-stakeholder panel formulates specific action points

Shipping Noise and Marine Mammals (2004)

Conclusions/Outcomes:

-Introduced the issue to new sectors

-Initiated new partnerships, multi-stakeholder dialog and calls for action on this broad-scale, chronic environmental issue

-Highlighted research and monitoring needs (PAM in ocean observing systems)

-Specific calls for progress on vessel-quieting technologies and formation of NOAA steering group

-Identified key need: engage UN's IMO on this issue

Report citation: Southall, B. L. (2005). Final report of the 2004 International Symposium "Shipping Noise and Marine Mammals: A Forum for Science, Technology, and Management." National Marine Fisheries Service, Office of Protected Resources, Technical Report. National Oceanic and Atmospheric Administration, Washington, D.C. (available through NOAA's Ocean Acoustics program and also: **http://sea-inc.net/assets/pdf/sn_2004%20ShippingSymposiumReport_FINAL.pdf**)

NOAA's 2007 symposium: "Potential Application of Vessel-Quieting Technology on Large Commercial Vessels"

- *Dates*: **1-2 May 2007**
- *Location*: **Silver Spring, MD**
- *Primary Sponsor*: **NOAA's Ocean Acoustics Program**
- *Planning/Coordination*: U.S. Marine Mammal Commission, Okeanos-Stiftung für das Meer, Chamber of Shipping of America, U.S. Navy
- ***Overall Objective*: Provide an objective assessment of the feasibility and economic aspects of various quieting applications for the designers, builders, owners, and operators of large commercial vessels**

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Vessel-Quieting Technologies (2007)

- *Issues covered*:
  - Vessel Acoustics and Ambient Noise
  - Potential applicability and cost/benefit analysis of existing and future vessel-quieting technologies
  - Non-regulatory incentives to reduce noise emission
  - "Menu" of quieting options for future consideration/action
- Notable events:
  - Detailed technical sessions on quieting technologies – key action areas related to propulsion systems re: cavitation
  - Focus on incentives, meaningful certification programs

Vessel-Quieting Technologies (2007)

Conclusions/Outcomes:

- Comprehensive and most successful strategy forward will include a **multi-pronged, collaborative approach** with:
  - more efficient technologies favoring quieter operations;
  - industry-driven incentives, partnerships, and certifications; and
  - spatially-based regulatory approaches regarding chronic noise.
- **Specific calls to engage directly with the IMO** on vessel-quieting technology to tackle this issue internationally

Report citation: Southall, B. L. and A. Scholik-Schlomer. (2008). Final report of the NOAA International Conference: "Potential Application of Vessel-Quieting Technology on Large Commercial Vessels," 1-2 May, 2007, Silver Spring, MD, U.S.A. (available through NOAA's Ocean Acoustics program and also: http://sea-inc.net/assets/pdf/sn_2007%20ShippingSymposiumReport_FINAL.pdf)

Progress Since 2004

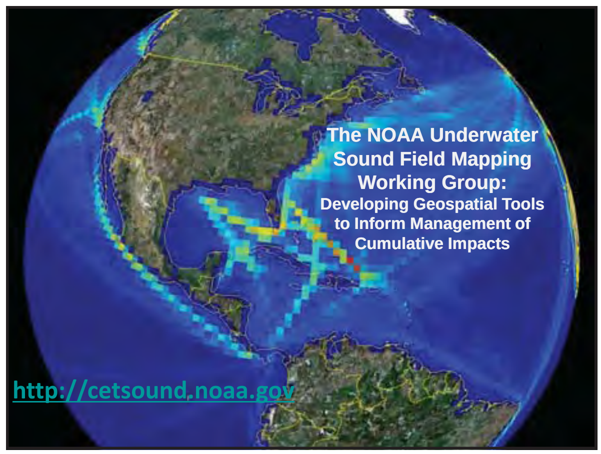
2004 NOAA Symposium: brought stakeholders together for the first time to discuss impacts and potential solutions

2007 NOAA Symposium: focused on technical details and basic costs and benefits of various noise reduction options

2008 Okeanos Workshop: defined goals for noise reduction

IMO (U.S. proposal, 2008)

2004	2005	2006	2007	2008	2009	2010
1st NOAA Symposium	NOAA Steering Group	- 2nd NOAA Symposium - IMO info paper	- Okeanos Workshop -IMO Corresp. Group forms	- IMO CG reports - Model basin technical response - AMSA report - ANSI standards		-IWC Session on masking noise - IMO CG recs. -EU MSFD



1

Terminology for Underwater Sound

Michael Ainslie (TNO)

Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving: A BOEM Workshop on the Status of Alternative and Quieting Technologies, 25-27 February 2013, Silver Spring, MD

Every science requires a special language because every science has its own ideas. It seems that one ought to begin by composing this language, but people begin by speaking and writing and the language remains to be composed

Étienne Bonnot de Condillac (1715-1780)

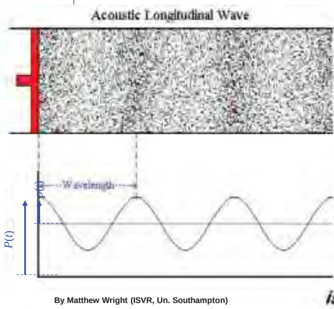
2

Objectives

- Define basic terminology of underwater sound
  - Sound pressure
    - Sound pressure level (SPL); sound exposure level (SEL)
  - Sound particle velocity
- Explain more advanced terminology
  - Source level (SL)
  - Propagation loss (PL)
- Standardisation
  - Demonstrate need (pitfalls)
  - Increase awareness of existing standards
  - Encourage participation in development of new ones

3

Fundamental properties of sound



- Acoustic particles
- Sound pressure $p(t)$
  - $p(t) = P(t) - P_{atm}$
  - Main focus
- Acoustic particle motion:
  - Displacement **x**
  - Velocity **u** = d**x**/dt
  - Acceleration **a** = d**u**/dt
- E.g. **u** = "sound particle velocity"

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Basic terminology of underwater sound

- Sound exposure E: $E(T) = \int_0^T p(t)^2 \, dt$ — T = integration time
- Sound exposure level (SEL):

$$\mathrm{SEL} = 10\log_{10}\frac{E}{p_{ref}^2 t_{ref}} \quad (p_{ref} = 1\,\mu\mathrm{Pa} \quad t_{ref} = 1\,\mathrm{s})$$

- Root mean square (RMS) sound pressure p_{RMS}

$$p_{RMS} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 \, dt}$$ T = averaging time

- Sound pressure level (SPL):

$$\mathrm{SPL} = 10\log_{10}\frac{p_{RMS}^2}{p_{ref}^2}$$

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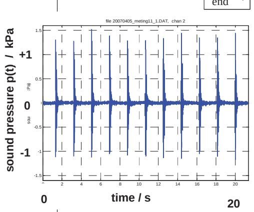
Sound pressure level: application to transient sound (I)

$$\mathrm{SPL} = 10\log_{10}\left(\frac{1}{T_{end} - T_{start}}\int_{T_{start}}^{T_{end}} \frac{p(t)^2}{p_{ref}^2} dt\right) \quad T_{start} = ? \quad T_{end} = ?$$



SPL depends on averaging time:

143 dB re 1 μPa	repetition time ('SPL_{eq}')
156 dB re 1 μPa	90% energy ('SPL_{90}')
179 dB re 1 μPa	peak-equivalent RMS ('SPL_{peRMS}')

- Absence of standardisation leads to: **36 dB difference** between highest and lowest
- → need for measurement and reporting standards

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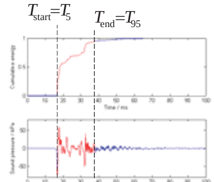
Sound pressure level: application to transient sound (II)

- Choice of averaging time: 90% energy rule → SPL_{90}

$T_{start} = T_5$ $T_{end} = T_{95}$



$$\mathrm{SPL}_{90} = 10\log_{10}\left(\frac{1}{T_{95} - T_5}\int_{T_5}^{T_{95}} \frac{p(t)^2}{p_{ref}^2} dt\right)$$

Example provided by Peter Dahl (APL, Un. Washington)

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Advanced terminology of underwater sound: source level and propagation loss

- Propagation loss (PL)
  - PL(r) ≡ SL – SPL(r)
  - Also known as transmission loss (TL)
- Source level (SL)
  - Property of source: related to **radiated power** or energy
  - **Far field** concept
  - No single widely accepted definition
    - ANSI (S1.1-1994): ~ "**SL is defined as SPL at 1 m**"
    - Consensus of ad-hoc European terminology working group*: ~ "**SL is not defined as SPL at 1 m**"

* "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units", edited by M A Ainslie, TNO-DV 2011 C235, Sep 2011

Advanced terminology of underwater sound: source level (continued)

- Meaning of "source level" depends on the type of source
  - Proximity to sea surface or seabed
  - Transient vs continuous sources
- Examples:
  - Sonar: submerged source; continuous (RMS)
  - **Airgun**: near-surface source; transient (zero to peak)
  - **Surface ship**: floating source; continuous (RMS)
    - at least 3 different definitions in use
  - **Pile driver**: attached to seabed
    - Where is the far field?
    - **No definition available** in shallow water
- Horses for ~~courses~~ sources

Our little friendB

dB re. 1 J/m²/Hz
255 dB re 1 μPa

1 μPa at 1 m
199.7 dB pk-pk re 1 μPa
dB re μPa/√Hz
dB re 1 lb
220 dB pp
200 dB rms
dB re μPa² m² s kg⁻¹
SL (dB Re: 1 μ Pa² / Hz @ 1 m /m²)
167 dB re. 1 μPa (pp)
dB/μPa/√Hz
235 dB re 1 μPa pp at 1 m
(dB/1 deg)
117.0 dB re μPa²
260 dB re. 1 μPa (0-peak)
−212 dB re 1 V/μPa

Towards standardisation (I): Existing standards (acoustical terminology)

- General acoustical terminology
  - ANSI (S1.1-1994): *Acoustical Terminology*
  - ISO (80000-8:2007): *Quantities and units – Part 8: Acoustics*
- Some inconsistencies between ANSI and ISO
  - Sound pressure level
  - …
- Some conflicts between air acoustics and underwater acoustics
  - Reference values
  - Frequency weighting

Towards standardisation (II): ANSI and ISO Working Groups

- ANSI
  - S1.1-1994 Acoustical Terminology
  - Update S1.1-201x
  - Chair: Jeff Vipperman (co-chair Charles Greene)
- ISO TC 43 (Acoustics) SC 3 (Underwater acoustics)
  - New sub-committee of TC43
    - Inaugural meeting at WHOI (June 2012)
    - Second meeting in Berlin (May 2013)
  - Three working groups
  - Chair: George Frisk
- Contact: Susan Blaeser (sblaeser@aip.org)

Towards standardisation (III): ISO TC 43 SC3 WGs

- Working Group WG1
  - Measurement standard: Radiated noise from **ships** (convenor: M Bahtiarian)
  - Ex WG55 (SC 1)
  - Inaugural meeting in June 2012, WHOI
- Working Group WG2
  - **Underwater acoustical terminology standard** (convenor: M Ainslie)
  - Inaugural meeting in May 2013, Berlin
- Working Group WG3
  - Measurement standard: Radiated noise from **impact pile driving** (convenor: S Robinson)
  - Inaugural meeting in May 2013, Berlin

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Towards standardisation (IV): European work

- Ad hoc European working group
- Consensus report
  "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units", edited by M A Ainslie, TNO-DV 2011 C235, Sep 2011
- Recommendations adopted by
  - Draft Science Plan: International Quiet Ocean Experiment
    Review Draft, 12 February 2013, Edited by I Boyd, G Frisk, E Urban and S Seeyave
  - European Commission expert group 'TSG Noise'
    "European Marine Strategy Framework Directive Good Environmental Status (MSFD-GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy: Final Report", S van der Graaf et al, Feb 2012.

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Conclusions (I): need for standardisation

- ANSI vs ISO: eg Sound pressure level
- Our little friendB: eg choice of reference values
- Source level
  - SL ≠ SPL at 1 m
  - "Horses for sources"
    - Different definitions for **airguns** and **surface ships**
    - Three different definitions of **surface ships**
    - **No definition for pile driving** (in shallow water)

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Conclusions (II): need for standardisation

- Conclusions from BOEM 2012 'Fish and Invertebrates' Workshop*

> "*… the current use of [underwater acoustical] terminology is inconsistent and not always appropriate.*"
>
> "*A common terminology needs to be developed … that is useful and understandable to [acousticians, biologists and regulators].*"

* Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities, Workshop Report, U.S. Department of the Interior, **Bureau of Ocean Energy Management, December 2012**. [Final Report, BOEM Workshop 'Fish and Invertebrates', Hawkins & Popper, March 2012]

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Conclusions (III): Progress towards standardisation of terminology

- ANSI:
  - Existing standard S1.1-1994
  - Update 'S1.1-201x' nearing completion
- ISO:
  - New sub-committee underwater acoustics (TC43 SC3)
    - WHOI, June 2012
  - Terminology working group
    - Berlin, May 2013
- Volunteers welcome: (Susan Blaeser: sblaeser@aip.org)

17

References

- ANSI (S1.1-1994): Acoustical Terminology, ANSI S1.1-1994 (ASA 111-1994), Revision of ANSI S1.1-1960 (R1976).
- ISO (80000-8:2007): Quantities and units – Part 8: Acoustics
- "Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units", edited by M. A. Ainslie, TNO-DV 2011. C235*
- European Marine Strategy Framework Directive Good Environmental Status (MSFD-GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy: Final Report", S van der Graaf et al, Feb 2012. **

*http://www.informatiehuismarien.nl/ihm/themas/Shortlist_Ecologische_Monitoring_Wind_op_Zee/Geluidsonderzoek/

** http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-11/index_en.htm

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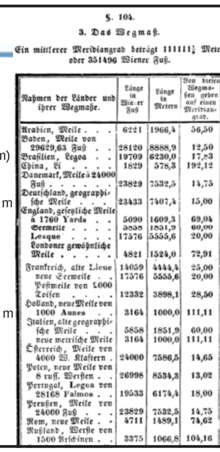
Questions?

- Roman mile: 5000 Roman feet (ca. 1479 m)
- Metric mile: 1500 m
- Statute mile: 5290 feet (1609.344 m)
- Survey mile: 5280 survey feet (1609.3472 m
- Nautical mile: 1852 m
- Scots mile: 320 rods (5920 feet)
- Portuguese *milha*: 2087.3 m
- Irish mile: 6720 feet
- Danish *mil*: 24,000 Danish feet (7532.5 m)
- German *meile*: 24,000 German feet (7586 m
- *Geographische meile*: ca. 7412.7 m
- Russian *milya*: 7468 m
- Norwegian or Swedish *mil*: 10,000 m
- Croatian *milja*: 11,130 m



§. 104.

3. Das Wegmaß.

Ein mittlerer Meridiangrad beträgt 111111 1/9 Meter oder 351496 Wiener Fuß.

Nahmen der Länder und ihrer Wegmaße.	Länge in Wiener Fuß	Länge in Metern	Von diesen Wegmaßen geben auf einen Meridiangrad.
Arabien, Meile	6221	1966,4	56,50
Baden, Meile von 29629,63 Fuß	28120	8888,9	12,50
Brasilien, Legoa	19709	6230,0	17,83
China, Li	1829	578,3	192,12
Dänemark, Meile à 24000 Fuß	23829	7532,5	14,75
Deutschland, geographische Meile	23433	7407,4	15,00
England, gesetzliche Meile à 1760 Yards	5090	1609,3	69,04
Seemeile	5858	1851,9	60,00
League	17576	5555,6	20,00
Londoner gewöhnliche Meile	4821	1524,0	72,91
Frankreich, alte Lieue	14059	4444,4	25,00
neue Seemeile	17576	5555,6	20,00
Postmeile von 2000 Toisen	12332	3898,1	28,50
Holland, neue Meile von 1000 Aunes	3164	1000,0	111,11
Italien, alte geographische Meile	5858	1851,9	60,00
neue metrische Meile	3164	1000,0	111,11
Österreich, Meile von 4000 W. Klaftern	24000	7586,5	14,65
Polen, neue Meile von 8 russ. Wersten	26998	8534,3	13,02
Portugal, Legoa von 28168 Palmos	19533	6174,4	18,00
Preußen, Meile von 24000 Fuß	23829	7532,5	14,75
Rom, neue Meile	4711	1489,1	74,62
Rußland, Werste von 1500 Arschinen	3375	1066,8	104,16

D32

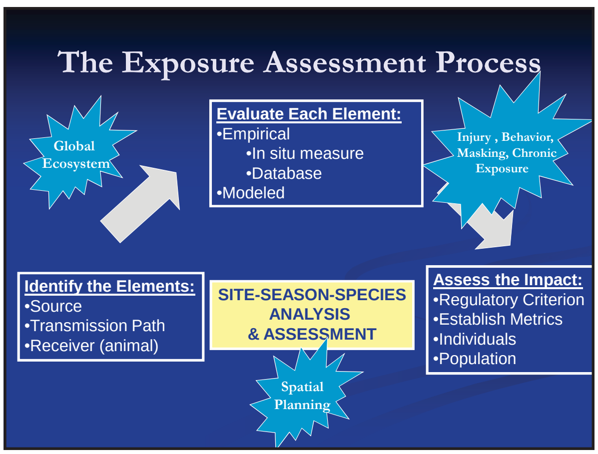
Spatial, Spectral and Temporal Properties of Sound Sources

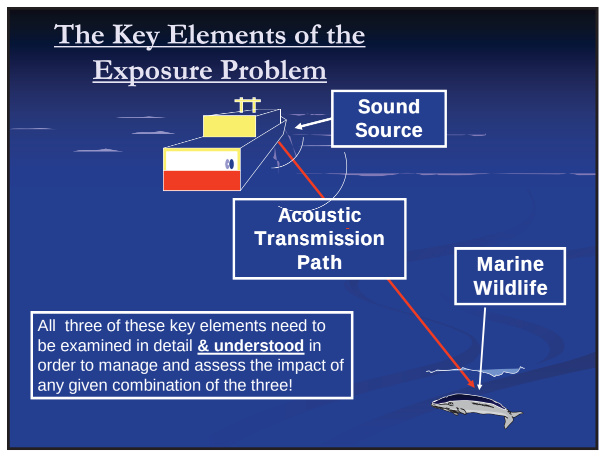
(& associated issues)

William T. Ellison
Adam S. Frankel
Marine Acoustics, Inc.
809 Aquidneck Ave.
Middletown RI 02842

Outline

- The Noise Exposure Problem
  - Exposure Assessment Issues
  - Key elements (Source-Path-Receiver)
- Source Properties
  - Spatial
  - Spectral
  - Temporal
- Some Source/Exposure Issues to Focus on to Assess Potential Quieting



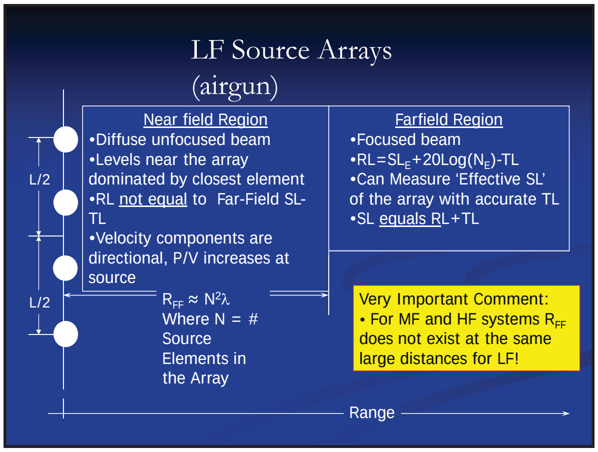


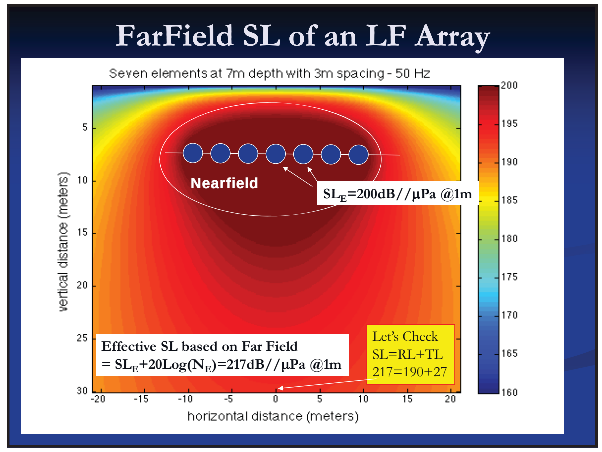
Describing a Source

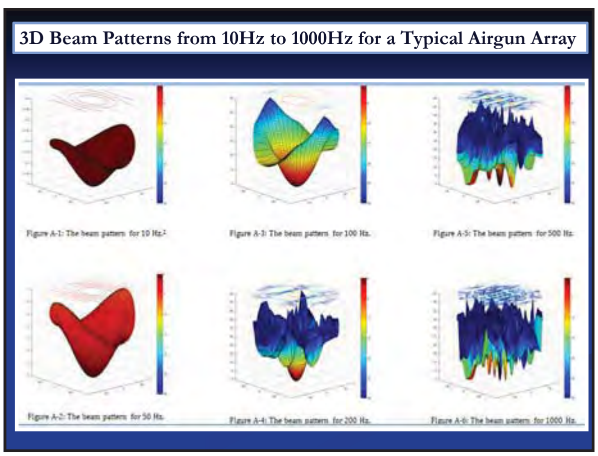
- Spatial
  - How big in size **{Omni Unit, Array, Complex}**
  - Movement **{Stationary, Slow, Fast}**
  - Distance to Aquatic Life **{Very Near, Near, or Far}** — Aversion?
- Spectral
  - Frequency Band **{HF, MF or LF}**
  - Bandwidth **{Narrowband, Broadband}**
  - Sound Type **{Pulse, Non-Pulse}**
  - Ambient Background **{Natural, Man-Made}**
- Temporal Characteristics & Typical Exposure Metrics
  - Sound Duration **{Short, Long}**
  - Duty Cycle **{Repetitive, Continuous, Single Sound}**
  - Exposure Metrics **(SPL, SEL, CSEL, SNR, Particle Velocity, Masking, Chronic)**

Key Issue: Very Near to a Source

- For an Array or Complex Structure
  - Near field region defined by the source frequency and spatial configuration of the source
  - Pressure and Particle Velocity have a complex relationship
  - Not easy to analytically describe or to measure *in situ*
  - Most likely region for direct acoustic injury
  - Explosives and some pulse-like sources may engender barotrauma effects (Pa-sec)

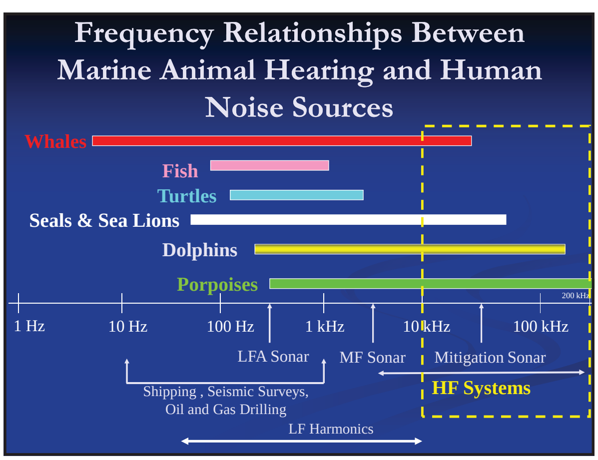


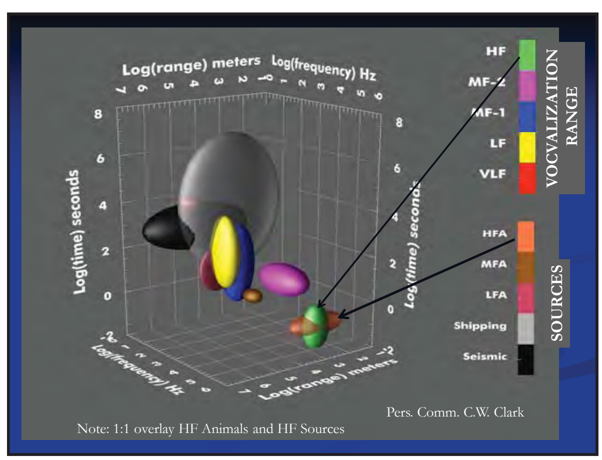




HF Issues

- Strong overlap HF Vocalizations and HF Active Systems
- Potentially high SL's
  - Small (almost non-existent nearfield)
  - Propagation effects due to absorption significant at higher frequencies, but are directly proportional to range & so near field unaffected
- For behavioral studies be careful. Unwanted HF components, e.g. harmonics from resonant sources, can be strongly indicative of close range.





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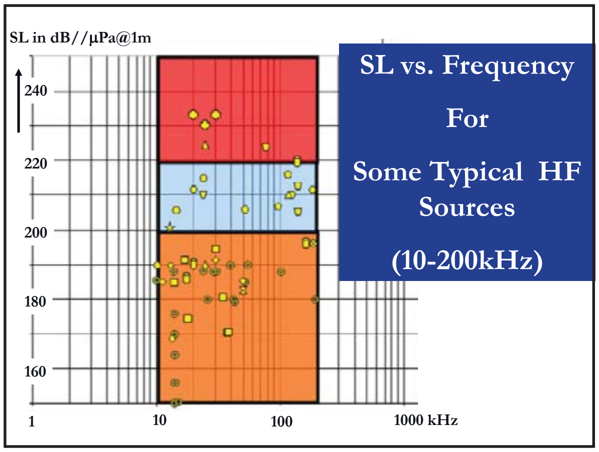
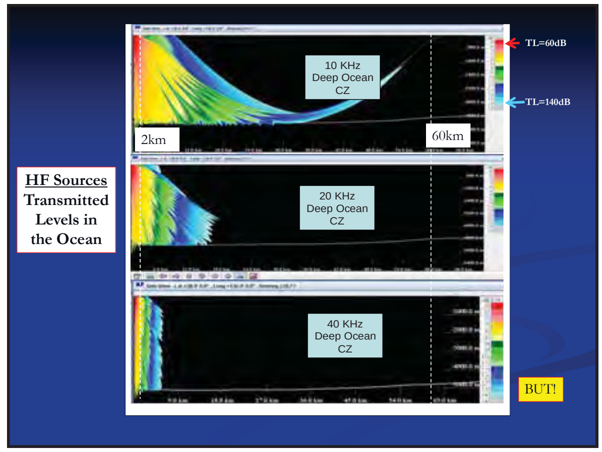


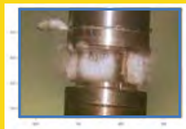


Summary

- All aspects of a source and its operation, including the spatial, spectral and temporal properties have the potential for quieting attributes
- Sound fields in the immediate vicinity of complex sources with broadband pulsive sounds (e.g. pile driving and airgun arrays) are difficult at best to model or measure.
- Chronic sound exposure and masking will both require new approaches to measurement and assessment.
- High Frequency Sources (>10kHz) can produce high exposure levels at short distances.

AIRGUNS – AN OVERVIEW

The acoustic source of choice
for the last **50** years



Peter van der Sman

PREAMBLE

One man's signal is another man's noise…

The oil and gas industry is one that actually exploits acoustic emissions to do their business. By far the most frequently used source today is the airgun while the bulk of the acoustic energy emitted is actually exploited for seismic surveying.

This presentation aims at explaining how airguns work, including relevant aspects related to their use in arrays to further optimize their performance for exploration. At the same time though insights are shared on how to reduce superfluous higher frequency emissions and that may help in reducing their acoustic footprint.

CONTENT

SOME BACKGROUND

- To allow efficient exploration for resources, accurate and detailed information about the subsurface is needed.
- Multiple techniques are available yet seismic methods are by far the most 'popular'.
- Of those, reflection seismic is the most commonly applied method. Here, the responses to a stimulus are used to map subsurface structures and properties much like in an echogram.
- Early on, impulsive sources were used as only these (not having computers) allowed interpretation.
- Chemical explosives like dynamite were typically used then.
- Post World War II, exploration for oil and gas moved offshore.

FROM DYNAMITE TO LOW-FREQUENCY IMPULSIVE SOURCES

1960: **An accident with explosives triggered R&D into alternative seismic sources and led to the development of the airgun.**

Dynamite 1960 1970 1980 1990 2000 2010
Tuning — Compact 3D → Air-gun

Air-gun
Bolt CGG
Lamont Sodera
GSI
Prakla Seismos
Litton

Steam-gun
Water-gun
'GI'airgun

The airguns that are used today are still operating according to the same principles. Naturally, their design was optimized, mostly so for reasons of reliability and for generating a stable output signal.

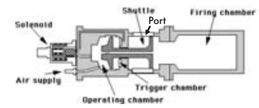
Savit, C.: "Seismic data acquisition", Geophysics TLE, 1989

1
AIRGUN BASICS

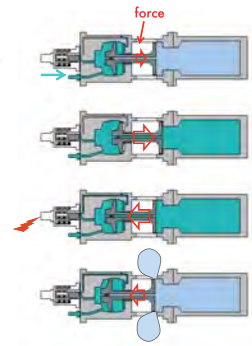
AN WELL KNOWN EXPERIMENT

The sudden bursting of a balloon results in a load, short duration sound. Releasing the same energy slowly by simply releasing the balloon only results in longer duration sound with low amplitude. The airgun we will discuss in the rest of this presentation performs somewhere in between these extremes. Please look for the similarities …

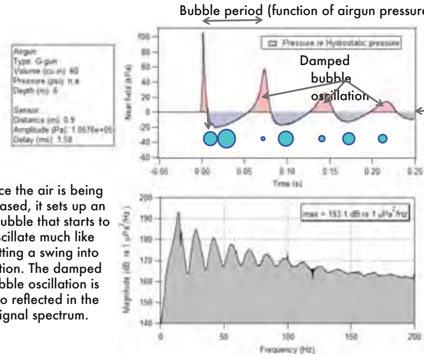
AIRGUN 101



Comparing the operation of an airgun to that of the balloon, we find similarities and also differences. The firing chamber is pressured up much like the balloon. Yet it does not fail. In fact it releases the air on command and in a controlled way thus generating the desired signal. And that over and over again… Notice that speed in which the shuttle is opening the ports is essential in generating the initial impulsive output!



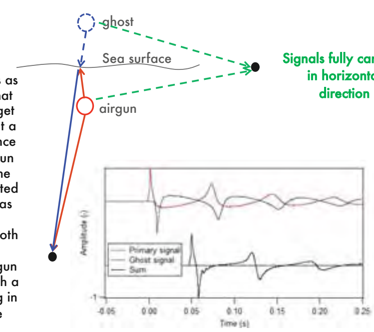
THE SIGNAL MEASURED CLOSE TO AN AIRGUN



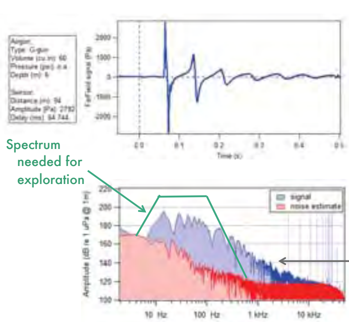
Once the air is being released, it sets up an air bubble that starts to oscillate much like putting a swing into motion. The damped bubble oscillation is also reflected in the signal spectrum.

SURFACE 'GHOST' AND DIRECTIVITY

The sea surface acts as a mirror for such that acoustic emissions get reflected. Looking at a point at some distance away from the airgun we observe both the direct and the reflected signal (referred to as the 'ghost'). Off towards the sides, both arrivals cancel. Underneath the airgun the ghost arrives with a small delay resulting in a strong response



THE SIGNAL BELOW THE AIRGUN AT LARGER DISTANCE



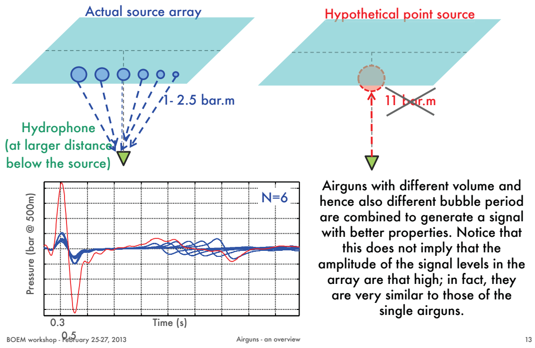
A single airgun signal is not really suitable for exploration:

- Too weak
- Time domain shape is unfavorable (echo's)
- Spectral content is unfavorable (low and varying signal-to-noise ratio).
- High frequency emissions often superfluous.

2 AIRGUN ARRAYS

Tuning and signature aspects

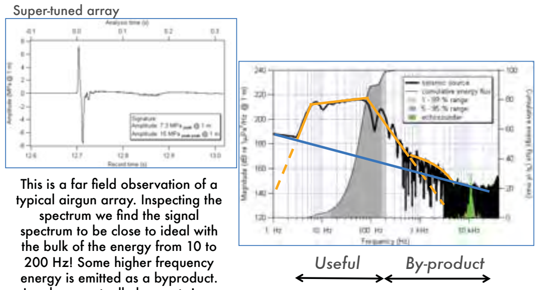
TUNING & NEAR- & FAR FIELD ASPECTS



Airguns with different volume and hence also different bubble period are combined to generate a signal with better properties. Notice that this does not imply that the amplitude of the signal levels in the array are that high; in fact, they are very similar to those of the single airguns.

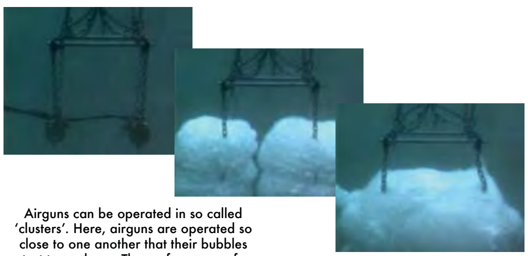
TUNING: USEFUL ENERGY AND BYPRODUCTS

Super-tuned array



This is a far field observation of a typical airgun array. Inspecting the spectrum we find the signal spectrum to be close to ideal with the bulk of the energy from 10 to 200 Hz! Some higher frequency energy is emitted as a byproduct. Levels are actually low, yet since the noise floor is also dropping off, this energy is still detectable.

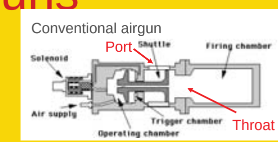
CLUSTERS



Airguns can be operated in so called 'clusters'. Here, airguns are operated so close to one another that their bubbles start to coalesce. The performance of a cluster is superior over that of a single airgun having a volume equal to the sum of the individual volumes and modern arrays frequently use this concept to improve their efficiency.

Courtesy: PGS

3. Optimizing airguns



NOISE 'ATTENUATION' TECHNOLOGIES OVERVIEW

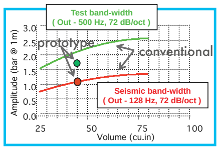
- At source element scale
  - The airguns themselves
    - Design for spectral bandwidth and level (and not for peak output in time)
  - Near the element
    - Attenuate out-of-band energy
- At source array scale (typically not considered)
  - Array design and (de-) tuning (timing, depth).
  - Around the array (bubble screen?)
- At survey scale (not discussed in this presentation)
  - Reduce signal level while maintaining SNR (more & better receivers, processing technologies, multiple sources, etc.)

AIRGUN AT THE MOMENT OF FIRING
WITH SIGNS OF CAVITATION

Airgun design is critical in that it will determine what the rise time of the signal will be. At the same time, the design can lead to undesired byproducts like cavitations as shown here. Cavitations will induce high frequency emissions while they may affect the lifetime of the airgun and the equipment in the vicinity.

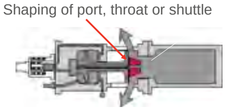
Shell Research, 1968

ATTENUATE OUT-OF-BAND ENERGY

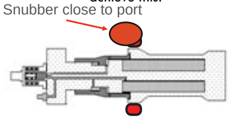


In the past, airguns were optimized for their output amplitude in the time domain, resulting in high frequency energy that is not really needed. Evaluation of an airgun prototype showed that it would be possible to reduce high-frequency emissions from airguns without affecting their contributions in the seismic band. A proposal was made to the industry suggesting two possible approaches to achieve this.

Shaping of port, throat or shuttle



Snubber close to port



van der Sman, "Airgun Design for Marine Seismic Operations". IAGC/ UKOOA Workshop , London, 1999

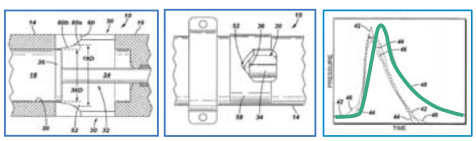
ATTENUATE OUT-OF-BAND ENERGY
ADD COMPLIANT MATERIAL (SNUBBER)

Nedwell, 2005

J. Nedwell showed that the noise attenuation principle worked fine, yet the solution proved not practicable as the dampening material was damaged rather quickly…

Spence et al, "Review of existing and future potential treatments for underwater sound from oil and gas industry activities", NCE REPORT 07-001, 2007 prepared for E&P Sound and Marine life JIP

ATTENUATE OUT-OF-BAND ENERGY
DESIGN OPTIMIZATION (CONTROLLING THE AIR FLOW)



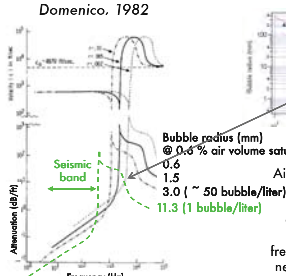
By careful design of the airgun it is possible to control the opening of the ports and the flow of air through them such that the rise time of the initial impulsive response is larger. This in turn reduces the superfluous high frequency emissions.
Status today: Effort are ongoing.

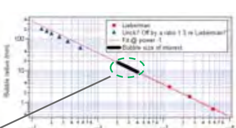
2006 Port & Throat design (method) patented by Hopperstad et al (Schlumberger)

4. Other mitigation techniques

BUBBLE SCREEN (1)
OPTIMIZING AIR BUBBLE SIZE AND DENSITY

Domenico, 1982





Air bubble curtains are long known to be able to attenuate noise in a marine environment. Bubble dimensions and distribution may be used to attenuate certain noise bands. Yet to attenuate frequencies from say 300 to 3000 Hz one needs fairly large bubbles and these are difficult to generate and distribute while they are also unstable…

BUBBLE SCREENS (2)
ENCAPSULATED 'BUBBLES'

M. Wochner, AdBm technologies

K.H. Elmer, "Hydro sound dampers"

Yet when encapsulating bubbles, one can obtain similar results yet without many of the problems related to genuine air bubbles. First results in stationary applications are looking very promising. Can this also be applied to airguns?

Summary & Acknowledgements

AIRGUN PRO'S ...

(Arrays of) Airguns for use in exploration	
Pro's	Weaknesses
Good safety record Well established technology (40+ Year) Readily available Bulk of emissions: • In 'seismic' band • Focused downwards • Efficient (low frequency vs size)	Little control over spectral shape Limited scalability (non optimal source strength)
Opportunities	Areas of attention
Optimized re-engineering. Acoustic mitigation measures. Alternate sources and methods may: • Address weaknesses • Improve environmental compatibility (e.g. reducing out-of-band emissions)	New survey methods (e.g. WAZ, VLF): • Coexistence with marine fauna • Noise 'budget'

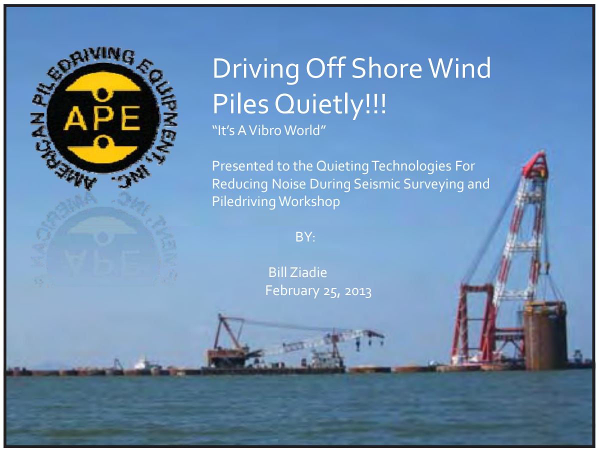
ACKNOWLEDGEMENTS

• *Paul Chelminski, Harry Harrison, Adrian Pascouet et al for their contributions in developing the airgun; a milestone in all aspects of HSE&S that is still making an impact on seismic exploration today…*

• *Phil Fontana, Gary Hampson, Mike Jenkerson, Robert Laws and so many other explorer for taking responsibility and helping to make exploration sustainable .*

• *The E&P Sound and Marine Life JIP as a framework to enable and nurture a scientific approach, pointing us all in the right direction…*

http://www.soundandmarinelife.org/Site/index.html



Presentation Outline:

- What Causes Noise During Traditional Piledriving?
- Current Limits on Waterborne Noise
  - Effects of Noise on Fish and Mammals
- Breaking through barriers of technology
  - Understanding the State of the Piledriving Industry as it Relates to Driving Large Marine Piles
  - Larger Offshore Structures are Demanding Larger Piles, Which Need Larger Impact Hammers

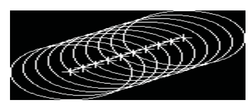
Presentation Outline:

- Larger Impact Hammers on Larger Piles Generates Larger Noise
- Currently Approaching SizeLimits of Impact Hammer Technology
- What Can Be Done Differently?
  - Rethinking Current Design Parameters
  - Rethinking Materials Being Used in Design
  - Rethinking Installation Methodology
- Noise (and Other) Advantages of Using Multiple Linked Hydraulic Vibratory Hammer Systems
- Project Examples
- Future Projects

Of Course Pile Driving is Noisy:

- There are 2 sources of noise relevant during piledriving:
  - Point Source- Generated at the point where the pile hammer strikes the pile

  - Line Source- Consist of an infinite number of evenly distributed individual point sources along the pile length



Waterborne Noise

- Current European Wind Farm Regulations set Max Ocean Noise at 160 dB at a Distance of 750 Meters (.466 miles)
  - Background Noise in Ocean is Considered 137 dB at 750 meters
- Effects of Noise on Fish
  - Impact Piledriving Generates a Flexural Wave in the Pile Which Occurs in a Millisecond at Impact and Which Radiates Rapidly Away From the Pile Creating a Rapid Increase then Decrease of High Sound Pressure
  - That Rapid Increase Can Kill Fish with Swim Bladders
  - Continuous Exposure to Noise Can Damage Hearing and Alter Behavior

Current Technology

- Current Design Mandates Driving with Very Large Impact Hammers
  - Even Though Typically Piles are Often Driven to Predetermined Depth, or "Tip Elevation" and Have No Load Bearing Criteria
  - Only 2 manufactures in the World (both European)
  - Few Hammers Available and are They are **Expensive**
  - Impact Hammers Exceed the 160 dB Limit for Waterborne Noise and need Attenuation
    - Bubble Ring/Barrier Curtains
    - Shields/Sleeves
    - No System is Perfect and All Are Time Consuming

Current Technology

- As Structures get Larger, so too will their Piles
  - Larger Piles are a Bigger Line Source for Noise
- We are Approaching the Limits of Impact Hammer's Size
  - Limits on Forging Size limits Max Hammer Ram Size/Weight
  - Drive Cap Requirement for Larger Diameter Pipe Piles is prohibitive

What Can Be Done Differently?

- Change Structure Design
  - Consider Multi-Pile Foundation Designs
    - Would Allow for Smaller Impact Hammers
  - Consider Larger Diameter Shorter Piles
    - Cannot Use Impact Hammer on Very Large Diameter Piles
  - Consider Large Diameter Helical Piles
    - Helixes Are Good for Uplift
    - Technology is Fledgeling
- Change Material Choice
  - Concrete is Less Resonant than Steel- Quieter Choice
  - Prestressed and Spun Concrete Piles are Already Commonly used in Marine Construction
  - Low Tolerance to Compressive Stress Requires Pile Cushioning. This Has Positive and Negative Consequences
    - Pile Cushion Provides Even More Noise Reduction
    - Pile Cushion Reduces Energy Transfer so Larger Hammer Needed

What Can Be Done Differently?

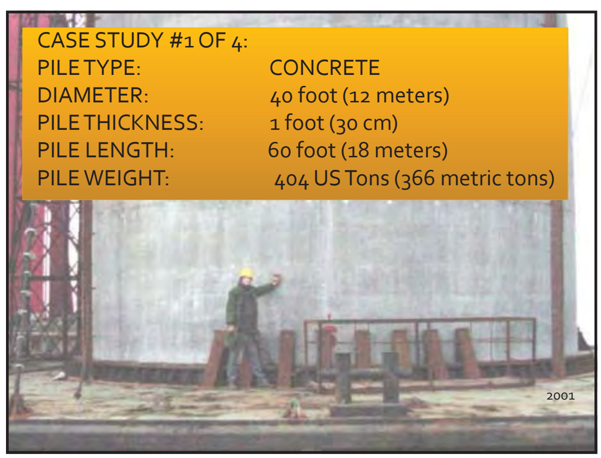
- Change Installation Method
  - Consider Vibratory Hammer Installation.
  - 72ft Diameter Piles 183ft Long Weighing 604 US Tons Have Been Successfully Driven to a Depth of 82 ft Using APE's Multiple Linked Hydraulic Vibratory Hammer System (MLHVH)
- Advantages of Using the MLHVH System
  - Because of How it Operates, There is No Impact Noise. This allows for the Pile to be Driven with No Attenuation Because dB Levels Remain Under 160 at 750 meters

What Can Be Done Differently?

- No Theoretical Limit to Pile Size Because of the Ability to Link as Many Hammers Together as is Required to Mobilize the Pile Weight. Only Limit is Dictated by Crane Size.
- Vibratory Hammers Allow for Pile Extraction and Adjustment for Plumb
- Proven Geotechnical Engineering Customized to Your Jobsite Soil Conditions
- Modular Design Using Standard Production Equipment- Spare Parts and Replacement Machines Are Readily Available
- Can be Supplied by Manufacturers in the USA, Which Makes for a Politically Attractive Selling Point.

MLHVH Project Examples

- 4 Projects Of Note
  - 40 foot (12m) diameter concrete piles
  - 44 foot (13.5m) diameter steel piles
  - 72 foot (22m) diameter steel piles
  - 15.4 foot (4.7m) tapered top diameter to 21.3ft (6.5M) bottom diameter steel piles
- FUTURE PROJECTS
  - What is possible?



Pile purpose:

- Change flow of Yangze River to speed up water current
- Flush out soil to "auto-dredge" river
- Create wall to protect ship lanes

HOW DO YOU DRIVE A SUPER PILE?

HYDRAULIC VIBRATORY HAMMER SIZE REQUIREMENT:

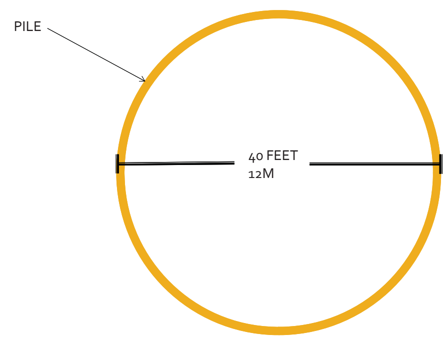
NEED AT LEAST **1300** U.S. TONS OF DRIVE FORCE

LARGEST SINGLE HAMMER AT THE TIME:
APE 400
DRIVE FORCE: **360** U.S. TONS

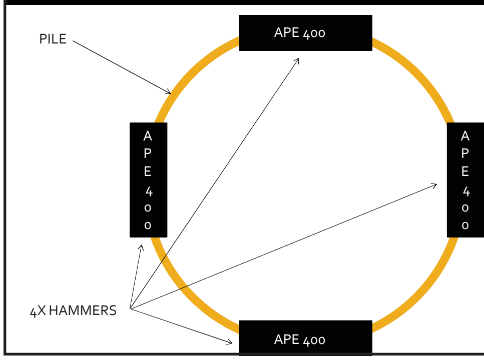
ANSWER: 4X 400'S LINKED TOGETHER:

APE QUAD 400:
DRIVE FORCE: **1,440** U.S. TONS

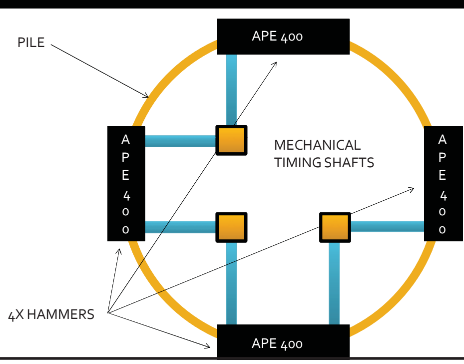
HAMMER DESIGN—TOP VIEW



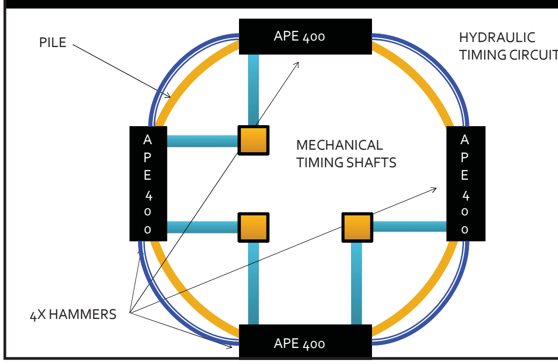
HAMMER DESIGN—TOP VIEW

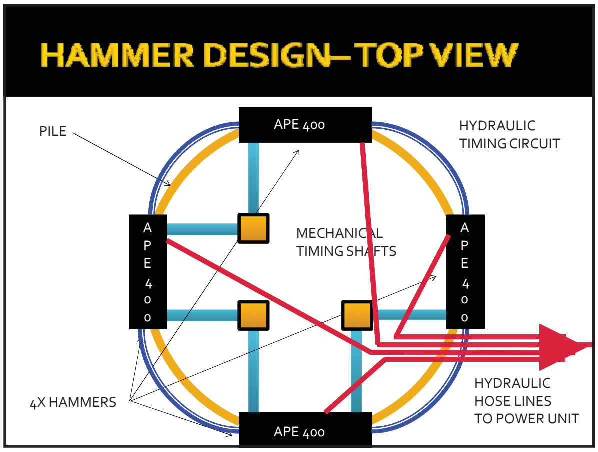


HAMMER DESIGN—TOP VIEW

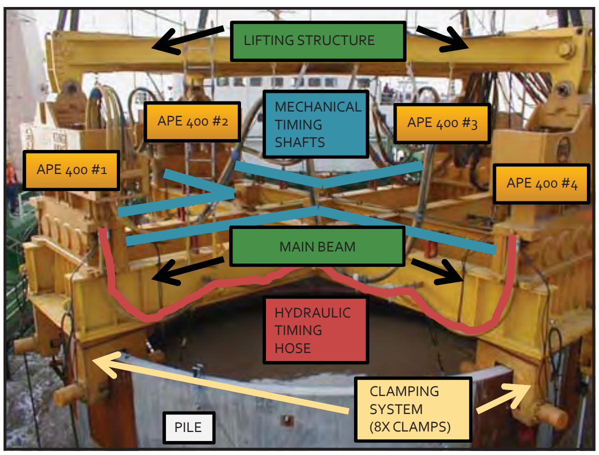


HAMMER DESIGN—TOP VIEW

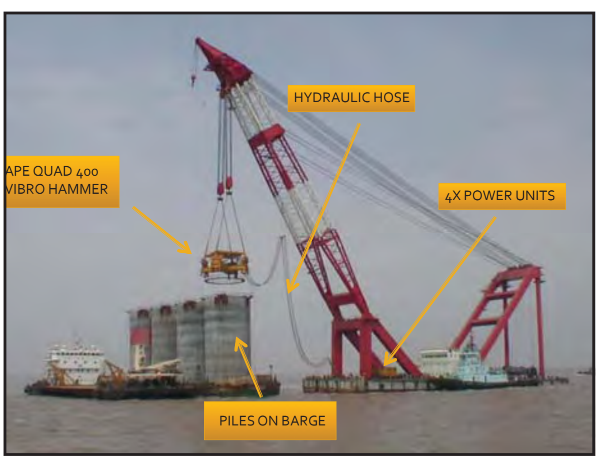



HAMMER DESIGN–TOP VIEW
PILE
APE 400
HYDRAULIC TIMING CIRCUIT
MECHANICAL TIMING SHAFTS
APE 400
APE 400
4X HAMMERS
HYDRAULIC HOSE LINES TO POWER UNIT
APE 400


HAMMER
PILE

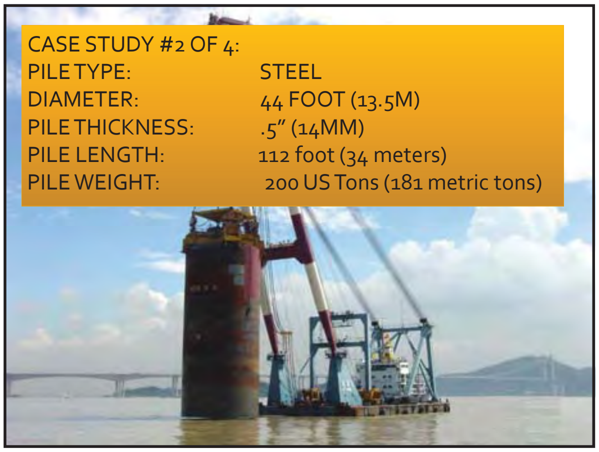

LIFTING STRUCTURE
APE 400 #2
MECHANICAL TIMING SHAFTS
APE 400 #3
APE 400 #1
APE 400 #4
MAIN BEAM
HYDRAULIC TIMING HOSE
CLAMPING SYSTEM (8X CLAMPS)
PILE


POWERED BY:
4 POWER UNITS LINKED TOGETHER
1050 HP EACH X 4 = 4,200 HP
CENTRAL COMPUTER


HYDRAULIC HOSE
APE QUAD 400 VIBRO HAMMER
4X POWER UNITS
PILES ON BARGE

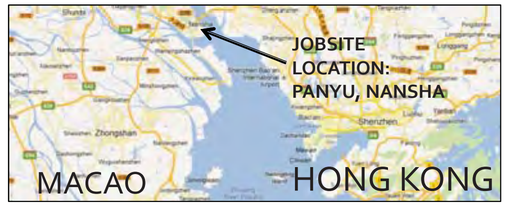

PILE DROVE IN 10 MINUTES
AMPLITUDE: .074" (1.9MM)
SOIL PENATRATION: 25 FEET
SOIL TYPE: SAND N15-20

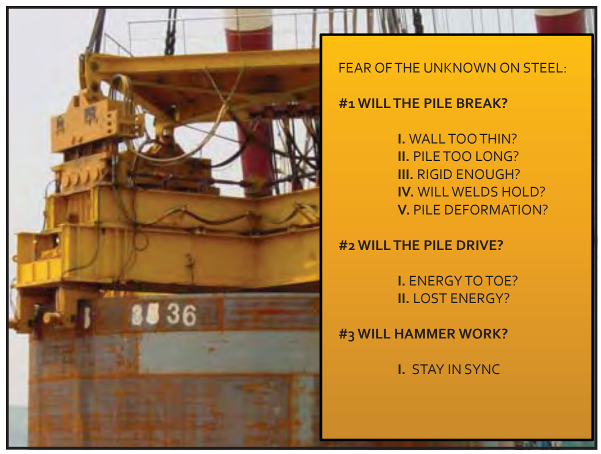
D44

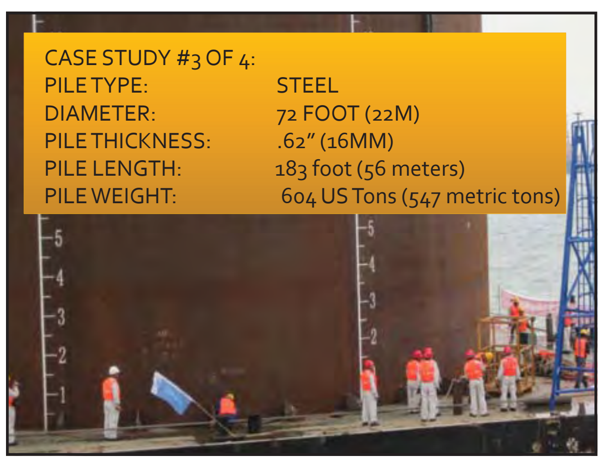


Pile purpose:

- Land reclamation for 5 star hotel
- Speed VS sheet piles (40 piles in 60 days)
- Large pile research and development for wind energy



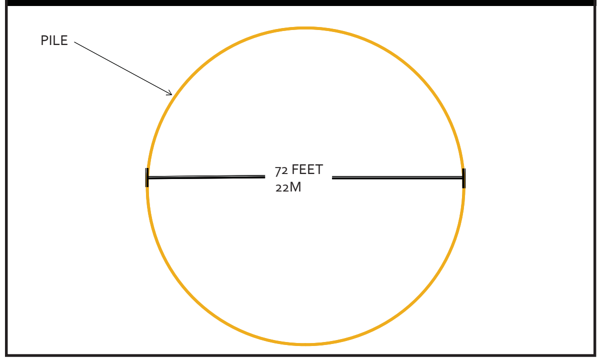




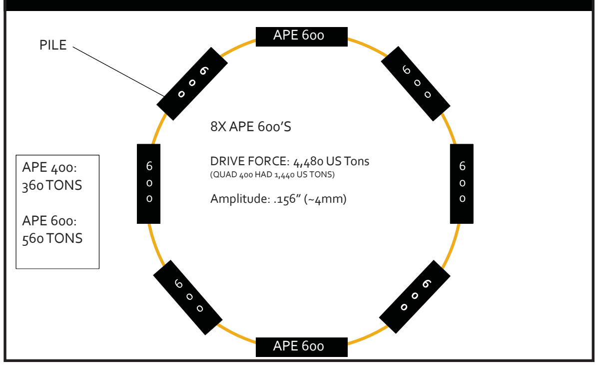
Pile purpose:

- Two man-made island walls for HongKong-Macao-Bridge
- Speed of construction (128 piles in 180 days)
- Environmental concerns of dolphin migration
- Wind pile research

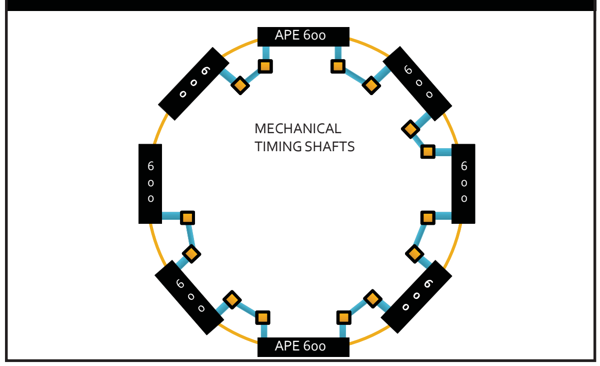
HAMMER DESIGN–TOP VIEW



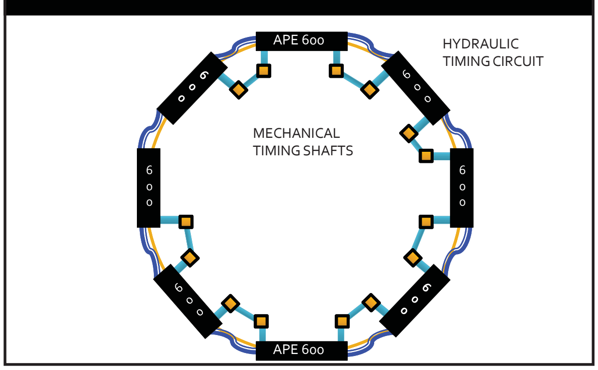
HAMMER DESIGN–TOP VIEW



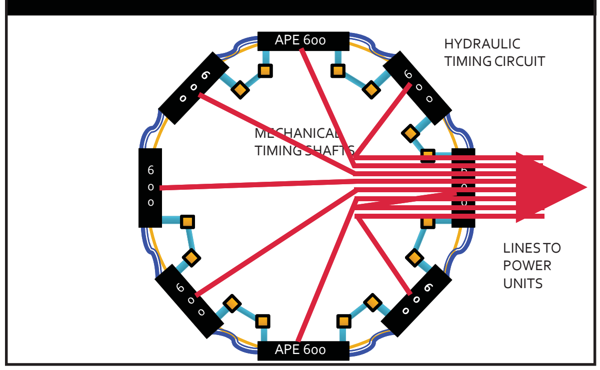
HAMMER DESIGN–TOP VIEW



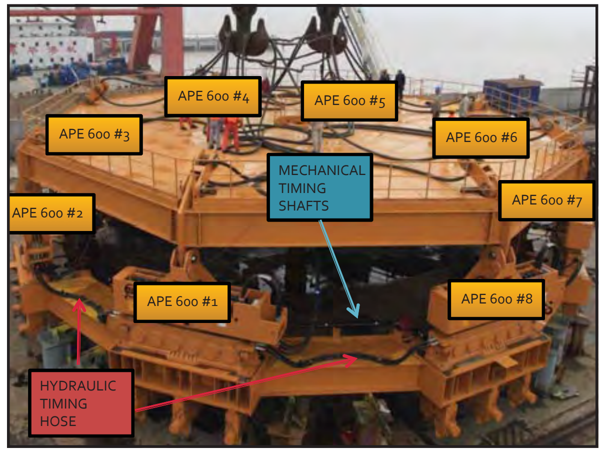
HAMMER DESIGN–TOP VIEW

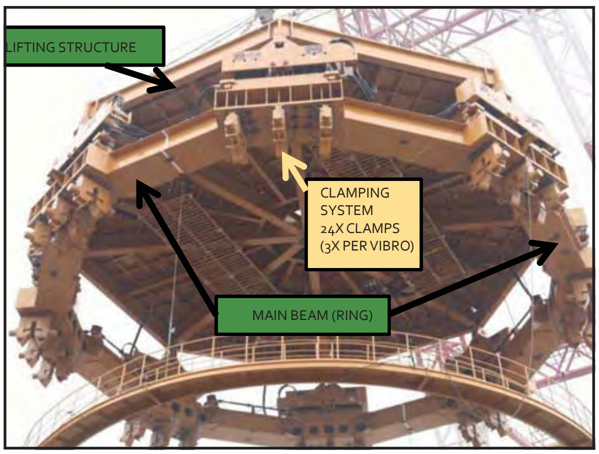


HAMMER DESIGN–TOP VIEW

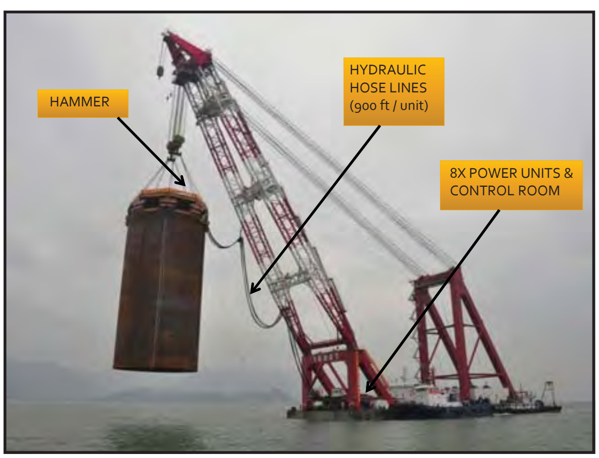


D46


APE 600 #4
APE 600 #5
APE 600 #3
APE 600 #6
MECHANICAL TIMING SHAFTS
APE 600 #2
APE 600 #7
APE 600 #1
APE 600 #8
HYDRAULIC TIMING HOSE


LIFTING STRUCTURE
CLAMPING SYSTEM 24X CLAMPS (3X PER VIBRO)
MAIN BEAM (RING)


8X 1200 HP POWER UNITS
9,600 HP TOTAL POWER
~2,600 GAL / MINUTE OF OIL FLOW


HAMMER
HYDRAULIC HOSE LINES (900 ft / unit)
8X POWER UNITS & CONTROL ROOM

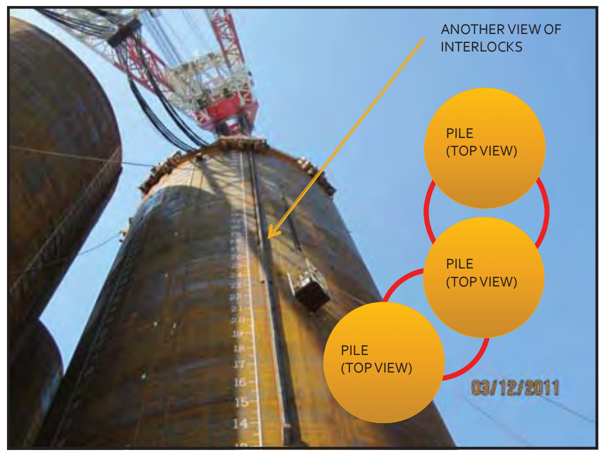

03/12/2011

D47


HAMMER IN ACTION

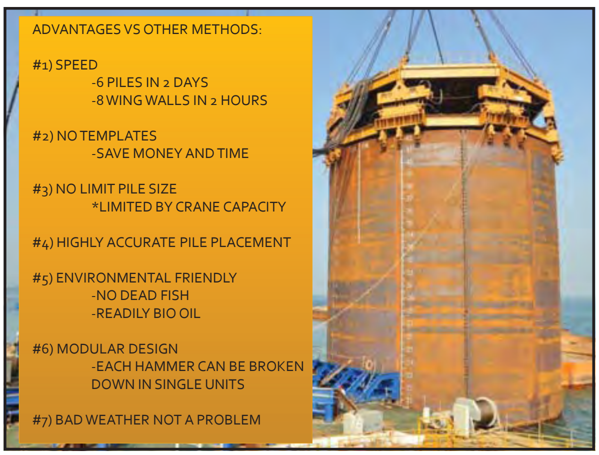

ALL 128 PILES DROVE TO GRADE
DRIVING TIME: 10-20 MINUTES
SOIL CONDITIONS: N23-37
SOIL TYPE: SAND, CLAY
PLACEMENT ACCURACY: > 1% DEGREE
FASTEST SPEED: 6 PILES IN 2 DAYS

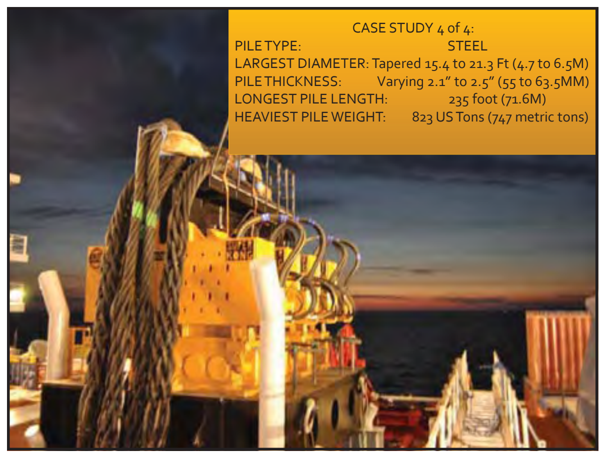

WING WALL INTERLOCKS

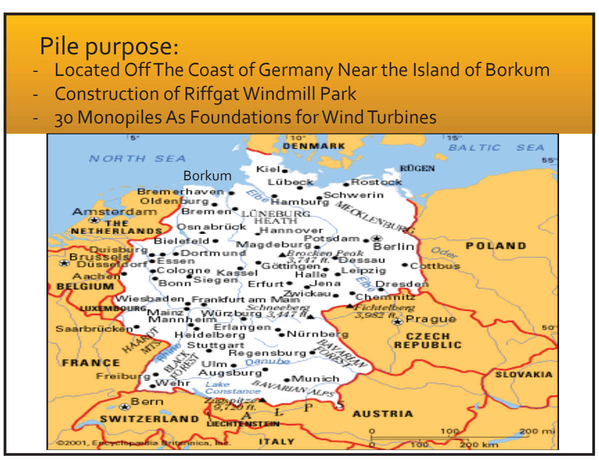

ANOTHER VIEW OF INTERLOCKS
PILE (TOP VIEW)
PILE (TOP VIEW)
PILE (TOP VIEW)
03/12/2011


37' FEET WIDE
"U" SHAPED
40 TONS
2011.10.07 11:58


F610-023


ADVANTAGES VS OTHER METHODS:
#1) SPEED
-6 PILES IN 2 DAYS
-8 WING WALLS IN 2 HOURS
#2) NO TEMPLATES
-SAVE MONEY AND TIME
#3) NO LIMIT PILE SIZE
*LIMITED BY CRANE CAPACITY
#4) HIGHLY ACCURATE PILE PLACEMENT
#5) ENVIRONMENTAL FRIENDLY
-NO DEAD FISH
-READILY BIO OIL
#6) MODULAR DESIGN
-EACH HAMMER CAN BE BROKEN DOWN IN SINGLE UNITS
#7) BAD WEATHER NOT A PROBLEM


CASE STUDY 4 of 4:
PILE TYPE: STEEL
LARGEST DIAMETER: Tapered 15.4 to 21.3 Ft (4.7 to 6.5M)
PILE THICKNESS: Varying 2.1" to 2.5" (55 to 63.5MM)
LONGEST PILE LENGTH: 235 foot (71.6M)
HEAVIEST PILE WEIGHT: 823 US Tons (747 metric tons)


Pile purpose:
- Located Off The Coast of Germany Near the Island of Borkum
- Construction of Riffgat Windmill Park
- 30 Monopiles As Foundations for Wind Turbines
NORTH SEA
BALTIC SEA
DENMARK
Borkum
Kiel
Lübeck
Rostock
Hamburg
Schwerin
Bremerhaven
Oldenburg
Bremen
Amsterdam
THE NETHERLANDS
Osnabrück
Hannover
Bielefeld
Magdeburg
Potsdam
Berlin
POLAND
Duisburg
Dortmund
Essen
Düsseldorf
Brussels
Cologne
Kassel
Göttingen
Halle
Leipzig
Dessau
Cottbus
Aachen
Bonn
Siegen
Erfurt
Jena
Dresden
BELGIUM
Wiesbaden
Frankfurt am Main
Zwickau
Chemnitz
LUXEMBOURG
Mainz
Mannheim
Würzburg
Prague
Saarbrücken
Erlangen
Heidelberg
Nürnberg
CZECH REPUBLIC
Stuttgart
Regensburg
FRANCE
Freiburg
Ulm
Augsburg
Munich
SLOVAKIA
Bern
SWITZERLAND
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ITALY
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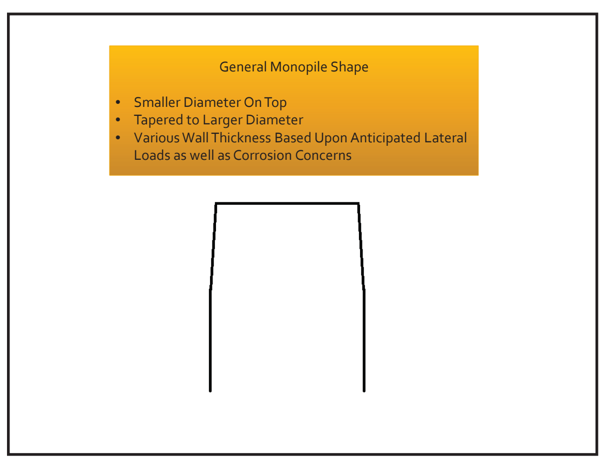
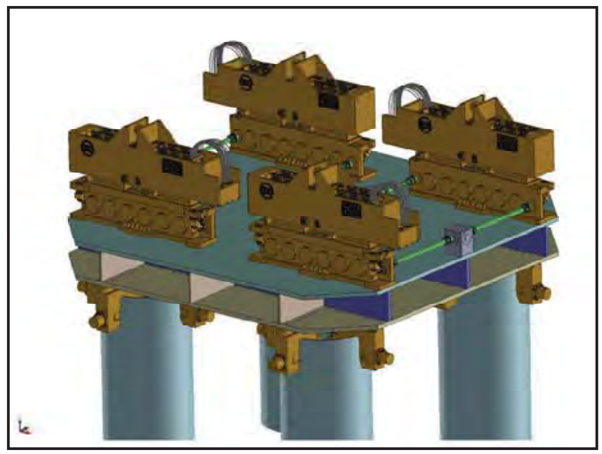
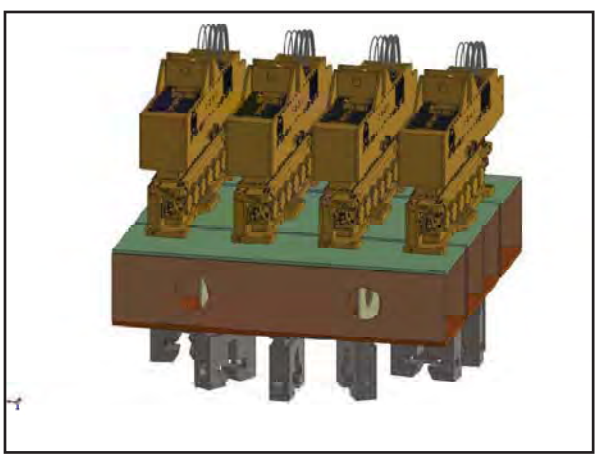
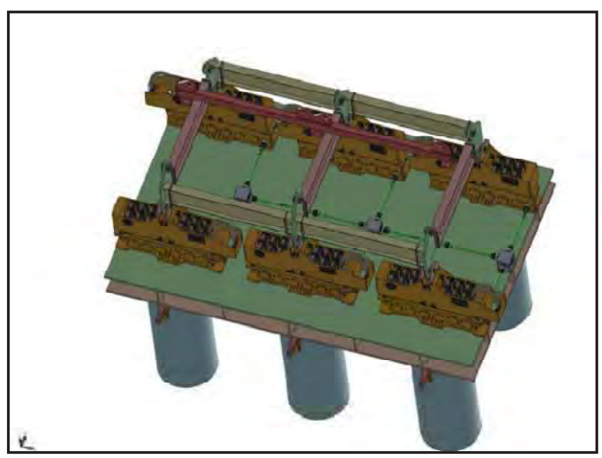

General Monopile Shape
• Smaller Diameter On Top
• Tapered to Larger Diameter
• Various Wall Thickness Based Upon Anticipated Lateral Loads as well as Corrosion Concerns


Large White And Red Cylinder is Noise Mitigation Sleeve


THE FUTURE:
- DEEP SEA MAN-MADE ISLANDS
- SHORE PROTECTION PROJECTS
- VERY FAST RECLAMATION
- OIL PIPELINE LEAK PROTECTION
WIND ENERGY PRODUCTION for Upcoming 10+ MW monopiles







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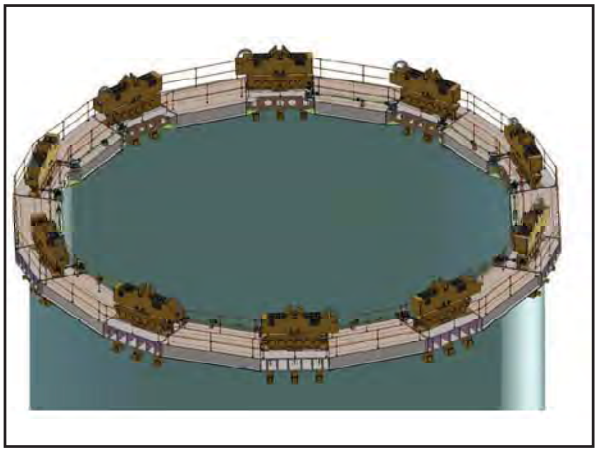

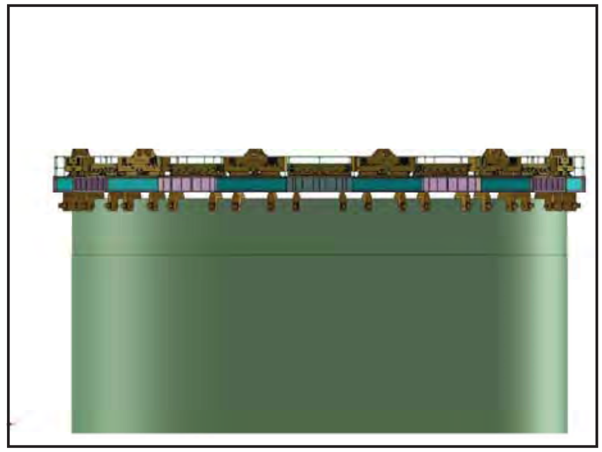


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D51

Introduction to Ship Radiated Noise

BOEM Workshop
Quieting Technologies For Reducing Radiated Noise
During Seismic Surveying and Pile Driving
25 February 2013

Chris Barber, Ph.D.

Ship Radiated Noise

The ship noise engineering community can tell you
- What makes noise on a ship?
- How loud are these sources?
- What technologies are available to reduce ship noise?
- How effective can these measures be?
- What is the cost to design in or back fit these measures

Open question remains:
- How quiet does the ship need to be?
  - Environmental Impact
  - Guidelines, requirements, regulations
  - Ship noise versus seismic and impulsive sources

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Some Definitions

- Radiated Noise
  - Ship noise that is transmitted into the water and can be detected by off-board receivers
    - Typically reported as One Third octave (OTO) Band
    - Narrowband (1 HZ) data used to characterize machinery tones
- Radiated Noise Source Level
  - Equivalent simple source (omnidirectional monopole) level
    SL dB re 1 μPa @ 1m
    - Back-propagated to 1m assuming spherical spreading from a ***far field, free-field*** measurement
- Platform Noise
  - Ship noise that can be detected by acoustic or vibration sensors
    - Not necessarily detectable as radiated noise
- Sonar Self-Noise
  - Received acoustic levels in the output of mission system receiving band(s) due to own-ship platform noise sources

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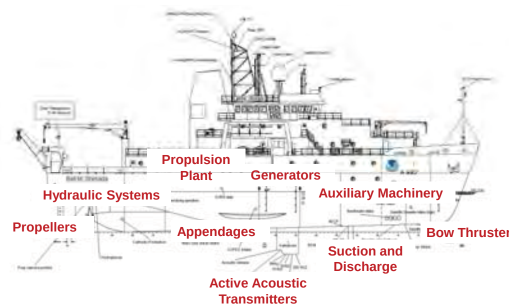
Ship Noise Sources



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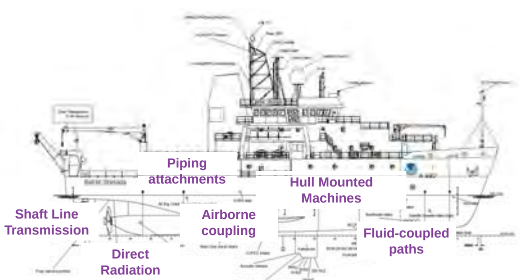
Ship Noise Paths



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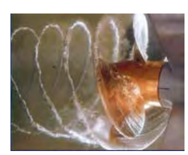
Propeller Cavitation

- Cavitation is ***LOUD***
  - Typical dominates broadband ship noise spectrum at mid to high frequencies
  - Cavitation erodes propeller blades, hull plating, coatings, etc.



  - Cavitation avoidance is both an acoustic and hydrodynamic goal

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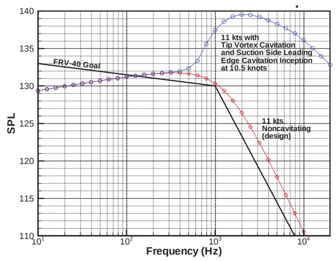
Propeller Cavitation

- Cavitation noise builds rapidly with increasing speed once onset occurs
- Design goal is to operate below inception speed
  - Often conflicts with mission requirements and efficiency optimization



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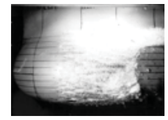
Non-Propulsion Flow-Related Noise

Hull and appendage cavitation



Rudders and Struts

Bow wave transients

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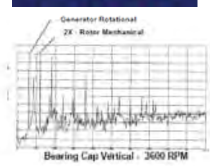
Machinery Noise Sources

- Main Propulsion System
  - Diesel Propulsion Engine
  - Diesel / Electric System
  - Marine Gas Turbine
  - Reduction gears

Auxiliary Machinery
Ship Service Generators
Sea Water Cooling Pumps
Fire Pumps



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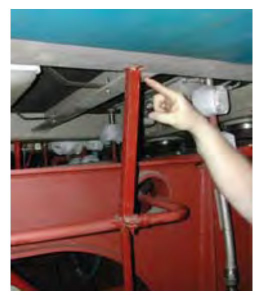
Sound Shorts

Unintentional sound shorts can defeat expensive noise control
- Vigilant Inspection as part of maintenance



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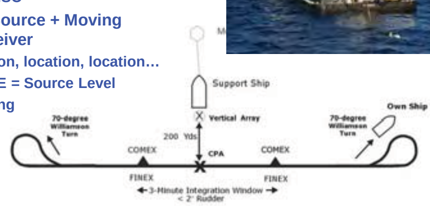
Radiated Noise Measurements

- Measurements options
  - Acoustic ranges
  - Portable systems
  - Shallow water measurements
- Standards
  - ANSI, ISO
- Moving Source + Moving Receiver
  - Location, location, location…
  - RANGE = Source Level
  - Tracking



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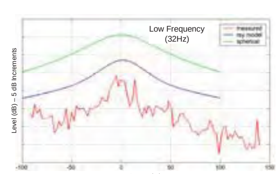
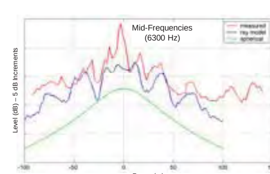
Shallow Water Measurements

- Simple source models coupled with simplified propagation assumptions *inadequate* to capture sound field variability for real sources in shallow water





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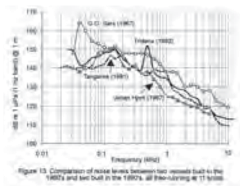
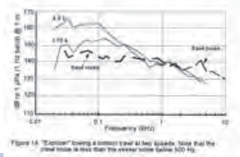
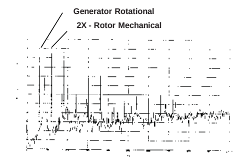
Example Radiated Noise Data





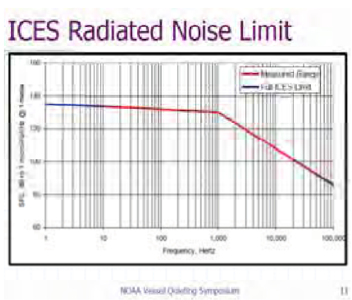


Ship Quieting Technology

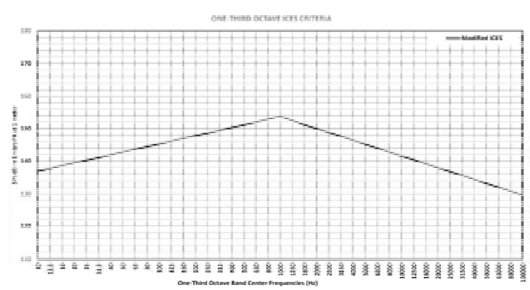
- Technology originates from Naval requirements
  - Detection & Detectability
- Menu of unrestricted technologies and methods available
  - Propeller design
  - Hydrodynamic optimization
  - Vibration Isolation machinery mounts
  - Modular machinery vibration isolation
  - Machinery health monitoring

Research Vessel Quieting

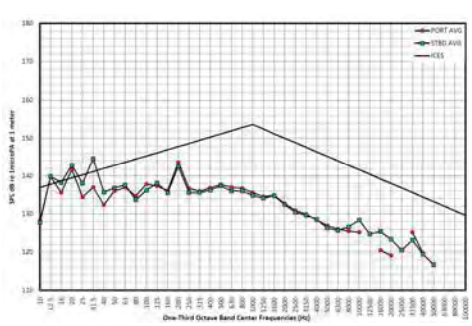
- Fisheries Research
  - ICES
- NSF - Greening the Research Fleet
- Mission System Impact



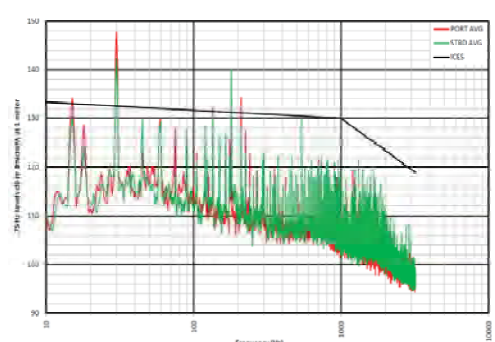
ICES Curve in One Third Octave Bands



Representative Ship Data



Representative Narrowband Data



Support Vessel and General Noise Requirements ?

- **Environmental Impact**

- **Shipboard Habitability**
- **Impact on Shipboard Mission Systems (self-noise)**
- ***Emerging guidelines, requirements and regulations***

Outline

- Overview of Information Technology
  - Complementary technologies
  - Methods to Reduce Unwanted Air Gun Noise
  - Alternative Acoustic Sources
- Environmental Assessment of Marine Vibrosesis
- Air gun source levels

Complementary Technologies

- Low-Frequency Passive Seismic Methods
  - ➢ Low Resolution – Possibly Augment Seismic Methods
  - Methods Using Natural Seismicity (earthquakes)
  - Methods Using Ocean waves
  - Methods Using Microseismic Surface Waves
- Electromagnetic Surveys
  - ➢ Low Resolution, Penetration – Characterize Fluids
  - Controlled Source Electromagnetic Surveys (CSEM)
  - Magnetotelluric Surveys
- Gravity and Gravity Gradiometry Surveys
  - ➢ Low Resolution, Gross Structural Features
- Fiber Optic Receivers
  - ➢ Better Signal/Noise – Possibly Reduce Source Level

Methods to Reduce Unwanted Air Gun Noise

- Bubble Curtains
  - Use an acoustic impedance mismatch to block sound transmission
  - ➢ Very difficult to operate in non-stationary systems
  - ➢ Need a significant barrier to block all frequencies (thickness of curtain, size and density of bubbles)
  - ➢ Weather and currents add operational complexity
- Parabolic Reflectors
  - Tow a parabolic reflector over the array (air bubbles or solid materials) to increase the directivity of the array
  - ➢ Very difficult to operate in non-stationary systems
  - ➢ Need a large reflector
  - ➢ Difficult to operate in shallow water due to bottom reflections
  - ➢ Weather and currents add operational complexity

Methods to Reduce Unwanted Air Gun Noise

- Air Gun Silencer
  - Use an absorptive shell around the air gun to reduce acoustic levels at frequencies above 700 Hz
  - ➢ Only tested on small air guns
  - ➢ Material only withstood 100 shots
  - ➢ Deemed to be impractical
- Modifications to Air Guns
  - Redesign air guns to reduce high frequencies while maintaining low frequencies (e.g. alterations in port or throat shape)
  - Patent filed – E-Source air Gun still under development
  - ➢ Efficacy still uncertain
  - ➢ Need to develop a new product

Alternative Air Gun Sources

- Marine Vibrators
  - Air guns generate energy almost instantaneously (impulse) rather than vibroseis which transmits its energy over time, and has lower rise times, peak pressures and little energy above 100 Hz, more choice in sweep types
  - Both hydraulic & electromechanical vibrators have been tested and have shown good data comparisons with air guns
  - ➢ Less energy in low frequencies than air guns
  - ➢ Hydraulic systems have worse harmonics than electromechanical systems (energy above 100 Hz)
  - ➢ Hydraulic systems need a more significant vessel retrofit than electromechanical systems

Alternative Air Gun Sources

- Marine Vibrators
  - Low-Frequency Acoustic Source (LACS)
    - ➢ Does not currently exist
  - Deep-Towed Acoustics/geophysics System (DTAGS)
    - ➢ Frequency range is above 220 Hz, above the seismic band
  - Low-Impact seismic Array (LISA)
    - ➢ No recent information
  - Underwater Tunable Organ-Pipe
    - ➢ Prototypes are for frequencies above 200 Hz

Environmental Assessment of Marine Vibroseis

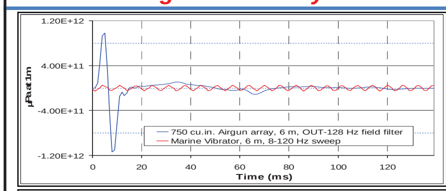
Goal of the project was to compare the environmental impact of air guns and marine vibrators using the NMFS and Southall criteria (using AIM)

- MV has lower peak pressure and rise time than air guns.
- Spectral properties of the MV signal well controlled
- Use of less-restrictive 'non-impulse' injury criterion for MV vs. 'impulse' criterion for air guns* results in smaller safety radius. M-wt for mid & high-frequency hearing in dolphins, etc., further reduces safety radius around MVs (and air guns).
- MVs have significantly lower proportion of energy emitted at frequencies above 100 Hz; advantage over air guns increases if the falloff rate above ~100 Hz could be further increased, e.g. to 100 dB/decade.
- Auditory masking should be greater with MVs than air guns, effect greater with pseudorandom signals than FM signals

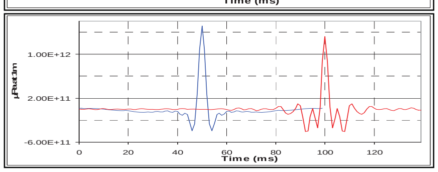
*** 215 vs. 198 dB SEL**

Funded by SAML JIP

Air Gun string vs. Servo-Hydraulic Marine Vibrator



Time Series

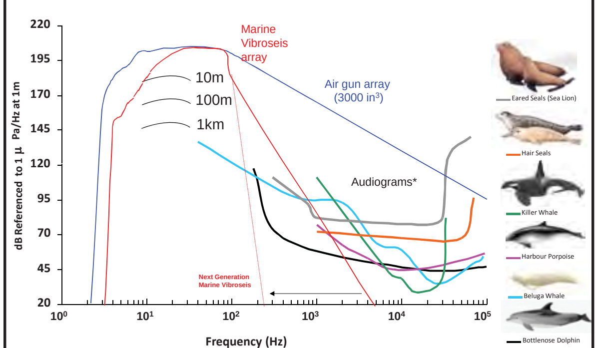


Phase Removed

Maximum peak-peak pressure

Marine vibrator (Single): 0.14 MPa-m (1.4 bar-m) Air gun (750 in³ subarray): 4.0 MPa-m (40 bar-m)

Seismic Sources and Marine Mammal Audiograms



*Animals perceive sound within area above audiograms

Environmental Assessment of Marine Vibroseis*

Jointly Prepared By:
LGL Ltd. environmental research associates & Marine Acoustics, Inc.

Presented by:
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Marine Acoustics, Inc.
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Middletown RI 02842
bill.ellison@marineacoustics.com

*Presented at JIP Program Review Meeting, 30 May 2012, Herndon,VA

Outline:

- Study Objectives
- Compare Airgun vs. Marine Vibrator (MV) Signals
- Types of Biota & of Impacts Considered
- First-Order Modeling: #s of Marine Mammals potentially (a) Injured & (b) Disturbed by Airguns vs. MV
- Results re
  - Disturbance
  - Masking
  - Auditory
  - Resonance?
- Main Conclusions

Objectives:

- Evaluate potential environmental impacts from seismic surveys using next-generation MV
- Examine how MV impacts would compare with airgun impacts
- Evaluate how an MV system could be operated to minimize impact (e.g., optimum duty cycle, sweep type, other mitigation measures)
- Identify data gaps & recommend studies to address them

Project Status: Completed

- Final report: issued April 2011
- Title:
  Environmental Effects of Marine Vibroseis
- Availability: on JIP website
  www.soundandmarinelife.org
- Conclusions:
  - Similar to preliminary summary at Oct. 2008 Program Review Meeting
  - Additional refinements, details, and recommendations

Airgun vs. MV signals:

Airguns	Marine Vibrators
Brief (10s of ms)	Longer (seconds)
Impulsive	Non-impulse (frequency sweep or other)
Duty cycle ~1%	~50% ±
Peak pressure: high	lower
Rise time: fast	slower

Energy per "shotpoint": assumed similar, but for MV energy is "spread out over a few seconds"

Frequency content: a major design goal for MVs is faster decrease (roll-off) above 100 Hz

A key project objective was to assess tradeoffs between presumed positive and negative features of MV.

Types of Biota Considered:

- Invertebrates
- Fish
- Sea Turtles
- Marine mammals, especially
  - Baleen whales
  - Toothed whales
  - Pinnipeds

(Baleen whales, Toothed whales:) Most detailed consideration, including modeling

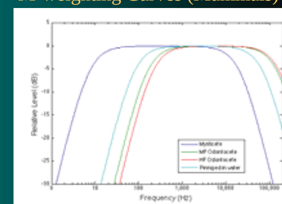
Possible Types of Impacts of Airguns and/or MV:

- Behavioral Disturbance
- Acoustic Masking
- Auditory: TTS, PTS
- Non-auditory, e.g.,
  - Resonance?
  - Behavior-induced injury?

Possible Types of Impacts of Airguns and/or MV:

- Behavioral Disturbance
- Acoustic Masking
- Auditory: TTS, PTS
- Non-auditory, e.g.,
  - Resonance?
  - Behavior-induced injury?

M-weighting Curves (Mammals)*



*Southall et al. (2007, *Aquat. Mamm.)*

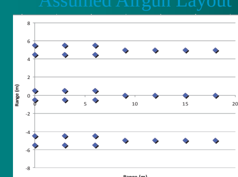
MV Effects on Marine Mammals Addressed by Modeling:

- What relative numbers of marine mammals are likely to be disturbed or (possibly) injured by otherwise-comparable seismic surveys conducted via MV vs. airguns?
- Are the MV vs. airgun results sensitive to
  - •Mammal type (e.g., baleen whale, dolphin, sperm whale);
  - •Water depths (shallow vs. deep);
  - •Duration/duty cycle of MV signals;
  - •Frequency roll-off rate of MV signals above 100 Hz

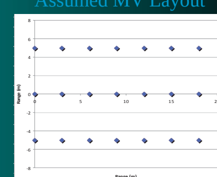
Scenario for Modeling:

- Northern Gulf of Mexico: shallow & deep sites (<100 m and 1000 m); same survey pattern at each.
- Airgun array with 30 guns (total 4140 in³) at 18 locations in 3 strings, vs. MV array with one MV at each of those 18 locations.

Assumed Airgun Layout

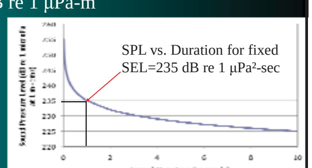


Assumed MV Layout



Scenario for Modeling (cont'd):

- Equal energy per shotpoint: Assumed airgun and MV arrays emit same total energy per shot or MV sweep: 235 dB re 1 µPa²-sec
  - **Airguns**: 261 dB re 1 µPa-m p-p (112.4 bar-m)
  - **MVs**:
    - 2 sec sweep: 232 dB re 1 µPa-m
    - 5 sec sweep: 228 "
    - 8 sec sweep: 226 "



Impact Criteria Considered:

Disturbance:
160 dB re 1 µPa (rms) †

Injury (cetaceans)
180 dB re 1 µPa (rms)

Existing U.S. NMFS criteria, at least for impulsive sounds

198° dB re 1 µPa²-sec – Cumulative SEL, impulses (airguns) *
215° dB re 1 µPa²-sec – Cumulative SEL, non-impulse (MV) *, **
[230 dB re 1 µPa (peak) – Do not exceed level] *

† Relevance of 160 dB (rms) to prolonged MV sounds is questionable.

* From Southall et al. (2007, *Aquatic Mammals*) M-weighted.
(For pinnipeds, 186 dB cSEL for impulses vs. 203 dB cSEL non-impulsive.)

** 17-dB higher assumed injury threshold for non-impulsive MV relative to airguns substantially reduces the injury potential of MV.

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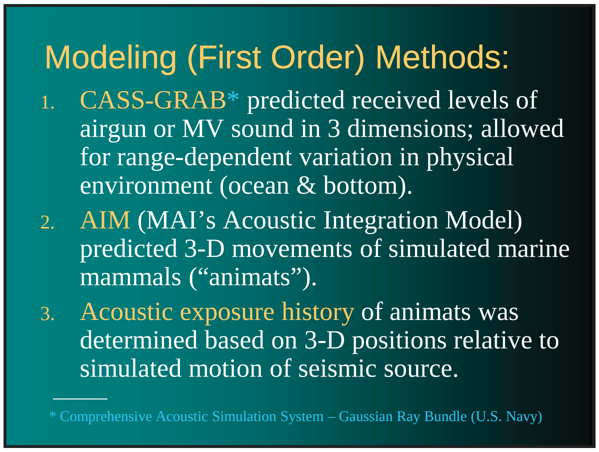
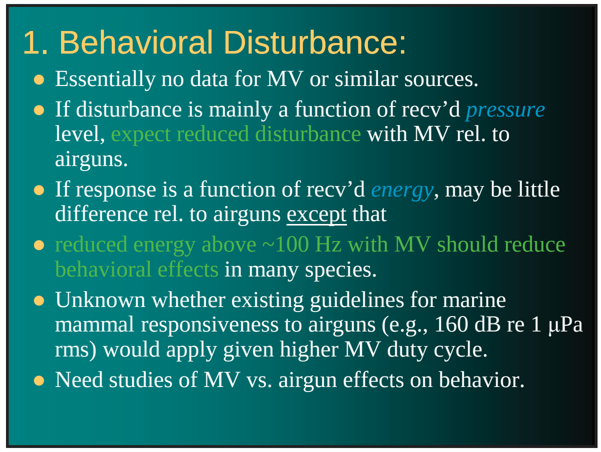
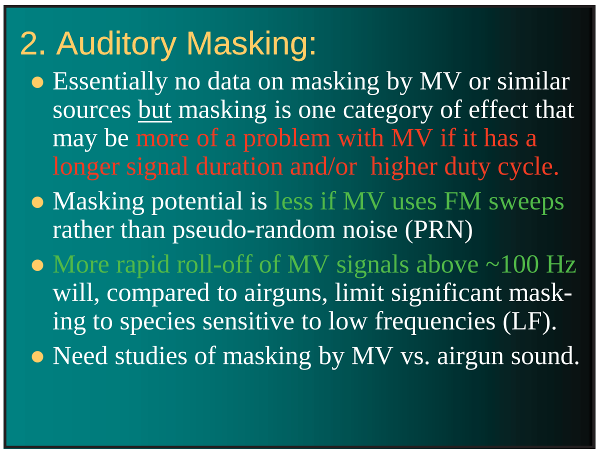
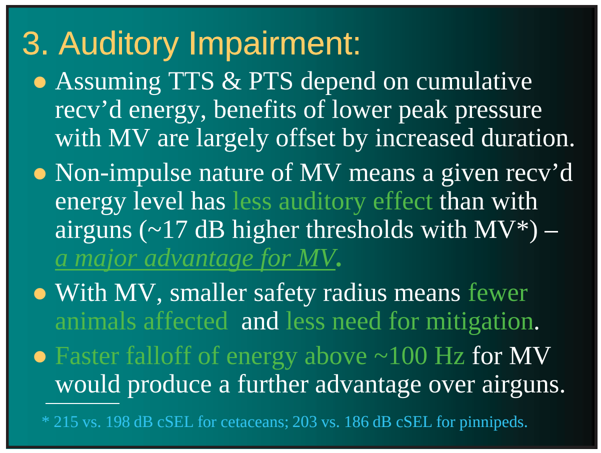
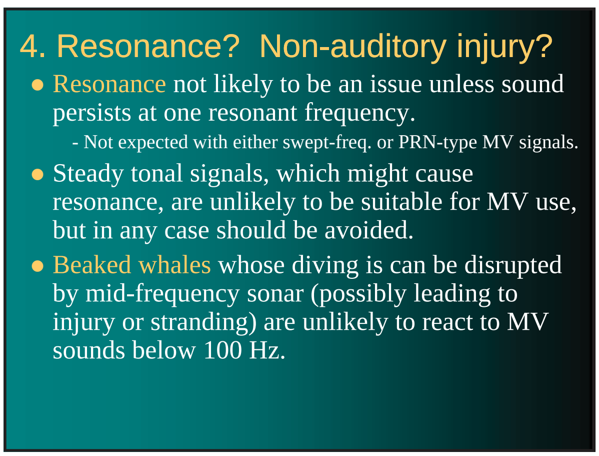
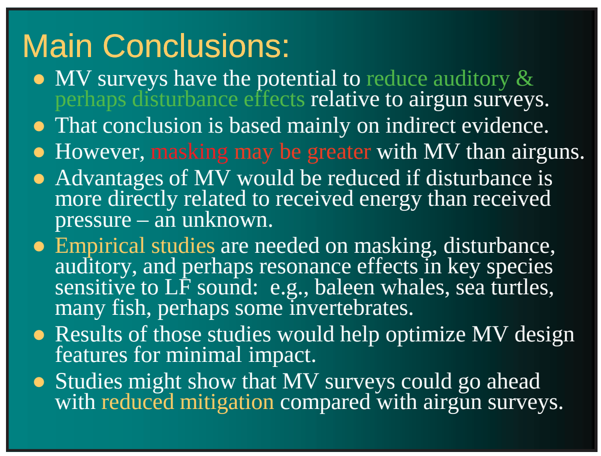

Modeling (First Order) Methods:
1. CASS-GRAB* predicted received levels of airgun or MV sound in 3 dimensions; allowed for range-dependent variation in physical environment (ocean & bottom).
2. AIM (MAI's Acoustic Integration Model) predicted 3-D movements of simulated marine mammals ("animats").
3. Acoustic exposure history of animats was determined based on 3-D positions relative to simulated motion of seismic source.
* Comprehensive Acoustic Simulation System – Gaussian Ray Bundle (U.S. Navy)


1. Behavioral Disturbance:
Essentially no data for MV or similar sources.
If disturbance is mainly a function of recv'd pressure level, expect reduced disturbance with MV rel. to airguns.
If response is a function of recv'd energy, may be little difference rel. to airguns except that
reduced energy above ~100 Hz with MV should reduce behavioral effects in many species.
Unknown whether existing guidelines for marine mammal responsiveness to airguns (e.g., 160 dB re 1 µPa rms) would apply given higher MV duty cycle.
Need studies of MV vs. airgun effects on behavior.


2. Auditory Masking:
Essentially no data on masking by MV or similar sources but masking is one category of effect that may be more of a problem with MV if it has a longer signal duration and/or higher duty cycle.
Masking potential is less if MV uses FM sweeps rather than pseudo-random noise (PRN)
More rapid roll-off of MV signals above ~100 Hz will, compared to airguns, limit significant mask-ing to species sensitive to low frequencies (LF).
Need studies of masking by MV vs. airgun sound.


3. Auditory Impairment:
Assuming TTS & PTS depend on cumulative recv'd energy, benefits of lower peak pressure with MV are largely offset by increased duration.
Non-impulse nature of MV means a given recv'd energy level has less auditory effect than with airguns (~17 dB higher thresholds with MV*) – a major advantage for MV.
With MV, smaller safety radius means fewer animals affected and less need for mitigation.
Faster falloff of energy above ~100 Hz for MV would produce a further advantage over airguns.
* 215 vs. 198 dB cSEL for cetaceans; 203 vs. 186 dB cSEL for pinnipeds.


4. Resonance? Non-auditory injury?
Resonance not likely to be an issue unless sound persists at one resonant frequency.
- Not expected with either swept-freq. or PRN-type MV signals.
Steady tonal signals, which might cause resonance, are unlikely to be suitable for MV use, but in any case should be avoided.
Beaked whales whose diving is can be disrupted by mid-frequency sonar (possibly leading to injury or stranding) are unlikely to react to MV sounds below 100 Hz.


Main Conclusions:
MV surveys have the potential to reduce auditory & perhaps disturbance effects relative to airgun surveys.
That conclusion is based mainly on indirect evidence.
However, masking may be greater with MV than airguns.
Advantages of MV would be reduced if disturbance is more directly related to received energy than received pressure – an unknown.
Empirical studies are needed on masking, disturbance, auditory, and perhaps resonance effects in key species sensitive to LF sound: e.g., baleen whales, sea turtles, many fish, perhaps some invertebrates.
Results of those studies would help optimize MV design features for minimal impact.
Studies might show that MV surveys could go ahead with reduced mitigation compared with airgun surveys.

D60

Acknowledgements:

- JIP and its Project Support Group
- Collaborators at LGL and MAI
- All those who provided advice and background information

Marine Vibrator JIP:
25 February 2013

Bob Rosenbladt – Shell Exploration and Production Company
Mike Jenkerson – ExxonMobil Exploration Company
Henri Houllevigue – Total E&P Research & Technology

Outline

- Where have we been
- Specifications
- Pro's and Con's of Airguns and Marine Vibrator
- Where are we now
- Future timeline

MV JIP: Where have we been

- Sponsors: ExxonMobil, Shell, Total
- Built a Team of Experienced Consultants
- Anti-Trust Issues
  - Significant time investment
- TEES at Texas A&M University
- Cast a Wide Net, Outside of Oil/Gas Industry to Capture a Broad Range of Technologies (Oil & Gas, Defense, Electronics etc.)

MV JIP: Where have we been

Search for Low Frequency Underwater Seismic Sources

Key Seismic Specifications

MV JIP Timeline (to date)

- Phase I: May 2008 to September 2009
  - Project Scoping
  - 26 Vendors Contacted & Assessed for Possible Transducers
  - Transducer Requirements Specified
- Phase II: November 2009 to March 2013
  - Legal Framework set up through TEES (Texas A&M)
  - 36 Vendors Contacted
  - 19 Confidential Requests for Information
  - 7 Requests for Proposal
  - 3 Selected

Requested Specifications

- Array output for 5 s signal
  - 5-10 Hz 190 dB re 1 µPa/Hz @ 1 m
  - 10-100 Hz 200 dB re 1 µPa/Hz @ 1 m
- Output variation over band
  - < 12 dB mandatory
  - < 6 dB desired
- Unit to unit variation
  - < 10% mandatory
  - < 5% desired

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Requested Specifications

- Variation between overhauls: < 10%
- Maximum transmission time: > 30 s
- Harmonic content above 150 Hz when driven with tone in 5-100 Hz range
  - > 40 dB down
- Reliability
  - 72 sweep hours between maintenance
  - 720 sweep hours between overhaul

Requested Specifications

- Operating temperature range
  - Better than -2°C to +50°C
- Storage temperature range
  - Better than -30°C to +80°C
- Operating depth range
  - 2 m to 30 m required
  - Up to 0.5 m desirable for shallow water version
- Signal types:
  - Pseudorandom, swept frequency, short chirps, coded sweeps

Pros and Cons of Airgun Arrays

Arrays of airguns for use in exploration	
Strengths	Weaknesses
Good safety record Well established technology (40+ Year) Readily available Bulk of emissions • In 'seismic' band • Focused downwards	Little control over spectral shape • Array tuning required • Potential directivity issues • Poor performance at shallow depths
Opportunities	Challenges
Optimized re-engineering Acoustic mitigation measures Alternate sources and methods may: • Address weaknesses • Improve environmental compatibility (e.g. reducing out-of-band emissions)	Mitigation measures as a result of • Coexistence with marine fauna • Difficulties with increasing # sources e.g. WAZ • Noise 'budget' limitations

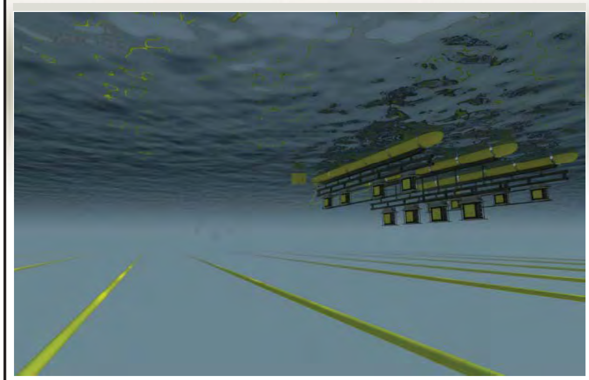
Pros and Cons of Marine Vibrators

Marine Vibrator for use in exploration	
Strengths	Weaknesses
Control of output frequency spectrum Control of sweep length Low peak output level Type of sweep can be controlled	Long duty cycle Vessel motion during output of signal Emerging technology competing with very mature airgun technology
Opportunities	Challenges
JIP pursuing 3 different technologies	Adequate Low Frequencies Possible harmonic output outside of planned frequency range Availability of limited # of devices Masking Issues – Duty cycle

Where are we now

- Phase III to Begin Imminently
- MV JIP Still Looking for up to 3 More Sponsors
- Contracts
  - Contract signed between TEES and PGS
  - Contracts in progress with 2 other Vendors
- Phase III to go Forward in Parallel with Vendors
- Expect First Prototype Tested and Evaluated in 18 Months

PGS Marine Vibrator



D63

PGS Marine Vibrator – Magnetic Drive Flextensional

- Advantages
  - **An environmentally friendly acoustic source**
  - **All electric system**
  - **A simple power and control system (no hydraulics)**
  - **Repeatable**

- Frequency range 5-100 Hz
- Source level approx. 2 barm
- Overall efficiency is about 6 times better than for an airgun
- High reliability – simplified design

MV JIP Timeline (future)

- Phase III: February 2013 to June 2015
  - Build 3 different prototypes
  - Test for Output and Reliability
- Phase IV: Late 2014 to 2016
  - Build and Field Test Commercial Systems

Summary

- Evaluated a Large Number of Possible Transducers
- Built a Team of Consultants
- Developed a Path Forward for JIP via TEES
- Selected 3 Vendors (out of 36 Contacted)
- Contract signed with PGS
- Contract in Progress with 2 Additional Vendors
- Expect First Prototype to be Tested within 18 Months

D64

Impact Pile Driving: frequency, angle and range dependence and their implications for current and potential quieting technologies

Peter H. Dahl
Applied Physics Laboratory
& Mechanical Engineering
University of Washington, Seattle, USA

Per Reinhall (Program Co-PI)
UW graduate students:
Mark Stockham (2009-2011)
Tim Dardis (2011-)
Darrel Farrel l (WSG student)

Research sponsored by
Washington State Dept. of Transportation

What to focus on for News Quieting Technologies?

1. Frequency broadly distributed over two decades range: 20-2000 Hz
2. The Mach wave and its components

On measuring *performance* of NQT

1. Ignore the Range/Depth dependence at your peril!

Research sponsored by
Washington State Dept. of Transportation

Experimental environment:

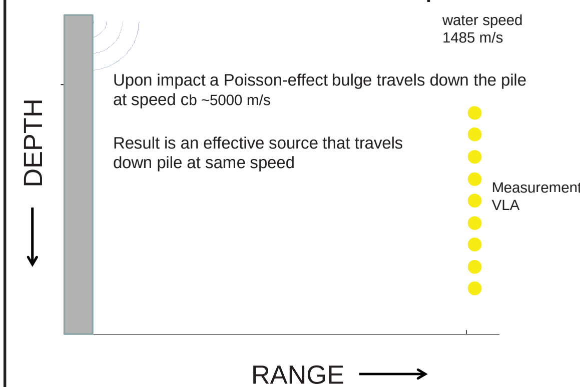
Puget Sound, WA… in November

Depth ~ 12 m

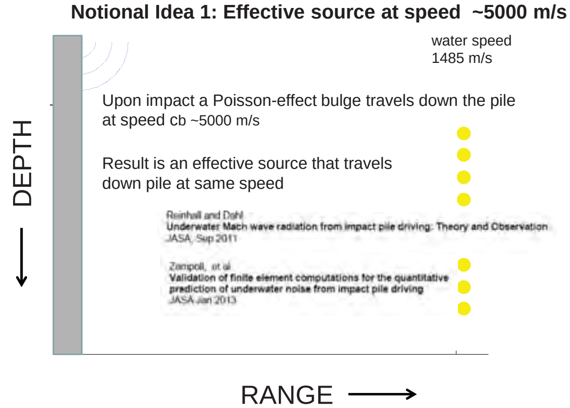
Sandy sediment (at least upper few m)

Measured speed 1485 m/s , iso-velocity

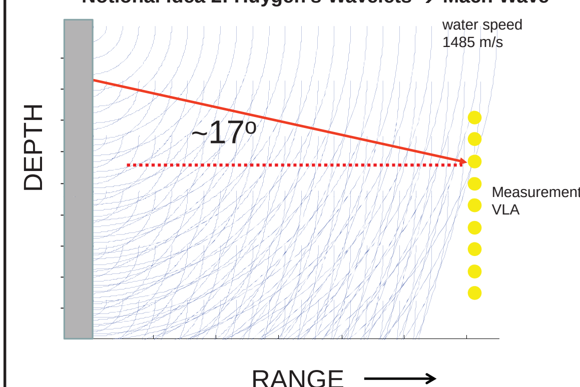
Notional Idea 1: Effective source at speed ~5000 m/s

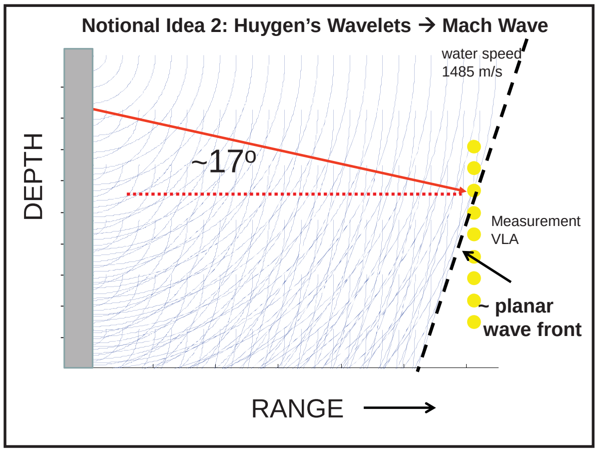


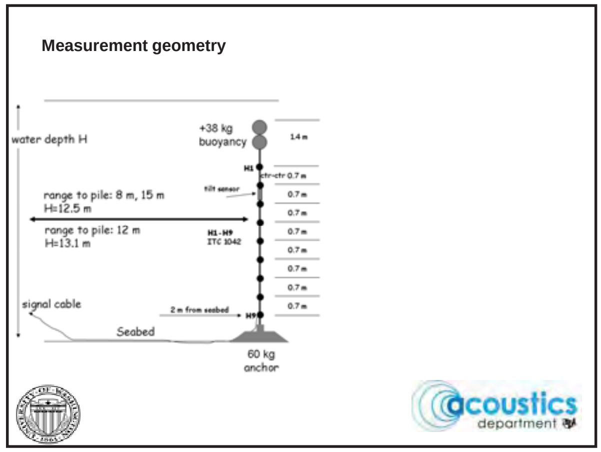
Notional Idea 1: Effective source at speed ~5000 m/s

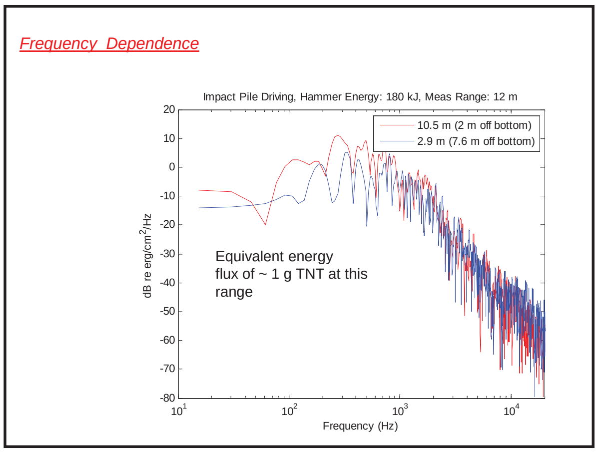


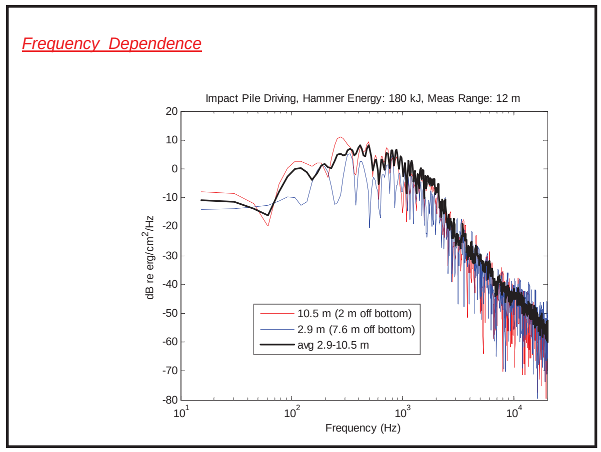
Notional Idea 2: Huygen's Wavelets → Mach Wave

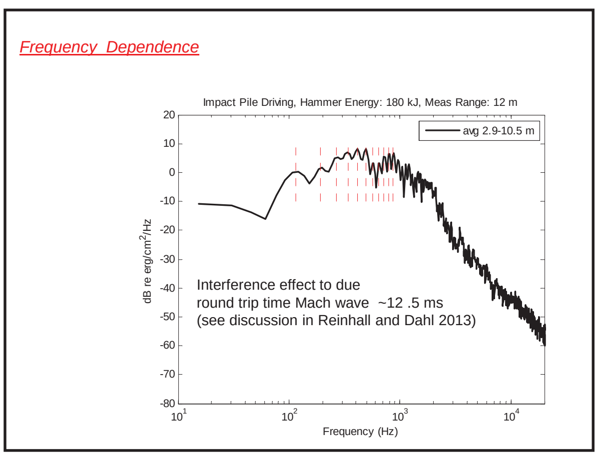


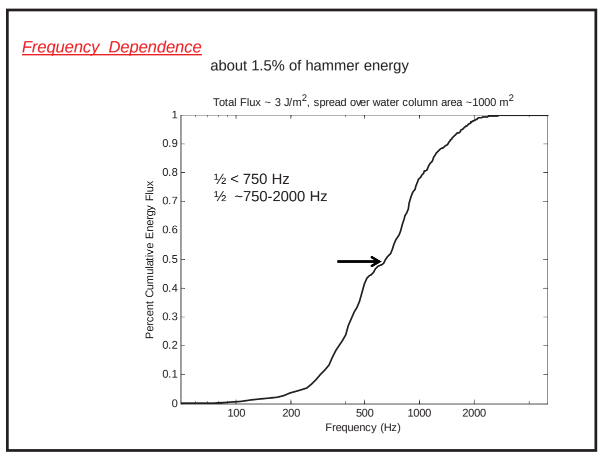

Notional Idea 2: Huygen's Wavelets → Mach Wave
water speed
1485 m/s
~17°
DEPTH
Measurement
VLA
~ planar
wave front
RANGE


Measurement geometry
water depth H
+38 kg
buoyancy
range to pile: 8 m, 15 m
H=12.5 m
range to pile: 12 m
H=13.1 m
H1-H9
ITC 1042
signal cable
2 m from seabed
Seabed
60 kg
anchor
acoustics
department


Frequency Dependence
Impact Pile Driving, Hammer Energy: 180 kJ, Meas Range: 12 m
10.5 m (2 m off bottom)
2.9 m (7.6 m off bottom)
Equivalent energy
flux of ~ 1 g TNT at this
range
dB re erg/cm²/Hz
Frequency (Hz)


Frequency Dependence
Impact Pile Driving, Hammer Energy: 180 kJ, Meas Range: 12 m
10.5 m (2 m off bottom)
2.9 m (7.6 m off bottom)
avg 2.9-10.5 m
dB re erg/cm²/Hz
Frequency (Hz)

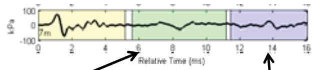

Frequency Dependence
Impact Pile Driving, Hammer Energy: 180 kJ, Meas Range: 12 m
avg 2.9-10.5 m
Interference effect to due
round trip time Mach wave ~12 .5 ms
(see discussion in Reinhall and Dahl 2013)
dB re erg/cm²/Hz
Frequency (Hz)


Frequency Dependence
about 1.5% of hammer energy
Total Flux ~ 3 J/m², spread over water column area ~1000 m²
½ < 750 Hz
½ ~750-2000 Hz
Percent Cumulative Energy Flux
Frequency (Hz)

Time-Angle Dependence

Three Primary Phases in the Arrival Structure

Phase 1	Phase 2	Phase 3
$\theta > 0$	$\theta < 0$	$\theta > 0$



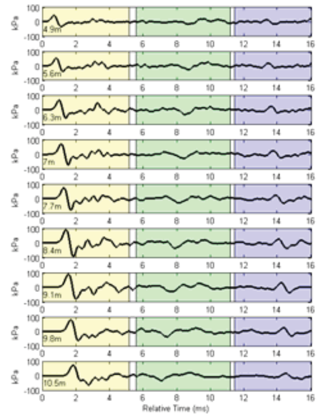
← RD 7 m

Due to reflection from the bottom of the pile
|R| ~ 3/8

Due to reflection from top bottom of the pile
|R| ~ 1

Arrival Structure

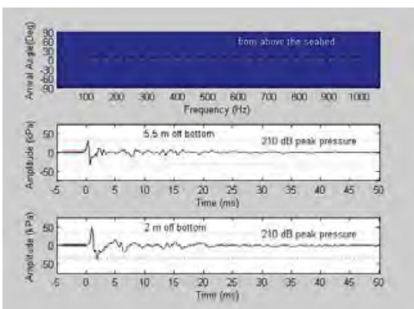
Range 12 m

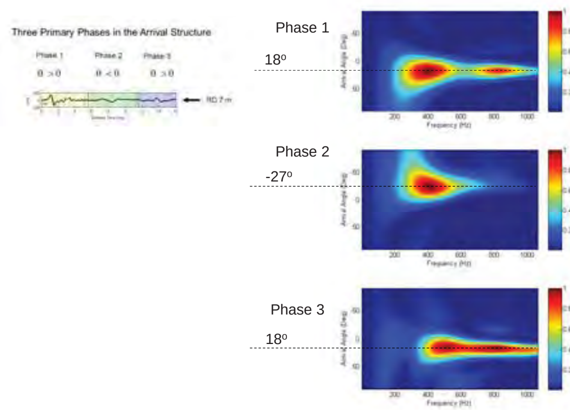


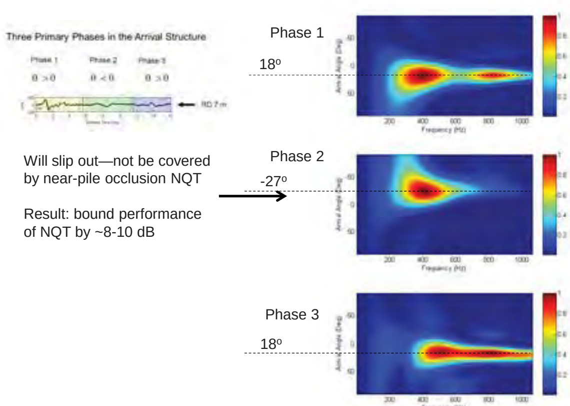
← RD 7 m

Time-Angle Dependence

Measurements of Impact Pile Driving
Vashon Island Ferry Terminal (Washington State)
Water Depth:12.5 m
Measurement Range: 15 m
Steel Pile Diameter: 0.76 m

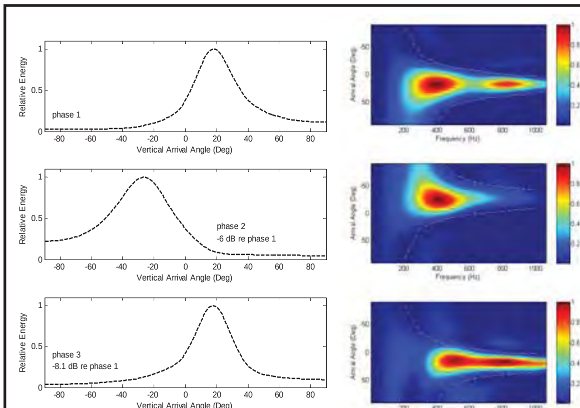






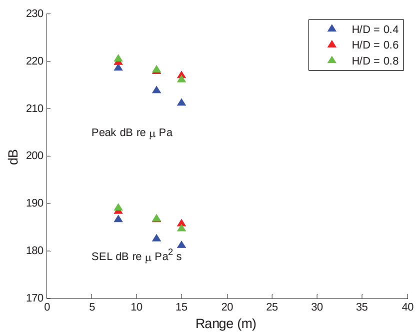
Will slip out—not be covered by near-pile occlusion NQT

Result: bound performance of NQT by ~8-10 dB



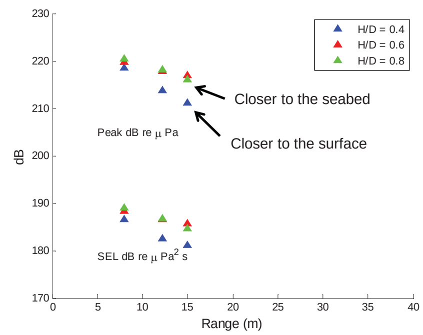
Range/Depth Dependence

Water Depth (D) = 12.5 m



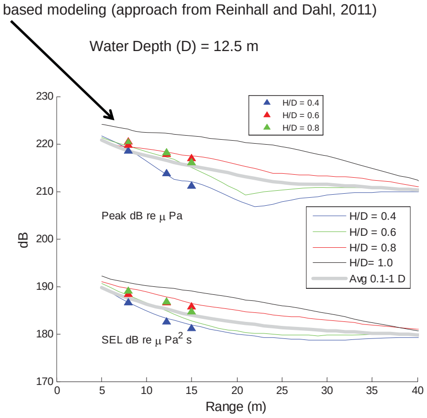
Range/Depth Dependence

Water Depth (D) = 12.5 m



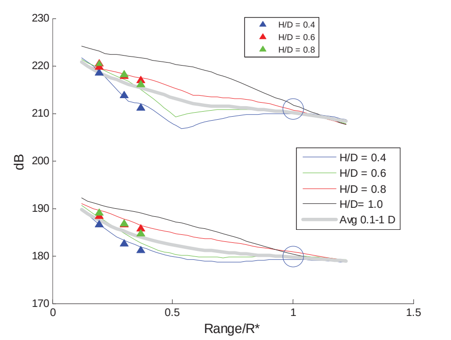
Parabolic wave based modeling (approach from Reinhall and Dahl, 2011)

Water Depth (D) = 12.5 m



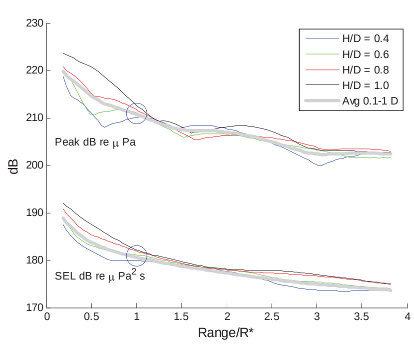
The importance of R*: the field becomes ~ depth independent for R > R*

Water Depth (D) = 12.5 m



The R* scale adapts to different water depths

Water Depth (D) = 8 m



Summary

1. Frequency dependence:

- half energy flux < 700 Hz, half ~ 700 - 2000 Hz
- high resolution spectra do not show lines, harmonics or tone-like features (in contrast to vibratory pile driving)
- NQ technologies targeting a narrow band of frequencies will be ineffective

1. Angle, and spatial dependence:

- Mach angle (θ_w) plays key role
- R* = Water Depth/tan(θ_w) ~ 3 Water Depths

For R < R* noise field is highly depth dependent with max variation at R/R* = 0.5

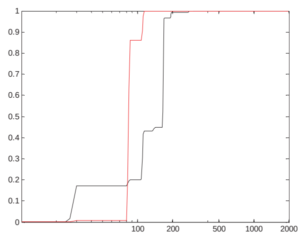
For R > R* noise field is less depth dependent

Research sponsored by Washington State Dept. of Transportation

acoustics department

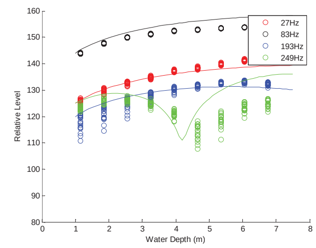
Recent Vibratory Pile Driving Study

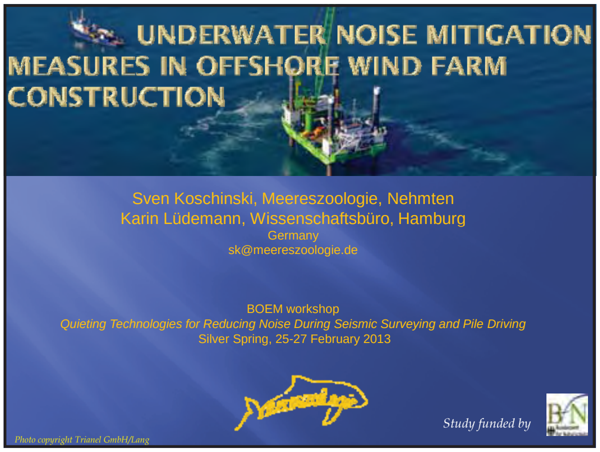
Percent Contribution to total mean square noise level



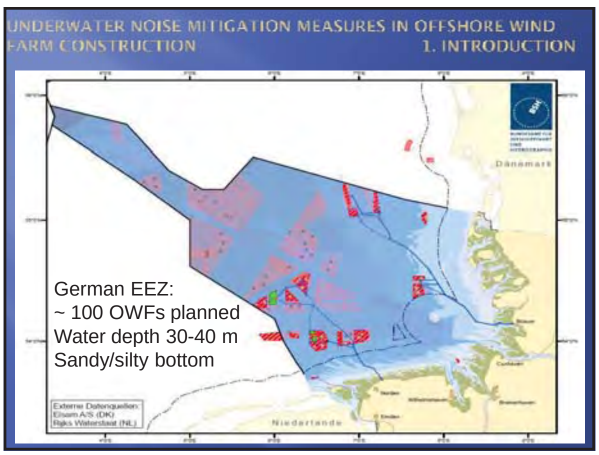
strong harmonic contributions (ka < 1)

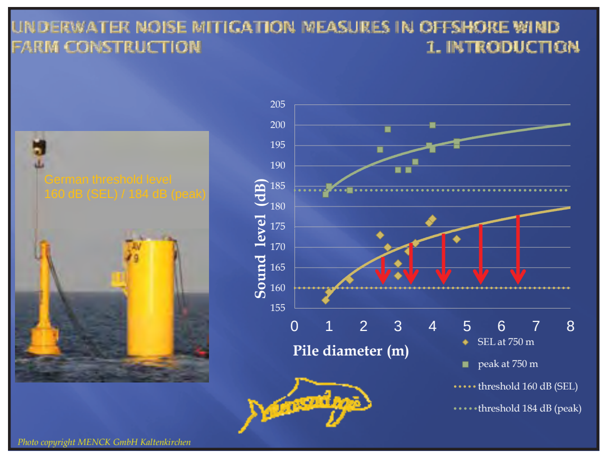
Recent Vibratory Pile Driving Study

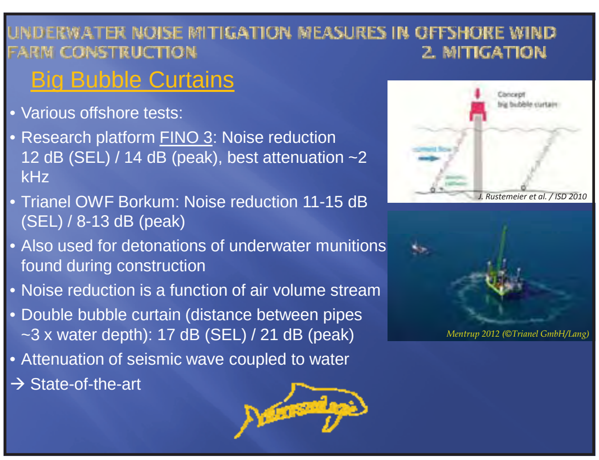


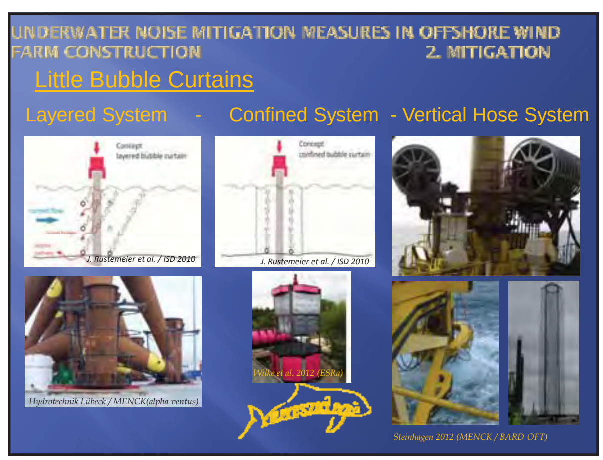

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
Sven Koschinski, Meereszoologie, Nehmten
Karin Lüdemann, Wissenschaftsbüro, Hamburg
Germany
sk@meereszoologie.de
BOEM workshop
Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving
Silver Spring, 25-27 February 2013
Study funded by
Photo copyright Trianel GmbH/Lang


UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
1. Introduction
2. Noise Mitigation Measures for Impact Pile Driving
3. Alternative „Low-Noise“ Foundations
4. Conclusions
Study funded by
Photo copyright Trianel GmbH/Lang


UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
1. INTRODUCTION
German EEZ:
~ 100 OWFs planned
Water depth 30-40 m
Sandy/silty bottom
Dänemark
Niederlande


UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
1. INTRODUCTION
German threshold level
160 dB (SEL) / 184 dB (peak)
Sound level (dB)
Pile diameter (m)
SEL at 750 m
peak at 750 m
threshold 160 dB (SEL)
threshold 184 dB (peak)
Photo copyright MENCK GmbH Kaltenkirchen


UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
2. MITIGATION
Big Bubble Curtains
• Various offshore tests:
• Research platform FINO 3: Noise reduction 12 dB (SEL) / 14 dB (peak), best attenuation ~2 kHz
• Trianel OWF Borkum: Noise reduction 11-15 dB (SEL) / 8-13 dB (peak)
• Also used for detonations of underwater munitions found during construction
• Noise reduction is a function of air volume stream
• Double bubble curtain (distance between pipes ~3 x water depth): 17 dB (SEL) / 21 dB (peak)
• Attenuation of seismic wave coupled to water
→ State-of-the-art
Concept big bubble curtain
J. Rustemeier et al. / ISD 2010
Mentrup 2012 (©Trianel GmbH/Lang)


UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION
2. MITIGATION
Little Bubble Curtains
Layered System - Confined System - Vertical Hose System
Concept layered bubble curtain
Concept confined bubble curtain
J. Rustemeier et al. / ISD 2010
J. Rustemeier et al. / ISD 2010
Hydrotechnik Lübeck / MENCK(alpha ventus)
Wilke et al. 2012 (ESRa)
Steinhagen 2012 (MENCK / BARD OFT)

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

Little Bubble Curtains – Several Variations

- Tests of various systems and configurations
- Perforated pipes close-fitting to pile
- Vertical hoses make use of tidal currents to create a bubble layer around the pile
- *OWF alpha ventus*: noise reduction 12 dB (SEL) / 14 dB (peak) – in direction of currents (incomplete system), OWF *Baltic II* 11-15 dB (SEL) - best attenuation 1 - 3 kHz
- OWF *BARD Offshore I*: up to 14 dB (SEL) / 19.5 dB (peak)

Photo copyright

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

Isolation Casings

- Principle: shielding, reflection, absorption/decoupling
- Steel pipe alone is not sufficient. Additional absorbing materials and bubble curtains are needed.
- Decoupling by rubber guiding pieces.

BEKA Shell

- 2 decoupled half shells (4 steel walls, 2 absorbent composite fillings, 2 bubble curtains)
- Best noise reduction 800 Hz to 6,4 kHz

Photo copyright Patrice Kunte, Bernhard Weyres

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

Isolation Casings

IHC Noise Mitigation System

- Air filled acoustically decoupled double steel wall with layered confined bubble curtain
- Experiment River de Noord (6 m water depth) good attenuation 150 Hz - 8 kHz
- Noise reduction under offshore conditions up to ~17 dB (OWF *Riffgat*, pile diameter 5.7 and 6.5 m)

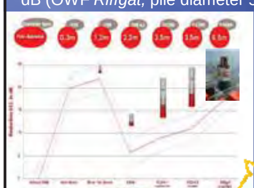


Photo copyright EWE/enova, IHC Merwede

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

Dewatered Cofferdams

- Principle: acoustic decoupling - pile driving in air by dewatering the annular gap
- Decoupling of guiding pieces
- Successful experiment in the Baltic Sea (15 m water depth pile diameter 2.13 m, 18 cm annular gap
- Broadband noise reduction by 23 dB (SEL) and 19 dB (peak)

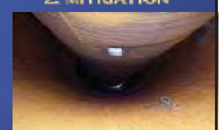
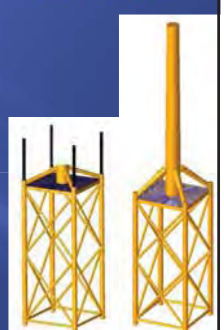


Photo copyright Thomsen 2012 (Lo-Noise ApS)

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

Cofferdams: Pile-in-pipe piling

- Variation of a proven foundation technology (Jacket)
- Cofferdams are part of the Jacket
- Dewatering by pressurized air
- Impact piling only above water level
- Validated concept
- Disadvantage: 300 – 400 t more steel is required at 40 m water depth

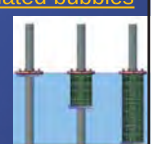


Overdick GmbH & Co. KG, Hamburg

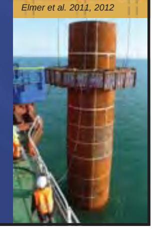
UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION — 2. MITIGATION

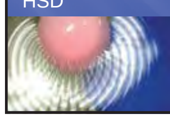
Hydro Sound Dampers (HSD) / encapsulated bubbles

- Gas filled elastic balloons and robust PE-foam elements fixed to nets or frames around pile
- Principle: Excitation with resonant frequencies cause scattering and absorption, foam elements act as impact absorbers
- Attenuation is adjustable at desired frequencies
- Proof-of-concept experiments in Germany and the US
- Next step: Experiments with a larger number of HSD



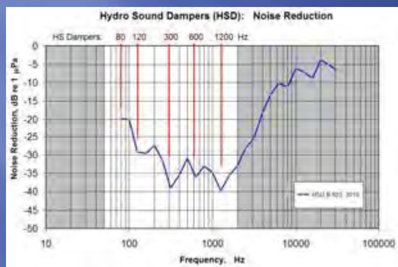
Elmer et al. 2011, 2012





UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 2. MITIGATION

Hydro Sound Dampers (HSD)



SEL reduction

Eigen-frequencies of HSD elements used

Elmer 2012

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 3. LOW NOISE FOUNDATIONS

Vibratory Pile Driving

- In combination with impact piling as a method to reduce the number of pile strikes
- Noise level 15 - 20 dB lower compared to impact pile driving
- *OWF alpha ventus*: measured broadband noise level 142 dB (SEL) @ 750 m
- Harmonics ("high frequency buzzing sound towards the end")

ITAP 2010 (alpha ventus)

ISD et al. 2007a (flexural oscillation of pile)

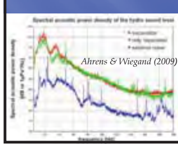
UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 3. LOW NOISE FOUNDATIONS

Drilled Foundations

- Vertical drilling with full-face or partial-face excavation machines
- For steel or concrete monopiles
- Larger diameters possible compared to impact piling
- Continuous noise: broadband rms SL 160 dB re 1 µPa (117 dB @ 750m)
- Noise emission mainly below 200 Hz, drill head 10-40 Hz, separator at higher frequencies

Herrenknecht/Hochtief Solutions

Fugro Seacore Ltd



Ahrens & Wiegand (2009)

Ballast Nedam

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 3. LOW NOISE FOUNDATIONS

Gravity Base Foundations

- Large box girders whose stability is achieved by self-weight of the structure and additional ballast
- State-of -the-art for water depths up to 20 m (e.g. *Nysted*/DK, *Lillgrund*/S, *Thornton Bank*/B)
- Soil preparation (if needed) creates dredging noise
- Most concepts need large installation vessels

Copyright: Dong Energy

Copyright: Seatower A/S

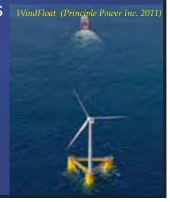
UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 3. LOW NOISE FOUNDATIONS

Floating Wind Turbines

- Floating concepts for deep and shallow water:
- SPAR buoy (HYWIND, SWAY)
- Ballasted semi-submersibles (WINDSEA, WINFLO, INFLOW, WindFloat, Floating Power Plant –combined with wave absorbers)
- Tension Leg Platforms (Blue H, GICON-SOF)
- SPAR and TLP State-of -the-art for oil and gas platforms
- Full-scale prototypes: HYWIND (N 2009), WindFloat (P 2011)

GICON GmbH, Rostock

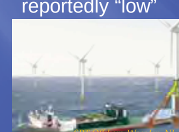
WindFloat (Principle Power Inc. 2011)



UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 3. LOW NOISE FOUNDATIONS

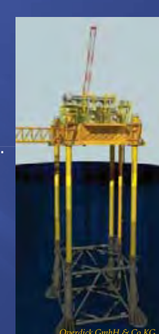
Bucket Foundations

- Large steel caissons are founded in sandy/soft sediments by suction pumps
- State-of –the-art for oil and gas platforms (converter platforms)
- Prototypes/concepts for wind turbines (monopod, three-legged jacket designs: e.g. self installing wind turbine SIWT)
- Noise emissions by suction pumps reportedly "low"



SPT Offshore, Woerden, NL

Ibsen et al. 2005 (Frederikshavn)



Overdick GmbH & Co.KG

D72

UNDERWATER NOISE MITIGATION MEASURES IN OFFSHORE WIND FARM CONSTRUCTION 4. CONCLUSIONS

- Progress in science and development in the past years
- Noise measurements prove broadband noise reduction between 10 and 20 dB (SEL)
- Noise reduction levels cannot be guaranteed
- Optimization of systems: Further development and research needed
- It is possible to meet the German legal requirements (160 dB SEL @ 750m) in many cases using noise mitigation methods
- Very large monopiles may be a problem
- Avoiding noise is better than reducing it. Look at alternatives.

THANK YOU FOR YOUR ATTENTION

Bringing the Big Bubble Curtain Offshore

Projekt: HYDROSCHALL OFF BW II.
Entwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten.

Förderkennzeichen 0325309A/B/C

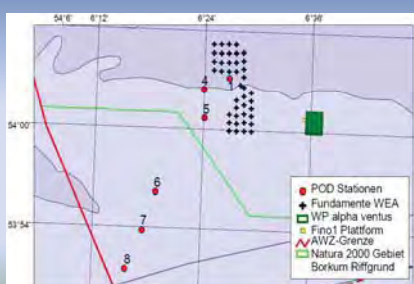
Bio Consult SH · itap · HYDROTECHNIK LÜBECK

Sponsored by

Trianel · PtJ

Bringing the Big Bubble Curtain Offshore

Offshore windfarm Borkum West II
50 km offshore, water depth 26-28 m



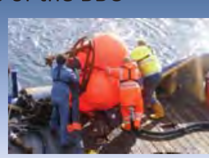
Bringing the Big Bubble Curtain Offshore

Offshore windfarm Borkum West II
40 tripod-foundations, pile diameter 2,4 m

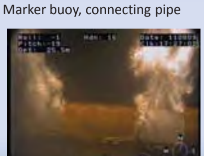
Bringing the Big Bubble Curtain Offshore

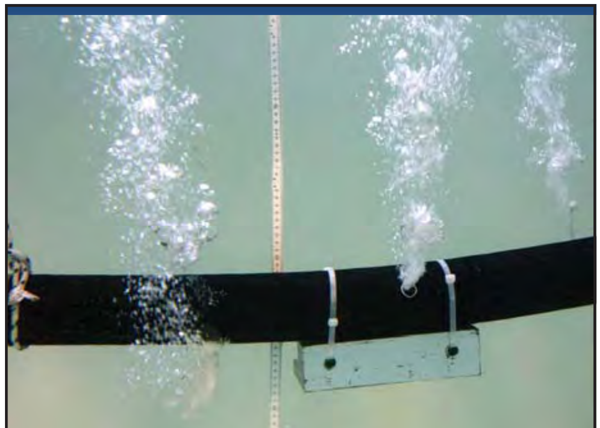
Components of the BBC


Nozzle hose


Marker buoy, connecting pipe


Compressor


Bubble Curtain in operation



Bringing the Big Bubble Curtain Offshore

Bringing the Big Bubble Curtain Offshore

Bringing the Big Bubble Curtain Offshore

Bringing the Big Bubble Curtain Offshore

Bringing the Big Bubble Curtain Offshore

Requirement for noise mitigation

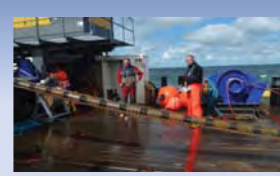
Noise reduction of 14 dB

Don't interfer with construction process

Bringing the Big Bubble Curtain Offshore

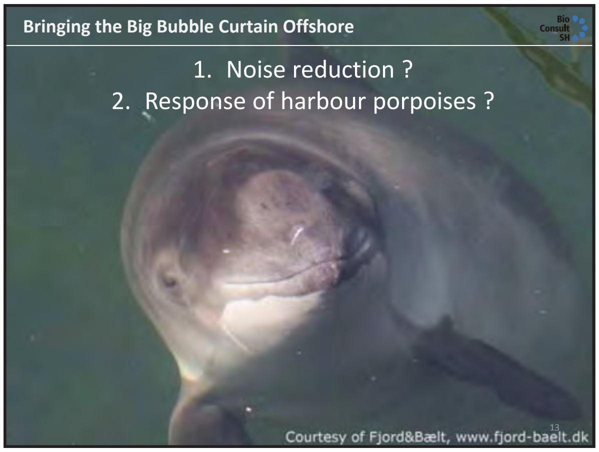
Experience from Borkum West II

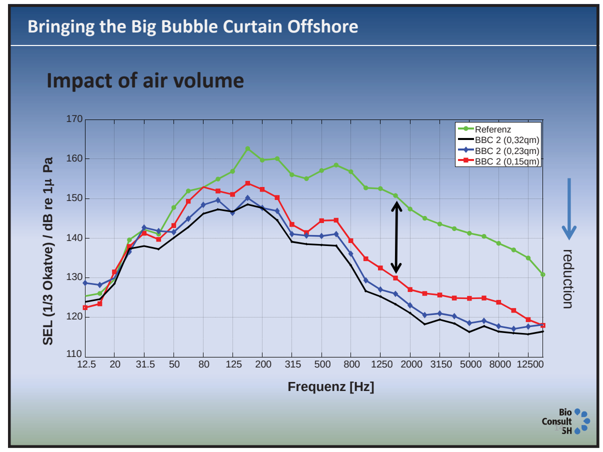
Method: 500 m nozzle hose are laid before arrivial of construction platform. Duration: < 1h.

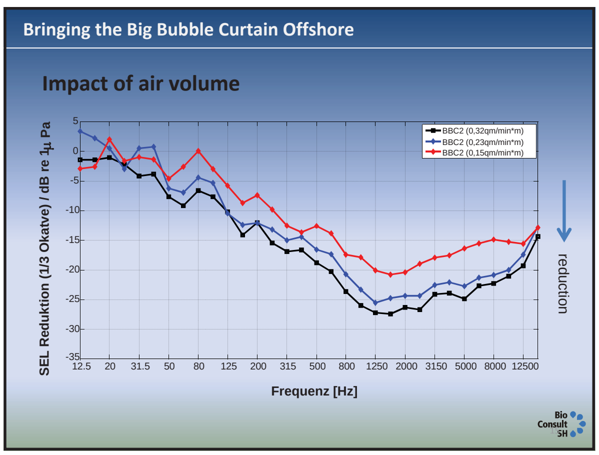


40 foundations + 20 additional tests

Nozzle hose lasted through all foundations





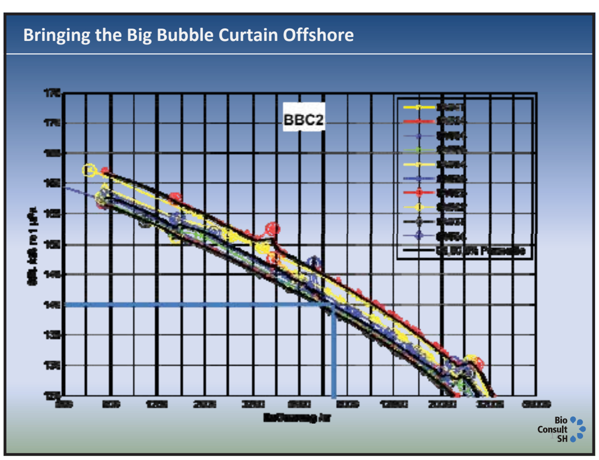


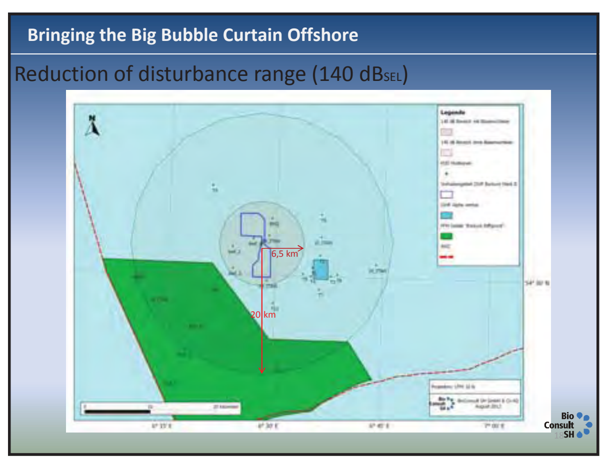
Bringing the Big Bubble Curtain Offshore

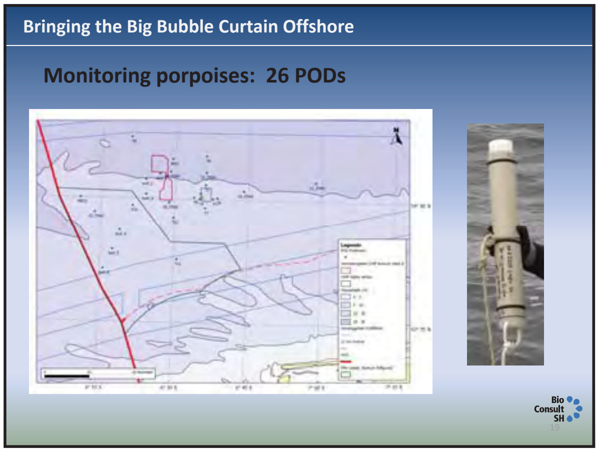
Noise reduction:

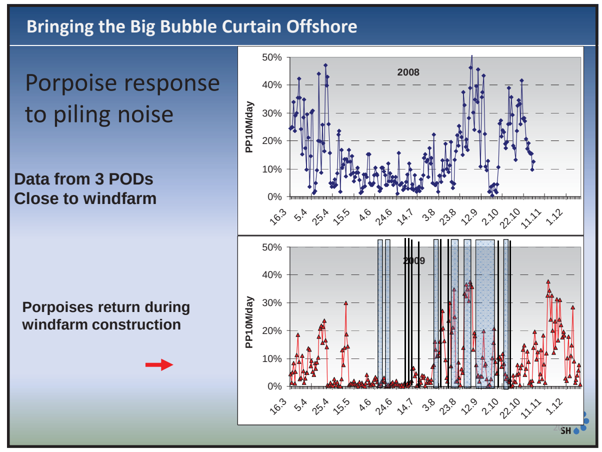
Nr.	BBC Configuration	Noise reduction	
		SEL [dB]	Peak [dB]
1	Nozzle hose BBC 1, large nozzle	9,6	12,8
2	Nozzle hose BBC 2 small nozzles	12,2	13,9
3	Double bubble-curtain at 25 m	15,5	18,7
4	Double bubble-curtain at 80 m	17,2	20,7

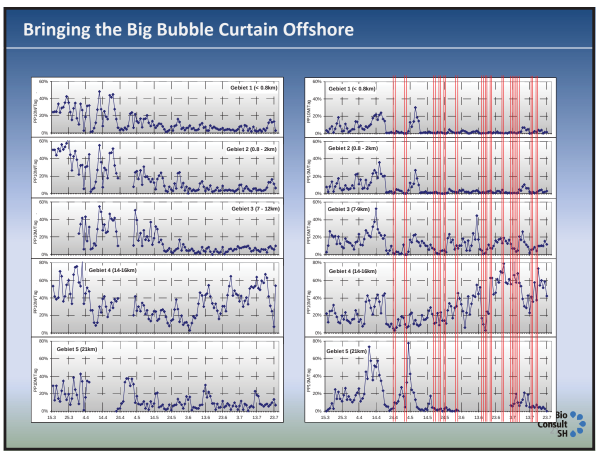
Quelle: itap GmbH, Oldenburg

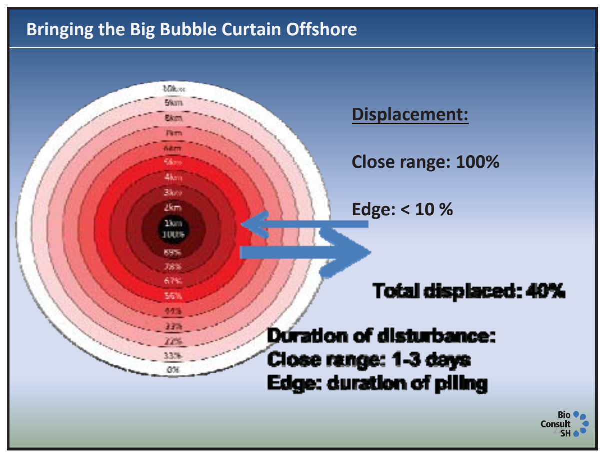


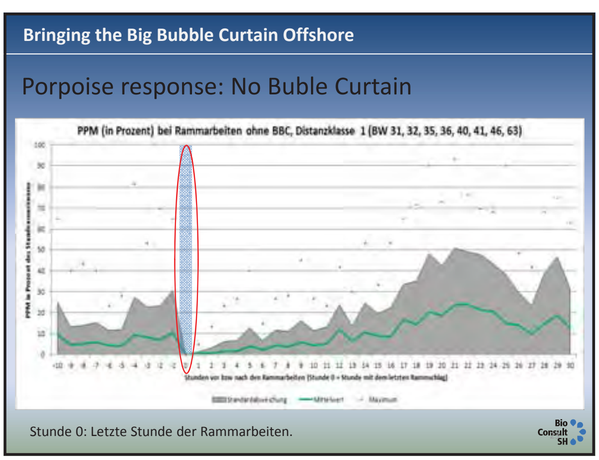


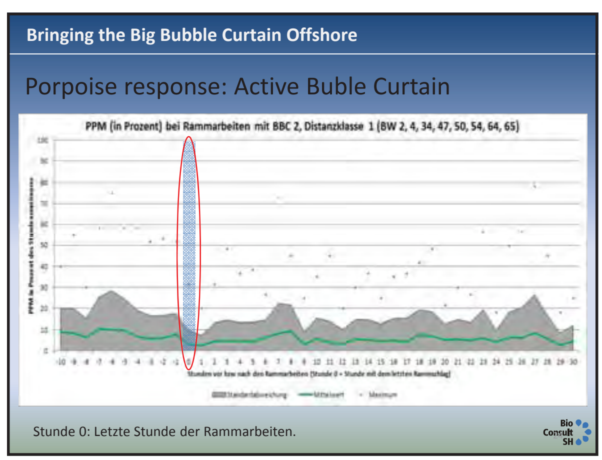

Bringing the Big Bubble Curtain Offshore
Monitoring porpoises: 26 PODs
Bio Consult SH


Bringing the Big Bubble Curtain Offshore
Porpoise response to piling noise
Data from 3 PODs Close to windfarm
Porpoises return during windfarm construction
2008
2009
PP10M/day
Bio Consult SH


Bringing the Big Bubble Curtain Offshore
Bio Consult SH


Bringing the Big Bubble Curtain Offshore
Displacement:
Close range: 100%
Edge: < 10 %
Total displaced: 40%
Duration of disturbance:
Close range: 1-3 days
Edge: duration of piling
Bio Consult SH


Bringing the Big Bubble Curtain Offshore
Porpoise response: No Buble Curtain
PPM (in Prozent) bei Rammarbeiten ohne BBC, Distanzklasse 1 (BW 31, 32, 35, 36, 40, 41, 46, 63)
Stunde 0: Letzte Stunde der Rammarbeiten.
Bio Consult SH


Bringing the Big Bubble Curtain Offshore
Porpoise response: Active Buble Curtain
PPM (in Prozent) bei Rammarbeiten mit BBC 2, Distanzklasse 1 (BW 2, 4, 34, 47, 50, 54, 64, 65)
Stunde 0: Letzte Stunde der Rammarbeiten.
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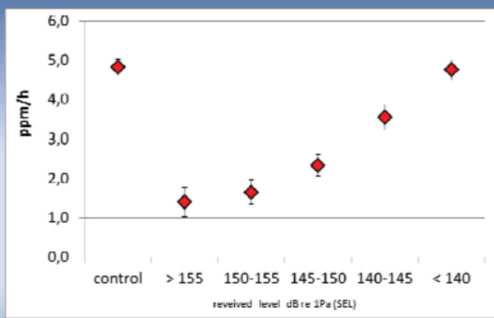
Bringing the Big Bubble Curtain Offshore

Porpoise response: Realtion to noise level



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Bringing the Big Bubble Curtain Offshore

Porpoise displacement:

Animal densitiy: 2,3/km^2

140 dB$_{SEL}$ range 20 km :
2900 animals disturbed and 1150 displaced

140 dB$_{SEL}$ range 6,5 km:
300 animals disturbed and 120 animals displaced

Porpoise population in German waters: 50,000

Bio Consult SH

Bringing the Big Bubble Curtain Offshore

Outlook:

Costs: 100,000 € per foundation

Current problem: Large construction vessels require > 1 km nozzle hose

Bio Consult SH

Noise Control Engineering, Inc.
Engineering Solutions to Acoustic Problems

INTRODUCTION:

Day 1, Breakout Session 1
Group 3 – Ship Noise

Introduction: Michael Bahtiarian

Facilitator: Dr. Ben Reeder

Noise Control Engineering, Inc., 799 Middlesex Turnpike, Billerica, MA 01821
Phone: 978-670-5339 Fax: 978-667-7047 nonoise@noise-control.com
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Noise Control Engineering, Inc.
Engineering Solutions to Acoustic Problems

Before we can discuss where we are going…

We have to know where we have been…

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Noise Control Engineering, Inc.
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Started in 1950's by our Navy's…

USS Albacore (AGSS 569) in Portsmouth, NH

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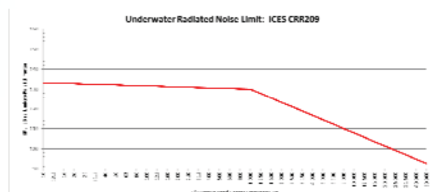
ICES Helped in 1990's



- International Council for the Exploration of the Seas Hallmark report:
  - CRR-209, dated 1995
  - Authored by Dr. Ron Mitson

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NOAA & FRV's/FSV's in 2000's

PISCES (FSV-3) & *SHIMADA* (FSV-4) Operating Together

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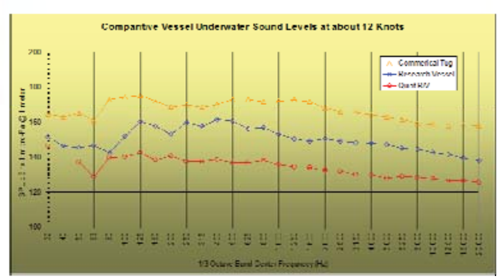
Measured Data



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D79

Noise Control Engineering, Inc.

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Much more coming 2010's

- **2009**: ASA Standard (S12.64) for meas.
- **2010**: DNV silent class.
- **2013**: ISO underwater standards.
- **2013**: IMO underwater guidelines.
- Other quiet R/V's and support ships.

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WHALE ACOUSTICS LABORATORY

SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

Measurements of Ship Radiated Noise

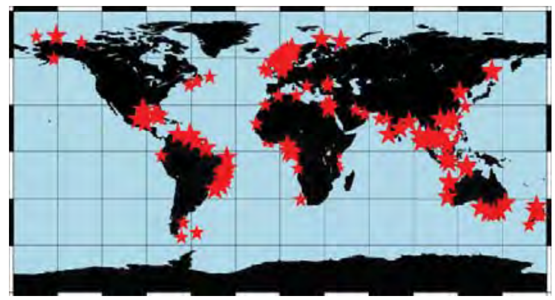
John Hildebrand
Scripps Institution of Oceanography
University of California San Diego

QUIETING TECHNOLOGIES FOR REDUCING NOISE DURING SEISMIC SURVEYING AND PILE DRIVING

Silver Spring, Maryland
25 February 2013

1

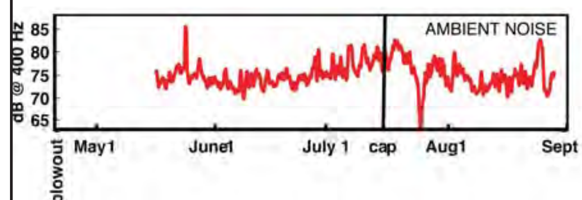
Global Offshore Seismic Exploration



Data for 1994 – 2005 Hildebrand 2009

Deepwater Horizon – HARP

Noise Index for MC HARP Site



Hourly estimate of ambient noise at MC HARP
400 Hz used as proxy for nearby ships

Icebreaking – USCG Healy

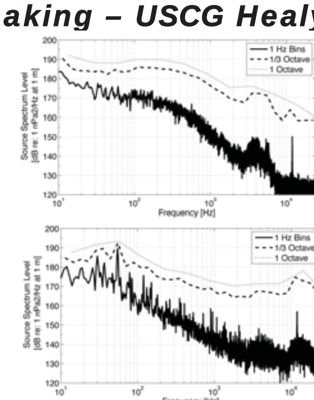
22 April 2013 5

Icebreaking – USCG Healy

80% Ice Cover

Transiting @ 5 kn

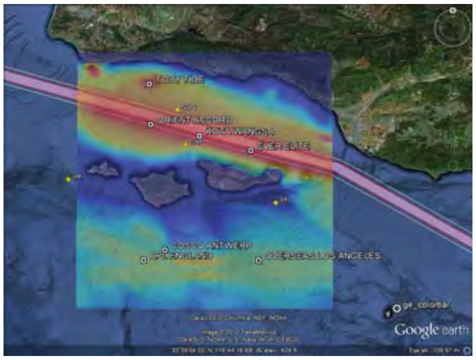
Holding Station < 1 kn



Roth et al. 2013

22 April 2013 6

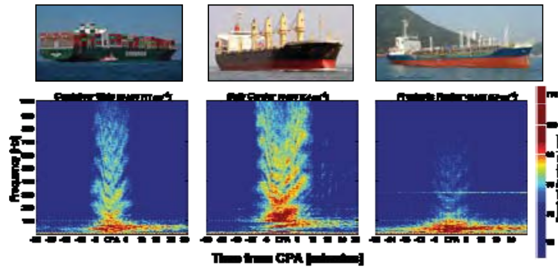
Santa Barbara Channel – AIS



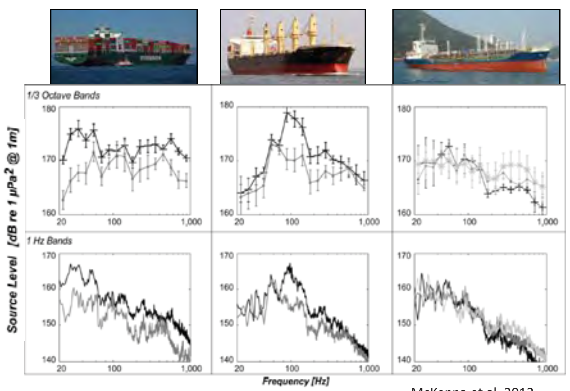
08 Jan 2009

1 hour ship passages

Received sound levels



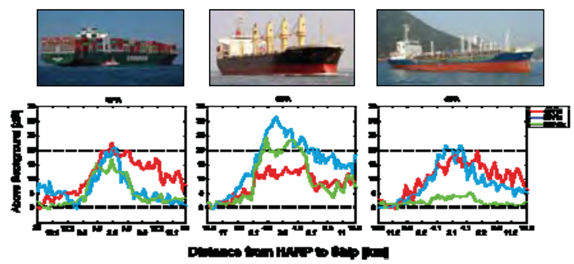
Source levels



McKenna et al. 2012

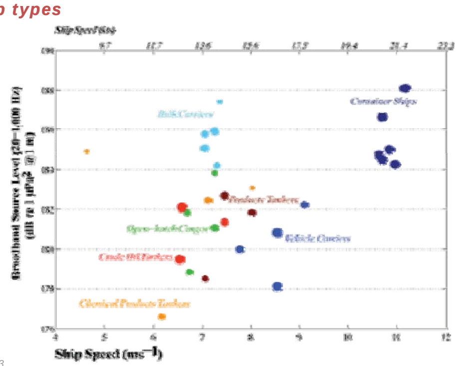
1 hour ship passages

Above background noise



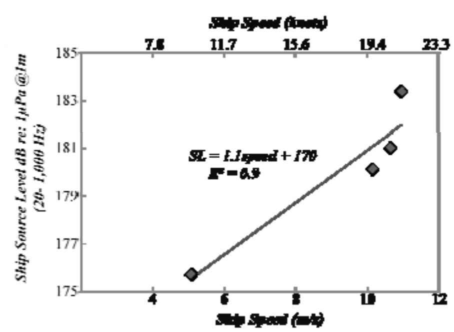
Ship source level and ship speed

All ship types



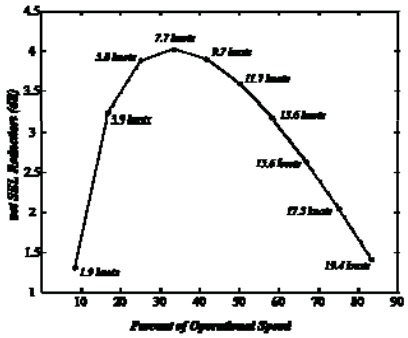
Container ship noise and speed

Multiple passages of same ship



Cumulative noise of ship passage

Reduction based on speed



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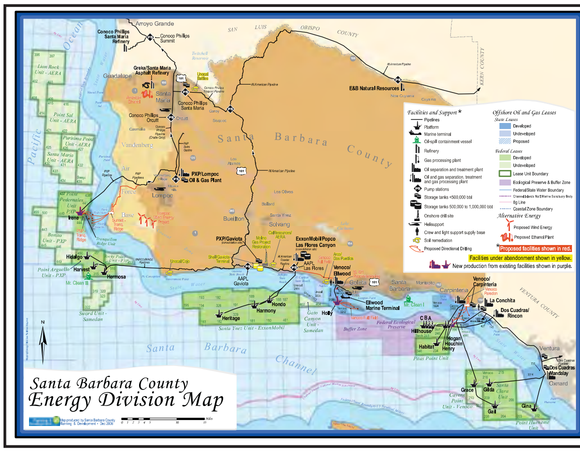
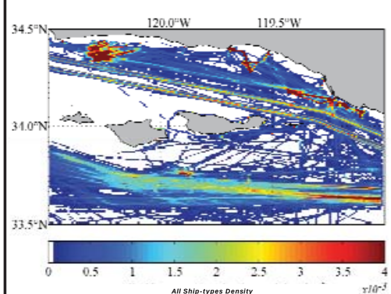
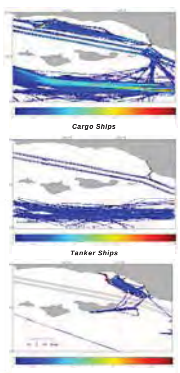


Ship traffic DENSITY in southern California





from Automatic Identification System (AIS) data August 2011

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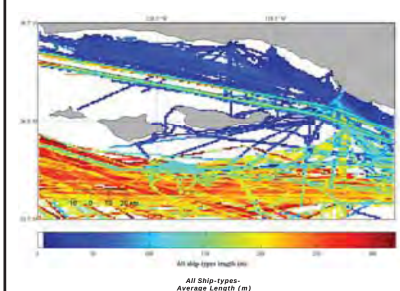
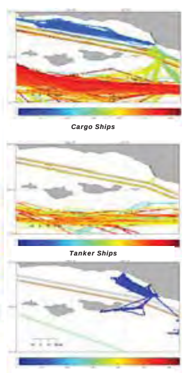
Ship traffic LENGTH in southern California





from Automatic Identification System (AIS) data August 2011

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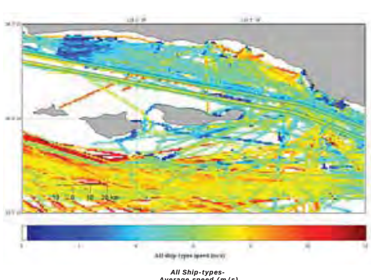
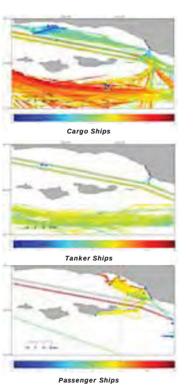
Ship traffic SPEED in southern California





from Automatic Identification System (AIS) data August 2011

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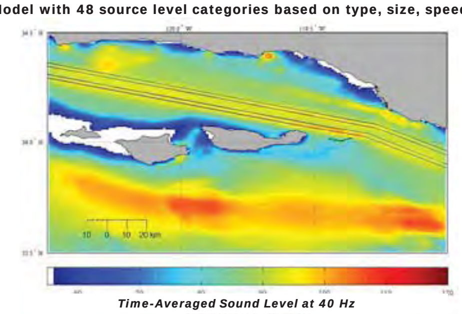
Cumulative sound levels- 1 month

Model ship source level inputs

Model with 48 source level categories based on type, size, speed



Kraken Propagation Model for 40Hz at 5m depth

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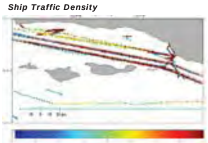
D83

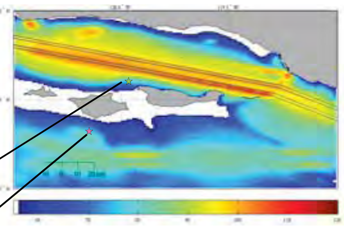
Cumulative sound levels- 1 day

Comparison with empirical data

Ship Traffic Density



site	predicted	empirical
Channel	77 dB	80.7 dB
South	72 dB	80.6 dB



Kraken Propagation Model for 40Hz at 5m depth (8 Jan 2009)

22 April 2013 19

THANK YOU

20

Design Options and Operational Considerations for Reducing Ship Radiated Noise

BOEM Workshop

Quieting Technologies For Reducing Radiated Noise
During Seismic Surveying and Pile Driving

25 February 2013

Chris Barber, Ph.D.

Ship Radiated Noise

The ship noise engineering community can tell you
- What makes noise on a ship?
- How loud are these sources?
- What technologies are available to reduce ship noise?
- How effective can these measures be?
- What is the cost to design in or back fit these measures

Open question remains:
- How quiet does the ship need to be?
  - Environmental Impact
  - Guidelines, requirements, regulations
  - Ship noise versus seismic and impulsive sources

Multipath
Science and Engineering Solutions
underwater acoustics test and evaluation

Ship Radiated Noise

Given a ship noise goal, requirement or operational constraint, an additional question arises:
- What can be done to ensure existing ships *operate* as quietly as possible when necessary?
  - Noise Control Maintenance
  - Reduced Noise Operational Guidelines
  - Real Time Noise Monitoring

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Ship Design and Noise Control Engineering

For new construction and retrofit / overhaul of existing ships
- Establish clearly defined noise requirements and objectives
  - Environmental underwater, airborne, shipboard habitability
- Compare design predictions or measurements to objectives
  - Computational models (new), Radiated Noise Test (existing)
- Identify primary noise sources and alternatives
  - Low or reduced-noise propulsion and machinery options
- Determine dominant noise transmission mechanisms
  - Path control via mounts, attachments, arrangements…
  - Noise reduction via silencers and material treatments
- Evaluate options based on cost vs. performance
  - Often true that reduced noise = improved efficiency for main and auxiliary propulsion

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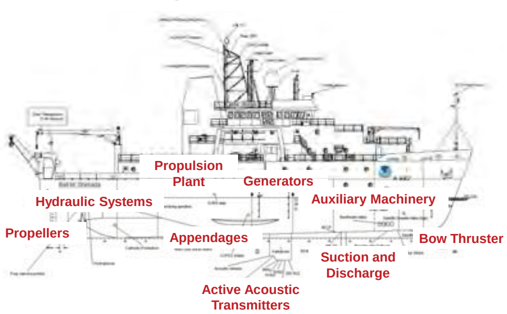
Ship Noise Sources



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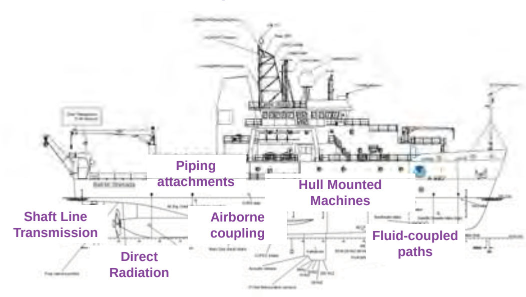
Ship Noise Paths



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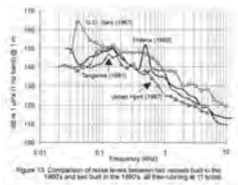
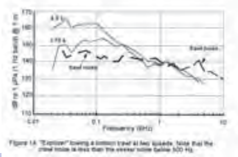
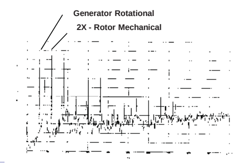
Example Radiated Noise Data







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Reduced-Noise Propulsion Design

- Cavitation is DOMINANT
  - Design main propulsor to avoid cavitation over broadest possible operational conditions
  - Improved efficiency and reduced erosion

- Dynamic Positioning Systems are typically extremely noisy
  - Options for reduced-noise bow thrusters or podded propulsors exist and can be cost effective

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Reduced Noise Machinery

- Main Propulsion System
  - Selection typically determined by considerations other than noise
  - Noise reduction via enclosures, mounts and other treatments

- Auxiliary Machinery
  - Reduced noise alternatives often cost effective
  - Isolation and path control can be very effective
    - Vibration Isolation Mounts
    - Pipe Hangers
    - Flex couplings
    - Silencers
    - Compartment treatments

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Noise Control Maintenance

Establish a routine inspection and maintenance program to identify and correct conditions that increase ship noise

- Propeller inspection and cleaning
  - Marine fouling of propellers causes cavitation onset at reduced speeds, substantially increases cavitation noise and damage at all speeds and reduces propeller efficiency
- Machinery condition
  - Normal degradation of pumps and other rotating machinery often produce increased vibration and noise levels
- Isolation treatments and unintentional "sound shorts"
  - Unintentional sound shorts can defeat expensive noise control
  - Include vigilant Inspection as part of maintenance

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Reduced Noise Operational Guidelines

Identify optimum equipment configurations and operating ranges to provide lowest noise output during noise-critical operations

- Based on a ship radiated noise test of baseline standard operating conditions and alternates, determine:
  - Ship speed for minimum noise (slower not always quieter)
  - Operational procedures and/or system constraints to reduce dynamic position system noise
  - Quietest machinery units when multiple redundant units are available
  - Reduced noise operational modes for systems with multiple settings
  - Non-essential noise sources - machines, systems and shipboard operations - that can be secured during noise-critical operations

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Real Time Noise Monitoring

Shipboard Noise and Vibration Monitoring system can provide real-time feedback to ship operators on ship noise levels during noise critical operations

- Cost-effective monitoring systems can be incorporated into new design ships or back-fitted to existing ships
  - Based on shipboard vibration sensors at noise critical locations,
    - hull above propellers for cavitation noise
    - directly on Main machinery noise sources
- Real-time ship noise estimates based on transfer function between vibration levels and a one-time ship radiated noise test
  - Provides both operational guidance and tracking of degradations indicating maintenance may be required

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Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving

A BOEM Workshop on the Status of Alternative and Quieting Technologies

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The Geokinetics Marine Vibrator

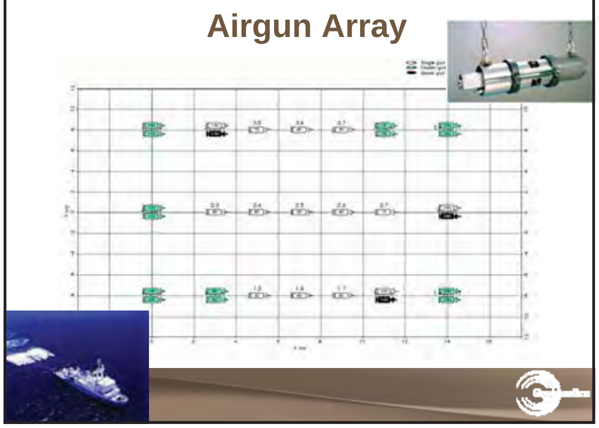
Outline

- What is Seismic Exploration
- Airguns: a Reference Point
- The Industry Motives for Marine Vibrators
- Comparing Airguns and Vibrators
  - Bandwidth
  - Sweep amplitude and length
- The Geokinetics Marine Vibrator
  - History
  - Description
  - Status
- Summary

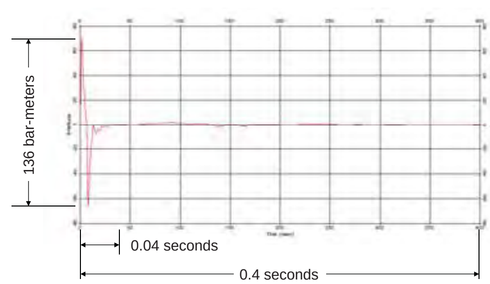
What are we doing?

- Reflection seismology is a method of exploration geophysics that uses the principles of seismology to estimate the properties of the earth's subsurface from reflected seismic waves. The method requires a controlled source of seismic energy.
- Reflection seismology is similar to sonar and echolocation.

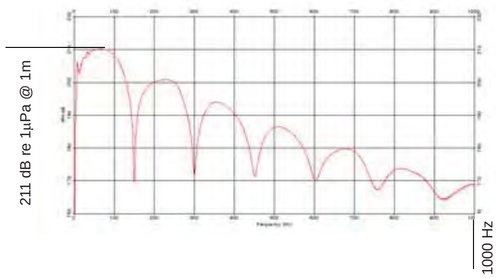
Airgun Array



Airgun Array Time Signature



Airgun Array Amplitude Spectrum



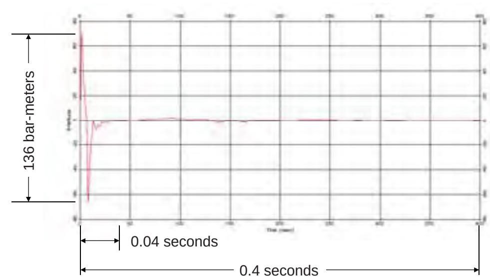
Industry Motives for Marine Vibrators

- Technical
  - potential for improved data quality
- Financial
  - potential for improved operational efficiency
- Regulatory
  - restrictive environmental regulations
  - ability to acquire data where airguns are restricted
- Environmental Stewardship
  - being a good corporate world citizen
- Public Relations
  - being seen as a good corporate world citizen

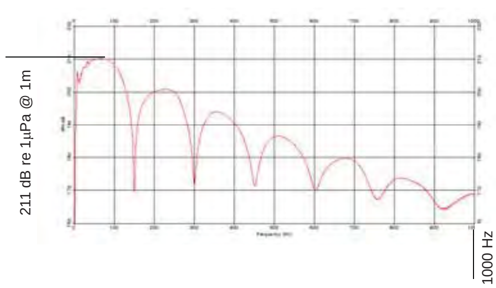
Comparing Airguns and Vibrators

- A difficult scenario
  - Impulsive vs. long duration
- Required comparisons
  - Useful energy for seismic exploration
    - Total energy within the frequency band of interest
  - Sound pressure level
    - Relative to environmental effect

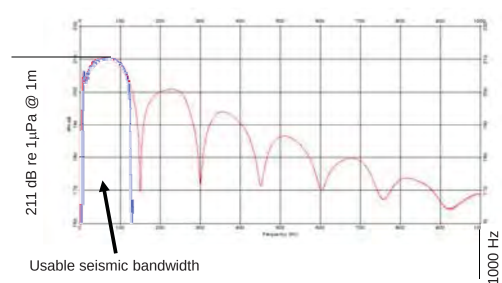
Airgun Array Time Signature



Airgun Array Amplitude Spectrum

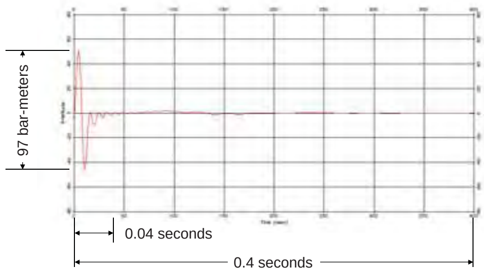


Airgun Array Amplitude Spectrum

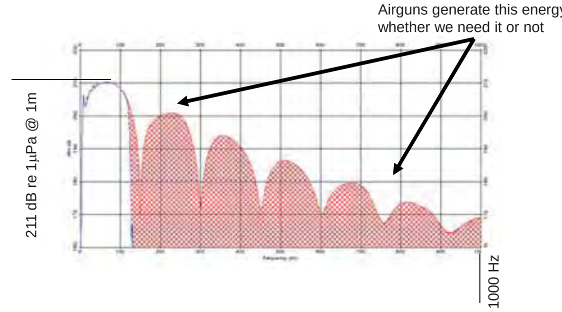


Airgun Array Time Signature

Limited to useful frequency band



Airgun Array Amplitude Spectrum

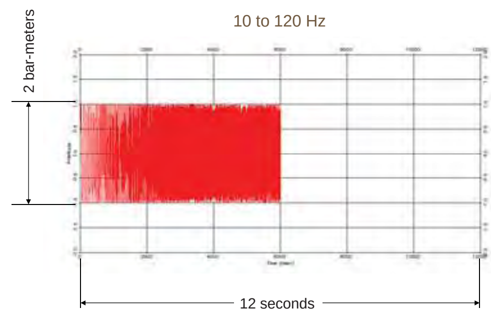


Marine Vibrators

- Because we can control the bandwidth of the vibrator signal, we can output an overall lower signal level

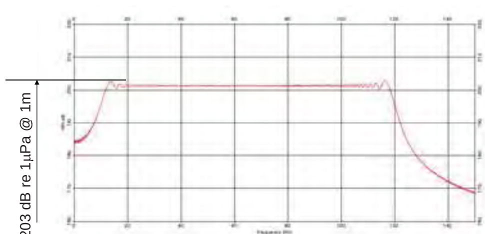
6 second Vibrator Sweep

10 to 120 Hz

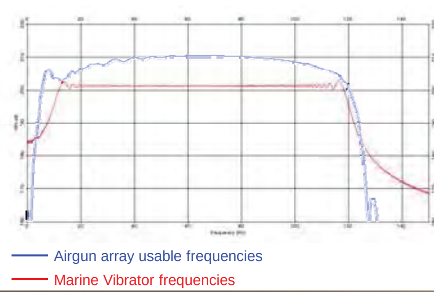


6 second Vibrator Sweep

10 to 120 Hz

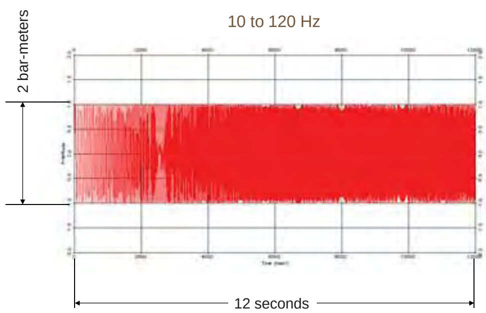


Amplitude Spectra Comparison



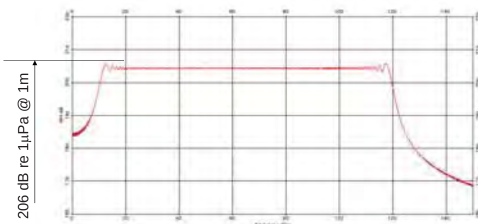
12 second Vibrator Sweep

10 to 120 Hz



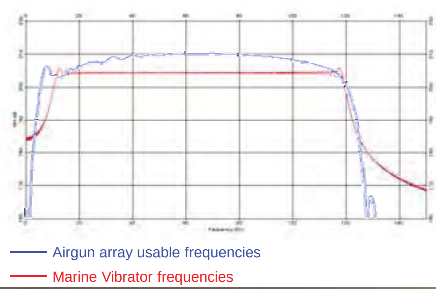
12 second Vibrator Sweep

10 to 120 Hz

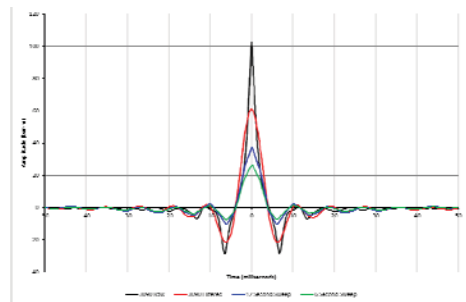


12 second Vibrator Sweep

10 to 120 Hz



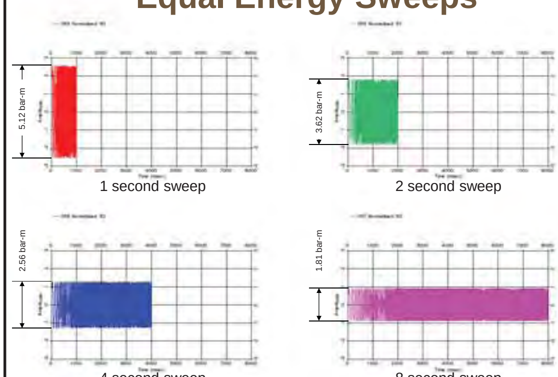
Zero Phase Equivalent Wavelets



Equal Energy Sweeps

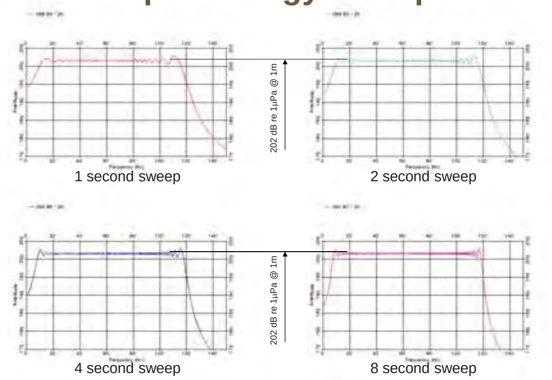
- By properly selecting the length and amplitude of a vibrator sweep we can tune the total energy output
  - Environmental factors
  - Operational factors

Equal Energy Sweeps



D90

Equal Energy Sweeps



The Geokinetics Marine Vibrator

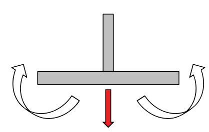
- A Collaborative project with PGS
- A significant design departure from previous marine vibrators
- Proof of concept demonstrated in 1999
- Design Specifications
  - Frequency Range 6 – 100 Hz
  - Output level ≈ 2 bar meters

The Geokinetics Marine Vibrator

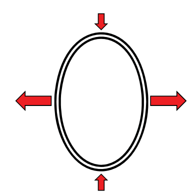
- Advantages:
  - Lower environmental impact
    - Lower amplitude levels
    - Capable of specialized "sweeps" using pseudo-noise technology
      - Emitted sound resembles noise from wave action
    - No in-water hydraulics
      - Total electrical system for drivers and controls
  - All other advantages associated with Vibroseis technology

How is it better?

- Efficient Flextensional shell design



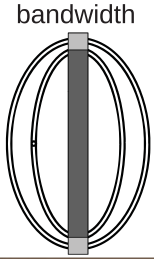
At low frequency, water flows around a moving piston

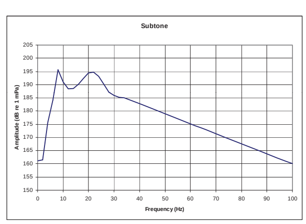


Flextensional shell minimizes water flow and maximizes pressure wave generation

How is it better?

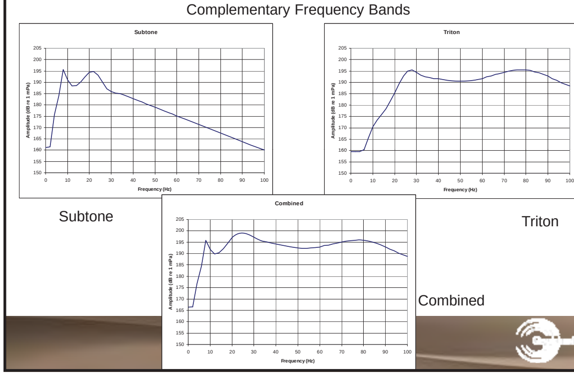
- Intentional resonances within seismic bandwidth





How is it better?

Complementary Frequency Bands



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Critical Questions

- Does it exist?
- Does it work?

Critical Questions

- Does it exist?

YES

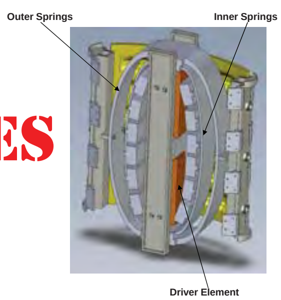
- Does it work?

Critical Questions

- Does it exist?

YES

- Does it work?



Marine Vibrator Timeline

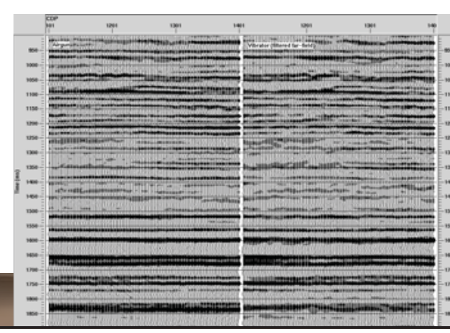
1994	1995	1996	1997	1998	1999	2000	2001		2007	2008	2009	2010	2011	2012	2013
Project Inception					POC Sea Trials			Hiatus	Commercialization Project			Geokinetics License	Calibration Tests		Sea Trials

POC Field Trials

- 2D Seismic Experiment - Gulf Of Mexico
  - shelf (Water Depth 30m)
- Streamer Cable
  - Receiver Spacing 12.5m
- Seismic Line shot twice
  - Airgun
    - 760 Cubic Inch
    - ~12 barm peak-peak
    - 3-93 Hz)
  - One Subtone and One Triton Marine Vibrator
    - 6.0 sec Linear Sweep
    - ~2 barm peak-peak
    - 3-93 Hz

Marine Vibrator vs. Airguns

Migrated sections (shallow) for airgun source (left) and vibrator source.
The section of the vibrator source is phase matched to the airgun data for comparison



Commercialization Project

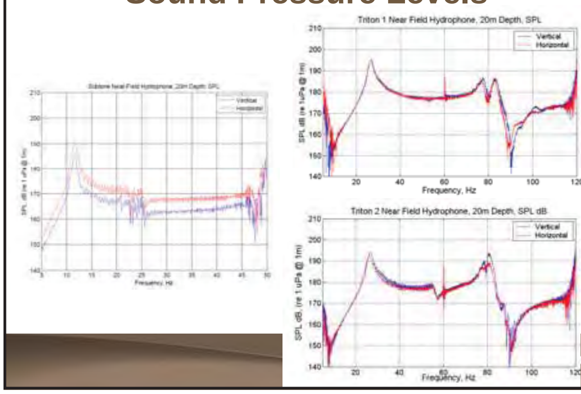
- Develop a more robust vibrator to withstand the rigors of seismic operations
  - Electromagnetic voice coils drivers replaced with more reliable drivers
  - Refinements of springs, cooling and pressure equalization systems
- Implement a feedback control system

Mean-time-between-failures measured in months, not hours

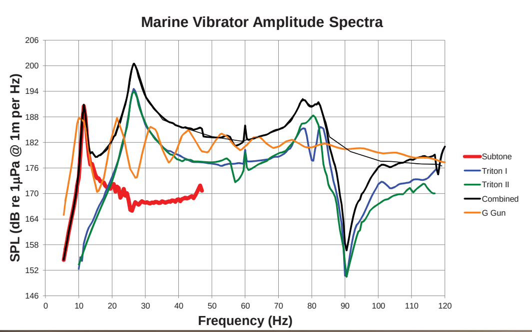
Commercialization Project

Calibration Tests 2011

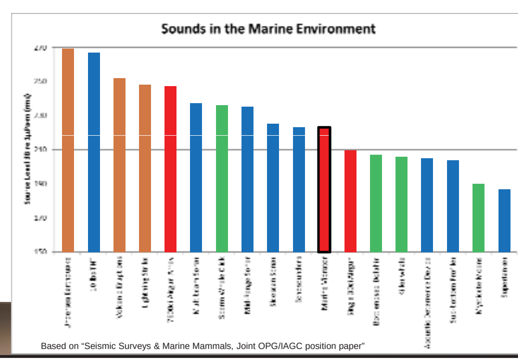
Sound Pressure Levels



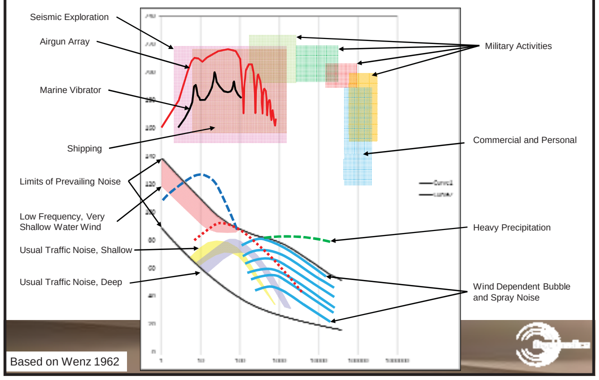
Calibration Test Results



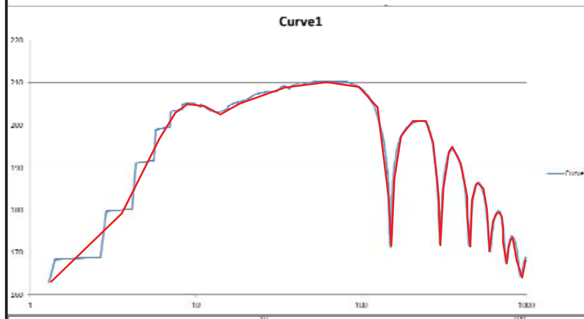
Sounds in the Marine Environment



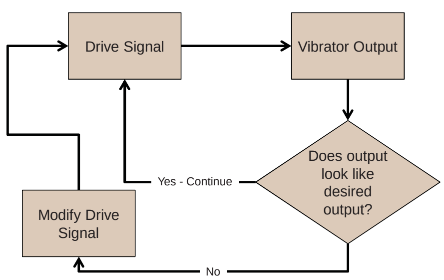
Anthropogenic Noise



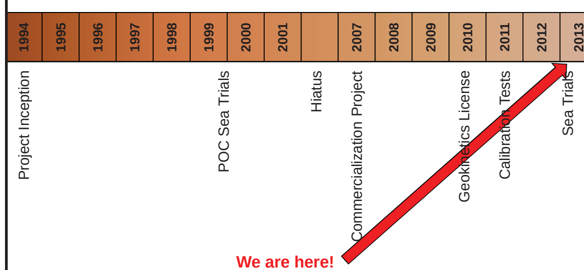
Based on Wenz 1962



Feedback Control System



Marine Vibrator Timeline



The Next Step

- In preparation for field trials
  - Data quality
  - "Fieldability"
  - Endurance
- Commercial Deployment

Outline

- What is Seismic Exploration
- Airguns: a Reference Point
- The Industry Motives for Marine Vibrators
- Comparing Airguns and Vibrators
  - Bandwidth
  - Sweep amplitude and length
- The Geokinetics Marine Vibrator
  - History
  - Description
  - Status
- **Summary**

Geokinetics Marine Vibrator
Summary

- The Marine Vibrator has demonstrated its ability to provide suitable energy for seismic data acquisition
- Commercialization project nearly complete
- Can provide all the same benefits of land Vibroseis data acquisition

Geokinetics Marine Vibrator
Summary

- Intuitively, the deployment of the Marine Vibrator is, environmentally, a step in the right direction
  - Our goal is to demonstrate this
- We believe that the Geokinetics Marine Vibrator can be commercially viable by year end

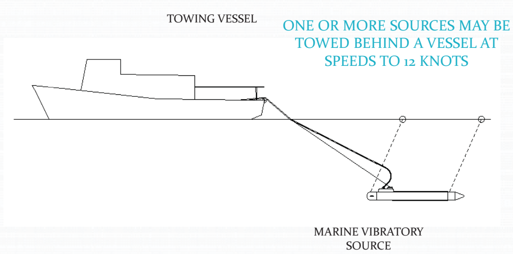
A Practical Marine Vibratory Sound Source

Stephen Chelminski
Chelminski Research
Antrim NH

Mission Statement:

- The design and development of a full size, working production prototype, Marine Vibratory Sound Source, based on the principles and design as set forth in my patent, US Patent No. 6,464,035 filed Oct 15, 2002 and pending US Patent and International Patent Applications.
- Proposed construction to be a modular, fully functional Marine Vibratory Sound Source, capable of working in and being tested in a marine environment. It will constitute of a combination of proof of concept and production prototype.

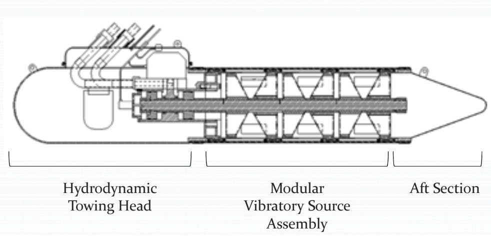
Operation: Marine Vibratory Sound Source



Operation

- Pressure balanced hydrodynamic system to provide a vibratory source which can be used at any water depth.
- Operational with pumped bio-hydraulic or sea water reducing environmental risk.
- Source units may be used for shallow water, transition zone, or stationary for water bottom surveys and may be dragged on the water bottom while operating.
- Multiple source units may be accurately synchronized when operated in water due to the uniform nature of the medium.

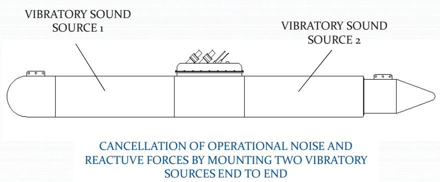
Marine Vibratory Sound Source



Operation

- A hydraulically powered actuator piston assembly vibrates a series of axially vibratable pistons affixed to the piston shaft.
- Each piston is placed along the shaft within a modular piston chamber that has an opposing stationary bulkhead
- As the vibratory pistons move back and forth with the shaft, water is pulsed between and out through ports of the piston chamber housings propagating waves out and around the marine vibratory system.

Operation: Tandem Marine Vibratory Sound Source



Acoustic Performance

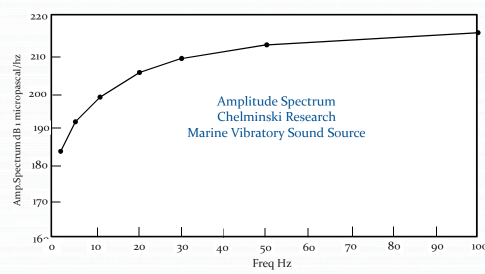
- The system will respond to hydraulic and signal input, whereby, the actuator module will drive the output piston assembly over a frequency range of 2 to 100 or more HZ.
- A high response servo valve is designed to open fully within the frequency range, but as with all servo valves at rated flow, it will have a pressure drop of approximately 1000 psi at rated flow and pressure.
- The Source as designed herein can input up to 200 GPM at 3000 psi, about 260 KW.

Acoustic Performance

- Frequency output response of the source will match the movement of the output piston assembly while the 8400 square inch (5.375 square meters) surface area of the elastomeric cylindrical diaphragm will help to evenly distribute the pressure pulses over the entire area.
- Based on a conservative value, a piston stroke of 0.25 inches at 20 Hz, the sound pressure level for a single radiating unit will produce a sound pressure level of 206 dB* referred to one micro Pascal at one meter.
- calculation: PAUL CHELMINSKI

*The calculation is based on an equation derived by HARDEE and HILL in an article in GEOPHYSICS, volume 48, No. 8.

Acoustic Performance



Engineering

- The construction of the source will be from high quality materials suited for the environment in which it will operate and engineered to be as robust as possible within its operational parameters. It is expected that service intervals will be after at least 1000 hours of operation.
- A significant portion of the engineering and design work has been completed.

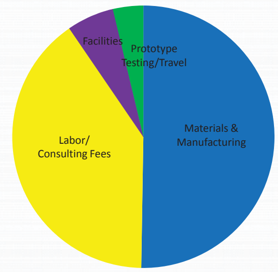
Engineering & Construction

- Major components must be custom forged or cast to specification with a lead time estimate of six to ten weeks.
- Target to start assembly is within twenty to thirty weeks after ordering materials.
- Initial low power testing will take place at the time of complete assembly at the assembly facility in New Hampshire.
  - The test will consist of filling the cylindrical diaphragm and piston chambers with fresh water and with the use of a small power supply, run the source at low power.
  - Additional testing will require the establishment of a test site either in a nearby lake or quarry or in the Atlantic Ocean off the New Hampshire coast.

Engineering & Construction

- After successful assembly and low-power testing in New Hampshire, the source unit will be trucked to an appropriate location for full power testing and subsequent field testing.
- Chelminski Research will be available to take part in rigging and testing operations.
- A hydraulic power supply and hoses, such as those used to power land vibrator units will be required, as well as a vibrator control unit, computer based monitoring equipment, and equipment capable of positioning the source at locations required for testing requirements.

Engineering & Construction



Marine Vibratory Sound Source

Cost % Estimates

Conclusion

- The Chelminski Research Marine Vibratory Sound Source addresses the issue of high frequency sound pollution:
  - The modular design provides for size and weight to be adjusted to adapt to survey requirements and be capable of routine use on a normal sized survey ship.
  - The Source is designed to be manageable to deploy and retrieve, possibly towable to 12 knots.
  - The Source functions within the window of sound energy and signal useful to exploration goals, designed to sweep from 2 to 100 Hz with a sound pressure level greater than 200 dB for a single unit, emitting pure frequency signals with no unintended spurious high frequencies.

Conclusion

- The power delivery system for the source can be either pumped bio-hydraulic fluid or pumped ambient sea water, with a diesel engine prime mover of up to 260 kw making the system safe and environmentally acceptable.
- The Source is almost fully engineered, manufacturing drawings partially finished and components specified. U.S. and International patents have been applied for.

Thank you

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VIBROSEIS

BOEM DEPT. OF ENERGY WORKSHOP

BOEM

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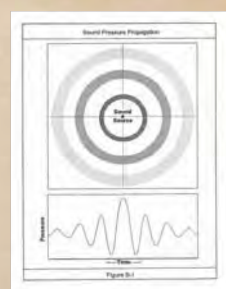
PAUL

- REVIEW OF UNDERWATER ACOUSTICS
- NOISE REDUCTION

- Sound is a wave of pressure variations propagating through a medium as shown
- Frequency (the number of cycles in a second) is expressed in Hertz
- Loudness (intensity) is expressed in decibels (dB)



- Noise Reduction is environmentally desirable in order to minimize biological risk for marine animal species
- Special sound signals have been used in acoustic barriers such as shown to prevent migrating salmon from entering turbines at Boneville Dam in Oregon

History and Past Projects

- The Use of high Explosive in Marine Seismic Surveys was nearly totally banned in the 1960's. The Conoco Oil Co. developed and patented a new technique commonly known as a vibrator energy source (Vibroseis)
- The use of large hydraulic vibrators on land surveys could not be duplicated in marine surveys; even in shallow transition zones

- New underwater speakers activated by hydraulic or electro dynamic energy were developed.
- Their ability to provide controlled signals in the frequency necessary for penetration of the ocean bottom made them superior to impact explosive sources.
- These speakers provide sound in the 5-200 Hz frequency, in contrast to the band width of explosive sources having 5-50,000 Hz

Typical Projectors

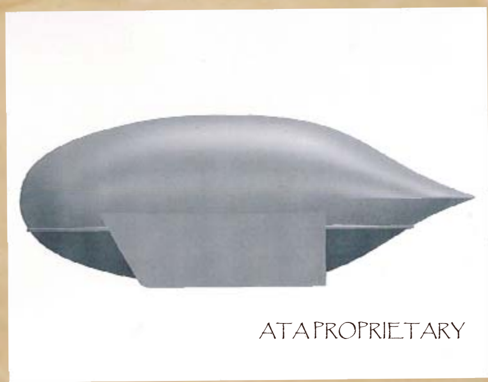
Survey on a lake in southern Texas for Mobile Oil in 1993. Similar equipment used for Texaco in Louisiana.

- All underwater sound has some effect on marine animals. Many of the animals of concern are only affected by medium to high frequency sound (above 500 Hz)
- Compared to impact sources the controlled signals from vibroseis units affect a fewer number of species. Extensive studies continue with a goal of better defining the situation.

- Vibroseis equipment and present development
- The required level of loudness (amplitude) for marine survey vibrators presents a challenge for piston type equipment.
- To achieve 200-205 dB in the frequency band of 5-200 Hz would require a large number of presently available piston units. This source level requires moving very substantial amounts of water. Hence the need for multiple units with large diameter pistons and consequently overall handling difficulty.

- Presently in development is a new concept of low frequency projection.
- A single unit can meet a source level of 5-205 dB in the band width of 5-200 Hz.
- The technology in the shown unit is covered by patent application.
- Complete equipment is expected to be available to seismic operators in the coming year.

new development equipment



- VIBROSEIS REPLACING AIR GUNS
  - The equipment presently under development will provide simpler operating procedures compared to air guns. Minimal maintenance is anticipated. The need for the high pressure compressors will be eliminated.
  - A complete installation using the new equipment is estimated to total approximately 35% of the cost of a complete air gun installation.
  - Increased regulatory requirements will favor this equipment application compared to the unacceptable damage from exposing marine animals to air gun array sounds.

- OPTIONS FOR THE FUTURE
  - Seismic survey operators will ultimately be facing regulations eliminating the use of air guns. As an option becomes available to them they will take that road.

Underwater noise abatement using large encapsulated air bubbles and its applications

Mark S. Wochner, PhD
CEO & Co-Founder

Underwater noise abatement using large encapsulated air bubbles and its applications

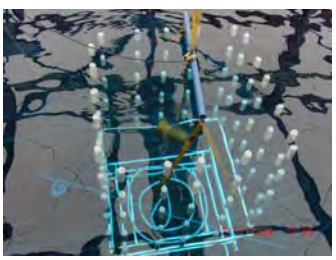
Acknowledgements:
Preston Wilson – *Primary Investigator, University of Texas*
Kevin Lee – *Research Associate, ARL:UT*
Andrew McNeese – *Mechanical Engineer, ARL:UT*

Students:
Ted Argo, Craig Dolder, Greg Enenstein, Kevin Hinojosa, Adrienne McCarty, Kyle Spratt, Laura Tseng

Funding Sources (past and present):

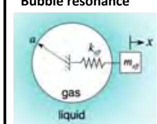
Outline

- Our theoretical work on encapsulated bubbles
- Measurements of encapsulated bubble attenuation on continuous sources and comparison with predictive models
- Examples of underwater noise reduction on impulsive sources



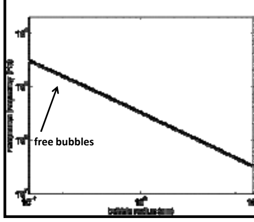
Bubble resonance and attenuation

Bubble resonance

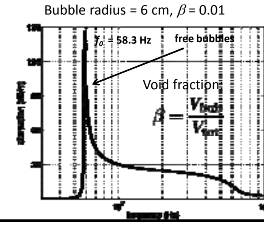


Bubbles behave like mass-spring systems
- larger bubbles → lower resonance frequency
- energy from the acoustic wave goes into resonating the bubble

(Commander & Prosperetti, JASA **85**, 732-746 (1989))



Monodisperse distribution of bubbles:
Bubble radius = 6 cm, β = 0.01



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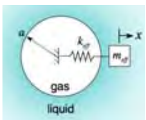
Bubble resonance



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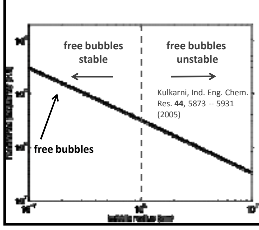
Large free bubbles are unstable

(Commander & Prosperetti, JASA **85**, 732-746 (1989))



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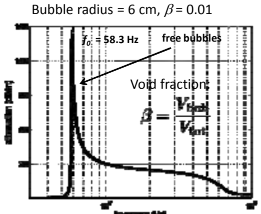

Bubble resonance and attenuation

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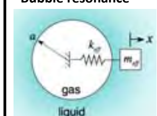

Bubbles behave like mass-spring systems
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Large free bubbles are unstable

Small bubbles don't resonate at desired frequencies (≤ 300Hz)

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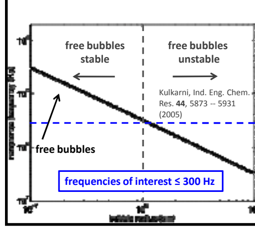

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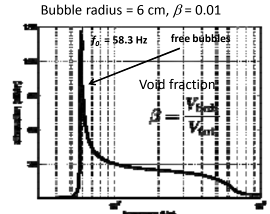
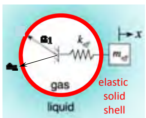


Bubble resonance and attenuation

Bubble resonance



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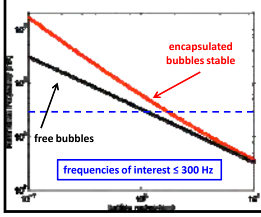


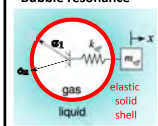
Encapsulated bubbles

Advantages:
- Predetermined volume of enclosed air
- Customizable resonance frequency
- Stationary array in predetermined position around noise source

Caveats:
- Shell must allow for resonant motion of encapsulated air volume
- Shell must be robust enough for deployment

Bubble resonance and attenuation

Bubble resonance



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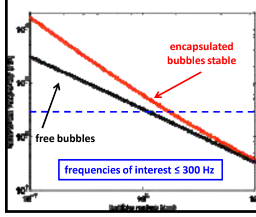
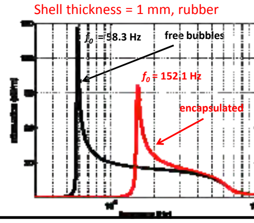


Monodisperse distribution of bubbles:
Bubble radius = 6 cm, β = 0.01,
Shell thickness = 1 mm, rubber



Small, freely-rising bubbles – high frequency (3 kHz – 5 kHz)

bubble radius ≤ 0.25 cm → bubble resonance frequency ≥ 1 kHz

Small, freely-rising bubbles – low frequency (50 Hz – 300 Hz)

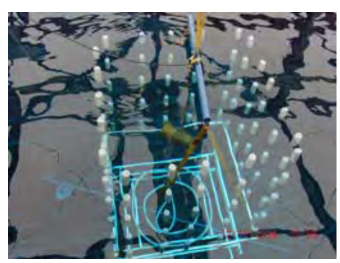
bubble radius ≤ 0.25 cm → bubble resonance frequency ≥ 1 kHz

Large encapsulated bubbles – low frequency (50 Hz – 300 Hz)

bubble radius = 3 cm → bubble resonance frequency = 100 Hz

Outline

- Our theoretical work on encapsulated bubbles
- Measurements of encapsulated bubble attenuation on continuous sources and comparison with predictive models
- Examples of underwater noise reduction on impulsive sources



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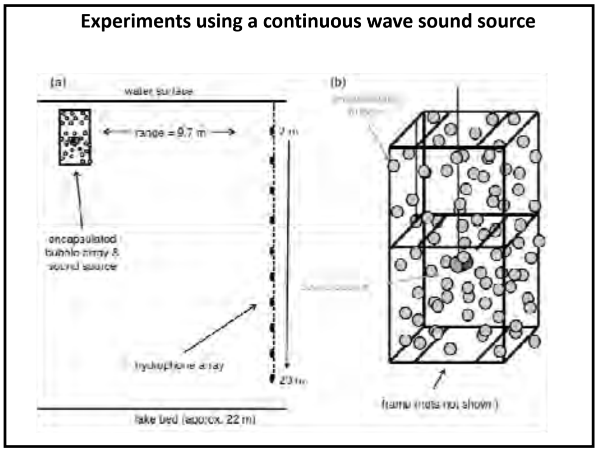
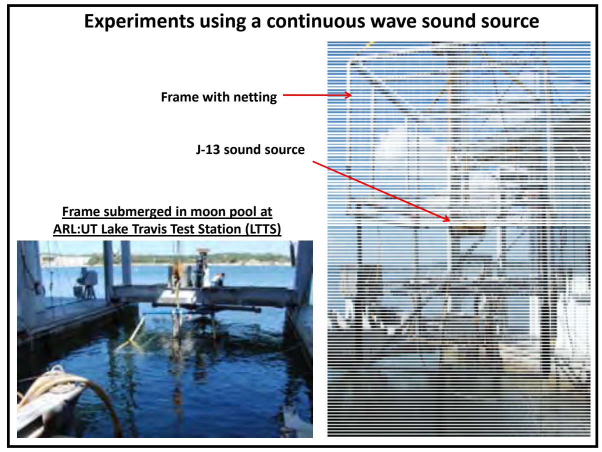
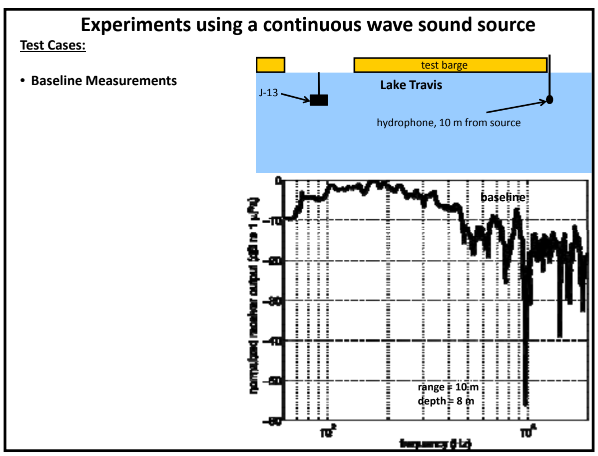
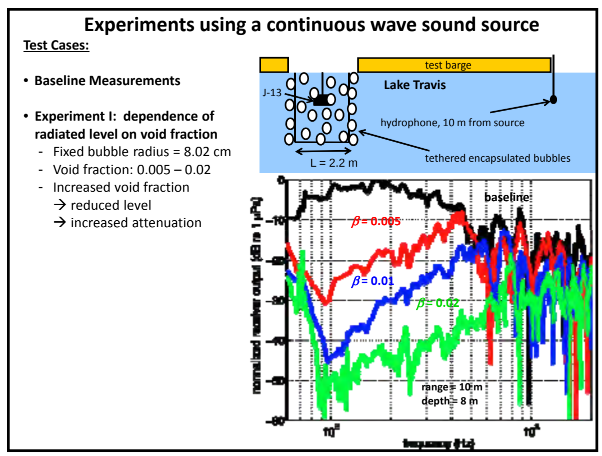
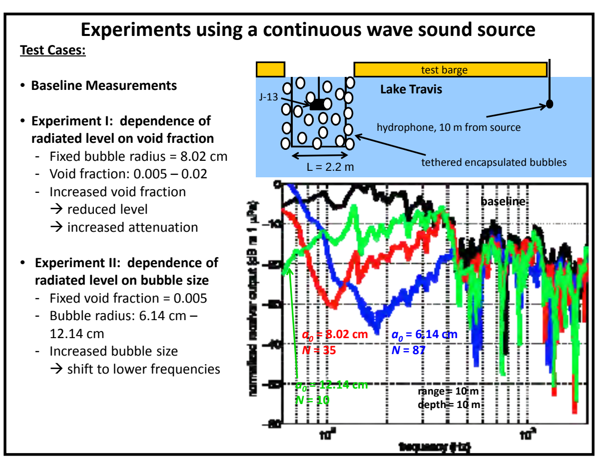

Experiments using a continuous wave sound source
(a)
water surface
range = 9.7 m
2 m
encapsulated bubble array & sound source
hydrophone array
23 m
lake bed (approx. 22 m)
(b)
frame (nets not shown)


Experiments using a continuous wave sound source
Frame with netting
J-13 sound source
Frame submerged in moon pool at
ARL:UT Lake Travis Test Station (LTTS)


Experiments using a continuous wave sound source
Test Cases:
• Baseline Measurements
test barge
J-13
Lake Travis
hydrophone, 10 m from source
baseline
range = 10 m
depth = 8 m
normalized receiver output (dB re 1 μPa)
frequency (Hz)


Experiments using a continuous wave sound source
Test Cases:
• Baseline Measurements
• Experiment I: dependence of radiated level on void fraction
- Fixed bubble radius = 8.02 cm
- Void fraction: 0.005 – 0.02
- Increased void fraction
→ reduced level
→ increased attenuation
test barge
J-13
Lake Travis
hydrophone, 10 m from source
L = 2.2 m
tethered encapsulated bubbles
baseline
β = 0.005
β = 0.01
β = 0.02
range = 10 m
depth = 8 m
normalized receiver output (dB re 1 μPa)
frequency (Hz)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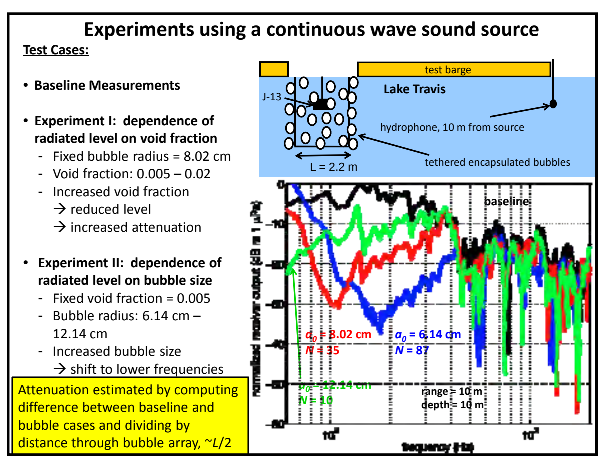
• Experiment II: dependence of radiated level on bubble size
- Fixed void fraction = 0.005
- Bubble radius: 6.14 cm – 12.14 cm
- Increased bubble size
→ shift to lower frequencies
test barge
J-13
Lake Travis
hydrophone, 10 m from source
L = 2.2 m
tethered encapsulated bubbles
baseline
a0 = 8.02 cm
N = 35
a0 = 6.14 cm
N = 87
a0 = 12.14 cm
N = 10
range = 10 m
depth = 10 m
normalized receiver output (dB re 1 μPa)
frequency (Hz)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Attenuation estimated by computing difference between baseline and bubble cases and dividing by distance through bubble array, ~L/2
test barge
J-13
Lake Travis
hydrophone, 10 m from source
L = 2.2 m
tethered encapsulated bubbles
baseline
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frequency (Hz)

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Effective medium models for sound propagation in bubbly liquids

Non-encapsulated bubble models:

Commander & Prosperetti (CP) (1989):
JASA **89**, 732-746 (1989).

$$k_m^2 = k^2 + 4\pi\omega^2 \int \frac{f(a)ada}{\omega_0^2 - \omega^2 + 2i\omega b}$$

Total damping: $b = b_{v_\ell} + b_t + b_a$ $\quad b_a \sim \omega k a$

viscous thermal radiation

Effective medium models for sound propagation in bubbly liquids

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$$k_m^2 = k^2 + 4\pi\omega^2 \int \frac{f(a)ada}{\omega_0^2 - \omega^2 + 2i\omega b_m}$$

Total damping: $b = b_{v_\ell} + b_t + b_{am}$ $\quad b_{am} \sim \omega k_m a$

viscous thermal radiation

Kargl's model is a modification of CP that takes multiple scattering into account by replacing

$c \rightarrow c_m \quad \rho \rightarrow \rho_m \quad \mu \rightarrow \mu_m$

The changes to density and viscosity are relatively small for void fraction ~ 1% → primary effect is through effective medium wavenumber in radiation damping term : $k \rightarrow k_m$

Effective medium models for sound propagation in bubbly liquids

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Encapsulated bubble models:

Church (1995):
JASA **97**, 1510-1521 (1995).

$$k_m^2 = k^2 + \frac{4\pi\omega^2\rho_\ell}{\alpha\rho_s}\int_0^\infty \frac{a_1 f(a_1)da_1}{\omega_0^2 - \omega^2 + 2i\omega b}$$

Total damping: $b = b_{v,s} + b_{v,\ell} + b_t + b_a$

shell viscous thermal radiation

Effective medium models for sound propagation in bubbly liquids

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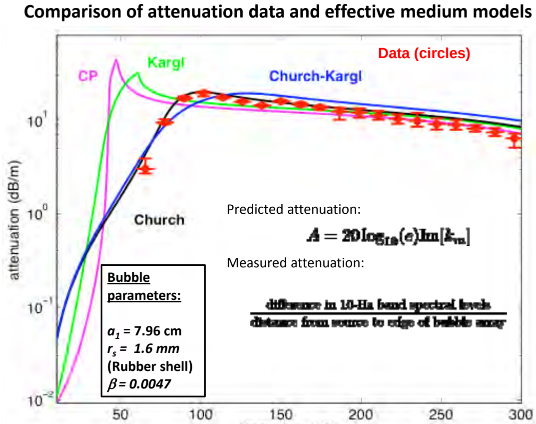
Church-Kargl (2012):
(Not yet published)

$$k_m^2 = k^2 + \frac{4\pi\omega^2\rho_\ell}{\alpha\rho_s}\int_0^\infty \frac{a_1 f(a_1)da_1}{\omega_0^2 - \omega^2 + 2i\omega b_m}$$

Comparison of attenuation data and effective medium models



Predicted attenuation:

$$A = 20\log_{10}(e)\mathrm{Im}[k_m]$$

Measured attenuation:

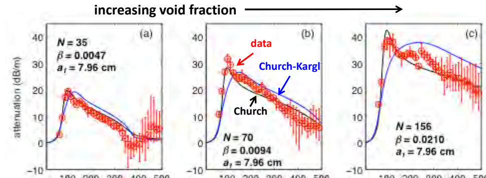
$$\frac{\text{difference in 10-Hz band spectral levels}}{\text{distance from source to edge of bubble array}}$$

Bubble parameters:

a_1 = 7.96 cm
r_s = 1.6 mm
(Rubber shell)
β = 0.0047

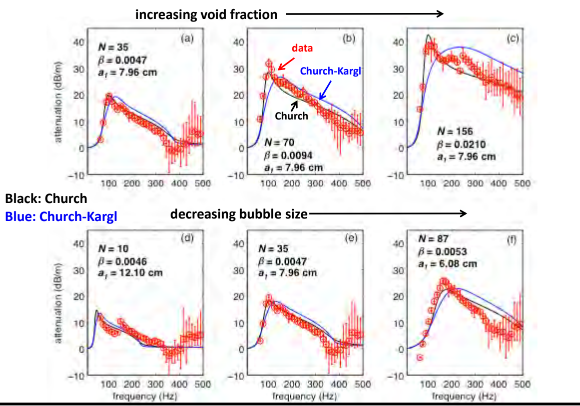
Comparison of attenuation data and effective medium models

increasing void fraction →



Black: Church
Blue: Church-Kargl

Comparison of attenuation data and effective medium models



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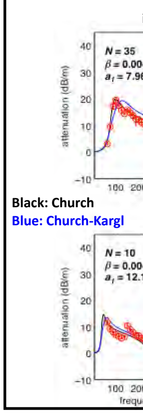

Void fractions used here are typical (~1%) of noise abatement systems – rel. large VF → multiple scattering effects significant

Church-Kargl as implemented may overestimate multiple scattering – under-predicts data by 20% or more near resonance

Church's model better predicts measured attenuation values values – agreement within 5-6% near resonance

The main point: Effective medium models quick and easy to compute – very useful for system design in noise abatement applications

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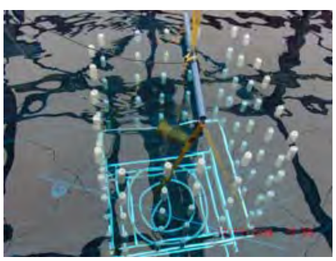


Impulsive noise sources

- Pile driving for marine construction projects – bridges, piers, offshore wind turbines, etc
- Seismic surveys using air gun arrays
- Underwater explosions: Demolition projects, munitions testing

Pile driving

Underwater explosions

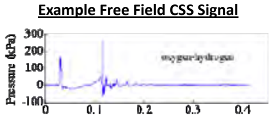
Seismic air gun array surveys

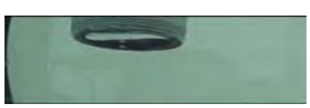
Offshore wind construction

Model impulsive noise source

Combustive Sound Source (CSS):
- Inverted cup with H_2-O_2 mixture
- Ignited by electrical spark → bubble expansion and collapse
- Peak sound pressure level measured ≈ 193 dB re 1 μPa

Example Free Field CSS Signal





Video courtesy of Andrew McNeese, ARL:UT

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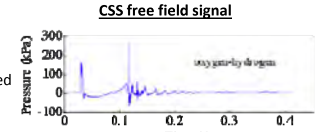
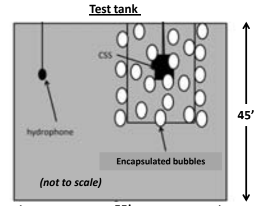
CSS free field signal



Large wooden test tank experiments:
- CSS source level exceeds allowable limits for Lake Travis, TX
- Diameter = 16.8 m, Depth = 12.2 m
- Same encapsulated bubble arrays used from 2010 lake experiments with J-13 source

Test tank



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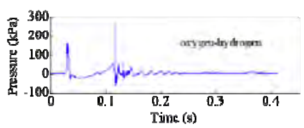
CSS free field signal



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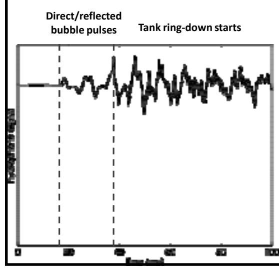
Level reduction with impulsive noise source

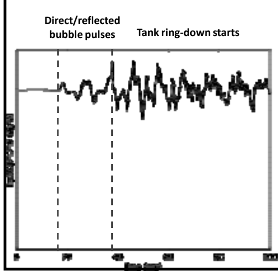
Acoustic signals:
• Direct bubble pulse followed by reflections from surfaces ≈ 25 ms
• Tank resonances are briefly excited and "ring down" ≈ 500 ms

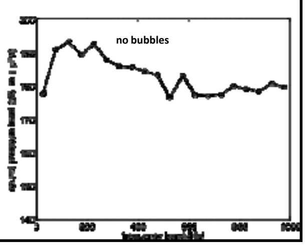


Level reduction with impulsive noise source

Acoustic signals:
• Direct bubble pulse followed by reflections from surfaces ≈ 25 ms
• Tank resonances are briefly excited and "ring down" ≈ 500 ms

50-Hz band level comparison:
• 50-Hz band digital filter bank
• RMS band levels computed for each band over duration of pulse





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• 50-Hz band digital filter bank
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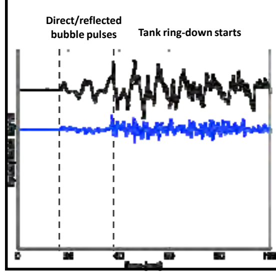

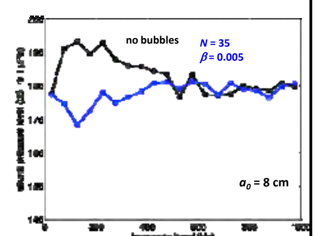

Level reduction with impulsive noise source

Acoustic signals:
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• 50-Hz band digital filter bank
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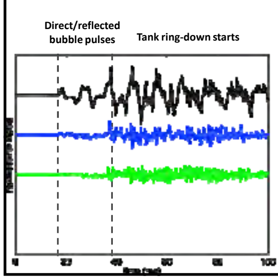
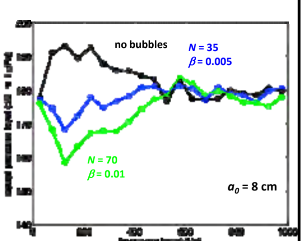


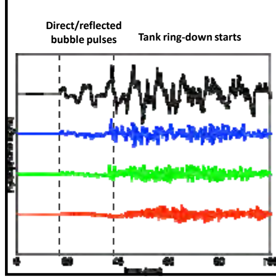


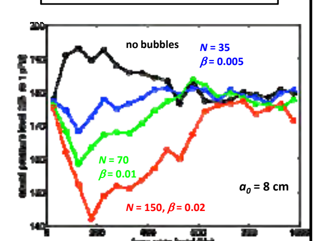
Level reduction with impulsive noise source

Acoustic signals:
• Direct bubble pulse followed by reflections from surfaces ≈ 25 ms
• Tank resonances are briefly excited and "ring down" ≈ 500 ms

50-Hz band level comparison:
• 50-Hz band digital filter bank
• RMS band levels computed for each band over duration of pulse

Attenuation increases with void fraction like CW experiments
- Peak level reduction = 47.5 dB @ 150 Hz – 200 Hz band





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Conclusions

- Large air cavities with elastic shells resonate acoustically like bubbles as long as their shells are sufficiently compliant
- Effective medium models are useful tools for noise abatement system design
  - Church's model for encapsulated bubbles seems most appropriate
- Various configurations of encapsulated bubble screens were experimentally shown to attenuate low-frequency underwater sound in a controllable manner
- Current work includes full-scale demonstrations of our system on pile driving and ship-borne noise

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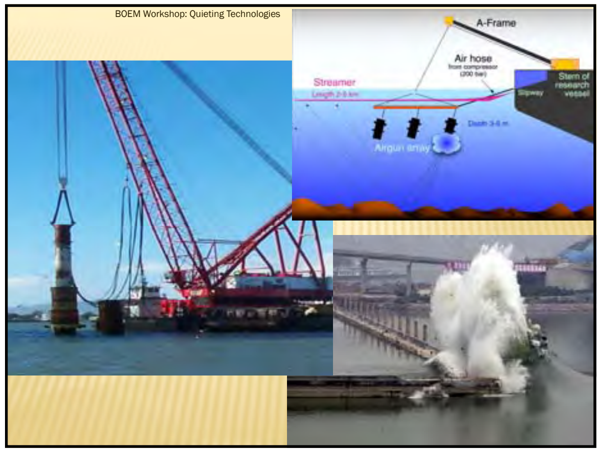
HOW QUIET IS QUIET?

Michele B. Halvorsen

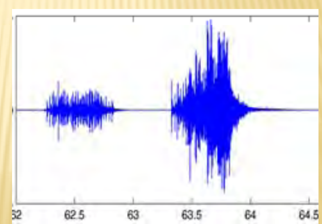
Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving Workshop

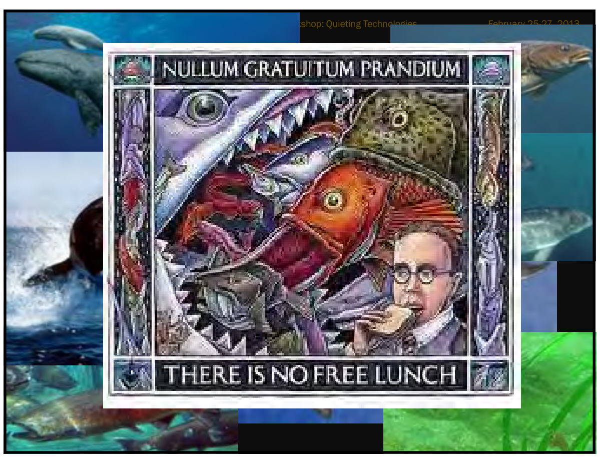


UNDERWATER NOISE

- Energy development in marine environments
  - Installation
  - Decommissioning
  - Exploration

IMPULSIVE SOUND SIGNALS





UNDERWATER NOISE

- Energy development in marine environments
  - Installation
  - Decommissioning
  - Exploring
- Concern for aquatic animals
  - Behavioral responses
  - Onset of effects
    - Barotrauma
    - Auditory - TTS

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CURRENT REGULATIONS

Fish

Effect	Metric	Fish mass	Threshold
Onset of physical injury	Peak pressure	N/A	206 dB re 1 μPa
	Accumulated Sound Exposure Level (SEL)	≥ 2 g	187 dB re 1 $\mu Pa^2 \cdot sec$
		< 2 g	183 dB re 1 $\mu Pa^2 \cdot sec$
Adverse behavioral effects	Root Mean Square Pressure (RMS)	N/A	150 dB re 1 μPa RMS

Marine Mammals

Effect	Metric	Threshold
Level B (disturbance)	Impulsive	160 dB re1 μPa RMS
	continuous	120 dB re1 μPa RMS
Level A (injury)	Root Mean Square Pressure (RMS)	180 dB re1 μPa RMS

UNDERWATER NOISE COMPONENTS

- Sound energy can cause damage
  - Frequency (fast rise time)
  - Intensity
  - Spectrum
- Two components of any sound wave
  - Pressure
  - Particle motion
- Near field (pressure & particle motion)
- Far field (mostly pressure, but some motion)

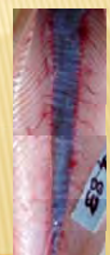
NOISE EFFECTS - BAROTRAUMA

Barotrauma is…
tissue injury caused by rapid pressure changes

- Sources:
  - Impulsive sound signals
    - Explosives
    - Pile driving
    - Air guns
  - Rapid decompression

NOISE EFFECTS - BAROTRAUMA

- Contraction and expansion of free gas in body
  - Swim bladder
    - Rupture
    - Damage surrounding tissues
- Change in state of gas
  - Natural blood-gases
    - Gas comes out of solution
      - Bubbles form in blood and tissues
        - Damage



- Physiological state of fish at exposure is critical
  - Neutrally buoyant fish
  - Tissue-gas equilibration with surrounding water

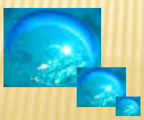
WHAT HAPPENS AT DEPTH?

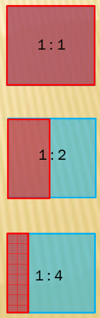
DEPTH PRESSURES

Depth (meters)	Atmospheres	Pascal
0	1	100 k
10	2	200 k
20	3	300 k
30	4	400 k

DEPTH PRESSURES

Depth (meters)	Atm	Impulsive signal (Pa)	Acclimation pressure (Pa)	Ratio	Injury risk
0	1	100 k	100 k	1 : 1	High - Mod
10	2	100 k	200 k	1 : 2	Low?
20	3	100 k	300 k	1 : 3	
30	4	100 k	400 k	1 : 4	unlikely





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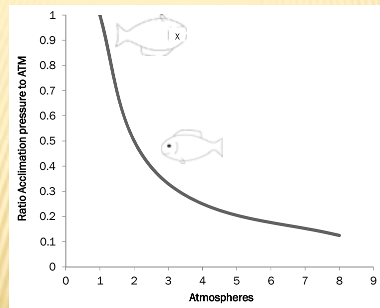
DEPTH PRESSURES



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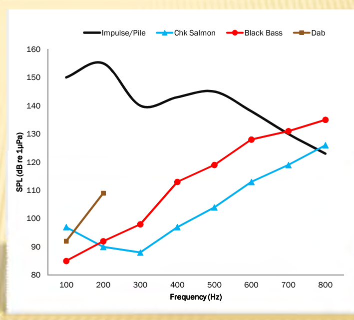
UNDERWATER NOISE EFFECTS - AUDITORY



Salmon: Halvorsen et.al., 2009; Bass: Holt et.al., 2010; Dab: Chapman & Sand 1973; Karl von Frisch- ear

SUMMARY

- At depths,
  - Ratio of received level vs acclimation pressure decreases
  - Gradient falls off faster than propagation loss
  - Auditory system is independent of depth
  - Depth component needs investigation
- Are criteria for quiet or for received level?
  - RL depends on where animal is located
  - Depends on where quiet occurs in space

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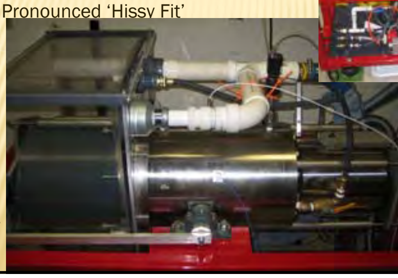
HICI-FT

- Expose fish to impulsive sounds
  - Sound Exposure Level
- Barotrauma injury assessment
- HICI-FT

Pronounced 'Hissy Fit'

Fish loading



Exposure

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Current and New Methods in Pile Driving Noise Sound Attenuation

Per Reinhall, Peter Dahl, Tim Dardis
University of Washington
Seattle, USA

BOEM Workshop February 25 -27
Washington DC

MECHANICAL ENGINEERING

Applied Physics Laboratory
University of Washington

Overview

- Review: Impact driving of a pile without sound attenuation
  - Modeling & measurements
- Impact driving with a double wall steel shield:
- Vibratory driving
- Lessons learned
- Higher performance sound attenuation
- Conclusions

Can noise from pile driving be effectively reduced by surrounding the pile with a sound shield in the water?

Injury and Disturbance Thresholds for Marine Construction Activity

Functional Hearing Group	Underwater Noise Thresholds: Vibratory Pile Driving Disturbance Threshold	Impact Pile Driving Disturbance Threshold	Injury Threshold
Cetaceans	120 dB RMS	160 dB RMS	180 dB RMS****
Pinnipeds	120 dB RMS	160 dB RMS	190 dB RMS****
Fish ≥ 2 grams			187 dB Cumulative SEL★
Fish < 2 grams		Behavior effects threshold 150 dB RMS***	183 dB Cumulative SEL★
Fish all sizes			Peak 206 dB
Foraging Marbled Murrelets		150dB RMS*	202dB SEL

*USFWS considers these to be effects analysis guidelines, not threshold criteria for foraging murrelets. Other factors (e.g., duration) are important to consider when determining whether exposure in these zones will result in adverse effects.

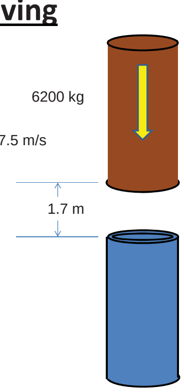
*** Hastings 2002, as cited

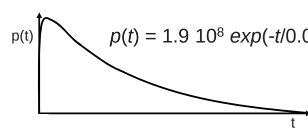
RMS - Root-mean-square: For pile driving, this is the square root of the mean square of a single pile driving

**** Source: Southal et al. 2007; 71 FR 3260 Jan. 20, 2006

★Source: Memorandum on the Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities (available: http://www.wsdot.wa.gov/Environment/Biology/BA#Noise)

Impact pile driving





$p(t) = 1.9\ 10^8\ exp(-t/0.004)$

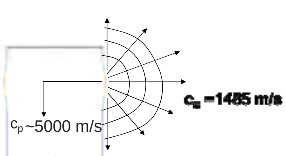
Max pressure = 190Mpa = 27.5ksi

Yield Strength (A36 Steel) = 250Mpa = 36ksi

Mechanism for sound generation during impact driving

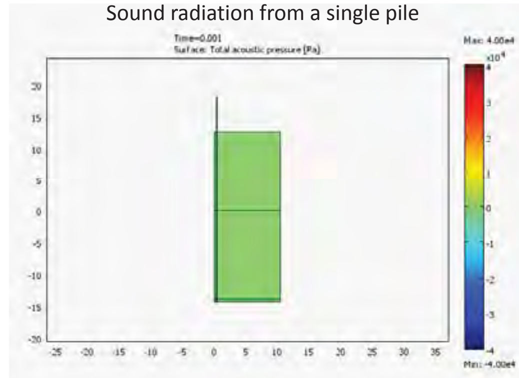
"Poisson's ratio effect" → Local radial swelling

This radial expansion propagates down the pile with high speed. The moving bulge disturbs the water as it propagates down the pile

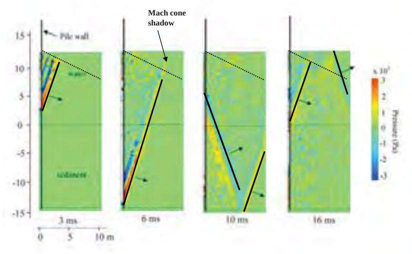


MECHANICAL ENGINEERING

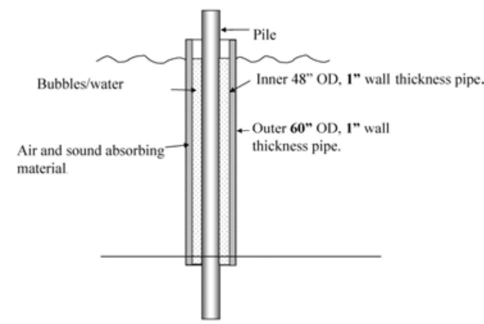
Sound radiation from a single pile



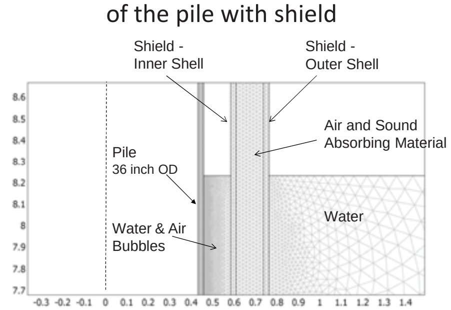
Four snapshots after impact

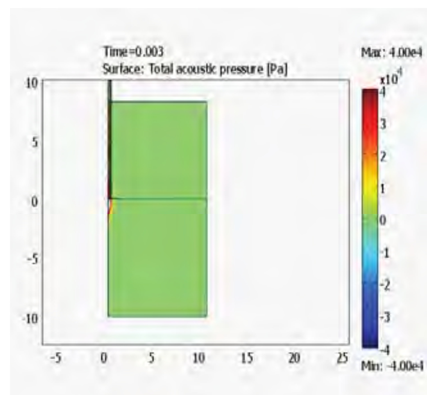


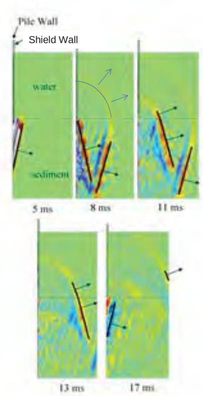
Pile Driving with a Sound Shield



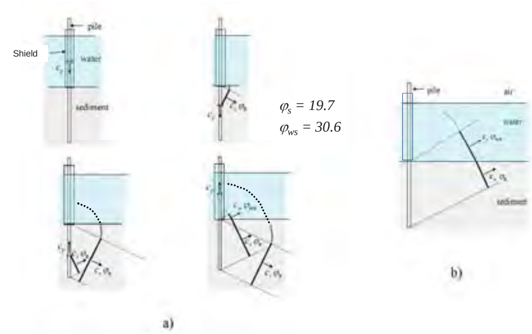
A full coupled fluid/structure interaction model of the pile with shield



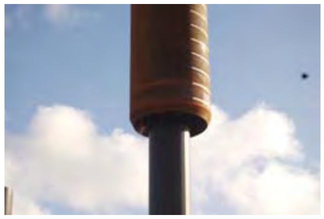




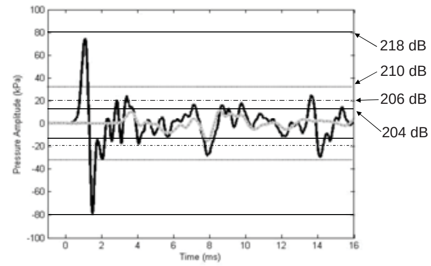
Simulation Results



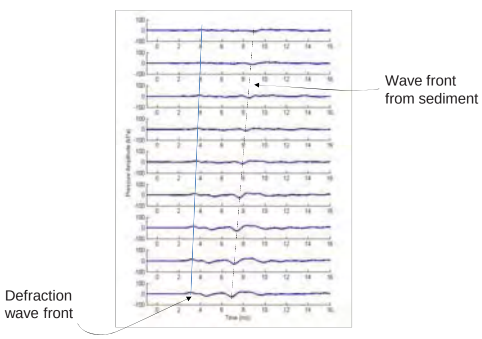
Sound shield testing



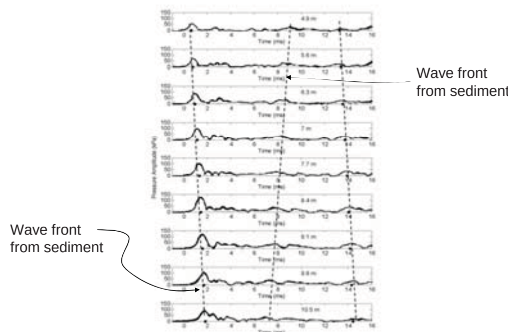
With and Without Shield



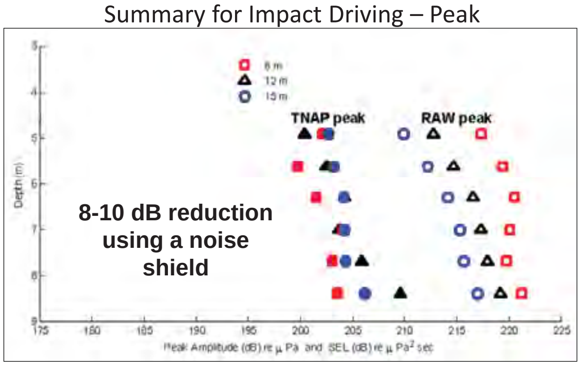
All hydrophones – w. Shield



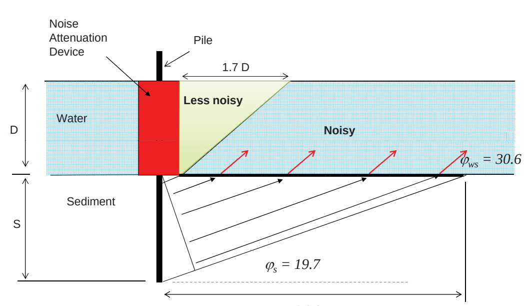
All hydrophones – w/o Shield



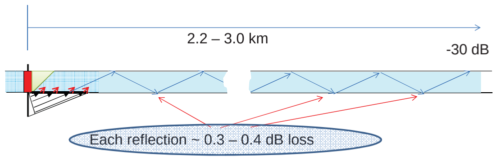
Summary for Impact Driving – Peak



The problem



The problem

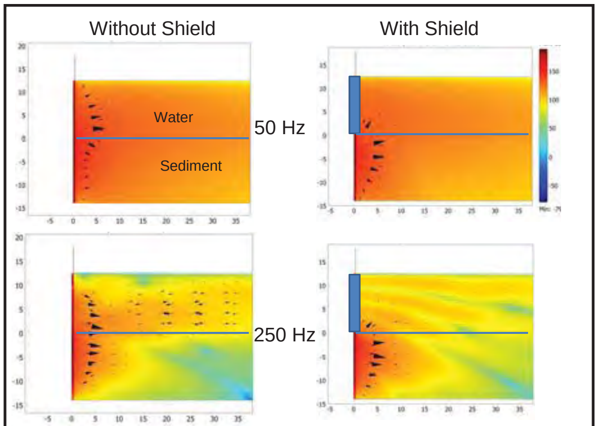


For example, a 30 dB relative noise reduction in constant water depth of 20 meters requires a distance of 2.2 – 3.0 km.

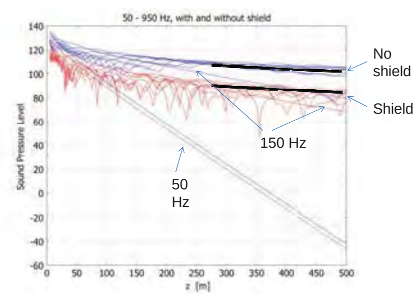
This distance can be much larger for bathymetries that cause the reflection angle to be less than the critical angle.

Vibratory Driving

- No impact
- Steady state sinusoidal excitation
- Less noisy but still loud
- Frequency < 1000Hz



Sound pressure as function of range – With and without shield



What have we learned?

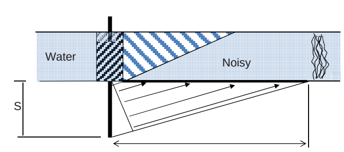
- A sound attenuation treatment that surrounds the pile in the water cannot prevent radiation of significant noise from the sediment.
- Impact driving: The double wall shield decreases the peak pressure with ~8 - 10dB at a range of 10 m. (field test)
- Vibratory driving: A (perfect) shield decreases the peak pressure with ~ 10dB. (preliminary analysis)

So *what can be done for higher performance*?

WIDE Bubble Curtain

Performance depends on:

- Bubble curtain parameters
- Sediment type



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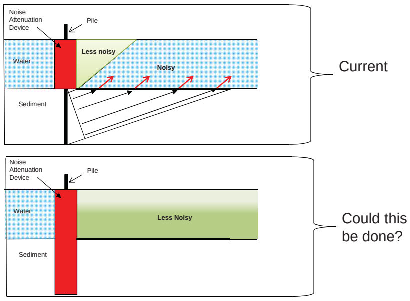
So *what can be done for higher performance*?

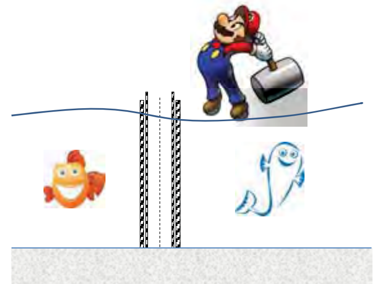
Need a protective shield along the entire length of the pile to prevent acoustic energy from spreading into the water.



Possible solutions

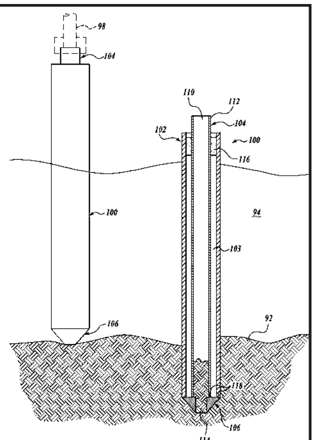
Double wall pile

The pile driving hammer strikes the inner pipe only.
The inner pipe is free to expand without interacting with the water. The outside pipe is the structural pile.



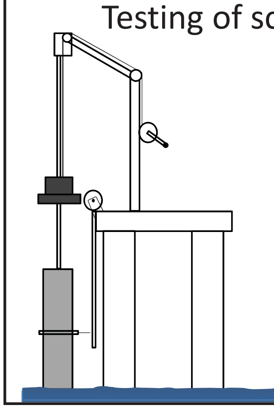
Double Pile

- Traditional Pile driving hammer used (98)
- Outer Pile (102) serves as noise shield and as primary load path for construction
- Inner Pile (104) serves to transfer the load from the hammer to the pile driving shoe (106)
- Acoustic coupling between the inner pile and the water is prevented by the outer pile and a annular air gap between piles (103)

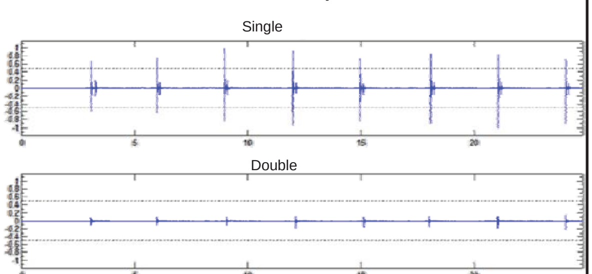


Ref: USPO EP2526231 A2

Testing of scaled prototype

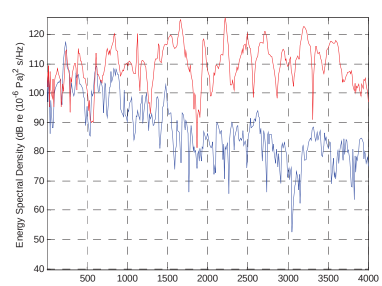


Double pile

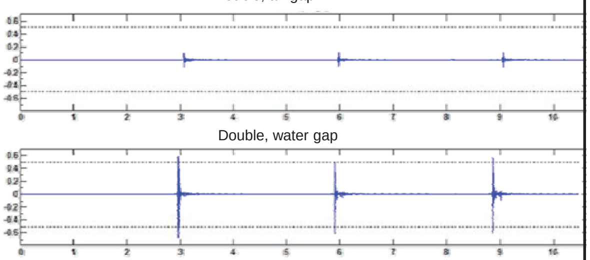


Peak sound reduction > 20dB @ 5m range

Single vs. Double



Air vs. Water in Gap



Double pile - attributes

- Traditional pile driving equipment and methods are maintained
- Significant lower noise levels achieved
- Future developments
  – utilization of a removable mandrel to
    - Improve driving efficiency as well as directional stability
    - Lower recurring material costs

Another possible route to less noise

Minimization of Poisson's ratio reduces the radial expansion of the pile wall thus decreasing noise generation

Conclusions

- A sound attenuation treatment that surrounds the pile in the water cannot prevent radiation of significant noise from the sediment.
- Impact driving: The double wall shield decreases the peak pressure with ~ 8 dB at 10m range.
- Vibratory driving: A (perfect) shield decreases the peak pressure with ~ 10dB.
- Double wall pile: > 20dB attenuation is predicted from 6" prototype pile testing.

Acknowledgment
This work was supported by the Washington State Department of Transportation and Federal Highway Administration

Alternatives and Mitigation of Support Ship Noise

Support ships

What are support ships needed for?

- Towing airgun arrays
- Driving piles
- Install foundations and platform top sides
- Supply material
- Towing barges and installation vessels
- Transfer personnel

Service Vessels: Difference to „normal“ ships

Merchant vessels	Offshore service vessels
Large displacement 10,000 to 100,000+ t	Small displacement 2,000 to 10,000 t
Speed 13 to 25 knots	Speed 0 to 15 knots
Single screw diesel mechanical propulsion	Twin screw diesel electric propulsion except tugs
Designed for service speed	Designed for several modes
1,000 to 90,000 hp propulsion power	1,000 to 10,000 hp propulsion power

Operating modes and noise sources

Service ships have 3 main operation modes:

- transit
- towing
- 0 speed dynamic positioning (DP)

Noise sources are

- Propeller cavitation
- Diesel engine noise
- During DP high power (→ noise output) variations
- Note: DP noise can be considerably higher level than transit
- Propulsor noise is also a problem for onboard habitability → IMO acts

The dominating problem

Almost all ships use screw propellers to generate thrust

- The unusual operating condition compared to normal ships: generate high thrust at close to zero speed → so-called bollard pull condition
- For double function transit propulsion and DP, or transit and towing → design compromise on propeller
- Main noise but not only generating mechanism: suction side sheet cavitation
- Machinery: Diesel generators are resiliently mounted, improvement necessity to be investigated
- Lack of knowledge of source level minimization in industry

Wind farm installation

Jack up ship

L 100 -150 m

Diesel electric

Twin screw podded

D118

Airgun towing

Ramform hull (PGS)

L 100 m

Installed power 4000 kW diesel electric

Triple screw CPP with nozzles

Offshore Service Vessel

Conventional hull

L 50 – 150 m

Diesel electric propulsion

Azimuth twin propulsion, tunnel thrusters, (retractable) azimuth thrusters

Great variation in design and function, geared and ungeared

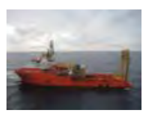
Tugs

L 50 – 100 m

Diesel mechanical propulsion

Single or twin screw, nozzle

Great variation in design and function,



Wikipedia

Multi purpose vessels

L 50 – 100 m

Diesel electric propulsion

Single or twin screw, mostly pods

Great variations in design and function,

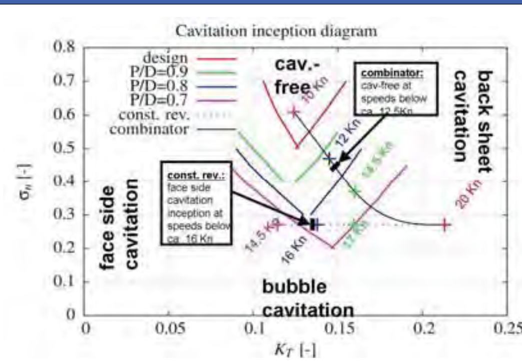
Controllable pitch propellers

- A screw propeller with adjustable blades
- Used primarily to allow constant shaft speed → operation of power-take-off
- Allows more flexibility at all speeds
- Speed control by adjusting blade pitch → loss of hydrodynamic shape
  → high low speed noise levels

Possible Solutions for lower source levels

- Allow deviation from shaft speed → combinator mode (shaft speed, pitch)
  → frequency controlled power-take-off
- Compromise design of propeller for transit speed and e.g. towing

Controllable pitch propeller design



Propulsors for Dynamic Positioning today

Pod

(Rectractable) azimuth thruster

Tunnel thrusters

Pump jet

Noise reduction of DP propulsors

- Speed controlled rather than pitch controlled
- Improved propeller design
- Reduce thrust loading → large diameter, more units
- Air injection
- Rim drive design
- Improve DP automation → minimize occurence of max load

Voith-Schneider-Propeller

From 4th international Voith Symposium

- A vertical axis propeller with individually controlled blades
- Very fast response
- Adjustable from transit to bollard pull with very little compromise
- Very low or no cavitation in bollard pull condition

Resiliently mounted 4-stroke diesel engines

Good resilient foundation brings underwater noise to acceptable levels (?)
Good = soft springs, high impedance foundation

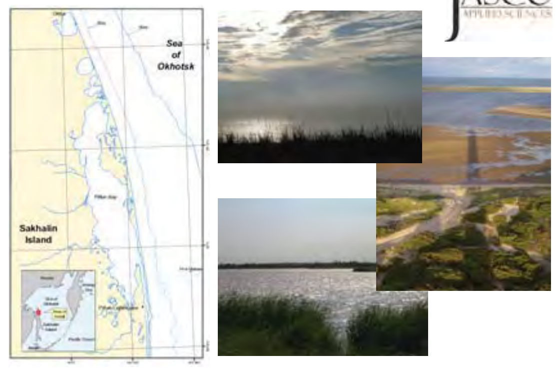
To be considered

- Diesel generators and thrusters commonly arranged in vicinity of living spaces → increasing demands for noise mitigation for habitability → helps mitigate underwater irradiated noise
- Otherwise no incentive to reduce underwater noise
- DP propulsion likely to dominate noise in an operating offshore field
- How does noise from service ships compare to merchant ships in terms of level and frequency distribution?
- Will continuous noise from ships during seismic surveys and pile driving be subject to future regulation?

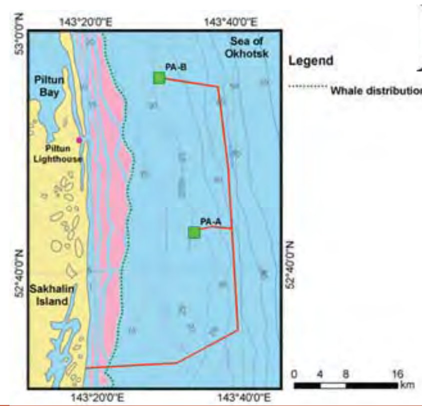
JASCO APPLIED SCIENCES

Coordinated management of anthropogenic noise from offshore construction

BOEM Workshop of Alternative and Quieting Technologies 25-27 February 2013



Western Gray Whale



The approach . . .

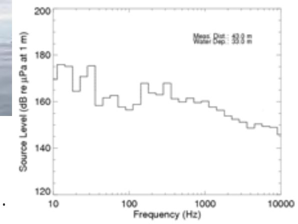
- Identify construction tasks that produce significant noise.
- Quantify acoustic levels produced by each operation through dedicated source level measurement programs.
- Develop and apply model-based methods to estimate radiated sound levels for pipeline construction and platform installation activities, with capability for mapping aggregate noise contours and zones of influence from all operations in the area.
- Implement noise mitigation methods that would reduce the noise footprint and minimize impacts on the WGW.
- Monitor sound levels during construction to ensure that thresholds are not exceeded in sensitive areas.

Multi-year Timeline

- 2004: Extensive measurement program of acoustic source levels from numerous vessels involved in activities comparable to upcoming operations at a nearby geographic location and additional sites.
- 2005: Float-in and installation of CGBS platforms Lun-A (learning opportunity: measurement, analysis and operational briefing) and PA-B (proximal to critical habitat: real-time monitoring).
- 2006: Offshore pipeline dredging and laying (proximal to critical habitat: real-time monitoring).
- 2007: PA-B topsides float-in and commissioning (proximal to critical habitat: real time monitoring).

Source level analysis

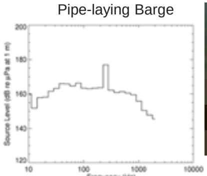
- Over 20 vessels measured.

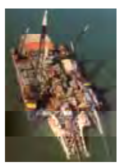


- Most in adjacent area, but as far as Australia, Thailand, Hong Kong...

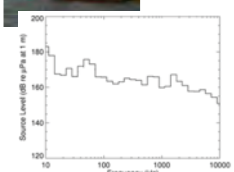
Deep-water Operations

Pipe-laying Barge

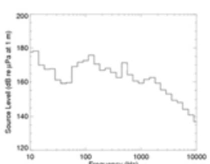




Supply Vessel

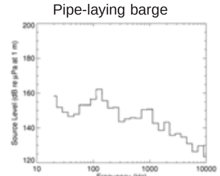


Anchor-handling tug

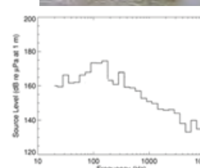


Shallow-water Operations

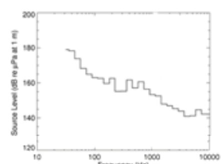
Pipe-laying barge



Support Vessel

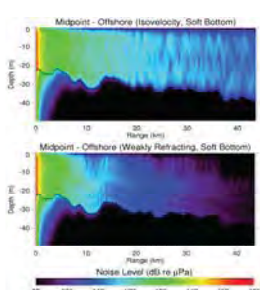


Dredger



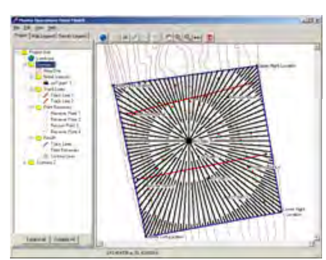
Numerical modelling of operational noise levels

- Acoustic source level database: third-octave spectral levels referenced to a distance of one metre.
- Propagation modelling: frequency dependent sound attenuation with distance using Parabolic Equation algorithm, which accounts for bathymetry and properties of water column and sea floor.



Marine Operations Noise Model with efficient radial gridding

- Optimized radial coverage of the area to improve modelling efficiency.
- Acoustic RL footprint of each source is computed
- Gridded levels from all sources in an operation are combined to generate RL contours from which impacts are assessed.



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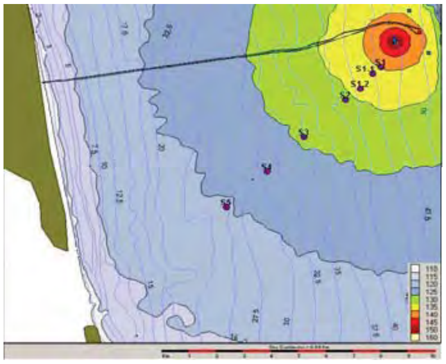
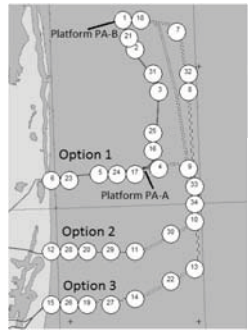
Model output example



Notional modelling stations for vessel spreads



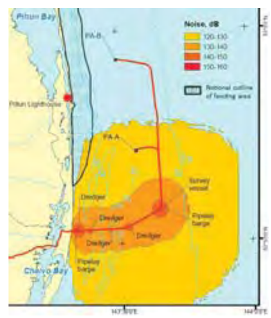
- Three possible routing options for the pipeline.
- Different construction schedule for each option.
- Source sites for model runs constrained to a limited set of stations.
- Timeline for each option broken into phases.
- For each phase, scenario with multiple sources at each of various stations.

Construction sequence and sample scenario

- PA-B pipe lay preparation
- PA-B pipe lay
- PA-B pipe lay and Lifts at PA-A
- PA-A pipe lay – early phase and Lifts at PA-B
- PA-A pipe lay – middle phase
- PA-A pipe lay – final phase
- PA-B tie-in and backfill in southern sector
- Completion of backfill

Modelling Station	Activity	Main Vessel	Auxiliary Vessels
13	Survey pipeline route	Dynamically Positioned Vessel	
13+	Pipe lay in deep water	Pipelay Barge 1	2x Anchor Handling Tug
14	Pipeline route dredging	THSD 1	
26	Pipeline route backfilling	THSD 2	
15	Dredging Shore Approaches	CSD	Spoil Dumper
15+	Pipe lay in shallow water	Pipelay Barge 2	1x Anchor Handling Tug

Modeled acoustic footprint of a construction scenario

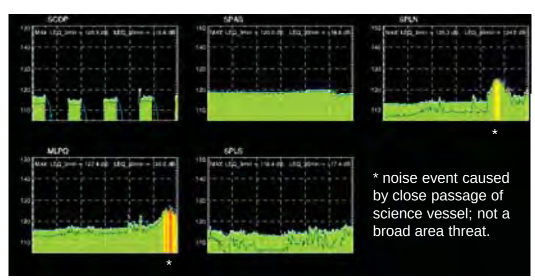


- Fundamental criterion for optimization was to minimize exposure to SEL > 120 dB re 1 μPa²-s.
- Scenarios were reviewed iteratively with operation planners to determine realizable changes that would reduce aggregate noise "hot spots" and reduce encroachment into feeding area.

Real-time Acoustic monitoring

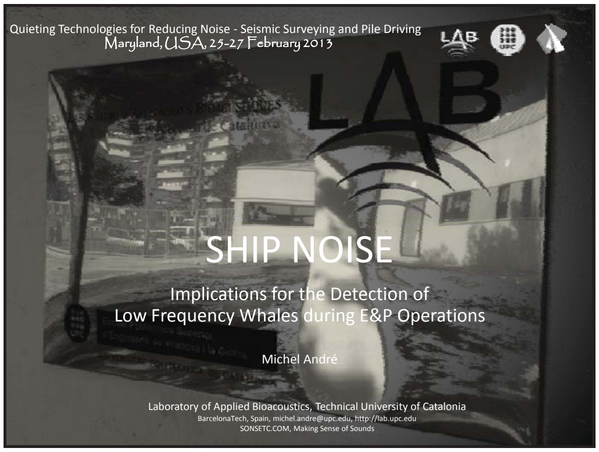
Real-time noise analysis with trend-based alerting

- Display includes colour indicator of "time to threshold".



Outcomes

- A real-time indicator based on a proportional, buffered metric allowed immediate assessment of trends in sound levels at all stations, enabling proactive and commensurate response.
- Monitoring team had access to round-the-clock lines of communication allowing direct interaction with vessels to reduce noise, even at levels significantly below action criteria.
- Never triggered requirement to initiate mitigation on the basis of either sustained noise (half-hourly means) or transient noise (three-minute means) action criteria. *Of course criteria will always be debated...*



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SHIP NOISE

Implications for the Detection of
Low Frequency Whales during E&P Operations

Michel André

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- EU funded projects on ship noise (SILENV, AQUO & SONIC)
- Measuring ship noise
- Modeling ship noise
- Masking effects of ship noise
- Implications during E&P Operations

SILENV, Ships oriented Innovative soLutions to rEduce Noise and Vibrations (N&V), http://silenv.eu/ (2009-2012)

AQUO, Achieve QUieter Oceans by shipping noise footprint reduction
http://aquo.eu (2012-2015)

SONIC, Suppression Of underwater Noise Induced by Cavitation (2012-2015)

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SILENV, Ships oriented Innovative soLutions to rEduce Noise and Vibrations (N&V), http://silenv.eu/ (2009-2012)

OBJECTIVES: Towards a Green Label for Ships
- Onboard Noise & Vibration Guidelines
- Airborne Radiated Noise Guidelines
- Underwater Radiated Noise Guidelines

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Onboard Noise Guidelines
- Machineries
- HVAC and Ventilation System
- Air Inlet and Exhaust Gas System

Sound Insulation and Damping Guidelines
Impact Insulation Guidelines

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Underwater Radiated Noise Guidelines
- Guidelines for Propellers (Design Stage and Maintenance)
- Guidelines for Machinery (Propulsion Engines and Generators; Gearbox)
- Requirements to fulfill the Green Label

[1] ANSI/ASA S12.64-2009/Part 1: Quantities and Procedures for Description and Measurement of Underwater Sound from Ship - Part 1: General Requirements.
[2] ICES Cooperative Research Report Nº 209. Underwater noise of research vessels, review and recommendations. ISSN 1017-6195, May 1995.

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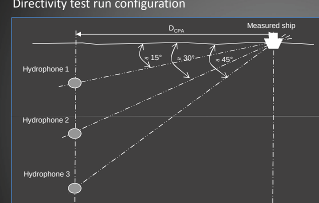
Underwater Radiated Noise Guidelines
Directivity test run configuration



If two (2) hydrophones are used, they shall be positioned at depths that result approximately in 15° and 30° angles from the sea surface at a distance equal to the nominal distance at CPA .
The additional hydrophones (if any) shall be positioned at a depth which results approximately in 45° angles from the sea surface at a distance equal to the nominal distance at CPA.

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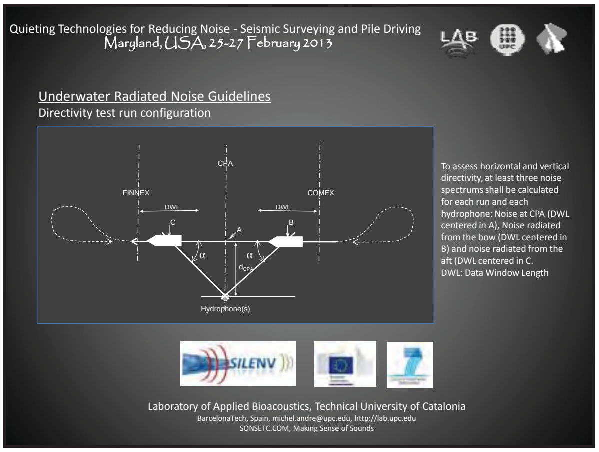
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Underwater Radiated Noise Guidelines
Directivity test run configuration
CPA
FINNEX
COMEX
DWL
DWL
C
A
B
Hydrophone(s)
To assess horizontal and vertical directivity, at least three noise spectrums shall be calculated for each run and each hydrophone: Noise at CPA (DWL centered in A), Noise radiated from the bow (DWL centered in B) and noise radiated from the aft (DWL centered in C.
DWL: Data Window Length
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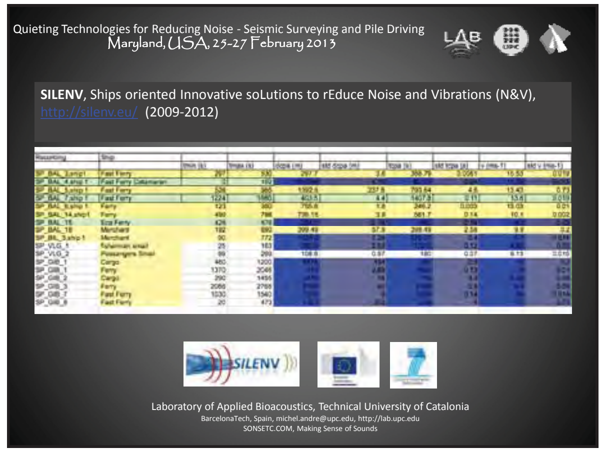
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SILENV, Ships oriented Innovative soLutions to rEduce Noise and Vibrations (N&V),
http://silenv.eu/ (2009-2012)
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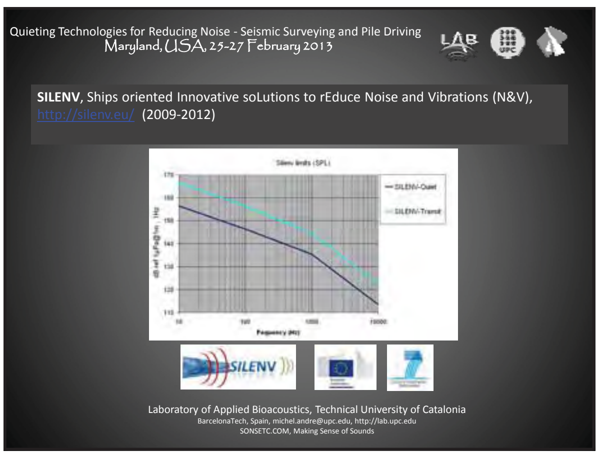
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SILENV, Ships oriented Innovative soLutions to rEduce Noise and Vibrations (N&V),
http://silenv.eu/ (2009-2012)
SILENV-Quiet
SILENV-Transit
SILENV
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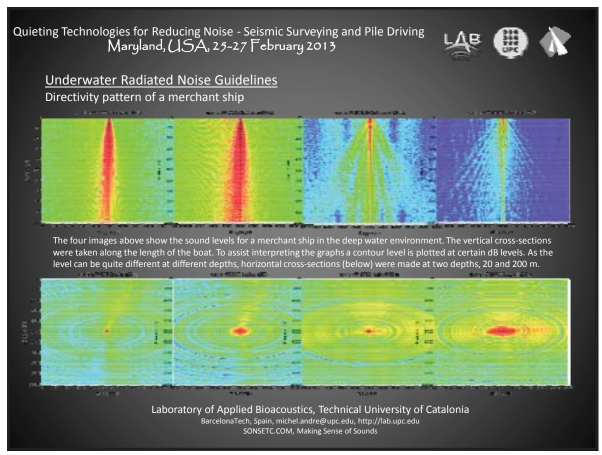
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Underwater Radiated Noise Guidelines
Directivity pattern of a merchant ship
The four images above show the sound levels for a merchant ship in the deep water environment. The vertical cross-sections were taken along the length of the boat. To assist interpreting the graphs a contour level is plotted at certain dB levels. As the level can be quite different at different depths, horizontal cross-sections (below) were made at two depths, 20 and 200 m.
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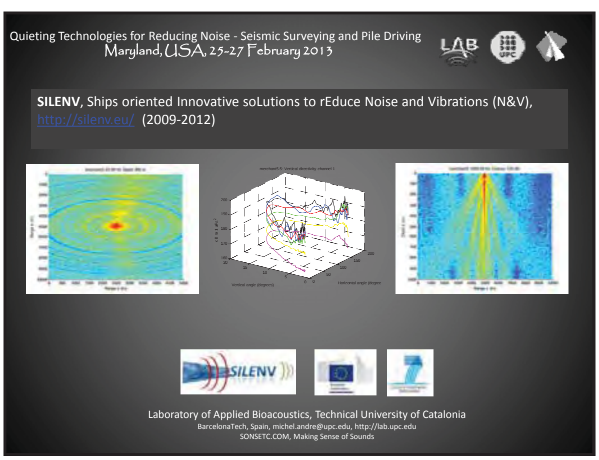
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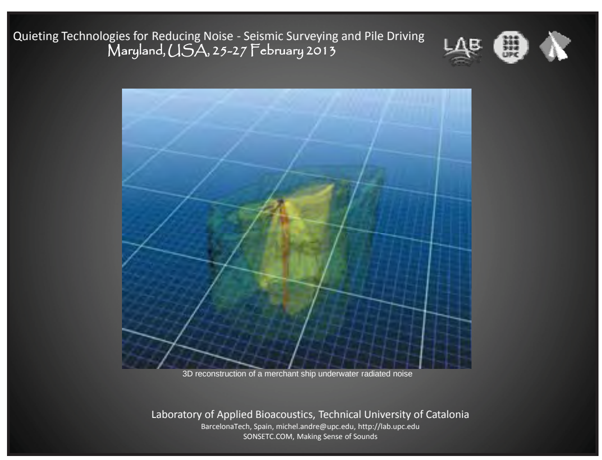
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3D reconstruction of a merchant ship underwater radiated noise
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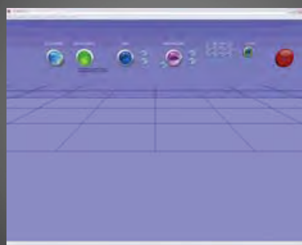
The environment shown here uses a Mediterranean summer deep-water sound speed profile using information from the NOAA World Ocean Database. Propagation was performed using the Ocean Acoustic Library; the simulation uses X3D with the H3D API and NumPy for computations. The translucent areas in the clips show the areas where the biological sound may be masked by the background noise and where detection may not be possible. The grid has a 1 km spacing.



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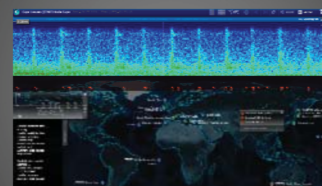
DETECTING BALEEN WHALES DURING E&P OPERATIONS
- The CTBTO analysis approach -



The LIDO database (http://sonsetc.com) processes and stores the automated real-time analysis of continuous acoustic streams from underwater observatories cabled or radio-linked to shore.

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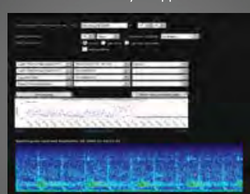

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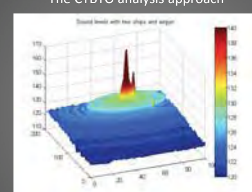

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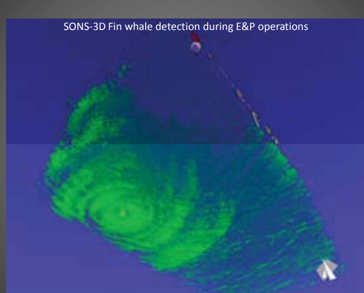

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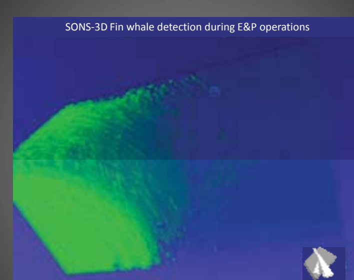

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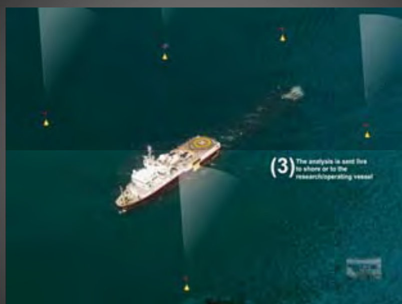

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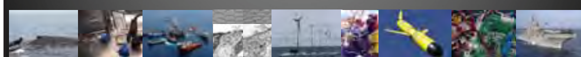
Conclusions

- Ship noise will probably be reduced in the next decades, but…
- Depending on target species, masking from ship noise may prevent detection by conventional towed PAM arrays
- Modeling the noise sources in presence around E&P and Pile-driving allows to optimize the positioning of acoustic sensors around the ship/platform
- 3D Modeling is a convenient and cost-effective solution when planning offshore operations
- "External PAM" solutions (expandable drifting buoys or gliders) represent an efficient alternative to conventional towed PAM arrays
- The real-time automated communication between buoys/gliders and the ship mitigates the masking effects of noise and allows an internet-based alert solution during offshore operations



Laboratory of Applied Bioacoustics, Technical University of Catalonia
BarcelonaTech, Spain, michel.andre@upc.edu, http://lab.upc.edu
SONSETC.COM, Making Sense of Sounds

Airgun Alternatives Presentations

Report Out

Complementary Technologies

- Techniques are complementary but can't replace seismic acquisition
  - Low-Frequency Passive Seismic Methods
  - Electromagnetic Surveys
  - Gravity and Gravity Gradiometry Surveys

Mike Jenkerson: Introduction Review of Synthesis

- Available on workshop website
- Seismic noise levels wanted up to 100 Hz, as low as feasible
- There is a certain level of energy that needs to be put into the ground for data collection
- Energy can be put in over time or fast

Airguns

- Some techniques are being proposed to reduce high frequencies generated by airguns
- Changes to ports and throats of guns
- Possible to detune airgun arrays to reduce environmental impact – spread out signal
- Still experimental, needs further testing and analysis to qualify techniques and benefits

Dr. William Ellison: Environmental Assessment of Marine Vibroseis

- Goal of project was to compare the environmental impacts of airguns and marine vibroseis using the NMFS and Southall criteria (using AIM)
  - MV has lower peak pressure and rise time than airguns
  - Spectral properties of the MV signal well controlled
  - Use of less-restrictive 'non-impulse' injury criterion for MV vs. airguns (215 dB vs. 198 dB SEL), results in smaller safety radius
  - M-weight for mid & high frequency hearing in dolphins, etc., further reduces safety radius around MV's (and airguns)
  - MV's have significantly lower proportion of energy emitted at frequencies above 100 Hz
  - Advantage over airguns increases if the falloff rate above ~100 Hz could be further increased, (e.g. to 100 dB/decade)
  - Auditory masking should be greater with MV's than airguns, effect greater with pseudorandom signals than FM signals

Funded by SAML JIP

Bob Rosenbladt: Marine Vibroseis JIP

- This JIP is separate from marine sound JIP funded by ExxonMobil, Shell, and Total
- Wanted to get transducer specs that were realistic and doable
- Developed spec and narrowed 36 vendors down to 3 vendors
- One vendor awarded contract (PGS) to develop technology
  - Other 2 still in contract negotiation

Pros and Cons of Airgun Arrays

Arrays of airguns for use in exploration	
Strengths	Weaknesses
Good safety record Well established technology (40+ Year) Readily available Bulk of emissions • In 'seismic' band • Focused downwards	Little control over spectral shape • Array tuning required • Degraded directivity • Poor performance at shallow depths • Limited scalability (non optimal source strength)
Opportunities	Challenges
Optimized re-engineering Acoustic mitigation measures Alternate sources and methods may • Address weaknesses • Improve environmental compatibility (e.g. reducing out-of-band emissions)	Mitigation measures as a result of • Coexistence with marine fauna • Difficulties with increasing # sources e.g. WAZ • Noise 'budget' limitations

Pros and Cons of Marine Vibroseis

Marine Vibrator for use in exploration	
Strengths	Weaknesses
Control of output frequency spectrum Control of sweep length Low peak output level Type of sweep can be controlled	Long duty cycle Vessel motion during output of signal Emerging technology competing with very mature airgun technology
Opportunities	Challenges
JIP pursuing 3 different technologies	Adequate Low Frequencies Possible harmonic output outside of planned frequency range Success of JV – emerging technology Availability of limited # of devices Masking Issues

Bob Rosenbladt: Marine Vibroseis JIP cont.

- First prototype is expected to be constructed and tested within 18 months with PGS
- Second prototype in 24 months
- Third prototype in 30 months
- Plan to construct and test arrays of successful prototypes
  - Two of three manufacturers will sell transducers to seismic industry

Bill Pramik: The Geokinetics Marine Vibrator

- Geokinetics Marine Vibrator will be commercially viable before year end
- Geokinetics Marine Vibrator has demonstrated its ability to provide suitable energy for seismic data acquisition
- Commercialization project nearly complete
- Can provide all the same geophysical benefits as land vibroseis data acquisition

Stephen Chelminski: A Practical Marine Vibratory Sound Source

- The modular design allows the source to be adapted to survey requirements
  - The source is designed to be manageable and towable up to 12 knots
- The Source functions within the window of sound energy and signal useful to exploration goals
  - Designed to sweep from 2 to 100 Hz with a sound pressure level greater than 200 dB for a single unit
- The power delivery system for the source can be either pumped bio-hydraulic fluid or pumped ambient sea water
  - This makes the system safe and environmentally acceptable

Paul Novakovic: Vibroseis History and Future

- Presently developing a new low frequency concept
- A single unit can meet a source level of 205 dB from 5-200Hz
- A patent has been applied for the technology
- Complete equipment is expected to be available to seismic operators in the coming year
- A complete instillation using the new equipment is estimated to total approximately 35% of the cost of a complete airgun installation

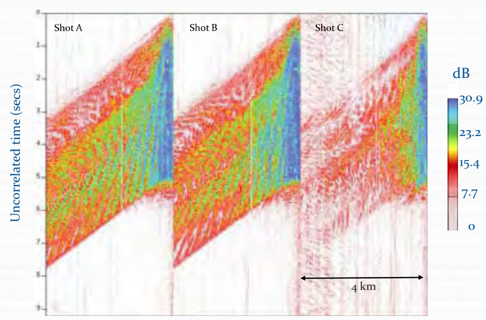
Environmental Conclusions

- Southall used M-weighting for injury assessment not behavior
  - Should we define different M-weighting for behavior?
- Need clarity on the regulatory level for MV
- Since MV reduces the high frequencies (above 100 Hz) generated by airguns – should reduce impact
- Environmental advantages and disadvantages of MV needs to be evaluated and compared to airguns
- Environmental testing during geophysical testing

Technology Conclusions

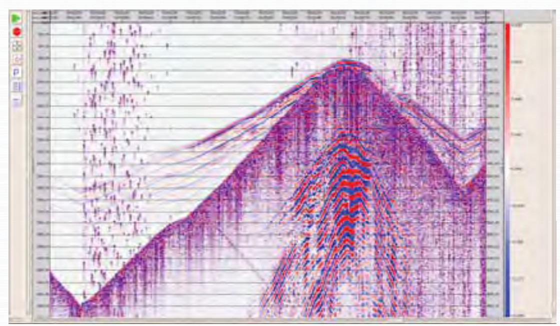
- Significant data processing capabilities with MV that are not available with airguns
- MV can potentially be used in areas that airguns can not
- Multiple vibrator concepts available
- Research being conducted on airgun adaptations
- All of these technologies or developments (airguns or MV) are in early stages and are not certain of technical success
  - Time will indicate the most viable technologies
  - There will be operational costs and delays associated with the development of new technologies

Marine Vibroseis in Norway

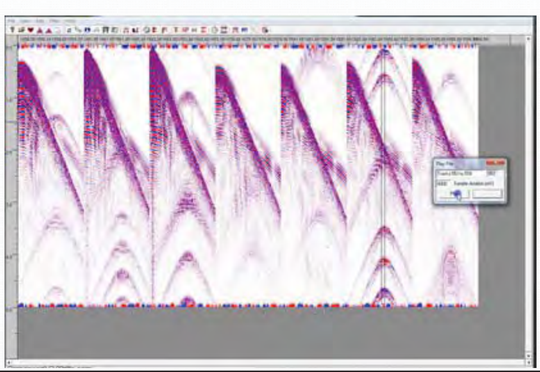


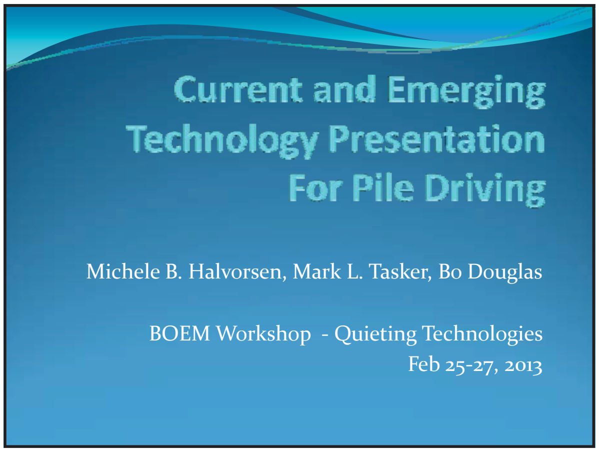
Uncorrelated shot records

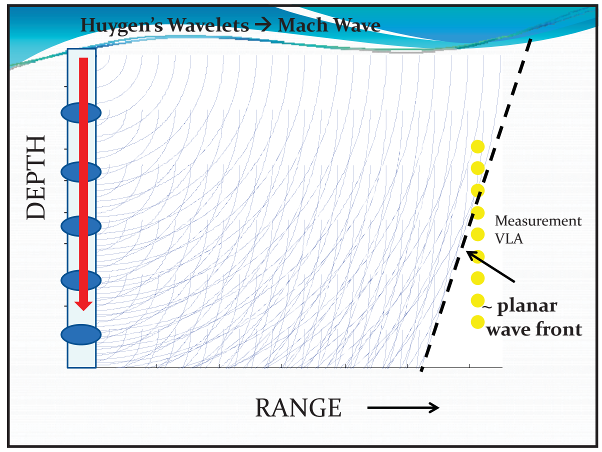
Ambient Noise

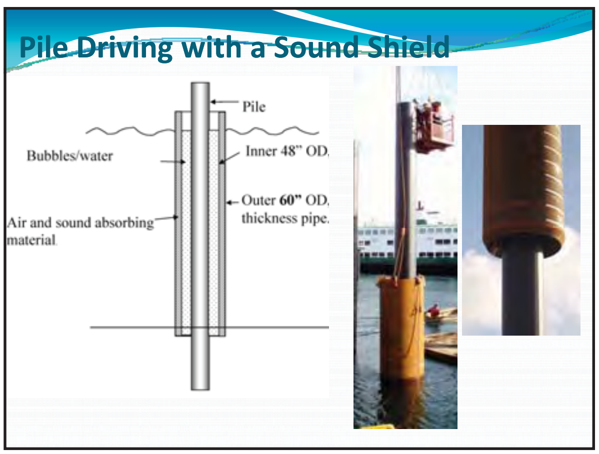


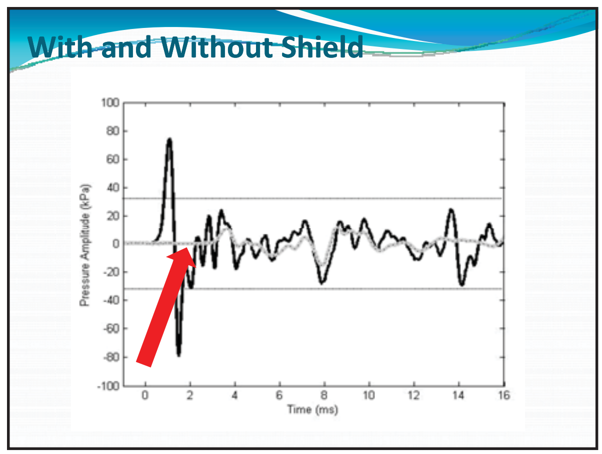
Whale Vocalizations on Seismic

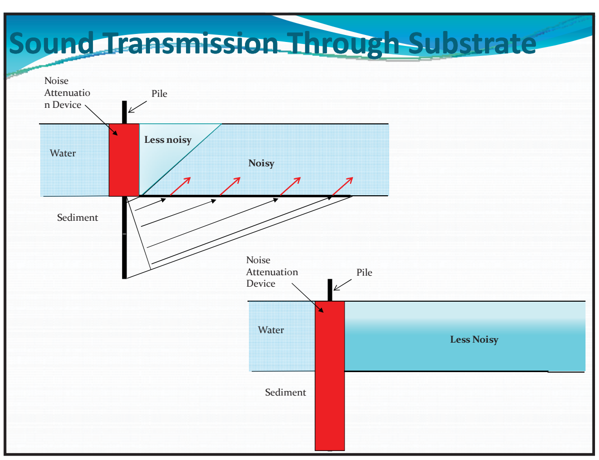


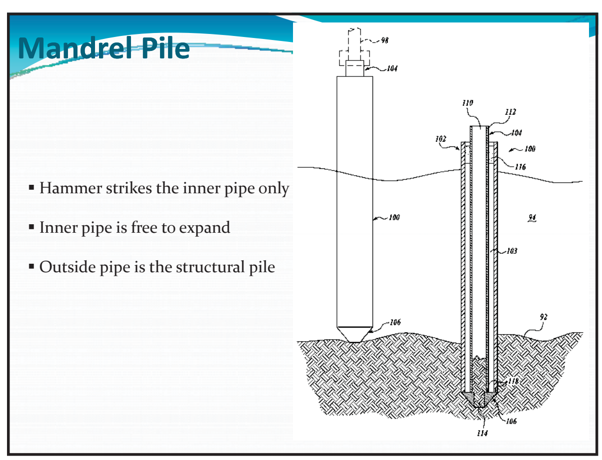

Current and Emerging
Technology Presentation
For Pile Driving
Michele B. Halvorsen, Mark L. Tasker, Bo Douglas
BOEM Workshop - Quieting Technologies
Feb 25-27, 2013


Huygen's Wavelets → Mach Wave
DEPTH
Measurement
VLA
~ planar
wave front
RANGE

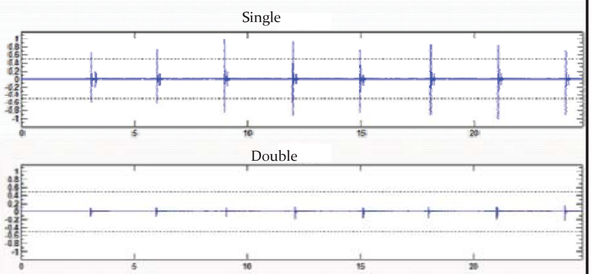

Pile Driving with a Sound Shield
Pile
Bubbles/water
Inner 48" OD.
Outer 60" OD.
thickness pipe.
Air and sound absorbing
material


With and Without Shield
Pressure Amplitude (kPa)
Time (ms)


Sound Transmission Through Substrate
Noise
Attenuatio
n Device
Pile
Water
Less noisy
Noisy
Sediment
Noise
Attenuation
Device
Pile
Water
Less Noisy
Sediment


Mandrel Pile
▪ Hammer strikes the inner pipe only
▪ Inner pipe is free to expand
▪ Outside pipe is the structural pile

Mandrel pile



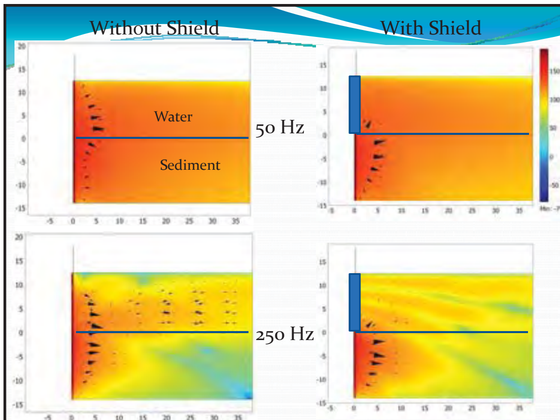
Peak sound reduction > 20dB @ 5m range

Another potential solution

- Reduces the radial expansion
- decreasing noise generation

Vibratory Driving

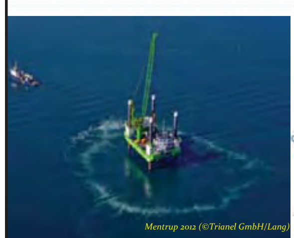
- No impact
- Steady state sinusoidal excitation
- Less noisy but still loud
- Frequency < 1000Hz

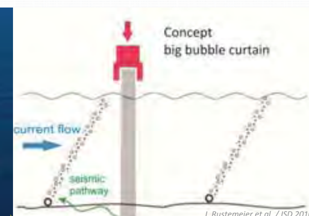


What have we learned?

- Sound transmission through sediment
  - Needs attention
- The double wall shield
  - Impulsive: ~8 - 10dB decrease @ 10 m
  - Vibratory: ~ 10dB

Large Diameter Active Bubbling Curtain





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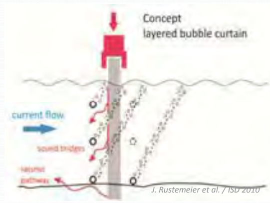
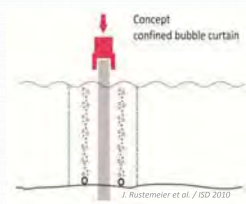
Small Diameter Active Bubbling Curtain





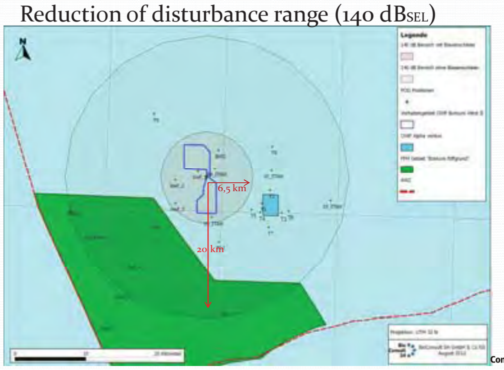
Sound Level Reduction

Configuration	Noise reduction	
	SEL [dB]	Peak [dB]
large nozzle	9,6	12,8
small nozzles	12,2	13,9
Double bubbling curtain at 25 m	15,5	18,7
Double bubbling curtain at 80 m	17,2	20,7

Quelle: itap GmbH, Oldenburg

Large Diameter Bubbling Curtain

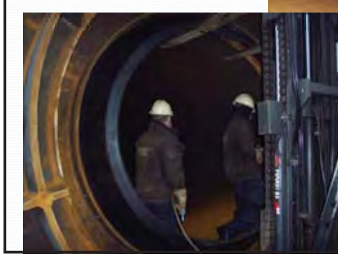
Reduction of disturbance range (140 dB SEL)



15

Dewatered Cofferdams

- Baltic Sea
  - 15 m depth
- Decrease 23 dB (SEL) ; 19 dB (peak)

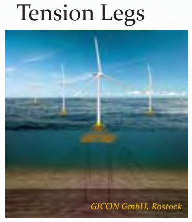


Alternatives to Pile

Drilling

Gravity Base

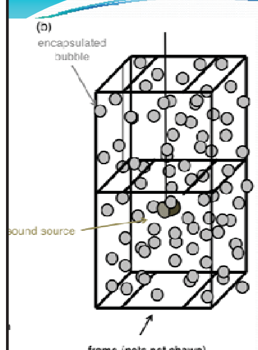
Tension Legs



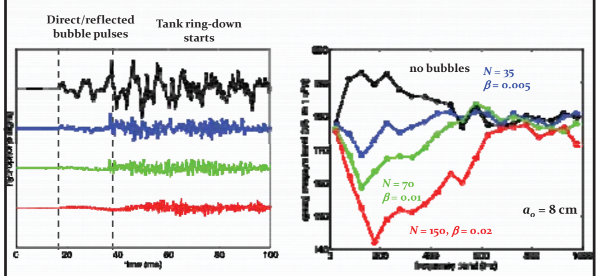
Bucket Foundations

Static Bubble Curtain

(AdBm Technologies)



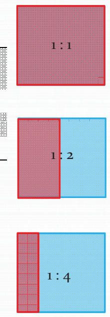
Level reduction with impulsive noise source



Peak level reduction = 47.5 dB
@ 150 Hz – 200 Hz band

Depth pressures

Depth (meters)	Atm	Impulsive signal (Pa)	Acclimation pressure (Pa)	Ratio	Injury risk
0	1	100 k	100 k	1 : 1	High - Mod
10	2	100 k	200 k	1 : 2	Low?
20	3	100 k	300 k	1 : 3	
30	4	100 k	400 k	1 : 4	unlikely



Thank you to our Presenters

Peter Dahl – Univ Washington
Sven Koschinski - Marine Zoology
Georg Nehls – Bioconsult Sh GmbH
Mark Wochner – AdBm Technologies
Michele Halvorsen – Pacific Northwest National Lab
Per Reinhall – Univ of Washington

Support Vessel Noise Presentations

- John Hildebrand, Vessel noise monitoring & modeling in Santa Barbara Channel
- Chris Barber, Design alternatives & operations considerations
- Dietrich Wittekind, Vessel noise sources, alternatives & mitigation
- David Zeddies, Sakhalin Island case study
- Michel Andre, Networked wide area acoustic monitoring & modeling

Current, new & potential solutions

- There are gains to be had from both design and operations advances.
- Avoiding propellor cavitation is key.
- But don't ignore narrowband machinery tones.
- Noise reduction should be part of the ship design process from the start.
- Owners and operators need to be aware of noise issues and plan operations accordingly.

Benefits from modeling

- We can calculate an optimal speed for transiting to minimize noise input to an area (8kts for container ships)
- We can model cumulative noise levels from shipping traffic and construction in an area.
- With source level information for all ships in an operation, you can model potential impacts of different operational scenarios and use this for mission planning for a specific project.

…and from monitoring

- Shipboard acoustic monitoring can have large benefits when problems are identified and corrected.
- Real time monitoring in the water can provide a feedback to operators if they exceed a given threshold level.

Solutions to vessel noise exist

- Reducing radiated noise from support vessels depends on both design & operational configuration.
- Most promising noise reduction strategies are:
  1. Reduce/avoid propeller cavitation
  2. Limit/avoid noise from bow thrusters
  3. Reduce radiated machinery noise via good design and husbandry (e.g. inspections and maintenance)

…but they need to be incentivized

Regardless of the benefits that could be gained from such changes, they will likely only occur through regulation, economic incentives, or "green" certifications that result in more favorable permit conditions and other benefits.

Seismic Alternatives Goals Sessions

Report Out

1. Recent Developments

- Vibroseis Developments
  - Multiple designs
  - Construction
  - Proof of Concept
  - Key criterion
    - Does it provide useful data
    - Engineering and data processing advances
  - Replace airguns or another tool in the toolbox
  - Slow process to implement any new technology

2. Spatial, Spectral, and Temporal Features

- Design of array options
- Use in shallower environments
- Can modify acoustics – flexibility
- Reduces high frequency noise
- Low frequency source
- How would the source be regulated (e.g., impulsive, continuous, intermittent)?

3. System and Site Specific Requirements

- Array configuration needs further development
- Applicable in shallow water
- Applicability in deep water ?
- Vibratory mechanisms
  - Hydraulics
  - Sea water
  - Electromechanical
- Power requirements
- Vessel reconfiguration and downtime

4. Potential Impacts

- Operational and cost effectiveness
  - Does it produce good data?
  - Initially more expensive
  - Reconfiguring vessels
  - Socioeconomic
  - Regulatory

4. Potential Impacts, cont.

- Environmental impacts
  - Expected to be more environmentally friendly – need verification
  - Potential electromagnetic fields
  - Potential hydraulic fuel spills
  - Effects on marine life may be direct or indirect (e.g., prey, presence of vessels)
  - Removal of high frequency could result in lower effects on odontocetes but effects on mysticetes uncertain, with particular concern about masking

5. Data Quality

- Seismic industry uses 3rd highest amount of computing power
  - #1 military, #2 weather forecasting
- Data acquisition and processing keep improving
- MV data comparable to airgun data
- Need side by side comparisons
- Shelf life of data

6. Reduce Sound Output

- MV
  - Increase in number of receivers
  - Higher shot density
  - Additional ships - expensive
  - Reduce sound output at higher frequency
- Airguns
  - Control spectrum and duration
  - Staggered shots
    - Poses processing challenges due to different signal signature

7. Changes in Environmental Impacts

- Change features of sound with MV
- Different species affected
- Real time vs. chronic impacts
- Cumulative impacts
- Impacts function of environment and marine fauna

7. Changes in Environmental Impacts

- Data gaps
  - Impact on other species (e.g., invertebrates, fish)
  - Context specific
  - Habituation
  - Impacts of airguns not well understood
- Case studies important (e.g., bowheads)
- Lab studies may be useful

8. Promising Technologies

- MV
  - Another tool in the toolbox
  - Socioeconomic and regulatory concerns
  - Potential use in environmentally sensitive areas
  - Use in extremely shallow waters (e.g., ≤ 2m)?
- Airguns
  - Detuned airguns (staggered)
  - Airgun silencers
  - E-airgun?

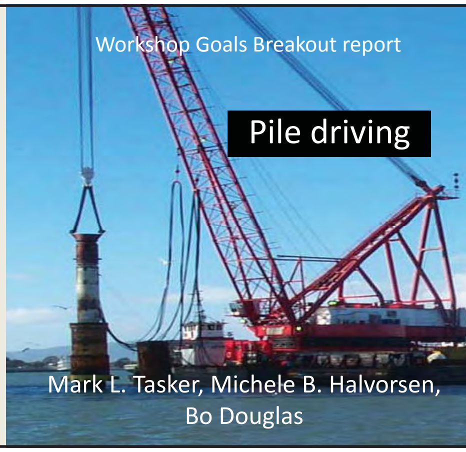
9. Next Steps

- Continue period of development
- Funding for support
- Proof of concept
- Agency and industry cooperation
- Communication
- Regulatory scheme needs to be adapted
  - Industry input regarding drivers (and incentives) for development of lower source levels (e.g., cost of mitigation)
  - Lower impacts = time and cost savings for permitting

9. Next Steps cont.

- Begin impact studies
  - Model outputs using AIM or similar
  - Near and far field data collection
- Collect biological data
  - Empirical data on impacts
  - In parallel with design and testing
  - Lab studies
- Side by side comparisons with airguns

D139



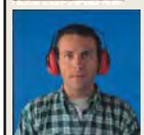
Workshop Goals Breakout report

Pile driving

Mark L. Tasker, Michele B. Halvorsen, Bo Douglas

Avoid noise – chose a different technology

Reduce noise – use one of the noise reduction technologies



Mitigate effect – e.g. turn off noise if receptor arrives

Sound has many properties

Which property "matters" depends on location and receptor (and knowledge is patchy)

In other words: What is your (local) goal?

Avoid noise

Some cross over – e.g. drill, pile, drill; floaters need some (pile driven) anchors, pin piles

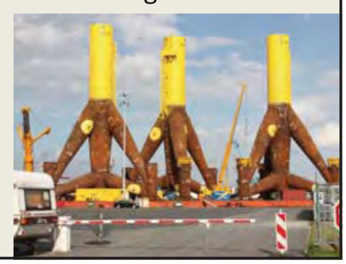
Factors other than noise are important, e.g. geology

Alternatives to driving

Drilling Gravity

Bucket foundations

Floating



(Driven) piling

Impact driving

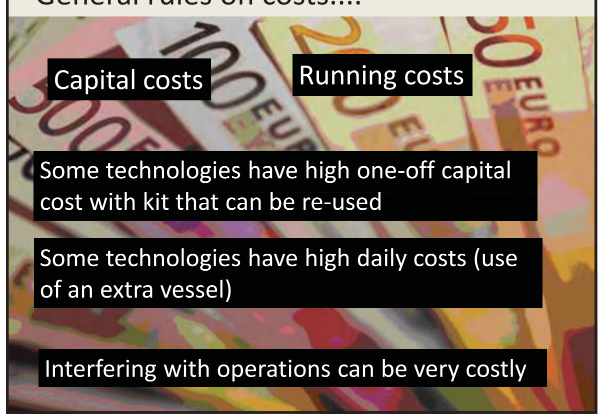
Vibratory driving

Two main propagation routes to water

Direct from pile

Indirect via seabed

General rules on costs....



Capital costs

Running costs

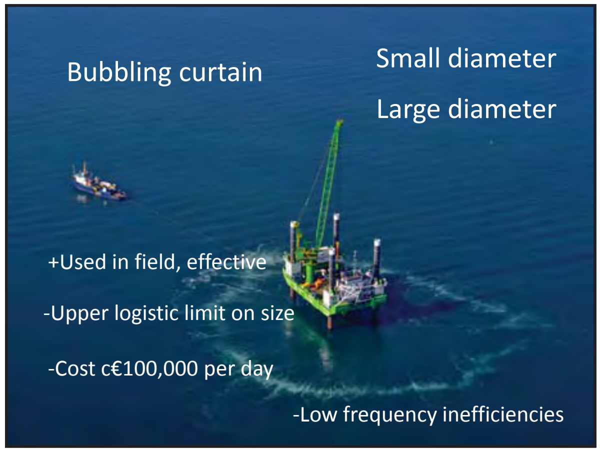
Some technologies have high one-off capital cost with kit that can be re-used

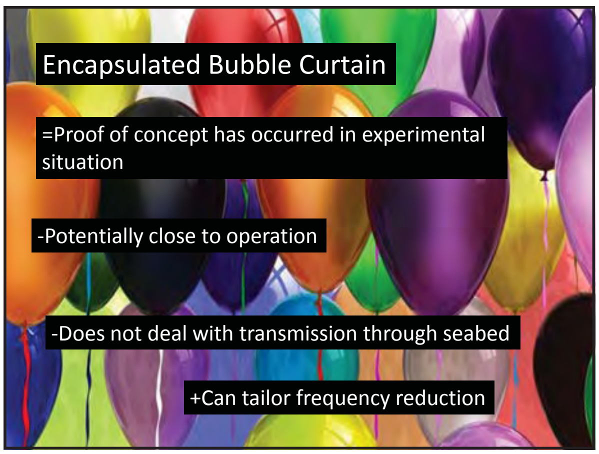
Some technologies have high daily costs (use of an extra vessel)

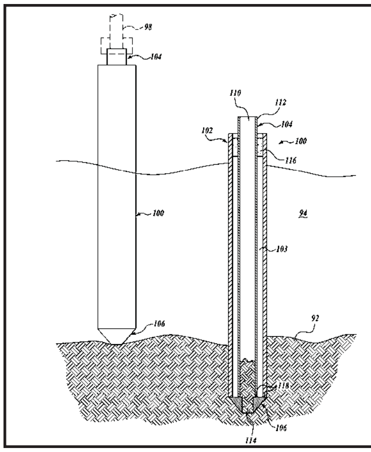
Interfering with operations can be very costly

The pile-driving noise reduction tool kit

- Bubbling curtains
  - Large diameter
  - Small diameter
- Encapsulated air
- Double-walled pile
  - Mandrel
  - Isolation casing
- Noodle net
- Reduced radial expansion pile (slits in pile)
- Pulse elongation
- Encapsulated bubble blanket
- Cofferdam
- Adaptation of substrate to reduce friction and vibration
- Pile caps
- Seafloor reshaping to deflect sound radiation







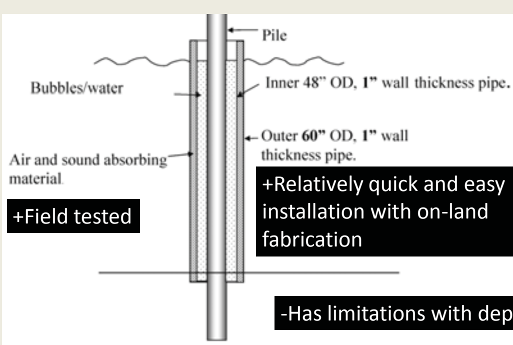
Mandrel

=Proof of concept at small scale

-Scaling up may not be simple

+Potentially reusable and easily handled kit

Solid surround with air absorbance next to pile



+Field tested

+Relatively quick and easy installation with on-land fabrication

-Has limitations with depth

Noodle net

+Good sound absorption

+More stable in current flow than bubbling

+Some field testing

+ Can be assembled by kids

D141

Lower Radial Expansion Pile

+Reduces pile bulging/swelling and associated noise

=Does not reduce pile integrity

-Needs field testing

Incentives to use/get greater uptake of technologies

What is needed?

Industry, regulators, academics working together – see Oil industry JIP

Multiple standard test facilities

Safety slide

Beware of:

Vibrosis

Local radial swelling

Piles

Double bubble

Mach wave leakage

Do keep with you:

Encapsulated bubble blanket

A good strong coffee dam can help

Additional goal from BOEM

- Describe the types of support vessels associated with OCS energy development
- Compare the support vessels in terms of the noise they generate relative to commercial vessels

Types of support vessels

- Installation vessels (e.g., jack-up ships, lift ships)
- Seismic survey vessels
- Tugs
- Offshore service vessels and platform supply vessels
- Drilling vessels
- Multipurpose vessels
- Anchor handling tugs
- Icebreakers
- Crew transport vessels
- Crane barges

Noise associated with these types?

- No consensus on which of these ship types are the noisiest
- There are some data available to begin to evaluate and compare their noise levels
- Monitoring process (measuring ship levels) should be incorporated into the BOEM permitting process

Goal 1 – Current, Emerging

Design level priorities

1. Non-cavitating propellors
2. Quiet thruster systems for DP
3. Vibration isolation for diesel engines & generators
4. Silencers for hydraulic systems
5. Vibration isolation and quiet design for electrical motors and auxiliary systems

Goal 1 – Current, Emerging

Operation level

- Mission planning
- Shipboard acoustic monitoring
- Ship husbandry and maintenance

Goal 2 – Spatial, Temporal, Spectral

- Propellor cavitation reduction will reduce broadband noise across the full spectrum
- Quieting diesel engines, electric motors and auxiliary machinery will reduce narrowband noise, mostly low frequency
- The above can be achieved in any area at any time (invariant spatially and temporally)

Goal 3 – Requirements, Limitations

- Icebreakers limited to pod thrusters that can mill ice and propel
- Drop down thrusters susceptible to damage in coastal waters; limited to tunnel thrusters in shallow water
- Bigger propellers to reduce shaft speed may not work in coastal waters
- Jet-power might be an alternative for shallow water (for smaller vessels only)
- Voith-Schneider in rear of ship only
- Multi-purpose use of vessels means that you are not going to retrofit the boat for every new task

Goal 4 - Potential impacts

Operational, cost-effectiveness impacts

Pros	Cons
Machinery maintenance	Expensive
Expanded number of quieter vessels per operation	Crew retraining may be required for complex equipment/vessels
Enhanced habitability	Time-consuming
Sonar works better	Measuring cost-effectiveness is challenging
Potential fuel efficiency gains	Reliability may go down, at least initially
	May constrain operations

Goal 4 – Potential impacts

Environmental impacts

- More cleaning of equipment may minimize invasive species introductions
- If new DP technology creates more downward thrust, then there may be increased turbidity and disturbance concerns in shallow water environments

Goal 6 – Sound reduction

- Cavitation avoidance, quiet propulsion -> 10-20dB reductions
- Cavitation-free DP systems -> 10-20dB reductions
- Shipboard acoustic monitoring -> 10-20dB of reduction if you identify and correct material condition failures
- CFD based self-optimizing design could lead to big improvements in hull and propeller design -> ??? dB
- Potential improvements with air injection along props and thrusters, but strong tradeoffs – loss of thrust, very expensive, hard to maintain
- Active vibration control also could have benefits but needs further development and still expensive ($10s-100K)

Goal 7 – Env impacts relative to existing technologies

- No known impacts over existing technologies
- Not talking about technologies that would result in tradeoffs between frequencies, though reducing broadband noise by eliminating cavitation may reveal tonal noise from machinery

Goal 8 – Most promising solutions

- Taking modeling of ship noise into account in ship design
- Hydrodynamically and acoustically optimizing propeller and thruster design
- Designing DP automation to take noise into account
- Shipboard acoustic monitoring to identify and correct problems
- Mission planning to minimize noise impacts

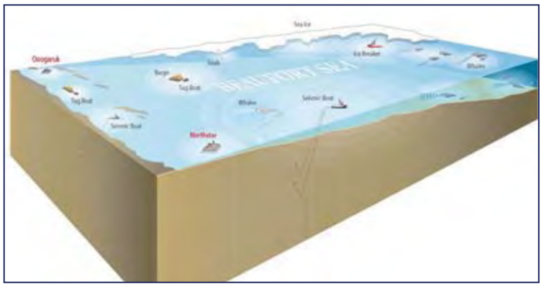
Goal 9 – Next steps for BOEM

- Create incentives for innovation and implementation
- Design and support data collection initiatives to characterize ship noise and evaluate impacts (environmental and economic)
- Adopt forthcoming new IMO regulations

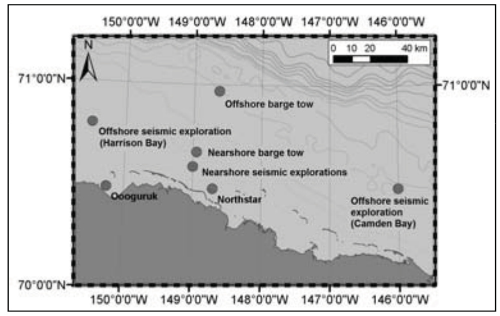
Remaining questions

- Should we be focused on designing new quieter ships or quieting the existing ships? Can we wait for the new ships to come online (may be decades)?
- Should we be asking the Navy for acoustic data?
- What should the environmentally or biologically-based acoustic limits (sound exposure levels) be? Perhaps geographically or species specific? Maybe start with a conservative floor level.
- Could we develop a very large bubble curtain to surround an entire offshore construction site? (Limited to filtering specific frequencies)

Aggregate Sound Exposure
(Cumulative Effects)



Aggregate Sound Exposure
(Cumulative Effects)



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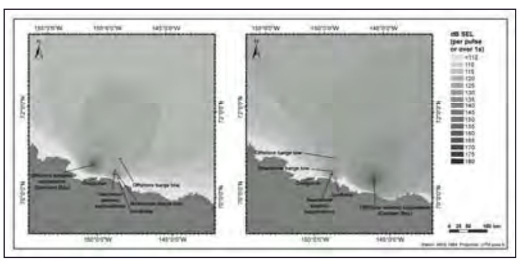

Aggregate Sound Exposure
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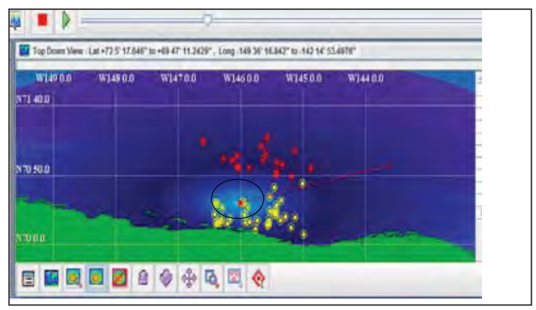

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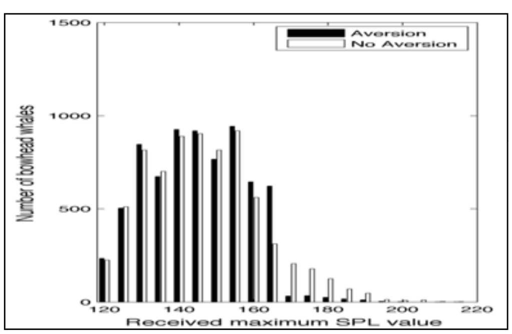

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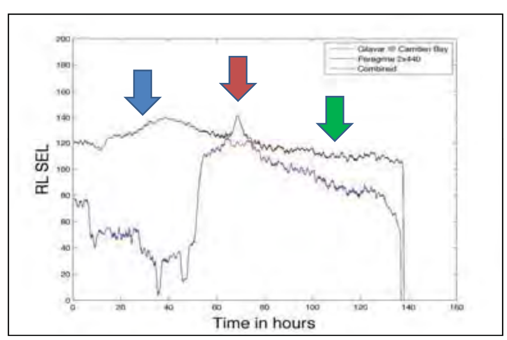

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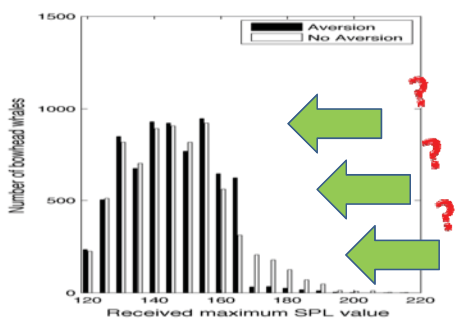

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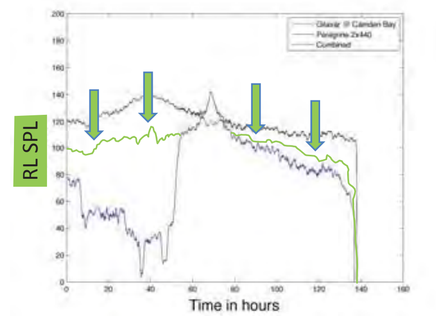

Aggregate Sound Exposure
(Cumulative Effects)

Way Forward

- Peer reviewed paper and workshops
- National Research Council Interest in pursuing a follow up, possibly a formal assessment of cumulative effects in the Alaskan Arctic
- ONR interested in joining this with PCAD work possibly through NOPP
- Chris Clark at Cornell looking at smaller time windows