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Review of Existing and Future Potential Treatments for Reducing Underwater Sound from Oil and Gas Industry Activities

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0.0 EXECUTIVE SUMMARY

Noise Control Engineering, Inc. (NCE) has been contracted by the Joint Industry Programme on E&P Sound and Marine Life (JIP) to compile, assess, and summarize information on technologies capable of reducing underwater sounds created by oil and gas industry activities. The purpose of this study is to investigate current and future potential treatment options for all sources of underwater sound, including sources associated with exploration, construction, transport, drilling, and production. Information was collected from various sources including technical and trade journal articles, contacts with representatives of companies that produce or develop noise control products and technologies, contacts with members of academia, and information provided directly by members of JIP and the International Association of Oil and Gas Producers (OGP). Additional information was collected through a workshop, organized and hosted by NCE and held on June 4-5, 2007, where members of JIP/OGP, the National Oceanographic and Atmospheric Administration (NOAA), US Minerals Management Service (MMS), the U.S. Army Corps of Engineers, and members of industry and academia discussed the research results that had been attained thus far as well as additional methods for reducing underwater noise.

In order to effectively identify treatments for reducing noise from any noise source, the mechanisms of noise creation must be known. For some sources such as air gun shots in open water, the mechanisms are largely straight-forward. However for other sources such as vessels and drilling platforms, multiple potential noise makers and noise paths are possible and the most pertinent mechanisms must be identified before effective treatments can be implemented. Because of this fact, this work was divided into two tasks: 1) identification of specific sources (or 'noise makers'), sound generation mechanisms, and noise paths that are most significant for a given activity, and 2) identification of possible treatments for those sources / mechanisms / paths.

The following is a brief summary of the methods of noise creation for various oil and gas industry activities and the treatments or alternative methods that have been identified as part of this work. Note that some treatments currently exist and could be implemented today. Other treatments still require further research in order to become viable commercial solutions, but hold potential for being useful methods of reducing underwater sound. Note that this report was written with the intention of presenting possible sound reduction options to those who may decide underwater noise reduction is needed for a given activity or those who must meet specific underwater noise requirements (either now or in the future). The identification of treatments for specific sources should not imply that any particular treatment is required.

- **Seismic Exploration –** Current seismic exploration techniques commonly use air guns to generate sound in the water. Air guns radiate sound directly into the water through the rapid expansion of compressed air. This creates a short duration impulse with high peak amplitude; spectral content can extend to many thousands of Hertz (Hz). The useful frequency range for seismic exploration is typically 5-100 Hz, and as such air guns (and other seismic sources) produce 'extra' sound at frequencies that may be of concern to animals. Only one attempt to reduce noise from air guns was found – an "air gun silencer". This treatment showed a maximum of 6 dB of attenuation at frequencies above 700 Hz for 50 bar air guns. The silencer uses an acoustically absorbent foam rubber that is oriented radially around the air gun. This treatment is currently a 'proof of concept' design and would require future research to become a viable solution. Similar, modified approaches may be possible that yield greater effectiveness and could be made into a commercial product. Several alternatives to conventional seismic sources have been identified. Electro-mechanical and petrol-driven acoustic projectors have been prototyped and show large reductions (30-65+ dB) in sound level above 100 Hz. Sound reduction at frequencies below 100 Hz is also possible through the use of alternative source signals and advanced cross-correlation processing procedures (published data shows a reduction on the order of 15 dB below 100 Hz). These systems are currently in development and may be commercially available in a few years. Tunable pipe organ seismic sources have also been used as replacements for existing sources, but are so far limited to higher frequency output (above 200 Hz). Other possible replacements for current seismic exploration methods include techniques that use sound from passing vessels, background sound of the ocean, and background seismic sounds instead of air guns or other conventional seismic sources. These techniques require longer acquisition times than the conventional survey, and may not be well suited for exploration of new areas. However, these techniques may work well in Life-of-Field applications where the area of interest has already been established, and would reduce or remove the need for mobilization of additional surveys of a given area. Electromagnetic surveys, shear wave generators, and air curtains have also been investigated.

- **Pile Driving –** Underwater noise from pile driving is believed to be dominated by radiation from the pile itself, although flanking paths through the ground have been identified as possible secondary influences. Other flanking paths may include transmission through barges where equipment is located and direct transmission from airborne noise created during hammer impacts. It is believed that vibratory piling methods create lower noise levels on average than impact methods by 10-20 dB, although a cost increase on the order of 2-3x for equipment can be expected. Suction piles present one of the largest opportunities to greatly reduce noise while potentially increasing installation speed. Noise from suction pile installation is expected to be very low since the only noise source is a suction pump located above water. Suction piles can be used in both deep and shallow waters. Press-in piling machines use static forces to drive piles into place, thus removing impulsive sound sources. They have been used in many environmentally sensitive applications due to their low noise design, including on beaches during turtle migration season. Press-in piling machines are semi-automated, and can minimize or even improve production speed. These machines can be used in a wide range of applications, and installations can be performed in shallow and deep waters. Bubble curtains of various types have been used in many shallow water applications with reductions in peak level and energy metrics ranging from 5-20+ dB. Other sound-blocking treatments include physical barriers and dewatered cofferdams, and have similar effectiveness. For practical reasons, these treatments are limited to shallow waters. Pile caps have also been used with good results, although the effect on piling efficiency needs to be studied further. Drilled, cast in place piles may be a low-noise option to replace current piling methods, but further research is needed.

- **Explosives –** Explosives radiate sound (and shock waves) directly into the water. Primary attempts at mitigation have focused around the use of bubble curtains as described above. Physical barriers can also be used in a similar manner. Again, these treatments are limited to shallow water but good results have been attained. Alternative explosives such as shaped charges, radial hollow charges, and shock-wave focusing techniques hold potential for making modest to large reductions in sound levels, although more data is needed. Shaped charges are currently being used and are preferred by some due to their focused, ‘clean’ cutting ability. Reductions in peak level on the order of 4 dB have been measured, with energy reductions on the order of 10 dB. Acoustic data on radial hollow charges and shock-wave focusing could not be found. Blasting mats similar to what is currently used on land may also be an option for sound reduction, but no data are currently available regarding effectiveness. When boreholes are used to remove obstacles, the hole should be capped with an inert material such as crushed rock; this can provide significant reductions in peak sound pressure. Slow burn rate explosives produce impulses that are much longer in duration and with slower rise times than conventional explosives; fewer fish mortalities have been observed when slow-burn explosives are used. Cutting tools are an alternative to explosives that can greatly reduce sound levels. Noise levels are estimated to be on the order of 80 dB lower when using cutting methods vs. explosives, and high level impulsive sounds are removed. However the time required for these techniques is longer than for explosives use.

- **Vessels (Propellers and Thrusters) –** Underwater noise from vessels is often dominated by propeller and thruster cavitation, particularly when operating at full speed or when positioning thrusters are operating. Many options for reducing noise from propellers and thrusters currently exist and have been implemented on a large number of commercial vessels to-date. Good propeller design, including large diameter, slow turning props, as well as blade shapes optimized to flow conditions, increased skew, and hull modifications to improve flow conditions are effective ways to reduce underwater noise. These modifications can potentially increase propulsion performance on some vessels, although decreases in performance are also possible. Ducted propellers and thrusters can also be designed to have significantly lower noise levels, particularly when outfitted with unconventional ‘forward-skew’ blades. Drop thrusters, Z-drives, and podded propulsion systems can be effective at reducing underwater sound by moving the thruster or propeller to locations with better flow conditions. Waterjets are excellent alternatives for high speed craft normally operating between 30 and 45 knots – propulsion efficiency is higher than for conventional open propellers, and noise can also be significantly reduced due to vastly increased cavitation inception speeds. Voith Schneider and rim drive propulsion systems, as well as alternative rudder designs, can reduce underwater noise and are evaluated in this report. Foul release coatings have been shown to provide some attenuation at certain frequencies, although this reduction is dependent on the operating conditions and increases in noise can occur. Propellers made from composite materials may also provide noise reductions due to the different shape options that are possible compared with conventional metal propellers. Various air bubble injection systems have been employed on some craft with large sound reductions at higher frequencies (above 500 Hz); however these systems are often plagued with issues of marine growth and can easily clog if not properly maintained. Special modifications to the trailing edge of propeller blades have been shown to eliminate ‘singing propeller’ problems. Lastly, the importance of regular maintenance is stressed in order to identify problems such as bent or broken blades or marine growth that can drastically increase noise and reduce propulsion efficiency.

- **Vessels (Machinery Noise) –** Machinery induced noise on vessels becomes dominant below cavitation inception speeds (8-12 knots on many commercial vessels) and can be significant at frequencies below 200 Hz even at full speed. As is the case with propellers and thrusters, treatments for machinery induced noise have been implemented on many commercial vessels and are readily available. Vibration from large machinery such as power generation and propulsion equipment are likely to be the most significant sources / paths of underwater sound, with possible additional contributions from large pumps and compressors. Airborne and "secondary structureborne" noise paths can also be important in some cases. Selection of inherently quiet machinery is the best option for noise reduction as this results in essentially no impacts on weight or space. Resilient mounting of machinery is a relatively low cost method of achieving significant reductions in underwater noise caused by machinery vibration. Options for mounting of individual items or multiple items on a common "floating deck" have been established and are commonly used in practice. Various damping methods are also available for added noise reduction from structureborne and secondary structureborne paths. Air bubble layers located along the underside of the hull have been used to reduce noise from all paths and multiple sources on many vessels; as noted above for propeller and thruster noise, these systems can become fouled if not properly maintained. Hull decoupling materials have also been used for similar purposes. Cladding treatments in machinery spaces such as fiberglass or mineral wool can be used to reduce airborne and secondary structureborne effects. Machinery enclosures can also be used for the same purpose, and have a slight improvement in effectiveness; however implementation generally requires greater engineering efforts and spatial impacts. Sea connected systems ("fluidborne paths") can also create detectable noise levels on vessels, although this is usually a concern only for very quiet vessels. Various flexible piping options exist to reduce noise from the fluidborne path, as well as multiple pulsation damper options.

- **Dredges –** Underwater noise from dredges is believed to be largely due to on-board machinery or propellers and thrusters (when present and operating). The limited available data indicates that noise produced at the dredging head is less significant than other machinery sources. As a result, treatments for dredges are similar to those described for vessels, although the specific machinery items requiring treatment will likely include items specific to dredging operations (i.e. dredging pumps). Additional data is necessary to better quantify the contributions from the dredge head relative to other sources.

- **Post Trenching –** Extremely limited information was found regarding underwater noise levels for post trenching, and no treatments were identified specifically for post trenching machines. It is believed that since trenching machines are towed by vessels, vessel noise is likely to be the dominant source of noise. As such, application of vessel treatments would be appropriate here. Additional information is needed in order to make a more informed determination of significant noise makers and treatments.

- **Hand Tools –** Noise measurements of underwater hand tools were found in one reference; some tools such as the Cox Bolt Gun can reportedly produce peak sound levels on the order of those seen during pile driving. No attempts to reduce underwater sound from these sources were identified. Some limited suggestions on noise reduction are provided in this report. Additional study is needed in order to provide more accurate recommendations.

- **Platforms –** Noise from production and drilling platforms is often dominated by vessel noise. As such, vessels supporting these platforms should be treated individually. In some cases it may be possible to develop methods that allow vessels to moor or otherwise secure themselves to platforms or other structures so that they can turn off their thrusters (which is the dominant source of noise). Such approaches should obviously be employed only when practical and when safety issues can be effectively resolved.

  Noise levels from platforms vary depending on the platform type. When vessel contributions are removed, drillships have the highest source levels, followed by semisubmersibles, FPSOs, and other floating platforms. Fixed platforms have lower underwater radiated noise levels than floating platforms, and gravel islands appear to have the lowest source levels of any oil and gas industry activity. Underwater levels from platforms containing positioning thrusters are highest when thrusters are operating. Thruster treatments described for vessels are applicable here. It is suggested that platforms be moored whenever possible to avoid thruster use.

  Little information has been published as to which sources and paths are most significant in creating underwater noise from platforms. Given the available information, it is believed that vibration from large power generation equipment is likely to be a dominant cause of underwater noise for all platform types. Other large equipment items such as turbines, compressors, and large pumps (e.g. mud pumps) may also play a significant role in certain circumstances, particularly when they are hard mounted directly to the supporting structure. Vibration treatments described for vessels such as use of low-vibration equipment and resilient mounting can also be applied here. The significance of airborne and secondary structureborne paths will depend on the specific platform type and construction, but these paths are believed to be more significant for floating platforms. Airborne noise paths through hull plating can be important on platforms where equipment is located below the waterline. Direct airborne transmission into the water can also be a secondary source of noise for equipment located near the edge of platforms or supported over open gratings with a line-of sight path to the water. Some airborne and secondary structureborne treatments described for vessels are applicable here, such as cladding treatments and enclosures. Identification of significant equipment items and selection of treatments will depend heavily on the equipment type, its location in the platform, and the desired noise goals.

  It is noted that some radiation from drill string casings may occur as a result of the various activities that take place within the casings. However, published data of measurements taken at various aspects around a drillship indicate this radiation may not be significant when compared to other paths. Additional study is required in order to better quantify the significance of this path. It is indicated in the literature that noise generated by the drill head itself does not appear to be a significant source of noise.

- **Hovercraft –** Underwater noise from hovercraft was found to be caused primarily from the propulsion fan, although contributions from the lift fans are also possible. Underwater noise is created through direct airborne transmission to the water. Therefore treatments that reduce airborne noise will also reduce underwater noise. Modifications to the fan blades and inflow

/ outflow characteristics have been identified as most practical. It is noted that hovercraft produce underwater sound levels that are much lower than for conventional vessels; use of hovercraft instead of conventional vessels may be an appropriate form of noise control for some applications.

- **Aircraft –** Aircraft, including jet airplanes, propeller planes, and helicopters, also produce underwater noise through direct airborne transmission. The major sources for jet planes include the jet engines themselves, while propellers and rotors are usually dominant for prop planes and helicopters, respectively. Propeller and helicopter motors appear to be secondary for conventional designs. "Hush kits" are available for jet engines and can reduce noise upwards of 10 dB at some frequencies. Similar to hovercraft fans and ship propellers, modifications to propeller and rotor geometry can result in reduced airborne and underwater noise. Newer aircraft are expected to be quieter than those manufactured 10 - 20+ years ago due to increased noise restrictions and regulations imposed at airports. These regulations focus on human hearing, so the primary reductions in noise are at frequencies that are most pertinent to humans. NoTAR ("No Tail Rotor") designs for helicopter have been proposed as a possible method to reduce noise; 0-7 dB reductions in overall level have been reported.

- **Pipelines –** No studies of pipeline noise or treatments were identified in the literature, and its significance relative to other sources was not found. It is suggested that pipeline noise may be caused by pump(s) attached to the pipeline, and therefore flexible connections and/or pulsation dampers may be effective treatments. Turbulence in the fluid may also cause noise and would need to be assessed on a case-by-case basis. Possible causes of turbulence are high flow velocities past a bend, orifice, etc. Additional study is needed.

A complete annotated table of treatments identified as part of this work is provided in Appendix A.

1.0 INTRODUCTION

Noise Control Engineering, Inc. (NCE) has been contracted by the Joint Industry Programme on E&P Sound and Marine Life[1] (JIP) to compile, assess, and summarize information on technologies capable of reducing underwater sounds from oil and gas industry activities. The goal of this work is to create a reasonably comprehensive database of currently available and future potential treatments that can reduce the underwater radiated sound from all oil and gas industry activities. JIP's interest in funding this work is to be able to identify methods of limiting the anthropogenic sound created by oil and gas industry activities in order to reduce the effects of these sounds on marine life.

When quantifying reductions in sound level from a given treatment, there are many metrics that can be used. Some of these metrics include long-term overall average level, sound levels at specific frequencies (applied both to short and long duration sounds), impulse peak amplitude (positive and negative peaks), impulse rise time, energy metrics, and even particle velocity. Each of these metrics can be important in a given context. For example, the negative impulsive pressure peak level, impulsive rise time, or total length of an impulse may be important when determining fish mortality, while long term sound levels over certain frequency bands may be important for determining whale avoidance criteria. Some of these metrics overlap, and there is not necessarily a consensus on which metrics are best suited for prediction of a given effect. To account for these issues, this report attempts to identify reductions (or increases) in sound using as many metrics as possible from the available information. It is left up to the reader to determine which metrics are pertinent to their particular application. Detailed descriptions of the metrics used in this report are provided in Appendix C.

When describing the effectiveness of a given treatment, this report generally provides changes in sound pressure level or energy in either decibels (dB) or absolute level. These values could also be expressed as changes in an 'affected radius' for a given sound source or level (i.e. a reduction in sound produced by a source would reduce the radius at which that source produces a given level). Since much of the literature uses the former approach, this method was adopted for this report as well. This also removes many of the complications associated with path effects that can vary for different locations and situations

This report is not intended to evaluate the potential impact of a given noise reduction on marine life, nor establish particular noise goals. Furthermore, the information and statements in this paper should not imply an obligation to use any particular abatement method. The treatments described in this report are provided as a reference for any group or individual who determines underwater noise reductions are necessary (either now or in the future), or is tasked with achieving a certain noise goal for a given activity. Methods of reducing impacts or noise exposure to marine life such as acoustic deterrent systems, gradual increase of acoustic energy (e.g. ramp-up methods currently used for seismic surveys), and visual or acoustic detection of marine life are not discussed here. This work does not attempt to characterize 'source levels' from oil and gas industry activities (which is the subject of another JIP funded project), except to give a general rank to help focus research efforts (see Section 2).

[1] www.soundandmarinelife.org

This report is divided into four sections, plus appendices. Section 2 provides general information on the methodology used to perform this study. Section 3 describes the sources identified for this study as well as notes on specific noise generation mechanisms and pertinent noise paths. Section 4 provides notes on specific treatments for each source type. An annotated table of treatments identified in this study is provided in Appendix A. Appendix B is a copy of the announcement for the Workshop that was held as part of these efforts, and includes a listing of presenters. Appendix C provides a description of the various metrics that are referenced in this report.

2.0 METHODOLOGY

This section describes the general approach used by NCE to research and create a database of treatments for underwater sound. Information was collected from various sources of information including technical and trade journal articles, contacts with representatives of companies that produce, own, or are developing noise control products and technologies, contacts with members of academia, and data provided directly by members of JIP and the International Association of Oil and Gas Producers (OGP). Additional information was collected through a workshop, organized and hosted by NCE and held on June 4-5, 2007, attended by members of JIP/OGP, the National Oceanographic and Atmospheric Administration (NOAA), US Minerals Management Service (MMS), the U.S. Army Corps of Engineers, and members of industry and academia. Methods for reducing underwater sound that had been uncovered in the research leading up to the workshop were presented to the attendees, both by NCE and by others with direct experience in a particular approach. These techniques were discussed amongst the group, and comments and new ideas were presented. Information and conclusions that resulted from these presentations and discussions have been implemented in this report. Such information is noted in this report as coming from the "Workshop" without further reference. Appendix B provides the workshop schedule which includes a list of speakers.

In order to effectively identify treatments for reducing noise from any noise source, the mechanisms of noise creation must be known. As a result, it was necessary to perform this study in two parts: 1) identification of sound sources, including pertinent sound radiation mechanisms, and 2) treatment identification. To initiate the study, a list of oil and gas industry activities and acoustic sources was developed, and a rough estimate of the underwater acoustic 'source level' and affected radius were determined based on published literature and available information[2]. The sources were then ranked in order of importance based on this information. Sources that tend to create higher noise levels or are detectable at larger distances were ranked as more significant, taking into account duration of noise events. This ranking was used to focus research efforts into identifying treatments for those sources that are most significant with regards to the creation of underwater noise.

As part of this task, NCE attempted to identify pertinent 'noise makers' that may be part of a particular source or activity – a diesel engine providing power to a drilling platform, for example – as well as relevant noise paths that lead to underwater sound. This information is imperative if effective and cost efficient treatments are to be identified and developed. If more than one

[2] Detailed sound level identification is not the focus of this study, but is rather the focus of a separate JIP funded study. Absolute source level information is not provided in this report.

possible noise maker or path was possible from a given source type, then these were also ranked in order of significance. Greater research efforts were given to higher ranked sources / radiation mechanisms.

The second part of the study involved identifying specific treatments of sources and noise paths. Information on treatment effectiveness as well as details on treatment implementation, costs, environmental impacts, and other non-acoustical impacts such as changes to space or weight, was collected from the literature, vendors, and other sources when available. As was discussed in Section 1, many metrics are used in the literature to describe a reduction (or increase) in sound level. NCE has included as many of these metrics as possible with the purpose of allowing the reader to determine which metric is most beneficial for their application. In the process of identifying feasible and useful treatments, NCE pursued those treatments that either showed proven results or significant potential for underwater noise reduction. If a treatment was found to not be feasible or have limited application, further investigations were reduced.

3.0 SOURCES

This section provides details of the sources investigated for this study. Section 3.1 provides a complete source list with a 'significance ranking' assigned by NCE (see Section 2). Section 3.2 provides details on the mechanisms for underwater noise generation for each source. (Treatment information is provided in Section 4 and Appendix A.)

3.1 Source List

Table 1 provides a list of the sources that were investigated in this study. Also included are the approximate frequency ranges affected by each source and the associated ranking given by NCE. Rank values range from 1 to 5, with 1 being most significant. As was stated in Section 2, this ranking was based on the approximate overall source level for the source type, the affected or detectable range from the source, and duration or prominence of sounds.

It is important to point out that the total range of overall sound levels for all sources covers a span of over 150 dB, so it is necessary to have each rank value cover a wide range of source levels. For example, explosives are ranked in category 1, but even within the explosives group there is a wide range of possible source levels, spanning 20 dB or more in overall level, depending on the size of the explosive and other factors. Another example is vessel noise, which can range by 30 dB or more depending on the specific vessel type and operating condition. This table is not meant to show equality between the various types of sources as much as it is a tool that was used by NCE to broadly group sources and focus research efforts. Source level characterization is not the goal of this report, but is the subject of a separately funded JIP effort.

TABLE 1: List of Sources with Assigned Rank and Affected Frequencies

Category	Source Type	Frequency Range	Rank (1-5)
SEISMIC EXPLORATION	Explosives	Broadband components from low frequencies (<10 Hz) to 10s of kHz. Highest at frequencies < 1000 Hz	1
	Air Gun	Primary components <120 Hz Broadband components up to 20+ kHz	1
CONSTRUCTION	Impact Pile Driving	Broadband components from low frequencies (<10 Hz) to 10s of kHz. Highest at frequencies < 1000 Hz	1
	Explosives	Broadband components from low frequencies (<10 Hz) to 10s of kHz. Highest at frequencies < 1000 Hz	1
	Dredges	20 – 6000+ Hz (Higher with propulsion)	2-3*
	Post Trenching / Jetting	N/A	N/A
	Underwater Hand Tools	100 to 1000+ Hz	2-5*
VESSELS	Tankers	Broadband components 10 Hz to 100,000 Hz possible. Highest levels / tones at frequencies below 1000 Hz	1
	OSV/PSV		1-2
	Tug/Tow Boats (work boats)		1-2
	Crew Boats		1-2
	Pipe Laying Vessels		1-2
	Icebreakers		1-2
	Hovercraft	Peaks at propulsion and lift fan blade rate & harmonics. Broadband components 10 Hz to 10,000+ Hz.	4
PRODUCTION / DRILLING	FPSO	N/A (Assumed similar to Drillships)	3**
	Drillships	Single Hz to several kHz minimum, 10s of kHz with thrusters	2
	Semisubmersibles	Dominant frequencies < 100 Hz, Some higher frequency components, 10s of kHz with thrusters	2-3
	Deep Water Floating Platforms	N/A (Assumed Similar to Semisubmersibles)	3**
	Fixed Platforms (Jack-Up, Steel, Gravity Base)	Dominant frequencies < 100 Hz, Some higher frequency components	4
	Caissons	10 – 1000+ Hz	3
	Gravel Islands	< 200 Hz	5
	Pipelines	N/A	N/A
AIRCRAFT	Fixed Wing (Jet)	10-8000 Hz	3
	Fixed Wing (Propeller)	50-1600 Hz	3
	Helicopters	10-800 Hz	3

*Rank depends on specific source. See details in Section 3.2
**Source level information was not available. Rank is estimated based on expected levels.

The sources ranked as being most significant are air guns, explosives, pile driving, and vessels (excluding hovercraft). Air guns, explosives, and pile driving sources produce impulsive sounds with high peak levels, as well as short rise-times and impulse durations. These sources create broadband sounds that extend to many kHz. Broadly speaking, explosives used for decommissioning or construction produce the highest peak sound levels of any of these sources, although the sound events are relatively infrequent (a few blasts a day). Air gun and pile driving impulses typically repeat every second to several seconds over the course of one or more days. Vessels create sound levels with amplitudes that are lower than these other sources, but they are ranked highly due to their prominence and their shear numbers in all non-terrestrial oil and gas related activities. For example, it is often the case that vessel noise dominates the measured sound from all drilling and production platforms (Richardson, 1995; McCauley, 1998; Greene, 1987), and the ocean's low frequency background sound is associated with noise from vessels (Urick, 1967).

3.2 Source Details

This section provides details on the identified mechanisms that create underwater sound for each source in Table 1. This includes paths of sound transmission and identification of specific 'noise makers' within a source, such as a generator on a platform. It is noted that for some sources in Table 1, studies of specific sound generation mechanisms are not available. Causes of underwater noise are sometimes inferred from available measurements, known physical laws governing sound radiation, and past experience. Such inferences are noted in this report.

3.2.1 Seismic Surveys

Conventional approaches to marine seismic surveys include the use of a high-level impulsive sound source. The most common and widely used examples of such sources are air guns, although explosives, "sparkers," and other impulsive sources are also used. This section focuses largely on air guns, although many of the treatments for seismic exploration discussed in Section 4.1 apply to seismic surveys as a whole.

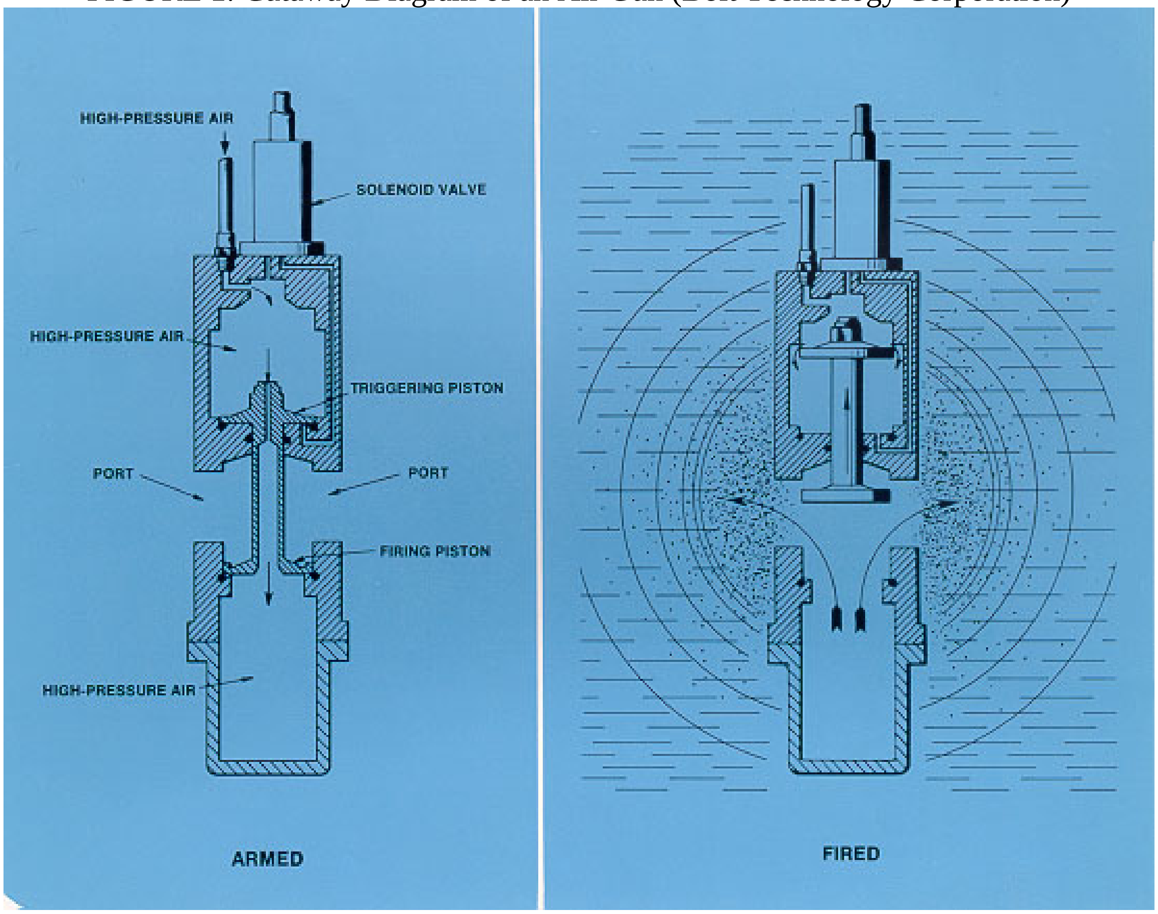
Air guns create an impulsive sound via a rapid release of compressed air in a metal cylinder. A diagram of this mechanism is provided in Figure 1. The impulse is largely broadband in nature, and can have frequency components that extend at least to 20,000 Hz (Goold, 1998). Frequencies that are used for seismic exploration are commonly in the 5-100 Hz range, and thus a significant amount of the acoustic energy produced by air guns is not used during seismic surveying.

Air guns by themselves are essentially omnidirectional (Duncan, 2000). In practice, some directionality exists from a single air gun due to reflections at the ocean surface. Air gun arrays are used to provide additional directionality, which is dependent on the size of the array. Caldwell (2000) shows a 20 dB difference between the overall level measured directly below an array vs. the overall level measured horizontally (although not at the water surface where pressure always vanishes)[3]. Directionality can be important in controlling unwanted sound from air guns in the sense that sound may be propagated in lateral directions where it is not necessarily useful for seismic exploration.

[3] Note that there is another JIP study is undertaking 3D characterization of sounds around an airgun array.

While some underwater sound may exist from vessels used to deploy air guns and air gun arrays, the amplitude of this sound is certainly secondary to the air gun itself.

FIGURE 1: Cutaway Diagram of an Air Gun (Bolt Technology Corporation)



Left side shows internal parts of a typical air gun. Right side shows release of compressed air in lower chamber into surroundings after piston is raised. Rapid release of compressed air creates impulsive sound.

3.2.2 Pile Driving

Underwater noise from impact pile driving is impulsive in nature. The impulse spectrum is broadband and can have components well into the kHz range (for example, see Laughlin, 2005b; Laughlin 2007). Low frequencies (<200 Hz) typically dominate the overall levels from impact pile driving.

While no direct study of sound generation mechanisms from pile driving was found, it is believed that the predominant underwater sound generation mechanism for pile driving is through excitation of, and radiation from, the pile itself. Excitation of the pile occurs when the driving hammer strikes the pile. Vibrations are carried through the length of the pile (and reflects back along the pile at its ends), and these vibrations radiate noise into the surrounding water. This assumption results from measurements of treatment effectiveness where the pile is shielded from the surrounding ocean (see Section 4.2).

There is also an indication that some sound may be propagated and radiated through the ocean floor (Laughlin, 2006a; Reyff, 2004). Laughlin (2006b) measured underwater noise from piling operations that took place outside the high water mark; noise was monitored in a nearby creek. Underwater levels were lower than would be expected from a direct measurement of a pile located in the water, but were not insignificant. It is assumed that some ground conditions and substrates are more susceptible to ground-flanking than others; additional study would be needed in order to quantify this effect. Flanking paths may also exist through barges that support pile driving equipment (Wursig, 2000) and through airborne flanking from the impact of the hammer on the pile above the water. These flanking paths are more likely to be significant when direct radiation from the pile has been treated.

Vibration pile driving is another method that is widely used. 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 10-60 Hz. (Note that this source is not impulsive.) 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 kHz (Greene, 2004; Nedwell, 2002). There is some indication that vibratory methods may have lower overall noise levels (Laughlin, 2005a; WSDOT, 2005; Nedwell, 2002; Blackwell, 2003). Reductions relative to impact methods could be on the order of 10-50 dB, although there is significant variability in the data. That said, impulsive effects are removed for vibratory methods which may be beneficial in certain applications.

It is noted that underwater sound data published in the literature typically shows a fairly wide variation in the levels generated by pile driving, even during the installation of a single pile. Differences in peak level of 5-10 dB or more from one hit to another are common. The same can be said about vibratory methods where variations of 20 dB or more are seen in data. As such, determinations of treatment effectiveness are sometimes rough, and data is often scattered.

3.2.3 Explosives

Explosives are used by the oil and gas industry for several applications, including decommissioning of offshore structures, removal of rocks and other obstacles, and seismic exploration in shallow waters (typically marshes or areas where air guns can not be used). In this report, treatments for explosives focus on decommissioning and obstacle removal. Most of the treatments identified for seismic exploration apply to explosives use in seismic applications (see Section 4.1).

Explosives are often identified as “high” explosives and “low” explosives. High explosives have very fast rates of detonation, on the order of 15,000 to 30,000 ft/s (4500 to 9000 m/s), whereas low explosives have detonation rates closer to 0.1 to 1 ft/s (0.03 to 0.3 m/s) (Urick, 1967). High explosives are commonly used in the field, and are the focus of this section. Low explosives are discussed as a potential alternative in Section 4.3 and in Item EX4 in Appendix A.

High explosives create very sharp pressure impulse due to the rapid conversion of solid chemicals into gaseous reaction products (Urick, 1967). This initial pulse is a shock wave that travels in all directions. The shock wave is followed by a series of pulses caused by oscillations of the “gas globe” or gaseous bubble that is left behind after the initial detonation. It is noted that these pulses do not occur if the gas globe breaks the water surface or if the explosion is contained in a structure that does not rupture.

The sound generated by a blast from a high explosive can extend from low frequencies (<10 Hz) to tens of kilohertz, and possibly higher. For open water blasts, or blasts used for decommissioning where the structure is successfully cut, the transmission path is essentially direct radiation. It was noted at the Workshop that secondary radiation by nearby structures may be possible. In this scenario, the explosion excites a structure, causing vibration that travels to other locations in the structure and radiates additional sound into the water. No studies of this phenomenon have been found in the literature.

For confined blasts, there is some transfer of sound through the structure or rock that is confining the blast. Nedwell (1992) provides a comparison of the pressures (as a function of time) produced by open water and confined blasts. Open water blasts appear to have a large, single (initial) pressure spike, whereas confined blasts appear to have 2 dominant spikes and an extended impulse time. Nedwell suggests that the reason for the 2 spikes in the confined blast is there are two paths of propagation – one through the rock and one through the water. The path through the rock would arrive first due to the higher speed of sound in that medium. Peak pressures are also shown to be reduced by 94% for confined blasting relative to open water blasts.

3.2.4 Vessels
In a broad sense, the primary causes of underwater radiated sound from vessels are fairly well understood. That said, analysis and prediction of underwater noise from vessels (as well as treatment selection) is far from trivial, and must typically be performed on a case by case basis. Noise radiation from vessels, including tankers, Offshore or Platform Supply Vessels (OSV or PSV), work boats, crew boats, pipe laying vessels, and icebreakers, is generally caused by propeller/thruster cavitation and machinery noise. Noise from sea connected systems can also play a role in the total underwater radiated noise signature from a vessel, but this is only significant when contributions from propulsion and machinery are minimized[4]. Each of these sources has their own intricacies and sub-categories for noise generation.

To get a rough sense of what noise-producing mechanisms are most important on vessels, a comparison of underwater noise from selected vessels operating under various conditions is provided in Figure 2. The spectra in this graph were previously measured by Noise Control Engineering and others as noted. Measurements were taken in the far field (distances ~100-300 meters) and corrected to an equivalent 1 meter 'source level' using spherical spreading assumptions (20 $\log_{10}$(range) scaling). This figure is not provided to identify specific source levels of different ships per se, rather it is meant to highlight several facts of underwater noise from vessels.

1. *Underwater noise from any vessel is strongly dependent on speed.*

[4] Other noise generation mechanisms also exist, such as flow noise from hull surfaces. These problems are less common and are generally treated only as needed.

This can be seen most clearly by comparing the levels measured for a research vessel (R/V) at 12.8 knots and 0 knots. Differences between these two conditions are on the order of 10-20 dB at and above 160 Hz. Similar differences have been shown for many other vessels (e.g. see Kippel, 2007).

The differences in noise level seen for slow vs. fast speeds can be largely attributed to propeller cavitation noise[5]. (This noise is also seen for thrusters when operating.) Cavitation noise commonly arises at speeds between 8 and 12 knots and grows in amplitude with increasing speed. 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 as well. Cavitation noise is often seen when vessels are underway at transit speeds (which is most of the time for many vessels), when vessels use controllable pitch propellers at 'off-design' pitch, when vessel are operating under high load conditions, or when dynamic positioning systems are used. Note that vessels moving slowly but with high thrust (such as during icebreaking or bollard pull) can have underwater radiated noise levels similar to what is seen at full speed, or higher; these noise levels are again caused by cavitation in most cases.

Propulsion machinery and power generation equipment can often be detected at lower frequencies, i.e. below 500 Hz. Machinery noise often dominates the spectrum at lower vessel speeds, but it can also be significant at higher speeds as well (Fischer presentation at Workshop). For the "R/V' in Figure 2, the peaks at 63 and 125 Hz are attributable to machinery noise, particularly at 0 knots.

2. *Underwater noise levels are not simply dependent on vessel size.*

The icebreaker and tug boat underwater noise levels in Figure 2 are very similar, even though they have vastly different sizes. Cavitation noise is the primary reason for the levels seen here. There is a correlation between noise and propulsion power, but there are also many other factors of ship design that are important for underwater noise generation (see Section 3.2.4.1 below).

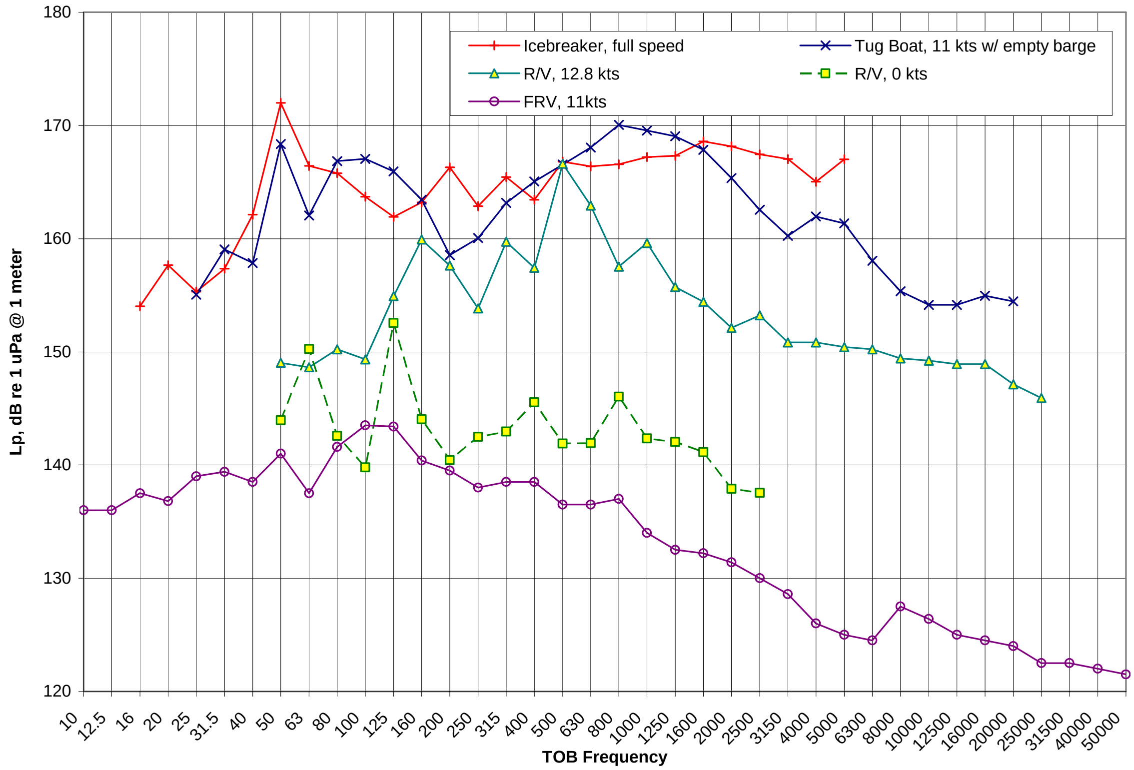
3. *Changes to the propeller design and machinery treatments can have large impacts on underwater noise.*

The 'FRV' (Fisheries Research Vessel) in Figure 2 has a modified propeller which delays the speed at which cavitation begins to speeds above 11 knots. When compared to the 'R/V' operating at 12.8 knots where cavitation is certainly present, the noise levels are seen to be 20-25+ dB lower at frequencies at and above 160 Hz. It is also seen that at 63 and 125 Hz, where machinery noise is significant in the R/V radiated noise, the FRV is 5-8 dB quieter. This is due to effective isolation of machinery and a low noise/vibration DC propulsion motor (see Section 4.4.2). Even at full speed (14 knots, not shown here) the FRV has lower underwater radiated noise than the other vessels presented.

[5] See Section 3.2.4.1 for a description of cavitation.

Sea-connected piping paths are generally an issue only for otherwise quiet vessels (such as the FRV seen in Figure 2). Even then, this path may only be an issue at low speeds. This path will likely be of little concern for commercial vessels, but they are discussed briefly in this report.

FIGURE 2: Comparison of Underwater Noise from Various Vessels



Icebreaker noise derived from Cosens (1993). FRV measured by US Navy. Others measured by NCE. This graph shows 1) the dependence of underwater noise on vessel speed ("R/V" at 0 knots vs. 12.8 knots), 2) vessel size is not necessarily an important factor in underwater noise (Icebreaker vs. Tug Boat), and 3) potentially large reductions can be made in ship noise when propeller cavitation is minimized and machinery noise is controlled (FRV).

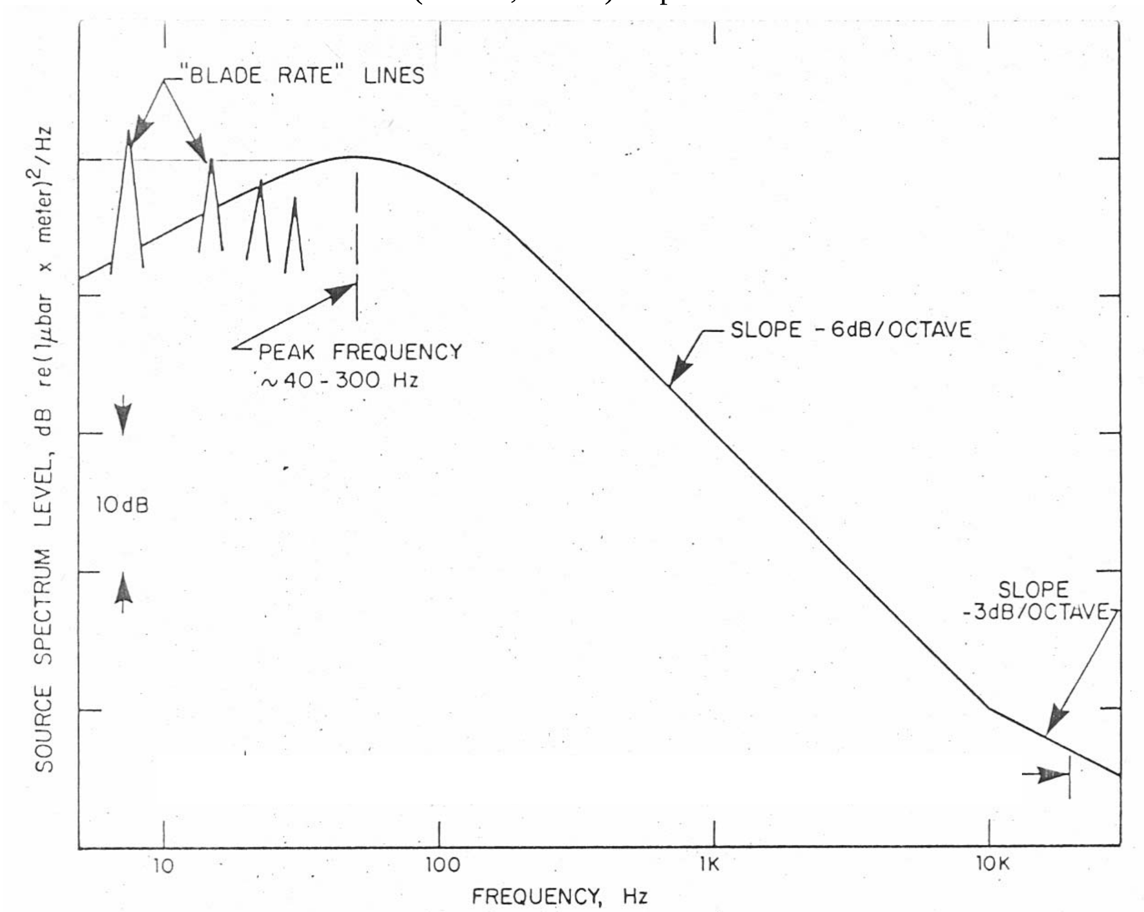
The mechanisms that cause underwater noise from propulsion, machinery, and fluidborne paths are vastly different. Because of this, each path is treated separately in this report. A summary of the pertinent mechanisms of noise creation for each of these categories is given below.

3.2.4.1 Propeller and Thruster Noise

Underwater sound generated from propellers and thrusters has a continuous spectrum (i.e. there are components of sound at all frequencies, a.k.a. 'broadband') with some tonal peaks at low frequencies (<100 Hz). Low frequency tones occur at blade rate frequencies and harmonics[6]. Broadband noise is generated by various cavitation mechanisms (explained below), and can have frequency components out beyond 100 kHz. A rough example of the overall spectrum shape is provided in Figure 3.

[6] Blade rate = propeller shaft rpm x number of blades / 60. Harmonics are at integer multiples of blade rate.

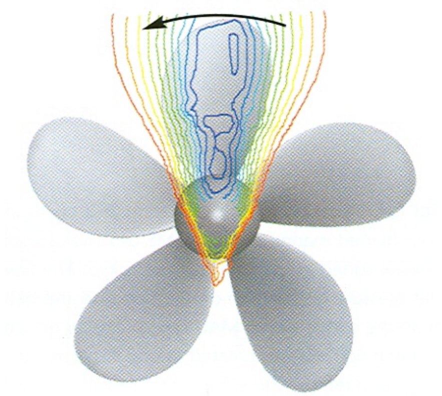
FIGURE 3: Sketch of Approximate Underwater Noise Spectrum from Cavitating Propellers (Brown, 1976a)Propellers



Broadband noise from cavitation covers the majority of the radiated spectrum. Tonal peaks, associated with blade rate and harmonics, can usually be detected at low frequencies, below 100 Hz.

Low frequency blade rate tones are generated when the propeller blades pass through the non-uniform flow created by the wake of hull surfaces and appendages located forward of the propeller or thruster. Shaft angle also plays a role, which effectively changes the angle of attack as a blade makes a full rotation. An example of a flow distribution entering a propeller is provided in the contour plot of Figure 4. In this figure, the flow is essentially uniform over the lower four blade positions. The fifth blade, at the top of the rotation, is passing through an area of lower flow velocity caused by shaft bossings, struts or a skeg supporting the propeller. When each blade passes through this non-uniform flow a vapor cavity expands and collapses, creating an acoustic monopole pulse which is radiated, spectrally, as tones at the blade rate frequency and harmonics.

FIGURE 4: Example of Non-Uniform Flow Into Propeller (Kawamura, 2005)



Lines indicate magnitude of incoming axial velocity. Blue lines show low velocity areas. The blade at the top of the rotation is passing through an area of lower flow velocity caused by shaft bossings, struts or a skeg supporting the propeller. When each blade passes through this non-uniform flow tones are created at blade-rate and harmonics.

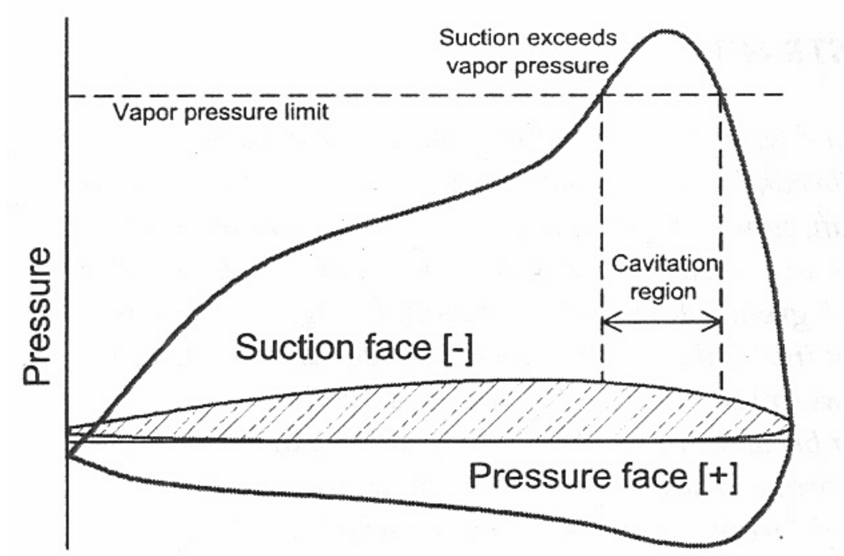
Cavitation occurs when the local water pressure drops below the vapor pressure limit. A diagram of this phenomenon is provided in Figure 5. In this diagram, the static pressure drops below the vapor pressure limit over a specific region of the propeller blade (suction, or forward side, in this case), and cavitation bubbles will form. Cavitation noise is generated when these cavitation bubbles collapse. This noise is largely omni-directional (note that at higher frequencies the blade and hull may have a baffling effect, reducing the apparent levels at some receiver locations). The specific operating conditions and locations when and where cavitation forms on the blade is a direct result of the specific blade design.

There are several forms of cavitation worth considering:

- *Tip vortex* cavitation – the blade tips trail load-dependent vortexes that form a string- or rope-like core cavity.
- *Leading edge* cavitation – a sheet-like cavity springs from the leading edge, usually on the low-pressure forward (suction) side.
- *Back-bubble* cavitation – at high speed the outer blade sections grow vapor bubbles at their thicker parts.
- *Hub vortex* cavitation –a rope-like cavity that springs and trails aft from the end of the hub cap. This is the hub counterpart of the tip vortex.

These different cavitation types will result in different underwater sounds. For example, Brown (1976a) notes that back-bubble cavitation is noisier than leading edge cavitation. Kuiper (1998) also provides additional information. The non-uniform flow field, seen in Figure 4, is very much responsible for cavitation related noise via its load-modulation effects (Kawamura, 2005). This is particularly true for leading edge and back-bubble cavitation types. These different forms of cavitation can become significant at different vessel speeds, and their formation will depend on the specifics of the blade design.

FIGURE 5: Example Pressure Distribution Over Propeller Blade Back & Face (MacPherson, 2005)



Cavitation occurs when the local water pressure drops below the vapor pressure limit. This will typically occur over a specific region of the propeller blade (suction, or forward side, in this case). The collapse of cavitation bubbles creates a strong, broadband acoustic noise source.

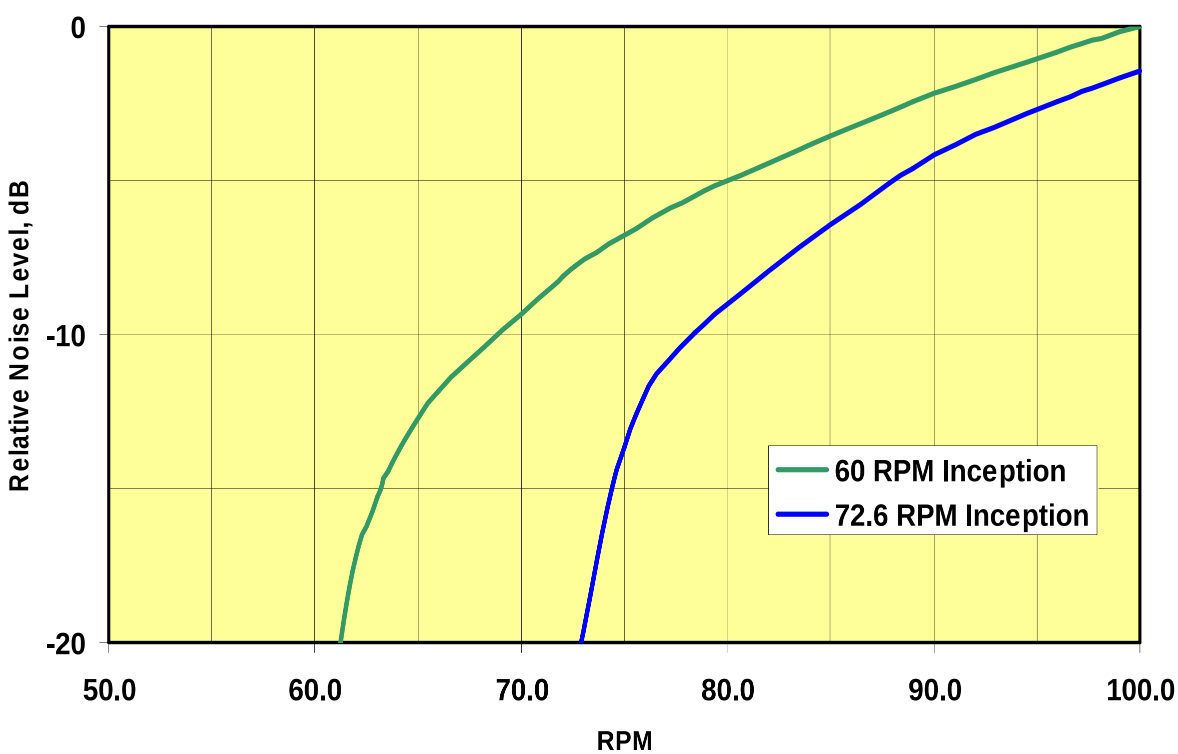
It is important to point out that the amount of noise generated from cavitation is directly dependent on the amount of cavitation formation. This can be characterized as the ratio of the blade area that is covered by cavitation bubbles to the total blade area (Brown, 1976a). The degree of cavitation is related to the ratio of vessel speed (which is also related to blade speed) to the vessel's "cavitation inception speed" (Brown presentation at Workshop). For propellers in calm water, the cavitation inception speed is simply the vessel speed at which cavitation begins to develop[7]. Below this speed there will be no noise from propeller cavitation, and the propeller as a whole becomes a relatively insignificant radiator of underwater noise (Fischer & Boroditsky, 2001).

For most small vessels, or those with heavily loaded propellers, cavitation inception speed is in the range of 8-10 knots. For larger ships or those with more lightly loaded propellers, the typical range is 10-12 knots. Carefully designed and operated naval vessels may achieve 15 knot inception speeds. Above cavitation inception, noise from cavitation rises as a function of speed-cubed or more at frequencies above roughly 300 Hz (Brown, 1977). Sound level differences from cavitation onset to fully developed cavitation (a difference in speed of roughly 10 knots for many vessels) can be upwards of 30 dB (Pinto, 1999). A similar relation exists for thrusters, where revolution rate is the critical parameter. Note again that cavitation can occur at slower speeds if the vessel is operating under high load conditions, such as during icebreaking, sudden changes in propeller speed, and bollard pull conditions. (The breaking of ice may be the most notable airborne noise above the water, but underwater the propeller cavitation is far louder.)

[7] As determined by "listening" for cavitation using a hydrophone. Note that this is often lower than the cavitation inception speed based on visual observation and much lower than that affecting power.

Figure 6 provides a theoretical comparison of the cavitation noise radiated by two vessels at various speeds using the equations presented by Brown (1976a) and Brown (Workshop). (The levels shown can be considered to be single frequency spectrum levels at frequencies above 300 Hz.) The vessels in this example have different cavitation inception speeds (corresponding to different shaft RPMs). It is seen that in the RPM region between the two cavitation inception speeds the difference in noise level is essentially infinite. Beginning at the higher cavitation inception speed (72.6 RPM), the differences between the two vessels get smaller, although reductions of 5 dB or more are seen below 85 RPM. The two curves will ultimately asymptote to the same line, but for practical speeds, differences of a few dB will remain. It is noted that this calculation is based on a first order approximation of cavitation area using ship speed (as noted above). Actual reductions in noise can be greater than what is seen here if the growth of cavitation with increasing speed is minimized.

FIGURE 6: Hypothetical Example of Underwater Radiated Noise vs. Propeller RPM for Two Vessels with Different Cavitation Inception Speeds(Brown, Workshop)



This figure shows the differences in noise level that are possible by increasing the cavitation inception speed for a given propeller/vessel. Between the lower and higher cavitation inception speeds the difference in noise level due to cavitation noise alone is (theoretically) infinite. Above this range, the difference decreases to a few dB at full speed. Larger differences may be possible if cavitation growth (i.e. the increase in the amount of cavitation with speed) can be minimized. This graph also shows that large reductions in noise can be achieved by operating at slower speeds, if possible.

Brown (2007) and Brown (Workshop) have also noted that an effective and simple way to reduce noise from vessels is to slow down. When this approach is combined with techniques to increase cavitation inception and reduce cavitation growth, very large reductions can be seen as evidenced by the large differences in the two hypothetical vessels seen in Figure 6 at less than full speed. Naturally, this approach would come at a cost (i.e. time and associated impacts).

The study of propeller and thruster cavitation is quite extensive and will not be discussed in more detail here. For more information on cavitation and noise generated by cavitation of propellers and thrusters, see, for example, Brown (1974), Brown (1976a), Carlton (1981), Nilsson (1981), Blake (1984), Breslin (1994), and Fischer (2005).

It is noted that other hull appendages may also cavitate at high vessel speeds; lifting appendages such as roll stabilizer fins and rudders are subject to cavitation, particularly on hydrofoil craft. Tip vortex cavities are sometimes observed from anti-roll fins on cruise ships. In fact, trailing fin-tip vortexes are sometimes drawn into a propeller resulting in intermittent severe vibration as well as propeller cavitation. While usually a naval problem, cavitation on sonar domes may occur, to the detriment of receiver signal-to-noise. On acoustic survey ships the structures supporting sonar transducers are liable to cavitate, if not properly faired and aligned with the local flow, and they can create wakes that add to the non-uniformity of inflow to the propeller(s). Similarly, bilge keels and other such appendages must be kept in repair, properly faired and aligned in order to avoid cavitation at high speed or propeller interference at any speed.

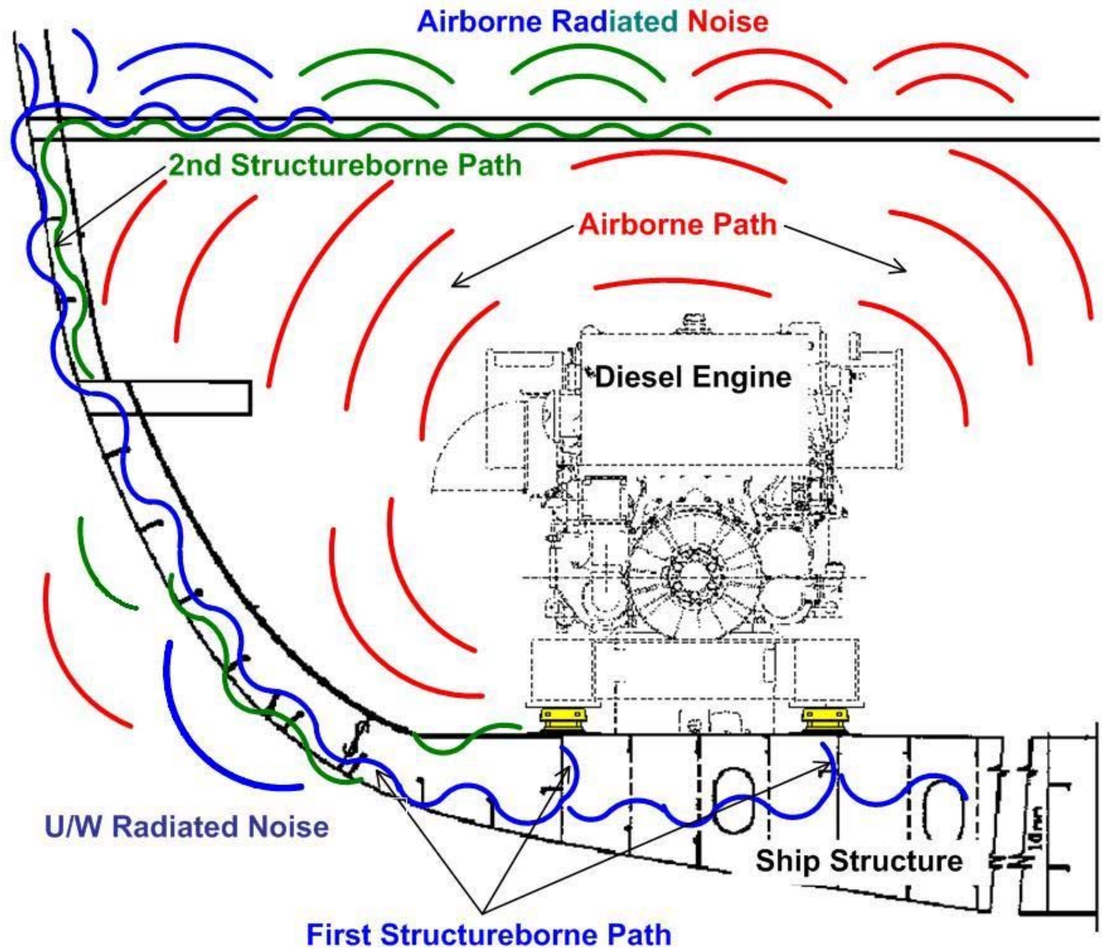
Lastly, another phenomenon called a “singing propeller” can create additional tones in the radiated noise spectrum. The amplitude of these tones can be large relative to the non-singing spectrum. This noise is created at one or more specific propeller blade resonance frequencies, which are excited by vortex shedding. Alternating (clockwise and counterclockwise) vortexes, parallel with the trailing edge, may be shed in a configuration called a “Karman vortex street”. The frequency of shedding varies with water velocity over the blade section and inversely with the combined local thicknesses of the blade section and flow boundary layers at the trailing edge. The associated alternating pressures can drive blade resonances that correspond in frequency and have adequate modal amplitude at the trailing edge. The shedding can also “lock on” to the vibration of the blade (i.e. maintain the same frequency even though flow conditions may have changed). The vibrating blades radiate sound into the water.

3.2.4.2 Machinery Noise

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. 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.

There are various mechanisms by which machinery can create underwater noise. Essentially, any machinery item will create both vibration and airborne noise. These excitations can generate underwater noise by means of several paths, called ‘first structureborne’, ‘secondary structureborne’, and ‘airborne’. A diagram of these various paths is provided in Figure 7.

FIGURE 7: Diagram Illustrating Three Significant Paths of Underwater Noise Generation from Machinery



Underwater noise from machinery is generated from local vibration and casing radiated airborne noise that cause the ship structure to vibrate. When these vibrations travel to or act directly on the ship's hull, underwater noise is created. This figure shows the three paths of noise from machinery to the water: 'first structureborne', 'secondary structureborne', and 'airborne'. Details of these paths are provided in the text below.

The first structureborne path (FSB) is related to the vibration of machinery. Vibrations are coupled to the ship structure through the machinery attachment points; these vibrations are carried throughout the entire ship. When the ship's hull is excited by these vibrations, underwater radiated noise is produced. The actual amplitude of the underwater noise is dependent on many factors, including the source vibration level, mechanical foundation impedance, distance of the source to the hull, details of structural connections between the source and the hull, plating thicknesses, radiating area and stiffener sizes (to name a few). Details of this mechanism are not important in the framework of this report and will not be discussed further.

The airborne noise path (AB) describes the noise that appears to pass through the ship's hull when a machinery item is located in a compartment that is adjacent to the water. The actual noise level that is created is dependent on the 'transmission loss' of the intermediate structure. The transmission loss of an untreated hull is largely dependent on plating thickness and stiffener spacing. It is important to point out that the airborne path only applies when the compartment containing a machinery source is directly adjacent to the ocean. Compartments that do not share a common partition with the ocean will not have a significant airborne noise path.

The secondary structureborne path (SSB) is a combination of the AB and FSB paths. Airborne noise that impinges on the source compartment boundaries (deck, bulkheads, and deckhead) causes those structures to vibrate. This vibration travels through the entire ship, as is the case for the FSB path. When the hull of the vessel vibrates as a result of the SSB path, underwater sound will result. Note that the SSB path will have little significance when a machinery item is located in a compartment that is directly adjacent to the ocean; in this case the AB path will be more significant than the SSB path. If the source compartment is not adjacent to the ocean then the SSB path will be (relatively) more significant.

For any vessel, the radiated noise levels caused by a particular machinery item will depend on the equipment itself (such as the airborne and vibration source levels, which are related to various parameters such as power – see Fischer, 1983), its function and duty cycle, pertinent noise paths, and the underwater noise goals for the vessel. Based on past experience, a general 'priority list' of equipment can be developed for most general designs of vessels common to the oil and gas industry (assuming no specific noise control treatments are applied). Topping this list is propulsion machinery such as diesel engines or turbines. Similarly, power generation equipment such as diesel generators are often a dominant source of radiated noise (these may be isolation mounted for crew habitability concerns, and would therefore be less significant than hard mounted propulsion engines). Pumps and other auxiliary machinery items would come next on the list; large pumps greater than 1000 HP and with long duty cycles being most significant. Furthermore, equipment located close to the ship's hull will be more significant than equipment located farther away. Propulsion gearboxes may also require some attention with regards to underwater noise. A detailed analysis is generally required in order to better define this list for any specific vessel.

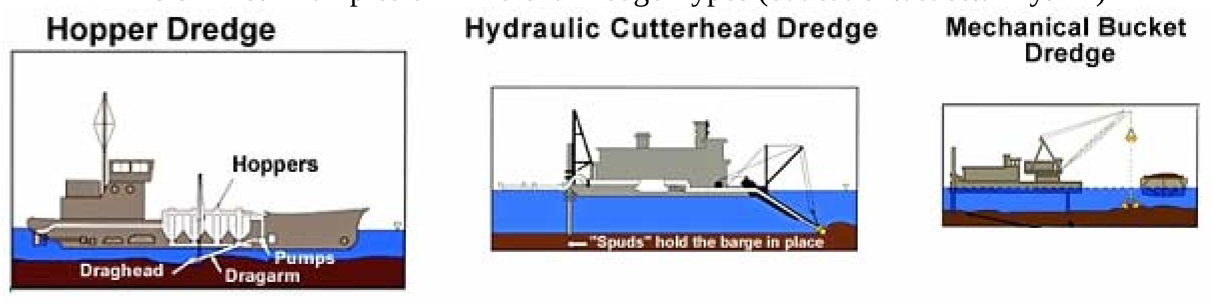
3.2.4.3 Sea-connected Systems

Sea-connected systems generally refer to pumps with piping that is directly connected to the ocean. Such connections are typically made through sea chests. Noise is generated in the fluid by the pump / piping system and is directly radiated into the sea. As noted above, this path is less likely to be a concern for commercial vessels.

3.2.5 Dredges

Dredges come in several forms. 'Hopper' dredges collect material from the sea floor and store it on board the vessel, then transit to another location to release the material. Material is often collected primarily via suction at a 'dredge head', although water jets or other similar tools can be used to help loosen the substrate. 'Transfer' dredges, also called 'Cutter Head' dredges, collect material and transfer or pump it to another location. The transfer of material off the dredge can occur via a pipeline that is routed far from the dredging operation (upwards of 10 miles) or to a 'hopper scow' or barge that is propelled and positioned using tug boats. The cutter head is typically a heavy-duty rotating structure which can be used to break and remove rocks or other heavy debris (explosives are used to break-up obstacles that can not be removed by the cutter head). 'Bucket' dredges are similar to transfer dredges in that they transfer material from the sea floor to a barge, although the removal is performed via a 'clamshell' or bucket that scoops material from the sea floor. Figure 8 provides examples of these various dredge types. Hopper dredges tend to move while collecting material, or otherwise use thrusters to maintain position. Transfer and bucket dredges are moored in place using 'spuds'.

FIGURE 8: Examples of Different Dredge Types (education.usace.army.mil)



Hopper dredges, seen on the left, suck material from the sea floor and store it on-board where it is then transited to a different location. Cutterhead dredges (middle) are moored in place and transfer materials removed from the sea floor to barges or on-shore locations via pipelines. Hopper and cutterhead dredges both use suction heads to remove material. Bucket dredges (right) are moored in place and use a 'bucket' to scoop material from the sea floor and dump it in a barge.

Underwater noise from hopper dredges tends to be louder than noise from transfer dredges by approximately 10 to 20 dB (Greene, 1987a). While reasons are not documented in the literature, this is likely due to the fact that hopper dredges use their propulsion system or thrusters while dredging. The potential presence of tug boats during transfer dredging operations means that significantly higher noise levels are possible, and the total noise in the vicinity of this activity may actually be similar to hopper dredges (noise from vessels is discussed in Section 3.2.4). This section focuses solely on the noise coming from the dredges themselves (although methods for quieting support vessels such as tugs should not be ignored in the big picture). Bucket dredging operations are significantly quieter than either hopper or transfer dredges by 10 to 60 dB, with the loudest noise coming from the bucket hitting the sea floor which is a very short event (USACoE, 2001).

Because dredges are essentially vessels with special dredging equipment attached, much of the information provided in Section 3.2.4 is applicable here as well. When in use, propellers and thrusters will likely dominate. Machinery noise can also be significant, particularly for transfer and bucket dredges. From the literature it is seen that underwater noise levels are generally higher (or at least different) during the actual act of dredging. Dredges utilize large pumps and additional power sources that are used specifically for dredging, and are likely to be responsible for a significant amount of the underwater radiated noise.

It is conceivable that at least some of the noise during dredging comes from the dredging head. The available literature, including Greene (1987a), Sachalin (2004), and Clarke (2002), provides little to no information on the relative amplitudes of noises that come from the vessel machinery relative to the dredging head for non-bucket dredging operations. The only practical information on this topic comes from Clarke (2002) who states (referring to a hopper dredge) “sounds of the draghead scraping across the sandy substrate could be discerned from propeller noise” for measurements where the vessel was 40 meters from the recording hydrophone. While not stated explicitly, it is believed that such segregation of noise sources could not be made outside of this range. In addition, the same study says (referring to a cutterhead dredge) “sounds… could not be partitioned into discrete components attributable to separate sound sources.” It is noted that the substrate was “fine sediments” in this case, and higher levels may result from the removal of rock or other heavy materials.

Given the available information it is believed that propellers and thrusters (when applicable) as well as on-board machinery are responsible for the vast majority of underwater radiated noise from transfer and hopper dredges. Additional study is necessary to better quantify the contributions from the dredge head relative to other sources. Ideally, this study would include comparisons of noise levels created during dredging of different materials.

3.2.6 Post Trenching

There is very limited information on underwater noise from post trenching machines. Nedwell (2004) provides measured data of the TRENCHSETTER, a deep water trenching vessel, while trenching operations are underway. The radiated noise spectra appear to be similar to what one would expect from a vessel, although no further study of noise generation mechanisms or source identification are given (it is not clear what type of machine or setup was used to perform the trenching itself). Nedwell (2001) may provide some underwater noise data from submerged post-trenching operations, but NCE was unable to procure a copy of this document for this study.

No other underwater sound data regarding typical submerged trenching machines could be identified in the literature. Blackwell (2003) provides underwater data from a ‘ditch witch’ and backhoe which were measured while cutting a hole in land-fast ice and digging a trench for pipe (water depth was ~12 m). Note that these machines are not standard or similar to conventional post trenching machines. It is presumed that the major noise from the ditch witch resulted from the actual cutting of the ice, although no indication is given in Blackwell. Possible noise generation mechanisms for the backhoe range from structureborne transmission to the ice with subsequent radiation from the ice to the water to noise associated with the digging action itself underwater, although sufficient information is not available to make a real determination.

Submerged trenching machines are commonly towed from a vessel and ride the pipe that they are burying. They do not have on-board propulsion systems, although they do have various means of displacing the material under the pipe. Since limited information is available, it is not possible to say what the specific noise generation mechanisms are for these machines. However, given the general prominence of vessel noise relative to other activities, it is likely that the vessel noise is the most significant factor and may dominate any noise coming from the trenching machine itself. It is possible that the various material displacement mechanisms cause sound, but the level of this sound is not known. Direct measurements are needed for further quantification.

3.2.7 Underwater Hand Tools

Information on noise from underwater hand tools can be found in Nedwell (1993) and Needham (1999). The sound levels from underwater tools vary depending on the specific equipment. Drills and grinders produce low sound levels (relative to the other sources investigated in this study) while impact wrenches and "Cox Bolt Guns" reportedly produce peak levels similar to those seen during pile driving.

The measurements made in these studies were made at the head of the diver that was using them (in the water outside of the helmet) or near the machinery. It stands to reason that much of the noise from these items comes directly from the equipment itself. However, in some cases such as the bolt gun, some coupling of vibration to the item or items being "worked" is certainly possible, and would cause additional radiation of sound.

3.2.8 Drilling and Production Platforms

Several references exist that provide measurements and assessments of noise from various platforms during production and drilling operations. In all cases, it is clear that noise from vessels associated with the platforms dominates the composite underwater noise signatures. Because vessel noise is discussed in Section 3.2.4, this section focuses on the noise originating from the platform itself. Noise from vessels should not be ignored when assessing the total noise caused by offshore drilling and production activities and appropriate treatments.

In general, assessments of 'noise makers' on platforms are somewhat limited. What is known or has been assumed in the literature is provided below. NCE has also made some educated guesses about particular noise makers and propagation paths based on the available data and past experience. Additional study would be required to better quantify specific causes of underwater noise from various platform types, and detailed analysis is certainly recommended when any specific platform is being assessed for noise reduction.

Details on the creation of underwater noise from various platform types are provided below.

<u>3.2.8.1 Fixed Production and Drilling Platforms</u>

Fixed platforms include jack-up rigs and platforms that are secured to the bottom either via mechanical means (i.e. piles) or gravity. The most useful source of acoustic information that was found came from Gales (1982) which is a study of many different platforms engaged in production and drilling activities. The available data show that there is little to no increase in noise levels from fixed platforms during drilling operations as compared to non-drilling operations. Gales states, "Underwater sound from platforms engaged in drilling did not in general exhibit markedly different characteristics from those engaged in production." More importantly, Gales states, "In general, none of the measured noise could be directly related to the mechanical action of the drill bits. It is possible that such noise may be generated, but if so there were no readily apparent clues to its identity."

Given this information, it is believed that most, if not all the noise created by the platform itself is due to sources that are located on the platform above the water. Gales also identifies a relation between underwater noise and power generation (lower noise levels were generally found when power was provided by shore connection). Given this result, and building on past experience (including Spence, 2006), major machinery items are likely to be largely responsible for underwater noise on fixed platforms. Dominant machinery items may include power generation equipment, mud pumps, water and gas injection pumps, large compressors, and other large machinery items ('large' being estimated as power ratings near or above 1000 HP). A more detailed analysis of specific platforms would be required in order to further refine this list.

Fixed platforms typically are supported with large structural beams or piping, and beam grillage structures are often the primary form of support. Plating is sometimes used between beams in the grillage, but these structures are generally very open (at last compared with floating platform types). Open grating may also be used in any given deck location. Given this structural makeup, and the fact that large equipment items are located on the platform above the water, three paths of noise are possible: first structureborne transmission (vibration from machinery passing from mechanical sources through structural members above the water to those below the water, which then radiate sound), direct airborne transmission from the machinery casing to the water, and secondary structureborne transmission (airborne noise excites the local structure above the water, creating vibrations that then travel below the water and radiate noise). (See Section 3.2.4.2 for additional details on structureborne paths.)

Of these possibilities, it is believed that the dominant path of noise generation in fixed platforms is the first structureborne path. Airborne noise may also play a role, but this is only possible if there is a direct line-of-sight to the water[8]. The secondary structureborne path is less likely to be of concern here since there needs to be significant plating surface area which the airborne noise would excite. Even then, the transfer of vibration energy from plating to heavy structural supports is weak, and this would further reduce the amount of energy that could travel to the water from this path (Spence, 2006).

While it is expected that the primary radiators are the structural supports of the platform, it is possible that some radiation from the drill string casing may be possible. However, it is seen in Section 3.2.8.3 that radiation from the drill string may be less significant compared to other paths of noise[9].

<u>3.2.8.2 Semisubmersible Platforms</u>

Underwater noise levels created by semisubmersible platforms are higher than that from fixed platforms. Nedwell (2004) presents measured noise levels for a semisubmersible when its thrusters are operating. The spectrum is smooth, with 20+ dB increases in levels compared to production only activities between 1 and 1000 Hz. The elevated spectrum continues out to 10,000 Hz in this case, with smaller differences seen at higher frequencies. This noise is clearly due to cavitation and the overall level is significantly higher than during any other operation. Therefore, when thrusters are used on semisubmersibles it is clear that this noise will dominate.

[8] This line of sight must be within a 13 degree 'cone' where propagation from air to water is possible. For more information, see Section 3.2.10.

[9] This assumption is based on data from a drillship where noise from on-board machinery is expected to be significantly higher than machinery induced noise on a fixed platform. Assuming that noise radiated by the drill string is roughly the same in both cases, drill string radiation may actually be significant when compared to the total noise for fixed platforms. Again, additional study is needed.

Nedwell (2004) also indicates that machinery noise can be heard when listening to the signal from a hydrophone suspended over the side of the platform. Furthermore, discrete tones were measured between 20 and 600 Hz in the spectral signal from these hydrophones during production activities (without thruster operation). Machinery induced noise, as described for vessels, is a likely explanation for these tones.

McCauley (1998) indicates that underwater noise during drilling is roughly 10 dB higher than during production. Nedwell (2004) also shows that additional tones are generated between 20 – 1000 Hz when drilling operations are commenced. The most prominent of these tones are at 130, 200, 350, and 600 Hz, with levels that are upwards of 30 dB higher than the levels at the same frequencies without drilling. Nedwell indicates that these increases in level may be due to natural frequencies in the drill string or cutting action of the sea floor. However, given the findings stated in Gales (1982) discussed above in Section 3.2.8.1, it is believed that the noise associated with cutting from the drill head will not be significant relative to the noise coming from the semisubmersible. Furthermore, it is seen in Section 3.2.8.3 that radiation from the drill string may be less significant than from other paths of noise. It is the opinion of NCE that the additional tones seen during drilling are likely caused by machinery that is used specifically for drilling, with noise being radiated through the platform structure[10]. It is suggested that additional study is needed in order to better identify the cause of these tones.

Gales (1982) also shows that that noise radiated directly from the air to the water from unmuffled diesel engine exhausts created “moderate” underwater noise levels[11]. These exhausts were apparently aimed directly at the water.

Based on available information, cavitation from thrusters is expected to be dominant over any other sound source. When thrusters are not being used, major machinery items will likely be the dominant noise source. As is the case with fixed platforms, significant machinery items may include power generation equipment, mud pumps, water and gas injection pumps, large compressors, and possibly any equipment item rated near or above 1000 HP. A more detailed analysis would be required in order to further refine this list. It is noted that semisubmersible designs can vary, with major equipment being located on the upper platform decks, in the pontoons, or in the supporting legs. Each of these cases would lead to different contributions from such machinery, and would need to be considered on a case-by-case basis.

No formal study or information was found regarding the dominant or significant paths of noise or radiation mechanisms on semisubmersibles. However the general construction of a semisubmersible indicates that these mechanisms will be similar to those found on vessels. The stiffened plating used on semisubmersibles can radiate machinery induced noise effectively into the water, and is also a conduit of vibration. As a result, the likely paths for noise radiation from

[10] The frequencies identified by Nedwell (2004) are typical of machinery induced noise. Note that similar tones were not seen for fixed platforms (in the available literature). This difference can be explained as follows. By its nature, the stiffened plating structure of a semisubmersible is a more efficient radiator of sound than beams or tubing which support fixed platforms in the water. Therefore, machinery sources that excite the semisubmersible’s hull will generate more radiated noise, particularly when that machinery is located close to the wetted hull structure. Again, this is a hypothesis and more study is needed in order to better determine the causes of these differences.
[11] Note that this would apply to other platform types as well.

machinery are the first and secondary structureborne paths for equipment located above the waterline, with airborne noise being a potential path for equipment located below the waterline adjacent to wetted shell plating (see Section 3.2.4.2). Equipment located closer to the waterline would be more likely to radiate significant underwater noise due to the FSB and SSB paths (for the same equipment item). As noted above, un-muffled exhausts may also be a cause of noise through direct radiation. Similarly, if equipment is located topside near the edge of the semisubmersible, direct airborne transmission is possible. Given the distances above the waterline for such equipment it is believed that direct airborne transmission paths would be secondary.

3.2.8.3 Drillships

Underwater noise from drillships is among the highest relative to the other drilling and production platforms when the noise contributions from support vessels are removed. Nedwell (2004) presents data measured at various distances and depths from a drillship. The data is relatively smooth and does not show evidence of peaks. It is presumed that the spectrum is the result of cavitation noise from thrusters being used to maintain position, although no indication of operating conditions were provided (the spectrum shape is similar to what is seen in Nedwell (2004) for the semisubmersible once thrusters are used).

Greene (1987b) indicates that bow aspect measurements of an anchored drillship have lower underwater noise levels than beam aspect (thrusters were not operating). This is the same result that one would expect on a vessel for noise being generated by the ship's hull via on-board machinery. It is expected that radiation from the drill casing would be symmetrical about the vessel, given its physical orientation and length. This is an indication that underwater noise radiation occurs more through the ship's hull than through drill casing. Further research may be necessary to quantify drill casing radiation.

Given the similarity of drillships to vessels, it is reasonable to believe that many of the same sources and radiation mechanisms are common. The dominant cause of underwater noise will likely be thrusters used to maintain position. When thrusters are not in use, machinery sources such as power generators, drilling machinery, propulsion equipment, ship power machinery, and utility equipment will likely dominate. In the case of drillships (and vessels in general), it is possible for smaller equipment items to cause significant noise levels if mounted directly to or in close proximity of the hull of the vessel. Paths of noise for machinery are similar to those described for vessels in Section 3.2.4.2 and methods of noise generation for thrusters are described in Section 3.2.4.1.

It is noted that some published information, such as Richardson (1995), indicate that the noise levels from drillships vary depending on the specific operation being performed by the drillship (drilling, tripping, well cleaning, etc.). Given the above argument regarding radiation from the drill casing, it is believed these differences are due to different machinery operating on the vessel as opposed to different noise levels being radiated by the drill casing. Further study is needed.

3.2.8.4 FPSO

No measured underwater noise data from FPSOs was identified as part of this study. However, given their form and function, it is reasonable to believe that the general sources and radiation mechanisms present in vessels are also the dominant causes of noise on FPSOs. Specific equipment that is most likely to cause noise on FPSOs is similar to that on platforms and semisubmersibles, namely power generation equipment, large pumps, and large compressors. As is the case on vessels and drillships, the proximity of these equipment items to the ocean (i.e. water line) will have a direct impact on the amount of underwater noise that is generated.

Furthermore, it is common for FPSOs to be moored to the sea floor in some manner. However in some cases it is necessary for thrusters to be used to maintain position (Paik, 2007). When in use, thrusters will likely dominate the underwater radiated noise from FPSOs (as was found for semisubmersibles). A discussion on thruster generated noise is provided in Section 3.2.4.1.

3.2.8.5 Deep Water Floating Platforms

No specific underwater noise information was found for deep water floating platforms. However, given their overall construction and function it is reasonable to believe that their sources and noise generation mechanisms will be similar to semisubmersible platforms. Naturally, no thrusters exist on a floating platform so this noise would not be of concern.

3.2.8.6 Gravel Islands

Gravel islands produce underwater noise levels that are among the lowest of any of the sources listed in Table 1. Sounds from gravel islands are often difficult to detect above 200 Hz (Blackwell, 2004).

The primary source of information regarding specific causes of noise and noise paths on gravel islands comes from Spence (2006). It is shown that the most likely cause of underwater noise on Northstar gravel island is vibration from large machinery, including power generating turbines, large compressors, water injection pumps, air compressors, AHUs, and the flare blower, with possible minor contributions from the oil shipping pumps and water booster pumps. This equipment was all rated at 800 HP and above. It was believed that the vibrations generated at the machinery traveled through the supporting structures, through the gravel itself and was radiated into the surrounding water.

Additional studies on this subject were not found.

3.2.8.7 Caissons

Caissons can come in multiple forms, and can either be weighted down on the sea floor by sand and gravel or can float in place. As noted by Richardson (1995), the radiated sound levels from these different constructions can vary, potentially significantly. Richardson provides levels measured from various caissons, but details as to which sources are causing noise or noise propagation paths are minimal.

Given the varying construction practices for caissons, it is not possible to succinctly identify the major sources and noise paths for the group as a whole. However, construction of certain caissons may be similar to other platform types – i.e. the use of stiffened plate for floating structures would indicate similarities with semisubmersibles and drillships, while gravel-filled caissons may be closer to fixed platforms from a noise sense. Additional study is needed to better identify sources and paths from caissons, and it is recommended that a detailed study be performed for any individual caisson being investigated for noise control.

3.2.9 Hovercraft

Hovercraft are generally very quiet, especially when compared to the other vessel types used by the oil and gas industry (and others). In fact, hovercraft are sometimes considered to be quiet alternatives to propeller-driven crewboats. One of the few but informative references on underwater noise from hovercraft comes from Blackwell (2005). In this study it was found that a tone caused by blade rate from the propulsion fan was the most dominant underwater noise caused by one particular hovercraft. The same study found that noise from the lift fan was barely detectable underwater; however it is possible that the lift fan(s) may be more significant on a different hovercraft design[12].

Underwater sound is created by direct airborne transmission from hovercraft; noise generated by the propulsion or lift fan is transmitted directly to the water. Structureborne noise paths are not significant given the air cushion design of the craft.

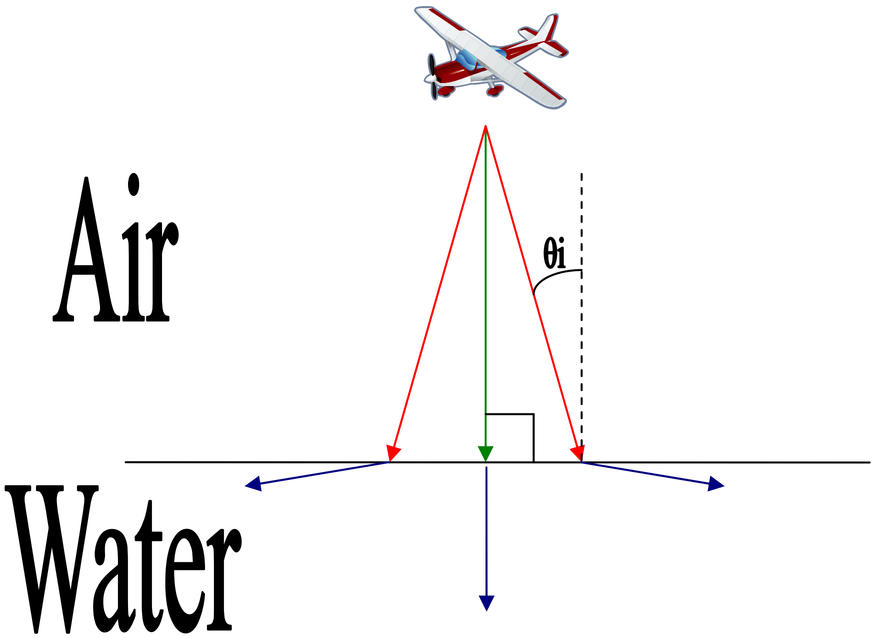
3.2.10 Aircraft

Aircraft, which includes jet and propeller driven fixed wing craft as well as helicopters, generate underwater noise by direct transmission through the air-water interface. This path is generally only a concern when there is a near-normal incidence with the water surface – see Figure 9. Because of the physical relationships of acoustic waves in air and water, there is only a small ‘cone’ of incident angles (θ_i) where airborne sound will enter the water as a propagating wave (Blackstock, 2000). Taking into account the speed of sound in air and water, this cone has a maximum angle of incidence of approximately 13 degrees (assuming a flat ocean surface). Beyond this angle, sound is reflected from the water surface and is not transmitted to the water (for all practical intents and purposes).

From inspection of Figure 9, it can be inferred that the affected area (i.e. the water surface area within the 13 degree cone) will grow as the aircraft rises in altitude. However, noise levels will be lower due to geometrical spreading losses from the air to the water.

[12] One might expect that the lift fans should also be a dominant contributor to underwater noise. For the hovercraft measured by Blackwell (2005), these fans may have simply produced inherently lower noise levels than the propulsion fan. Therefore the lift fans can not be ruled out as potentially significant (relative to the total radiated noise) on other hovercraft without additional data.

FIGURE 9: Diagram Showing Concepts of Direct Transmission Airborne-to-Underwater Sound



Airborne sound incident on the water surface will only propagate in the water if it is within an angle $\theta_i \leq 13^o$.

The primary causes of noise for jet propelled aircraft are the jet engines (Fahy, 2004). The engines generally produce many tones at frequencies of 500 Hz and above. It is noted that source levels are strongly dependent on operating condition and sound levels can vary between takeoff, landing, and cruising conditions. It is also noted that airframe noise can be significant during landing. The primary source on propeller planes is the propeller itself and the helicopter rotor is similarly the dominant source for helicopters. Sometimes it is possible to detect tones from the engines and other rotating parts on helicopters (Richardson, 1995). Perry (1992) also indicates that the interaction of wake between the main and tail rotors can be significant in some helicopter designs. In general, the strongest tones from propeller aircraft and helicopters are blade rate and multiples, with decreasing amplitude for higher order multiples. These tones typically are not distinctly seen above 500 Hz.

3.2.11 Pipelines

It was mentioned during the workshop that noise from pipelines may create significant noise levels. Measurements and analysis of pipeline noise were not found as part of this study. It is speculated that any noise generated from a pipeline may be a result of the 'fluidborne' noise within the pipe – i.e. the pressure fluctuations within the fluid that is being carried by the pipe. These fluctuations could be generated by the pump attached to the piping, and would likely show up as tones in the noise spectrum. Additional broadband noise may also result if turbulent flow conditions occur within the pipe. This can result from sharp bends, valves, and pipe discontinuities. It is expected that this noise would be more in the mid- to high-frequency range. Additional study would be needed to confirm any of these assumptions, and to determine the significance of pipeline noise.

4.0 TREATMENTS

A summary of treatments identified in this study is provided here. A compiled list of treatments for all sources, complete with treatment effectiveness, costs, and other details is provided in Appendix A.

4.1 Seismic Source Treatments

Almost all of the treatments and approaches identified to reduce sound generated by seismic exploration are not commercially available and are in various forms of development. However, all of them have been used in the field to varying degrees. The majority of these techniques replace existing seismic sources with alternative sources; these techniques also show the greatest potential for reduction of underwater sound levels. Details on all treatments identified for seismic exploration are provided in Section SE in Appendix A.

One approach described by Nedwell (2005) is called an "airgun silencer" which can be used to augment existing air guns. This silencer uses acoustically absorbent foam rubber to reduce sound levels at frequencies above those useful for seismic exploration. Test results show reductions in sound level of 0-6 dB above 700 Hz. An overall increase in sound level by 3 dB was measured, caused by an increase in sound near 100 Hz. This is in the frequency range useful for seismic exploration and the author suggests that this may allow for fewer air guns to be used for a given application. This approach is currently in the 'proof-of-concept' stage; other silencer configurations based on this approach may be possible that can yield greater effectiveness.

Alternative sources, currently in development, include: a piston-type source that is excited via internal combustion called "LACS" (Askeland 2006, Askeland 2007); a pulsating shell that is electrically driven to generate sound, a.k.a "marine vibrator" (Tenghamn 2006); a tunable, underwater organ pipe driven by a piston speaker (Morozov, 2007). (A hydraulically driven source was also discussed in Bouyoucos (1975), but no recent work could be identified.)

These alternative source types show significant potential for reducing underwater sound levels during seismic exploration. The possible benefits include:

- *Large reduction of sound at unwanted or non-useful frequencies (greater than ~100 Hz).* For these systems, the source signal can be contoured to only contain those frequencies of interest for seismic exploration (or at least significantly reduce output of unwanted frequencies). The electrically-driven marine vibrator system has also been shown to make use of feedback loops to reduce unwanted sound generation at higher frequencies due to non-linear distortion effects. Harmonics have been shown to be 35-65+ dB lower than the fundamental frequency during a sine sweep (Tenghamn, 2006).
- *Reduction in peak amplitude of source signal.* Tests using the LACS and marine vibrator systems have shown seismic data results that are approximately equal to or better than those obtained using air guns and explosives. These tests generally involve source signals that are significantly lower than what is obtained using air guns and explosives. Published reductions are on the order of 15 dB.

A reduction in source level using these alternative source types is possible due to the use of alternative source signals, specifically swept sine and repeatable pseudo-random signals. These signals spread out the acoustic energy over time, so the same resolution can be obtained without the large peak sound level (and sound power) typical of current impulsive methods. Also, because the source output is known, it is possible to use advanced cross-correlation techniques to literally pull signals out of noise (i.e. improve Signal-to-Noise ratio or SNR). Askeland (2007) shows that it is possible to identify a known signal that has an amplitude 19 dB lower than the background noise using these techniques. By using these processing methods, not only is the sound level reduced but the total acoustic energy is also reduced relative to conventional seismic sources.

It is noted that simply replacing high level impulsive sounds (i.e. current methods) with lower level continuous sounds (alternative sources) may not have a positive net effect on marine life in all cases. However, in the cases of the sources described above, the total acoustic energy input into the water is reduced relative to conventional methods, partially through the use of advanced processing methods. Thus, a positive net effect may be realized[13]. Lower source levels than what is currently published for these alternative sources may be possible if longer integration times of these alternative signals are used. However, this would have an impact on how fast a vessel towing the source could move. Tenghamn (Workshop) has indicated that the marine vibrator system can be used at typical seismic survey vessel speeds. Askeland (2006) has used the LACS at vessel speeds of 2.8 knots.

The LACS and marine vibrator systems have been tested in water depths ranging from 4 feet to 380 meters. The maximum usable water depth is a current limitation of these systems. It is believed that these systems could be used in water deeper than 380 meters if multiple or larger sources are used (increasing the effective source level) or longer integration times are used (see above).

These sources are still in the development/proof-of-concept stage, but some may not be far from being used in commercial applications. Tenghamn (Workshop) has indicated that a commercial version of the marine vibrator system may be available in 2 years; the current source design will break after about 2 weeks of use, and alternative materials and driving mechanisms are being explored. It has also been indicated that the mechanical piston/combustion source (LACS) is currently available for vertical seismic profiling. The underwater tunable organ pipe system appears to be an early prototype, and has only been used with frequencies above 200 Hz; however this system provides significant potential as an alternative source and commercial development may not be too far off if the concept is pursued.

Other replacements for conventional impulsive seismic sources include techniques that use non-anthropomorphic sounds. Natural sources such as sound generated from wind on the ocean surface and small seismic events (micro-seism) have been used to generate accurate images of structures below the ocean floor. Noise from passing vessels has also been used for these purposes. Penetration depths up to 1000 meters using vessel noise were indicated by McGee (Workshop). Contrary to other seismic survey methods, some of these techniques (particularly those using micro-seism sources) require long acquisition times; acquisition times on the order of hours or days are not uncommon. Because of this, these methods may not be well suited for

[13] A separate study of the effects of marine vibroseis on marine life is currently being funded by the JIP.

exploration of new areas. However, they may be very appropriate for 'Life-of-Field' surveys where the area of interest is already well established and there will likely be a significant amount of background noise due to vessel activity. These approaches are being used by universities in some areas of research such as the identification of hydrates in the ocean floor. Adapting these techniques for the oil and gas industry may take some time, but they hold great potential for making significant reductions in sound levels at all frequencies.

Electromagnetic surveys do not require an acoustic sound source, and are currently available; however, they are not (currently) a replacement for conventional acoustic surveys. In this approach, a DC or AC electromagnetic signal is produced in the water which then propagates into the sea floor, reflects off structures, and bounces back to the surface in a similar fashion to acoustic signals. The signal is detected by receivers located on the sea floor. The source can be either stationary or towed, and is located either on or just above the sea floor. The data that is acquired is good for identifying the contents of reservoirs, which is information that can not be obtained through acoustic surveys. However, electromagnetic methods are less accurate at determining physical extents of a reservoir than conventional acoustic methods. Thus, these surveys are better suited for determining the viability of a reservoir as opposed to finding new locations to drill. There are currently several companies that can perform various versions of these surveys commercially, and the technology appears to be continually developing.

Two reports were identified, Sixma (1996a) and Sixma (1996b), that discuss the use of a bubble curtain to block some of the laterally radiated sound energy created by air guns. (For a larger discussion on bubble curtains, see Section 4.2.) In this method, bubble curtains are located on two sides of the seismic source (parallel to the direction of the vessel towing the source) with the purpose of blocking sound in those directions. The original application was meant to reduce acoustic interference caused by modal propagation and reflection in shallow waters. It was shown that reductions of 9 dB are possible at 40 Hz, with increasing effectiveness up to 30 dB above 80 Hz. Increases in level were sometimes seen near 20 Hz. It was noted that these reductions were measured for all locations where there was no line-of-sight with the source; measurement locations with a direct line-of-sight path to the source showed effectively no reduction in sound. While this approach certainly shows merit, it 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. Furthermore, it would need to be determined if this approach is feasible and effective for use in deep waters; the bubble curtain has limitations as to how deep it can be located, and therefore there is some limit as to the shielded area at large distances from the source.

Lastly, it is noted that shear wave generators may be an alternative to existing source types that have the potential to reduce sound levels generated in the water. In this approach, the sea floor is excited directly in shear. Shear waves can be used to acquire seismic data in a similar fashion to existing methods. The advantage here is that fluids can not support shear waves, and therefore no sound (theoretically) would be generated. In practice, it is likely that at least some sound is generated, either by the generator itself (which is located in the water) or by other means. For example, some shear wave generators also create compression waves, which do radiate into the water. Measurements of noise levels caused by shear wave generators have not been identified. Furthermore, it was noted in the Workshop that shear wave data is hard to interpret.

4.2 Pile Driving Treatments

There has been a fair amount of work performed in reducing noise (and impulse pressures, etc.) from pile driving. Essentially all of this work has focused on shallow water applications: construction of bridges, piers, etc. No attempts aimed specifically at treating noise from deep water pile driving could be found, although some approaches have been identified that can be used in deep water applications[14]. Details on the treatments identified for pile driving are provided in Section PD in Appendix A.

For shallow waters, ‘bubble curtains’ have been the primary focus of noise control efforts based on their sound attenuation capabilities (when properly designed) and cost effectiveness. A bubble curtain is a sheet or ‘wall’ of air bubbles that are produced around the location where the piling will occur. The bubbles are created by forcing air through small holes drilled in metal or PVC rings using air compressors. The bubbles in the bubble curtain create an acoustical impedance mismatch which is effective in blocking sound transmission. A description of the general construction and makeup of a bubble curtain can be found in Longmuir (2001). Reductions in peak pressure, RMS pressure, and energy are typically on the order of 5-20 dB or more. In order to be effective the bubble curtain must fully enclose the pile through the entire water column; the ring emitting the bubbles must be seated properly on the sea floor to avoid acoustic flanking and a reduction in effectiveness. Furthermore, the effectiveness of the curtain is dependent on several factors including the thickness of the curtain, size of the bubbles, and bubble density, among others.

Bubble curtains are susceptible to currents which can disrupt the continuity of the curtain. Two concepts have been developed to help overcome this issue. Bubble ‘trees’ use several bubble rings which are stacked vertically. A description and image of this concept is provided in Item PD1a in Appendix A. By using multiple layers of bubbles the potential for disruption of the bubble curtain by currents is significantly reduced. Of course, the complexity of the system is increased, and it is indicated by Laughlin (2007) that additional rings do not increase effectiveness when there are no currents (there may even be a decrease in performance). A second solution for combating currents is to use a confined bubble curtain where a sheet of fabric or other solid material is used to guide bubbles and prevent bubble dispersion. A description of this approach is given in Item PD1b in Appendix A.

The feasibility of bubble curtains is limited to shallow and costal waters. This is due to several factors: 1) the size of the compressor increases as water depths increase (this size becomes less feasible for depths of several hundred feet), 2) given a specific bubble size, density, and bubble curtain thickness, the effectiveness of a bubble curtain decreases with increasing water depth (Shagapov, 1998), and. 3) for bubble trees, the spacing between each bubble ring should be on the order of 10-35 feet (Petrie, 2005; Longmuir, 2001; CADOT, 2001). This would require a very large number of rings for large water depths. (A bubble tree would likely be required due to greater susceptibility to currents at larger depths.) Similarly, constrained bubble curtains would

[14] It could be said that a ‘treatment’ for pile driving is to increase the efficiency of the operation. Inefficient piling approaches will likely increase noise, and would certainly increase the duration of a project. It is assumed here that for conventional approaches the pile driving efficiency would be analyzed and optimized for any project to reduce time on-site (and associated costs). Such methodologies will not be discussed further here.

require a significant amount of material to cover the entire water column. Other practical limitations regarding deployment and cost may also apply.

A second approach for reducing pile driving noise is to use a solid physical barrier. This approach was deemed as less practical than bubble curtains by Longmuir (2001), although Laughlin (2007) worked with at least one design where a steel casing is lined with foam. This design provided upwards of 20 dB of attenuation (peak, RMS, and SEL). Lucke (workshop) also presented results of using closed cell foam (alone) as a barrier material; similar effectiveness was seen. Furthermore, it is also possible to remove the water from a solid casing that surrounds a pile, creating a 'dewatered cofferdam'. This approach has been shown to be effective, although implementation would likely take more effort than other barrier approaches. As is the case with bubble curtains, application of these treatments are only feasible in shallow waters. Implementation in deep waters is not practical.

The effects of 'pile caps' on underwater sound generation have also been measured by Laughlin (2006a). Pile caps are circular discs that are placed between the impact head of the piling hammer and the pile. For practical materials, peak level reductions of 1-8 dB were measured. A negative effect on piling efficiency may result but was not investigated.

There is some indication that different pile types create different underwater sound levels. Laughlin (2005a) and WSDOT (2005) report that steel H-piles produce significantly lower peak levels than circular concrete and steel piles. The data is scattered, although differences between H-piles and circular piles may on the order of 10-20 dB. Use of alternative piles may be somewhat limited, as H-piles may not be appropriate for all situations.

A few approaches have been identified that replace existing piling methods and can significantly reduce underwater sound levels. One of these is a technology called 'suction piling' and it presents one of the largest opportunities to greatly reduce noise while potentially increasing installation speed (Mather, 2000). A suction pile is a large drum with the bottom face removed. The drum is located on the ocean floor, and air and water are sucked out thereby sinking the pile into the ground. Grout ballast can also be added for supplemental strength; if ballast is not used then the pile can easily be completely removed by reversing the installation process. The top face of the drum is attached to the structure to be supported, such as an offshore platform, and can also be used for mooring. Examples of suction piles are provided in Figure PD7 in Appendix A. Although underwater sound measurements of suction pile installations were not found, it is believed that the noise of this procedure will be negligible relative to existing methods since the only noise source is the suction pump. All impulsive type sounds are removed using this approach. Suction piles can be used in both deep and shallow waters, providing a large advantage over other noise reduction techniques.

A second approach that replaces conventional piling methods is the use of a 'press-in piling machine' (Goh, 2005). Press-in piling machines are unique, self contained units that use static forces to install piles. A diagram of this machine is provided in Figure PD8 in Appendix A. The machine uses other piles that have already been installed as leverage to install new piles (installation of the first piles are also possible using this machine, without the need for impact or other conventional methods). Underwater noise levels were not found, but they are expected to be significantly less than those produced using existing methods. All impulsive types of noise are removed by using this technique. This system was originally developed for land based use in highly sensitive areas where human hearing impacts, vibration, erosion, and other similar concerns are paramount. For example, press-in piling operations have been granted permits on beaches during turtle migration season (Carter, Workshop). Because every pile is driven statically, the load capacity of each pile is known; no further verification tests are required. This approach has been used extensively on land and in shallow waters. While the conventional application of this approach requires consecutive piles to be located adjacent to one another, the piling machine can also be located on a barge or other structure, thus allowing for pile installation at any location (including deep waters). The current technology allows for installation of piles with diameters of up to 5 feet (1.5 meters); larger piles can be simulated by installing multiple smaller piles adjacent to one another. Other pile types can also be installed, including sheet and H-piles.

A third approach is the use of cast-in-place piles. A sketch showing this concept is given in Figure PD9 in Appendix A. In this approach, a pile casing is drilled into position and then filled with concrete. This approach has been used for land based applications only and has not been used for marine or deep water installations. The potential for noise reductions are significant (relative to impact methods), although some sound will be generated through the drilling process. This method may not be feasible for use in water.

Lastly, it is important to note that vibratory piling methods may be a reasonable solution for reducing the peak noise levels and removing impulsive sounds in certain applications. As indicated in Section 3.2.3, vibratory methods have been measured by several authors to be significantly quieter than impact methods. Rise times and peak over and under pressures are also significantly reduced using this method, which is primary concern in many applications such as mitigating fish mortality. However, there is some concern that replacing an impulsive type source with a continuous one may not necessarily yield a net gain. Further research is needed in order to better quantify the impacts of vibratory hammers.

4.3 Treatments for Explosives

As discussed in Section 3.2.3, explosives are used for seismic exploration, obstacle removal, and decommissioning of offshore structures. Treatments for seismic exploration are discussed in Section 4.1. This section focuses on mitigation of noise from explosives during decommissioning and obstacle removal. Details on treatments for explosives are provided in Section EX in Appendix A.

One seemingly straight-forward approach to reducing noise from conventional bulk explosives is to properly assess the amount of explosive that is required for a given job. A discussion of this approach is provided by Keevin (1996). (Techniques such as delayed charge detonation are commonly employed but are not discussed further here.) The optimization of charge weight was briefly discussed at the Workshop. It was stated that most often the maximum amount of explosive (typically 50 lbs of TNT or equivalent for a given charge) will be used in order to ensure the obstacle is removed since follow-up detonations can be costly and time consuming. A relation between charge weight and sound pressure is provided by Richardson (1995). A 2-fold reduction in charge weight would only yield a 2 dB reduction in underwater peak pressure, and similarly a 4-fold reduction in charge weight would yield a 4 dB reduction. As such, the benefit of noise reduction using this approach may not outweigh the potential for an insufficient blast, requiring additional shots, unless the actual required amount of explosive is very small.

Some options are available that can significantly reduce the amount of required explosive material. One option is the use of 'shaped charges'. As stated in Continental (2004), shaped charges "are designed to collide or 'focus' the detonation front to concentrate more energy along the fracture line, and thus reduce the size of the charge needed to cut a piling." The effectiveness of this approach has been the subject of limited study. Saint-Arnaud (2004) presents data that shows a 4 dB average decrease in peak pressure, a 13 dB decrease in "impulse" (See Appendix C), and a 10 dB decrease in energy flux density when compared to conventional bulk charges in the same application. It is noted that the data is very scattered. Shaped charges may also help to speed up decommissioning activities since the focused charges can be more effective at cutting structures than bulk charges.

Other methods are being developed which have the potential for large reductions in explosive material and may provide reductions in underwater sound levels. 'Radial hollow charges' are an adaptation of shaped charges mentioned above. As described in Continental (2004), these are "short, linear-shaped charges bent into an arc with the explosives initiated simultaneously at the central axis. The detonation front runs radially outward, detonating the explosive simultaneously on both sides of an inverted v-shaped liner. The liner collapses, producing a flowing radial cutting jet. Because of this diverging flow, a relatively long cut can be produced in a flat or curved steel plate. By joining a number of these types of charges together, it is possible to cut along plates and around pipes using relatively low explosive weights." Indications of specific reductions in explosive material were not found, although based on the configuration of these charges the amount of material is expected to be less than for shaped charges. As such, reductions in sound may be similar or greater than shaped charges. A diagram showing the use of radial hollow charges is given in Figure EX2 in Appendix A.

'Shock-wave focusing' is another method under development that can reduce the required amount of explosive materials needed for a given job. This is a method in which explosives and waveguides are used to "focus the energy of the shock-wave through a steel piling, and by exerting very high compressive/tensile stresses on the target area, initiate controlled brittle fracturing." (Continental, 2004). The charges used are hollow and flexible, and can be wrapped around tubes internally or externally. A conceptual diagram is provided in Figure EX3 in Appendix A. Continental (2004) states, "Shock-wave focusing can reduce the explosive weight of a cutting charge by up to 90% when compared with standard shaped charges. Shock-wave focusing charges are particularly effective for targets with thicker walls, but to be effective, they require that the opposite surface be backed by either water or air. Grout-backed surfaces are not effectively severed by shock-wave focusing methods." Tests in air show good results, but tests in water have had limited success (Reverse, 2004).

It is noted in Committee (1996) that "none of the explosive cutting techniques, except bulk charges, can be used to sever wells with multiple casing strings except by repeated explosion done from the outside, one layer at a time." This provides an obvious limitation for the use of Shaped Charges, Shock Wave Focusing, and Radial Hollow charges, although their use is certainly applicable to many other situations. It is noted that mechanical cutting methods can be used to remove these structures (see below).

In some applications it may be possible to block the sound created by explosives from radiating into the greater ocean environment. Bubble curtains have been used in several applications, both for explosives use and pile driving. Details on bubble curtains are provided in Section 4.2 and Items PD1a and PD1b in Appendix A. It is noted that the thickness of the bubble curtain must be such that the curtain integrity is not compromised as a result of the explosion. Similarly, solid physical barriers can be used to block sound propagation from explosives. Bubble curtains and solid barriers need to completely surround the sound source through the entire water column, and are thus limited to shallow waters. Keevin (1997) presents data showing the effectiveness of a bubble curtain use with explosives. Reductions in peak pressure, impulse, and energy flux density were all greater than 90% on average. Reduced fish kills were also noted. No studies were found that investigate the effectiveness and implementation methods of physical barriers for explosives, although good results were found using solid barriers for pile driving (see Section 4.2).

It may also be possible to reduce underwater noise from explosions by using blasting mats. Blasting mats are currently used for land-based applications, and are typically made of recycled rubber tires that are tied together with steel cables. They are placed over the charges to minimize the amount of flying debris (in air) and sound from the explosion. Vendors contacted for this study indicate that the mats can be used underwater and have done so in a few cases (primarily for control of debris). There is no published information on the acoustical effectiveness of this treatment in water. Further testing would be required. Blasting mats are relatively inexpensive from a materials perspective, and could be used in deep waters. Logistics of locating the blasting mat would need to be developed and refined, and may be the most significant cost factor.

Slow burn-rate explosives, such as black powder, are explosives that have slower detonation velocities as compared with dynamite and TNT. It is noted in several locations that fish mortality is significantly reduced when black powder is used (Richardson, 1995; Keevin, 1997). This may be due to the longer rise-times and pulse durations seen with black powder as compared with other conventional explosives. This appears to be true in spite of the fact that higher peak pressures can result from the use of black powder.

When boreholes are used to remove rocks and other obstacles, ‘capping’ or ‘stemming’ techniques have been shown to be very effective. In this approach the top of the borehole is packed with an inert material such as crushed rock. This can provide upwards of 19+ dB of attenuation in peak pressure relative to an un-capped borehole (Hempen, 2007). This method is inexpensive and easy to implement, however it is noted that ‘partial confinement’ – i.e. a borehole that is not sufficiently filled with material – will reduce the effectiveness of this treatment. A system where the borehole is covered from above using a large metal plate or blasting mat (see above) may be preferred in some instances assuming an effective seal can be constructed between the cover and borehole. This technique can also be combined with existing capping methods to help reduce partial confinement effects and potentially increase effectiveness.

Lastly, it is noted that various cutting methods are available to remove offshore structures as an alternative to explosives use. A review of these techniques is provided by Twachtman (2000), and Twachtman (2004) provides detailed cost analyses. The methods discussed include diamond wire cutting, abrasive cutting, mechanical cutting, and torch cutters. Of these methods, diamond wire cutting appears to be the most feasible and practical, particularly in deep waters. These operations are carried out using divers or underwater vehicles, both manned and remotely operated. No data was identified regarding the underwater sound levels produced during these activities, although data from cutting tools used by divers are provided by Nedwell (1993). Peak sound levels are 80+ dB lower than those produced by blasts, and it is expected that cutting methods in general would produce lower sound levels than explosives. Impulsive sounds would also be largely, if not entirely removed using cutting methods. Cutting methods require longer time on-site than when explosives are used.

4.4 Vessel Treatments

Treating noise related issues on vessels has been the subject of a lot of work over the past century. Airborne noise in compartments on vessels is typically a concern for crew comfort and communication, as well as long term hearing damage. Fortunately, many of the techniques used to control airborne noise can also control underwater noise. Underwater noise has been a concern of navies worldwide since WWII, and has become an increasingly important issue for commercial and research vessels[15]. A benefit to a vessel that has a low underwater radiated noise signature is that it will generally produce lower airborne noise levels on-board as well.

The specific underwater noise treatments that would be used on any given vessel will depend on the physical makeup of the ship (overall vessel layout, propeller parameters, plating thicknesses, frame spacing, etc.), details of the sources (diesel engines, turbine, electric motors, pumps, etc.), and the desired underwater noise level or requirement. It is not possible to give detailed design guidance for all circumstances. General guidelines are outlined here for the dominant sources found on most vessels. Furthermore, some sources of noise will be specific to certain kinds of operations and vessels. For example, it was noted at the Workshop that noise from a rope hitting the deck or hull on a trawler was detected in the underwater noise signature during a particular measurement. Pertinent sources and treatments for any vessel should be evaluated on a case-by-case basis.

As discussed in Section 3.2.4, underwater noise from vessels falls broadly into three categories: propeller or thruster induced noise, machinery induced noise, and fluidborne noise through sea-connected piping systems. A summary of treatments applicable to these categories are discussed separately below.

4.4.1 Propeller and Thruster Treatments

The dominant contribution to the underwater radiated noise spectrum from propellers and thrusters is cavitation noise. Treatments and/or blade designs that delay the onset of cavitation (i.e. cavitation inception speed – see Section 3.2.4.1) or reduce cavitation growth at a given

[15] It is noted that underwater noise has been a concern of some for much longer. For example, whalers in the 1800s would place “matting” in the oar locks to prevent excess noise (Olmstead, 1841).

speed can be used to reduce underwater noise from vessels (Pinto, 1999; Kawakita, 2000; Seoul, 2002). Details on propeller and thruster treatments are provided in Section PT in Appendix A.

Several sources discuss specific measures for raising the cavitation inception speed for propellers; for example, Greeley (1982), Asmussen (1986), Bruggeman (1988), Pylkkanen (1991), Fischer (2001), Kinnas (2002), and Jebsen (2005). Similar design guidance is available for thrusters in Brown (1974), Brown (1977), and Fischer (2006). The best way to reduce cavitation is to increase the uniformity of the flow conditions in and out of the propeller or thruster, and to design the propulsor's blades for those specific flow conditions while mitigating sensitivity to variations in the flow and load. It is always best to reduce propeller loading as much as possible by increasing propeller diameter and reducing the rotation rate.

The design of a quiet propeller or thruster includes modifications to common design parameters and features, such as changes in tip speed, blade outline ('skew'), blade sections thickness, propeller pitch-diameter ratio and its radial distribution, and even the number of blades. No special materials or additional 'treatments' are required and the reduction in noise level can be significant, on the order of 3-10 dB or more. These modifications are often possible for existing vessels by replacing existing propellers with improved low-noise versions. Propeller blade costs are similar to conventional blades, with the only significant potential difference coming from machining costs. Other modifications such as changes to the hull to improve flow conditions must usually be considered at the design stage. It is recommended that any propeller or thruster that is required to have reduced sound levels be analyzed by an expert, as advanced modeling and analysis tools are available to the expert user.

It is noted that many vessels currently employ controllable-pitch propeller designs (CPP). When used properly, the pitch of the propeller is changed with different engine RPMs to best match inflow conditions. This technique can result in increased propulsion performance and reduced noise. However, it is common for vessels to use CPP designs with engines that operate at a fixed speed; vessel speed is then controlled solely through blade pitch. This design can lead to very high noise levels, as cavitation is possible (and likely in practice) even at 0 pitch since tip speed is constant (and high). It is strongly suggested that when CPP designs are used, the propulsion engine or motor should be allowed to vary in speed, and an optimal configuration of RPM and blade pitch should be identified for each speed to keep noise levels as low as possible.

One particular blade design that has the potential for large reductions in underwater radiated noise is the "forward-skew" blade design (Brown, 1999). An example image of a forward-skew blade is provided in Item PT2b in Appendix A. Brown states that "the forward-skewed blade-tip region suffers less change in load (lift) per unit change of incidence than a straight-edged blade – and a lot less than a back-skewed blade." This makes it less susceptible to variations in inflow and vessel speed. This design can be implemented on both propellers and thrusters. Brown presented measured data at the Workshop from a design modification to the bow thruster on the R/V ROGER REVELLE. It was shown that the new forward-skew blade design reduced underwater noise by 5-18 dB at the 1000 Hz third-octave band over much of the thruster's operating range. In addition, NCE has recently been in contact with the operator of a survey vessel where the original propeller was replaced with a forward-skew design due to poor acoustical performance. The vessel could not perform its normal functions which included the use of sonar at 12 kHz due to interference from noise created by the propeller. After the new forward-skew blade was implemented the noise reportedly dropped by 20 dB at this frequency and the vessel can now perform surveys at full speed (11.5 knots) (NCE, 2007). This same technology has also been applied to pumps with good results (Brown, Workshop). Forward-skew blade designs must be implemented in tunnels or nozzles to prevent fouling or physical damage to marine life. It is noted that nozzles can be used to increase thrust by as much as 20% when properly designed for heavily loaded propulsors (this is a "Kort nozzle").

Beyond modification to the propellers themselves, other design choices can be made to locate the propeller in a position where there are better flow characteristics. This will help to reduce noise by delaying cavitation inception, but may yield a reduction in propulsive efficiency due to loss of the "wake fraction" factor[16]. Such approaches include the use of drop-down thrusters, Z-drives, and podded propulsion systems. These approaches are best considered and implemented at the design stage, but modifications to existing vessels are sometimes possible.

Waterjets have also been shown to have lower underwater radiated noise than equivalent open propellers for high speed vessels (Anonymous, 1994; Kallman, 2001). These studies typically focus on airborne on-board noise levels instead of underwater noise, although there is some correlation between the two. Waterjets are currently used primarily on high speed military craft and ferries, although their use could be appropriate for high speed vessels used by the oil and gas industry for similar duty. Recent innovations in waterjet impeller design such as forward-skew blades (similar to what is described above) have been shown to significantly increase cavitation inception speed, thereby reducing noise (Lanni, 2000). Brown indicated at the Workshop that cavitation at 30 knots was "not significant" for a forward-skew impeller design under test. Shafting, bossings and struts being absent, waterjets can provide efficient and quieter operation at high speeds.

Voith Schneider propulsion systems are another alternative to conventional propulsion systems with potential for reduced underwater noise. No underwater noise data was identified in this study, although these designs are used on minesweepers. Other design modifications such as new rudder designs and propellers made from composite materials also hold potential for reducing cavitation growth and increasing inception speed. Additional information on these systems is provided in Appendix A.

Some treatments are available for existing designs where propeller replacement or re-design is not possible. Masking systems consist of a layer of air bubbles injected into the water via a low pressure compressor in order to block underwater noise radiation (the concept is, in principle, the same as for bubble curtains used in pile driving and for explosives). Several methods have been implemented in practice (often on naval vessels). In one approach the air bubbles are injected

[16] Propeller efficiency benefits from the wake created by hull appendages upstream of the propeller. A propeller reaches maximum efficiency when there is zero net kinetic energy of the water as the vessel passes by (relative to an observer sitting in the water). Vessel appendages will drag the water forward, creating kinetic energy in that direction. The propeller can then make use of this energy to increase its propulsion efficiency by returning the energy of this water to 0 (i.e. the propeller pushes backwards on this forward moving water, thus causing it to stop and have zero kinetic energy). If the propeller is moved to another location where the vessel drag does not cause this wake then the added efficiency of this effect is lost.

via holes drilled in a belt attached to or near the vessel's hull, allowing the bubble layer can pass over or under the propeller (bubbles passing over the propeller would not reduce noise radiated into the ocean from the propeller, but would reduce on-board noise caused by propeller pressures). A second approach uses bubbles emitted from holes drilled in the propeller itself. For this method, air must be supplied through the shaft, and the system must be carefully designed to avoid cavitation generation. In a ducted propeller or a tunnel thruster, air can be admitted through the wall to mix with tip gap and vortex cavities to effectively reduce radiated noise. For all of these systems, reductions of 10 dB or more at frequencies above 500 Hz are possible, although some increase in noise at low frequencies is also likely. The costs of these systems is also non-trivial (particularly for propeller injection locations), and maintenance can be bothersome as these systems are prone to marine growth which can clog the system.

Foul release coatings have also shown some noise reduction effects (Mutton, 2006), however results are varied. Such treatments could also be applied to existing propellers if developed more fully.

As discussed in Section 3.2.4.1, singing propellers are caused by the excitation of structural blade modes via flow induced vortex shedding. Singing propellers can typically be cured by propeller edge modifications, as described in Item PT13 in Appendix A. It is also possible to 'de-tune' the propeller to move shedding frequencies out of the range of blade natural frequencies, and vice versa. If, for example, blades are made thicker, the resonant frequencies of the water-loaded blades are typically increased while the vortex shedding frequencies tend to be reduced.

It is important to note that ice strengthened propellers are typically very noisy due primarily to their thicker blade sections and need to operate in both the forward and backing directions. Special attention needs to be paid to ice strengthened propellers if noise reductions are to be achieved (Thiele, 1981; Erbe, 2000).

Lastly, while it may seem trivial, regular maintenance of propellers and thrusters can help keep noise levels low. Propellers that are subjected to marine growth, even in low amounts, are more likely to cavitate at lower speeds and have more pronounced cavitation at higher speeds than 'clean' propellers. Regular maintenance can also help identify propellers that have been damaged. Propeller damage inevitably produces higher levels of underwater noise, and may reduce efficiency as well.

4.4.2 Machinery Treatments

As discussed in Section 3.2.4.2, there are three significant paths that allow machinery to create underwater noise: first structureborne (FSB), secondary structureborne (SSB), and airborne (AB). Identification of the dominant noise path(s) in any vessel design is critical in optimizing treatments for underwater radiated noise. Based on past experience, it is the opinion of NCE that FSB noise will be dominant for many commercial vessels (in the absence of any noise control treatments). AB and SSB paths may also be important, depending on the specifics of the vessel and machinery. Detailed analysis is required to identify machinery items on a given vessel that would require treatment in order to meet a specific noise goal.

Details of various treatment options are provided in Sections MV and MA in Appendix A. Of these treatments, one of the most useful and cost effective for commercial vessels is selection of low noise / low vibration equipment. This approach has minimal impact on space and weight, and cost increases may be relatively small to moderate. Second to this, vibration isolation systems (resilient mounts) can be used to reduce structureborne noise from machinery, and will result in similar reductions in underwater noise (vibration isolation systems are very common on vessels of many types). Examples of common resilient mounts are shown in Figure MV1a(1) in Appendix A. A diagram of a resiliently mounted genset is also provided in Figure MV1a(2) in Appendix A. Single stage mounting systems[17] can reduce vibration and underwater noise by 20 dB or more at frequencies above 100 Hz, and a well designed system can have significant reductions below 100 Hz.

In many cases it may be found that resilient mounting of power generation equipment and propulsion equipment will be sufficient for commercial vessels with moderate noise goals, (after propeller induced noise is resolved). It is noted that mounting of propulsion equipment is sometimes more complicated than mounting of generators since propulsion units often need to withstand thrust forces from the propeller and shaft. Use of thrust bearings and torsional couplings can remove thrust loads from propulsion engines, making them more amenable to resilient mounting. However, large direct-drive diesel engines may not benefit from resilient mounting (Southall, 2004).

Damping treatments can be effective at reducing vibration levels (which applies to FSB and SSB paths) and subsequently underwater noise when used in appropriate locations. However, these treatments often add thousands of pounds of weight to the vessel. Furthermore, for some damping materials, their use is limited to areas where they are not in contact with potable water, long term exposure to oil, or in living compartments. Damping treatments are generally used only when resilient mounts are already in place and additional reductions are required.

As discussed previously, silencers should always be used on exhaust stacks. Fiberglass and mineral wool treatments can be used in machinery spaces to block airborne sound transmission and reduce vibrations generated by impinging airborne noise. These treatments are likely to be most appropriate as a first line of defense to reduce AB and SSB noise. For obvious reasons these materials typically are not appropriate for installation on the deck of machinery spaces; damping treatments are one alternative for these locations. Floating decks can also reduce SSB and AB influence on ship structures below machinery, thus providing insulation against all three paths simultaneously.

Bubble layers, known as “masking systems” have also been implemented on many vessels. Air is emitted into the water via holes drilled in a belt attached to or near the vessel’s hull. Effectiveness is similar to that seen for pile driving curtains, although some increase in level at frequencies below 80 Hz has been documented. It is important to note that masker systems installed on vessels have historically been plagued with problems of fouling, and regular

[17] A single stage system is the most commonly found isolation arrangement. It uses a single set of isolation mounts between the subbase and foundation; see Figure MV1a(2). Double stage and other mounting arrangements are possible when additional isolation performance is needed.

maintenance is mandatory to keep these systems operational. Furthermore, such systems are effective only when the vessel is moving.

As was discussed for propellers and thrusters, proper maintenance of machinery can help keep noise and vibration levels as low as possible. This will also help ensure equipment stays operating at proper efficiency, and maximizes equipment lifetime.

The overall design of power generation and propulsion systems can result in large reductions in underwater noise. For example, diesel electric systems[18] often have lower underwater noise levels than diesel-gear driven vessels. This arrangement readily allows the diesel generators to be resiliently mounted, thereby reducing underwater noise from vibrations. Electric motors often have inherently lower noise and vibration levels than diesel engines, which would lead to reductions in underwater noise. If an electric motor required resilient mounting, this would be easier than for a propulsion diesel engine due to the reduced number of piping and other connections.

It is noted that diesel-electric propulsion systems can have greater overall efficiencies than geared propulsion diesel designs. This can be true in spite of the fact that a gearbox is more efficient than the conversion of power from mechanical to electrical and back to mechanical again. The reason for the overall increase in efficiency is that multiple small generators can be used; those generators that are needed can operate close to their optimal loading (i.e. near maximum) while others are secured. Therefore the overall diesel efficiency may be improved, resulting in a more efficient system at less than full load. Electric motors are often lighter than diesel engines as well. It is suggested that diesel-electric systems be considered when new vessels are designed in order to reduce underwater noise.

Lastly, the total cost of machinery and propulsion treatments were discussed at the Workshop. Fisher (Workshop) has provided an estimate of $150-$750 thousand dollars for a ‘first-order’ noise reduction on a given vessel. This would include (roughly) resilient mounting treatment design and installation, airborne and secondary structureborne treatment design and installation, as well as analysis and installation of a modified propeller design. This cost is likely to be less than 1% of the total vessel cost. Actual costs and total noise reduction will naturally depend on the specific vessel.

4.4.3 Sea Connected System Treatments

There are two general treatments that are readily available for reducing fluidborne levels inside of piping attached to pumps: flexible pipe connections and pulsation dampers. Flexible pipe connections reduce sound pressure levels by creating an impedance mismatch for fluidborne (and structureborne) energy (Purshouse, 1986). Noise attenuation is broadband, with increasing effectiveness at higher frequencies. In general, dogleg configurations should be used to maximize acoustical effectiveness (see Item FB1 in Appendix A), though double, in-line arch flex hose may be acceptable for space-limited applications.

[18] Diesel generators with electric propulsion motors.

Pulsation dampers are acoustical absorbers that are either located in-line or in parallel with the pipe (i.e. connected as a short, terminated side branch). Parallel dampers are "tuned" to have a resonant frequency, and thus work only at that one frequency. This frequency can be selected to be the rotation rate or blade rate of a pump, for example. Their effectiveness at this frequency 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. Parallel dampers also have the potential to operate effectively at lower frequencies than in-line dampers.

Detailed information is provided in Section FB in Appendix A.

4.5 Dredge Treatments

As discussed in Section 3.2.5, transfer and hopper dredges create more sound than bucket dredges. As such, this section primarily focuses on those louder sources (although some of the treatments described here would also be applicable to certain aspects of bucket dredges). It was shown in Section 3.2.5 that propellers and thrusters, when present and operating, are likely to be the dominant contributors to underwater noise from dredges. Noise resulting from on-board machinery will become dominant when propellers and thrusters are not used. The significance of the noise radiated by the suction / cutting head relative to on-board machinery/propellers is believed to be minimal, but should be the subject of further study. While some treatments can be envisioned that may help reduce noise from the dredge head, such as bubble curtains mounted directly to the dredge head or decoupling materials, such treatments are speculative and may be difficult to implement in practice. No attempts to control noise from the dredge head specifically have been found, and it is recommended that other sources be treated (as needed) before the dredge head unless additional data can highlight its significance.

Given the similarity to vessels (discussed in Section 4.4), many of the treatments for vessels are also applicable here. Controlling thruster noise is expected to be of particular importance for hopper dredges while maintaining position for dredging (dynamic position mode). Propellers are also likely to be a significant source while transiting. The quiet propeller and thruster designs provided in Section PT in Appendix A can be used on hopper dredges to reduce noise levels from these sources. Note that designs should take into account the specific loads that are expected for the given dredge and specific designs may differ from those of other vessels. It is also noted that the use of more thrusters operating at lower loads can help reduce noise during dynamic positioning, although at greater cost.

For machinery sources, the FSB path is likely to be the most significant, particularly for hard mounted machinery, although AB and SSB paths may be significant in some cases. Details on these treatments are listed on Sections MV and MA in Appendix A. It is noted that resilient mounting of large dredging pumps may not be straight forward or feasible due to imbalance loads and other non-acoustical considerations. Because of this, it may be advantageous to use the "floating deck" design described in Item MV2 in Appendix A. By using this approach, the pump and prime mover can be mounted directly to a single common structure that can provide adequate supporting stiffness for both items, and this structure would then be resiliently mounted to the vessel. Note that this can also reduce SSB noise from the deck. Again, the specific treatments used on any dredge should be tailored to the needs of that vessel through detailed analysis.

Lastly, it was noted in Section 3.2.5 that tug boats are used to control barges used for some transfer dredge operations. These boats can be a significant source of noise. In order to reduce noise from these vessels, it is suggested that procedures be put in place that would not require these tugs to continuously operate. One option may be to allow the tugs and barge to moor in place near the dredging operation. This would allow the tugs to power down until they are needed to move the barge to the dump site. Mooring could be accomplished through the use of suction piles, which could be removed and re-located as needed (See Item PD7 in Appendix A). Other options are certainly available as well. Alternatively (or in addition), these vessels can be designed to have reduced noise levels using the methods described in Section 4.4.

4.6 Post Trenching Treatments

No attempts at reducing noise from post trenching operations were identified as part of this study. It is speculated in Section 3.2.6 that the noise from these operations is dominated by the noise from the vessel towing the trenching machine and therefore a first step in reducing post trenching noise would be to use the vessel treatments described in Section 4.4. However, additional studies would be needed to better qualify this assessment.

4.7 Hand Tool Treatments

While underwater noise from hand tools has been identified as significant in some cases, no treatments of these noise sources could be identified in the literature. It is speculated that some treatment possibilities may exist in certain circumstances. For example, use of a dewatered cofferdam or a local bubble curtain may be employed to help control noise, but these approaches have limitations, particularly for deep water applications, as discussed in Sections 4.2, 4.3 and Items PD1 and PD5 in Appendix A. Decoupling materials may also be an option, but would require further study for this application (see Item MV6 in Appendix A).

In the specific case of bolt guns used on large metal structures, it may be possible to use a removable / re-usable damping pad to help reduce any sound radiation that results from the vibration of the structure being ‘worked’. For example, a large damping tile or set of tiles with a magnetic backing could be used to damp steel structures and reduce sound re-radiation. However, this approach has drawbacks with regards to logistics of applying and retrieving the damping. Additional research would be needed in order to better quantify the feasibility of these or other possible treatments.

For now the best possible approach would be to use equipment that has been shown to have lower underwater radiated noise (which may also require additional research).

4.8 Drilling and Production Platform Treatments

Analysis of the various platform types and causes of noise identified in Sections 3.2.8 through 3.2.13 indicates that platforms can generally be grouped into two categories for the purpose of noise assessment and treatment design: free standing and floating structures. Free standing structures are considered to be fixed platforms such as jack-ups and other platforms that are fastened to the ground either through piles or gravity, as well as gravel islands and some caissons. Floating structures include drillships, semi-submersibles, FPSOs, floating platforms, and floating caissons. The delineation of these groups results from their overall construction styles, which influence how acoustic and vibration energy is transmitted through and from the structure. For example, floating structures primarily use stiffened plating, where fixed structures use beam or piping supports and beam grillage networks. Each of these constructions lend themselves to different propagation mechanisms from machinery. Equipment items responsible for underwater noise on each of these platforms was found to be the similar, specifically large power generation equipment, pumps, etc., although details of specific equipment items causing noise will vary from platform to platform. Furthermore, some floating structures use thrusters, a dominant source of noise; fixed structures do not.

These categories have been created to simplify the treatment assessment for the purposes of this report. It is important to note that these groupings should not imply that the same treatment or group of treatments is applicable to every platform type within one of these categories. On the contrary, treatments that work well on a specific platform may not work well on another platform of the same type, even one that appears on the surface to have similar characteristics. For example, it was discussed at the Workshop that semisubmersibles can have large power generation equipment located on the upper decks, in the legs, or in the pontoons. Each of these situations would require different treatments, implemented in varying degrees. Similarly, some applications allow for mooring and thus thruster noise is not an issue; whereas others require thrusters to be used. Because these structures vary widely it is recommended that detailed analyses be performed for any specific structure so the most effective treatments can identified.

It is important to note again that the noise from almost any platform will be dominated by vessels operating in the area (when present). The discussion moving forward will assume that noise reduction of the platform itself is desired and the treatments discussed are focused on the reduction of noise caused by sources integral to the platform. However, vessel noise should not be ignored when assessing appropriate treatments for offshore drilling and production operations. The treatments for vessels described in Section 4.4 would certainly apply to the various vessels that support these platforms.

It is noted that one possible method of reducing vessel noise would be to reduce the amount of time they are required to use thrusters and propulsion – i.e. for dynamic positioning. One suggestion would be to allow vessels to tie up to a mooring station or a temporary anchor, possibly provided by a suction pile (see Item PD7 in Appendix A). When this is not possible (such as in water depths greater than 3-4 thousand feet), it may be possible to design supports or structures that would allow vessels to be secured to the platform so that thrusters would not be needed. Any mooring or supporting structure would obviously need to account for wave motion, and may need to keep the vessels in a fixed lateral location relative to the platform. Naturally, these structures should not be used if they would interfere with the safety of the vessel or the platform, or adversely affect the local environment. While such structures may be possible, they would require further investigation. This idea was discussed during the Workshop and was met both with resistance and acceptance. It was noted that existing mooring structures would not be sufficient to perform this task (particularly in deep waters), but new kinds of supporting structures may be possible.

This idea is presented here simply as a concept that may be worth considering in order to make potentially large reductions in underwater noise from platforms. It is also noted that this solution may not be appropriate for all vessels in all locations, but it may be perfectly reasonable in other situations. For example, one attendee of the Workshop cited an offloading facility where supertankers are required to tie up and power down while offloading instead of using thrusters to maintain position. It is likely that this has a major impact on the underwater noise in the immediate area. Furthermore, by allowing thrusters and propulsion to be secured, there would be a savings in fuel costs and possibly man-power.

Lastly, it is noted that as with vessels, maintenance can be an important factor in keeping underwater noise levels low on any platform. Damaged equipment and thrusters can produce significantly increased underwater sound levels, and can also reduce efficiency and lead to other problems.

4.8.1 Treatments for Free Standing Platforms, Including Fixed Platforms and Gravel Islands

Free standing platforms are often made up of beam or pipe supports below the water, with beam grillage structures providing primary support for equipment, personnel, etc. above the water. As discussed in Section 3.2.8, this arrangement lends itself to the first structureborne noise path from machinery items, much more so than secondary structureborne noise. As such, the treatments identified in Section MV of Appendix A for reducing vibration are appropriate here. Of these, the resilient mount treatments are likely to be the most cost effective, next to selection of inherently quiet machinery.

The importance of a stiff foundation (and subbase) when using resilient mounts is restated here. This can be particularly important for supporting structures that use beam grillages with very large beam separation (>2-3 meters). It is recommended that additional beams should be used in the vicinity of large resiliently mounted equipment to make the local structure sufficiently stiff to allow for proper resilient mount performance. Spence (2006) indicates that noise reductions of 5-10 dB below 100 Hz may be possible without resilient mounts by optimizing the structure supporting equipment items for dynamic loads (relative to existing practice which can include grillage spans of ~6 meters). The analysis presented by Spence focused on low frequencies, less than 100 Hz, but the effects would also translate into reductions at frequencies above 100 Hz. Equipment items that were mounted on very weak foundations (dynamically speaking) may have amplified impacts. Detailed analyses are recommended to optimize specific structures for weight and stiffness.

If SSB paths are deemed to be significant, the treatments of Section MA in Appendix A would be applicable. Treatments such as fiberglass insulation can be used to reduce the excitation of platform structures from airborne noise. Damping treatments and floating decks can also be used on decks where absorptive treatments are not practical. Silencers should generally be used for machinery exhaust stacks, as discussed in Gales (1983). Airborne noise radiated by machinery may create underwater noise when the structure supporting equipment is open and there is a line-of-sight path to the water (when the angle of incidence is within a 13 degree ‘cone’). In these cases, a barrier may be effective at reducing underwater noise (See Item MA4 in Appendix A).

It is indicated in Section 3.2.8 that noise radiation from the drill string casing is probably not a significant source relative to other machinery sources. No treatments specific to drill casings were found, although it is possible that a cladding or decoupling material could be used to reduce noise radiated from the casing. This treatment would need to be able to withstand very high static pressure loads at large depths while retaining its acoustic effectiveness. Another approach may involve vibration isolation of the string/casing from the rest of the structure. This is probably not a trivial approach, but, at a minimum, reductions at high frequencies may be possible. Investigations into the significance of this path should be undertaken before any conclusions regarding appropriate treatments can be reached. It is noted that if the casing is being excited by mechanical vibration from machinery sources it may be easiest to reduce vibration at the source.

Damping treatments, such as those described in Item MV3, may not be practical for these structures since damping is not as effective on large structural beams as they are on plate structures. It may be possible to use damping or decoupling materials on platform supports, but such an approach would require treatment of large surface areas (since all supports would need to be treated to avoid flanking) and this may not be a cost effective approach in many cases. Source treatments are likely to be more feasible, although if noise goals are stringent then damping or decoupling may become reasonable options. Another option for platforms would be the use of Ballast-Crete located in certain sections of the platform supports to provide additional damping (see Item MV4 in Appendix A).

There are two other paths that may be overlooked but are potentially significant for otherwise low noise structures. One of these is the fluidborne path from pumps with connections to the ocean. This path was indicated as being significant in Gales (1982) for a quiet man-made island. Treatments for this path are provided in Section FB in Appendix A. A second path is direct radiation from the casing of submerged pumps. Additional research would be required to determine the significance of this source/path.

4.8.2 Treatments for Floating Structures, Including Semisubmersibles, Drillships, FPSOs, and Floating Platforms

These structures all use stiffened plating construction, and are therefore similar to vessels. As such, noise generation and mechanisms will be similar to vessels, as well as treatment options and analysis techniques. As shown by Nedwell (2004), thruster noise will dominate the underwater noise spectrum when operating. Therefore it is recommended that these structures be moored whenever possible. If mooring is not an option, thrusters should be designed to be quiet. Thruster treatments and quiet thruster design options are discussed in Section 4.4.1 and Section PT in Appendix A.

When thrusters are not operating, large on-board machinery is believed to be the major cause of underwater noise. FSB and SSB paths are likely to be the dominant causes of underwater noise for machinery located above the waterline. Below the waterline, airborne noise transmission through hull plating can also be a significant source of noise. Furthermore, all equipment exhausts should be muffled, and equipment located topside should not be allowed to directly radiate into the water. Treatments for these various paths are discussed in Sections MV and MA in Appendix A.

It is restated that the need to treat specific sources will depend on the details of the sources, their location, supporting structures, and the noise goals. It may be found that more equipment would need to be mounted on a drillship than on a semisubmersible or FSPO in order to meet the same noise goal due to the potential proximity of equipment to the water. As discussed in Section 4.5, direct resilient mounting of large pumps such as mud pumps may not be possible. In such cases, floating deck treatments may be appropriate – See Item MV2 in Appendix A.

Similar to fixed platforms, drill string casing radiation is a potential source of noise, but current indications do not show its significance. Investigations into the role of this path should be undertaken before any conclusions regarding appropriate treatments can be reached.

4.9 Hovercraft Treatments

Underwater noise from hovercraft is essentially limited to noise generated by the propulsion and lift fans. Airborne noise created by these fans is transmitted directly into the water (see Section 3.2.9). As such, practical treatments are limited to methods of reducing the levels of airborne noise generated by the fans. It may be desirable to focus these efforts on the propulsion fan since this is indicated in Blackwell (2005) as the major source. However additional data is needed to confirm this as a general statement for all hovercraft; lift fans may be significant on other hovercraft designs.

Similar to what is discussed in Section 4.4.1 as 'good propeller design', the airborne noise generated by these fans is largely dependent on the fan blade design and air flow characteristics in and out of the fans. The fan blades should be designed for the expected flow conditions while mitigating sensitivity to variations in the flow and load. Note that the details of a good hovercraft fan blade design will be different that those for propellers due to the physical differences between air and water. Optimization of the airflow, particularly the flow into the propulsion fan where obstructions are likely to be present, can also result in reduced airborne and underwater noise. Additional details are provided in Section HC in Appendix A.

Since no structureborne paths exist for hovercraft, resilient mounting and damping treatments will not have any effect on underwater noise levels.

4.10 Aircraft Treatments

Similar to hovercraft, reduction of underwater noise from aircraft essentially means a reduction in airborne noise generation (other solutions such as flight paths at greater altitudes are not discussed here). A significant effort to reduce airborne noise from aircraft has been in place since 1990 in the United States, and similar efforts are underway elsewhere in the world. The purpose of these efforts has been to reduce the impact of aircraft noise on humans. As a result of this, aircraft built today are more likely to be quieter than those built 20 years ago.

NASA has been involved in large scale efforts to reduce noise levels from jet engines, as reported in Huff (2005). This work focuses around identifying the specific causes of noise in jet engines and making modifications to those engines in order to reduce radiated noise. Reductions of 10 dB are stated as goals. "Hush kits" are available for jet engines and can reduce noise upwards of 10 dB at some frequencies.

Efforts to reduce noise from propeller-driven planes have been identified in Brown (1982), and efforts to reduce helicopter noise are reported in Nagaraja (1992). These approaches are focused on modifying the propeller or rotor shapes, spacing, and contours so that reductions in noise levels are achieved. Again, propeller blades and rotors should be designed for the expected flow conditions while mitigating sensitivity to variations in the flow and load. Reductions in tip speed will generally provide reduced noise levels. Published noise reductions are typically on the order of 3-10 dB over 'conventional' designs.

JanakiRam (1992) discusses a novel helicopter design that does not use a tail rotor ('NOTAR'). This design is shown to reduce noise by 0-7 dB over conventional designs, due to the removal of main rotor / tail rotor interaction. It is stated that this design also provides improved yaw control.

Additional details on these treatments are provided in Section AC in Appendix A.

4.11 Pipeline Treatments

No studies were identified that discuss treatments to reduce pipeline noise. Furthermore, as discussed in Section 3.2.11, the exact causes of pipeline noise are not known. If fluidborne noise created by the pump is responsible for this noise then the treatments discussed in Section 4.4.3 and Section FB in Appendix A are also applicable here. If noise is related to turbulence in the pipe then the solution may be to investigate the specific cause of turbulence, e.g. elevated flow rates past a bend. These solutions would be implemented on a case by case basis. Additional study is needed in order to better identify causes of pipeline noise and appropriate treatments.

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APPENDIX A – Compiled List of Underwater Noise Treatments

This appendix contains a compiled list of treatments identified as part of this study. Treatments are grouped by source type, as follows:

- SE – Seismic Exploration Treatments and Alternatives
- PD – Pile Driving Treatments and Alternatives
- EX – Treatments and Alternatives for Explosives
- PT – Propeller and Thruster Treatments and Alternatives
- MV – Machinery Vibration Treatments
- MA – Machinery Airborne and Secondary Structureborne Noise Path Treatments
- FB – Fluidborne Noise Path Treatments
- HC – Hovercraft Treatments
- AC – Aircraft Treatments

Each section contains a table summarizing the overall treatment effectiveness, cost, and availability. Following each treatment table are annotations providing details of these items as well as additional details on how the treatment is used, potential drawbacks or need for future research, references, and vendors (when applicable).

SECTION SE:
SEISMIC EXPLORATION TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range or Metric		
SE1	Air Gun Silencer	Silences unwanted frequencies from Air Guns	0-3 dB increase 0-6 dB reduction 1.3-2x increase	< 700 Hz > 700 Hz Peak impulse level	N/A (In development)	F/FF
SE2a	Marine Vibroseis – 'LACS' Combustion Excited Piston	Replacement of impulsive type source with pseudo-random noise source	~15 dB 25-45 dB 45 dB min (est)	0-100 Hz 100-1000 Hz >1000 Hz	N/A (In development)	N/F
SE2b	Marine Vibroseis – Electronically Driven Marine Vibrator	Replacement of impulsive type source with swept sine or pseudo-random noise source	~15 dB 60 dB min 60 dB min (est)	0-100 Hz 100-600 Hz >600 Hz	N/A (In development)	F
SE2c	Underwater Tunable Pipe Organ	Replacement of impulsive source with a swept sine source	N/A, potentially similar to SE2a&b	N/A, potentially similar to SE2a&b	N/A (In development)	F/FF
SE3	Ambient Noise Techniques	Replacement of current techniques – uses wind noise or other low level sources as seismic source	Potential for elimination of anthropogenic sound creation	All	N/A (In development)	F/FF
SE4	Ship Noise Sources	Use of ship noise (i.e. propeller cavitation) as 'low level' seismic source	Potential for large reduction of source sound, ~40-50+ dB	All	N/A (In development)	F/FF
SE5	Electromagnetic Survey	Use of electromagnetic signal instead of acoustic signal.	Large reduction in sound. Some sound exists due to vessels	All	$1-4M per survey	F/FF (Currently not a replacement for acoustic sources)
SE6	Air Curtain Barrier	Air Bubble curtains are used to block sound propagation in *some* directions	9-30+ dB 0 dB to some increase in level	40-80+ Hz <30 Hz	N/A	N
SE7	Shear Wave Generators	Creates shear waves in ocean floor. Shear waves can not cause acoustic radiation in fluids.	N/A	N/A	N/A	N/F

(SE1) Air Gun Silencer

- *Notes on Treatment*: The purpose of this treatment is to reduce the amplitude of sound generated at frequencies above those used for seismic exploration. This may be particularly beneficial for marine life with greater hearing sensitivity at higher frequencies (kilohertz range). The treatment can to be used in conjunction with existing air guns. Acoustically absorptive foam rubber is secured to metal plates which are oriented radially outwards from center axis of an air gun. A picture of the treatment is provided below (Nedwell, 2005). At higher frequencies acoustic energy is absorbed by the foam rubber, thus reducing unwanted sound.

  Nedwell (2005) shows reductions of 0-6 dB at frequencies above 700 Hz. Below this frequency, 0-3 dB increases in level are seen, particularly around 100 Hz. This leads to a 3 dB increase in overall level due to the prominence of low frequency energy. Nedwell claims that this increase in low frequency energy in the 'useful' frequency band can reduce the total number of required air guns to achieve a given level. Nedwell also shows that the impulse peak (positive and negative peak) is higher for the silenced air gun than for the unsilenced air gun by a factor of 1.3 – 2 for a 50 bar air gun. Rise times appeared to be similar for silenced and unsilenced air guns.

- *Limitations / Need for Future Research*: This treatment is currently a proof-of-concept and would require further development to become a commercial product. Treatment effectiveness is currently seen only for small (50 bar) air guns. It is reported that the effectiveness for higher pressure air guns was reduced due to an over-compression of the acoustical material. Materials with higher stiffness are recommended by Nedwell for future iterations of this treatment. Furthermore, the material was seen to only withstand approximately 100 shots before needing to be replaced.

  It was noted during the Workshop that a modified design where the absorbent material is located farther from the air gun may be beneficial. This would reduce the pressure levels seen by the material which may allow the same materials to be effective for larger air guns, increase the life of the materials while in-use, and may allow for silencing of multiple air guns (i.e. arrays). Increased effectiveness may also be possible.

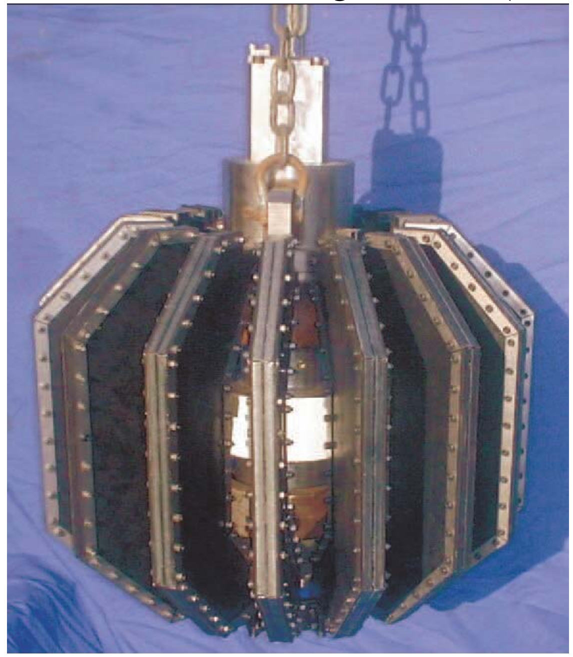
- *Description of Estimated Costs*: Overall costs of this technique are not known as this product is in development.

- *Other Non-acoustic Impacts*: Treatment may make deployment and retrieval more difficult, particularly if larger silencers are used farther from the air gun.

- *References and Additional Information*: Nedwell (2005), Nedwell (Workshop).

- *Vendors*: Subacoustech (www.subacoustech.com)

FIGURE SE1: Picture of Air gun Silencer (Nedwell, 2005)



Acoustically absorptive material is located radially around a conventional air gun.

(SE2a) Marine Vibroseis – 'LACS' Combustion Driven Piston

- *Notes on Treatment*: The LACS is an acoustic source that is a replacement for air guns and other impulsive seismic sources. A picture and schematic diagram are provided below. Sound is generated through the motion of the pistons located on either end of the unit. The pistons are excited via the combustion of petrol in the combustion chamber. Combustion takes place within the unit and is not exposed directly to the water. Combustion gasses are brought above the water surface via exhaust pipes.

FIGURE SE2a(1): Picture of Combustion Driven Piston “LACS” (Askeland, 2007)

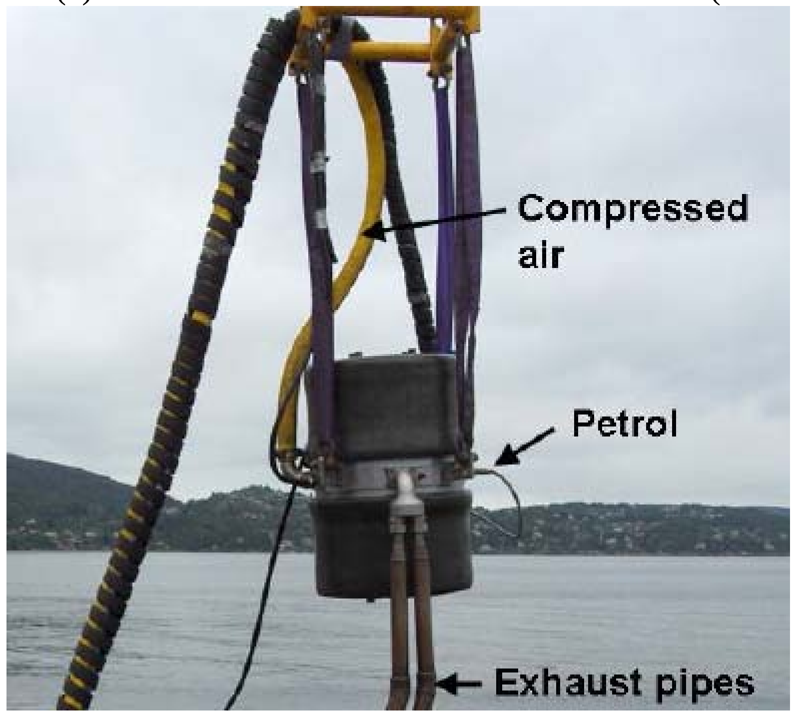
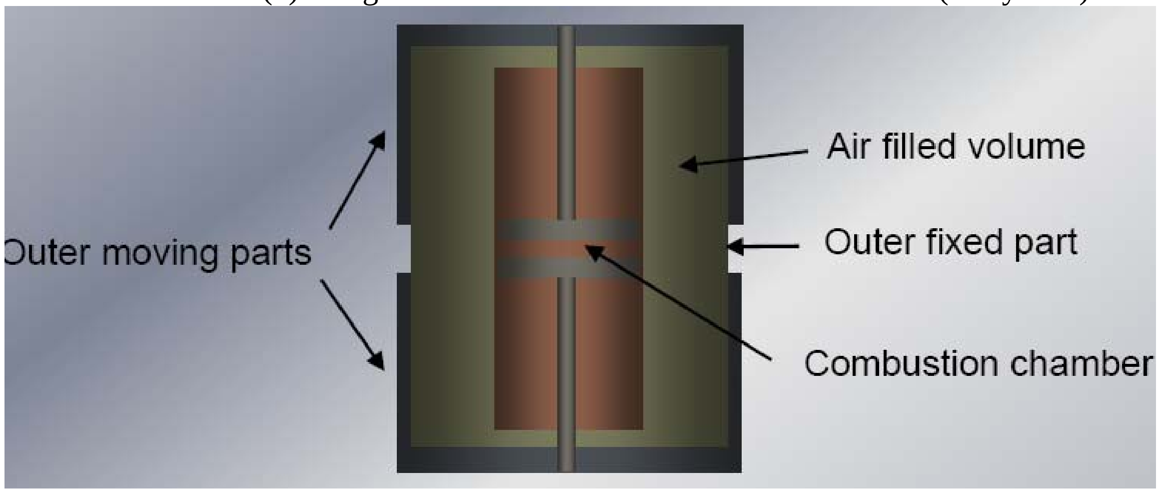


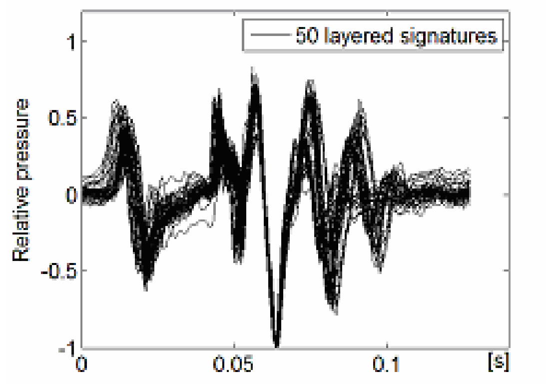
FIGURE SE2a(2): Diagram of Combustion Driven Piston “LACS” (Naxys AS)



Sound is generated via the motion of the ‘outer moving parts’ or pistons. These parts are excited via combustion of petrol in the combustion chamber.

The LACS provides an opportunity to significantly reduce peak and overall sound levels at all frequencies, both above and within the useful range for seismic exploration. The output signal waveform is controlled through the design of the system, and as a result the output at non-seismic frequencies (i.e. above 100 Hz) can be significantly reduced. The time waveform output from 50 consecutive shots is shown in Figure SE2a(3). It is seen that this source creates repeatable ‘pseudo-random’ signal. This signal can be repeated over the course of several seconds to create an equivalent air gun shot; 50-100 pulses can give approximately the same penetration depth as one small air gun shot. The LACS can fire up to 10 pulses/sec, creating a semi-continuous source. It is noted that there are no additional signals from “bubble noise” that are associated with air guns.

FIGURE SE2a(3): Typical Output of LACS (Askeland, 2007)



This graph shows that the pressure vs. time output of the LACS is highly repeatable. Although not shown here, this curve contains predominantly low frequency components, below 100 Hz. Output at higher frequencies is minimized through the design of the system.

Reductions in sound below 100 Hz (and overall level) are achieved because the signal is spread out over a greater time period as compared with conventional sources. Additional reductions in low frequency and overall sound level can be achieved using advanced processing methods. The pressure produced by the LACS can be recorded using a nearby hydrophone. This signal is then cross-correlated with the signal received by the streamer. It has been shown that this processing method can be used to identify a seismic signal whose amplitude is 19 dB less than the background noise. Advanced correlation techniques such as "iterative correlation" and "Semi Periodic Chirp Sequences" (SPCS) can also be used to reduce sidelobes in the processed seismic data (reduced ghosting effects). As a result of these factors, the total acoustic energy of the LACS is less than that produced by conventional sources.

The estimated sound reduction listed in the table above is based on published results for frequencies below 100 Hz and comparisons of available data for LACS vs. air gun acoustic spectra above 100 Hz. Data for LACS acoustic spectrum above 1000 Hz is not available so effectiveness is approximated. Relative to the levels generated below 100 Hz, maximum levels above 100 Hz are -15 dB at 200 Hz, and decrease by approximately 10 dB per octave. Air guns show a 5-10 dB reduction per octave above 100-150 Hz with no large discontinuities.

It is noted that the relative motion of the source and receiver, due to vessel motions or changes in the bottom-profile, can cause errors if not accounted for. Methods of correcting for this relative motion are provided in Hampson (1995). Good results were obtained with vessel speeds of 2.8 knots (Askeland, 2006). Furthermore, it was indicated in the Workshop that this source can be used in present state for vertical seismic profiling.

- *Limitations / Need for Future Research*: The maximum usable water depth is a current limitation of this system. Published test results have been in water depths up to 380 meters. It is believed that the system can be used in greater water depths if multiple sources are used (increasing the effective source level), a larger source is manufactured, or longer integration times are used. Mr. Askeland has indicated to NCE that tests that have taken place since the Workshop which have penetrated up to 300 meters into the sea floor to the rock basement using 11 second long pulse sequences.

- *Description of Estimated Costs*: Unit costs are not known at this time since the unit is under development. Operating costs should be similar to current costs using air gun arrays. Source requires fuel for combustion and low pressure compressed air.

- *Environmental Impacts*: Some impact will be present due to the combustion of petrol. The LACS can make 3600 shots on one liter of petrol. During published testing, 43 shots were fired every 16 seconds. This results in approximately 2.5-3 liters of petrol per hour.

- *Other Non-acoustic Impacts*: New processing techniques will need to be implemented.

- *References and Additional Information*: Askeland (2006), Askeland (2007), Hampson (1995), Askeland (Workshop).

- *Vendors*: Naxys AB (www.naxys.no)

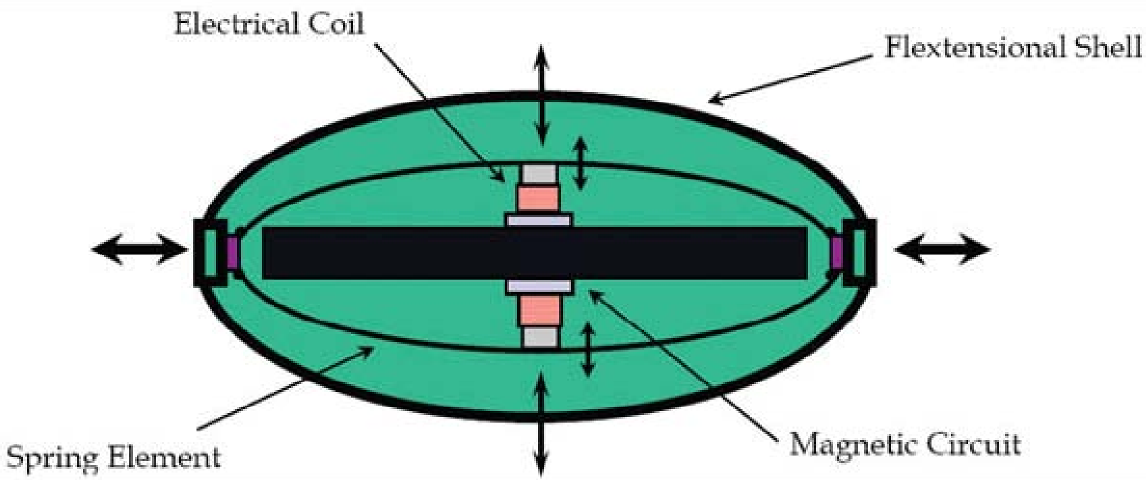
(SE2b) Marine Vibroseis – Electronically Driven Marine Vibrator

- *Notes on Treatment*: The electric ‘marine vibrator’ is another seismic source that replaces conventional impulsive seismic sources. A picture of the unit and a schematic diagram are provided below. The source creates sound through the motion of a ‘flextensional shell’. Excitation and control of motion is performed through electronic equipment (signal source and amplifier). The output signal waveform can be contoured through creation of the electronic signal and feedback loops. The output signal can be a swept sine, peudo-random noise, or virtually any other useful signal type.

FIGURE SE2b(1): Picture of Electrically Driven Marine Vibrator (Tenghamn , 2006)

The 'marine vibrator' is essentially an underwater speaker. Two transducers are used to cover the frequency range of 6-100 Hz. The larger unit in the back of the image covers the 6-20 Hz range and the smaller unit in the front of the image covers the 20-100 Hz range.

FIGURE SE2b(2): Diagram of Electrically Driven Marine Vibrator (Tenghamn, 2006)



The 'marine vibrator' is similar to a stereo speaker in that an electrical coil is placed in a magnetic field, and a voltage potential is applied across the coil. The resulting current in the coil produces a force that excites the shell. This motion then radiates sound into the water. Because the system uses an electric signal, virtually any waveform can be output. This also allows the use of electronic feedback loops to further reduce higher frequency components (>100 Hz).

The system currently uses two transducers to cover the entire frequency range. A larger transducer creates sound between 6-20 Hz, and a smaller transducer creates sound from 20-100 Hz. The combined system covers the 6-100 Hz frequency range. The transducers make use of mechanical resonances, one from the shell and one from the internal spring, in order to achieve significant output levels at low frequencies. The system efficiency is close to 25% (electrical energy in vs. acoustical energy out).

The primary advantages of the system include significant reduction of sound at frequencies above the useful seismic range (above 100 Hz) as well as a reduction in the overall sound level (controlled by frequencies below 100 Hz). Sound generation at frequencies above 100 Hz is due to non-linear distortion effects only. Such effects can be reduced through the use of electronic feedback loops. Reduction in overall sound level is achieved because the signal is spread out over time relative to impulsive sources. Cross-correlation methods can be used to process data and further reduce source levels (as discussed in Item SE2a).

It was also noted at the Workshop that the 'production efficiency' of this approach is similar to conventional methods. That is to say that when using the marine vibrator, the survey vessel speed is the same as when conventional sources are used. Thus, a given area can be covered in the same amount of time as for conventional methods.

Seismic data acquired using this technique was shown at the Workshop to be comparable to data acquired using air guns. It was also indicated that the total acoustic energy output of this system is significantly lower than that produced by conventional systems.

The estimated effectiveness of this technique is based on published results for frequencies below 100 Hz and comparisons of available data for the marine vibrator vs. air gun acoustic spectra above 100 Hz. Acoustic spectra above 600 Hz are not available and effectiveness has been approximated. Published data indicate that during a swept sine test harmonics were 35-65+ dB lower than the fundamental tone in the range of 0-600 Hz.

The system is claimed to be well suited for shallow water applications where air guns can not be used (the conventional approach would be to use explosives in boreholes). Deeper water applications are also possible, although arrays of sources may be required for very deep waters.

It is noted that the acoustic output of this source is easily controllable using electronic amplifiers, etc., and thereby the necessary acoustic output can be "dialed-in" to prevent excessive sound creation. Furthermore, it may be possible and relatively simple to use deterrent type signals with this projector where acoustic signals are used to scare marine life out of the immediate vicinity without the need for additional equipment.

- *Limitations / Need for Future Research*: The maximum usable water depth is a current limitation of this system. Published testing is in water depths of 4-6 feet, and Tengham (Workshop) presented data that was taken at 30m water depth. It is believed that the existing system could be used in greater depths, possibly several hundred meters or more, particularly if multiple sources are used (increasing the effective source level), a larger source is manufactured, and/or alternative source signals/processing methods are used.

  It was indicated at the Workshop that this system can be made into a commercial product in approximately 2 years. The current system will break after a few weeks. The vendor is currently looking into different drive mechanisms to improve reliability.

- *Description of Estimated Costs*: Costs are not known at this time since the unit is under development. Operating costs should be similar to current costs using air gun arrays. Source only requires power for electronics.

- *Other Non-acoustic Impacts*: New processing techniques will need to be implemented.

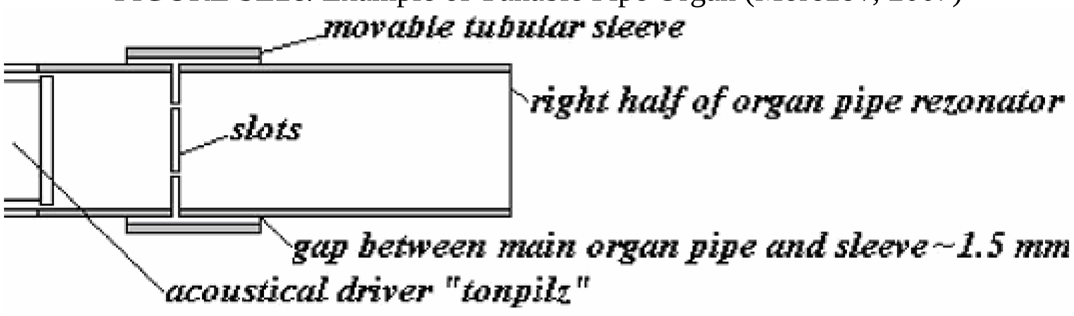
- *References and Additional Information*: Tenghamn (2006), Tenghamn (Workshop).

- *Vendors*: PGS Marine Geophysical (www.pgs.com)

(SE2c) Underwater Tunable Pipe Organ

- *Notes on Treatment*: Morozov (2007) describes a system where a pipe of variable length is located underwater and driven with 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. An example of this device is provided below.

FIGURE SE2c: Example of Tunable Pipe Organ (Morozov, 2007)



The system as described by Morozov is capable of deployment in water depths up to 5000 meters. System efficiencies are shown to be 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 seconds.

While it was not explicitly discussed by Morozov, cross-correlation methods similar to those described in Items SE2a and SE2b could also be used with this device, thereby requiring lower source levels.

- *Limitations / Need for Future Research*: The system appears to be in the early stages of development. The ability to produce signals as low as 5 Hz would require physically large sources, although the size may not be prohibitive with the right design. The amplitude of higher harmonics was not discussed, and would need to be investigated. It may be possible to use a feedback loop as discussed in Item SE2b to reduce the amplitude of these harmonics.

- *Description of Estimated Costs*: Costs are not known at this time since the unit is under development. Source only requires power for electronics.

- *Other Non-acoustic Impacts*: New processing techniques would need to be implemented.

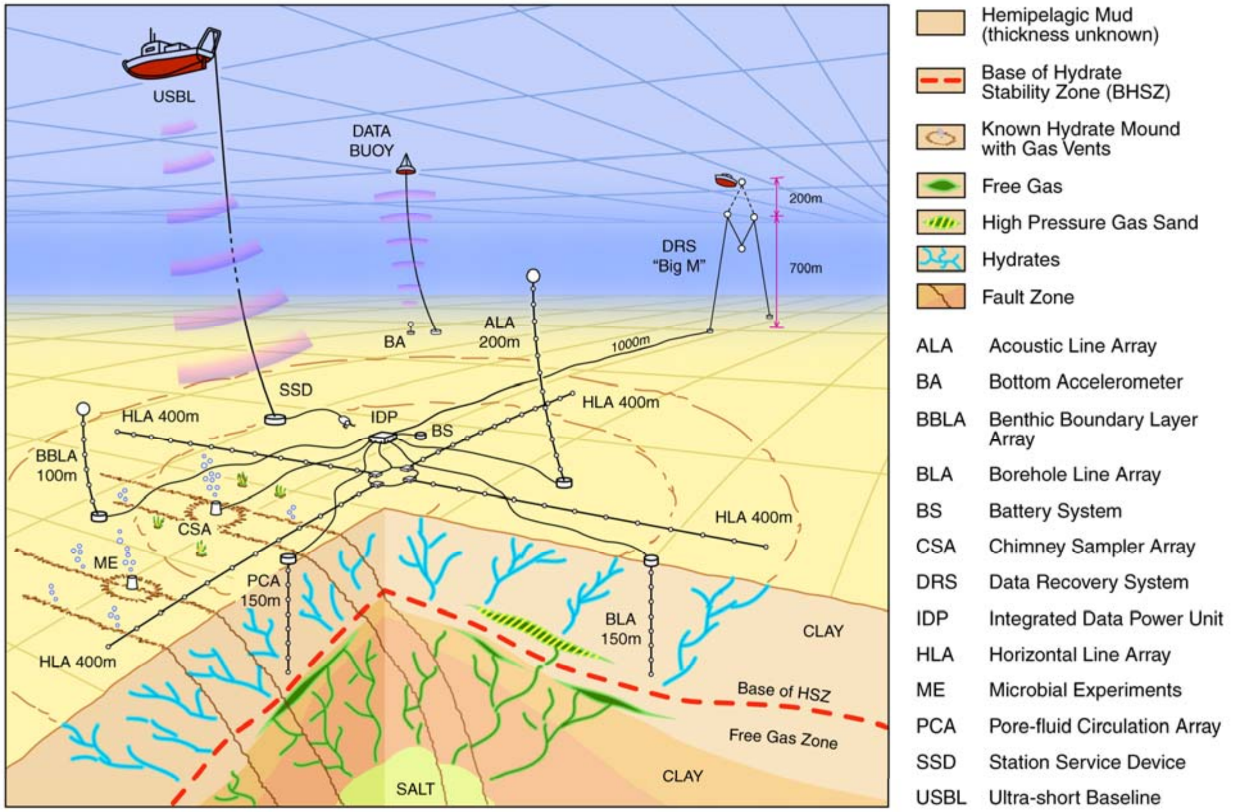
- *References and Additional Information*: Morozov (2007).

(SE3) Ambient Noise Techniques

- *Notes on Treatment*: Several approaches that replace conventional seismic sources with ambient ocean noise have been identified. One of these methods uses a technique called "Spectral Factorization". An implementation of spectral factorization described by Harrison (2004 & 2005) uses a vertical hydrophone array that is attached to a buoy and drifts in the ocean. Uncorrelated, ambient noise generated by wind on the surface of the water is measured and analyzed. Using the spectral factorization technique, the sub-bottom profile can be extracted. Given the fact that ambient noise is used as the source, effectively all anthropogenic sounds from seismic exploration are removed. Comparisons of data obtained using this technique to data obtained using a seismic source show similar results.

  Other methods include the use of ambient noise created by waves on shorelines and micro-seisms (naturally occurring low level earthquakes that occur on a regular basis). The University of Mississippi owns and operates several underwater arrays using these and similar techniques to identify sub-surface features. A slide from Dr. Thomas McGee's presentation at the Workshop which shows the various arrays used at the University, is provided below. Of the various arrays that are available, Dr. McGee highlighted the borehole array (used with microseisms), the horizontal cross array (used with wind and wave signals), and the vertical array (used with passing ship noise – See Item SE4).

FIGURE SE3: Diagram of Various Underwater Arrays used for Ambient Noise Seismic Data Collection (McGee, Workshop)



Gas Hydrate Sea Floor Observatory - Mississippi Canyon Block 118

Various configurations of hydrophone arrays can be used with different ambient source signals to identify sub-surface structures. For example, borehole arrays can be used to measure microseisms, the horizontal cross array can be used to measure wind and wave signals, and the vertical array can be used to measure passing ship noise (See Item SE4).

Limitations / Need for Future Research: Because the source level of these signals is very low (it is the background 'noise'), data must be collected over long periods of time in order to be useful. Acquisition times on the order of days or longer are common for micro-seism signals and thus permanent or semi-permanent hydrophone installations are required. Because of this, these methods may not be well suited for exploration of new areas. However, they may be very appropriate for 'Life-of-Field' surveys where the area of interest is already well established, and there will likely be a significant amount of background noise due to vessel activity.

Siderius (2006) presents data from a floating buoy measuring wind noise with profile depths up to 155 meters. Significantly deeper penetration depths may not be possible with this specific approach. The path of the floating hydrophone array is likely to be limited to natural currents.

These techniques are currently being used primarily by universities for research on hydrates. Adapting these techniques for the oil and gas industry may take some time, but they hold great potential for making significant reductions in sound levels at all frequencies.

- *Description of Estimated Costs*: Overall costs of this technique will depend on the specific application. If used for exploration of new areas costs may be high relative to existing methods. However if used for Life-of-Field surveys costs may in fact be less than conventional approaches over the long term since the array would only need to be deployed and retrieved once, and data could be continually collected.

- *References and Additional Information*:

  Spectral Factorization: Harrison (2004), Harrison (2005), Siderius (2006).

  Micro-seisms/Seismic Interferometry: Curtis (2006), S.P. (2005), Draganov (2007).

  General: McGee (Workshop).

(SE4) Ship Noise Sources

- *Notes on Treatment*: Similar to the ambient noise techniques of seismic profiling described in Item SE3, ship noise can also be used as a seismic source. This approach has been used by several researchers to map the sub-bottom profile of the ocean. In each case there were no modifications to the vessels, and the vessels are often 'vessels of opportunity'. The approach described by Davies (1992) uses noise from a cavitating propeller as a seismic source. Advanced cross correlation techniques were used to extract a sub-bottom profiles similar to what would result from a conventional survey using an air gun. Another approach described by Koch (2005) uses "geoacoustic inversion" techniques with noise from passing vessels.

Dr. McGee presented at the Workshop a comparison of seismic data obtained using vessel noise compared to data obtained by an air gun. The data was taken from a survey performed in the 1990s by the University of Aarhus, Denmark, where a hydrophone was mounted at the stern of a vessel above the propeller. The data showed similar results, with penetration depths up to 1000 meters. Dr. McGee also indicated that the vertical array (seen in Figure SE3) at the University of Mississippi is currently used for this purpose. They use "matched field processing" techniques to identify sub-surface structures.

As was discussed for Item SE3, this approach may be well suited for Life-of-Field surveys due to the prominence of vessels near offshore installations. However, if the approach used by the University of Aarhus is determined to be viable, then surveys of new areas could also be performed using this technique.

- *Limitations / Need for Future Research*: This approach appears to have good potential, although information on practical applications is limited. Additional study is likely needed to fully develop this approach. It is noted that matched field processing techniques have been used in submarine warfare and are not necessarily new. Adapting these techniques to suit the oil and gas industry may take some time, although Dr. McGee indicated at the Workshop that this may be possible in a matter of a few years.

- *Description of Estimated Costs*: Overall costs of this technique are not known and will depend on the specific application of this technology. That said, long term costs could be similar to if not less than existing seismic exploration methods.

- *References and Additional Information*:

  Ship Noise Sources: Davies (1992), Koch (2005), Park (2005), McGee (Workshop).

  Geoacoustic Inversion: Chapman (2004), Sun (no date), http://www.mpl.ucsd.edu/people/gerstoft/asa/

(SE5) Electromagnetic Surveys

- *Notes on Treatment*: Electromagnetic surveys use electromagnetic signals rather than acoustic signals to identify features below the sea floor. There are several electromagnetic approaches that are currently available, although all approaches are similar in several ways. In all cases, an electromagnetic signal is produced in the water which then propagates into the sea floor, reflects off structures, and bounces back to the surface in a similar fashion to acoustic signals. The signal is detected by receivers located on the sea floor. The source can be either stationary or towed, and is located either on or just above the sea floor. The source is typically made up of two large electrodes, spaced roughly 300 meters apart. The source can deliver as much as 1250 amps into the water at frequencies ranging between 0.1 and 50 Hz (electromagnetic waves, not acoustic waves). Once the data is available (see below) initial results can be obtained within 24 hours.

In general, the data that is acquired is good for identifying the contents of reservoirs, which is information that can not be obtained through acoustic surveys. This can be useful in eliminating extraneous drilling which can lead to 'dry holes'. However, electromagnetic methods are generally less accurate at determining physical extents of a reservoir than conventional acoustic methods. Because of this, electromagnetic surveys are better suited for determining the viability of a reservoir, and are not good for finding new locations to drill (and are therefore currently not a replacement for existing acoustic seismic methods).

One application of this approach is called controlled-source electromagnetic (CSEM), where a continuous AC signal is produced at a single frequency, typically between 0.1 and 10 Hz. The source is towed by a vessel, and is located roughly 30 meters off the sea floor. The receivers are spaced approximately 1 km apart over a large area, and are held to the bottom by concrete anchors. When the survey is complete, the receivers are separated from their anchors by an acoustic release, and are allowed to float to the surface for retrieval. Once retrieved, the data collection process begins. A survey of this type can take 1 or more weeks to complete, depending on the survey area.

A second approach is called MTEM. This approach uses a stationary source located on the sea floor. The source generates a pulsed coded, broadband signal with frequency content between 0.1 and 50 Hz. The receivers are also located on the sea floor, but are spaced closer together than in the CSEM approach. The modified approach allows for better spatial resolution and the ability to perform surveys in shallow water. Furthermore, the receivers are cabled to a support vessel, so the data is available instantaneously. It is possible to move the receiver array so that up to 5 km can be covered in a day (single line). 2 dynamically positioned vessels are needed to perform his kind of survey.

In either approach, vessels are required so there is not a complete removal of sound. However the vessel sound should be significantly less than what is produced by conventional acoustic seismic signals. There are currently several companies that can perform various versions of these surveys commercially, and the technology appears to be continually developing.

- *Limitations / Need for Future Research*: Given the low spatial resolution, this approach is not currently a replacement for acoustic exploration of new areas. The CSEM method works best in water depths greater than 1500 feet (450 meters). The MTEM method can be used in much shallower waters. Penetration depth below the sea floor is limited to 3-4 km. In either case, receivers need to be deployed and retrieved (or at least moved), which makes this approach slower.

- *Description of Estimated Costs*: Survey costs have been quoted by various vendors to be on the order of $1-4M per survey, which depends on mobilization costs and survey size/time (survey area was not provided). Some up-front modeling may also be needed in order to determine the feasibility of the survey at additional cost.

- *Environmental Impacts*: For the CSEM method, the concrete pads are left behind after the survey is complete. Buchanan (2006) indicates that there is minimal environmental impact that results from the existence of the electromagnetic field. Fechhelm (2005) indicates that there is a minor deterrent effect on animals that use electromagnetic fields to hunt and for navigation. It has been indicated by one vendor that the electrodes should not be contacted.

- *References and Additional Information*: Fechhelm (2005), Buchanan (2006), Ziolkowski (2006), Tompkins (no date).

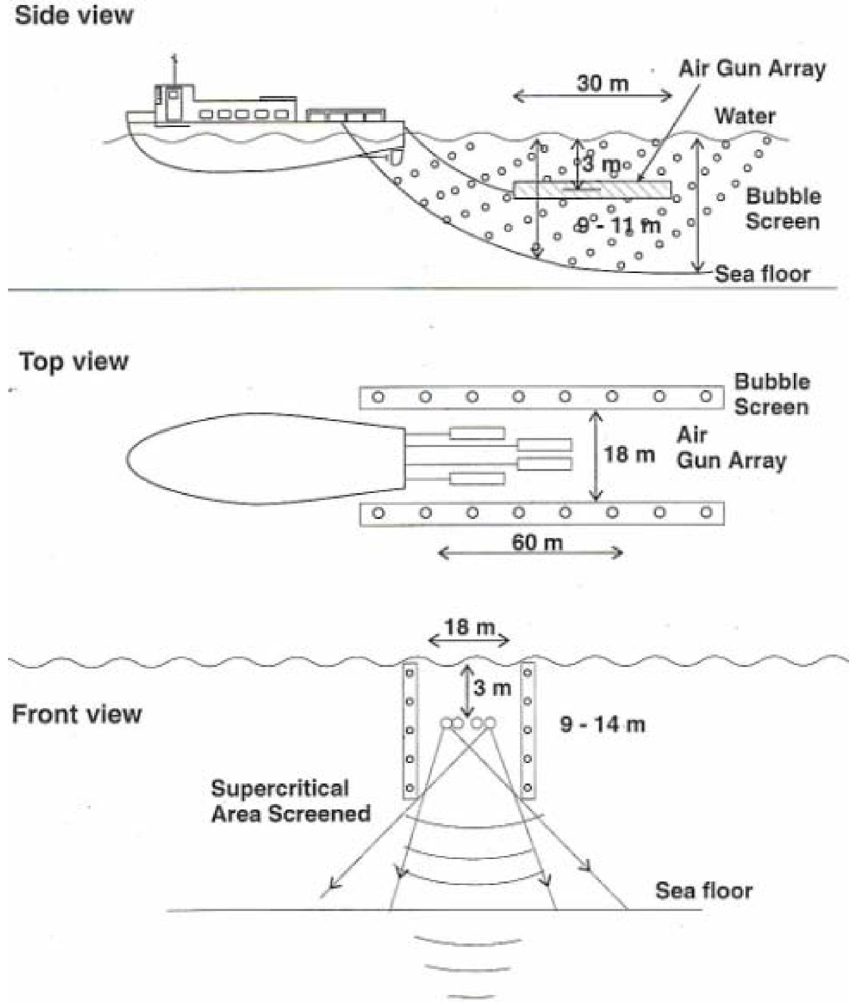
- *Vendors*: Offshore Electromagnetic Mapping, Ltd. (www.ohmsurveys.com), Electromagnetic Geoservices ASA (www.emgs.com), MTEM Ltd. (www.mtem.com), Western Geco (www.westerngeco.com).

(SE6) Air Curtain Barrier

- *Notes on Treatment*: Sixma (1996a) and Sixma (1996b) discuss the use of a bubble curtain to block some of the laterally radiated sound energy created by air guns. In this method, bubble curtains are located on two sides of the seismic source (parallel to the direction of the vessel towing the source) as seen in Figure SE6. (For a discussion on bubble curtains, see Item PD1). The original application of this technique was to reduce acoustic interference caused by modal propagation and reflection in shallow waters. This technique can also be used to limit the area affected by seismic sources.

  It was shown that reductions of 9 dB are possible at 40 Hz, with increasing effectiveness up to 30 dB above 80 Hz. Increases in level were sometimes seen near 20 Hz. It was noted in the literature that reductions were measured for all locations where there was no line-of-sight with the source. However, once the source could be seen by the receiver the curtain no longer was effective at reducing sound.

FIGURE SE6: Diagram of Air Curtain Barrier (Sixma, 1996b)



A bubble curtain is located on two sides of a vessel with a deployed air gun or air gun array. The curtain effectively blocks transmission of sound to locations that do not have a direct line-of-sight path to the air gun. Other locations see little to no reduction in sound.

- *Limitations / Need for Future Research*: While this approach certainly shows merit, it 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, it would need to be determined if this approach is feasible and effective for use in deep waters; the bubble curtain has limitations as to how deep it can be located, and therefore there is some limit as to the possible shielded area at large distances from the source.

- *Description of Estimated Costs*: Costs were not identified in the literature, although costs may be on the same order of magnitude as those identified in Item PD1a.

- *References and Additional Information*: Sixma (1996a) and Sixma (1996b)

(SE7) Shear Wave Generator

- *Notes on Treatment*: Shear waves created in the ocean floor can be used to identify sub-surface features. In the context of reducing noise generated in the ocean, the (theoretical) advantage to using shear waves that shear motion of the sea floor does not create acoustical radiation (water can not support shear waves). A "shear wave generator" is located on the ocean floor in order to create such waves. One example of a shear wave generator is provided by Cole (1992). The University of Mississippi also has built a shear wave generator and has used it to collect seismic data with "good results" (information courtesy of Dr. Tom McGee). A similar generator is available from Bolt Technology (www. bolt-technology.com).

  Measurements of actual sound pressure levels in the water during the use of a shear wave generator could not be found. For the generator described by Cole (1992), the system uses propellers, and thus would not completely eliminate noise (although levels may be significantly less than conventional acoustical seismic sources). Similarly, the generators made by the University of Mississippi and Bolt Technology create "P" (compression) waves in addition to shear waves, and likely create some sound in the water. The amplitude of this sound relative to conventional sources is not known.

FIGURE SE7: Example of a Shear Wave Generator (www.bolt-technology.com)

- *Limitations / Need for Future Research*: Source must be located on the sea floor. Actual sound levels generated are not known. It was noted by one attendee of the Workshop that seismic shear wave data is hard to interpret.
- *Description of Estimated Costs*: N/A.
- *References and Additional Information*: Cole (1992)
- *Vendors*: Bolt Technology Corporation (www.bolt-technology.com)

SECTION PD:
PILE DRIVING TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Metric		
PD1a	Bubble Curtain or Bubble Tree	Air bubbles are used to block sound propagation	5-20+ dB	O/A RMS, +/-Peak, SEL	Project costs on order of $50-200+ k	N
			No Change	Rise Time		
PD1b	Confined Bubble Curtain	A fabric or solid curtain is used to confine bubbles and prevent disruption from currents	9-22 dB	O/A RMS, +/-Peak, and Particle Velocity.	Project costs on order of $100-200+ k	N
			30% increase 3x increase	Pressure pulse time Velocity Pulse time		
PD2	Alternative Piles	H-Piles and concrete piles may reduce underwater noise	10-20 dB (approx)	Peak	N/A	N
PD3	Pile Caps	Caps of various materials are used between the impact piling head and the pile to reduce underwater sound	1-20+	Peak, RMS, and SEL	Low material cost	N/F
PD4	Physical Barrier	A physical (i.e. steel) barrier internally lined with foam or other material is used to block underwater sound	15-23 dB 17-27 dB 14-21 dB	Peak RMS SEL	N/A May be similar to Bubble Curtain	N/F
PD5	Dewatered Cofferdam	Removal of water around pile to remove direct radiation path	15 dB 3-35 dB	Peak RMS	N/A, Assumed more than bubble curtain, lined barrier	N
PD6	Vibratory Hammers	Alternative to impact hammers	10-20+ dB	O/A	2-3 x cost for impact hammers	N
PD7	Suction Piles	Replacement for existing piling techniques	Very Large Reductions	All	Potential cost savings.	N

PD8	Press-in Piles	Piles are pressed into place using static pressure	Very Large Reductions	All	N/A	N
PD9	Drilled, Cast-In-Place piles	Pile casing is drilled into place and then filled with cement	Significant Reductions	All	N/A, assumed more expensive than existing methods	F

(PD1a) Bubble Curtains and Bubble Trees

- *Notes on Treatment*: A wall of air bubbles is used to block sound radiated by a pile while it is being driven. The bubbles create an acoustic impedance mismatch which decouples the sound from one side of the curtain to the other. Some absorption effects may also take place at higher frequencies – i.e. kHz range (Domenico, 1982a). The bubbles are created by forcing air through small holes drilled in a metal or plastic ring. Examples are shown below. The ring is located on the sea floor, and an air compressor is used to push air through the system.

FIGURE PD1a(1): Examples of Bubble Curtain Rings. Left Side (Reyff, 2004). Right Side (Laughlin, 2005a)

The rings shown here are used to create air bubbles. Air is pumped into the rings via a compressor and is released through small holes drilled in the rings. Rings have been made of plastic and metal. Hole size, spacing, and number of rows will have an impact on the effectiveness of the curtain.

Several sources were identified that discuss the theoretical aspects of air bubbles in water and bubble curtains. Shagapov (1998) provides a simplified model of sound reflection from and transmission through an air bubble wall. Using the equations provided by Shagapov, several insights can be gained.

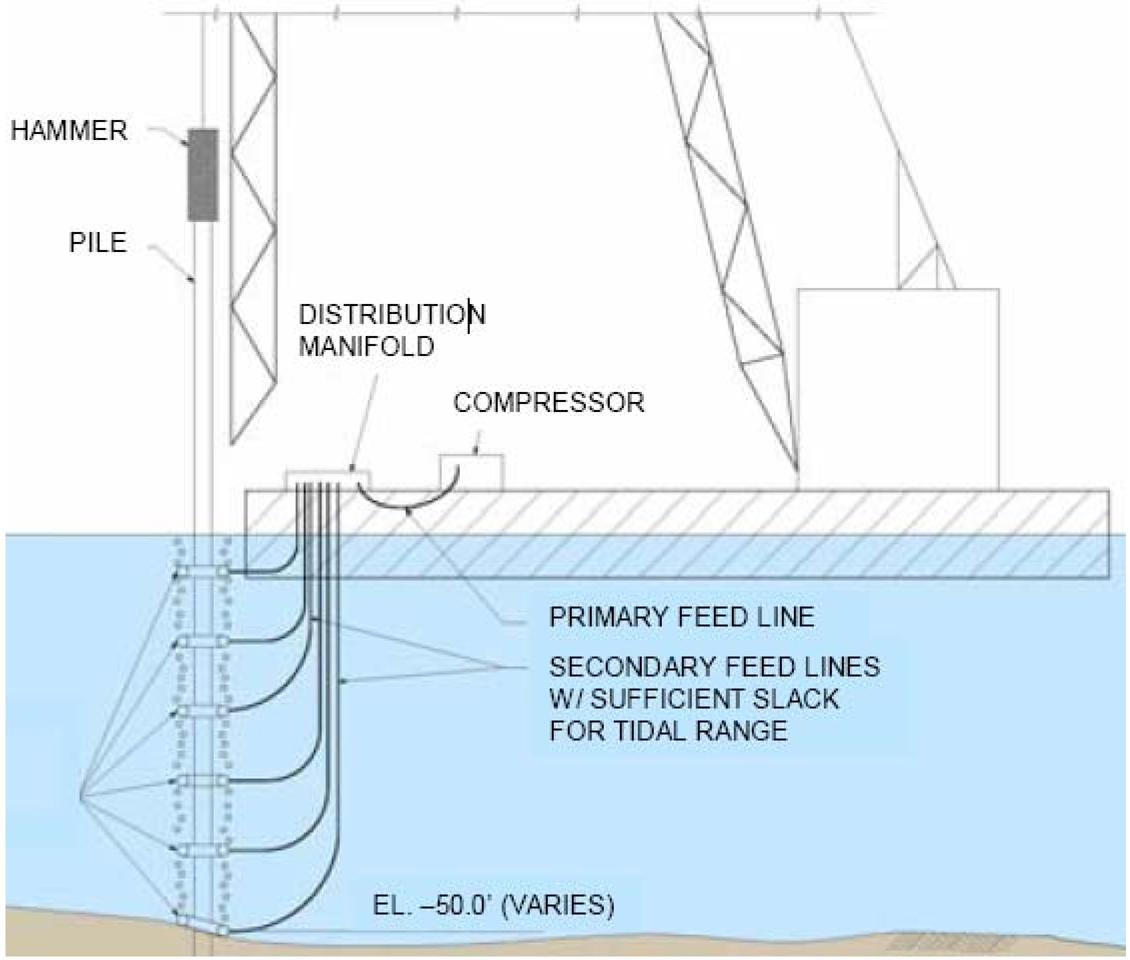
1. Bubble curtain effectiveness is based not only on bubble size, but also on the thickness of the air curtain, ‘bubble density’ (i.e. volume of air per total unit volume), and water depth.

2. Overall effectiveness increases with increased air curtain thickness and higher bubble density.
3. The effectiveness is seen to decrease if the size of the bubble is made smaller while holding all other parameters constant. However, with smaller bubble sizes it may also be possible to increase the total air density. Sensitivity to bubble size alone is not as strong as for the other parameters.
4. Effectiveness is seen to decrease with increased water depth (higher static pressures).

These conclusions have been largely verified in practice. Vagle (2003) states that many small bubbles are preferable to fewer larger bubbles. With reference to point 3 above, smaller bubbles may allow for higher bubble densities, yielding a net positive result. Furthermore, smaller bubbles have been shown to rise to the surface slower than large bubbles, which may also allow for a denser bubble field (Ross, 2005). Laughlin (2005a) and Petrie (2005) have described designs where multiple rows of holes are used in a single ring (e.g. see the right side of Figure PD1a(1) above). This likely corresponds to an increased curtain thickness, which is shown by Shagapov to increase effectiveness.

Bubble curtains are susceptible to currents. The effectiveness of a bubble curtain can be partially or completely compromised in moderate to strong currents. Use of bubble “trees” can be effective in mitigating deleterious current effects. A diagram of a bubble tree concept is given in Figure PD1a(2). The spacing between each bubble ring should be on the order of 10-35 feet (Petrie, 2005; Longmuir, 2001; CADOT, 2001). It is noted that Laughlin (2007) found that bubble trees did not increase the effectiveness of the bubble curtain when currents were not present.

FIGURE PD1a(2): Bubble Curtain 'Tree' (Petrie, 2005)



Bubble trees use multiple rings to help reduce the negative effects of currents by maintaining a contiguous bubble wall. A conventional bubble curtain would only use one ring, located on the sea floor. Air is distributed to the rings via primary and secondary distribution manifolds. As seen here, the bubble curtain needs to completely surround the pile through the entire water column. Seating of the bottom ring on the sea floor is important. If not seated properly the effectiveness of the curtain will be compromised.

Detailed construction and installation descriptions are given by Longmuir (2001) and CADOT (2001). Additional sources show that holes of diameter 1 – 1.5 mm drilled in the bubble curtain ring have yielded good results. Smaller holes may be possible. Available data indicate a 6-20 mm spacing between holes has been used on various projects. In general, higher effectiveness is seen for systems with smaller hole sizes spaced closer together. Multiple compressors may be required depending on the size of the system. Primary and secondary distribution manifolds should be used for uniform bubble distribution.

Different references list different requirements for compressor sizes. Stated compressor output requirements range between 1500 cu ft / minute (42 cu meter / minute) to 750 cu ft / minute (21 cu meter / minute). Other sources prescribe 150 cu ft / minute (4 cu meter / minute) per secondary line, or 70-105 cu ft / minute (2 - 3 cubic meters / minute) per linear meter of pipe in each layer. Naturally, the actual requirements for any given setup will depend on the details of the design.

The literature shows 5-30 dB reductions are possible for positive and negative peak impulse pressure and broadband overall level when bubble curtains are used, although reductions of 5-20 dB are most commonly found. Lucke (Workshop) indicated a 16 dB decrease in both peak level and "energy flux density" (See Appendix C). Reyff (2004) presents data which indicates similar dB reductions in +/- peak, Sound Exposure Level (i.e. energy), and RMS level. For example, one comparison shows a 10 dB reduction in peak level and Sound Exposure Level (SEL) with a 12 dB reduction in RMS level. Another comparison shows a 20 dB reduction in peak level, a 16 dB reduction in sound energy accumulation, and a 15 dB reduction in RMS level. Laughlin (2005c) shows data which indicates reductions in peak, RMS, and SEL. For the most effective bubble curtain implementations, one data set indicates a 9, 16, and 11 dB reductions in these quantities, respectively, while another shows reductions of 14, 11, and 12 for the same quantities. Laughlin (2005b) also shows similar relative levels between these metrics. In general, it is seen that the relative amounts of reduction seen in these various metrics are similar for a given measurement, at least within the level of accuracy that can be expected from field measurements of pile driving activities.

Rise times appear to be similar with and without bubble curtains where data is provided. Laughlin (2005b) and Laughlin (2005c) specifically calculate the rise times for treated and untreated piles. The data is generally scattered and there are no clear differences. MacGillivray (2005) indicates that this metric is inconvenient as the pulse changes shape when a bubble curtain is used (See Item PD1b below).

Ellison/Laughlin (Workshop), Shagapov (1998), and others generally indicate that larger reductions should be and have been seen at higher frequencies. For example, Wursig (2000) shows the overall level (RMS), which is controlled by the levels at frequencies below 400 Hz, was reduced only by 3-5 dB, however 8-10 dB reductions were seen from 400-800 Hz and 15-20 dB from 1600 to 6400 Hz. In contrast, some references (including Lucke, Workshop) indicate that reductions at low frequencies were greater than reductions at higher frequencies. Reasons for this discrepancy are not entirely known, but may have to do with the background noise created by the bubble curtain itself and/or flanking paths.

Drake (2004) gives details on a method for increasing the bubble rise time through the use of additives. Potential additives include n-propanol, 2-ethyl haxanol, octanol, ExxonMobil Chemical Exxal-8 alcohol, ExxonMobil Chemical Exxal-9 alcohol, ExxonMobil Chemical Exxal-13 alcohol, and sodium dodecyl sulfate. Use of such additives can increase bubble rise times by factors of 3 or 4. Use of any additive would need approval by appropriate regulatory bodies.

- *Limitations / Need for Future Research*: Bubble curtains must completely surround the noise source (360 degrees) and must be contiguous through entire water column. Gaps in the bubble curtain (such as at the sea floor) can seriously compromise its effectiveness (Laughlin, 2005b). Bubble curtains are limited to shallow waters and coastal areas for practical and economic reasons (Continental, 2004), and may also have reduced effectiveness at larger depths (Shagapov, 1998). Application to slanted piles is limited unless a large number of bubble rings are used or the ring diameter is increased. The effectiveness of bubble curtains may be limited by flanking paths, particularly flanking paths through the ground. Studies of which ground conditions are more prone to such flanking paths have not been identified. Bubble systems often make some noise through their operation, and may add to the total underwater sound at some frequencies, or at least limit the effectiveness of the system.

- *Description of Estimated Costs*: Costs of implementation on past projects range from $50-200k. Costs of $4,000 per pile have been reported by Laughlin (2005a) on a particular project.

- *Environmental Impacts*: Adverse effects may be present with some additives used to slow bubble rise time (if used). Injected air should be ‘clean’.

- *Other Non-acoustic Impacts*: System will require a significant engineering effort for construction and implementation. Air distribution manifolds need to be properly sized and constructed to allow for uniform distribution of bubbles. Non-uniform bubble distribution will lead to a loss in curtain performance. Use of a bubble curtain system may slow production as the system needs to be re-positioned for each pile. It may be necessary to include the barge containing piling equipment in bubble curtain, or at a minimum, the barge should not interfere with the bubble column (Wursig, 2000). Minor maintenance and inspection may be required for long term projects (>1 month). Vagle (2003) indicates that bubble curtains will compromise the effectiveness of a silt curtain, if used.

- *References and Additional Information*:

  Bubble Curtains in Practice: Longmuir (2001), CADOT (2001), Vagle (2003), Reyff (2004), Wursig (2000), Petrie (2005), MacGillivray(2005), Laughlin (2005a), Laughlin (2005b), Laughlin (2005c), Laughlin (2006a), Laughlin (2007), Ellison/Laughlin (Workshop), Lucke (Workshop).

  Theory: Shagapov (1998), Domenico (1982a), Domenico (1982b), Khabeev (2006).

(PD1b) Constrained Bubble Curtains

- *Notes on Treatment*: Constrained bubble curtains operate in a similar manner to conventional bubble curtains (PD1a). A sheet of fabric, metal casing, or other material is used to constrain the air bubbles to prevent breakdown of the bubble curtain from currents. An example of a constrained bubble curtain is provided below. Gunderboom, a vendor of constrained bubble curtain systems, states their curtain "is made of a water-permeable polypropylene/polyester fabric; the patented, double-layer SAS™ curtain is either suspended by flotation billets and anchored in place, or installed on a rigid frame surrounding the area of activity. As compressed air is released at the bottom of the curtain, the space between the two fabric layers inflates, creating a sound-[blocking] bubble wall." Other non-commercial approaches have also been identified (Knoll, 2004; MacGillivray(2005)).

FIGURE PD1b: Confined Bubble Curtain (Reyff, 2004)

A physical curtain can be used instead of a bubble tree (as described in Item PD1a) to help maintain the integrity of a bubble wall when currents are present.

Published data indicate effectiveness values similar to those of unconstrained curtains. However, it is generally the case that the constrained bubble curtains were implemented because local currents would minimize the effectiveness of an unconstrained curtain. MacGillivray (2005) shows that peak and RMS pressures were reduced on average by 9 dB while peak and RMS particle velocities were reduced by 12 dB.

MacGillivray also uses a "pulse length" metric, consisting of the time it takes for 90% of the energy to be accumulated, to determine the effect on the pulse shape instead of rise-time (See Item PD1a above). This was done for both pressure and velocity measurements. It was found that pressure pulse times tended to be slightly longer when the bubble curtain was used, on the order of 30%. However, velocity pulse times were longer by a factor of 3 on average.

- *Limitations / Need for Future Research*: Bubble curtains are limited to shallow waters and coastal areas for practical and economic reasons (Continental, 2004). System will require a significant engineering effort for construction and implementation. Use of system may slow production as system needs to be re-positioned for each pile. Application to slanted piles requires the use of a larger curtain.

- *Description of Estimated Costs*: Costs of implementation on past projects range from $100-200k.

- *Environmental Impacts*: Minimal, assuming injected air is 'clean'.

- *Other Non-acoustic Impacts*: See Section PD1a.

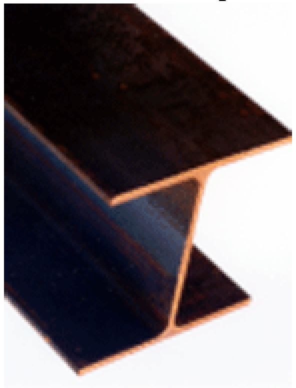
- *References and Additional Information*: http://www.gunderboom.com, Knoll (2004), MacGillivray(2005), Gunderboom, Workshop.

- *Vendors*: Gunderboom (www.gunderboom.com)

(PD2) Alternative Piles

- *Notes on Treatment*: It has been indicated by Laughlin (2005a), Reyff (2004), and WSDOT (2005) that steel H-piles, seen below, may produce lower underwater peak sound levels than circular steel or concrete piles. Differences may be on order of 10-20 dB. Furthermore, concrete piles have been shown to have significantly reduced peak levels by Laughlin (2007). It is noted that this reduction may in fact be due to the wood pile cap that is used for installation of all concrete piles (see Item PD3).

FIGURE PD2: Example H-Pile



- *Limitations / Need for Future Research*: Data is currently sparse. Additional testing is required before definitive conclusions can be made. Use of H-piles may not be appropriate in some situations for non-acoustical reasons.

- *Description of Estimated Costs*: Material cost differences are expected to be small relative to other piles.

- *Other Non-acoustic Impacts*: More H-piles may be needed to achieve the same goal as compared to using circular piles. This will increase installation time.

- *References and Additional Information*: Laughlin (2005a), Laughlin (2007), WSDOT (2005), Reyff (2004).

(PD3) Pile Caps

- *Notes on Treatment*: Laughlin (2006a) has shown that the use of pile caps can significantly reduce underwater pressure levels generated by impact piling. Examples of pile caps are shown in Figure PD3 below. Four different materials were tested, each with varying results. Wood performed the best with measured peak pressure reductions of 11-26 dB. Micarta showed 7-8 dB reductions, and Nylon had 4-5 dB reductions. Conbest showed reductions of only 1-5 dB. Reductions in RMS and SEL also were seen to fall into these ranges. Rise times were indicated to be longer when cap materials were used. Wood showed the largest increases, although there is some scatter in the data. Untreated piles had rise-times of 1.5-1.8 msec, where treated piles had rise times that ranged from 3.7-37.7 msec. It is noted that the untreated pile rise times are on the short end of the rise times published elsewhere in the literature.

Laughlin indicates that Micarta may be the preferred material over wood since the wood caps tended to break down the quickest and were prone to catching fire. Micarta and the other tested materials were less susceptible to these problems.

FIGURE PD3: Examples of Pile Caps (Laughlin, 2006a)

Pile caps are disks that are located between the pile and the driving head. Different materials can be used, and result in different noise reductions. Wood pile caps are commonly used for concrete piles.

- *Limitations / Need for Future Research*: The effect of pile caps on driving efficiency was not studied directly, except it was noted that wood did not transfer the impact energy well. Laughlin (2007) also shows that wood caps loose their effectiveness as they become compressed. Further research may be needed in order to optimize pile cap materials and determine overall effect on pile driving efficiency.

- *Description of Estimated Costs*: Costs of pile caps are estimated to be small relative to other project costs. One cap may only last for a few piles.

- *Other Non-acoustic Impacts*: Caps may slow production process.

- *References and Additional Information*: Laughlin (2006a), Laughlin (2007)

(PD4) Physical Barrier

- *Notes on Treatment*: Laughlin (2007) describes the use of a circular barrier that has been internally lined with two inches of closed cell foam. A drawing and picture of this concept is provided in Figure PD4 below. The barrier must completely surround the driven pile throughout the entire water column. Peak sound level reductions of 15-23 dB were reported. 17-27 dB reductions in RMS sound level were also shown, as were 14-21 dB reductions in Sound Exposure Level (i.e. energy). A small increase in rise time is indicated, although the limited data is scattered.

  A similar approach was also shown in Laughlin (2007) where the lining was removed. The effectiveness of this approach was typically less than with the lining.

  Lucke (Workshop) used a closed-cell foam barrier with no steel casing to create a holding pool for animals being studied near pile driving activities. Two sheets of 8 mm thick foam was used (total thickness of 16 mm). It was indicated that this pen provided an 18-28 dB reduction at frequencies between 500 Hz - 8000 kHz. There was a drop in attenuation from 11 kHz and 16 kHz, and above 16 kHz the attenuation rose back up to 20 dB. It is interesting to note that these results are similar to those found by Laughlin (2007) where a steel outer casing was used. This may be worth further investigation as a foam barrier may be easier to handle and locate than a steel/foam composite.

FIGURE PD4: Example of Internally Lined Barrier (Laughlin, 2007)

The above images show one approach to an acoustic pile driving barrier. A circular steel casing is used with an internal foam lining. Acoustical effectiveness is on the order seen for bubble curtains (Item PD1), and may be preferred in some cases because of reduced up-front engineering requirements. Foam-only barriers may also be possible (Lucke, Workshop).

- *Limitations / Need for Future Research*: Barrier must be relocated for each pile. This will likely require special lifting equipment. Can only be used in shallow waters where length of barrier is not too cumbersome.

- *Description of Estimated Costs*: Costs are not known. Material costs are expected to be minimal. Additional vessels and/or special lifting equipment may be required. Total costs may be less than those associated with bubble curtains especially when engineering costs are considered.

- *References and Additional Information*: Laughlin (2007), Lucke (Workshop)

(PD5) Dewatered Cofferdam

- *Notes on Treatment*: In this approach, a solid barrier such as a tube is located around the pile, and extends through the entire water column (similar to what is described in Item PD4 above). The water inside of this barrier is then completely removed. This completely decouples the water from the direct radiation path of the pile. Reyff (2004) indicates that this method can reduce peak levels by 15 dB and overall RMS levels by 5-35 dB. Reyff also indicates that the ground flanking path was prominent in these measurements at some locations.

- *Limitations / Need for Future Research*: Set-up of dewatered cofferdam is likely to require more time than other similar methods such as lined barriers and bubble curtains. Barrier needs to be set on the sea floor such that no leaks are possible.

- *Description of Estimated Costs*: Costs are not known, but are estimated to be higher than those associated with lined barriers or possibly even bubble curtains due to the extra time required for set-up.

- *Other Non-acoustic Impacts*: Procedure may be slow.

- *References and Additional Information*: Reyff (2004)

(PD6) Vibratory Hammers

- *Notes on Treatment*: A vibrating mechanism (‘vibratory hammer’) is used in place of an impact hammer. The vibratory hammer vibrates continuously or near-continuously at a frequency in the range of 10-60 Hz. The driving frequency of the vibratory hammer is the dominant frequency in the underwater noise spectrum, followed by harmonics of this frequency. Broadband components above 500 Hz are also seen, extending to several kHz.

  It has been indicated by WSDOT (2005) that vibratory methods produce underwater noise that is 10-20 dB lower than using impact methods (assumed peak). Nedwell (2002) and Blackwell (2003) measured differences on the order of 20-50 dB (peak). In general, a vibratory hammer will create sounds with much larger “rise times” than impact methods since the sound wave produced is sinusoidal. Similarly, the large peak overpressures and underpressures seen with impact piling are not present. For these reasons, this is stated to be the preferred method of pile driving in WSDOT (2005).

  A comparison of the total energy output or SEL was not found in the literature. NCE performed a rough SEL calculation for vibro-piling based on SEL and peak pressure values published in the literature, and assuming a 10 dB difference in peak level, a 1 second separation between impact hits, and a vibration frequency of 20 Hz. The resulting SEL values were comparable.

  Vibratory methods are most effective in granular soils, and in driving non-displacement piles (www.piledrivers.org).

- *Limitations / Need for Future Research*: Additional testing and data are needed in order to develop more conclusive results regarding the effectiveness of this method in reducing underwater noise. Reyff (2004) indicates that there is variability in the data and no significant conclusions can be made. This may be due in part to the variation in noise when driving a single pile from beginning to end with vibratory methods (similar variation is also seen in impact piling). Vibratory methods may not be feasible in some substrates. 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.

- *Description of Estimated Costs*: Cost of purchasing equipment is 2-3 times cost of purchasing an equivalent impact hammer.

- *Other Non-acoustic Impacts*: Different engineering practices may be necessary in order to maximize driving efficiency and minimize driving time. Machinery is larger than some impact piling hammers. Machinery may require different skills in order to properly locate and use.

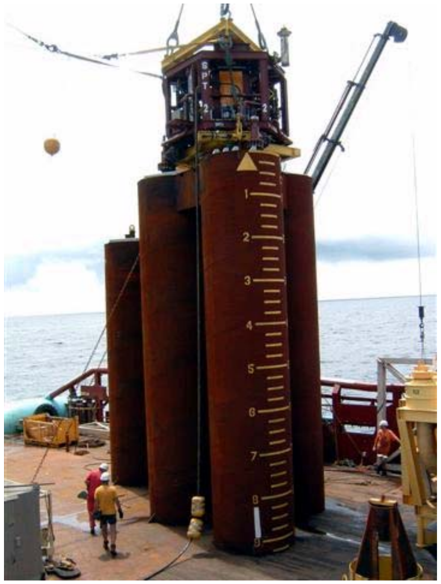
- *References and Additional Information*: Nedwell (2002), Nedwell (2003), Blackwell (2003), Reyff (2004), WSDOT (2005).

(PD7) Suction Piles

- *Notes on Treatment*: Suction piles are a replacement for conventional piles as well as conventional piling methods. A suction pile is essentially a large drum with the bottom face removed. The pile is located on the sea floor 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 the penetration into the sea bed. Grout ballast can be poured into the piles once they are located in place. Examples of suction piles are shown below.

  Suction piles have been used on many projects, and a significant portion of the oil and gas industry is currently using this technique. Suction piles can be used in both shallow and deep water installations. Installation has taken place in "a wide range of soil conditions from soft to stiff clays, in loose to dense sands and in layered soils." (http://www.suctionpile.com). Suction piles can also be used as anchors for mooring vessels and other structures. A detailed report on the capabilities, analysis, and current limitations of suction pile anchors is given by Andersen (2005).

FIGURE PD7: Suction Pile Examples (http://www.suctionpile.com)



Suction piles are large drums with the bottom face removed. Water is sucked out of the drums after being located on the sea floor. The drum sinks into the ground and is an effective replacement for a conventional pile. All impulsive sounds are removed during installation, and the total noise is very low.

No information is available regarding underwater sound during installation. However, the potential for sound reduction is very significant as this procedure completely removes impulsive sounds, replaced only with sounds associated with the removal of water from the pile using a suction pump. It is estimated that the sounds of the suction pump are insignificant relative to what currently exists with existing piling methods.

This approach can also provide a reduction in installation time and costs (Mather, 2000).

- *Limitations / Need for Future Research*: Some soils may not be appropriate for this method, although current indications show a wide range of applicable substrates.

- *Description of Estimated Costs*: Expected to be similar to or less than costs associated with existing methods. Engineering costs may be similar or exceed current methods, but savings in installation time and effort may reduce overall costs using this method.

- *Environmental Impacts*: The only impacts that could be identified are those relating to the permanent installation and abandonment of the pile when grout ballast is used. If ballast is not used the pile can be pumped back out for complete removal. Overall, fewer impacts may be present relative to existing pile driving techniques.

- *References and Additional Information*: Mather (2000), Andersen (2005).

- *Vendors*: SPT Offshore (http://www.suctionpile.com), Sapiem ENI (http://www.saipem.eni.it)

(PD8) Press-in Piles

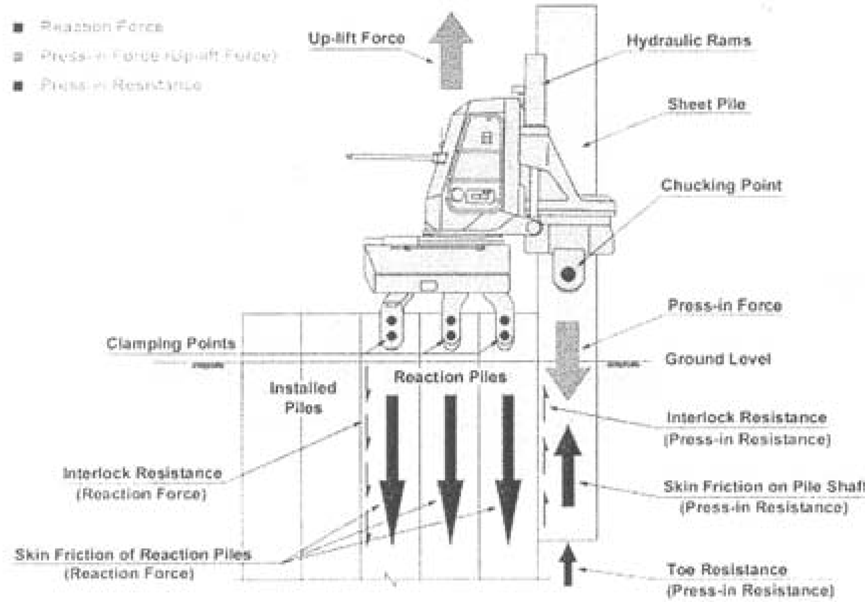
- *Notes on Treatment*: Press-in piling machines are unique, self-contained units that use static forces to install piles. The machine uses leverage gained by holding on to previously installed piles while installing new piles. The first piles are installed by weighing down outriggers on the piling machine with piles or other static loads. A sketch of the machine and the concept is provided below. This source removes all impulsive types of 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. Measurements of ground vibrations during land based pile installation provide partial confirmation of this assumption (White, 2007).

  Many different piles can be used with this machine, ranging from various sheet pile types to circular piles and H-piles. When used in the configuration indicated in the figure above, the unit can 'walk' along the piles and easily position itself for installation of the next pile. This procedure significantly increases the speed of the piling process. Water jet and internal auguring systems have also been used to augment the machine's piling capabilities in "hard ground conditions" (Goh, 2005).

  It has been shown by White (2007) that the strength of piles installed using this method is higher than those installed by conventional impact methods, as well as "enhanced plugging and residual base load, and reduced friction fatigue." Since every pile is driven statically, the load capacity of each pile is known; no further verification tests are required.

  This system was originally developed for land-based use in highly sensitive areas where human hearing impacts, erosion, and other similar concerns are paramount. For example, press-in piling operations have been granted permits on beaches during turtle migration season (Carter, Workshop). This approach has been used extensively on land and in shallow waters. The system does not require a lot of space in order to install piles; typically 7 feet laterally is all that is required. The system is also portable and can be delivered to a site in 2-3 trucks.

FIGURE PD8: Press-in Piling Machine (Goh, 2005)



The press-in piling machine holds on to previously installed piles in order to statically drive a new pile. Once the pile has been driven, the machine can 'walk' along the piles and position itself for the installation of a new pile. An animation of this process can be seen at www.giken.com. Piles can be installed in a line, along a radius, at 90 degree angles, etc. The piling machine can also be installed on a barge and used in deep-water applications.

No templates are needed during installation. The machine uses a laser-guide system for reference. The machine can install piles along a radius or create 90 degree corners. Corners are achieved by installing extra piles in the opposite direction to provide reaction forces. These extra piles can be retrieved afterwards if necessary. Batter piles can also be installed.

The piling machine can also be located on a barge or other structure, thus allowing for pile installation at any location, potentially including deep waters. The current technology allows for pile diameters of up to 5 feet (1.5 meters); larger piles can be simulated by installing multiple smaller piles adjacent to one another.

During the Workshop it was demonstrated that a variation on this approach can be used to drive a tube by slowly rotating it and applying static vertical force. This system can drive a pile through 2 feet of reinforced concrete in 6 minutes.

- *Limitations / Need for Future Research*: The technique currently requires piles to be relatively close to each other, if not directly adjacent, unless the machine is mounted to a barge or other large structure that can be used for counterbalance and positioning. Piling machines are limited to installations where the compressive strength of the soil material is roughly 15,000 psi or less.

- *Description of Estimated Costs*: Cost information was not provided. Cost of machine may be more than conventional pile drivers, although speed of installation is indicated to be faster than using conventional methods.

- *References and Additional Information*: Goh (2005), Yetginer (2003), White (2002), White (2007), Carter (Workshop).

- *Vendors*: Giken (www.giken.com)

(PD9) Drilled, Cast-In-Place piles

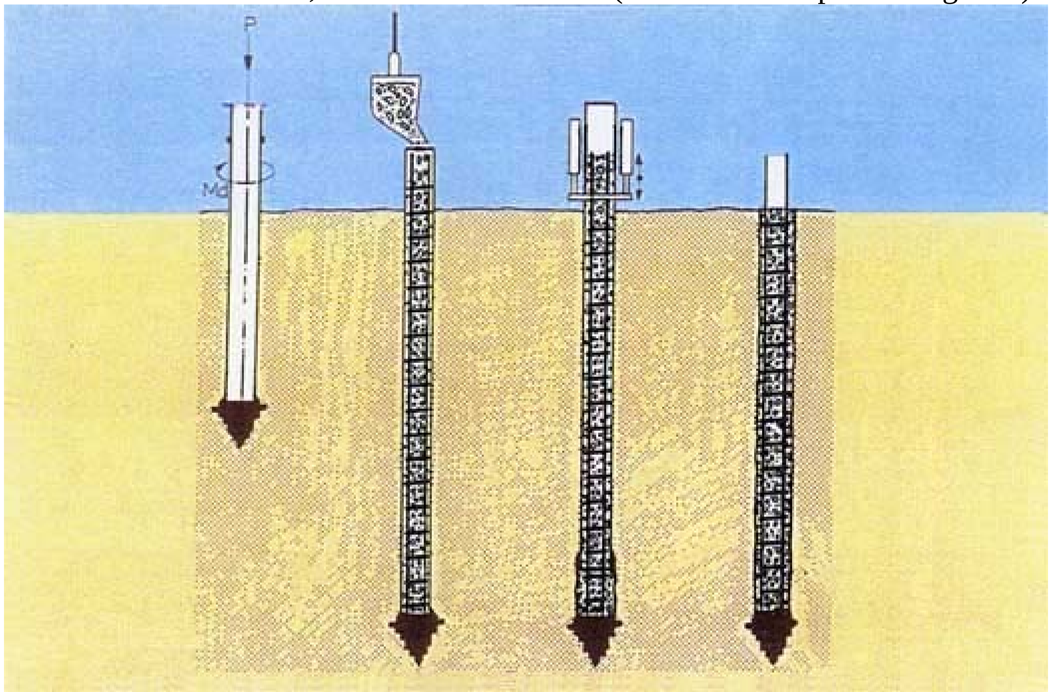
- *Notes on Treatment*: A technique has been developed by American Piledriving, Inc (www.americanpiledriving.com) where a pile casing is drilled into place and then filled with concrete. A sketch of the process is provided below. The approach uses no impact or vibratory hammers, and therefore offers a potential for noise reduction. Some sound will be associated with the drilling process (including associated machinery); quantification of this sound was not found in the literature.

- *Limitations / Need for Future Research*: Applications are for land only at this time. Applicability to marine environments is unknown, especially deep water applications. Size of drill head may prevent use of pile guides in sub-sea template.

- *Description of Estimated Costs*: Costs are not known, however they are expected to be higher than existing methods due to the one-time use of drill heads and specialty equipment.

- *Vendors*: American Pile Driving (www.americanpiledriving.com)

FIGURE PD9: Drilled, Cast-In-Place Process (www.americanpiledriving.com)



Pile casings are drilled in place and then filled with concrete. Drill head is a special, one-time use item.

SECTION EX:
TREATMENTS FOR EXPLOSIVES (CONSTRUCTION AND DECOMMISSIONING)

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Metric		
EX1	Shaped Charges	Special type of explosive that focuses energy in desired direction. Less material is required vs. bulk charges.	~4 dB ~13 dB ~10 dB	Peak Impulse Energy Flux	$150 - $500 per pound	N
EX2	Radial Hollow Charges	Special application of shaped charges	Assumed similar or better than Shaped Charges	All	$150 - $500 per pound	N/F
EX3	Shock-Wave Focusing	Focusing of shock-waves from explosives fractures material. Less explosive is needed	Assumed similar or better than Shaped Charges	All	N/A	F/FF
EX4	Slow burn rate explosives	Reduces rise-time, longer impulse length	Increase Increase Decrease	Peak pressure Impulse length Rise-time	~$10 / pound	N
EX5a	Bubble Curtain or Bubble Tree	Air bubbles are used to create a ‘wall’ to block sound propagation	5-25+ dB	O/A, Peak	Project costs on order of $50-200+ k	N
EX5b	Confined Bubble Curtain	A fabric curtain is used to confine bubbles and prevent disruption from currents	13-22 dB	O/A, Peak	Project costs on order of $100-200+ k	N
EX6	Physical Barrier	A solid barrier is used to block sound from the explosion	N/A	N/A	Estimated minimum $50k	N
EX7	Blasting Mats	Rubber blasting mates are used to reduce noise radiated away from explosion	N/A	N/A	$10-$15 per square foot	N
EX8	Borehole Stemming	When borehole blasting, blocking the top of the borehole reduces radiated pressures	10-19 dB 6-7 dB	+Peak -Peak	Negligible	N
EX9	Cutting Tools	Alternative to blasting for decommissioning	Large Reductions Elimination	Peak pressure Impulse	~$800k - $1,400k for 4 and 8 leg structures	N

(EX1) Shaped Charges

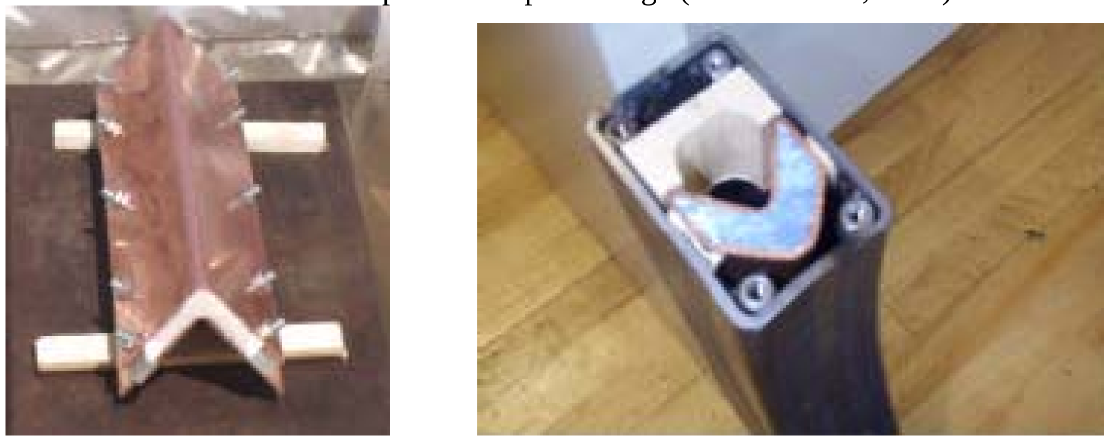
- *Notes on Treatment*: Shaped charges are alternatives to conventional bulk charges that use significantly less explosive material. They accomplish this by creating a focused explosive blast in a desired direction. Saint-Arnaud (2004) states:

  > The penetration capability of the shaped charge comes from the formation of a concentrated jet of material from the liner. The high pressure developed by the explosive reaction produces a jet traveling at very high velocity, typically 3 to 15 km/s (10000 to 50000 ft/s). Ductile materials, such as pure metals, are used to produce shaped charge because the formed jet can extend more before breaking and produce more penetration at high stand-offs. Denser materials produce higher penetration because the jet material is less eroded by the target.

  The focused charge requires less explosive material for a given application relative to conventional bulk charges. Material reductions of over 90% are possible while accomplishing the same goal of object removal/cutting. Saint-Arnaud (2004) provides data on measured differences between shaped charges and C4 explosives used to cut test piles. The results from this study are scattered; large differences in pressure are seen even when comparing results from bulk charges on two different test piles. However, there is a general trend in the data showing lower sound levels with shaped charges. Reductions in peak overpressure (calculated by NCE using the provided data) varied between -3/+12 dB with the average being +4 dB (positive value indicating a reduction in peak pressure). Reductions in impulse and energy flux density (also calculated by NCE) ranged between +1/+20 dB and -1/+16 dB, with average values of 13 dB and 10 dB, respectively. These effectiveness ranges were not due to multiple test conditions, rather differences in pressure level at different measurement locations for the same blasts. (It is noted that the above calculations were performed using a 20*log approach for peak pressure and impulse and a 10*log approach for Energy Flux Density.)

  Examples of shaped charges are provided below. Twachtman (2000) states, “the cut made by a properly designed and placed shaped charge is clean and looks somewhat like a torch cut.” Additional details on various types of shaped charges are also provided. Shaped charges usually require a “stand-off” distance from the object being cut, and thus a casing or locating device must be designed. When severing piles, the shaped charge will typically surround the pile from the outside or will be placed adjacent to the pile’s inner wall. Explosive material is located along the full 360 degrees around the pile.

FIGURE EX1: Examples of Shaped Charge (Saint-Arnaud, 2004)



The image on the left side shows a shaped charge, consisting of explosive material in a metal lining. The image on the right shows the shaped charge in a casing that provides the appropriate stand-off distance. When severing piles, shaped charges will be completely surround the pile from the outside or inside pile wall.

- *Limitations / Need for Future Research*: Saint-Arnaud (2004) provides the only data that was found regarding the effectiveness of this approach. Additional studies are necessary. Qinetiq's website (www.qinetiq.com) indicates that shaped charges can be used to reduce underwater sound levels, but does not quantify this reduction.

- *Description of Estimated Costs*: Shaped charges cost approximately $150 - $500 per pound. This is compared to $4 - $8 per pound for bulk charges. Engineering costs are also assumed to be higher than those incurred with bulk charges.

- *Other Non-acoustic Impacts*: Stand-off distance of explosive requires special mounting arrangement. A casing is required to protect explosive from water. Casing must be able to withstand pressures at deployed water depths. Proper design can be difficult, and requires knowledge of target specifications. Manufacturing time can be on order of weeks.

- *References and Additional Information*: Twachtman (2000), Saint-Arnaud (2004), QinetiQ (www.qinetiq.com)

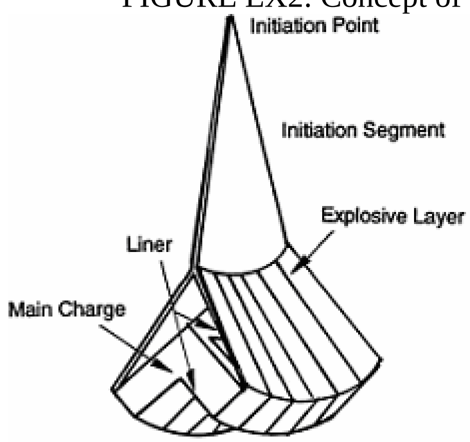
- *Vendors*: Dynawell (www.dynawell.de), Accurate Energetics (www.aesys.biz), EBA&D (www.ebco-aerospace.com)

(EX2) Radial Hollow Charges

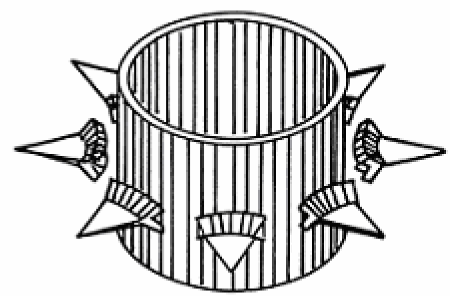
- *Notes on Treatment*: This is a special application of Shaped Charges (Item EX1). A concept diagram is provided in Figure EX2 below. When using this approach to sever a pile, the specially shaped charges are located in intervals around the pile (as compared to standard shaped charges where the explosive material would completely surround the pile over a 360 degree angle). This results in a reduction of required explosive material and a potential for reduced sound generation.

  It is indicated in Continental (2004) and Committee (1996) that this technique can reduce the amount of required charge, although the acoustic reduction is not specified. Given the configuration seen below, it is assumed that material reductions are greater than those for the shaped charges seen in Item EX1. The approach is described in Continental (2004) as "short, linear-shaped charges bent into an arc with the explosives initiated simultaneously at the central axis. The detonation front runs radially outward, detonating the explosive simultaneously on both sides of an inverted v-shaped liner. The liner collapses, producing a flowing radial cutting jet. Because of this diverging flow, a relatively long cut can be produced in a flat or curved steel plate. By joining a number of these types of charges together, it is possible to cut along plates and around pipes using relatively low explosive weights."

FIGURE EX2: Concept of Radial Hollow Charge (Committee, 1996)



Schematic of a Radial Hollow Charge



Schematic of a Radial Hollow Charge Arranged for Cutting a Leg from Outside

When using this approach to sever a pile, the specially shaped radial charges are located in intervals around the pile. This is slightly different from standard shaped charges where the explosive material would completely surround the pile over a 360 degree angle. This results in a reduction of required explosive material and a potential for reduced sound generation.

No studies were found that measure sound level reductions using this approach. Given the similarity to shaped charges, it is assumed that the effectiveness would be similar or improved since there would be less explosive material used.

- *Limitations / Need for Future Research*: Amount of material and sound reduction are not known.

- *Description of Estimated Costs*: See EX1.

- *Other Non-acoustic Impacts*: Increased complexity, particularly regarding mounting arrangement and stand-off distances.

- *References and Additional Information*: Committee (1996), Continental (2004).

(EX3) Shock-Wave Focusing

- *Notes on Treatment*: This is another approach that is in development that would be a replacement for bulk explosives. In this approach explosives are used with waveguides that focus the shock wave to a particular region of the structure to be demolished. Stresses in the material at the focal point of the explosion are large enough to cause failure, and are lower elsewhere. Because of this focusing technique, the amount of material required is significantly reduced. Reductions in explosive material are estimated to be 90% relative to standard shaped charges (which already use upwards of 90% less material than bulk charges).

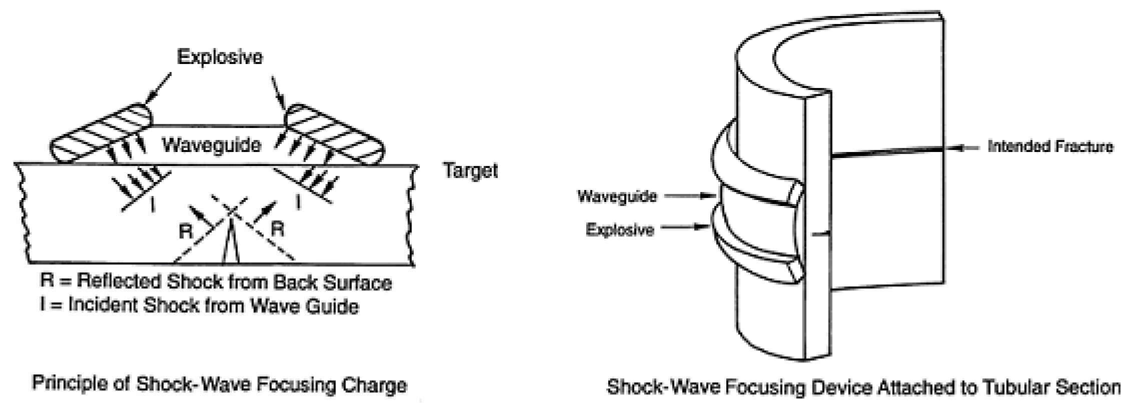
  No studies were found that measure the sound generated using this method. However, given the large reduction in required explosive material, it is possible that this approach would provide sound reductions similar to if not greater than shaped charges (see EX1). A concept diagram is provided below. A detailed study on the use of this technique is provided in Reverse (2004).

- *Limitations / Need for Future Research*: There has been limited success so far in underwater applications. Grout-backed surfaces are not effectively severed by shock-wave focusing methods. The target must be backed by air or water. Optimal waveguide geometry and charge parameters are still in development. Measurements of underwater pressures resulting from this technique are currently not available.

- *Description of Estimated Costs*: Costs are not known at this time. Explosives required for this technique are expected to be similar to those used for shaped charges (Item EX1). Additional costs may be related to manufacture of waveguides and up-front engineering.

- *References and Additional Information*: Reverse (2004), Continental (2004).

FIGURE EX3: Concept of Shock Wave Focusing Charge (Committee, 1996)



Two rings of explosive material are detonated simultaneously. The blast wavefronts from each ring are oriented using a waveguide such that the combination of the two blasts is enough to produce a failure in the structure at a focal point.

(EX4) Slow Burn Rate Explosives

- *Notes on Treatment*: Slow burn rate explosives, also called 'low explosives', are explosives that have a slower detonation velocities as compared with dynamite and TNT (on the order of 0.1 to 1 ft/s). Black powder is an example of a slow burn rate explosive. Black powder produces a pressure waveform that is dissimilar to other conventional explosives, in that it has a much longer impulse time with a relatively slow rise-time. Peak pressures have been seen to exceed those of other explosives (dynamite, for example), but it is indicated that even in these cases fewer fish have been killed when black power is used (Richardson, 1995; Keevin 1997; Gunderboom, Workshop).

- *Limitations / Need for Future Research*: Additional studies on the effects to marine life and identification of acoustic metrics are needed. Low detonation velocity may have an impact on effectiveness for object removal and cutting. May not be appropriate in all situations.

- *Description of Estimated Costs*: Costs are estimated at $10 per pound. Engineering costs are expected to be similar to other projects using explosives.

- *Environmental Impacts*: Unknown. Assumed similar to conventional explosives.

- *References and Additional Information*: Urick (1967), Richardson (1995), Keevin (1997), Gunderboom (Workshop).

(EX5a) Bubble Curtains and Bubble Trees

- *Notes on Treatment*: See Pile Driving Treatments, Item PD1a. Keevin (1997) presents additional data of bubble curtain use with explosives. Effectiveness at reducing peak pressure, impulse, and energy flux density were all greater than 90% on average. Reduced fish kills were also noted.

- *Additional References*: Keevin (1997), Langefors (1978).

(EX5b) Constrained Bubble Curtains

- *Notes on Treatment*: See Pile Driving Treatments, Item PD1b.

(EX6) Physical Barrier

- *Notes on Treatment*: A solid, physical barrier is used to block and contain sound from the sound source (explosion). The barrier must completely surround the sound source and must extend through the entire water column. Physical barriers can be made from metal or other solid composite materials. A foam or other internal lining may be beneficial as described in Item PD4. In some cases, the water contained within the barrier can be removed ('dewatered cofferdam' – See item PD5), and can lead to (theoretically) very large sound reductions. This would require additional equipment and time. Physical barriers also can be used to prevent structural damage to nearby objects.

  Data showing the effectiveness of barriers with explosives could not be found. Keevin (1997) states that one application of a barrier "was successful in reducing peak pressures below the 100 psi (690 kPa) maximum limit." Furthermore, good results have been seen in applications of barriers to pile driving (see Items PD4 and PD5).

- *Limitations / Need for Future Research*: Barriers are limited to shallow waters and coastal areas for practical and economic reasons (Continental, 2004). No measurements of treatment effectiveness with explosives have been found to date.

- *Description of Estimated Costs*: Costs are not known, but may be similar to those identified in PD4. Note that the required barrier size may be larger than what is required for pile driving to prevent damage to the barrier.

- *Other Non-acoustic Impacts*: Barriers will likely be heavy and will require special lifting equipment. Locating and construction of the barrier on-site will require special efforts.

- *References and Additional Information*: Keevin (1997), Continental (2004).

(EX7) Blasting Mats

- *Notes on Treatment*: Blasting mats are currently used in land-based applications primarily to help mitigate flying debris, but also can reduce noise. Similar applications of the same mats may be possible for underwater use. Blasting mats are typically made from recycled rubber tires that are tied together with steel cables. They are placed directly over the charges. Vendors of the products say that they can be used underwater and have done so in a few cases.

  Blasting mats may also provide an opportunity for noise mitigation in deep water applications. Blasting mats can also be used as an alternative or augmentation of blast stemming (see Item EX8). This is particularly true in sandy soils where stemming may not be an option.

- *Limitations / Need for Future Research*: While blast mats have been used in underwater blasting projects, the effectiveness in reducing underwater sound is not known and would need to be tested. Positioning of blasting mats may be cumbersome and require special machinery and methods. It is likely that a diver would be needed to assist with installation; however it is common for divers to be used with installation of explosives.

- *Description of Estimated Costs*: Material costs are $10-$15 per square foot. One vendor quoted a 10 x 19 ft mat at $2550. Additional costs may be associated with installation and removal.

- *Environmental Impacts*: Some parts of the mat may separate during explosion that would not be recoverable.

- *Other Non-acoustic Impacts*: Mats are heavy. A 10 x 19 ft mat weighs 9600 lbs (4400 kg). Special machinery / vessels will be necessary in order to install mats.

- *References and Additional Information*: Discussions at the Workshop.

- *Vendors*: Four Star Blasting Mats (www.blastingmats.com), Dynamat (www.dynamat.qc.ca/english/index.html), Nu-Roads Environmental (www.nu-roads.com/products.html), D&L Thomas Equipment (www.driller.com/driller/blasting/mats.html).

(EX8) Borehole Stemming

- *Notes on Treatment*: When using a borehole to remove obstacles, ‘stemming’ or ‘capping’ the borehole has been shown to significantly reduce the pressures that are radiated into the water. This technique consists of inserting an inert material such as crushed rock in the top of a borehole. An example of this concept is shown below. This technique is performed in practice primarily to increase the effectiveness of the blast, and Keevin (1997) indicates that 50% of the explosive energy is lost if the borehole is not stemmed. Keevin discusses the differences between various capping materials, and indicates that that the optimum crushed rock particle size should be approximately 1/12 of the borehole diameter.

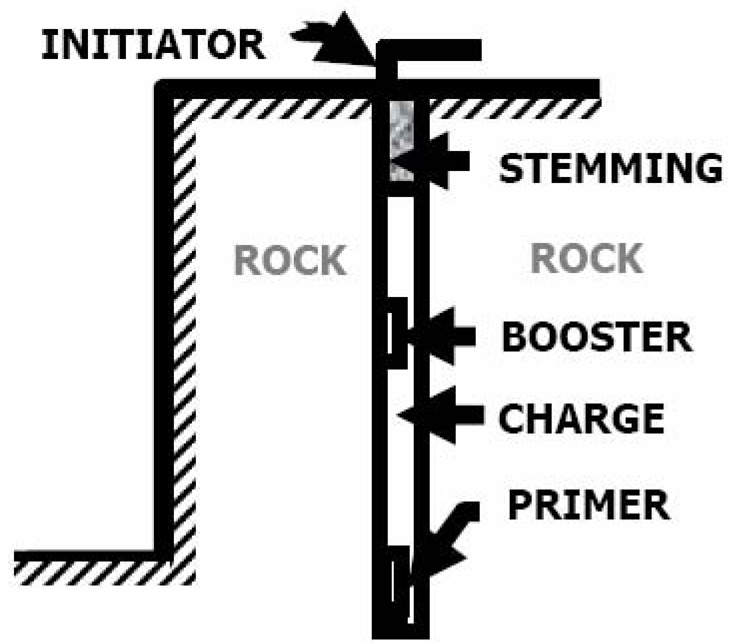
Keevin also indicates that peak pressures are reduced by an order of magnitude (i.e. 90%) when the borehole is capped or ‘stemmed’. Hempen (2007) provides positive and negative peak pressure data for capped borehole blasts as well as a “less confined” blast. Data for the first two peaks are provided. When comparing measurements taken at similar distances, the data shows that the first and second positive peaks are reduced by 88% and 69%, respectively (19 and 12 dB), while the first and second negative peaks are reduced by 63% and 64%, respectively (6 and 7 dB).

- *Limitations / Need for Future Research*: Incomplete or insufficient capping can lead to reduced effectiveness. Blasting mats, used instead of or in addition to the methods described above, may be an option to help ensure proper capping (see Item EX7). Nedwell (1992) indicates that part of the received impulse may be due to transmission through the rock. If this is true then the total reduction possible will be limited by the energy passing through this path. Attempts to isolate or decouple part of the rock from the water may be effective (again, possibly through the use of blasting mats) but large areas may need to be covered for significant improvements to be detected.

- *Description of Estimated Costs*: Costs are minimal since capping material is readily available. Installation costs are also expected to be minimal.

- *References and Additional Information*: Nedwell (1992), Keevin (1997), Hempen (2007), Jordan (No Date).

FIGURE EX8: Borehole Capping Concept (Jordan, no date)



Crushed rock is inserted into the top of a borehole to 'cap' or 'stem' the blast. This is a low cost method of reducing the underwater sound that is generated while also increasing the effectiveness of the blast.

(EX9) Cutting Tools

- *Notes on Treatment*: As an alternative to using explosives, it is possible to use various cutting tools to remove offshore structures. These tools include diamond wire cutters, abrasive cutters, mechanical cutters, and torch cutters. A brief summary of each of these is provided below. Additional details can be found in Twachtman (2000 & 2004).

  Diamond wire cutting systems are automated tools that work by running a diamond wire across the object to be cut. The cutting wire is ¼-inch steel containing steel rings embedded with diamonds. The wire is mounted on a frame which can be clamped on the object to be cut. The system somewhat resembles a bandsaw when in operation. Cutting is performed from the outside of the pile. Examples of these systems are provided below. These systems can be used by a diver or mounted to an ROV, and can be used in deep or shallow waters. Of the systems reviewed, this is clearly the most feasible, reliable, and has the greatest potential to replace explosives for decommissioning offshore structures.

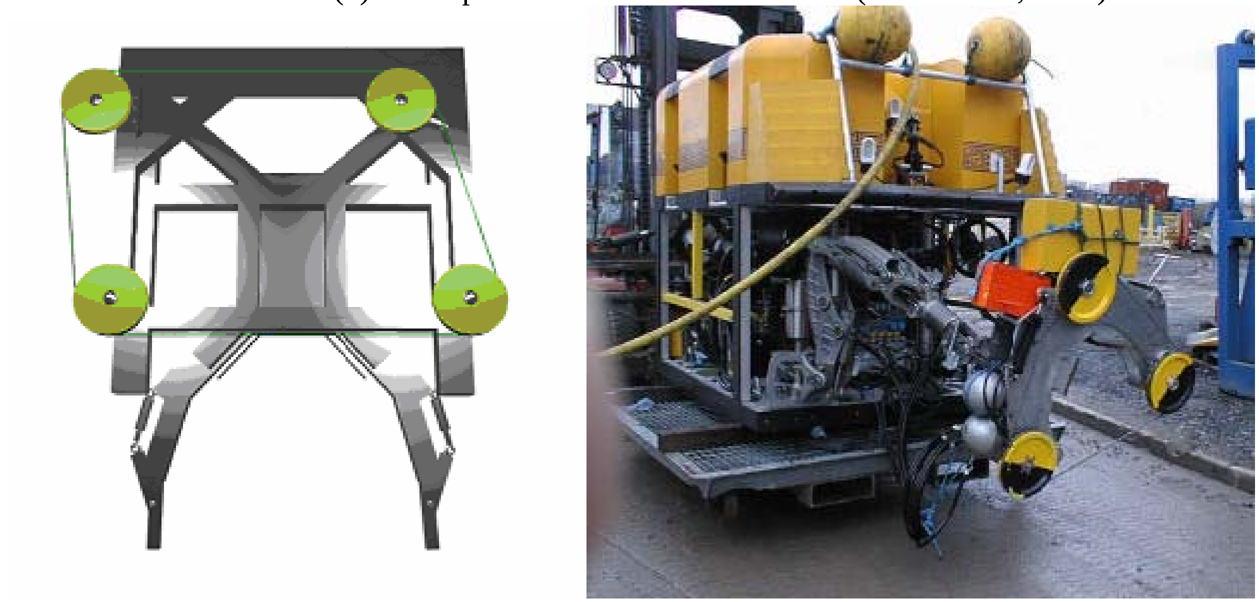
Abrasive cutting methods use water jets injected with concentrations of sand, slag, garnet, or other abrasive materials. Internal and external abrasive cutting methods are available. This method must be implemented by a diver, so some depth restrictions exist. Mechanical cutters use specialized blades to mill though structures. These are typically used inside of circular piles. An example is provided below. Regarding torch cutting, Twachtman (2004) states, "In underwater arc cutting, an outside jet of oxygen and compressed air is needed to keep the water from the vicinity of the metal being cut…. In shallow water and for simple structures such as caissons, diving is sometimes the preferred method. In deep water, because of the physical limitations associated with diving, an ROV or ADS system is commonly used in conjunction with a cutting torch. Diver cuts usually cost far more than other cutting technology and the risk involved to the diver – especially in deep water – makes torch cutting generally less attractive than other removal options."

Measured underwater noise levels for these systems were not found, although Nedwell (1993) provides some data for hand-held cutting tools (i.e. grinders). It is seen that the overall (RMS) level from these tools is well below the peak levels produced by explosives by some 80 dB or more; comparisons of peak vs. peak are expected to be similarly large. Non-explosive methods clearly produce noise more continuously than explosives, but they do not produce the same over/underpressure, rise time, and similar characteristics seen with impulsive sounds which may be of concern when considering fish mortality or other similar impacts on animals.

- *Limitations / Need for Future Research*: Abrasive and mechanical cutters are not as reliable as explosives to sever piles. Twachtman (2000) indicates that there are a number of operational issues that need to be resolved before these methods can be used in deep waters. There are more delays with these systems if they fail, and a complete cut during the first pass is less likely to occur than if explosives are used. Some issues may be associated with the detection of a fully severed pile, as the current detection methods are not as sensitive to abrasive and mechanical cutting as they are to explosives. These issues do not necessarily apply to diamond wire cutting methods.

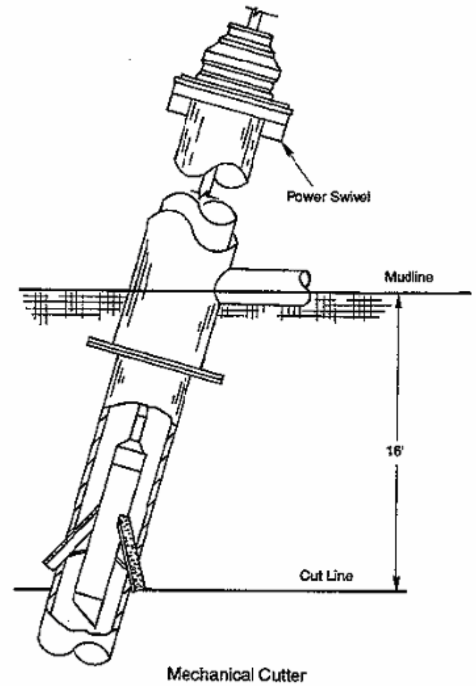
- *Description of Estimated Costs*: Twachtman (2004) provides a detailed analysis of costs associated with non-explosive removal of offshore structures. It is shown that the average cost of removal of platforms in the Gulf of Mexico from 1991 – 2000 was $885,000 for 4-leg structures and $1,344,000 for 8-leg structures. It is also noted that the cost of removal significantly increases for water depths below 200 feet (60 meters).

FIGURE EX9(1): Examples of Diamond Wire Cutters (Twachtman, 2000)



Diamond wire cutting systems can be used to sever piles without the need for explosives. The image on the left shows the wire mounted to a clamp which is then attached to a pile. The wire is moved in towards the pile as the cut progresses. These systems can be mounted to ROVs, as seen in the image on the right.

FIGURE EX9(2): Example of Mechanical Cutter (Twachtman, 2000)



Mechanical cutters are located inside of piles, and cut along the circumference until severed.

- *Environmental Impacts*: Twachtman (2004) states that no environmental issues have been found relating to these methods.

- *Other Non-acoustic Impacts*: Decommissioning operations using cutting tools are slower than the use of explosives. Examples of cutting times for diamond wire systems are 20 and 2.5 hours for an 82" and 48" caisson, respectively (Twachtman, 2000). It is noted by Twachtman that advances are underway that will speed-up the cutting time. Mechanical cutters are slower than diamond wheel methods.

  If piles need to be cut below the mudline, a hole must be dug (or "jetted") around the pile to provide access. This process may be a cause of significant increase in the total time required on-site, depending on the method used. Bill Streever of BP Exploration (Alaska) Inc. has indicated to NCE by that this removal of material at the base of the pile to gain access below the mudline has historically been the largest cause of delay during mechanical removal of offshore structures.

Abrasive cutting sometimes results in uneven cutting and clogged hoses. Abrasive cutting also has water depth limitations, and the current (as of 2000) minimum tube inside diameter that can be accessed is 7 inches. Abrasive cuts may be poor in water depths greater than 200-250 feet, although abrasive cutters have been mounted on ROVs and deployed to depths over 1100 feet. Mechanical cutting methods can produce uneven cuts from lateral movement of un-cemented strings, and require replacement of worn blades. Larger lifting equipment is needed for mechanical cutters.

- *References and Additional Information*: Twachtman (2000), Twachtman (2004).

SECTION PT:
PROPELLER AND THRUSTER TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST ESTIMATE	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
PT1a	Low Noise Propeller Design	Propellers can be designed to have reduced noise relative to conventional designs without the need for additional treatments	3-10+ dB	All	No Additional Material Cost. Machining costs may be increased	N
PT1b	Low Noise Thruster Design	Thrusters can be designed to have reduced noise relative to conventional designs without the need for additional treatments	3-10+ dB	All	No Additional Material Cost. Machining costs may be increased	N
PT2a	Ducted Propellers	A duct is located around the propeller to potentially reduce noise and increase efficiency	Varies depending on implementation	All	Increased costs associated with manufacture of duct	N
PT2b	Forward-skew Blade	Propeller and thruster blades incorporate a forward skew instead of a conventional backwards skew	3-20+ dB	All	No Additional Material Cost. Machining costs may be increased	N
PT2c	Ring Propellers	A full or partial ring is used around the edge of the propeller. Leads to reduced noise	N/A	N/A	Assumed increased cost relative to open propeller	N
PT3	Drop Thruster	A retractable thruster is used in place of a conventional tunnel thruster	5-15+ dB	All	2-6x tunnel thruster designs	N
PT4	Z-Drives and Podded Systems	Systems that locate the propeller in an area with improved flow characteristics	5-10+ dB	All	Approx $200,000 - $300,000 per unit	N
PT5	Waterjets	Alternative to conventional propeller systems for high speed vessels	5-20+ dB estimated	All	Higher than conventional propulsion systems	N
PT6	Rim Drive Propulsion	New thruster design that can reduce noise	5-10 dB	O/A	Approx $150,000 per unit	N/F
PT7	Voith Schneider Propulsion	Alternative to trainable propeller systems for maneuvering – used on minesweepers.	N/A	N/A	Higher than conventional propulsion systems	N

PT8	Propac Rudder	Rudder design with claimed increase in efficiency	N/A	N/A	Increased cost is likely	N
PT9	Foul Release Coatings	By applying this coating to a propeller some beneficial effects on noise are seen.	0-10 dB 0-10 dB increase in sound for some conditions.	50-10,000 Hz >1000 Hz	N/A	F/FF
PT10	Composite Material Propeller	Propellers made from composite materials	N/A	N/A	N/A	F
PT11a	Propeller Bubble Emission	Air bubbles are emitted from the propeller blades into the water	>10 dB 0-10 dB Increase	>500 Hz 20-80 Hz	High	N
PT11b	Thruster Bubble Emission	Air bubbles are emitted into the stream of an operating tunnel thruster	0-20 dB Possible increase	>100 Hz <100 Hz	Est $20,000 - $50,000	N
PT12	Air Bubble Masker	An air bubble layer is emitted at or near the vessel hull and is used to block sound radiation from propellers	>10 dB 0-10 dB Increase	>500 20-80	Est $30,000 - $75,000	N
PT13	Anti-singing Edge	A special design is used for the trailing edge of the propeller blade to reduce or prevent singing propellers	Removal of singing tone when problem exists	Frequency of tone	No Additional Material Cost	N
PT14	Regular Maintenance	Growth and damage to propellers can significantly increase underwater radiated noise. Regular maintenance can reduce this impact	Varies. Large reductions are possible for highly fouled or damaged propellers / thrusters	All	Small when performed with other scheduled maintenance	N

(PT1a) Low Noise Propeller Design

- *Notes on Treatment*: Propellers can be designed to delay cavitation inception and reduce cavitation growth. This will reduce the underwater noise levels produced by the propeller. General design guidelines for quiet propellers are provided below.

  a) Propeller tip speed should be kept as low as possible by increasing propeller diameter and reducing shaft RPM. As a rule of thumb, cavitation will begin when tip speed reaches 18 m/s.
  b) A skewed impeller shape has significantly better low frequency performance than one with a radial leading edge. Note that the blade must be designed to handle larger stresses than a non-skewed blade.
  c) For ducted impellers, consider trade-off between increased tip clearance, which reduces unsteady load at tips that operate in the fin wake, and effect on tip vortex cavitation and thrust performance.
  d) Adjust blade pitch distribution to unload tip.
  e) Consider odd number of blades which respond to lower amplitude wake harmonics, and therefore generate lower unsteady hydrodynamic forces.
  f) Increased impeller pitch may produce the same thrust but at a lower rotation rate, which is equivalent to a lower tip speed. Note that this can also increase the loading of the blade, causing other cavitation effects.
  g) The chord length near blade tip should be maximized.
  h) The angle at the propeller between the shaft line and the overhead buttock lines should not exceed 10 degrees for preliminary design to ensure that the tangential and radial wake components are suitably small. At the conclusion of the feasibility design stage, a detailed examination of the cavitation performance of the propeller should be performed, using the wake field of a similar ship. At the conclusion of model tests, the cavitation performance should be examined using the actual wake. Additional recommendations on hull/wake/propeller interaction are described in Holden (1980).

  In general, twin screw designs can reduce noise relative to single screw designs since two lightly loaded propellers are better for noise than one heavily loaded propeller. This also provides propulsion redundancy which can be useful in emergency situations. Counter-rotating propellers have been shown to be lower in noise than propellers rotating in the same direction for vessels with two propellers (Nishiyama, 1990; Zhu, 1997). Naturally, two propellers will be more expensive than one.

  When implemented properly, controllable-pitch propeller designs (CPP) can result in lower noise than fixed pitch designs. In a proper design the pitch of the propeller is be changed with engine RPM to best match inflow conditions. This technique can also result in increased propulsion performance. However, it is common for vessels to use CPP designs with engines that operate at a fixed speed; vessel speed is then controlled solely through blade pitch. This approach can lead to very high noise levels, as cavitation is possible (and likely in practice) even at 0 pitch since tip speed is constant (and high). It is strongly suggested that when CPP designs are used, the propulsion engine or motor should be allowed to vary in speed, and an optimal configuration of RPM and blade pitch should be identified for each speed to keep noise levels as low as possible.

Modifications to the ship hull can also be analyzed and implemented into the vessel design at the design stage. Such modifications would be performed with the intention of improving the flow into the propeller thus reducing cavitation noise. This approach generally requires extensive model testing.

It is recommended that any propeller design be evaluated by a qualified analyst. Analysis methods range from conventional methods using lifting lines and lifting surfaces to computerized CFD and BEM analyses.

- *Description of Estimated Costs*: Engineering costs for improved propeller designs can be on the order of $50-200k. Additional material costs for improved propellers are small. Machining costs may be higher for some propeller designs; some modifications to manufacturing processes may be required.

- *Environmental Impacts*: Increases and decreases in efficiency can result depending on the specifics of the original and new designs.

- *Other Non-acoustic Impacts*: Model testing is often required in order to fine-tune the design.

- *References and Additional Information*: Brown (1976a), Holden (1980), Greeley (1982), Asmussen (1986), Bruggeman (1988), Pylkkanen (1991), Fischer (2001), Kinnas (2002), Jebsen (2005), BAHAM (No Date).

- *Vendors (Designers)*: NAB & Associates (nab@nabassociates.net), Sistemar (www.sistemar.com), Groningen Propeller Technology, Rolls Royce Naval Marine (marine.rolls-royce.com)

(PT1b) Low Noise Thruster Design

- *Notes on Treatment*: Similar to propellers, thrusters can be designed so that cavitation is delayed until higher thrusts are generated and cavitation growth is reduced. This will reduce the underwater noise levels produced by the thruster. Several of the notes provided in PT1a are applicable here. Further design guidance from Fischer (2006) is provided below.

  a) The centerline of the tunnel should be a minimum of one duct diameter above the baseline to minimize the inflow gradient between the top and bottom of the tunnel.
  b) The centerline of the tunnel should be a minimum of one duct diameter below the lightest water line.

c) The minimum distance from the lower opening edge to the impeller is one duct diameter.
d) The minimum length of the tunnel at centerline is two duct diameters. Otherwise there is potential for turbulent flow, which also reduces thrust.
e) The hull should be dished or flared downstream of the tunnel opening. The major axis of the dish should be approximately 15 degrees below the horizontal (or follow flow lines) and the angle from the tunnel opening to the edge of the un-dished hull should not exceed 15 degrees.
f) The radius of the inlet along the hull interface should be at least 0.05 times the duct diameter.
g) If a grill is used the grill should follow the water streamlines, typically 15 to 20 degrees off the horizontal.
h) The grill itself should not be made of flat bar but should be aerodynamically shaped with rounded leading edges. Grills should take up as little free area as possible. Maximum opening blockage should be 10% to 15%.
i) Struts holding the impeller should be faired as much as possible to reduce wake turbulence, especially for thrust generated in a direction where the flow hits the struts before the impeller.
j) Reduce strut cross sectional area as possible.
k) Place generous fillets between strut and tunnel wall to reduce vortices.
l) For multiple tunnel thruster arrangements, distance between tunnel centerlines should be at least two duct diameters for controllable pitch impellers, and 1.5 diameters for fixed pitch impellers (FP).
m) Increased impeller pitch may produce the same thrust but at a lower rotation rate, which is equivalent to a lower tip speed. Note that this can also increase the loading of the blade, causing other cavitation effects.
n) Impeller tip speed should be as low as possible over as much of the operating range as possible.
o) A skewed impeller shape has significantly better low frequency performance than one with a radial leading edge. Skew for thrust in one direction should not harm thrust in the other direction; requires careful hydro-acoustic design.
p) Consider trade-off between increased tip clearance, which reduces unsteady load at tips that operate in the strut wake, and effect on tip vortex cavitation and thrust performance. Adjust blade pitch distribution to unload tip

It is recommended that any thruster design be evaluated by a qualified analyst.

- *Description of Estimated Costs*: Engineering costs for improved propeller designs can be on the order of $50-200k. Additional material costs for improved propellers are small. Machining costs may be higher for some propeller designs; some modifications to manufacturing processes may be required.

- *Environmental Impacts*: Increases and decreases in efficiency can result depending on the specifics of the original and new designs.

- *References and Additional Information*: See Item PT1a, Brown (1974), Brown (1977), Fischer (2006).

- *Vendors (Designers)*: See PT1a.

(PT2a) Ducted Propellers

- *Notes on Treatment*: A ducted propeller uses a duct around the perimeter of the propeller to modify the propulsion performance and noise characteristics of the propeller. An example is shown in Figure PT2a below. The duct commonly employs an airfoil shape to either accelerate (Kort Nozzle) or decelerate (pump jet) the flow into the propeller. This is done to enhance propulsion performance, cavitation performance, or both. A Kort Nozzle can increase propulsion efficiency by as much as 20% for heavily loaded propulsors by generating thrust over an airfoil duct shape. These configurations are commonly found on low speed vessels such as tug boats.

  Vanes can also be outfitted on forward or aft sides of ducts to help make the inflow to the propeller more uniform (a.k.a. pre-swirl and post-swirl vanes); this can lead to reduced noise (DOD, 2002; BAHAM, no date). Depending on the dimensions of the duct, noise radiated by a ducted propeller will be directional (Brown, 1976a). Beaming will occur in the fore/aft directions and will be frequency dependent (high directionality at high frequencies, low directionality at low frequencies).

  Furthermore, the duct itself can be lined or filled with an acoustically absorbent material (Brown, 1976a). Depending on the design, reductions can be significant (see Item MV6) although some increase in noise at low frequencies should also be expected. Protection of these absorbent materials from cavitation and other marine effects is another challenge.

  It is indicated by BAHAM (no date) that noise levels may be higher in off-design conditions such as sharp turns than for non-ducted propellers. Erosion of the interior of the duct due to cavitation may also be an issue that needs consideration.

FIGURE PT2a: Example of Ducted Propeller (www.marinepropulsion.net)

- *Description of Estimated Costs*: Costs will naturally be higher compared to open propeller designs. However, overall efficiency may be increased depending on the specific design, thereby reducing fuel costs.

- *Environmental Impacts*: Increases and decreases in efficiency relative to conventional open propeller designs are possible.

- *Other Non-acoustic Impacts*: Increased complexity of design, particularly in way of supporting structures. There is slightly reduced maneuverability with ducted propellers.

- *References and Additional Information*: Brown (1976a), Brown (1999), DOD (2002), Brown (2007), BAHAM (no date).

- *Vendors(Designers)*: See PT1a.

(PT2b) Forward-Skew Blades

- *Notes on Treatment*: Unconventional, forward skew propellers have been implemented in ducted propeller designs and thrusters to significantly improve noise and thrust performance (Brown, 1999; Brown, 2007; Brown, Workshop). A visual comparison of conventional and forward-skew designs is provided below. Note that the rotation direction is clockwise for both propellers. Brown (Workshop) states that "the forward-skewed blade-tip region suffers less change in load (lift) per unit change of incidence than a straight-edged blade – and a lot less than a back-skewed blade." This makes it less susceptible to variations in inflow and vessel speed.

Brown presented measured data at the Workshop showing the results of a design modification to the bow thruster on the R/V ROGER REVELLE. The forward-skew blade design reduced underwater noise by 5-18 dB at the 1000 Hz third-octave band over much of the thruster's operating range. In addition, NCE has recently been in contact with the operator of the survey vessel NORTHERN RESOLUTION, where the original propeller was replaced with a forward-skew design due to poor acoustical performance. The vessel could not perform its normal functions which included the use of sonar at 12 kHz due to interference from noise created by the propeller. After the new forward-skew blade was implemented the noise reportedly dropped by 20 dB at this frequency and the vessel can now perform surveys at full speed (11.5 knots) (NCE, 2007). This same technology has also been applied to pumps with good results (Brown, Workshop).

Forward-skew blade designs must be implemented in tunnels or nozzles to prevent fouling or physical damage to marine life; the design also benefits from the existence of the duct. Other advantages and treatments applicable to ducted propeller and thruster designs are also applicable here (see Item PT2a).

FIGURE PT2b: Comparison of Conventional (Left) and Forward-Skew (Right) Propeller Blades (Provided by Neal Brown, NAB Associates)

Image on the left shows the original, conventional propeller and the image on the right shows the new forward skew propeller (both installed on the same vessel, one after the other). Both propellers are clockwise turning. The sharp tip or 'bird beak' on the forward skew blade is on the leading edge.

- *Description of Estimated Costs*: There are no additional material costs associated with the design of a forward-skew blade as compared to a conventional blade. Machining costs may be increased due to added complexity or unfamiliarity with design.

- *Environmental Impacts*: Increases and decreases in efficiency relative to conventional designs are possible.

- *References and Additional Information*: Brown (1974), Brown (1976b), Brown (1999), Brown (2007), Brown (Workshop).

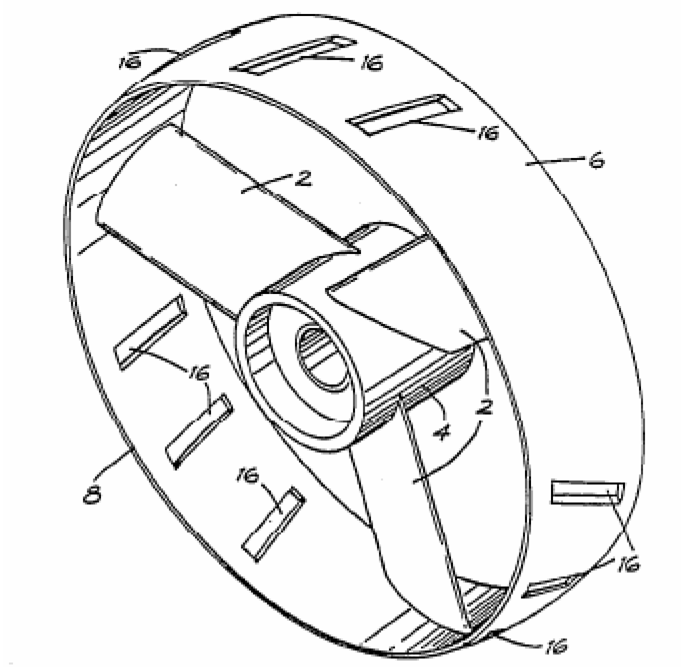
- *Vendors(Designers)*: NAB & Associates (nab@nabassociates.net).

(PT2c) Ring Propellers

- *Notes on Treatment*: BAHAM (no date) discusses the use of a ring propeller. This is a propeller that has a continuous ring attached to the blade tips (as opposed to using a duct). Because the tip clearance is effectively zero there is no loss of efficiency due to tip clearance effects. BAHAM shows that the open water efficiency is greater than for open propellers, although it is less than for ducted propellers. This approach removes the need to manufacture and install a separate duct and can have higher reliability. It is indicated that this design can have lower underwater noise, although measured data was not identified.

  A second option is to use a "Tip vortex free" propeller or tip vortex fence. This is essentially the same as the ring propeller but the sections of the ring between the propeller are removed. The potential advantages of this design are similar to the ring propeller, although BAHAM indicates that this design can be used with or without a duct. Again, no noise data is provided for this design, although Anonymous (2001 a-c) suggest it can help reduce noise (and on-board vibration).

FIGURE PT2c: Diagram of Ring Propeller (Church, 1989)



Propeller blades are attached to the outer ring. This ring rotates with the blades.

- *Description of Estimated Costs*: Costs will be somewhat higher than with open propeller designs, but potentially less than ducted designs. Overall efficiency may be increased depending on the specific design, thereby reducing fuel costs.

- *Environmental Impacts*: Increases in efficiency relative to conventional open propeller designs are possible. Efficiency is expected to be less than for a ducted design.

- *Other Non-acoustic Impacts*: A rotating ring increases moment of inertia (i.e. increases the mass that is moving at a distance from the center of rotation, and is more resistant to changes in RPM). The ring therefore requires a light material.

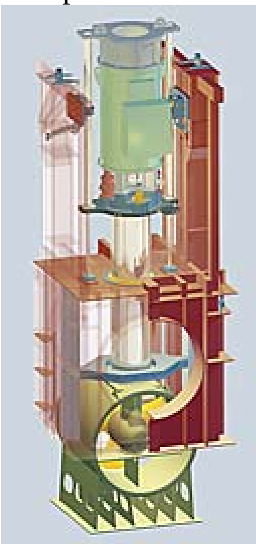
- *References and Additional Information*: Church (1989), Anonymous (2001a-c), BAHAM (no date).

(PT3) Drop Thruster

- *Notes on Treatment*: A 'drop thruster' is a thruster that can be lowered below the vessel. Drop thrusters have better inflow and outflow characteristics since they are separated from the vessel and supporting structures that can cause flow non-uniformities. Lower underwater noise will result from the improved flow characteristics, as well as improved thrust. Drop thrusters also allow for azimuthing, increasing the control capabilities of the vessel.

  Drop thrusters have some limitations with regards to water depth; for obvious reasons, they can not be used in very shallow waters. One solution for this issue is a combined retractable / tunnel thruster, as seen in Figure PT3 below. This design has the same capabilities as any drop thruster, and can be used as a tunnel thruster for shallow water operation.

FIGURE PT3: Combination Drop / Tunnel Thruster (www.brunvoll.no)



This image shows a retractable drop thruster. The thruster can be positioned below the vessel, allowing for better flow and reduced noise. When not in use or operating in shallow water, the thruster can be pulled into the vessel and used like a conventional thruister.

- *Description of Estimated Costs*: Drop thruster designs can cost 2-6 times more than conventional tunnel thruster designs. Engineering and installation costs are also higher than costs associated with conventional designs.

- *Environmental Impacts*: Increases in efficiency may result, yielding reduced environmental impacts relative to 'standard' designs.

- *Other Non-acoustic Impacts*: Use in very shallow waters may be limited for some designs. Fouling may occur in shallow waters when thruster operates near bottom. Installation of a drop-down thruster is more complicated than in tunnel designs. Sufficient internal height/depth requirements are needed to accommodate thruster.

- *References and Additional Information*: Bekker (2005), Fischer (2006).

- *Vendors*: Thrustmaster (www.thrustmastertexas.com), Brunvoll (www.brunvoll.no)

(PT4) Z-Drives and Podded Systems

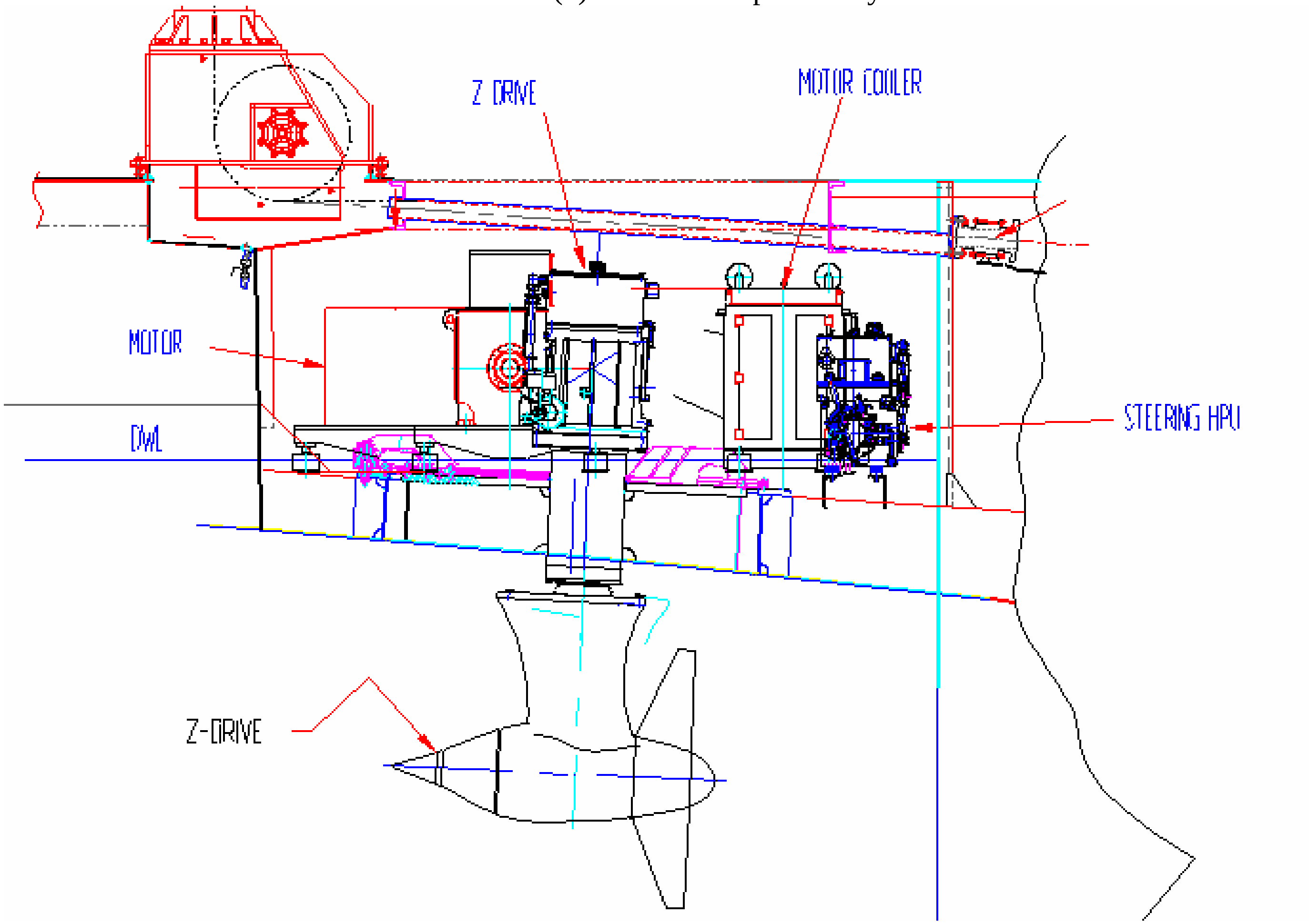
- *Notes on Treatment*: Z-Drives and podded propulsion systems (also called 'azipods') use special gearing and machinery arrangements to locate the propeller further from the vessel / structure. This is done to achieve better inflow and outflow characteristics. These systems see less hull-wake deficit, reducing underwater noise. Furthermore, these systems can allow for steerable thrust, often covering a full 360 degree arc. Z-Drives also have the ability to be located in the middle or forward portions of the vessel (Baniela, 2005).

  Z-drives use a double-gear system to locate the propeller away from ship structures, as seen in Figure PT4(1) below. In these systems, the prime mover is located on the vessel and is attached to the upper gear. The lower gear is located in the water and is then connected to the propeller. As a result of this arrangement, increased levels at gear mesh frequencies (100 – 5000 Hz range) may result, and can be significant if gear tolerance is poor.

  Podded systems have a submerged electric motor directly coupled to the propeller, without gearing. See Figure PT4(2). Podded propulsors are often operated with the propeller forward in a 'puller' configuration; this can provide a minimum of disturbed flow into the propeller. It is important to note that because the motor is in direct contact with the seawater this design may not necessarily result in lower underwater noise at all frequencies. High noise levels at low frequencies (due to the motor) are evident in podded systems tested to date. Isolation mounted motors may partially overcome this problem (Brungart, 2002). This noise may also be a result of a "dirty" electrical drive signal; cleaning up this signal may also help to reduce this noise (Workshop).

  In either case, the design of a Z-drive or podded propulsion system should be analyzed to ensure that noise reductions will be achieved.

FIGURE PT4(1): Z-Drive Propulsion System



In a Z-drive system, the propeller is attached to a steerable pod that is located farther from the hull than in a conventional design. This positioning of the propeller can lead to reduced underwater noise. The propeller is driven through two gears, one located inside the vessel and one located in the pod.

FIGURE PT4(2): Azipod Propulsion System (http://www.uscg.mil/d9/glib/images/launch/Mack%20Launch%20010.jpg)

An azipod system is similar to a Z-drive system in that the propeller is moved away from the ship, potentially providing lower radiated noise. However, the driving motor is located within the pod, removing the need for gears. Noise from the motor has proven to be significant in recent designs, but solutions are possible.

- *Description of Estimated Costs*: Absolute costs for "standard" Z-drives are on the order of $200,000. It is noted though that shafting complexities (including balancing) are significantly reduced in these designs. Quiet, high quality Z-drives with low noise gears can cost roughly 40% more than standard Z-drives.

- *Environmental Impacts*: Some decrease in efficiency may result due to the removal of the hull wake deficit (see Section 4.4.1).

- *Other Non-acoustic Impacts*: Requires different design for propulsion system.

- *Additional Information*: Baniela (2005), Brungart (2002).

- *Vendors*: Schottell, Aquamaster, Niigata, Rolls Royce, Duckpeller, Steerprop.

(PT5) Waterjets

- *Notes on Treatment*: Waterjets operate by sucking water from the ocean and accelerating it out of the aft of the vessel, thereby creating thrust. Waterjets should only be used on high speed craft – waterjets have significantly improved propulsion efficiency relative to conventional propulsion systems at speeds of 30 and 45 knots (normal transit loads). Below this speed waterjets are less efficient than propellers and may not be appropriate. Anonymous (1994) and Kallman (2001) state that water jets typically have lower radiated noise than equivalent open screw propellers. These studies focus on airborne noise reductions on-board the vessel, however similar reductions should be expected in underwater radiated noise.

  Waterjet impellers with an unorthodox forward-skew of the leading edge toward the blade tips have been shown to greatly increase inception speed and tolerance to inflow non-uniformity (Lanni, 2000; Brown, Workshop) – see Item PT2b. Brown indicated at the Workshop that cavitation in an impeller using this design was not significant at 30 knots. This delay in inception speed will help to reduce underwater noise.

  Waterjets are becoming more common in many marine sectors such as ferries and shipping, and may also be appropriate for use in the oil and gas industry. Waterjets also do not require appendages similar to conventional propulsion systems, and therefore can reduce vessel drag. Similarly, vessels outfitted with waterjets can be used in shallower waters than those using propellers. Waterjets are also lighter than conventional propulsion systems.

- *Description of Estimated Costs*: The overall costs of waterjet systems may actually be similar to conventional propulsion systems. This is due in part to the fact that waterjets are typically modularized, and so there is reduced effort in installation, including shaft balancing.

- *Environmental Impacts*: Improvements to propulsion efficiency are likely for higher speeds (30-45 knots) over open propeller designs. This can result in reduced environmental impacts. Waterjet systems are also lighter than conventional systems, thereby reducing the load on the vessel.

- *References and Additional Information*: Anonymous, 1994; Kallman, 2001, Lanni (2000), Brown (Workshop).

- *Vendors*: Rolls Royce Naval Marine (marine.rolls-royce.com), Wartsila (www.wartsila.com), HamiltonJet (www.hamjet.co.nz), UltraJet (www.ultradynamics.com).

(PT6) Rim Drive Propulsion

- *Notes on Treatment*: A relatively new technology that is being pursued is called "rim drive". An example is the "EPS Thruster" created by Van der Velden Marine Systems. An image of this thruster is provided below. The thruster is unique in that the blades are driven from the perimeter as opposed to the center. A permanent magnet electric motor is integrated into the outer ring. As a result this system does not require shafting, gears, or a separate electric motor or diesel engine. The system is designed in such a way that there is no mechanical contact between the rotor and stator. Water is allowed to flow freely between the rotor and stator, which are individually sealed.

  Testing of the EPS thruster currently indicates that overall noise reductions of 5-10 dB are possible relative to conventional designs. Slight improvements in thrust efficiency have also been indicated (Maat, 2006). Maat indicates that the thruster can be resiliently mounted to the vessel to reduce on-board noise and vibration.

  The EPS thruster currently has a size limitation. This limitation is due to the journal bearing needs to be usable at high speeds while also resisting corrosion and other marine effects. EPS currently makes this thruster in powers up to 160 kW and is developing a 340 kW unit for primary propulsion.

FIGURE PT6: EPS Thruster (Maat, 2006)

A 'rim drive' thruster uses a motor that is integrated into the perimeter of the thruster. The blades are also attached along the perimeter. The system is compact and has been shown to have reduced underwater noise levels.

Rolls-Royce and Brunvoll are also developing their own versions of this technology (Tinsley, 2006). It is indicated that one of these units can provide 800 kW of thrust (as a stern thruster). It is also indicated that these companies are planning on using the technology for primary propulsion, and Brunvoll is developing a similar system for its drop thrusters (see Item PT3). No indications of underwater sound levels were provided.

- *Description of Estimated Costs*: System costs are on the order of $150,000 based on a rough quotation provided by one manufacturer. Some system simplification is apparent since no gears or separate prime mover is necessary, potentially leading to reduced installation costs.

- *Environmental Impacts*: Increases in efficiency may result, yielding reduced environmental impacts relative to 'standard' designs. The unit will also be lighter than conventional systems.

- *Other Non-acoustic Impacts*: Reduced weight. There is no need for a separate prime mover since it is integral to the system.

- *References and Additional Information*: Maat (2006), Tinsley (2006).

- *Vendors*: Van der Velden Marine Systems (www.vdvelden.nl), Rolls Royce Naval Marine (marine.rolls-royce.com), Brunvoll (www.brunvoll.com).

(PT7) Voith Schneider Systems

- *Notes on Treatment*: Voith Schneider systems operate in a very unique manner that is unlike almost any other propulsion system. The system is made up of several long blades that extend vertically downwards from the vessel, as seen in the image below. The operation of the system is described on the Voith Schneider website as follows:

  … a rotor casing which ends flush with the ship's bottom is fitted with a number of axially parallel blades and rotates about a vertical axis. To generate thrust, each of the propeller blades performs an oscillating motion about its own axis. This is superimposed on the uniform rotary motion. Blade excursion determines the amount of thrust, while the phase angle of between 0° and 360° determines its direction. As a result, the same amount of thrust can be generated in any direction…

FIGURE PT7: Voith Schneider Propulsion System (www.voithturbo.de)

An animation of how this system works can be seen at www.voithturbo.de

Voith Schneider systems can generate thrust in any direction, and have the ability to quickly change the direction of thrust. Such systems have been employed on many tug designs. These vessels can literally spin 360 degrees without any lateral motion.

Voith Schneider systems are being used on European mine sweepers, and are therefore assumed to have some reduced noise levels relative to conventional systems. Additional details are not known.

- *Description of Estimated Costs*: Costs of installing Voith Schneider propulsion systems were not identified but are expected to be significantly higher than conventional systems due to increased complexity and uniqueness.
- *Environmental Impacts*: Changes to efficiency relative to conventional designs are not known.
- *Other Non-acoustic Impacts*: Increased draft. Vessel must be designed specifically to accommodate this propulsion system which may involve very different layouts and construction methods.
- *Vendors*: Voith Schneider (www.voithturbo.de/vt_en_pua_marine_vspropeller.htm)

(PT8) PropacRudder

- *Notes on Treatment*: The PropacRudder is a rudder system available from Wartsila that claims increased propulsion efficiency and lower noise over conventional designs. The manufacturer claims the following:

> *PropacRudder is characterized by a streamlined "torpedo"-shaped bulb on the rudder horn immediately abaft and coaxial with the propeller hub. The bulb ensures a more homogeneous water flow both in front of the propeller and in the propeller slipstream. The bulb increases propulsion efficiency by the "wake gain" effect, which means that it reduces the water speed into the propeller so that less power is needed to produce the same propeller thrust. The bulb also reduces propeller-induced hull noise and vibration by eliminating hub vortices and separation, and cavitation behind the propeller hub collapsing on the propeller.*

Underwater noise data is not available for PropacRudder systems. Additional study would be necessary in order to quantify any reduction in noise.

- *Description of Estimated Costs*: Costs of PropacRudder systems were not identified but are expected to be higher than conventional rudder designs. Engineering and installation costs are also expected to be higher than costs associated with conventional designs.

- *Environmental Impacts*: Increases in efficiency are claimed, and would yield reduced environmental impacts relative to 'standard' designs.

- *Vendors*: Wartsila (www.wartsila.com)

(PT9) Foul Release Coating

- *Notes on Treatment*: A foul release material has been applied to several propellers by Mutton (2006). The effects on underwater noise were investigated, and some reduction was found. The noise reduction varied with frequency and specific operating condition. Amplification was found at some frequencies under some conditions. The actual mechanisms causing the change in sound are not clear.

- *Description of Estimated Costs*: Costs are not known at this time.

- *Environmental Impacts*: Unknown. Coating would require approval from regulatory agencies.

- *Other Non-acoustic Impacts*: Coating may need re-application after some period of time (years).

- *References and Additional Information*: Anderson (2003), Mutton (2006).

(PT10) Composite Material Propeller

- *Notes on Treatment*: QuinetiQ (2007) reports improved cavitation performance of a propeller made from composite materials. No underwater noise data is available; however the improved cavitation performance is expected to reduce underwater noise. The article states the following regarding this approach:

  > Theoretical models give a cavitation inception speed of 30% higher for the composite propeller design, compared with the original nickel aluminum bronze (NiBrAl) propeller. This was found to be a result of the improved shape, rather than the use of new materials - though the combination provides a number of benefits, explains Colin Podmore, Project Manager. 'The use of the lighter composite materials meant that the blades could be thicker without significantly adding to the weight of the propeller. Thicker blades offer the potential for improved cavitation performance, so reducing vibration and underwater signatures. Propeller also has improved lift expectancy.

- *Description of Estimated Costs*: Costs are not known at this time.

- *References and Additional Information*: QuinetiQ (2007).

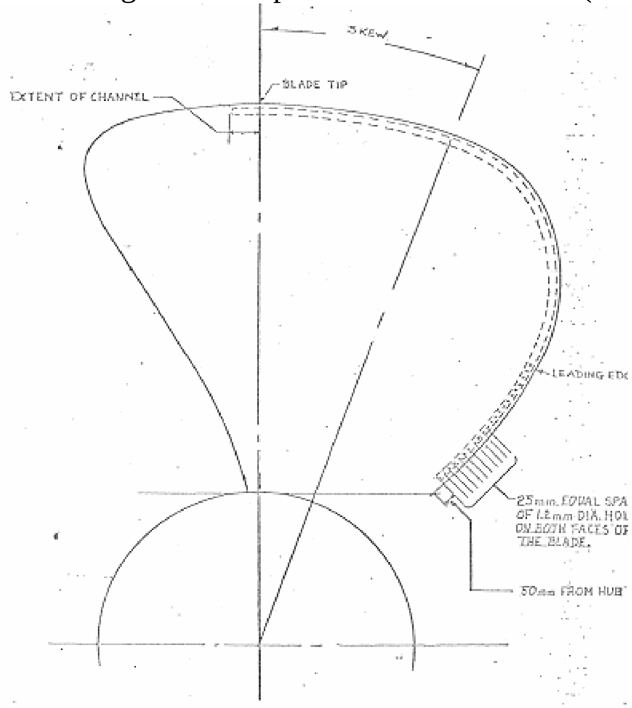
(PT11a) Propeller Bubble Emission

- *Notes on Treatment*: Air bubbles are emitted into the water through small holes located in the propeller blades. An example diagram is provided below, and is also see Figure PT12 ("PRAIRIE"). The presence of the air bubbles changes the local acoustic impedance of the water, thereby modifying the characteristics of the cavitation noise. Effectively there is a "cushioning" of the collapsing of the cavitation bubbles.

  Noise reductions are believed to be on the order of 10 dB or more at frequencies above 500 Hz. Some increase in noise may result at frequencies below 80 Hz. It is noted that much of the data showing the effectiveness of these systems is classified.

  Noise reduction may be compromised due to increased cavitation effects. These systems are prone to marine growth, and holes can clog requiring regular cleaning.

FIGURE PT11: Diagram of Propeller Bubble Emission (DND, 1979)



Small holes are drilled in the propeller blade where air bubbles are emitted. Air is supplied via a compressor and piping which runs down the propeller shaft. Hole location, size, and spacing for one design are shown here.

- *Description of Estimated Costs*: Costs of implementation are expected to be very high. Furthermore, maintenance costs to keep holes clean can also be significant. System may need to be run constantly to avoid fouling.

- *Other Non-acoustic Impacts*: System is complex. Air lines must pass through propeller shaft to a manifold for distribution. System must account for rotation of propeller.

- *References and Additional Information*: DND (1979), DTNSRDC (1981)

(PT11b) Tunnel Bubble Emission

- *Notes on Treatment*: Air bubbles are emitted into the water through small holes located in the inlet and outlet of a thruster's tunnel wall. The physics of this approach is based on the same principle as what is described for the propeller bubble emission system (Item PT11a). The effectiveness of the system will be dependent on the amount of air injected into the tunnel. It is believed that too much air will cause decreased thrust and noise performance. Brown (1975) indicates that holes should be drilled 2-3mm apart at 1.5 mm in diameter, although these parameters will vary depending on desired airflow and available pressure from a compressor.

  These systems have been installed on naval vessels. It is noted that much of the data showing the effectiveness of these systems is classified. Reductions are estimated to be on the order of 0-20 dB above 100 Hz, with some increase in level being possible below this frequency.

  These systems are prone to marine growth. Holes can clog requiring regular cleaning.

- *Description of Estimated Costs*: Costs of implementation are not known, but are estimated at $20-50k. Maintenance costs to keep holes clean can also be significant.

- *References and Additional Information*: Brown (1975).

(PT12) Air Bubble Masker

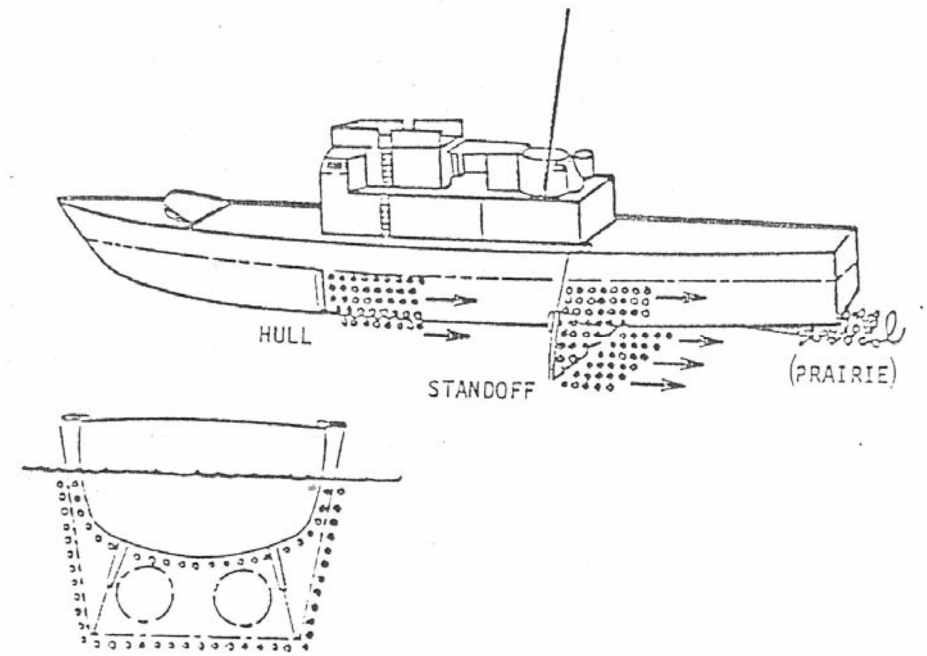
- *Notes on Treatment*: This treatment is similar to that described in Item MV5. Air bubbles are emitted into the water through small holes located on a structure offset from the hull, upstream of the propeller. An example is shown in the diagram below ("standoff"). The bubbles are designed to pass below the propeller, and provide an acoustic impedance which effectively blocks sound transmission. Air bubbles are typically created via an air compressor.

  The effectiveness of this approach is similar to that described in PD1, although some increase in noise at frequencies below 80 Hz is possible. Locating the curtain below the propeller may prove to be difficult for commercial vessels. Increased noise and reduced propulsion performance may result if bubbles enter the propeller's inflow.

  The air injection holes used to create bubble layers are prone to fouling. Significant costs can be expected for regular maintenance and inspection.

  It has been estimated that such a system can require upwards of 600 HP on a vessel moving at 20 knots.

FIGURE PT12: Diagram of Various Bubble Emission Systems (DTNSRDC, 1981)



This diagram shows the implementation of several masker systems based on air bubble emission into the water. The 'standoff' system emits a bubble sheet that passes below the propeller, shielding the ocean surroundings from propeller induced noise. The 'PRARIE' system is described in Item PT11a. The 'hull' system is similar to the standoff system except the bubbles travel along the hull with the purpose of blocking noise generated by machinery (see Item MV5).

- *Description of Estimated Costs*: Engineering and installation costs could not be determined, but are estimated to be in the range of $30,000-$75,000 or more depending on the system and configuration. The system may need to be run constantly to avoid fouling.

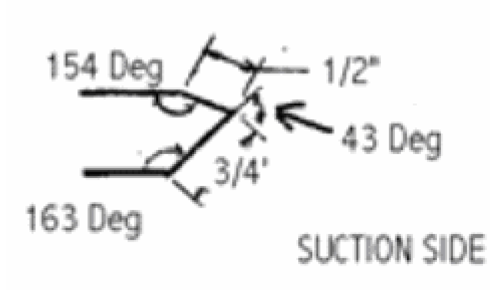
- *Environmental Impacts*: Some impact is expected due to operation of air compressors.

- *References and Additional Information*: See Item MV5.

(PT13) Anti-singing Edge

- *Notes on Treatment*: When singing propellers are encountered, an effective method of reducing the associated tone is to modify the propeller's trailing edge. An example of such a modification is provided below. The objective in making this modification is to break up, alter, or otherwise weaken the naturally occurring vortex shedding phenomenon that leads to the singing tone creation. This modification can be applied to existing propellers, and thus can be used only when necessary.

FIGURE PT13: Anti-Singing Edge



The above diagram shows a possible profile of a propeller's trailing edge in order to eliminate the effects of a singing propeller.

It is also possible to 'de-tune' the propeller to move shedding frequencies out of the range of blade natural frequencies, and vice versa. If, for example, blades are made thicker, the resonant frequencies of the water-loaded blades are typically increased while the vortex shedding frequencies tend to be reduced.

- *Description of Estimated Costs*: Engineering and modification costs (for an existing propeller) are estimated to be on the order of several thousand dollars.

(PT14) Regular Maintenance

- *Notes on Treatment*: Propellers that are subjected to marine growth, even in low amounts, are more likely to cavitate at lower speeds than 'clean' propellers and will exhibit greater amounts of cavitation at higher speeds. Regular maintenance can also help identify propellers that have been damaged, which can lead to significantly higher levels of underwater noise.

FIGURE PT14: Example of Fouled Thruster

- *Description of Estimated Costs*: Costs of maintenance will vary, however propeller maintenance should be part of any regular maintenance routine used for the rest of the vessel.

- *Environmental Impacts*: Increases in propulsion efficiency can result from cleaning and repairing propellers and thrusters.

SECTION MV:
MACHINERY VIBRATION TREATMENTS

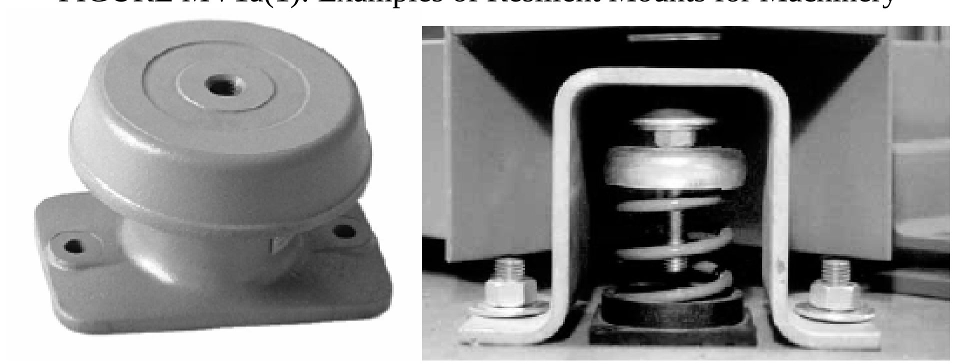
REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS*		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
MV1	Resilient Isolation of Equipment	Reduction of vibration by mechanically isolating machinery from supporting structure	0-20+ dB 10-25+ dB	20-100 Hz >100 Hz	$20-$2000 Per mount Add'l for other connections	N
MV2	Isolated Deck / Larger Structure	Isolation of deck or larger area containing multiple equipment items that require isolation mounting	0-20+ dB 10-25+ dB	20-100 Hz >100 Hz	$20-$2000 Per mount Add'l for deck	N
MV3a	Damping Tiles	Reduces vibration energy in structures. Used on stiffened plating near machinery sources, plating adjacent to water, and locations in-between.	5-10+ dB Depending on type, amount, and location	>30 Hz	Material: $5-$15 / sq ft Additional costs apply	N
MV3b	Spray-on Damping	Reduces vibration energy in structures. Used on stiffened plating near machinery sources, plating adjacent to water, and locations in-between.	3-8+ dB Depending on type, amount, and location	>30 Hz	$15 - $30 per square foot Additional costs apply	N
MV4	Ballast-Crete	Used in lieu of conventional liquid ballast. Provides additional damping.	N/A 5+ dB estimated	>30 Hz (est)	Varies See Details	N
MV5	Air Masking System	Air bubble curtain is used to shield vessel hull from rest of ocean	>10 dB 0-10 dB Increase	>500 Hz 20-80 Hz	Est. $20,000 - $50,000+	N
MV6	Decoupling Materials	A decoupling material is applied to the exterior (wet side) plating in order to reduce the radiation efficiency of the structure.	>10 dB 0-10 dB Increase	>500 Hz 20-80 Hz	Est $25-$100 per square foot	N
MV7	Low Noise Equipment	Equipment that creates low vibration levels is selected	Varies, 5 dB is common	All	Est. 1-5x noisier equipment	N

*Effectiveness is for treated item / path only. If other sources are significant or dominate the underwater noise signature, total noise reduction will be less than what is quoted here.

(MV1) Resilient Isolation of Equipment

- *Notes on Treatment*: Resilient mounts are effectively springs that react to the motions of the mounted machinery. They work by reducing the vibration and forces imparted by machinery to the supporting structure (i.e. vessel, platform, etc.). Vibration in the structure can travel to areas in contact with water and create underwater noise. Pictures of typical isolation mounts are provided below.

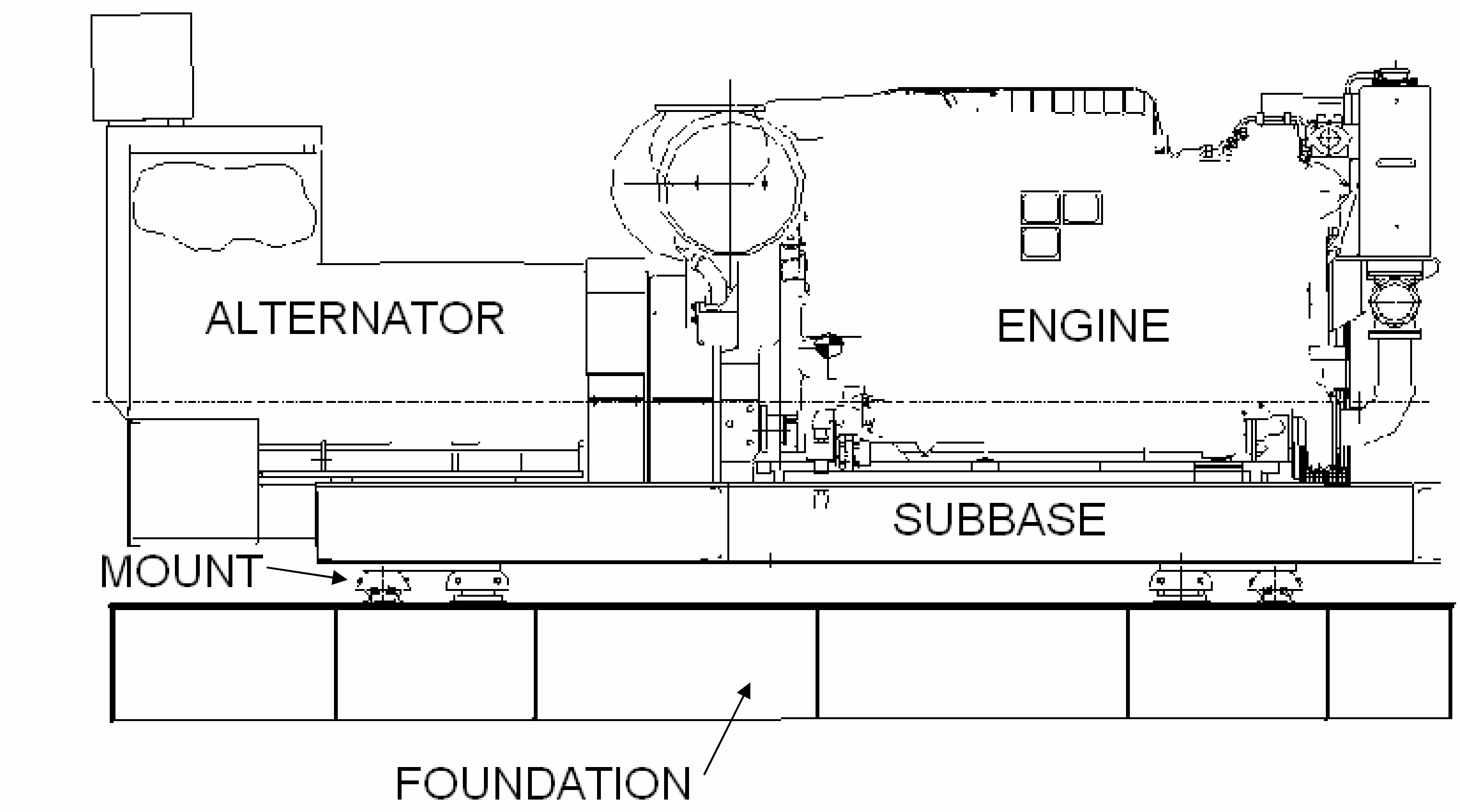
FIGURE MV1a(1): Examples of Resilient Mounts for Machinery



These are two examples of typical resilient mounts. The mount on the left uses rubber as the isolation material (rubber not seen here) and the mount on the right uses a spring. Different mount types will have different effectivensses. The effectiveness will be frequency dependent.

Isolators are located between the equipment and primary structure. Equipment feet are mounted to a frame or "subbase" (typically steel). The resilient mount is connected between the subbase and foundation. A minimum of 4 mounts per equipment item are generally required, although it is typically desired to use as few mounts as possible. The number of mounts required will depend on the rated load of the selected mounts and the desired natural frequencies of the mounted system. A diagram showing the locations of resilient mounts, subbase, and foundation is provided below.

FIGURE MV1a(2): Diagram of Mounting Concept



This image shows a typical single stage isolation system for a diesel generator. The mounts are located between the engine and the supporting structure (ship, platform, etc). The mounted equipment will typically be supported by a 'subbase', which should have high dynamic stiffness in order for the mounts to work effectively. Similarly, the foundation (i.e. below mount structure) should also have high dynamic stiffness. Increasing these stiffnesses can result in better mount performance.

Resilient mounts come in three types: elastomeric (rubber), spring, or combined elastomer-spring mounts. Typically, elastomeric and combined elastomer-spring mounts are preferred because they have better overall isolation performance ands work well over a greater frequency range. For spring mounts, there is typically some frequency range near 500-2000 Hz where performance is poor; this is due to undamped modes in the spring itself. Elastomeric and combined elastomer-spring mounts do not have this problem. Conversely, it is easier to get better low frequency (<100 Hz) performance from a spring isolator since they can allow for greater displacements.

Mounting systems can be arranged in varying degrees of complexity. The simplest mounting system is a 'single stage' system where one set of mounts is used (as seen in Figure MV1a(2)). Double stage mounting systems can be employed when vibration isolation is highly critical, such as on submarines and fisheries research vessels. These systems use two sets of resilient mounts, separated by a 'blocking mass'. Other configurations are also possible.

When resilient mounts are used, the mass of the machinery and the mounting system will combine to create a system that has several natural modes of vibration (a.k.a. resonances). For a single stage system there are six of these modes. These modes correspond to rigid body translations and rotations in the three primary axes, although some coupling between modes often occurs. It is typically desired to design the system so that these modes are below 1/3 to ½ of the lowest forcing frequency for the mounted item (e.g. rotation rate of the machinery). A system with a lower set of natural frequencies will generally have softer mounts, which results in better vibration isolation.

Special attention should be given to the design of the subbase and foundation of any resiliently mounted machinery item. Both should be dynamically stiff structures with resonant frequencies well outside of the range of the mounting system natural frequencies. These resonance frequencies should also be well above the lowest forcing frequencies of the mounted equipment. Local stiffening of the subbase and foundation at the resilient mounts is recommended ("gusseting"). The specific design of the subbase and foundation can have a significant impact on the performance of the isolation system. Differences of 5 to 25 dB (depending on frequency) have been reported by Odegaard (2005) for the same isolation system using different subbase and foundation arrangements, with better performance resulting from the use of highly stiffened structures.

When isolation mounting a propulsion engine, special isolation mounts may be necessary if thrust forces are seen by the machinery. Some resilient mount types can accept thrust forces. Alternatively, a thrust bearing can be used (separate from the mounted machinery) with a flexible or "torsional" coupling to allow transfer power from the engine to the shaft while limiting vibration transmission and transfer of thrust to the engine and mounts. Note that low speed direct drive diesel engines should not be resiliently mounted as the effectiveness is minimal and may result in increases in vibration / underwater noise levels (Southall, 2004).

Use of resilient mounts will result in larger machinery motions than for a conventional hard-mounted installation (due to sea motion). Limit stops are recommended to prevent excessive motion that would damage the mounts. These are often integrated into the mount design. In addition, all connections to a resiliently mounted machinery item such as piping, exhaust, etc., will need to use resilient elements. This can be accomplished through the use of flexible hose, resilient arch pieces, bellows, and other flexible joints. Use of these flexible joints will reduce or eliminate vibration flanking paths, and will allow the equipment to move freely.

Additional considerations and guidelines should be followed when designing a resilient mounting system, as discussed in Fischer (1983).

- *Description of Estimated Costs*: Resilient mounts typically cost on the order of $20 - $2000 per mount, depending on the mount and quantity. Installation and engineering will be extra. Some vendors will provide engineering services to determine appropriate mount models and locations. It is also important to point out that other resilient connections will be necessary such as piping, exhaust, etc. These items are often low cost but some engineering effort will be required. Total costs incorporating all design factors and installation will be on the order of several thousand dollars. Mounts should be replaced every 10 years (or according to manufacturer's recommendations).

- *Other Non-acoustic Impacts*: Increased space requirement – mounts will either increase the height or width of installation, depending on the design. Increases are on the order of the mount and subbase size, roughly 0.3 meters. Increased weight – installation requires a subbase which may not have otherwise been installed. Mount weight is negligible. Mounts should be inspected for creep on a regular schedule (~1x per year). All piping or other connections to mounted equipment or structure will need to be resilient. See Item FB1.

- *References and Additional Information*: Fischer (1983), Southall (2004), Fischer (Workshop).

- *Vendors*: Barry Controls (www.barrycontrols.com), Christie & Grey (www.christiegrey.com), Kinetics Noise Control (www.kineticsnoise.com), Lord Corporation (www.lordmpd.com), Trelleborg (www.trelleborg.com).

(MV2) Resilient Isolation of Deck or Larger Structure

- *Notes on Treatment*: This treatment works in a similar fashion to individual equipment isolation by reducing the vibration imparted by machinery to the supporting structure (i.e. vessel, platform, etc.). In this arrangement, a floating or 'false' deck structure is made where many equipment items are hard mounted. Resilient isolators are located between the floating deck and primary structure. The advantage of this system is multiple equipment items can be resiliently mounted on one floating deck. This allows for direct, hard connections (piping, for example) between equipment items located on the floating floor. Connections to structure and equipment located off the floating deck will still require resilient connections.

This approach is useful when multiple equipment items need resilient mounting, such as a multiple, adjacent gensets or pump systems. Equipment items that may be hard to mount individually, such as pumps that operate with an imbalance, can be hard mounted to the larger floating deck which will will locally simulate a hard mounting while still providing isolation to the vessel.

Floating deck structures must be designed to have high dynamic stiffness. The first natural frequency is generally desired to be at least 100 Hz or above, and should be at least 25% greater than the highest equipment rotation rate. Mounts should be located at points of high stiffness, i.e. at large stiffeners, on both the floating deck and foundation (this is similar to resilient mounting of individual equipment items).

It is noted that while the primary purpose of using a floating deck is to reduce noise from the FSB path, SSB noise resulting from excitation of the deck will also be reduced since the real deck is shielded from airborne noise.

- *Description of Estimated Costs*: Resilient mounts typically cost on the order of $20-$2000, depending on the mount and quantity. Additional costs apply regarding the design and construction of the floating deck. Mounts should be replaced every 10 years (or according to manufacturer's recommendations).

- *Other Non-acoustic Impacts*: See MV1.

- *Vendors*: See MV1 for mounts. Floating deck structure typically can be made by the shipyard.

(MV3a) Damping Tiles

- *Notes on Treatment*: Damping treatments work by absorbing vibration energy through shear motion. Damping is effective when applied to thin plates; application to stiffeners or beam-only structures has a reduced effect. Damping tiles are applied to the middle 70% of plating between stiffeners. Tiles are glued in place. Application usually takes place during vessel construction, prior to equipment installation. Damping tiles are usually applied in thicknesses from 0.5 – 1.5 times the local plating thickness. Effectiveness will depend on several factors such as the ratio of tile to plating thickness, damping properties of the tile, tile stiffness, location of application, plating material, and use of a constraining layer (see below). Overall reductions of 5-10+ dB can be seen for properly designed installations. Note that some increase in radiation efficiency can result from the use of damping tiles, resulting in lower than expected effectiveness based on reduction in vibration level alone.

  Damping treatments are generally of two varieties: constrained and unconstrained. Unconstrained damping consists only of the damping material that is directly attached to plate structures. Constrained damping uses an additional steel or aluminum plate on top of the damping material. The constraining plate thickness is typically 0.5x the thickness of the structural base material.

Constrained (a.k.a. "constrained layer") damping can be more effective at reducing vibration levels than unconstrained damping, at the cost of additional weight. Not all damping materials are appropriate for constrained damping installations.

Appropriate locations for application will vary depending on the specific situation. For single hull vessels (including drillships), application of tiles to the side shell and areas around significant machinery items will likely be most effective (some locations are restricted, see 'Other Impacts' below). For semisubmersibles, damping may be appropriate in legs above water line, and possibly near major machinery items.

It is noted that damping treatments are effective at reducing noise from FSB paths, although some reduction for AB and SSB paths are possible as well.

- *Description of Estimated Costs*: Material costs are on the order of $5 - $15 per square foot, depending on tile thickness. Additional costs will be incurred for installation and engineering, as well as additional material costs for constrained layer damping.

- *Environmental Impacts*: When burned, tiles produce toxic fumes. For vessels, increased weight may reduce fuel efficiency.

- *Other Non-acoustic Impacts*: Increased weight – Tiles are roughly 96 lb/ft^3 (1540 kg/m^3), or 2.7 lb/ft^2 (13 kg/m^2) for a 0.35" (8.9 mm) thick tile. Depending on coverage, the weight increase can be significant. Some restrictions exist regarding possible locations of damping tiles. Damping tiles can not be located in living spaces, fuel oil tanks, or potable water tanks. Tiles will disintegrate over time if in direct contact with petroleum products.

- *References and Additional Information*: Beranek (1988), Nashif (1995), Jones (2001).

- *Vendors*: Primary vendor of damping tiles for US Navy vessels is EAR Specialty Composites. Other vendors include American Acoustical Products, BRD Noise and Vibration Control, DB Engineering, MSC, PPG, Sorbothane, Soundcoat, Technicon.

(MV3b) Spray-on Damping

- *Notes on Treatment*: See notes for MV3a. Spray-on treatments are provided by several vendors, each with varying effectivensses. Spray-on treatments have several advantages over damping tiles, in that they are generally lighter (for the same application), easier to apply, and often can be applied even after machinery has been installed or as a retro-fit. Many spray-on materials are also non-toxic. The effectiveness of spray-on treatments will vary, but it can be expected that such treatments will have similar or lower performance to damping tiles. Spray-on thicknesses vary, as do application methods, but it is common for spray-on damping treatments to be applied in more than one stage (i.e. a fraction of final thickness per application).

Similar to damping tiles, spray-on damping treatments have limitations as to where they can be applied. Typically, they can not be immersed in water, and exposure to oil should be limited. It is possible to add a polyurethane, latex or epoxy layer to protect against oils and greases. Application typically requires a cleaning of the application surface with a solvent such as diluted vinegar and water.

It is possible to use constrained layer damping (See MV3a) with spray on treatments, however this is far less common.

- *Description of Estimated Costs*: Material costs are estimated at $10-30 per square foot. Actual costs will depend on coverage area, applied thickness, and quantity pricing. Additional costs will be incurred for application.

- *Environmental Impacts*: Surface cleaning preparation typically involves use of a solvent.

- *Other Non-acoustic Impacts*: Increased weight – Spray-on damping treatments can add significant weight, although increases are less than what would be found for damping tiles (MV3a). Some restrictions exist for possible damping locations.

- *References and Additional Information*: See MV3a.

- *Vendors*: Mascoat (http://www.mascoat.com), Quiet Solution (http://www.quietsolution.com).

(MV4) Ballast-Crete

- *Notes on Treatment*: Ballast-Crete is a thixotropic ballast material (is capable of being pumped) that is used in lieu of conventional liquid ballast. The material provides greatly enhanced damping of structures in contact with the material. When used in appropriate locations, such as in wing tanks or other areas between machinery and the ocean, damping effects have the potential to significantly reduce underwater noise.

  It is noted that underwater noise reductions have not been directly measured. However measured reductions in vibration level are indicative of reduced underwater noise potential. Further study would be needed to better quantify reductions.

  Ballast-Crete is available in densities from 200-450 pcf. Higher density material generally provides better damping.

- *Description of Estimated Costs*: Cost varies depending on density and quantity. The following pricing was provided by the vendor:

  - 100 tons of 200 pcf : $150,000
  - 1000 tons of 200 pcf : $250,000
  - 5000 tons of 200 pcf : $900,000
  - 1500 tons of 300 pcf : $1.6m
  - At higher densities the price increases significantly because of the cost of raw materials.

- *Environmental Impacts*: When necessary, material should be properly disposed. Material is inorganic and contains no toxic compounds. pH is approximately 12.

- *Other Non-acoustic Impacts*: May not be appropriate for all situations. Analysis is recommended to determine suitability. Material is heavy. Can not be dumped into ocean.

- *References and Additional Information*: Fischer (Workshop).

- *Vendors*: BC Technical, Inc. (Contact: Robert Chester, bchester.bct@verizon.net)

(MV5) Air Masking System

- *Notes on Treatment*: A layer of small bubbles is produced that extends along some portion of the vessel's hull, creating an acoustical impedance mismatch that blocks sound transmission into the open ocean. The concept of bubble curtains is provided in Item PD1a in Pile Driving Treatments. A belt is applied to the hull of the ship with small holes for bubble emission, as seen in Figure PT12. Additional construction information is given in (DND, 1979). The bubble curtain must begin forward of any major machinery or noise producing items so that the bubbles can extend towards the rear of the vessel. Coverage of the entire vessel may not be necessary in all cases. Large vessels may need only partial coverage closer to machinery sources because influence far from sources is minimal. Small vessels may require nearly full hull coverage to avoid flanking paths. Multiple air curtain 'stages' or sets of injection points may be necessary for some vessels in order to ensure uniform coverage.

  The effectiveness is seen to be good at higher frequencies, with noise reductions of 10 dB or more being possible. Increases in level at frequencies below 80 Hz are also possible. It is noted that the effectiveness of this treatment is derived from measurements of airborne noise on-board vessels over or near the propeller; in these situations air emission systems have been implemented over the propeller to reduce on-board noise. These results are also applicable to transmission from the vessel to the water, assuming proper design of the masker system. Underwater measurements of vessels using masker systems were not identified.

Bubbles are sometimes produced from a compressor and/or blower located on-board. Gray (1979) suggests an alternate, natural emitter of air bubbles using a special structure that protrudes from the hull. NCE has had similar experience with natural emission systems; these systems require vessels speeds of 20 knots or more. Mechanical delivery systems are needed for slower speeds.

Bubbles should not enter the inflow of the propeller; cavitation and added noise, as well as decreases in propulsion efficiency, will result. The vessel must be underway to allow bubbles to sweep along the vessel's hull. Sonar transducers must be mounted forward of the bubble sheet or else sonar operation during bubble usage will be compromised.

Matveev (2004) discusses an alternative arrangement where the vessel is designed with a large cavity in the vessel's bottom into which a large volume of air can be pumped ("Air Cavity Ships" or ACS). The air layer can reduce noise transmitted into the water from the hull, and has the added beneficial effect of reducing drag by 15-30%. Power consumption of the air injection system is estimated at 3% of total propulsion power. The low frequency performance of this system may be improved relative to conventional masker systems due to the (potential) increased thickness of the air layer. It is noted that some portion of the hull remains in contact with ACS systems; location and extent of the air cavity must be carefully selected to balance drag reductions with acoustical performance.

- *Description of Estimated Costs*: Material costs for conventional masker systems include air compressors, blowers, piping, injectors, etc. Engineering and installation costs are estimated to be in the range of $20,000-$50,000 or more depending on the system and configuration. Cleaning and maintenance costs can also be significant (see below). ACS systems need to be integrated in the vessel design, and therefore may not add significantly to the total cost of the vessel.

- *Other Non-acoustic Impacts*: Holes for bubbles have been shown to be subject to fouling. Regular cleaning is absolutely necessary in order to keep system functioning. ACS may be less susceptible to fouling.

- *References and Additional Information*: Gray (1979), DND (1979), DTNSRDC (1981), Matveev (2004), Matveev (2005).

(MV6) Decoupling Materials

- *Notes on Treatment*: Decoupling materials are treatments that are applied to the exterior surface of the vessel's hull and decrease its radiation efficiency (i.e. less sound is radiated for the same vibration level). Effectiveness is similar to air bubble masker systems since the fundamental mechanisms at work are similar. The decoupling material is typically a foam rubber, polyethylene foam, or other similar compliant material. The material as a whole creates an acoustic impedance mismatch, blocking sound transmission.

These treatments do not necessarily increase damping effects; in such cases changes to vibration level will be minimal. The coating should be compliant, thus acting to isolate the water from the vibrating surface. However, compression of the material under static water loads should be considered when selecting a material. Thicker coatings will generally produce larger reductions in sound.

Brown (1974) suggests using a layer of closed cell neoprene foam cemented directly to the hull. A layer of solid neoprene can be applied over the foam layer for protection. Hamm (1996) presents data from tests performed in a laboratory where a 3/8" (9.5 mm) sheet of decoupling material was applied to a 3/8" thick steel plate. The data show effectiveness between 10 and 30 dB at frequencies above 800 Hz, with 0-10 dB reductions from roughly 100-800 Hz. Some increase in sound is seen below this frequency.

- *Description of Estimated Costs*: Material costs are on the order of $25-$100 per square foot. Additional costs will be incurred for installation and engineering.

- *Environmental Impacts*: Treatment must remain fixed to vessel's hull.

- *Other Non-acoustic Impacts*: Treatments will add some weight to the vessel. Maintenance has been cited as an issue. Tiles may be prone to falling off, and therefore regular maintenance and inspection is required.

- *References and Additional Information*: Brown (1974), Sandman (1995), Hamm (1996), Fischer (Workshop)

- *Vendors*: Many are possible, e.g. DOW, Rubatex.

(MV7) Low Noise Machinery

- *Notes on Treatment*: Often, machinery that has lower vibration levels can be selected from certain manufacturers. The reasons for lower noise machinery vary, but often have to do with manufacturing quality, tolerances, and overall design. Differences in machinery source levels will vary, but differences of 5 dB are common (for machinery of the same type). Differences of 10 dB or more are also found, particularly when a machinery item is poorly made. Larger differences can be seen for machinery of different types. For example, reciprocating pumps are generally much louder and more vibroactive than screw pumps. Selecting machinery with low noise levels does not have any additional impacts on space or weight.

- *Description of Estimated Costs*: Higher quality machinery will often cost more, but not always. Costs of 1-5x can be expected.
- *References and Additional Information*: Fischer (1983), Fischer (2001), Fischer (Workshop)

SECTION MA:
MACHINERY AIRBORNE AND SECONDARY STRUCTUREBORNE TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS*		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
MA1	Exhaust Silencers	Reduces noise from exhaust stacks.	5-20 dB 10-30 dB	30 – 125 Hz >125 Hz	$100-$20,000+	N
MA2	Fiberglass / Mineral Wool / “HTL” Cladding	When applied to boundaries of machinery space, noise from AB and SSB paths are reduced	-3 – 3+ dB 0 – 25+ dB 15 – 35 dB	<125 Hz 125 – 1000 Hz >1000 Hz	$0.75 - $4 per square foot	N
MA3	Machinery Enclosures	An enclosure is used to surround the machinery item to block and absorb airborne noise	-3 – 5 dB 5 – 30 dB 25 – 35 dB	<125 Hz 125 – 500 Hz >500 Hz	$20-$50k+ Depending on size	N
MA4	Barriers	Blocks airborne transmission into the water	5-20+ dB, depending on implementation	All	Low – can be constructed on-site	N
MA5	Air Masking System	Air bubble curtain is used to shield vessel hull from rest of ocean. See MV5	>10 dB 0-10 dB Increase	>500 Hz 20-80 Hz	Est. $20,000 - $50,000+	N
MA6	Low Noise Equipment	Equipment that creates low vibration levels is selected	Varies, 5 dB is common	All	Est 1-5x noisier equipment	N

*Effectiveness is for treated item / path only. If other sources are significant or dominate the underwater noise signature, total noise reduction will be less than what is quoted here.

(MA1) Exhaust Silencers

- *Notes on Treatment*: Silencers are used to reduce airborne noise which can be transferred to the water. Silencers are located in-line with diesel and turbine exhaust ducting. Silencers are passive devices that absorb sound, and can reduce airborne levels by 10-30 dB above 125 Hz (smaller reductions are also seen below this frequency. Spark arresting silencers are generally required for marine and offshore applications. A picture of a typical silencer is provided below.

FIGURE MA1: Typical Exhaust Silencer (www.silex.com)

- *Description of Estimated Costs*: Costs will vary from $100-$20,000+ depending on size and manufacturer.

- *Environmental Impacts*: Increased pressure loss may have an impact on fuel efficiency.

- *Other Non-acoustic Impacts*: Exhaust system will have increased pressure drop. Pressure drop will depend on the specific silencer but can be expected to be on order of 2-16 inches of water. Acoustic effectiveness is often directly related to pressure drop. Silencers generally have larger diameters than the attached ducting, so sufficient clearances will need to be provided.

- *Vendors*: Kinetics Noise Control (www.kineticsnoise.com), Industrial Acoustics (www.industrialacoustics.com), Silex (www.silex.com), Stoddard Silencers (www.stoddardsilencersinc.com), Universal Silencers (www.universal-silencer.com), Vibro-Acoustics (www.vibro-acoustics.com).

(MA2) Cladding Materials

- *Notes on Treatment*: Cladding materials are used to 'block' and absorb sound to prevent airborne transmission into the water and secondary structureborne excitation of nearby structures. Cladding materials include fiberglass and mineral wool treatments in densities ranging from 3 pcf to 7 pcf or more. High Transmission Loss or "HTL" treatments consist of a 'mass layer', typically a sheet of 1.5 mm barium sulfate, which is located between two layers of fiberglass insulation.

The approximate effectiveness of these treatments vs. frequency is given in the table above. In general, effectiveness increases with increasing frequency. Thicker treatments will have more effectiveness than thinner treatments, as will denser treatments (for this reason, mineral wool is generally more effective than fiberglass). HTL treatments have a slight acoustical performance increase compared to mineral wool with the same overall thickness. This improvement is a few dB in the 1000-4000 Hz range. However, this additional effectiveness comes at a price of increased mass and installation complexity.

Cladding treatments can have very good overall effectiveness in reducing AB and SSB paths. SSB noise reduction may be compromised since cladding treatments can not be used on the deck. Damping or other treatments such as floating decks may be necessary in order to minimize this flanking path.

- *Description of Estimated Costs*: Fiberglass and mineral wool material costs range from $0.75-$4.00 per square foot. HTL materials costs are higher. Installation and engineering costs will also be incurred.

- *Environmental Impacts*: Insulation materials can be hazardous if inhaled. Direct contact with skin should be avoided.

- *Other Non-acoustic Impacts*: Some increase in mass will result, depending on the extent of treatment application and thickness. Use of cladding treatments will reduce effective size of space. This is typically a minimal issue in machinery spaces.

- *Vendors*: Johns Manville (www.jm.com), Owens Corning (www.owenscorning.com), Reilly Benton International (www.reilly-benton.com), Rockwool (www.rockwool-marine.com).

(MA3) Machinery Enclosures

- *Notes on Treatment*: Enclosures are structures that are made to surround a specific machinery item for the purpose of blocking and absorbing airborne noise. Enclosures must completely surround the machinery and can not contain holes or gaps where sound can 'leak' though. Penetrations in the enclosure must be properly gasketed, sealed, or otherwise treated. The interior of the enclosure should be lined with fiberglass or mineral wool insulation to provide additional acoustical absorption. The enclosure should be isolated from the machinery to prevent structureborne transmission and reduction of enclosure effectiveness. Openings for intake or exhaust of cooling air should be fitted with silencers with transmission losses equal to or greater than that of the enclosure partitions. Enclosure partitions should be as far as possible from the machinery itself (preferred minimum distance on the order of 1 meter).

  While enclosures are an effective method at reducing airborne noise (and subsequently SSB noise) at frequencies above 125 Hz, they are often cumbersome to implement in marine applications. As noted above, all penetrations must be properly sealed so the enclosure's effectiveness is not compromised. This can sometimes be problematic for issues relating to air flow and cooling.

Similarly, the enclosure must be designed to allow for regular maintenance access, and panels must be replaced after maintenance is complete (this often does not occur in practice).

When compared to cladding materials (fiberglass and mineral wool – see MA2) enclosures have slightly increased effectiveness and reduced weight impacts. However, the location of enclosures is usually more difficult to accommodate than cladding treatments, and installation and maintenance are more difficult.

- *Description of Estimated Costs*: Costs will vary depending n the size of the enclosure. For a typical diesel generator, costs can be in the $20-$50k+ range.

- *Other Non-acoustic Impacts*: A significant engineering effort is required to properly design and install a machinery enclosure. Enclosures require a significant amount of space, which may be problematic for small machinery rooms on vessels or other locations.

- *References and Additional Information*: Fischer (1983).

- *Vendors*: Industrial Acoustics Company (www.industrialacoustics.com), Acoustical Surfaces Inc. (www.acousticalsurfaces.com)

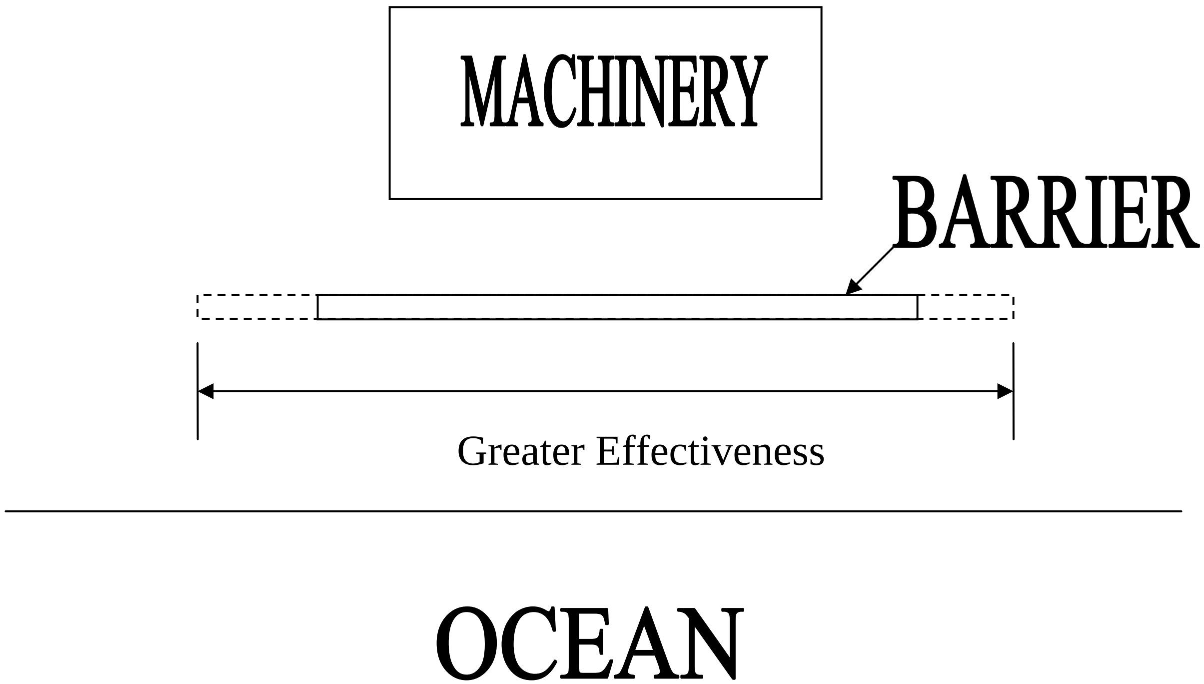
(MA4) Barriers

- *Notes on Treatment*: A barrier is essentially a wall or other solid surface that blocks noise traveling in a direct path from a source to receiver. In this case, the receiver would be the water, and would thus only be applicable for sources located outdoors with a line-of-sight path to the ocean. Furthermore, the angle of incidence (i.e. angle between the direction of the propagating sound wave and the ocean surface) must be less than ~13 degrees. See Figure 9 in Section 3.2.10 for additional details. This arrangement may occur for offshore platforms where machinery is located close to the platform edge or if there is an open grating below the machinery with a line-of-sight to the ocean.

  The effectiveness of a barrier is largely dependent on its physical extents and proximity to the machinery. Larger barriers will provide greater effectiveness. See Figure MA4 below. Also, See Fischer (1983) for additional design information.

  Barriers are generally made out of materials similar to those used for other parts of the structure – stiffened steel plating is common for marine and offshore applications. The only acoustical constraint on the material is its transmission loss should not be less than the effectiveness of the barrier (effectiveness here would be computed as if the barrier were infinitely stiff and massive). If penetrations in the barrier are needed for piping, etc., such penetrations will need to be properly sealed.

FIGURE MA4: Barrier Effectiveness



This is a sketch showing the implementation of a barrier. The barrier is placed between the acoustic source (machinery) and the receiver (ocean, within a 13 degree incident angle 'cone'). The majority of the sound is blocked by the barrier, although some sound does still travel to the receiver due to refraction around the barrier edges. Larger barriers will result in greater effectiveness.

- *Description of Estimated Costs*: Costs will vary, but no special materials are needed to construct a barrier. Cost is estimated to be low for most installations. Some engineering costs apply.
- *Other Non-acoustic Impacts*: Barrier will take up space. However, in some cases this impact can be minimized. Some additional weight will be seen.
- *References and Additional Information*: Fischer (1983).

(MA5) Air Masker

- *Notes on Treatment*: See MV5. Note that extent of coverage for AB paths is less than what would be required for FSB and SSB paths.

(MA6) Low Noise Equipment

- *Notes on Treatment*: See MV6.

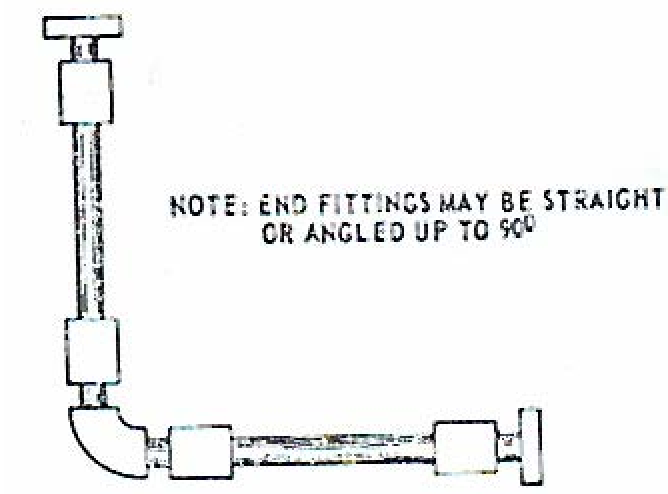
SECTION FB:
FLUIDBORNE TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
FB1	Resilient Piping Connections	Resilient in-line piping connections	0-20 dB 30-50 dB (dogleg)	<200 Hz >200 Hz	$100 - $2000 Depending on Size and qty	N
FB2a	Pulsation Dampers – In-Line	An air bladder connected in-line with pipe to absorb acoustic energy	~10+ dB	>180 Hz	Approx $600+ per unit	N
FB2b	Pulsation Dampers – Parallel	An air bladder connected in-line with pipe to absorb acoustic energy	20-30+ dB	Single 'tuned' Frequency	$800 - $2500	N

(FB1) Resilient Piping Connections

- *Notes on Treatment*: Flexible piping connections can reduce underwater noise in sea connected systems by reducing the in-pipe sound levels. The flexible piping creates an impedance mismatch which can be effective at reducing both fluidborne levels and flanking vibrations that may be present in the pipe. Flexible piping is generally soft in the lateral directions but stiff in the longitudinal direction. Because of this, flexible connections should be assembled in a dogleg configuration. Flexible piping can be made from simple (or wire mesh reinforced) rubber hose, or 'single arch' or 'double arch' pieces. Examples are provided in Figures FB1(1) and FB1(2).

FIGURE FB1(1): Flexible Hose in Dogleg Configuration (NAVSHIPS, 1974)



For a 'dogleg' configuration, two flexible pipe sections are oriented 90 degrees to each other. This allows for maximum flexibility in all directions, and reduces fluidborne and vibration transmission. Flexible pipe can be straight tube (as seen above), double arch couplings (as seen in Figure FB1(2)), or other similar items.

FIGURE FB1(2): Example of Double Arch Piece (www.flexhose.com)

Typical flexible connections will significantly reduce high frequency underwater radiated noise. Insertion losses vary depending on the specific arrangement, materials used, static pressure, and whether acoustic or mechanical excitation is dominant. Dogleg configurations can have noise reductions up to double those seen for single element installations, and increases in noise can be seen at low frequencies for straight element arrangements (White, 1973). Straight flexible tubing in a dogleg configuration generally performs best at higher pressures, although this takes the most space. Arch piece connectors perform well overall, however special attention should be paid to the control rods – these can provide flanking paths for vibration and should be sufficiently isolated from the rest of the connection.

The following design guidance is provided when using flexible connections, based on NAVSHIPS (1974):

For a flexible hose dogleg system, the free length (that length of hose unconstrained by clamps, fittings, nipples, spigggots, etc.) should be at least equal to 18.0 cm plus 4 hose diameters for each leg. While dogleg configurations are preferred, double arch hose are generally acceptable. Single right angle hose configurations are permissible provided they are at least equal in length to the dog leg configuration and the hose manufacturer's minimum bend ratio is not exceeded.

Flex hose installations should have a heavy rigid pipe hanger support at the equipment end of the configuration attached to the equipment sub-base. A similar support should be attached to the opposite side of the hose and firmly attached to a structural frame. If needed, a resilient pipe support can be used at the 90 degree bend of the dogleg.

- *Description of Estimated Costs*: Flexible connectors range from $100 to $2000 depending on size, type, and quantity.

- *Other Non-acoustic Impacts*: Flexible hose dogleg configurations can require a large amount of space depending on pipe sizes.

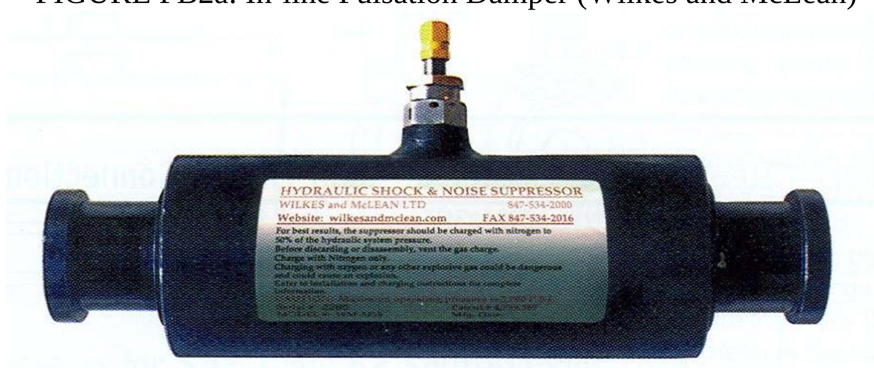
- *References and Additional Information*: Purshouse (1986), White (1973), NAVSHIPS (1974).

- *Vendors*: Unaflex (www.unaflex.com), Flexicraft Industries (www.flexicraft.com), Straub (www.straub-couplings.com), Flexhose Co. Inc. (www.flexhose.com)

(FB2a) Pulsation Dampers – In-Line

- *Notes on Treatment*: In-line pulsation dampers are acoustical absorbers that are located in-line with a fluid filled pipe. In-line dampers typically use an air filled bladder that reacts to pulsations in the fluid. A picture of an in-line damper is provided below:

FIGURE FB2a: In-line Pulsation Damper (Wilkes and McLean)



Data from the manufacturer indicates that pulsation amplitudes, such as those created by pump blade rate, can be reduced by as much as 20 dB, although other sources cite lower effectiveness (Jamieson, 1996). In-line dampers have been shown to reduce pulsations at frequencies above 180 Hz, and it is assumed that higher frequencies will show better attenuation.

- *Description of Estimated Costs*: Material costs are approximately $600 per unit.

- *Vendors*: Wilkes and McLean, Ltd. (www.wilkesandmclean.com), CoorsTek (www.coorstek.com)

(FB2b) Pulsation Dampers – Parallel

- *Notes on Treatment*: Parallel pulsation dampers are similar to in-line dampers in function, except they are attached to the pipe as a 'branch'. Parallel dampers are tuned to have a resonant frequency, and thus work only at that one frequency. This frequency can be selected to be the rotation rate or blade rate of a pump, for example. Their effectiveness at this frequency can be large. Parallel dampers also have the potential to operate effectively at lower frequencies than in-line dampers. A picture of a parallel damper is provided below. Note that there is a minimal pressure drop associated with this type of pulsation damper.

FIGURE FB2b: Parallel Pulsation Damper (Flexicraft Industries)

- *Description of Estimated Costs*: Material costs are $800 - $2500 per unit.

- *Other Non-acoustic Impacts*: Some engineering analysis will be required to identify the proper location, size, and design of the damper.

- *Vendors*: Flexicraft Industries (www.flexicraft.com)

SECTION HC:
HOVERCRAFT TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
HC1	Optimization of Airflow	Attempt to make airflow into and out of propulsion and lift fans uniform	Est 0-10+ dB	O/A	Engineering costs dominant. Some additional manufacturing costs may result	N
HC2	Modified Blade Profiles	Fan blade profile can be contoured for better performance in a given airflow field	Est 0-10+ dB	O/A	Engineering costs dominant. Some additional manufacturing costs may result	N

(HC1) Optimization of Airflow

- *Notes on Treatment*: Airflow into and out of the propulsion and lift fans should be as uniform as possible. This is often not 100% possible given the existence of other structures in the path of the airflow, particularly for propulsion fan intakes. Through detailed airflow analysis, such obstructions can be moved or contoured to allow for better airflow characteristics resulting in improved fan performance and lower noise.

- *Description of Estimated Costs*: No additional material costs are likely. Engineering costs will be incurred due to additional analysis, however this can be performed for an entire class of vessels. Some manufacturing costs may increase due to specialized design requirements.

- *Environmental Impacts*: Increases in fan performance may result thereby lowering environmental impacts.

- *Vendors (Designers)*: NAB & Associates (nab@nabassociates.net)

(HC2) Modified Blade Profiles

- *Notes on Treatment*: Similar to ship propellers, fan blade profiles can be contoured to better match air inflow and outflow characteristics. Alternative blade designs can reduce airborne noise which would in turn reduce underwater noise. Improved fan performance may also result, depending on the specific design.

- *Description of Estimated Costs*: No additional material costs are likely, although some modified manufacturing techniques may be necessary for some extreme blade geometries. Engineering costs will be incurred due to additional analysis, however this can be performed for an entire class of vessels. Some manufacturing costs may increase due to specialized design requirements.

- *Environmental Impacts*: Increases in fan performance may result thereby reducing environmental impacts. Reductions in efficiency are also possible.

- *Vendors (Designers)*: NAB & Associates (nab@nabassociates.net)

SECTION AC:
AIRCRAFT TREATMENTS

REF #	TREATMENT NAME	BRIEF DESCRIPTION	EFFECTIVENESS		COST PER UNIT	AVAILABILITY (N) Now (F) Future (FF) Far Future
			Reduction	Frequency Range		
AC1	Hush Kit	A silencer used for quieting jet engine noise	7-10 dB	O/A**	$2,000,000 per engine	N
AC2	New Aircraft	Replacement of older aircraft for new, quiet aircraft	Possible reductions of 10+ dB	O/A	Cost of new airplane	N
AC3	Modified Blade Design	Design of reduced noise propellers and rotors for prop planes and helicopters	Possible reductions of 3 to 10+ dB	O/A	Minimal Material Cost	N

** See details below

(AC1) Hush Kit

- *Notes on Treatment*: A ‘hush kit’ is a silencer that is outfitted to the exhaust, and sometimes the intake, of a jet engine. Many models simply bolt onto the engine housing, although some installations may require the removal of thrust reversers (typically replacements are integrated into the system). An example of a hush kit installation is provided in Figure AC1 below.

  Hush Kits require relatively low maintenance. Inspections and minor ‘tune ups’ such as greasing of bearings can be performed under normal turbine maintenance schedules.

  FIGURE AC1: Hush Kit Example (www.qtaerospace.com)

  The hush kit is seen on the rear (left) portion of the engine. It is seen that hush kits can be designed to work with thrust reversers.

  Noise reductions cited in table above were taken from Stage III Technologies (http://www.stageiii.com/). Note that while these levels are listed as being “overall” reductions, they may in fact be dB(A) level reductions. This is based on the fact that these kits are used primarily to reduce noise disturbances in humans. Actual reductions vs. frequency were not found.

- *Description of Estimated Costs*: Material costs are roughly $2M per kit.

- *Environmental Impacts*: Some loss in efficiency of engine will result. 0 - 1.5% increase in fuel requirement is reported.

- *Other Non-acoustic Impacts*: Minor addition to weight of aircraft. Associated reduction in cargo capacity.

- *Vendors*: Quiet Technology Aerospace (http://www.qtaerospace.com/), Stage III Technologies (http://www.stageiii.com/)

(AC2) New Aircraft

- *Notes on Treatment*: Newer aircraft are being designed to radiate lower airborne noise levels. This is due to implementations of new noise regulations from international government authorities over the past 20 years. These regulations call-out specific noise criteria based various factors such as type of craft, size, number of engines, etc. Details on US regulations are published in FAA (2001). Under these rules, many aircraft had to meet the strictest ("Stage 3") requirements by the year 2000.

  Furthermore, there has been a significant effort to analyze and reduce noise from jet engines by NASA. Huff (2005) provides an overview of the modeling and measurements along with techniques for making jet engines inherently quieter. Reductions of 10 dB are stared as goals.

  It is noted that these reductions are focused on reducing levels found to be annoying to humans, and may be only partially applicable to frequencies of concern for marine life. (Human hearing is most sensitive between 500 and 8000 Hz).

- *Description of Estimated Costs*: Costs primarily include those associated with buying a new airplane.

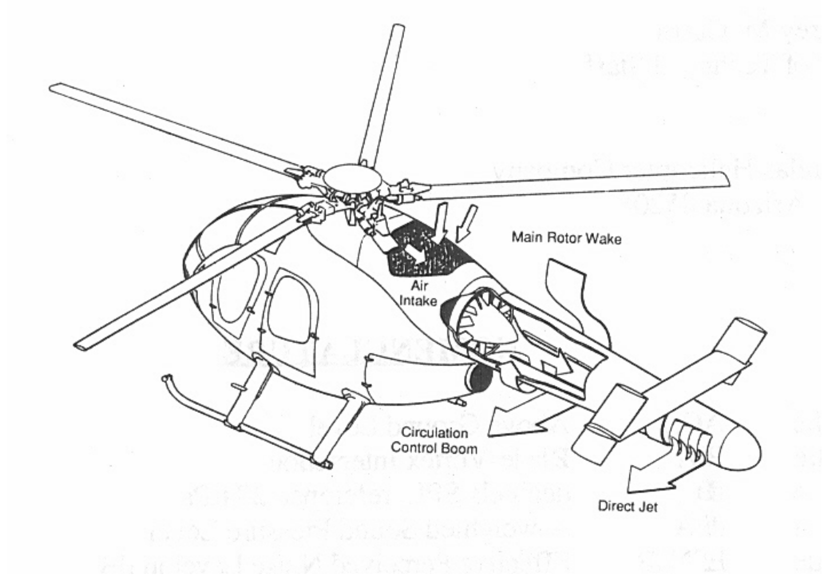
- *Environmental Impacts*: Huff (2005) indicates further work is needed to apply noise control without reducing jet velocity. There is also a potential for enhanced performance when replacing old aircraft, reducing environmental impacts.

- *References and Additional Information*: Kearsey (1992), FAA (2001), Huff (2005), http://www.nasa.gov/centers/glenn/about/fs03grc.html

(AC3) Modified Blade Design

- *Notes on Treatment*: Similar to ship propellers, propeller blade and rotor profiles can be contoured to better match air inflow and outflow characteristics. Alternative blade designs can reduce airborne noise which would in turn reduce underwater noise. Specifically for helicopters, incorporating features in the main rotor such as different tip geometries, blade twist, advanced airfoils, increased chord lengths, and lowering the tip Mach number, have been suggested (Nagaraja, 1992). Such modifications can result in 0-5 dB improvements. NOTAR (NO TAil Rotor) and 'Fan-In-Fin' designs which use a ducted fan to replace the tail rotor have also been suggested by JanakiRam (1992); 0-7 dB improvements have been shown for the NOTAR design. A diagram showing the NoTAR concept is provided below. Modifications to rotor blade spacing have been shown to reduce noise levels at blade rate and harmonics, although this noise reduction comes at a price of reduced fuel efficiency.

FIGURE AC3: Diagram of NoTAR Concept (JanakiRam, 1992)



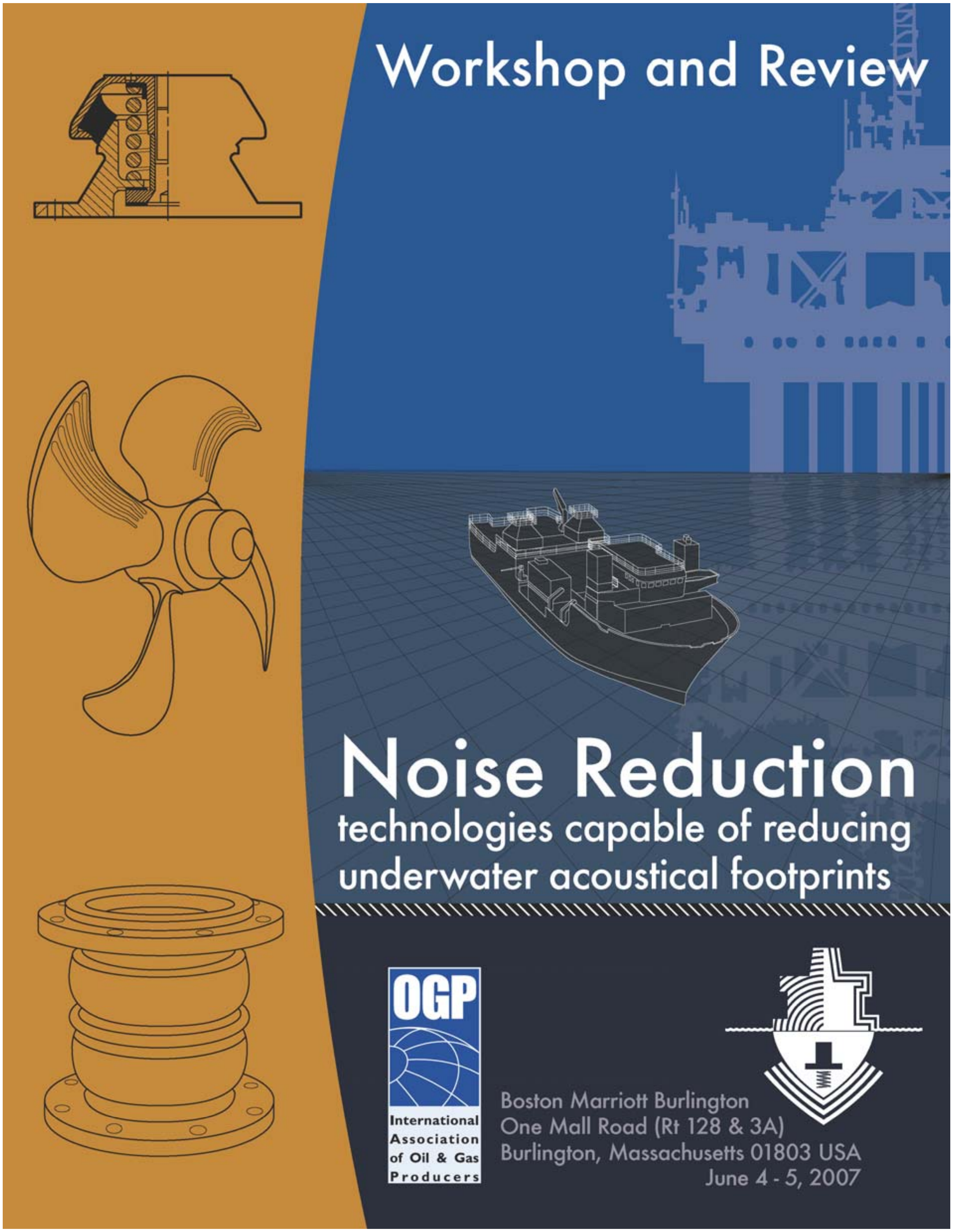
In the NoTAR helicopter design, the tail rotor is completely removed and is replaced with an internal fan which blows air down the tail. This air can then be directed in various ways to provide stability and control of the craft.

- *Description of Estimated Costs*: No additional material costs are likely for propeller and rotor modifications, although some modified manufacturing techniques may be necessary for some extreme blade geometries. Engineering costs will be incurred due to additional analysis; however this can be performed once for an entire class of aircraft. Costs are not known for NoTAR implementation.

- *Environmental Impacts*: Some decrease in fuel efficiency is possible for some designs. Other designs may increase efficiency and performance.

- *Additional Information*: Nagaraja (1992), JanakiRam (1992)

APPENDIX B – Workshop Announcement


Workshop and Review
Noise Reduction
technologies capable of reducing
underwater acoustical footprints
OGP
International
Association
of Oil & Gas
Producers
Boston Marriott Burlington
One Mall Road (Rt 128 & 3A)
Burlington, Massachusetts 01803 USA
June 4 - 5, 2007

Workshop and Review of Noise Reduction Technologies Capable of Reducing Underwater Acoustical Footprints

Boston Marriott Burlington — June 4-5, 2007

Focusing on technologies capable of reducing underwater sound from oil and gas industry activities

Organized by Noise Control Engineering, Inc.
Funded by the International Association of Oil and Gas Producers

OGP
International Association of Oil & Gas Producers

Noise Control Engineering welcomes you to participate in a discussion of the various sound reduction techniques that are currently being used to reduce underwater noise, and potential technologies for the future. The workshop will review various options for reducing noise from all facets of oil and gas industry activities, including noise generated by vessels, seismic exploration, pile driving, platforms, and more. Discussions of these treatments will be aimed at identifying the most effective methods of noise reduction that are feasible with a minimum of non-acoustical drawbacks.

Boston Marriott Burlington
One Mall Road (Rt 128 & 3A)
Burlington, Massachusetts 01803 USA
http://marriott.com/property/propertypage/BOSBU

The Marriott is located 22 miles northwest of Boston's Logan Airport.
Special room rates of $159.00 per night have been reserved for attendees of this workshop.
When booking a room at the Marriott, be sure to use code "NSLNSLA" to receive the reduced rate.
The reduced rate is guaranteed only until May 16th so please make your reservation soon.
You can book online at **www.burlingtonmarriott.com**

For questions and to reserve your seat at this workshop, please e-mail Jesse Spence, jesse@noise-control.com

SCHEDULE

Day 1

08:00 AM	Continental Breakfast
09:00 AM	Introductory Remarks and Overview *Bill Streever (BP Exploration (Alaska) Inc.),* *Jesse Spence (Noise Control Engineering)*
09:30 AM	Seismic Exploration *Presenters include Jeremy Nedwell (Subacoustech),* *Rune Tenghamn (Petroleum Geo-Services),* *Bjorn Askeland (University of Bergen, Norway), and* *Tom McGee (University of Mississippi Center for Marine Resources and Environmental Technology)*
10:30 AM	Break (Coffee and refreshments)
10:45 AM	Continuation of Seismic Exploration
12:30 PM	Lunch Buffet
01:30 PM	Pile Driving *Presenters include* *Klaus Lucke (Forschungs- und Technologiezentrum Westkueste),* *William Ellison (Marine Acoustics, Inc.),* *John Micketts (Gunderboom),* *Michael Carter (Giken)*
03:00 PM	Break (Coffee and refreshments)
03:30 PM	Continuation of Pile Driving
04:15 PM	Explosives
05:00 PM	Reception (Light fare with open bar)
06:00 PM	Close of Day 1

Day 2

08:00 AM	Continental Breakfast
09:00 AM	Vessels (Tankers, Icebreakers, OSVs, PSVs, Work Boats, Crew Boats) *Presenters include* *Brandon Southall (NOAA),* *Neal Brown (NAB Associates), and* *Ray Fischer (Noise Control Engineering)*
10:30 AM	Break (Coffee and refreshments)
11:00 AM	Continuation of Vessels
11:30 AM	Dredges and Post Jetting / Trenching
12:30 PM	Lunch Buffet
01:30 PM	Production and Drilling Platforms, including fixed platforms, semisubmersibles, drillships, FSPOs, deep water floating platforms, caissons, and gravel islands.
03:00 PM	Break (Coffee and refreshments)
03:30 PM	Continuation of Production and Drilling Platforms
04:30 PM	Aircraft and Hovercraft
04:45 PM	Closing Remarks *Bill Streever (BP Exploration (Alaska) Inc.)*
05:00 PM	Close of Day 2

Schedule and presenters subject to change.

APPENDIX C – Descriptions of Various Metrics

The following is a brief description of the various metrics that are mentioned in this report.

Energy Flux Density – This is essentially the same as Sound Exposure Level (SEL), although it is sometimes presented in non-decibel format. The equation for calculation would then be

$$EFD = \int_{T_1}^{T_2} p^2(t)\, dt$$

Impulse (See Saint-Arnaud, 2004) – This metric is calculated using the following formula:

$$I = \int_{T_1}^{T_2} p(t)\, dt$$

The integral is commonly taken over the initial positive pressure peak only. It is noted that underpressures (i.e. pressures less than 0) would reduce this value, while overpressures would increase it. This is in contrast to Energy Flux Density or SEL where the pressure is squared, and so any perturbation would cause an increase in level.

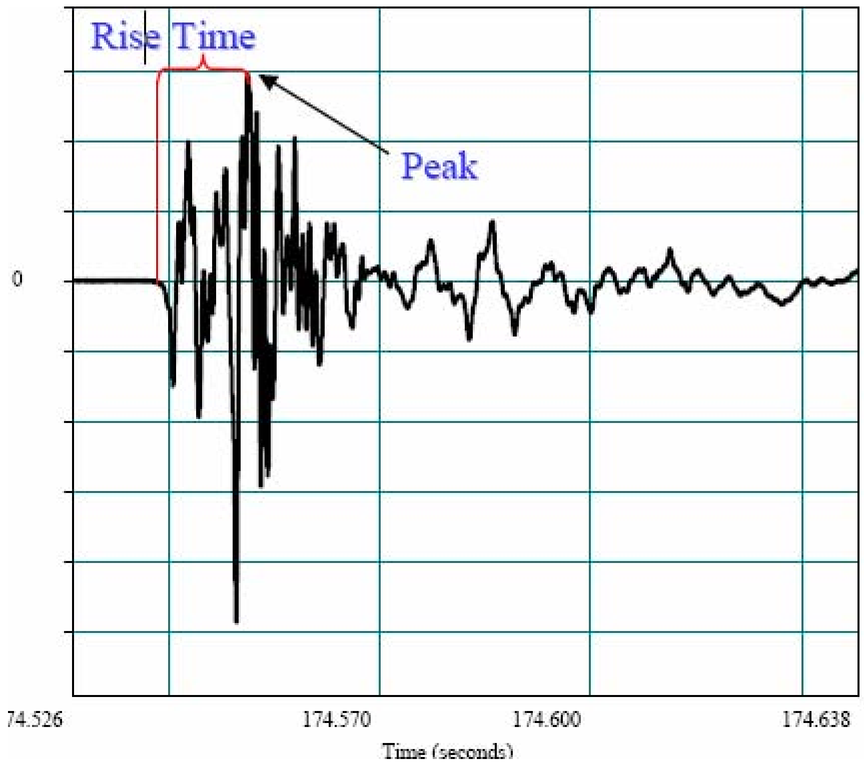
Overall RMS Level – The root mean squared pressure level of a signal. This level accounts for all frequency components that may be present. RMS levels are converted to decibels using the formula $20*\log(|p_{RMS}|/p_{ref})$ where p_{ref} is the reference pressure, 1 μPa for water. P_{RMS} can be calculated using the formula

$$p_{RMS} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} p^2(t) dt}$$

Peak Level – The absolute maximum or minimum level seen for a given sound event. Peak levels are converted to decibels using the formula $20*\log(|p_{peak}|/p_{ref})$ where p_{ref} is the reference pressure, 1 μPa for water.

Pulse Length – The time it takes for an impulse to accumulate 90% of its total energy.

Rise Time – The time it takes an impulsive signal to go from background levels to absolute peak level. An example is given below (Laughlin, 2005a).



Sound Exposure Level (SEL) – The summation of acoustic pressure squared produced by a single event. It is calculated using the formula

$$SEL = 10 * \log\left(\int_{T_1}^{T_2}\left(\frac{p(t)}{p_{ref}}\right)^2 dt\right)$$

This metric is used as an indication of total energy. This is also sometimes referred to as the Sound Energy Accumulation. In practice, it is common to select the beginning and end times T_1 and T_2 to encompass the middle 90% of the acoustic energy, thereby removing the first and last 5%.

Sound Pressure Level (SPL) – Calculated as SPL = 20 log ($|p|/p_{ref}$), where p_{ref} is the reference pressure, 1 μPa for water. This can be used to calculate overall RMS levels and levels at specific frequencies or in defined frequency bands.