ENVIRONMENTAL ASSESSMENT OF MARINE VIBROSEIS

Prepared by

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and

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Prepared for

Joint Industry Programme, E&P Sound and Marine Life
International Association of Oil & Gas Producers
209-215 Blackfriars Road, London SE1 8NL, U.K.

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Because several personnel at LGL and MAI made major contributions to this EA, it is suggested that the document by cited as "LGL and MAI (2011)" rather than by author. The main preparers were as follows; the sequences of names are alphabetical and are not intended to indicate relative contributions:

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EXECUTIVE SUMMARY

The primary objective of this report is to evaluate the potential environmental impacts from seismic surveys using next-generation marine vibroseis (MarVib) as the energy source, examine how those impacts would compare with airgun impacts, and evaluate how a MarVib system could be operated so as to minimise impact. The report also evaluates mitigation measures that might be applied during MarVib operations, including standard mitigation measures used during airgun-based seismic surveys as well as other measures specific to MarVib. The report concludes with comments concerning key data gaps that limit our ability to predict MarVib effects, and recommended studies to fill some of the key data gaps.

Three key questions addressed in the report are as follows:

(1) Is marine vibroseis—especially new-generation marine vibroseis—an environmentally viable and beneficial method of obtaining seismic data?

> The report concludes that MarVib methods implemented in the manner now anticipated, e.g., with strong suppression of unwanted higher-frequency components, should in most respects have less environmental impact than surveys using airgun arrays. (The report assumes that components above ~100 Hz, or if possible, above some frequency lower than 100 Hz, would be suppressed more strongly than is possible with airguns.) It is acknowledged that, given the scarcity of direct information on biological effects of MarVib (and similar) sounds, this conclusion depends strongly on indirect evidence and some assumptions. One important assumption is that disturbance is more directly related to received sound pressure than to received acoustic energy; that assumption needs verification or refinement. Also, another type of biological effect, masking, could be more of a problem with MarVib than with airguns. Masking and other effects of MarVib can be reduced through application of mitigation methods, in some cases closely related to those often applied during airgun-based surveys, and in other cases unique to MarVib.

(2) Under what circumstances does marine vibroseis offer reduced environmental impact compared to airguns?

> Use of MarVib sources rather than airguns is expected to reduce most types of environmental impacts in all habitats and environments. Behavioral effects, auditory effects, and physiological effects of most types are expected to be less with MarVib, regardless of water depth or other environmental conditions. Behavioral effects are expected to be reduced given the lower pressure levels at any given distance from MarVib. (However, as noted in (1) above, if behavioral responses are more directly linked to received acoustic energy than to received sound pressure, the advantage of MarVib would be reduced.) Permanent auditory effects and physiological effects are in most cases expected to be limited to short distances even for airguns, and corresponding distances for MarVib are expected to be less than for airguns. Masking of natural environmental sounds is one type of effect that could at times be more problematic with MarVib if, as expected, the MarVib system operates at a higher duty cycle than applies with airgun arrays.

(3) Are the available data sufficient to determine whether marine vibroseis is environmentally beneficial?

> There have been almost no direct studies of the biological effects of MarVib operations. As a result, there are some key data gaps concerning possible biological effects, and several tentative conclusions about MarVib effects are supported by very meagre data. It is nonetheless possible to conclude that MarVib will (in most respects) have reduced environmental impacts as compared

to airguns. It is likely (and reasonable) that MarVib projects will, when first implemented, be subject to close scrutiny and to precautionary requirements. As scientific and monitoring data on the environmental effects of MarVib projects accumulate and predictions about relative effects of MarVib vs. airguns are confirmed or amended, some of these concerns and precautionary measures probably will be relaxed.

For purposes of this assessment, marine seismic surveys with future-generation MarVib systems are assumed to differ from airgun-based surveys in several major ways. • The sound signal transmitted at or near each grid location ("shotpoint") is expected to be longer in duration (seconds vs. 10s of milliseconds for an airgun pulse) but will have a substantially lower source pressure level. • Total acoustic energy transmitted at each location may be similar to that with airguns, or perhaps somewhat reduced if the necessary geophysical data can be recovered from a lower-energy signal through enhanced signal processing possible with MarVib. (Most of the conclusions in this assessment make the precautionary assumption that total transmitted acoustic energy per location will be similar to that with airguns. If a lower source energy level can be used, this would further reduce the environmental effects.) • The rise time of the MarVib signals will be slower than that of airgun pulses, and MarVib signals will be "non-pulse" whereas airgun signals are impulsive, at least near the source. • As noted above, a major design goal for MarVib, as compared to airguns, is a faster decrease (roll-off) in source spectrum levels at frequencies above ~100 Hz or, if possible, above a somewhat lower inflection point. This would substantially reduce the biological effects, particularly on species that are most sensitive to higher frequency sounds and not very sensitive to low-frequency (LF) sounds, e.g., the odontocete cetaceans.

Baleen whales, sea turtles, many fish, and some invertebrates are believed to be most sensitive to relatively LF sounds, including sounds at or near the predominant frequencies emitted by both airguns and anticipated MarVib systems. On the other hand, toothed whales, dolphins and porpoises (odontocetes) plus some fish and invertebrates are known or expected to be relatively insensitive to LF sounds. Pinniped sensitivity to LF sounds is intermediate. Sirenians (manatees, dugongs) may also have moderate sensitivity to LF sound. Underwater hearing sensitivity in polar bears and sea otters has not been measured. Overall, it is expected that baleen whales, sea turtles, many fish species, and some invertebrate species are inherently more likely to be affected by either airgun or MarVib sounds than are other groups — especially odontocetes.

Better suppression of harmonics or other unneeded higher-frequency components of the MarVib signals (e.g., above 100 Hz) is expected to have relatively little benefit for baleen whales and other animals with sensitive LF hearing. However, the lower levels of the MarVib signals at low frequencies would be a benefit. In contrast, better suppression of components above ~100 Hz would reduce effects on animals that are relatively insensitive to low frequencies but somewhat sensitive to frequencies in the 100–1000 Hz band. This reduction in effect would be over and above any reduction achieved with the lower received pressure levels with a MarVib source.

Categories of Impact

The major categories of biological effect considered in this assessment are masking, behavioral disturbance, hearing impairment (temporary and permanent), and non-auditory injury or physiological effects. The report assesses relative effects of future-generation MarVib systems as compared with airgun arrays for each of those categories of biological effect, considering marine mammals, sea turtles, marine fishes, and (more generally) invertebrates. For cetaceans, anticipated behavioral and auditory effects of MarVib vs. airgun surveys are examined in a more quantitative way by applying an acoustic modelling approach to deep and shallow water scenarios in the northern Gulf of Mexico. It should be kept in mind that there are no specific data concerning the effects of MarVib sounds on any marine animals aside from some very limited data for fish and shrimp. The following paragraphs summarize *predicted* MarVib effects and associated comparisons with airgun effects.

Masking: This is the one type of biological effect that is likely to be more of a problem with MarVib than with airguns. Because of the anticipated longer duration of MarVib signals as compared with airgun pulses, a MarVib source is expected to transmit for a higher proportion of the time than does an airgun array, i.e., the MarVib source will have a higher duty cycle. Therefore, MarVib sounds may mask faint natural sounds for more of the time than would occur with airguns. Slight masking effects could potentially (at times) extend out to a distance a few tens of kilometres away from the source. Stronger sound signals would be masked only for receivers closer to the vibrators. Even the weaker sounds would be masked only during the intermittent times when MarVib signals are being received, and then only when the spectra of the two sounds overlap. Because of the instantaneous narrowband nature of FM sweeps, masking effects of MarVib should be limited if the MarVib signals are FM in nature.

Little is known about the effects of intermittent masking by LF anthropogenic sounds on marine animals in the wild. However, this is a subject of increasing concern, at least for baleen whales and perhaps for other animals whose hearing is most sensitive to low frequencies (e.g., sea turtles and many fish). Provided that future MarVib systems do not emit much sound above the low frequencies useful to geophysicists, masking should not be a significant issue for odontocetes and perhaps not for other marine mammal groups aside from baleen whales. In a relative sense, however, for marine animals near the source, marine vibrators could potentially cause more masking of LF sounds than would occur with airguns.

Disturbance: Behavioral disturbance effects from MarVib operations are expected to be no greater than those during airgun operations, and quite possibly less. However, there are no specific data on the responses of any of the main types of marine animals to MarVib signals, and for most types of animals data on responses to airgun signals are also sparse. If animal responses are most directly related to received pressure level, then reactions to MarVib surveys (with lower source pressure levels) should be considerably reduced relative to reactions to airguns. If animal responses are more directly related to received energy level, then responses to MarVib and airgun sources might extend to similar distances. Arguments for either possibility can be advanced, but the lack of data on behavioral responses of marine animals to MarVib sound is a data gap that needs to be filled before this will be resolved.

A further unknown in assessing potential disturbance is whether received sound levels should be frequency-weighted, e.g., using the M-weighting curves of Southall et al. (2007, *Aquatic Mammals* 33:411-522) or possibly using the audiograms of the species concerned. If so, expected disturbance effects would be reduced for pinnipeds and especially odontocetes relative to baleen whales, and stronger suppression of components above ~100 Hz during MarVib surveys would reduce the expected effects from MarVibs vs. airguns. The assessment assumes that some form of frequency weighting is scientifically appropriate in predicting behavioral effects in marine mammals and probably also in other taxa. However, to date, the U.S. regulatory authority has required flat-weighting when predicting numbers of marine mammals that would be exposed to sufficient airgun sound to elicit behavioral disturbance.

Auditory Impairment: At least in marine mammals, temporary and permanent auditory impairment (TTS and PTS) are assumed to be mainly a function of cumulative received energy level. If so, the higher pressure levels of airgun sounds would be largely offset by the longer signal duration of MarVib sounds. However, MarVib sounds would be non-pulse sounds whereas airgun sounds are impulsive, at least in the region close to the source. For a given received energy level, impulsive sounds are expected to have larger auditory and (in theory) tissue-damage effects. Thus, even after allowing for the longer durations and higher duty cycles of MarVib sounds, auditory effects are expected to be reduced with MarVib, and to extend a lesser distance, as compared with a corresponding airgun source. For cetaceans, Southall et al. (2007) concluded that, to cause the same auditory effect, the cumulative received energy level of a non-pulse sound (e.g., MarVib) must be about 12–17 dB higher as compared with impulse (e.g., airgun) sound. Therefore, during a MarVib survey, a cetacean would have to be several times closer to the sound source in order to incur the same auditory effect (TTS or PTS) as might occur during an airgun survey emitting the same signal energy per "shotpoint".

The specific distances out to which TTS or PTS might extend would depend on the circumstances. However, for the MarVib scenarios in the northern Gulf of Mexico examined in this assessment, PTS would be limited to very close distances, if it occurs at all, and the number of individual animals that might incur PTS would be very small or zero. In an actual seismic survey in which • some animals avoid the approaching seismic source and • real-time mitigation measures are implemented, even fewer cases of hearing impairment would be expected.

It has not been demonstrated that, in realistic field conditions, a MarVib source (or airguns) would cause TTS or PTS in any type of marine animal. For cetaceans and perhaps pinnipeds, it can be inferred from available data that TTS and (less likely) PTS might occur in the occasional animal that is very close to a MarVib source during at least one transmission. For sea turtles, fish, and invertebrates, it is unknown whether these auditory effects could occur in animals close to a MarVib source. If hearing impairment is possible, it would be limited to close distances. In the case of benthic-dwelling animals, this would mean that these theoretical auditory effects would only be possible in shallow water or if the source were towed close to the bottom.

Other Injury or Physiological Effects: Of the various types of non-auditory injury or physiological problems that have been suggested, resonance effects are perhaps of most relevance. Given the longer duration of MarVib signals than of airgun pulses, there would be some concern about resonance of body cavities or structures in large animals if constant-frequency (CF) signals were used. However, MarVib signals are expected to be either FM sweeps or frequency-coded signals (pseudo-random noise, PRN). CF signals are unlikely to be suitable for use in a MarVib system, and in any case should be avoided if possible given the concern about resonance.

Impacts by Type of Marine Animal

Although specific data concerning MarVib effects are extremely limited, some of the likely effects on various categories of animals can be predicted based on other related data and general biological and acoustic principles.

Low-Frequency Cetaceans (Baleen Whales): These are assumed to be the marine mammals that are most reliant on and affected by LF sounds, although specific audiometric data are lacking for all baleen whale species. Effects of LF MarVib signals on baleen whales are expected to be stronger than for other marine mammals that are less well attuned to LF sound. MarVib operations are more likely to cause masking, behavioral disturbance, and (perhaps) auditory impairment in baleen whales than in other marine mammals. Masking and disturbance effects, in particular, may extend to greater distances in baleen whales than in other groups. The longer signal duration and higher duty cycle of MarVib than of airgun sounds could cause increased masking with MarVib. Suppression of the higher frequency components of MarVib sound (e.g., above 100 Hz) will provide little advantage to these whales, as most of the MarVib effect on them is expected to be attributable to the predominant LF components.

Mid- and High-Frequency Cetaceans: These animals constitute the odontocetes or toothed whales, including dolphins, porpoises, beaked whales, sperm whales, etc. The predominant low-frequency (<100 Hz) components of MarVib signals are expected to have relatively little masking, disturbance, or auditory effect on these animals, as their lower limit of functional hearing is considered to be ~150–200 Hz. It is the weaker components of the seismic signals above 100–150 Hz that will account for most of the (presumably limited) MarVib effect. Further suppression of unneeded components of MarVib sound above ~100 Hz would substantially reduce the limited MarVib effects on these cetaceans.

Pinnipeds in Water: Seals and sea lions are intermediate between baleen whales and odontocetes in terms of the frequencies to which they are most sensitive. There are no data on the effects of MarVib sounds on pinnipeds. Pinnipeds (as compared with cetaceans) seem to be relatively non-responsive to airgun sound. However, at least one species of seal, the harbour seal, appears to incur TTS with less exposure to underwater sound than is necessary to cause TTS in odontocetes such as the bottlenose dolphin and beluga.

Other Marine Mammals: There are either no or few available data concerning effects of airguns, and no data concerning effects of MarVibs, on any of the "other marine mammals": sirenians (manatees and dugongs), polar bears, and sea otters. Sirenians and sea otters tend to occur in relatively shallow, coastal waters, and polar bears are usually on ice or land or swimming at the surface of the water. Thus, none of these animals is expected to be much affected by either airgun or MarVib signals.

Sea Turtles: Auditory data show that sea turtles are sensitive to low frequency sounds, so they could potentially be affected by MarVib as well as airgun signals. However, the ways in which sea turtles use underwater sound are unknown. MarVib sounds might cause some masking, in which case the longer signal duration and higher duty cycle of MarVib than of airgun sounds could cause increased masking with MarVib. If so, better suppression of MarVib components above 100 Hz could be beneficial to sea turtles. There is some limited information indicating that exposure of sea turtles to high levels of airgun sound can elicit avoidance effects and auditory impairment (TTS). If so, use of MarVib instead of airguns might (hypothetically) somewhat reduce these effects.

Fishes: Direct empirical information on how exposure to MarVib sound affects fishes is extremely limited. Many fish species are most sensitive to relatively low frequencies, potentially including frequencies emitted by next-generation MarVib systems. In many species, it is the particle velocity component rather than pressure to which fishes are most sensitive. The potential for masking is higher with MarVib signals compared to airgun pulses because of the longer signal duration and higher duty cycle for MarVib signals. However, the likelihood that seismic surveys would cause disturbance, hearing impairment, or non-auditory injury / physiological effects may be lower with MarVib than for airgun sound because of MarVib's lower signal amplitude and/or non-pulse characteristics, and even for airguns, hearing, injurious and physiological effects appear to be limited to short distances.

Invertebrates: The only specific data are from a single study involving exposure of shrimp to high-level sound from an early design of MarVib; no disturbance effects or non-auditory injury were detected. No empirical information is available concerning either masking or sensory impairment in marine invertebrates exposed to MarVib sound. As with fishes, MarVib sound might theoretically cause more masking than would airgun sound, but MarVib sound is less likely to cause disturbance, impairment of sound detection abilities, or non-auditory injury/physiological effects. Overall, MarVib sound would likely have less effect on marine invertebrates as compared with airgun sound. However, the possibility of auditory damage in cephalopods exposed to MarVib sound deserves study given a recent report of auditory injury in captive cephalopods exposed to prolonged low-frequency FM sound.

Impact of Altered Signal Properties

The sound signals expected to be emitted by next-generation MarVib systems will differ in important ways from airgun signals. Differences include being non-pulse rather than impulsive in character, having reduced peak pressure but increased signal duration and probably increased duty cycle, and having well-controlled spectral properties.

Non-Pulse Signals: This is expected to be an important mitigating factor inherent to MarVib sources. As a result, marine mammals should tolerate exposure to higher cumulative energy levels from MarVib than from airguns before auditory impairment would be expected. The same is probably true for at least some other types of marine animals. Southall et al. estimated that the cumulative energy exposure would need to be ~17 dB higher with non-pulse than with impulse sound before PTS (auditory injury) would occur.

Reduced Peak Pressure: The reduced peak pressure with MarVib would mean that (other factors being equal) any biological effect that is primarily a function of received pressure level should be lower than during an airgun-based survey. If disturbance effects in some marine animals are mainly a function of received sound level and not much affected by signal duration, disturbance would be limited to smaller distances around a MarVib source than around an airgun array, and fewer individual animals might be disturbed during a MarVib survey. However, it is not known to what extent disturbance would also be affected by the increased duration and duty cycle of MarVib signals.

Increased Signal Duration and Duty Cycle: The likely increases in signal duration and duty cycle with MarVib would probably offset, to varying degrees, the benefits of the lower pressure level:

- Disturbance: The lower pressure level with MarVib might provide some benefit (less disturbance) even if received energy level is the same as with airguns.
- Auditory impairment: The likely increase in signal duration and duty cycle of MarVib signals are expected to largely offset the advantage of the lower pressure level. Even so, MarVib would still have notably reduced potential to cause auditory impairment because of the higher cumulative sound exposure level necessary to cause auditory effects when sound is non-pulse, at least in marine mammals.
- Masking: The increased signal duration and duty cycle of MarVib signals are expected to cause a stronger masking effect in low-frequency specialists (e.g., baleen whales) than would occur with the more intermittent airgun signals.

Well-controlled Spectral Properties: The more precise control over signal characteristics anticipated with future-generation MarVib than with airguns should allow some reduction in environmental impacts. With MarVib, less energy is expected to be emitted at frequencies above those relevant to geophysicists, e.g., at >100 Hz, or preferably some lower inflection point. This will reduce effects on animals that have relatively low sensitivity to the predominant low-frequency components and higher sensitivity to components above 100 Hz that can be better suppressed with MarVib than with airguns.

Mitigation Measures for MarVib vs. Airguns

Available information indicates that animals can tolerate the receipt of more acoustic energy from a non-pulse MarVib source than from impulsive airgun sound without incurring auditory impairment. Therefore, mitigation radii are expected to be smaller during MarVib surveys than during airgun surveys. Also, some biological effects such as disturbance may be more a function of received pressure than of cumulative received energy. If so, a MarVib source could have a further advantage over airguns. However, available data are not sufficient to show whether disturbance radii are more directly related to received energy level or to received sound pressure level — an important data gap.

Acoustic modelling applied to northern Gulf of Mexico scenarios indicated that, even without specific mitigation measures, the number of marine mammals that might incur auditory damage from a MarVib survey is low — fewer than one individual of any of the three representative cetacean species considered (sperm and Bryde's whales; bottlenose dolphin). That was true with either the 180 dB re 1 μPa_{RMS} do-not-exceed pressure criterion recognized by the U.S. National Marine Fisheries Service (NMFS) as well as with the more justifiable 215 dB re 1 $\mu Pa^2 \cdot sec$ SEL criterion recommended by Southall et al. (2007). With either criterion, predicted numbers were higher during an airgun survey than with MarVibs. The modelling results do not mean that specific mitigation of MarVib surveys would be unnecessary, but do imply that some MarVib effects may be sufficiently limited that there would be less need for specific mitigation than with airgun surveys.

One exception to this generalization is the matter of masking, which is expected to be more of a problem because of the higher duty cycle with MarVibs than with airguns. The main concern would be for baleen whales and perhaps sea turtles and various fish — animals for which the most important sounds are at low frequencies. MarVib operating and design procedures that would reduce masking, as discussed in Chapter 7, may be important.

General operating procedures that could be beneficial for mitigation during MarVib surveys are, for the most part, the same as during an airgun survey. Specific MarVib design considerations that might be helpful in reducing masking and other biological effects include • reduce duty cycle (unless this would necessitate increasing source pressure level substantially); • suppress MarVib sound components outside the bandwidth relevant for geophysical purposes, e.g., those above 100 Hz, or a lower cutoff frequency if practical; • (tentatively) use FM signals rather than PRN signals unless use of the latter allows a considerably lower source level (see below); and • assess (probably via acoustic modelling) whether some practical adjustment of operating depth might reduce exposure of key species to MarVib sound at the site and season of the planned survey.

MarVib Signal Types to Reduce Impact

Earlier MarVib designs used FM signals, i.e., upsweeps, but geophysicists are interested in the possibility of using PRN signals or other similar coded signals in future MarVib designs if these signals provide environmental or signal-processing advantages. However, in animals sensitive to low-frequency sound (e.g., baleen whales), masking and disturbance effects of LF PRN signals may be greater than corresponding effects from FM signals. If MarVib designers have the option to use either PRN or FM signals, then before they choose which signal type to use, it would be desirable to obtain empirical data on the relative biological effects associated with each of these signal types.

Any signal type that might elicit resonance of air-filled body cavities or other structures should be avoided. The most problematic type of signal might be a constant-frequency (CF) signal sustained at a resonant frequency. We are not aware of any interest in using CF signals in a MarVib system, but if there were some requirement to consider the use of CF signals, directed research on their resonance effects would be desirable.

Recommended Studies

Because there are almost no empirical data concerning the environmental effects of MarVib systems, a large number of data gaps and recommended studies could be identified. However, it is probably more useful to identify a smaller number of recommendations that are of particular importance. That is the approach taken in the “Recommended Studies” section.

Before a major research program concerning the biological effects of MarVib systems is launched, it would be beneficial to have more specific information about the design options available to MarVib developers. If the range of design options can be narrowed before beginning direct research on biological effects, biological studies can be better focussed on the most relevant questions and design options.

Weighting Functions: There is controversy about the degree to which sound at frequencies outside the range of best hearing should be downweighted; this probably depends on the type of biological effect under consideration (masking, disturbance, or auditory impairment). This uncertainty is important as the type of weighting curve (if any) that is applied can make a large difference in predicted impact and mitigation radii. Research on this topic is warranted for the various major groups of marine mammals, sea turtles, and fish.

Masking: Masking is one type of biological effect that might be greater with MarVib than with airguns. Therefore, there is a particular need to have specific data on the effects of exposure to realistic MarVib sounds on emission of animal calls, detection of those calls by conspecifics, and detection of other sounds relevant to those animals. No specific data of these types currently exist for MarVib sounds, and there are few relevant data for other similar types of sounds. Some progress could be made through quantitative modelling approaches. However, well-controlled empirical studies are also needed (notwithstanding the logistical difficulties) for representative species that are particularly dependent on low-frequency sound, i.e., baleen whales, many fish, and possibly sea turtles.

Disturbance: There are essentially no existing data concerning the disturbance effects of MarVib sounds on any type of marine animal, and the limited data from studies of behavioral responses to other types of intermittent non-pulse sounds are of questionable applicability to MarVib (Chapter 6). Therefore, there is a strong need for systematic, well-controlled studies of behavioral reactions of key marine taxa to MarVib sounds, with emphasis on taxa most sensitive to LF sounds (baleen whales, sea turtles, and some fish).

One important question is whether, when other factors are held constant, behavioral responses are more directly related to received sound pressure levels or received sound energy levels. The results of this study would bear directly on whether existing pressure-based disturbance criteria for airgun-based surveys (e.g., the 160 dB re 1 μPa_{RMS} criterion as often applied in the U.S. for marine mammals) can be applied to MarVib projects, or whether a different (and probably more restrictive) criterion is appropriate for MarVib.

If multiple signal types (e.g., FM and PRN) remain as viable options for MarVib systems, then it would be valuable to compare the behavioral responses of representative LF-sensitive marine animals to those types of signals via controlled exposure experiments. Behavioral responses to FM signals may be less than those to PRN signals, but this needs to be tested. Similarly, if varying degrees of suppression of “higher”-frequency signal components remain as alternatives, or if varying signal durations or duty cycles remain as options, then it would be desirable to test the behavioral responses of representative LF-sensitive marine animals to MarVib sounds with those alternative signal properties. In planning this research, close attention should be given to developing an appropriate research design and optimum methodology. The ongoing JIP effort to conduct full-scale tests of the responses of tagged whales to sounds from airgun arrays will provide experience with many procedures needed for this type of research.

Auditory Impairment: Data on sound levels necessary to elicit temporary hearing impairment (TTS) are the key data used in assessing potential auditory impairment, at least in marine mammals. Although some data on sound exposures necessary to elicit TTS have been obtained from marine mammals and fish, these data do not apply directly to MarVib-type sounds. There is a need for TTS information from more species of marine animals sensitive to LF sounds, including data on the effects of intermittent LF sounds with received signal levels that gradually increase and then decrease in a manner representative of a passing MarVib source.

Other Injury or Physiological Effects: Resonance effects in marine mammals are not well documented or understood, and there is some concern that exposure to high-level LF sounds, especially if sustained over time, could cause resonance effects in marine biota and human divers. However, the likelihood of resonance with the types of signals expected to be used by MarVib systems is low. If MarVib designers consider the use of constant-frequency tonal signals (not currently expected), then the possibility of resonance should be addressed, perhaps initially via a modelling approach.

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Overall, this assessment found that new-generation MarVib systems show potential for allowing marine seismic surveys to occur with reduced impacts on marine life relative to the impacts of airgun-based seismic surveys. However, this conclusion is based largely on indirect evidence — there is almost no direct empirical information on the effects of MarVib operations on marine animals. In at least one respect (masking), effects of MarVib-based seismic surveys may at times exceed the effects of airguns. Also, the environmental advantages of MarVib would be reduced if disturbance effects of MarVib (when tested) prove to be more directly related to received energy than to sound pressure level.

Given that MarVib systems show promise as being able to reduce the overall effects of marine seismic surveys, it would be useful to undertake carefully-planned empirical studies to document the effects of MarVib operations on masking, disturbance, auditory impairment, and perhaps resonance in key types of marine animals known to be sensitive to low-frequency sound. Those animals include baleen whales, sea turtles, many fish, and perhaps some invertebrates. These data would also be valuable in optimizing MarVib design features for minimal environmental impact. These new data might demonstrate that MarVib-based seismic surveys could at times go ahead with reduced need for mitigation measures, or in circumstances where airgun-based surveys are not allowed or are more seriously restricted.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

%	percent
&	and
?	unknown
@	at
~	approximately
<	less than
<*>	time average
>	greater than
≤	less than or equal to
≥	greater than or equal to
=	equals
↑	increasing
↓	decreasing
§	section
°	degrees
2-D	two-dimensional
3-D	three-dimensional
4-D	four-dimensional
AG	airgun array
AIM	Acoustic Integration Model
AK	Alaska
ANSI	American National Standards Institute
bar-m	bar-metre; unit used for peak-to-peak source levels
B.C.	British Columbia
BOEMRE	(U.S.) Bureau of Ocean Energy Management, Regulation & Enforcement
c	plane wave velocity
c	sound speed in water in m/sec
CA or Calif.	California
CASS/GRAB	Comprehensive Acoustic Simulation System/Gaussian Ray Bundle
cf.	compare
CF	Constant Frequency
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
cm	centimetre
cm/s	centimetre per second
cm/sec	centimetre per second
CPA	closest point of approach
CR	Critically Endangered
CV/C.V.	coefficient of variation
C-weighting	frequency-selective weighting for aerial hearing in humans derived from the inverse of the idealized 100-phon equal loudness hearing function across frequencies
D	Data Deficient
d	depth in metres

dB	decibels
DBDB-V	Ocean Floor Depth Digital Bathymetric Database Variable Resolution
D_{DR}	transmit data record
df	bandwidth
DoN	Department of the Navy
DPS	distinct population segment
dt	time
dyne/cm^2	dyne per square centimetre; 1 µbar equals 1 dyne/cm^2
E	east/eastern
E	Endangered
e	source distance below the surface in m
E&P	Exploration and Production
e.g.	for example
EA	Environmental Assessment
EIS	Environmental Impact Statement
Eq.	Equation
ESA	U.S. Endangered Species Act
f	frequency in Hz
Fig.	Figure
FM	frequency modulated
GDEM-V	Generalized Digital Environmental Model Variable Resolution
GI gun	generator-injector gun
HESS	High Energy Seismic Survey
HF	high-frequency
hr	hour
Hz	hertz
I	acoustic intensity
i.e.	that is to say
IAOGC	International Association of Oil & Gas Producers
in^3	cubic inches
Isl.	Island
Isls.	Islands
IUCN	International Union for Conservation of Nature and Natural Resources
JIP	Joint Industry Programme
JNCC	Joint Nature Conservation Committee
k	acoustic wave number in m^{-1} ($2\pi f/c$)
kg	kilogram
kHz	kilohertz
km	kilometres
km/hr	kilometres per hour
km^2	square kilometres
kt	knot
LC	Least Concern
LF	low frequency
LFA	low frequency active
LGL	LGL Ltd., environmental research associates

m	metre
m/sec	metres per second
MAI	Marine Acoustics Inc.
MarVib	marine vibroseis
MF	mid-frequency
microbars	μbar; unit of pressure; 1 μbar equals 1 dyne/cm^2
microvars	particle velocity of 1 cm sec- x 1/*pc*
min	minutes
MMPA	(U.S.) Marine Mammal Protection Act
MMS	(U.S.) Minerals Management Service (now BOEMRE)
MPa	megapascal
msec	millisecond
M-weighting	generalized frequency weightings for various groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds
M_{hf}	M-weighting curve for high-frequency odontocetes
M_{lf}	M-weighting curve for low-frequency for baleen whales
M_{mf}	M-weighting curve for mid-frequency odontocetes
M_{pw}	M-weighting curve for pinnipeds in water
N	north/northern
n	number
n.mi.	nautical miles
NA	reliable data not available
NCDDC	NOAA National Coastal Data Development Center
NE	north-east
N_E	number of elements in the array
NL	Not Listed
NMFS	(U.S.) National Marine Fisheries Service
NOAA	(U.S.) National Oceanographic and Atmospheric Administration
NRC	(U.S.) National Research Council
NT	Near Threatened
OBCs	ocean bottom cables
OBS/Hs	ocean bottom seismometers/hydrophones
p	pressure
P_0	SL of the source element in dB//Pref @ 1m
Pa	Pascals
PGS	Petroleum Geo-Services
PP-P	peak to peak pressure in the pulse
PRN	pseudo-random noise
PSG	Project Support Group
psi	pounds per square inch
PTS	permanent threshold shift
Q	ratio of the bandwidth at the ½ power points divided by the centre frequency
R	distance from the array (on main beam) in metres
R_0	Reference range, 1 m
RL	received level

RMS	root mean square
s	array element spacing in metres
S	south/southern
SA	South Africa
SD	standard deviation
SE	south-east
SE	standard error
sec	second
SEL	sound exposure level
SL_E	SL of an individual element
SPL	sound pressure level
SSP	sound speed profile
Subsp.	Subspecies
SURTASS-LFA	Surveillance Towed Array Sensor System–Low Frequency Active
SVP	sound velocity profile
T	Threatened
t	time
T_{DUR}	time duration
T_p	length of the dominant pulse
T_{SWEEP}	time for the MarVib signal to sweep through desired frequencies
TTS	temporary threshold shift
T_{xmit}	interval between two signals
u	particle velocity
U.S. or U.S.A	United States of America
UNEP-WCMC	United Nations Environment Programme-World Conservation Monitoring Centre
V	Vulnerable
vs.	versus
V_v	vessel speed
W	west/western
watts/m^2	watts per square metre
YOY	young-of-the-year
Z_0	characteristic plane wave impedance
θ	angle from the vertical measured at the surface directly above the source
λ	c/f = acoustic wavelength in m
μPa	micropascals
μPa^2	micropascal squared
ξ	particle displacement
π	pi
ρ	density
ρc	characteristic impedance (density x sound velocity)

CHAPTER 1. PURPOSE AND NEED

1.1 THE JOINT INDUSTRY PROGRAMME

This Environmental Assessment (EA) has been prepared by LGL Limited, environmental research associates, and Marine Acoustics, Inc., in response to a request by the OGP E&P Sound and Marine Life Joint Industry Programme (JIP). The primary objective of the JIP is to

> "identify specific, operationally focused questions that relate to the effects of sound generated by the offshore E&P industry on marine life, and to pursue a research programme that will test scientific hypotheses and produce the data needed to address these questions (http://www.soundandmarinelife.org/Site/index.html)."

The JIP states (http://www.soundandmarinelife.org/Site/index.html) that the studies supported by its programme will

1. afford a more comprehensive understanding of the potential environmental risks from oil and gas operations;
2. inform and update policy decision makers, and regulatory development processes that affect [industry] operations globally;
3. determine the basis for mitigation measures that are protective of marine life, cost effective, and credible with outside stakeholders; and
4. feed into planning for efficient E&P project development that is environmentally protective.

The JIP identified five major "categories" of research topics of interest:

1. Sound source characterisation and propagation;
2. Physical and physiological effects and hearing;
3. Behavioral reactions and biologically significant effects;
4. Mitigation and monitoring; and
5. Research tools.

An overall objective for the environmental assessment (EA), as stated in JIP's Request for Proposals, was to "allow industry investors to better determine the usefulness of the next generation of marine vibroseis technology in areas with various marine mammals and other marine life". The JIP identified a series of more specific "required characteristics" of the EA. These are incorporated into the following subsection.

1.2 OBJECTIVES AND NEED

There are growing concerns about the impacts of anthropogenic activities on marine mammals, sea turtles, fish, and invertebrates. Activities that generate significant levels of underwater sound, such as airguns, sonar, and industrial drilling and construction activities have been the focus of intense interest and increasing numbers of studies and regulatory requirements.

A marine vibrator (MarVib) is an energy source for marine seismic surveys that propagates non-impulsive signals into the seafloor over an extended period of time (seconds), as opposed the near-instantaneous signals provided by impulsive sources. A MarVib produces lower peak pressures than airguns, and has therefore been suggested as being likely to have less environmental impact than traditional airguns. A typical airgun array will generate impulses with a nominal source level (in the downward direction) of ~255 dB re 1 μPa @ 1 m (zero to peak), whereas an array of MarVibs designed for a similar purpose would generate more prolonged signals whose source level would be lower, possibly on the order of 223 dB re 1 μPa @ 1 m RMS (Smith and Jenkerson 1998; Bird 2003).[1] The RMS ("average pressure") units used in characterizing the source level of a prolonged signal such as that from a MarVib are not appropriate in characterizing the source level of airgun array. However, at any given distance below the source, the peak pressure would be considerably higher for the airgun array. In shallow waters, the MarVib source would produce a significantly lower peak pressure on the bottom and might, therefore, have a reduced impact on benthic and epibenthic organisms (Bird 2003). Similarly, for an animal in the water column a specified distance below the source, the MarVib would produce a significantly lower peak pressure.

Besides providing a lower peak pressure, a MarVib system might also have other environmental benefits in certain applications (e.g., PGS 2005; Spence et al. 2007; Okeanos 2010): • It may emit a reduced proportion of its total energy at frequencies above about 100 Hz, as compared to airguns. • MarVib output signals may be better controlled, allowing extraction of the desired seismic information using lower energy levels. • MarVib systems may be operable at deeper depths in the water column, as compared to airguns, thus reducing potential near-surface impacts.

On the other hand, a MarVib is expected to have a considerably higher duty cycle (i.e., is emitting sound for a higher percentage of the time) than does an airgun array, and thus might have greater potential to cause acoustic masking. Also, the assumed higher duty cycle of the MarVib would mean that the MarVib would have less or perhaps no advantage over the airgun array if the comparison is based on total received acoustic energy (which depends on duration of exposure). How closely the MarVib energy level would need to match that for airgun signals is a MarVib design issue, related to the relative energy levels needed to extract the necessary seismic information from the received signals. Furthermore, the possibility of resonance effects upon exposure to the more prolonged MarVib signals needs to be considered. This would include resonance of large gaseous cavities, including the lungs. The potential effects on both marine mammals and on human divers must be considered. However, if future MarVib signals are swept frequencies, the possibility of resonance and also the degree of masking would be reduced or eliminated. These and other questions are addressed in this EA.

Tests and limited operational use have demonstrated that, at least in some situations, the MarVib is a satisfactory energy source from a geophysical perspective (Smith and Jenkerson 1998). Preliminary tests on fish and shrimp positioned adjacent to a MarVib indicated that this source did not cause deaths or conspicuous injury (Linton 1995). The MarVib had no more effect on fish and shrimp than did airguns, and possibly less. There have been no studies or observations concerning behavioral or other effects of the MarVib on marine mammals or sea turtles. There has, however, been considerable recent analysis, experimentation, and monitoring concerning effects of somewhat related low-frequency (<1 kHz) sonar signals on various marine biota.

The primary objective of the project is to undertake a generic environmental assessment that will allow industry to better determine the usefulness of the next generation of marine vibroseis technology in

[1] For a multiple-element source consisting of either airguns or MarVibs, nominal source levels are higher than the actual sound pressure levels that would be measureable anywhere in the water near the source array. The quoted values are the levels that would be emitted by a theoretical point source with the same effective far-field source level as the distributed array of airguns or MarVibs. See next section for further explanation.

different types of areas where there are different types of marine mammals and other marine life. The environmental assessment involves

(a) Modelling of the acoustic (and particle velocity) footprints from various marine vibroseis sources;

(b) An evaluation of the impact of the increased duty cycle of marine vibroseis units and an assessment of impacts compared to impulsive sources (such as airguns);

(c) An assessment of potential impacts to cetaceans sensitive to low-, mid-, and high-frequencies, and to pinnipeds, sirenians, sea otters, and polar bears;

(d) An assessment of potential impacts to sea turtles, fish, and invertebrates;

(e) An evaluation of potential physiological impacts, behavioural changes, masking, and other impacts to the various species groups;

(f) An evaluation of the overlap between the hearing of the various species groups and the frequency content of marine vibroseis sources;

(g) A comparison of potential impacts from airguns and "next generation" MarVibs;

(h) An assessment of marine conditions and habitats where "next generation" MarVibs may be more appropriate than airguns;

(i) An evaluation of possible mitigation measures that could be adopted to minimise or mitigate impacts from "next generation" MarVibs;

(j) Recommendations on which sweep types would be most effective in minimising environmental impact;

(k) A comparison of the nature and known or projected effectiveness of potential mitigation measures to be adopted for "next generation" marine vibroseis compared to those used during traditional seismic surveys using airguns; and

(l) Development of a global approach that will facilitate the selection of the most appropriate seismic survey methods in various geographic areas.

This EA is intended to provide a detailed review of the available data for marine vibroseis (particularly in its most modern form) and to compare those data with data available for currently-used airguns. The following questions are assessed:

1. Is marine vibroseis—especially new-generation marine vibroseis—an environmentally viable and beneficial method of obtaining seismic data?
2. Under what circumstances does marine vibroseis offer reduced environmental impact compared to airguns?
3. Are the available data sufficient to determine whether marine vibroseis is environmentally beneficial?
4. If the data are not sufficient, what information needs to be gathered? What field tests will need to be conducted?

This EA

(1) evaluates the technical data available on marine vibroseis (especially new-generation equipment) insofar as environmental effects are concerned;

(2) conducts modelling to assess the acoustic and particle velocity footprint of marine vibroseis sources;

(3) assesses the potential biological impact of marine vibroseis units on key biological receptors;
(4) assesses the relative impacts of potential MarVib systems with varying signal parameters, including various signal durations, roll-off rates for higher-frequency components, and signal types (sweep vs. coded signals);
(5) recommends mitigation measures to minimize potential impacts; and
(6) recommends future studies to assess impacts of MarVibs on fauna.

A desktop EA of this type is intended to allow industry to determine whether new technologies provide environmental benefits over existing technologies, under what circumstances new technologies could be used to the greatest benefit, and what information is needed in the future to allow for a continuing evaluation of technological advances.

1.3 ACOUSTIC MEASURES AND TERMINOLOGY

Basic acoustic terminology is presented in numerous published sources (e.g., Kinsler et al. 1982; ANSI 1986, 1994; Richardson et al. 1995; Harris 1998; NRC 2003; Southall et al. 2007; Spence et al. 2007:183*ff*). The main definitions used in this assessment are provided below, and are consistent with the terminology used in Southall et al. (2007):

- *Pulses*. Pulses are brief, broadband, atonal, transient sounds, e.g., explosions, gun shots, airgun pulses, and pile driving strikes. Pulses are characterized by a rapid rise from ambient pressure to maximal pressure and (at least near the source) by short duration.
- *Nonpulse (intermittent or continuous) sounds*. Nonpulse sounds can be tonal, broadband, or both. Nonpulse sounds can be of short duration but they lack the rapid rise times of true pulses. Nonpulse sounds include those from shipping, aircraft, drilling, and active sonar systems. MarVib sounds are considered nonpulse. Because of certain propagation effects, it is possible that a sound that is pulsed near the source may be perceived by a distant receiver as a nonpulse sound.
- *Peak sound pressure*. This is the maximum instantaneous sound pressure measureable in the water at a specified distance from the source airgun. The units of pressure are typically bars (English) or, in metric units, either Pascals (Pa) or micropascals (µPa). The metric values are commonly expressed in logarithmic form as decibels relative to 1 µPa (dB re 1 µPa).
- *Peak-to-peak sound pressure*. This is the algebraic difference between the peak positive and peak negative sound pressures. Units are the same as for peak pressure. When expressed in dB, peak-to-peak pressure is typically ~6 dB higher than peak pressure for a source near the sea surface.
- *Root mean square (RMS) sound pressure*. In simple terms, this is an average sound pressure (expressed in dB re 1 µPa) over some specified time interval. For airgun pulses, the RMS value depends strongly on that time interval. In the literature describing biological effects of airguns, the averaging time is commonly taken to be the approximate duration of one pulse, which in turn is commonly assumed to be the time interval within which 90% of the pulse energy arrives. With that averaging time, the RMS sound pressure level of an airgun pulse (in dB) measured over the pulse duration is typically ~10 dB less than the peak level, and ~16 dB less than the peak-to-peak level. However, these offsets from peak or peak-to-peak values vary with the varying pulse

duration, and depend on distance from source, bottom conditions, and other factors (e.g., Greene et al. 1997; McCauley et al. 1998; Blackwell et al. 2007; MacGillivray and Hannay 2007; Tolstoy et al. 2009). For pulsed sounds, RMS values measured over the pulse duration are very difficult to interpret because of the variable pulse duration.

- *Sound pressure levels (SPLs)*. SPLs are given as the dB measures of the pressure metrics defined above. The RMS SPL is dB re 1 μPa for underwater sound and dB re: 20 μPa for aerial sound.
- *Source level*: Source level is, at least theoretically, the level measured or estimated at a nominal distance of 1 m from the source. It is often expressed as dB re 1 μPa @ 1 m. For a distributed source, such as an array of airguns (or MarVibs), the nominal overall source level as used in predicting received levels at long distances exceeds the level measureable at any one point in the water near the sources. It is difficult to measure the actual sound pressure level close to a full source array, so assumptions are made that enable its output to be modelled. In characterizing the output of airgun arrays, it is recognized that at some distance much greater than the dimensions of the source array (i.e., in the 'far field'), the peak energy pulses from the various individual source elements arrive at the same time and add together constructively to form the 'far field' response of the source. This response is corrected or back-projected to one metre from the source array to produce the 'far field' signature of the source at one metre, which is a standard modelled measure of a source array output. Because a seismic source array is a 'distributed' rather than a 'point' source, the peak energy pulses from individual source elements do not align at locations close to the seismic source array (in the 'near field'). This is a result of the differences in travel time from the various elements to a given point. The actual sound pressure level at any point close to the source array is lower than that calculated using the 'far field' calculation, and generally is not much (if any) higher than the source level (at 1 m) from the strongest individual element of the source array.
- *Sound exposure level (SEL or energy flux density)*. This measure represents the total energy contained within a pulse, and is in the units dB re 1 $\mu Pa^2 \cdot sec$. For a single airgun pulse a fraction of a second in duration, the numerical value of the SEL measurement, in these units, is usually 5–15 dB *lower* than the RMS sound pressure in dB re 1 μPa. The "RMS – SEL" difference often tends to decrease with increasing range as a result of the temporal "stretching" of the pulse during propagation. The increasing duration of the airgun pulse as it propagates to greater distances is largely attributable to multiple reflections at the sea surface and sea bottom, and at acoustic boundaries within the seafloor. For a signal a few seconds in duration, e.g., a MarVib transmission, the SEL level in dB re 1 $\mu Pa^2 \cdot sec$ would be several dB *higher* than the RMS level in dB re 1 μPa.
- *Duration*. Duration is the length of the sound, usually measured in seconds. For an impulsive sound such as an airgun pulse, the duration may be calculated in a number of different ways. Greene (1997) described duration of an airgun pulse as the interval over which 90 percent of the sound energy arrives at the receiver, and that definition has been widely used in the biological literature.

Over the past decade, the U.S. National Marine Fisheries Service (NMFS) guidelines regarding levels of impulsive sound that might cause disturbance or injury have often been based on the "RMS sound pressure" metric. However, the RMS value depends on the extent to which the sound pulse has been "stretched" in duration during propagation, which varies with environmental conditions, so the RMS measure is often criticized (e.g., Madsen 2005). There is now reason to believe that auditory effects of transient sounds on marine mammals are better correlated with the amount of received energy than with the level of the strongest pulse (Southall et al. 2007) and therefore SEL is increasingly the unit of choice in evaluations. Further complicating the situation, there is increasing evidence that auditory effect in a given animal is not a simple function of received acoustic energy. Frequency, duration of the exposure, and occurrence of gaps within the exposure can also influence the auditory effect (Mooney et al. 2009; Finneran and Schlundt 2010; Finneran et al. 2010a,b).

1.4 Historical Perspective

Concerns about the potentially adverse effects of anthropogenic noise on marine mammals began in the 1970s (e.g. Payne and Webb 1971) just as the environmental movement was spreading through developed nations and as rising oil prices resulted in exploration moving into previously frontier areas such as northern Alaska and some offshore waters. Effects of marine seismic programs involving airguns and other non-explosive sources on marine mammals were already attracting concern, in at least some jurisdictions, as far back as the early 1980s. Southall et al. (2007) provide an overview of the historical perspective, and only a brief summary is provided here.

Experiments conducted in the 1980s using airguns (single or in arrays) indicated that bowhead whales (*Balaena mysticetus*) and gray whales (*Eschrichtius robustus*) usually avoided marine seismic operations if the sound pressure levels exceeded 160–170 dB re 1 μPa on an approximate RMS basis (Malme et al. 1983, 1984, 1986, 1988; Richardson et al. 1986; Ljungblad et al. 1988). RMS, in this context, refers to the sound pressure level averaged over the duration of the received airgun pulse (see § 1.3, above). In contrast, upon exposure to prolonged underwater sounds from industrial activities such as drilling and construction, similar avoidance was elicited out to distances where the RMS levels were notably lower, ~120 dB re 1 μPa (Malme et al. 1984; Richardson et al. 1990, 1995). Researchers did note considerable variability in cetacean responses, with some individuals approaching sound sources far closer (and tolerating exposure to higher received sound levels) than did other individuals. The procedures during these early experimental and observational studies of marine mammal response to industrial sound were not as well controlled as now attempted during "controlled exposure experiments" (Tyack 2009a). However, the studies in the early 1980s did provide early demonstrations of the now well-known phenomenon that behavioral reactions to sound exposure are not uniform across a given marine species. Responses often differ based on the type of sound, individual animal, activity of the individual at the time of exposure, the history that an individual has with anthropogenic noise, and possibly biological factors such as sex, age, and health. These types of variable responses to low-frequency (<1 kHz) sounds are not limited to marine mammals; they have also been shown in fish (e.g., Popper et al. 2007; Popper and Hastings 2009a,b).

By the early- to mid-1980s, certain jurisdictions began to impose mitigation requirements on some types of industrial activities involving significant impulsive or continuous sound sources, including seismic surveys involving airguns. These mitigation measures included elements such as safety radii, shut-down criteria, and seasonal restrictions. In the 1990s, concern about the environmental effects of anthropogenic low-frequency (LF) underwater sound were elevated as a result of academic studies and navy activities involving use of LF sounds to study large-scale ocean properties (e.g., Munk et al. 1994; Worcester and Munk 2004) and for navy sonar applications (e.g., Biassoni et al. 2000; Croll et al. 2001). This heightened concern resulted in increased interest in establishing scientifically defensible criteria for safe levels of noise exposure for marine mammals (NRC 1994, 2000, 2003; Richardson et al. 1995) and more recently for fish and sea turtles. This interest, at least for marine mammals, was further heightened by the stranding deaths of some cetaceans (mainly beaked whales) in a number of incidents that coincided with the use of mid-frequency military sonars (e.g., Frantzis 1998; Evans and England 2001; Fernandez et al. 2005; Cox et al. 2006; Filadelfo et al. 2009).

Whereas there are no universally-agreed mitigation measures in place for seismic operations around the world, a number of jurisdictions have developed guidelines and recommended or required mitigation measures for seismic surveys involving airguns. In 1995, the U.S. National Marine Fisheries Service (NMFS) issued one of the first sets of exposure criteria with their "do not exceed" criteria for underwater pulses from seismic airguns. NMFS set the exposure limit to 190 dB re 1 µPa for pinnipeds and most odontocetes, and 180 dB re 1 µPa for all mysticetes and sperm whales.[2] This was later amended to 180 dB re 1 µPa for all cetaceans. NMFS implemented these precautionary criteria to ensure that physical injury would not occur. However, based on the limited data available then (and now), it cannot be said with any surety that higher received levels of sound would result in auditory or other injuries. These criteria were designed to prevent injury, and recognized that behavioral changes would often occur at lower received levels. In 1997, the High Energy Seismic Survey (HESS) team convened an expert panel to consider noise exposure criteria, primarily for waters off California, and that panel largely endorsed the existing NMFS criteria, with the exception of the criterion for pinnipeds (HESS 1999). However, the HESS panel recognized the need for more specific data, and the variability that was likely to occur based on species. In the UK, a mitigation zone of 500 m is set around an active seismic source (JNCC 2004), a distance based primarily on the ability of observers to see marine mammals at the surface rather than specified sound levels or impact criteria. In several other jurisdictions, mitigation zones are also established without consideration of the actual sound levels at the receiver. In Canada, the mitigation zone is typically 500 m but has sometimes been set at a longer distance, or at a distance based on the predicted or measured distances for 180 and 190 dB re 1 µPa (RMS) levels. Requirements vary among jurisdictions and change from time to time (Weir and Dolman 2007), and in any event may not be appropriate for MarVib systems.

No specific attention has been given to corresponding criteria for seismic surveys based on MarVib technology. However, there has been considerable discussion of appropriate criteria for exposure of marine mammals to LF sonar signals. For many years, the regulatory thresholds for these types of signals have often been set (in the U.S.A.) as 160 dB re 1 µPa (RMS) for behavioral disturbance ("Level B takes") and 180 dB re 1 µPa (RMS) for injury ("level A takes") (Scholik-Schlommer et al. 2009). The SURTASS-LFA program has been using a continuous risk curve relating "risk" to exposure rather than a single received level (RL) threshold (DoN 2007). The uncertainty about which criteria are most appropriate is discussed in Chapter 6 on "impacts".

Again, a "do not exceed" level of 180 dB re 1 µPa (RMS) is often discussed, with lesser levels of "risk" anticipated at progressively lower received levels.

In the U.S., under the Marine Mammal Protection Act (MMPA), Level A harassment includes exposure levels that could result in physical injury (e.g., Permanent Threshold Shifts [PTS]), whereas Level B harassment encompasses behavioral disturbance, avoidance, and mild Temporary Threshold Shifts (TTS). Slight changes in behaviour, within the normal range of variability in behaviour (including minor displacement and alterations in the breathing and dive cycles that are well within the normal range of

[2] ***Odontocetes*** are the toothed whales, including sperm whales, dolphins, porpoises, and various small or moderate-sized whales that have teeth (e.g., pilot whales, killer whales, beaked whales). ***Mysticetes*** are medium and large-sized whales that have baleen plates but no teeth in their mouths, including species such as the right, fin, minke, humpback, and several other whales. ***Pinnipeds*** include the hair or true seals ("phocid seals"), the eared seals and sea lions ("otariids"), and the walrus.

variability but detectable by statistical analyses), may not rise to the level of being considered Level B harassment in the U.S. (e.g., NMFS 2001).

An *ad hoc* expert panel recently proposed science-based injury criteria for cetaceans and pinnipeds exposed to strong underwater or in-air sounds (Southall et al. 2007). They distinguished various categories of marine mammals, including pinnipeds and three groups of cetaceans. They also distinguished impulse sounds (like airgun pulses) from non-impulse sound (like marine vibroseis sweeps). For each combination of marine mammal group and sound type, Southall et al. (2007) proposed a cumulative energy exposure and a peak pressure level above which auditory injury might occur. For any type of cetacean exposed to impulse sounds (such as airgun sounds), the proposed injury criteria were a cumulative energy exposure (SEL) of 198 dB re 1 $\mu Pa^2 \cdot sec$ or a peak pressure of 230 dB re 1 µPa. Corresponding proposed injury criteria for cetaceans exposed to non-impulse sounds (such as marine Vibroseis) were 215 dB SEL or 230 dB peak pressure (Southall et al. 2007, p. 443). The lower assumed SEL tolerance to impulse sounds (198 vs. 215 dB re 1 $\mu Pa^2 \cdot sec$) relates to the increased injury potential for an impulse with rapid rise time. For pinnipeds, the corresponding proposed criteria were 186 dB SEL or 218 dB peak pressure for impulse sounds, and 203 dB SEL or 218 dB peak pressure for non-impulse sounds (Southall et al. 2007, p. 443).

These injury criteria proposed by Southall et al. involve many generalizations, assumptions, extrapolations, and simplifications, some of which are discussed in Chapter 6 on potential impacts. Different criterion values may be more appropriate for some particular species and situations, e.g., lower SEL criteria for porpoises (Lucke et al. 2009), and varying criteria depending on frequency, duration, and intermittency of exposure (Mooney et al. 2009; Finneran and Schlundt 2010; Finneran et al. 2010a,b). The assumption of higher tolerance to non-impulse vs. impulse sounds is of particular importance in any assessment of the effects of airgun sounds vs. MarVib sounds. However, it is also important to note that SEL is a function of duration of exposure as well as received level. If SEL is the relevant metric in evaluating effects, then the longer duration of MarVib sweeps than of airgun pulses will to some extent offset the lower source level and higher criterion values for MarVib signals as compared with airguns. These tradeoffs are illustrated in the model calculations summarized in Chapter 5, and are discussed further in Chapter 6 on potential impacts.

Behavioral disturbance by airguns and other pulsed sources is often (at least in the U.S.A.) assumed to occur at received levels ≥160 dB re 1 µPa (RMS). This criterion is used by NMFS in estimating the potential number of “takes by harassment” that might result from a particular marine seismic survey. The 160 dB (RMS) criterion was originally based on limited observational data, principally from 2 or 3 species of mysticetes (Malme et al. 1983, 1984; Richardson et al. 1986). The use of this level for odontocetes and pinnipeds has not been well-justified, and even for mysticetes is not always appropriate. The actual received levels of airgun sounds when behavioral disturbance or avoidance becomes evident vary widely within and among these groups of marine mammals, and can be notably higher or (at times) lower than 160 dB re 1 µPa (RMS). [For recent reviews, see Nowacek et al. (2007), Southall et al. (2007), and Tyack (2009b).]

Southall et al. (2007) sought to define science-based behavioral response criteria (as well as the aforementioned injury criteria) for different categories of marine mammals and of sounds. However, Southall et al. concluded that the available data were too variable and context-dependent to justify identifying single criterion levels above which behavioral responses are likely and below which they are unlikely. Southall et al. suggested that it would be more appropriate to evaluate behavioral effects based on a risk function, i.e., assuming that the probability of behavioral effects increases progressively with increasing sound exposure.

Acoustic impact criteria applicable to other types of biota are less well developed than are the criteria for cetaceans and pinnipeds. There is an ongoing effort to develop science-based criteria for fish and sea turtles within an Acoustical Society of America Working Group. Although technical papers related to this topic have been published recently, there have as yet been no reports or progress statements from the Working Group.

With the increasing awareness of the potential impacts of anthropogenic noise on marine animals of various types, interest has been focused on adapting existing technologies used for seismic data acquisition to determine whether that potential impact can be reduced without sacrificing the data quality.

1.5 Approach to Modelling in this Environmental Assessment

In this report, modelling is applied to estimate the 3-D acoustic field emanating from a typical airgun array source and from a similarly-configured Marine Vibrator source with varying operational characteristics (see Chapters 4 and 5). An appropriate sound propagation model is used to estimate the received levels from the various source configurations operating at representative deep and shallow sites in the Gulf of Mexico. In addition, we estimate the relative exposure of marine mammals that reside in the deep and shallow analysis areas. The objective is to compare sound fields and numbers of marine mammals exposed to varying sound levels under otherwise similar conditions.

More specifically, the acoustic modelling illustrates the comparative effects of MarVib and airgun source arrays on representative marine mammals by considering the potential effects of "comparable" MarVib and airgun operations at either of two specific sites in the northern Gulf of Mexico, one shallow site and one deep site. The purpose was not to provide a definitive Environmental Assessment of these two system types, as the outcome would depend on the specific site, parameters of the seismic sources, and trackline design. Rather, the purpose here is to compare the anticipated effects of MarVib and airguns on numbers of marine mammals that might be affected by "comparable" MarVib vs. airgun operations, also considering the effects of water depth and of varying certain MarVib parameters, specifically signal duration and higher-frequency roll-off rate. Three representative species of marine mammals occurring in the Gulf of Mexico are considered: one toothed whale species (sperm whale), one dolphin species (bottlenose dolphin), and one baleen whale (Bryde's whale). Chapter 5 predicts numbers of these species that might receive sufficient airgun or MarVib sound for either behavioral effects or potential injurious effects (e.g., auditory damage). In estimating numbers of mammals exposed at relevant levels, this analysis considers both the RMS sound pressure criteria currently used by NMFS in regulating marine seismic operations (160 and 180 dB re 1 μPa for behavioral disturbance and potential injury, respectively) and the science-based injury criteria recommended by Southall et al. (2007), mainly involving cumulative sound exposure level.

Results from the acoustical and exposure modelling are used (in Chapter 6) to assess the potential impacts on marine mammals. Comparative impacts of MarVib vs. airgun systems on other major types of marine animals, including invertebrates, fish, and sea turtles, are also addressed in a more general way in Chapter 6. Chapter 7 concerns mitigation approaches for MarVib vs. airgun sources, and Chapter 8 provides Conclusions and Recommendations.

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CHAPTER 2. AIRGUN AND MARINE VIBRATOR SOURCES

Oil and gas exploration and development typically begins with seismic exploration. Sound waves generated by seismic survey equipment are directed toward the sea floor and penetrate the undersea geology. Sound waves reflected by the subsurface geology are recorded and the data used to produce detailed maps of geological features. The methods used to generate and record the sound waves used for geological exploration are varied. A number of recent environmental impact statements (e.g., MMS 2006, 2007) have provided overviews of currently-used acoustic sources. Sections 2.1 and 2.2 below provide an overview of the methodologies available, focusing on the two methods of principal interest here: traditional airguns and marine vibroseis.

2.1 MARINE SEISMIC SURVEY METHODOLOGIES

2.1.1 Two-Dimensional and Three-Dimensional Seismic Surveys

In recent decades, most marine seismic surveys have been conducted using airgun arrays, although other potential sound sources include water guns (nowadays infrequently used) and sparkers (used in some high resolution surveys). The surveys can be divided into two main types based on the type of data they record—either two-dimensional (2-D) that record a cross-sectional image of the underlying geology and are characterized by spacing of a kilometer or more between survey lines, and three-dimensional (3-D) surveys that use close spacing of survey lines (25–100 m) to provide high-resolution, three-dimensional images. The industry often employs 2-D surveys over a broad area and then focuses 3-D activity on a more restricted area of interest. The description that follows pertains primarily to surveys with airguns. A survey involving MarVibs as sources is likely to differ in some respects, but the specific manner in which MarVib operations would be conducted is uncertain. MarVibs have rarely been used in the past, and future MarVib sources and operations may differ in important respects from previous trials.

Airguns used in seismic surveys may have chambers that range in size from tens of cubic inches (in^3) to several hundred in^3. An airgun array may consist of one to several tens of airguns of various sizes. The number and size of individual airguns used may be varied according to the specific objectives of the survey. Total volume of an array may vary from under 100 in^3 to several thousand in^3. Airgun arrays emit pulsed sound that is directed downward insofar as possible, although some does propagate horizontally, in some cases for hundreds of kilometres or more (Greene and Richardson 1988; Bowles et al. 1994; Nieukirk et al. 2004).

A typical seismic vessel is 70–120 m long and tows 2–4 strings of airguns, with each airgun string including 2–9 airguns. The actual array is usually 12–18 m long and 16–108 m wide and the strings are towed parallel to the direction of travel and to each other. The array is also usually towed 30–200 m behind the vessel at a depth of 4–8 m.

To record the acoustic signals, 1–14 hydrophone streamer cables are towed with the front end (100–200 m) behind the source vessel at a depth of 2–6 m. If more than one streamer is towed, the streamers are typically spread out laterally over a width of 400–900 m, with the width depending on number of streamers and the individual spacing required for that particular survey. Each hydrophone streamer can be as much as 10 km long. Hydrophone streamers are passive listening devices consisting of multiple hydrophone elements that receive the airgun acoustic signals reflected from geological features in the seafloor. Long streamers (several km in length) are used for deep penetration surveys, whereas shorter streamers are deployed for shallow penetration surveys.

In some surveys, generally in shallow waters, ocean bottom cables (OBCs) containing hydrophones are deployed onto the seafloor in lieu of towing streamer(s) behind the source vessel. In this case, the source vessel tows airguns (but not streamers) back and forth above the OBCs, and the OBCs (rather than streamers) receive the returning seismic signals.

In addition to hydrophone streamers or OBCs, ocean bottom seismometers/hydrophones (OBS/Hs) can also be deployed from the source vessel or a support vessel. The OBS are usually deployed in a grid pattern on the sea floor. Many OBS/Hs can be deployed during a single marine seismic cruise. Depending on survey objectives, the hydrophone streamers may or may not be deployed when OBS/Hs are being used as receivers.

Typical vessel speeds for marine 3-D surveys are ~4–5 knots (kt) (7–9 km km/hr). In industry seismic surveys, the source array usually is discharged at intervals of 18.75 m, 25 m, 37.5 m, or 50 m. This results in one shot every 10–15 seconds (sec) in most surveys, but occasionally at longer intervals (e.g., 20 sec for some industry surveys for deep targets; occasionally as much as 1–4 min during some academic research surveys where shots are more widely spaced). Typical spacing for successive shot-points during industry surveys is either 25 or 37.5 m, i.e., airguns are activated between 50 and 75 times per nautical mile. Although a single source vessel is the normal configuration, occasionally multiple source vessels operating in coordination are used (Wide-Azimuth Survey).

3-D survey data are acquired on a line-by-line basis. Acquisition of a single trackline usually takes a few hours, depending on the size of the survey area. Once a line has been completed, the vessel turns 180º onto another trackline (usually not the adjacent one) and starts acquiring data in the opposite direction. Turns can take as long as 2–3 hr depending on whether streamers are being towed and on the length of those streamers. Seismic vessels typically operate 24 hours a day (although there may be restrictions for operations based on visibility and other conditions), and a survey may continue for days, weeks, or months. During the survey, airguns are not fired continuously, as equipment deployment, maintenance, turns, and other required shut downs interrupt the survey time.

The term "4-D" seismic survey is also employed by the oil and gas industry. A 4-D survey is essentially a 3-D survey repeated over a previously surveyed area to allow for temporal comparison of survey data.

2.1.2 High-Resolution Seismic Surveys

High-resolution seismic surveys (often referred to as site-clearance or geohazards surveys) are conducted to collect required site-specific information (on potential geo-hazards, anchoring conditions, and sensitive seafloor resources) in support of the preparation of an exploration or development plan. High-resolution surveys may also be required along proposed pipeline routes to identify potential geo-hazards and sensitive seafloor resources prior to construction and installation of facilities.

A typical high-resolution seismic survey consists of a vessel towing a 0.6- to 2-km hydrophone streamer cables and one or a few airguns ~25–30 m behind the ship at a depth of ~3–6 m. A 2-D high-resolution survey usually has two source strings with a single airgun on each, whereas a 3-D high-resolution survey usually has two or more airguns per string. The vessel travels at 3–4 kt (6–7 km/hr), and the airguns are fired approx every 7–10 sec. During a high-resolution survey, it is common for additional higher-frequency acoustic sources to be operated simultaneously with the airguns. These sources can include some of the following: boomer, sparker or minisparker, sub-bottom profiler, fathometer, and side-scan sonar.

2.2 ACOUSTIC SOURCES USED IN MARINE SEISMIC SURVEYS

A variety of acoustic sources are used during exploration activities and in support of development. These include fathometers, multi-beam bathymetric sonar, sub-bottom profilers, acoustic Doppler current profilers, sparkers, pingers, water guns, airguns, and MarVibs. The focus of this assessment is airguns and MarVibs and these two methods are dealt with in some detail below.

2.2.1 Airguns and Airgun Arrays

An airgun is a stainless steel cylinder filled with high-pressure air. The seismic signal is generated when air is almost instantaneously released into the surrounding water column. The compressed air is supplied by compressors on board the source vessel. Seismic pulses are typically emitted at intervals of ~10 sec, but at times are spaced from 5 to 20 sec or more apart during industry surveys, and sometimes farther apart in research surveys.

When discharged, an airgun creates predominantly low-frequency (predominantly <150 Hz) acoustic impulses in the water. Compressed air is fed into the main chamber while the solenoid is closed. Once the solenoid is triggered, air is released into the surrounding water. This release of highly compressed air, typically at a pressure of about 2000 pounds per square inch (psi), generates an oscillating air bubble. In the case of airguns, expansion and oscillation of the air bubble(s) generates a strongly peaked, high-amplitude acoustic impulse that is used for seismic profiling.

The main features of the pressure signal generated by an airgun are the strong primary peak and the subsequent bubble pulses or "bubble train". The train of bubble pulses is an undesirable feature of the airgun signal because it interferes with the detection of distinct sub-bottom reflections. To increase the pulse amplitude and dampen the bubble train quickly, geophysicists usually combine multiple airguns together into arrays. Airgun arrays provide several advantages over single airguns:

- The peak pressure of an airgun array (in the vertical direction) increases nearly linearly with the number of airguns.
- Airgun arrays project maximum peak levels toward the seabed (i.e., in the vertical direction) and lower levels in near-horizontal directions.
- By using airguns of several different volumes that are spaced and triggered optimally relative to one another, airgun arrays may be "tuned" to increase the amplitude of the primary peak and simultaneously decrease the relative amplitudes of the subsequent bubble pulses.

Geophysicists use several different kinds of airguns for seismic surveying. The most commonly used type of airgun uses the motion of an internal shuttle to release pressurized air from the gun chamber through venting holes on the gun casing. Conventional airguns are available with a wide range of chamber volumes, from under 5 in^3 to over 2000 in^3, and the predominant frequencies in the emitted energy vary inversely with gun volume. Because of the high pressures involved in their operation, traditional airguns are subject to wear from significant recoil forces that can adversely affect their reliability. Recent advances in airgun technology have led to the development of "recoilless" G guns and sleeve-guns in an attempt to solve these issues.

A third airgun type is the generator-injector gun (GI gun). This airgun produces a different overpressure signature than conventional airguns. GI guns use two independently-fired air chambers to tune the air bubble oscillation and minimize the amplitude of the bubble pulse. Using one or more GI guns, geophysicists can achieve high peak-to-bubble amplitude ratios without using a larger array. GI guns are therefore often used in place of single airguns, or small airgun arrays.

Throughout this assessment, the various types of airguns (e.g., traditional airgun, G guns, and GI guns) are all referred to simply as airguns unless it is important to specifically state what type of seismic device is being addressed.

2.2.2 Marine Vibroseis

Traditional airguns have dominated the seismic industry for decades. The use of vibrators in the marine environment has, to date, largely been confined to situations where towed airgun arrays cannot be used, such as on sea ice. On-ice or land vibroseis units involve tracked vibrators supported by tracked cable vehicles. Receivers are typically placed every 30–35 m and vibrator source points are placed at equivalent intervals. The standard land (or on-ice) vibroseis unit emits a frequency sweep across the 5–90 Hz range, although harmonics may extend to ~1.5 kHz. Each sweep typically has a duration of 5–12 sec. Because of the length of the sweep and the silent periods between sweeps (also several seconds in duration), vibroseis signals are considered transient but they are not impulsive.

During the 1980s, MarVibs were developed for deep target marine seismic applications, but MarVib techniques have been slow to make the transition to full commercial use (Bird 2003). Because there is at present no widely used MarVib equipment, the specific characteristics that a future MarVib system might have remain somewhat hypothetical. However, it is assumed that they would be designed to emit sound at frequencies from approximately 5 or 10 Hz to 90 or 100 Hz, with higher frequency components (harmonics and otherwise) being avoided to the maximum extent possible. In future designs, it is expected that higher-frequency components would be notably weaker than for airguns or previous experimental MarVib units. Although older-generation MarVib systems produced swept-frequency signals (and corresponding swept-frequency harmonics), it is possible that future MarVib systems might produce signals with specially coded patterns to facilitate signal processing. Signal duration would probably be on the order of 5–12 sec, probably with a short interruption after the signal before transmission of the next signal. Again, the specific characteristics of the signals are hypothetical in the absence of operational systems.

2.2.2.1 Current Marine Vibrator Technologies

A MarVib operates by using hydraulic or electrical power to drive an actuating plate that generates the required vibrations. Current MarVibs are broadband marine sources that generate modulated frequencies from 10 to as much as 250 Hz, with harmonics extending to higher frequencies. However, the higher frequency components, above ~90 Hz, are of no direct geophysical value and would presumably be suppressed to the extent possible in future MarVib designs. MarVibs have been used in deep water, shallow water, and transition zones. They can operate over a wider range of depth than airguns, including considerably deeper depths. MarVibs have been demonstrated to at least 100 m depth and might theoretically be useable much deeper if deployment logistics were practical (R. Tenghamn *in* Okeanos 2010:9).

In contrast to airgun arrays, which produce impulsive sounds with nominal source levels reaching as high as 16 MPa @ 1 m (out to 1 kHz), i.e., ~264 dB re 1 µPa @ 1 m (peak to peak), marine vibroseis systems that may be developed will produce more prolonged sound signals with nominal source levels likely below ~0.6 MPa @ 1 m out to 1 kHz but mostly below 100 Hz (i.e., ~236 dB re 1 µPa @ 1 m, RMS).[3] The bandwidth, rise times, and durations of acoustic signals from the two sources are expected to be significantly different.

As an example of an existing technology MarVib system, PGS have developed a MarVib unit (Fig. 2.1; PGS 2005) based on a flextensional shell with a driver based on electrical coils operating in a magnetic

[3] As described in § 1.3, these nominal source levels are levels that would be emitted by a theoretical point source producing the same far-field levels as are received from a given array of airguns or MarVibs. Actual levels at all locations in the water near a distributed array of airguns or MarVibs would be lower. In deep water, maximum levels in the water ~100 m directly below assumed airgun and MarVib sources would be on the order of 244 dB re 1 µPa (pk-pk) and 196 dB re 1 µPa (RMS), respectively, i.e., about 40 dB down from the nominal source level.

FIGURE 2.1. The full PGS marine vibrator system (PGS 2005).

field and spring elements that transfer the force from the electrical drive to the flextensional shell (Fig. 2.2). Two resonances have been made possible, one from the shell interacting with the equivalent fluid mass, the other from the spring elements. This design makes it possible to generate high power with two sources covering frequencies between 6 and 100 Hz (Fig. 2.3). Both vibrators in the unit can operate simultaneously. Sweeps can also be stacked to increase total power if the array is static (for example anchored to the sea floor) or the total number of array components can be increased if the array is being towed (PGS 2005).

2.2.2.2 Future Marine Vibrator Technologies

The next generation of marine vibroseis units being developed may be electro-mechanical, hydraulic, or use some other as yet unknown technology. Although knowledge of marine vibroseis units developed and used during and since the 1980s may (when used cautiously) be valuable for assessment of the properties and environmental effects of the next generation of marine vibroseis technology, an important design criterion for new technology MarVib systems will be to achieve very tight control over sound bottom sediments. Sounds propagating via indirect paths travel longer distances and often arrive later than sounds arriving via a direct path. (However, sound traveling in the bottom may travel faster than that in the water, and thus may, in some situations, arrive slightly earlier than the direct arrival despite traveling a greater distance.) With airgun pulses, these variations in travel time have the effect of lengthening the duration of the received pulse, or may cause two or more received pulses from a single emitted pulse. Near the source, the predominant part of a seismic pulse is ~10–20 ms in duration. In comparison, the pulse duration as received in the water at long horizontal distances can be much greater. For example, for one airgun array operating in the Beaufort Sea, pulse duration was ~300 ms at a distance of 8 km, 500 ms

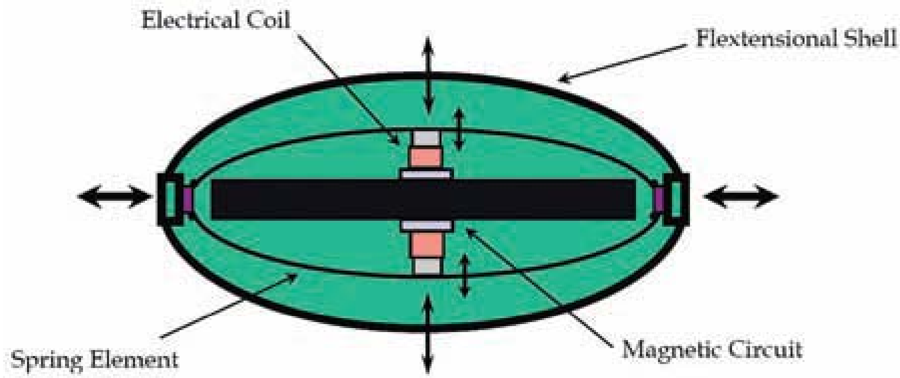

FIGURE 2.2. Schematic of an electro-mechanical MarVib unit (PGS 2005).

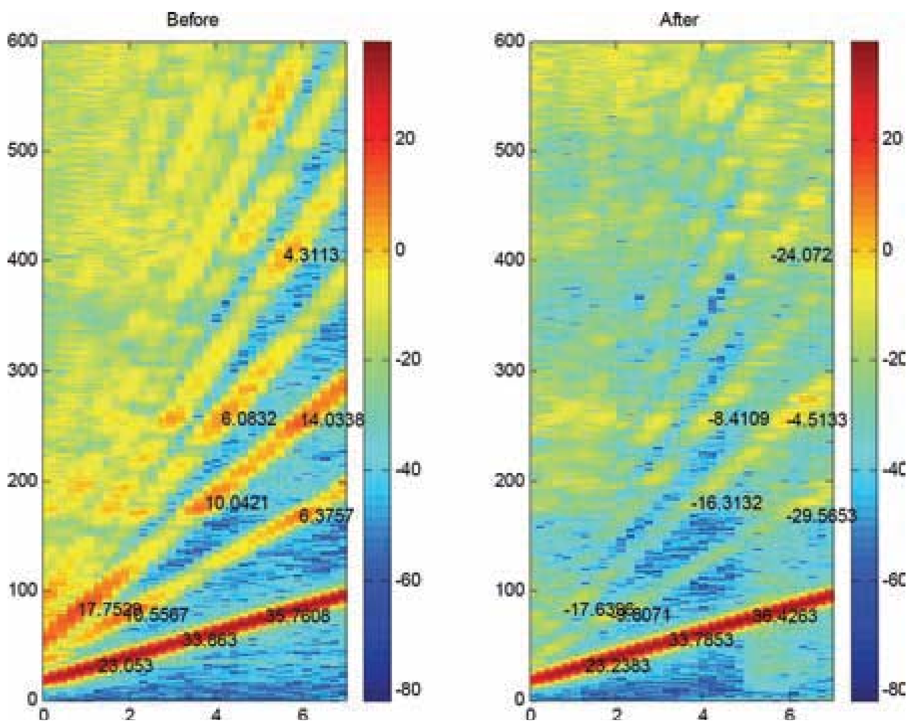

FIGURE 2.3. Attenuation of harmonics with the marine vibrator control system (PGS 2005). These spectrograms plot frequency in Hz (vertically) vs. time in seconds (horizontally).

at 20 km, and 850 ms at 73 km (Greene and Richardson 1988). The received pulses were presumably composites of signal components that had travelled along different paths through the seafloor and water column, with varying travel times depending on the path.

The RMS level for a given airgun pulse (when measured over the duration of that pulse) depends on the extent to which propagation effects have “stretched” the duration of the pulse by the time it reaches the receiver (e.g., Madsen 2005). As a result, the RMS values for various received pulses are not perfectly correlated with the SEL (energy) values for the same pulses (e.g., Tolstoy et al. 2009). There is increase-ing evidence that biological effects are more directly related to the received energy (e.g., to SEL) than to the RMS values averaged over pulse duration (Southall et al. 2007).

Another important aspect of sound propagation is that received levels of low-frequency underwater sounds diminish close to the surface because of pressure-release and interference phenomena that occur at and near the surface (Urick 1983; Richardson et al. 1995; Potter et al. 2007). Paired measurements of received airgun sounds at depths of 3 vs. 9 or 18 m have shown that received levels are typically several decibels lower at 3 m (Greene and Richardson 1988). For a mammal whose auditory organs are within 0.5 or 1 m of the surface, the received level of the predominant low-frequency components of the airgun pulses would be further reduced. In deep water, the received levels at deep depths can be considerably higher than those at relatively shallow (e.g., 18 m) depths and the same horizontal distance from the airguns (Tolstoy et al. 2004a,b).

Pulses of underwater sound from open-water seismic exploration via airgun arrays are often detected 50–100 km from the source location, even during operations in nearshore waters (Greene and Richardson 1988; Burgess and Greene 1999). At those distances, the received levels are usually low, <120 dB re 1 μPa on an approximate RMS basis. However, faint seismic pulses are sometimes detectable at even greater ranges (e.g., Bowles et al. 1994; Fox et al. 2002). In fact, airgun signals sometimes can be detected thousands of kilometres from their source. For example, sound from seismic surveys conducted offshore from Nova Scotia, the coast of western Africa, and northeast of Brazil were reported as a dominant feature of the underwater noise field recorded at sound-channel depth along the mid-Atlantic ridge (Nieukirk et al. 2004).

As noted earlier, there are (to our knowledge) no comparable empirical data on characteristics of marine vibrator sounds as received in the water more or less to the side of an operating MarVib system. However, given the known properties of underwater sound propagation, it can be assumed that

1. MarVib signals could also be stretched in time with increasing propagation distance, but this stretching would be proportionally less than for airgun pulses because of the longer duration of MarVib signals near the source.
2. Received levels of MarVib signals would be reduced just below the surface relative to deeper depths, similar to the pattern with airgun signals.
3. At any given distance from the source, received levels of MarVib signals, on a peak pressure or RMS pressure basis, will be lower than those of airgun signals designed for the same application. SEL values of MarVib and airgun signals will be more similar.
4. Given their lower source levels, MarVib signals will diminish below natural background levels (and become inaudible) closer to the source than occurs for airgun signals.

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CHAPTER 3. AFFECTED ENVIRONMENT

3.1 Factors Affecting Sound Propagation in the Marine Environment: Geology, Bottom Topography, and Bottom Substrates

Under shallow water conditions, the topography and physical properties of the ocean floor have a major influence on sound propagation. At low frequencies, sound can easily penetrate sediments (Clay and Medwin 1977; Hamilton 1980). The differential speed of the sound waves within the sediments and bedrock has a significant effect on the path taken by the sound waves, and bottom properties also influence reflection and absorption of sound, and thus transmission loss. An area with a dense substrate such as hard sand or bedrock will result in high levels of sound reflection back into the water column, whereas less dense sediments such as mud reflect much less sound, resulting in high absorption rates (Clay and Medwin 1977; Hamilton 1980; Medwin 2005).

3.1.1 Temperature and Salinity

The speed of sound in the oceans is dependent on variations in temperature, salinity, and pressure (depth). Near the surface, temperature variations occur that are dependent on season, weather conditions (such as wind speed and solar heating), and diurnality. These variations can result in vertical gradients that influence sound speed. Depending on the type of gradients that develop, sound may experience upward or downward refraction. If the surface waters have been mixed by wind and wave action so that temperatures are fairly constant, sound speed will increase with depth and upward refraction results (this also occurs in cold polar waters). Under temperate or tropical thermocline conditions, temperature and sound speed decrease with depth, although as temperatures become more constant at great depths, sound speed again increases (Pickard and Emery 1990).

3.1.2 Deep Water Propagation and Acoustic Ducting

Where the vertical SSP (sound speed profile) features a mid-water minimum, attributable to the effects of temperature and pressure, sound is refracted toward the depth at which this minimum occurs. In water >2000 m deep, the deep sound channel permits refracted sounds to travel long distances without losses from reflection at the bottom. This channel is ~1000 m below the surface at mid-latitudes and is located at the surface at higher latitudes (Pickard and Emery 1990; Medwin 2005). Long-distance propagation is most efficient if the sound source is within the deep sound channel, but even when the source is above channel depth, some of its sound can (depending on water and bottom properties) become trapped in the sound channel and propagate to long distances (e.g., Nieukirk et al. 2004).

3.1.3 Shallow Water Propagation

Under shallow water conditions (depth <200 m), SSPs are downward refracting or nearly constant with increasing depth because of the influences of solar heating and wind action. These influences lead to considerable interaction between the surface and bottom. The scale of this effect is dependent on the surface temperature (with higher near-surface temperatures leading to greater surface sound speeds and thus greater downward refraction). In well-mixed surface waters or cold polar waters, sound speed increases with depth, and sound is channeled in a surface duct formed by downward reflection from the surface and upward refraction by the positive vertical sound speed gradient (Medwin 2005). Because of the great variation in water and substrate properties related to location and season, long-range propagation in shallow water is viewed as highly complex and therefore difficult to predict and model.

3.1.4 Wind and Waves

Waves determine how sound is reflected at, or transmitted through, the air-water boundary. Sound propagation may be significantly reduced when wave action is heightened (Weston and Ching 1989). As noted earlier, wind and wave action also results in a more constant temperature profile by mixing surface and deeper waters. This temperature profile often results in an upward-refracting SSP.

3.1.5 Absorption

As sound waves propagate, absorption of sound energy occurs. Absorption occurs even in particulate-free waters. Absorption of sound energy contributes to the transmission loss linearly from the source and is given by an attenuation coefficient in units of dB/km. Absorption increases with the square of frequency (Francois and Garrison 1982a,b; Medwin 2005) and therefore, low frequencies are favoured for long-range propagation.

3.1.6 Shallow Source and Receiver Effects

Near the water's surface, the sound field is influenced by reflections from the water-air boundary. These reflections, or "ghosts", result in interference patterns (maxima and minima in the sound field) with sound traveling directly from the source. If both the source and the receiver are very shallow, this so-called "Lloyd's mirror interference" may result in the receiver recording a different value than would be expected from standard spherical spreading from the source (Medwin 2005).

3.1.7 Area-Specific Ambient Noise

Ambient or background noise is natural background sound, at times including components from distant and individually-indistinguishable anthropogenic sources. Ambient noise levels are highly variable with time and location. Ambient sound level is strongly influenced by the interrelated factors wind speed and wave height, with ambient sound levels tending to increase with increasing wind speed and wave action. Ambient noise levels also vary based on whether the location is a shallow coastal one or a deep offshore one, whether it is polar, temperate, or tropical, and on the biological communities that inhabit the region. Background noise will be elevated if the area is close to major shipping lanes or coastal development. In general, sound components from readily identifiable nearby sources are not considered to be part of the ambient sound, although components from distant and indistinguishable sources (e.g., distant shipping or reverberation from distant seismic surveys) are included.

Ambient noise levels at a given frequency commonly vary by 10–20 dB from day to day, and variations may occur over widely-varying time frames (from seconds to seasons; Richardson et al. 1995).

3.2 MARINE INVERTEBRATES

Marine invertebrates provide the basis of the marine food web along with phytoplankton, and support the survival of other marine invertebrates and vertebrates. The hundreds of thousands of marine invertebrate species exhibit great variability in form and function, ranging in size from microscopic zooplankton to 900-kg giant squid.

Of relevance to MarVib activities are those invertebrates potentially sensitive to low-frequency (e.g., <100 Hz) sound and vibrations. Limited studies suggest that various invertebrate groups are capable of detecting and may be affected by airgun noise. Only certain groups of crustaceans (such as lobsters, crabs, and shrimps) and mollusks (such as octopuses, squids, cuttlefishes and nautiluses) are known to sense low-frequency sound. For example, both Offutt (1970) and Goodall et al. (1990) reported lobsters capable of detecting underwater sound at frequencies as low as 20 Hz, and Packard et al. (1990) reported the detection of 1–100 Hz underwater sound by octopuses and squids. These crustacean and mollusk groups are the focus of this review.

3.2.1 Sound Production in Invertebrates

Invertebrates as diverse as barnacles, amphipods, shrimp and lobster are all capable of producing sound (Au and Banks 1998; Tolstoganova 2002). The majority of invertebrates produce sound by scraping or rubbing body parts. As with non-marine organisms, the sounds produced by marine invertebrates are associated with significant life functions such as territorial behaviour, breeding, courtship, and aggression. Table 3.1 provides a summary of invertebrate sound production in terms of frequency range, source levels and dominant frequencies.

Snapping shrimp are a ubiquitous source of sound in warm-water portions of the oceans (Au and Banks 1998). The shrimp produce sound by rapidly closing one of their frontal claws. The closing motion produces a jet of water and a loud click. Snapping shrimp clicks can have source levels as high as ~166–172 dB re 1 µPa @ 1 m (RMS) with a frequency range of 2–200 kHz (see Table 3.1).

TABLE 3.1. Summary of underwater sound production and detection capabilities of decapod crustaceans and cephalopod molluscs.

Group	Sound Production: Frequency Range (Hz)	Sound Production: Source SPL (dB re 1 µPa @ 1 m)	Detection: Frequency Range (Hz)	Detection: Dominant Frequency (Hz)	Detection: Minimum Threshold SPL (dB re 1 µPa)
Decapods					
Lobsters (*Homarus*)	87–261 [a, b]	$18.5_{(?)}$ [a, b]		20–5000 [i]	
Lobsters (*Panulirus*)	3300–66,000 [c]	$50.1–143.6_{(?)}$ [c]			
Lobsters (*Nephrops*)				20–200 [m]	
Crabs	100–18,000 [d]				
Shrimps	2000–200,000 [e]	$166–172_{(RMS)}$ [e]	100–3000 [f]	100 [f]	$105_{(RMS)}$ [f]
Cephalopods					
Octopuses			1–1000 [g]		
Squids			1–1500 [g, h, i]	100-200 [h]	
Cuttlefishes			20–8000 [j, k]		

Notes: (?) = unspecified.
Sources: [a]Pye and Watson 2004; [b]Henninger and Watson 2005; [c]Latha et al. 2005; [d]Tolstoganova 2002; [e]Range provided is transformed from 183–189 $_{(Peak-Peak)}$, as reported in Au and Banks (1998); [f]Lovell et al. 2006 ; [g]Packard et al. 1990; [h]Hue et al. 2009; [i]Mooney et al. 2010; [j]Komak et al. 2005; [k]Rawizza 1995; [l]Offutt 1970; [m]Goodall et al. 1990.

3.2.2 Sound Detection

The hearing abilities of marine invertebrates are the subject of ongoing debate. Aquatic invertebrates (with the exception of aquatic insects) do not possess the equivalent physical structures present in fish and marine mammals that can be stimulated by the pressure component of sound. It appears that marine invertebrates respond to vibrations rather than pressure (Breithaupt 2002). Statocyst organs (an organ of balance containing mineral grains that stimulate sensory cells as the animal moves) apparently function as a vibration detector for at least some species of marine invertebrates (Popper and Fay 1999). The statocyst is a gravity receptor and allows the swimming animal to maintain a horizontal attitude.

Among the marine invertebrates, decapod crustaceans have been the most intensively studied. Crustaceans appear to be most sensitive to low frequency sounds (i.e., <1000 Hz; Table 3.1) (Budelmann 1992; Popper et al. 2001), with some species being particularly sensitive to low-frequency sound (Lovell et al. 2006). Other studies suggest that some species (such as American lobster) may also be more sensitive to high frequencies than has been previously reported (Pye and Watson 2004).

It is likely that cephalopods also use statocysts to detect low-frequency aquatic vibrations (Budelmann and Williamson 1994). Kaifu et al. (2008) provided evidence that the cephalopod *Octopus ocellatus* detects particle motion with its statocyst. Studies by Packard et al. (1990), Rawizza (1995), Komak et al. (2005), and Mooney et al. (2010) have quantified some of the optimally detected sound frequencies for various octopus (1–100 Hz), squid (1–500 Hz), and cuttlefish (20–8000 Hz) species. Using the auditory brainstem response approach, Hu et al. (2009) showed that auditory evoked potentials can be obtained in the frequency ranges 400–1500 Hz for the squid *Sepiotheutis lessoniana* and 400–1000 Hz for the octopus *Octopus vulgaris*, higher than frequencies previously observed to be detectable by cephalopods.

3.3 Marine Fish

There are thousands of species of marine fish; a recent estimate of the number of marine and diadromous species is 16,025 (Nelson 2006). (Diadromous fishes have life histories that include the use of both the freshwater and the marine environments.) Because this assessment is generic rather than site specific, the fish species addressed here are those considered of general ecological or economical concern. Fish are also discussed relative to their known sensitivity to low-frequency impulse sound.

Marine fish are known to vary widely in their ability to hear sounds. Although hearing capability data only exist for fewer than 100 of the 27,000 fish species (Hastings and Popper 2005), current data suggest that most species of fish detect sounds below 1500 Hz (Popper and Fay 2010). Some marine species, such as shads and menhaden, can detect sounds above 180 kHz (Mann et al. 1997, 1998, 2001). Also, at least some species are acutely sensitive to infrasound, down to below 1 Hz (Sand and Karlsen 2000). Reviews of fish-hearing mechanisms and capabilities can be found in Fay and Popper (2000) and Ladich and Popper (2004; see also Table 3.2).

All fish species have hearing (inner ear) and skin-based mechanosensory systems (lateral lines). Amoser and Ladich (2005) hypothesized that, as species within a particular family of fish may live under different ambient sound conditions, the hearing abilities of the individual species are likely to have adapted to the dominant conditions. The ability of fish to hear a range of biotic and abiotic sounds may affect their survival rate, with better adapted fish having an advantage over those that cannot detect prevailing sounds (Amoser and Ladich 2005).

Fish ears are able to respond to changes in pressure and particle motion in the water (van Bergeijk 1964; Schuijf 1981; Kalmijn 1988,1989; Shellert and Popper 1992; Hawkins 1993; Fay 2005). Two major pathways have been identified for sound transmittance: (1) the otoliths, which are calcium carbonate masses in the inner ear that act as accelerometers when exposed to the particle motion component of sound, cause shearing forces and stimulate sensory hair cells; and (2) the swim bladder, which expands and contracts in a sound field, re-radiating the sound's signal within the fish and in turn stimulating the inner ear (Popper and Fay 1993).

Researchers have noted that fish without an air-filled cavity (swim bladder), or with reduced swim bladders or limited connectivity between the swim bladder and inner ear, are limited to detecting particle motion and not pressure, and therefore have relatively poor hearing abilities (Casper and Mann 2006). These species have commonly been known as 'hearing generalists' (Popper and Fay 1999), although a recent reconsideration suggests that this classification is oversimplified (Popper and Fay 2010). Rather, there is a range of hearing capabilities across species that is more like a continuum, presumably based on the relative contributions of pressure to the overall hearing capabilities of a species (Popper and Fay 2010). Results of direct studies of fish sensitivity to particle motion have been reported in numerous recently published papers (Horodysky et al. 2008; Wysocki et al. 2009; Kojima et al. 2010).

TABLE 3.2. Summary of underwater hearing and sound production characteristics of fish.

Species or Group	Sound Production[a] Frequency Range (Hz)	Sound Production[a] Dominant Frequency (kHz)	Sound Production[a] Source Level (dB re 1 µPa @ 1 m)	Hearing Frequency Range	Hearing Threshold (dB re 1 µPa)
Hagfishes & lampreys	Unknown	Unknown	Unknown	Unknown	Unknown
Sharks and Rays	Unknown	Unknown	Unknown		
Sturgeons	<100 to >1000[1]	Unknown	Unknown	Unknown	Unknown
Herring-likes	Unknown	Unknown	120 to 130[5]	30 Hz to 4 kHz[2-8]	110 @ 1 to 1.2 kHz[6-8]
Alosine herrings (shads and allies)	Unknown	Unknown	~130 to 180[5]	200 Hz to 180 kHz[5] or 200 kHz[8]	~155 @ 40 kHz[5]
Salmon, smelts, etc.	Unknown	Unknown	Unknown	<1 to 800 Hz[9, 10]	94 @ 100 to 120 Hz[9, 10]
Cod-likes		50 to 1 kHz[11]		<1 Hz to 1 kHz[10, 12 – 16]	74 @ 200 Hz[10, 14]
Pipefishes & seahorses	Unknown	Unknown	Unknown	Unknown	Unknown
Scorpionfishes	Unknown	Unknown	Unknown		
Perch-likes	30 to 5000[16, 17]	100 to 3000[16, 17]	127[16]	85 Hz to >2 kHz[12 - 20]	
Tuna and billfishes	Unknown	Unknown	Unknown	50 Hz to 1.1 kHz[22, 23]	89 to 111 @ 500 Hz[22, 23]
Flatfishes	Unknown	Unknown	Unknown		
Coelacanths	Unknown	Unknown	Unknown	Unknown	Unknown

Notes: * - Values given are, at best, examples from published and unpublished sources. Sound production and hearing of most fishes in most groups have not been studied. Frequency bins in this table sometimes bracket the low end for some species and the high end for other species within a given group. This is particularly true of the very anatomically, behaviorally, ecologically, and bioacoustically diverse Order Perciformes (perch-like fishes), which includes over 9000 species in 148 families world-wide (fresh and salt water combined), or over one-third of all fish species (Helfman et al. 1997). It includes, besides the tunas and billfishes (listed separately here) basses, tilefishes, remoras, jacks, snappers, grunts, sculpins, porgies, and many other groups.

- There is little known about elasmobranch hearing sensitivities and the mechanisms thereof. With the inevitable ambiguities of the relevant stimulus, such as particle motion vs. sound pressure, describing hearing or other mechanosensory thresholds may be meaningless. Some of the problems inherent in making generalizations involving different data sets collected in different ways on different or even the same fishes are reviewed by Hawkins (1981).
- In cases where cells are left blank it is the opinion of the preparers that the group represented is so species diverse and/or the available data sets are so different in nature as to make such a brief description meaningless or misleading. A more complete treatment is available in U.S. Navy (2005).
- Because of the physical limitations of recording and measurement equipment and environments wherein fish will produce natural sounds, source levels are often difficult or impossible to obtain and are usually not available.

Sources: [1]Johnstone and Phillips 2003; [2]Denton et al. 1979; [3]Schwartz and Greer 1984; [4]Enger 1967; [5]Mann et al. 2001; [6]Mann et al. 2005; [7]Akematsu et al. 2003; [8]Gregory and Claburn 2003; [9]Hawkins and Johnstone 1978; [10]U.S. Navy 2005; [11]Hawkins and Rasmussen 1978; [12]Sand and Karlsen 1986; [13]Chapman and Hawkins 1973; [14]Chapman 1973; [15]Tavolga and Wodinsky 1963; [16]Luczkovich et al. 1999; [17]Gilmore 2003; [18]Ramicharitar et al. 2001; [19]Ramicharitar and Popper 2004; [20]Tavolga and Wodinsky 1965;[21]Iverson 1967; [22]Iverson 1969; [23]Chapman and Sand 1974; [24]Zhang et al. 1998; [25]Fujeida et al. 1996.

Most marine fish, including cartilaginous fishes (the sharks, skates, rays, and chimeras of the Class Chondrichthyes), are hearing generalists and react to sounds <1500 Hz. Experiments on cartilaginous fish have demonstrated poor hearing abilities and frequency sensitivity from 200 to 1000 Hz, with best sensitivity at lower ranges (Casper et al. 2003; Casper and Mann 2006). The hearing capability of Atlantic salmon also indicates a rather low sensitivity to sound (Hawkins and Johnstone 1978). Laboratory experiments yielded responses only to 580 Hz and only at high sound levels. The poor hearing of salmon is also likely attributable to the lack of a link between the swim bladder and inner ear (Jorgensen et al. 2004). There are limited data on hearing in sturgeon; initial studies by Meyer and Popper (2002) suggest that sturgeon may be able to detect sounds from below 100 Hz to perhaps 1000 Hz or a bit more (Popper 2005). Lovell et al. (2006) tested the sound reception and the hearing abilities of the paddlefish (*Polyodon spathula*) and the lake sturgeon (*Acipenser fulvescens*) using a combination of morphological and physiological approaches and found that both fish are responsive to sounds ranging in frequency from 100 to 500 Hz.

In contrast to the hearing generalists, herrings and their allies (Clupeiformes), some cods and allies (Gadiformes in part), some squirrelfishes (Perciform family Holocentridae, in part), and a number of other fish have specialized swim bladders that are either directly linked to or extend close to the inner ear. These fish have more sensitive hearing and are often referred to as 'hearing specialists' and may react to sounds at frequencies up to as much as 4000 Hz. Wilson et al. (2009) recently reported that ultrasound detection in the Gulf menhaden (*Brevoortia patronus*), a Clupeiform fish species, also involves the gas-filled bullae located in the head and the lateral line. The bullae are associated with the ear via the bulla membrane, and with the lateral line via the lateral recess membrane.

A recent paper by Wright et al. (2010) presents the results of a study of auditory sensitivity in settlement-stage larvae of six coral reef fish species. Using the auditory brainstem response method, they found that five of the six species heard sound of frequencies ranging from 100 to 2000 Hz, whereas the larvae of the other species did not detect sound of frequencies higher than 800 Hz. Larvae of all six species showed highest sensitivity to sounds with frequencies ranging from 100 to 300 Hz.

The lateral line system of a fish also allows for sensitivity to the particle velocity component of sound (Hastings and Popper 2005). This system is a series of receptors along the body of the fish (mainly bony fish and elasmobranches) that detects water motion, relative to the fish, that arises from sources within a few body lengths of the animal. The sensory unit of the lateral line is the neuromast. Fish use neuromasts to detect low frequency acoustic signals (160–200 Hz) over a distance of a few body lengths (Denton and Gray 1989 *in* Hastings and Popper 2005).

Chapter 4 (§4.4, §4.5) describes various aspects of the particle velocity field around a theoretical MarVib source. It also illustrates the sensitivity of a fish (the cod) to particle velocity (see Fig. 4.8).

3.4 SEA TURTLES

There are seven species of sea turtles: the green, hawksbill, loggerhead, olive ridley, Kemp's ridley, leatherback, and flatback turtles. All species are listed as threatened or endangered under the U.S. ESA or on the 2010 IUCN Red List of Threatened Species (IUCN 2010), and all are listed in CITES Appendix I (Table 3.3).

There have been a limited number of studies on sea turtle hearing. However, the available data indicate that sea turtles can hear moderately low-frequency sounds, including some of the frequencies that are prominent in airgun pulses and expected to predominate in MarVib signals.

TABLE 3.3. Summary of the status, global population size, habitat, and general distribution of sea turtles.

Species	Status[1] ESA/IUCN	Global Population[2]	Habitat[3]	Distribution
Green turtle (*Chelonia mydas*)	T or E/E	88,520	Coastal, seagrass beds	Global, tropical and subtropical
Hawksbill (*Eretmochelys imbricata*)	E/CR	60,000–78,000	Coral reefs, mangroves, hard bottom habitats	Global, tropical and subtropical, 30°N–30°S
Loggerhead (*Caretta caretta*)	T/E	43,320–44,560	Oceanic, coastal estuaries	Global temperate, tropical, and subtropical
Olive ridley (*Lepidochelys olivacea*)	T or E/V	2,000,000	Oceanic	Global tropical, subtropical, and warm temperate
Kemp's ridley (*Lepidochelys kempii*)	E/CR	5000	Temperate and tropical coastal	Gulf of Mexico; W North Atlantic
Leatherback (*Dermochelys coriacea*)	E/CR	35,860	Mostly oceanic	Global 71°N-47°S
Flatback (*Natator depressus*)	NL/DD	8050–32,520	Nearshore soft-bottoms	Australia

: [1] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = Not Listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: CR = Critically Endangered, E = Endangered, V = Vulnerable, DD = Data Deficient. All species are also listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in Appendix I, meaning threatened with extinction from international trade (UNEP–WCMC 2009).
[2] Population sizes for adult females from Spotila (2004).

Ridgway et al. (1969), Lenhardt et al. (1985), and Bartol (2004, 2008) provided detailed descriptions of the sea turtle ear structure. The middle ear is well designed as a peripheral component of a bone conduction system, and a thick tympanum, a layer of subtympanal fat, and other structures likely enhances low-frequency bone conduction hearing (Lenhardt et al. 1985; Bartol et al. 1999; Bartol and Musick 2003). Sea turtles may be able to localize the direction from which an underwater sound is being received (Lenhardt et al. 1983).

The majority of studies on sea turtle hearing have examined green (Ridgway et al. 1969) and loggerhead (Bartol et al. 1999; Lenhardt 2002) turtles. Recent studies have also assessed auditory brainstem response in captive juvenile and subadult green and juvenile Kemp's ridley turtles (Bartol and Ketten 2006; Ketten and Bartol 2006).

These studies indicate that at least some species are capable of hearing low-frequency sounds (Ridgway et al. 1969; Lenhardt et al. 1983; Bartol et al. 1999), with sensitivity varying with age (Bartol and Ketten 2006). The range of maximal sensitivity for sea turtles is 100–800 Hz, with an upper limit of ~1000 Hz (Ridgway et al. 1969; Bartol et al. 1999; Bartol and Ketten 2006). Hearing below 80 Hz is apparently less sensitive but still potentially of use (Lenhardt 1994).

Green turtles are most sensitive between 200 and 700 Hz, with maximum hearing sensitivity at 300–500 Hz with slight variation for juveniles and subadults (Ridgway et al. 1969; Bartol and Ketten 2006). The overall range of green sea turtle hearing is 60–1000 Hz (Ridgway et al. 1969). Juvenile loggerheads are reported to hear well between 250 and 1000 Hz (Bartol et al. 1999) and are most sensitive at 250 Hz; however, the researchers did not assess hearing sensitivity below 250 Hz or above 1000 Hz. Two juvenile Kemp's ridley turtles generally had a lower upper range and lower range of sensitivity compared to what is known for green and loggerhead turtles.

3.5 MYSTICETES

There are currently 15 recognized species of living baleen whales (mysticetes). Baleen whales are widely distributed in all of the world's major oceans; their conservation status, populations, habitats, and distribution are given in Table 3.4. Most baleen whales were heavily exploited by commercial whaling industries, in some cases over several centuries. There has been recovery of some species or stocks in recent years, although others have shown little or no recovery despite protection, and remain highly vulnerable to extinction. Most mysticete species are listed as endangered under the U.S. ESA and on the 2010 IUCN

TABLE 3.4. Summary of the status, global population size and trends, habitat, and general distribution and movements of mysticetes.

Species	Status[1] ESA/IUCN	Global Population Size/Trend[2]	Habitat	General Distribution/ Migratory Movements[3]
N Atlantic right whale (*Eubalaena glacialis*)	E/E	~393/?	Coastal, shallow shelf waters, occasionally offshore	Mostly temperate/subpolar N. Atlantic; winter US & Africa; summer SE Canada/NE US.
N Pacific right whale (*Eubalaena japonica*)	E/E	~400/?	Coastal, shallow shelf waters, occasionally offshore	Mostly temperate/subpolar; summer Sea of Okhotsk to Gulf of AK; winter grounds/migratory patterns unknown
Southern right whale (*Eubalaena australis*)	E/LC	~7000/↑	Coastal, shallow shelf waters, occasionally offshore	30–60°S; summer Antarctica, S Ocean; winter/spring Argentina, S Africa, S Australia
Bowhead whale (*Balaena mysticetus*)	E/LC	~16,000/↑	Associated with ice, juveniles in shallow waters in late summer.	Arctic/subarctic; summer arctic, winter subarctic; migrate spring/fall, calve spring
Pygmy right whale (*Caperea marginata*)	NL/DD	NA	Coastal–pelagic, shallow–deep	Subantarctic/temperate waters 30–52° S; winters S Africa; unknown Breeding/calving/migration
Gray whale (*Eschrichtius robustus*) Eastern N Pacific population Western Pacific population	 NL/LC E/CR	18,813/ — 2521	Mostly shallow coastal lagoons	E. population: Winter Mexican lagoons; spring/fall migration coastal NE Pacific; summer Bering/Chukchi W. population: Summer Sea of Okhotsk; winter SE China
Humpback whale (*Megaptera novaeangliae*)	E/LC	~27.000–36.000/↑	Shallow–deep	Widely distributed; some remain in high latitudes year round
Minke whale (*Balaenoptera acutorostrata*); N. Atlantic, N. Pacific, and Dwarf subsp.	NL/LC	~960,000/—	Shallow–deep, often coastal	All N Hemisphere oceans; breeding areas unknown. Dwarf subsp. S hemisphere; winters Australia, New Caledonia, S Africa, Brazil; summers 65° S
Antarctic minke whale (*Balaenoptera bonaerensis*)	NL/DD	760,000/?	Shallow–deep	Summer feeding Antarctic; winter breeding tropical/subtropical open ocean and off Brazil
Bryde's whale (*Balaenoptera brydei*) and Eden's or pygmy Bryde's whale (*B. edeni*)	NL/DD	90,000/?	Shallow=deep	40° N–40° S; seasonally temperate W Pacific; year-round S Africa, Gulf of Calif.; breeding S Africa; feeding not known; pygmy Indian Ocean, Australasia, and W Pacific
Omura's whale (*Balaenoptera* cf. *B. omurai*)	NL/DD	NA/?	Shelf, tropical/subtropical	Western Pacific and eastern Indian oceans
Sei whale (*Balaenoptera borealis*)	E/E	>54,000/?	Mostly offshore	Global, temperate waters; specific breeding grounds unknown
Fin whale (*Balaenoptera physalus*)	E/ E	~100,000–150,000/?	Mostly pelagic, continental slope	Global, rare tropical/polar; common in Mediterranean Sea; some remain in higher latitudes year round; breeding areas, unknown but assumed mid-latitude pelagic waters
Blue whale (*Balaenoptera musculus*): Pygmy, Antarctic, N. Hemisphere subsp.	E/E	~10,000–13,000/↑	Coastal/ pelagic shallow-deep	Global; winter continental shelf, incl. Bermuda; some summer low-latitude upwelling areas in Pacific; some may be year-round residents

[1] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = not listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: CR = Critically Endangered, E = Endangered, DD = Data Deficient. All species but the West Greenland population of the minke whale are also listed in by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in Appendix I, meaning threatened with extinction from international trade (UNEP–WCMC 2009); the exception is listed in Appendix II.
[2] Population estimates from various sources: NA = reliable data not available; Trends from IUCN (2010): ↑ = increasing, ↓ = decreasing, — = stable, ? = unknown.
[3] Summer feeding in high latitudes and winter breeding/calving in low latitudes unless otherwise stated.
[4] Burdin et al. (2010).

Red List of Threatened Species (Table 3.4). In addition, Critical Habitat is designated under the ESA for the North Atlantic and North Pacific right whales.

The hearing abilities of mysticetes have not been studied directly, but can be inferred from vocalizations, the sounds to which they do and do not respond, and their auditory anatomy. Optimum hearing is likely within the frequency range of vocalizations, but hearing may extend beyond that range because other environmental sounds may also be important to mysticetes (Ketten 2004; Southall et al. 2007).

Behavioral and anatomical evidence indicates that mysticetes hear well at frequencies below 1 kHz (Richardson et al. 1995; Ketten 2000). For baleen whales as a group, the functional hearing range is thought to be ~7 Hz to 22 kHz or possibly 25 kHz, and baleen whales constitute the "low-frequency" (LF) hearing group (Southall et al. 2007; Scholik-Schlomer in press). Spectral peaks in mysticete vocalizations are generally between 12 Hz and 3 kHz, with the most important frequencies for particular species varying within this range. Fin and blue whales produce infrasonic signals at frequencies as low as 10–12 Hz, and commonly at 16–25 Hz. However, the calls of some other baleen whale species (especially those occurring predominantly in shallow waters) tend to be mainly at somewhat higher frequencies. The upper limit of functional hearing for mysticetes as a group is thought to be about 22 kHz (Southall et al. 2007). However, Scholik-Schlomer (in press) indicates that U.S. regulatory procedures may assume an upper limit of 25 kHz. Frankel (2005) reported that gray whales reacted to 21–25 kHz whale-finding sonar. Some baleen whales react to pinger sounds up to 28 kHz, but not to pingers or sonars emitting sounds at 36 kHz or above (Watkins 1986). In addition, baleen whales produce sounds at frequencies up to 8 kHz and, for humpbacks, with components to >24 kHz (Au et al. 2006).

The anatomy of the baleen whale inner ear seems to be well adapted for detection of low-frequency sounds (Ketten 1991, 1992, 1994, 2000), but there are no direct measurements of hearing sensitivity in baleen whales. The absolute sound levels that they can detect below 1 kHz are probably limited by the background noise level rather than absolute hearing sensitivity (Clark and Ellison 2004). Ambient noise levels are generally higher at low frequencies than at mid frequencies. At frequencies below 1 kHz, natural ambient levels tend to increase with decreasing frequency.

3.6 ODONTOCETES

Of 72 recognized species of living odontocetes (toothed whales) occurring worldwide (Jefferson et al. 2008), 67 can occur in marine waters (Table 3.5, which also includes the newly-described Arabian common dolphin). Of the species included in Table 3.5, there are four species or populations listed under the U.S. ESA: the sperm whale, the Southern Resident Population of killer whales, the vaquita or Gulf of California harbour porpoise, and the Cook Inlet population of beluga whales.

Odontocetes are a diverse group in distribution, habitat use, acoustic abilities, and behaviour. Most inhabit marine waters, although some have adapted to an estuarine environment (e.g., the Tucuxi dolphin, Irawaddy dolphin, and finless porpoise) and four or five species of river dolphins occur only in fresh water.

Many odontocetes avoid vessels and are not easily sighted when at the surface (e.g., Richardson et al. 1995; Barlow and Gisiner 2006), and a number of beaked whale species are known only from beached animals or skulls. As a result, information on ecology, population sizes, and distribution is limited for many species. On the other hand, many dolphins spend considerable time near the surface in large groups, commonly interact with vessels, and are often taken as bycatch in fishing operations and/or held in captivity. Accordingly, dolphin species of the genera *Stenella*, *Delphinus*, and *Tursiops* have been the subject of more research, and population sizes are better known. Sperm whales, although they dive

TABLE 3.5. Summary of the status, global population size and trends, habitat, and general distribution and movements of marine odontocetes.

Species[1]	Status[2] ESA/IUCN/CITES	Global Population Size/Trend[3]	Habitat	General Distribution/ Migratory Movements
Sperm whale (*Physeter macrocephalus*)	E/VU/I	500,000 – 2 million/?	Deep water, continental slope	Cosmopolitan, most abundant tropical waters
Pygmy (*Kogia breviceps*), dwarf (*K. sima*) sperm whales	NL/DD/II	NA/?	Continental shelf edge, deep water	Cosmopolitan in warm waters
Baird's beaked whale (*Berardius bairdii*)	NL/DD/I	NA/?	Pelagic	Pacific N of 35ºN, Bering Sea, Sea of Okhotsk
Arnoux's beaked whale (*Berardius arnuxii*)	NL/DD/I	NA/?	Pelagic deep water	Southern oceans from 34ºS to ice edge
Shepherd's beaked whale (*Tasmacetus shepherdi*)	NL/DD/II	NA/?	Pelagic deep water	Circumpolar in cold temperate waters of S Hemisphere
Cuvier's beaked whale (*Ziphius cavirostris*)	NL/LC/II	NA/?	Pelagic deep water	Worldwide, except polar waters
Longman's beaked whale (*Indopacetus pacificus*)	NL/DD/II	NA/?	Pelagic	Tropical Pacific and Indian Ocean
Hector's beaked whale (*Mesoplodon hectori*)	NL/DD/II	NA/?	Pelagic	All oceans in S hemisphere
True's beaked whale (*Mesoplodon mirus*)	NL/DD/II	NA/?	Pelagic	N Atlantic Ocean, 30ºN–50ºN
Gervais' beaked whale (*Mesoplodon europaeus*)	NL/DD/II	NA/?	Pelagic	Tropical and warmer temperate Atlantic
Sowerby's beaked whale (*Mesoplodon bidens*)	NL/DD/II	NA/?	Continental shelf edge, slopes	N temperate to sub-polar N Atlantic
Gray's beaked whale (*Mesoplodon grayi*)	NL/DD/II	NA/?	Pelagic	Circumpolar temperate S Hemisphere
Pygmy beaked whale (*Mesoplodon peruvianus*)	NL/DD/II	NA/?	Pelagic	Tropical oceans, 15ºS–25ºN
Andrew's beaked whale (*Mesoplodon bowdoini*)	NL/DD/II	NA/?	Pelagic	Circumpolar temperate S hemisphere
Spade-toothed whale (*Mesoplodon traversii*)	NL/DD/II	NA/?	Pelagic	Only 3 stranding records from temperate S Pacific
Hubb's beaked whale (*Mesoplodon carlhubbsi*)	NL/DD/II	NA/?	Pelagic	Cold temperate N Pacific
Ginkgo-toothed beaked whale (*Mesoplodon ginkgodens*)	NL/DD/II	NA/?	Pelagic	Temperate and cooler tropical waters Pacific and Indian oceans
Stejneger's beaked whale (*Mesoplodon stejnegeri*)	NL/DD/II	NA/?	Pelagic	Cold North Pacific, Sea of Japan, Bering Sea
Strap-toothed whale (*Mesoplodon layardii*)	NL/DD/II	NA/?	Pelagic	Circumpolar temperate and subantarctic
Blainville's beaked whale (*Mesoplodon densirostris*)	NL/DD/II	NA/?	Pelagic	Tropical and warmer temperate worldwide
Perrin's beaked whale (*Mesoplodon perrini*)	NL/DD/II	NA/?	Pelagic	Strandings known from California
Northern bottlenose whale (*Hyperoodon ampullatus*)	NL/DD/I	NA/?	Pelagic , submarine canyons.	Subarctic north Atlantic to Nova Scotia;
Southern bottlenose whale (*Hyperoodon planifrons*)	NL/LC/I	NA/?	Pelagic	30ºS to ice edge; summer Antarctica, winter more temperate
Beluga (*Dephinapterus leucas*)	NL[4]/NT/II	100,000 – 150,000/? Some subpop. ↓	Coastal, estuaries	Arctic/subarctic; ice-covered seas winter, warm estuaries early summer
Narwhal (*Monodon monoceros*)	NL/NT/II	NA/?	Edge of pack ice	Arctic, seasonal movements follow ice
Killer whale (*Orcinus orca*)	NL[5]/DD/II	1000s to tens of 1000s/? S Residents BC, WA ↓;	Open ocean to estuaries/ fjords.	Tropical to pack ice
False killer whale (*Pseudorca crassidens*)	NL/DD/II	Tens of thousands/?	Pelagic	Tropical to temperate worldwide

TABLE 3.5. Continued.

Species[1]	Status[2] ESA/IUCN/CITES	Global Population Size/Trend[3]	Habitat	General Distribution/ Migratory Movements
Pygmy killer whale (*Feresa attenuata*)	NL/DD/II	Hundreds of thousands/?	Deep water	Pantropical
Melon-headed whale (*Peponocephala electra*)	NL/LC/II	Tens of thousands/?	Pelagic	Pantropical, 20ºN–20ºS;
Long-finned pilot whale (*Globicephala melas*)	NL/DD/II	Millions/?	Pelagic	Mid-latitude N Atlantic and S hemisphere
Short-finned pilot whale (*Globicephala macrorhynchus*)	NL/DD/II	Tens of thousands/?	Pelagic	Circumglobal 40ºS–50ºN
Risso's dolphin (*Grampus griseus*)	NL/DD/II	Hundreds of thousands/?	Steep slopes, seamounts, escarpments	Tropical, mid-temperate worldwide,~55ºS–60ºN
Short-beaked common dolphin (*Delphinus delphis*)	NL/LC/II	Millions/?	Shelf, pelagic, high relief	Tropical and temperate, worldwide
Long-beaked common dolphin (*Delphinus capensis*)	NL/DD/II	>25 000/?	Nearshore	Tropical and warm temperate of some oceans
Arabian common dolphin (*Delphinus tropicalis*)	NL/-/II	NA/?	Coastal	Coastal Arabian Sea, South China Sea
Fraser's dolphin (*Lagenodelphis hosei*)	NL/LC/II	Hundreds of thousands/?	>1000 m deep	Tropical occasionally temperate
Indo-Pacific humpback dolphin (*Sousa chinensis*)	NL/NT/I	A few thousand/↓	Coastal and estuarine	Indian Ocean, southern China, Borneo, northern/ eastern Australia
Atlantic humpbacked dolphin (*Sousa teuszii*)	NL/VU/I	NA/↓	Marine estuaries, river mouths	Western Sahara to Angola
Bottlenose dolphin (*Tursiops truncatus*)	NL/LC/II	Millions/?	Continental shelf and upper slope <1000 m deep or pelagic	Temperate and tropical excluding Indian Ocean
Indo-Pacific bottlenose dolphin (*Tursiops aduncus*)	NL/DD/II	NA/?	Coastal and shelf	Rim of Indian Ocean from western Pacific to Red Sea and Persian Gulf
Pantropical spotted dolphin (*Stenella attenuata*)	NL/DD/II	Millions/?	Deep waters	Tropical worldwide
Atlantic spotted dolphin (*Stenella frontalis*)	NL/DD/II	Millions/?	Continental shelf <250 m deep	Tropical and warm temperate western north Atlantic
Spinner dolphin (*Stenella longirostris*)	NL/DD/II	~2 million/?	Pelagic; near oceanic islands	Pantropical 30º–40ºN and 20º–30ºS
Clymene dolphin (*Stenella clymene*)	NL/DD/II	Thousands/?	Depths 700 to >3000 m	Tropical warm Atlantic
Striped dolphin (*Stenella coeruleoalba*)	NL/LC/II	Hundreds of thousands/?	Pelagic, shelf edge	Tropical and temperate
White-beaked dolphin (*Lagenorhychus albirostris*)	NL/LC/II	Tens of thousands/?	Continental shelf	Subarctic north Atlantic, to edge of pack ice
Atlantic white-sided dolphin (*Lagenorhynchus acutus*)	NL/LC/II	Tens to hundreds of thousands/?	Continental shelf, slope, canyons	Temperate and subarctic North Atlantic
Pacific white-sided dolphin (*Lagenorhynchus obliquidens*)	NL/LC/II	~1 million/?	Continental margins, occasionally inshore	Temperate North Pacific
Dusky dolphin (*Lagenorhynchus obscurus*)	NL/DD/II	NA/?	Coastal, shelf <200 m deep	Discontinuous in southern Pacific;
Peale's dolphin (*Lagenorhynchus australis*)	NL/LR-lc/II	NA/?	Shallow coastal	Argentinean and Chilean waters south of 40ºS
Hourglass dolphin (*Lagenorhynchus cruciger*)	NL/LC/II	Hundreds of thousands/?	Pelagic	Southern hemisphere south of 45ºS

TABLE 3.5. Concluded.

Species[1]	Status [2] ESA/IUCN/CITES	Global Population Size/Trend[3]	Habitat	General Distribution/ Migratory Movements
Commerson's dolphin (*Cephalorhynchus commersonii*)	NL/DD/II	NA/?	Inshore, open coasts, fjords, bays, harbours, river mouths	Argentina, Tierra del Fuego, Falkland Isls., Kerguelen Isls.
Heaviside's dolphin (*Cephalorhynchus heavisidii*)	NL/DD/II	NA/?	Coastal, within 8-10 km of shore, <100 m	Coastal southwestern Africa
Black or Chilean dolphin (*Cephalorhynchus eutropia*)	NL/NT/II	NA but low/↓	Open coasts, bays, river mouths, estuaries	Coastal Chile and Tierra del Fuego
Hector's dolphin (*Cephalorhynchus hectori*)	NL/EN/II	7400/↓	Shallow	Coastal New Zealand
Rough-toothed dolphin (*Steno bredanensis*)	NL/LC/II	NA/?	Pelagic	Worldwide tropical, subtropical, warm temperate
Northern right whale dolphin (*Lissodelphis borealis*)	NL/LC/II	Hundreds of thousands/?	Shelf and slope >2000m	Cooler temperate and subarctic northern Pacific, 30º–50ºN
Southern right whale dolphin (*Lissodelphis peronii*)	NL/DD/II	NA/?	Mostly pelagic, occasionally coastal	Between subtropical and Antarctic convergences S hemisphere
Tucuxi (*Sotalia fluviatilis*) or Costero (*S. guianensis*)[6]	NL/DD/I	NA/?	Coastal, estuarine and riverine waters	Amazon–Orinoco River system, coastal from Columbia to southern Brazil
Irrawaddy dolphin (*Orcaella brevirostris*)	NL/CR/I	>1000/↓	Mangrove wetlands, estuarine, shallow coastal	Discontinuous in E Indian Ocean, coasts of SE Asia, India, Indonesia
Australian snubfin dolphin (*Orcaella heinsohni*)	NL/NT/I	<<10,000/?	shallow coastal, estuarine	Tropical and subtropical zones of Australia, possibly parts of New Guinea
Finless porpoise (*Neophocaena phocaenoides*)	NL/VU worldwide, E in China/I	Thousands/↓	Coastal and estuarine waters	Tropical Asia, central Japan to Java and Persian Gulf
Harbour porpoise (*Phocoena phocoena*)	NL/LC/II	Thousands/? Many Subpopulations ↓	Shallow coastal and shelf	Arctic to temperate northern Atlantic and Pacific, Black Sea
Vaquita (*Phocoena sinus*)	E/CR/I	~250 ↓	Shallow, lagoons, waters <30 m	Northern Gulf of California
Spectacled porpoise (*Phocoena dioptrica*)	NL/DD/II	NA but rare/?	Pelagic	Circumpolar colder temperate to Antarctic
Burmeister's porpoise (*Phocoena spinnipinnis*)	NL/DD/II	NA/?	Coastal <100 m deep but up to 1000 m.	Cape Horn to N Peru
Dall's porpoise (*Phocoenoides dalli*)	NL/LC/II	Hundreds of thousands to millions/?	Inshore to pelagic	N Pacific and adjacent seas, 20º–65ºN

[1] Excludes all four species of river (freshwater) dolphins, the Ganges and Indus river dolphins (*Platanista gangetica*) Amazon river dolphin (*Inia geoffrensis*) Yangtze river dolphin (*Lipotes vexillifer*), and Franciscana or La Plata dolphin (*L. vexillifer*).
[2] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = not listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: CR = Critically Endangered, E = Endangered, VU = Vulnerable, DD = Data Deficient, LC – Least Concern / Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC 2009): Appendix I = Threatened with extinction; Appendix II = not necessarily now threatened with extinction but may become so unless trade is closely controlled; Appendix III: protected in at least one country, which has asked other CITES Parties for assistance in controlling the trade.
[3] Population estimates from various sources: NA = reliable data not available; Trends from IUCN (2010): ↑ = increasing, ↓ = decreasing, — = stable, ? = unknown
[4] Cook Inlet Population
[5] Southern Resident Population
[6] It has been proposed that the coastal form of the Tucuxi be recognized as a separate species from the riverine form (Caballero et al 2007).

deeply and for extended periods, are also fairly well known from historic whaling records and recent studies.

Odontocetes rely on underwater sound to communicate and to obtain information about their surroundings (Au 1993; Richardson et al. 1995; Au et al. 2000; Reeves et al. 2002). The hearing abilities and sound production characteristics of some odontocete species have been studied in detail (e.g., Au et al. 2000; Miller et al. 2005; Southall et al. 2007). However, available data come from a limited number of species and, for almost all of those, from very few (often only 1 or 2) individuals. The results from the bottlenose dolphin, where hearing by numerous individuals has been studied, show considerable variability in the hearing abilities of different individuals (Houser and Finneran 2006). Nonetheless, for odontocetes as a group, considerable information about hearing is available. For species that have been studied, hearing sensitivity is relatively poor at low frequencies (e.g., <150 Hz) where seismic survey sounds have most of their energy. The functional hearing range for odontocetes as a group is considered to be from about 150 Hz at the low end to 180 kHz at the upper end (Southall et al. 2007). However, there is some limited sensitivity (at least in some of the odontocete species) to strong sounds below 150 Hz.

The small to moderate-sized toothed whales whose hearing has been studied have relatively poor hearing sensitivity at frequencies below 1 kHz, but extremely good sensitivity at and above several kHz. There are very few data on the absolute hearing thresholds of most of the larger, deep-diving toothed whales, such as the sperm and beaked whales. However, Cook et al. (2006) found that a Gervais' beaked whale showed evoked potentials to sounds with frequencies 5 kHz up to 80 kHz (the entire frequency range that was tested), with the best sensitivity at 40–80 kHz. Finneran et al. (2009) also found that this species had functional hearing up to 80–90 kHz. Insofar as we are aware, there are no specific data on low frequency hearing in any beaked whale, but the anatomy of the beaked whale ear is similar to that in other odontocetes known to have relatively insensitive hearing at low frequencies.

Most odontocete species have been classified as belonging to the "mid-frequency" (MF) hearing group with functional hearing from ~150 Hz to 160 kHz (Southall et al. 2007), although individual species may not have such a wide functional frequency range. High-level sounds at frequencies slightly outside the functional range, e.g., below 150 Hz where seismic signals contain most of their energy, could also be detectable. The remaining odontocetes—the porpoises, river dolphins, and members of the genera *Cephalorhynchus* and *Kogia*—are distinguished as the "high frequency" (HF) hearing group with functional hearing from about 200 Hz to 180 kHz (Southall et al. 2007).

Small odontocetes are almost certainly less sensitive to the low frequencies that contribute most of the energy in pulses of sound from airgun arrays than are mysticetes (above) or pinnipeds (below). However, at least some of the odontocetes have sufficient hearing sensitivity at low and moderate frequencies to detect airgun sounds out to distances well beyond 10 km (Richardson and Würsig 1997). Their ability to detect airgun sounds is largely related to the presence of some airgun sound components at frequencies of a few hundred Hertz (Richardson and Würsig 1997). If components above 100 Hz can be excluded or largely excluded from future MarVib signals, that should further reduce the prominence of MarVib signals to odontocetes beyond the reduction that would be associated with reduced peak pressure.

3.7 Pinnipeds

Pinnipeds are classified into three taxonomic groups: Odobenidae (the walrus), Phocidae (the "true" or earless seals), and Otariidae (the "eared" seals). There are ~34[4] species of pinnipeds occurring worldwide

[4] The Japanese sea lion (*Zalophus japonicus*) is considered extinct (IUCN 2010).

(Rice 1998; Nowak 1999; Jefferson et al. 2008). The conservation status, populations, habitats, and distributions of pinnipeds are summarized in Table 3.6. Two pinniped species are currently being considered for listing under the U.S. ESA as threatened or endangered, the bearded seal and ringed seal (NMFS 2008a). The status of a third species, the ribbon seal, was reviewed and NMFS published a finding that a listing under the ESA was not warranted at that time (NMFS 2008b). A status review of the spotted seal was conducted and NMFS issued a proposed ***threatened*** status for the southern distinct population segment (DPS), which occurs in the Yellow Sea and Sea of Japan, and "not warranted" status for the Okhotsk and Bering Sea SPSs (NMFS 2009).

Pinnipeds produce both in-air and underwater sounds. Underwater sounds mainly appear to be associated with mating, mother-pup interactions, and territoriality. Otariids use in-air vocalizations to defend territories, attract females, and maintain the mother-pup bond, whereas in otariids, underwater calls are mainly used to establish dominance.

Underwater audiograms have been obtained using behavioral methods for three species of phocinid seals, two species of monachid seals, two species of otariids, and the walrus (reviewed in Richardson et al. 1995: 211*ff*; Kastak and Schusterman 1998, 1999; Kastelein et al. 2002). The functional hearing range for pinnipeds in water is considered to extend from 75 Hz to 75 kHz (Southall et al. 2007), although some individual species—especially the eared seals—do not have that broad an auditory range (Richardson et al. 1995). In comparison with odontocetes, pinnipeds tend to have lower best frequencies, lower high-frequency cutoffs, better auditory sensitivity at low frequencies, and poorer sensitivity at the best frequency.

At least some of the phocid seals have better sensitivity at low frequencies (≤1 kHz) than do odontocetes. Below 30–50 kHz, the hearing thresholds of most species tested are essentially flat down to ~1 kHz, and range between 60 and 85 dB re 1 µPa. Measurements for a harbour seal indicate that, below 1 kHz, its thresholds deteriorate gradually to ~97 dB re 1 µPa at 100 Hz (Kastak and Schusterman 1998). The northern elephant seal's threshold remains essentially flat at ~72 dB re 1 µPa down to 200 Hz, then increases to ~90 dB re 1 µPa at 100 Hz (Kastak and Schusterman 1998, 1999).

For the otariid (eared) seals, the high frequency cutoff is lower than for phocinids, and sensitivity at low frequencies (e.g., 100 Hz) is poorer than for seals (harbor seal).

3.8 SIRENIANS

Manatees and the dugong are classified as members of the order Sirenia. Of the three species of manatee, the Amazonian manatee occurs mainly in rivers and is not considered further here. The conservation status, populations, habitats, and distribution of marine sirenians are given in Table 3.7.

West Indian manatees are capable of hearing sounds from 15 Hz to 46 kHz, based on a study involving behavioral testing methods, with their best sensitivity at 6–20 kHz (Gerstein et al. 1999). The ability to detect high frequencies could be an adaptation to shallow water, where the propagation of low frequency sound is limited (Gerstein et al. 1999). However, manatees have comparatively good sensitivity at low frequencies. Based on measurements of evoked potentials, manatee hearing is apparently best around 1–1.5 kHz (Bullock et al. 1982). It is also possible that manatees are able to feel low-frequency sounds and vibrations using vibrotactile receptors or because of resonance in body cavities or bone conduction. Dugong hearing is reportedly "acute" (State of Queensland 1999) but additional information is unavailable. Dugongs are known to produce calls that range in frequency from 1 to 8 kHz (Nair et al. 1975; Marsh et al. 1978; Nietschmann 1984 *in* Nishiwaki and Marsh 1985; Anderson and Barclay 1995).

TABLE 3.6. Summary of the status, global population size and trends, habitat, and general distribution and movements of pinnipeds.

Species	Status[1] ESA/ IUCN/CITES	Global Population Size/Trend[2]	Habitat	General Distribution and Movements
Walrus				
Pacific walrus (*Odobenus rosmarus divergens*)	NL/DD/III	~200,000?/?	Shallow, coastal, pack ice	Polar Pacific and Arctic, E Siberian Sea to W Beaufort Sea; move S with ice in fall and N with ice in spring
Atlantic walrus (*O. r. rosmarus*)	NL/DD/III	up to 22,500?/?	Shallow, coastal, pack ice	Polar N Atlantic and Arctic; move S with ice in fall and N with ice in spring
Phocids (True or Earless Seals)				
Bearded seal (*Erignathus barbatus*)	NL[3]/LC/NL	>500,000/—	Drifting sea ice in shallow water	Circumpolar in N Hemisphere S of ~80°; some winter in Bering Sea, migrate N to Chukchi Sea in summer
Harbour (common) seal (*Phoca vitulina*)	NL/LC/NL	>500,000/—	Coastal	Coastal N Pacific and N Atlantic; seasonal migrants south to New England, New York, New Jersey
Spotted seal (*Phoca largha*)	NL[4]/DD/NL	~400,000?/?	Associated with sea ice	Polar Pacific Ocean, from Seas of Okhotsk and Japan to Bering and W Beaufort
Ringed seal (*Pusa hispida*)	NL[3]/LC/NL	~4–7 million/?	Associated with sea ice	Circumpolar through Arctic Ocean, Hudson Bay, Baltic and Bering Seas
Baikal seal (*Pusa sibirica*)	NL/LC/NL	80,000–100,000/—	Islands, shoreline, ice	Lake Baikal and its rivers and streams
Caspian seal (*Pusa caspica*)	NL/EN/NL	111,000/↓	Islands, ice	Caspian Sea and its feeder rivers
Ribbon seal (*Phoca fasciata*)	NL/DD/NL	~240,000/?	Pelagic except offshore pack ice winter and spring	Polar Bering Sea, S Chukchi Sea, and Sea of Okhotsk
Gray seal (*Halichoerus grypus*)	NL/LC/NL	~300,000/↑	Coastal	Northern N Atlantic
Harp seal (*Phoca groenlandica*)	NL/LC/NL	6 million/↑	Pack ice	Arctic & N Atlantic; migrate N to feed during summer, S with advancing ice
Hooded seal (*Cystophora cristata*)	NL/VU/NL	~650,000/↓	Sea ice, shelf, maybe deep oceanic waters fall, winter	Centr., W N Atlantic; breeding in Gulf of St. Lawrence, E Newfoundland, Davis Strait, Jan Mayen Isl.
Southern elephant seal (*Mirounga leonina*)	NL/LC/II	~600,000/?	Oceanic islands, coastal to pelagic during foraging	Breed on oceanic islands in subantarctic and S Argentina; during non-breeding season, some migrate S to near Antarctica
Northern elephant seal (*Mirounga angustirostris*)	NL/LC/NL	~115,000/↑ California ↑; Mexico — or ↓	Coastal to pelagic during foraging and migrating	NE Pacific; large breeding colonies at Channel Islands off S Calif., smaller colonies off central Calif. and Baja Calif.; breed in winter, migrate N to the central and NE Pacific as far as Alaska
Leopard seal (*Hydrurga leptonyx*)	NL/LC/NL	~200,000/?	Pack and landfast ice, pelagic during foraging	S Ocean around Antarctica; migrate N during winter
Weddell seal (*Leptonychotes weddellii*)	NL/LC/NL	~800,000/?	Near-shore fast ice	Antarctica, South Georgia, South Sandwich Islands, South Shetland Islands, South Orkney Islands
Crabeater seal (*Lobodon carcinophagus*)	NL/LC/NL	~15 million/?	Pack ice	Southern Ocean, pack ice; near subantarctic islands
Ross seal (*Ommatophoca rossii*)	NL/LC/NL	~220,000/?	Pack ice	Circumpolar Southern Ocean
Mediterranean monk seal (*Monachus monachus*)	E/CR/I	400/↓	Coastal	Mediterranean Sea, northwest African coast
Hawaiian monk seal (*Monachus schauinslandi*)	E/CR/I	1300–1400/↓	Coastal	Northwestern Hawaiian Islands

TABLE 3.6. Concluded.

Species	Status[1] ESA/ IUCN/CITES	Global Population Size/Trend[2]	Habitat	General Distribution and Movements
Otariids (Eared Seals)				
Antarctic fur seal (*Arctocephalus gazella*)	NL/LC/II	1.5–4 million/↑	Oceanic islands, coastal to pelagic during foraging	Breeding colonies on oceanic islands in subantarctic and near Antarctica, 95% on South Georgia; during non-breeding season, some migrate S to near Antarctica
Juan Fernandez fur seal (*Arctocephalus philippii*)	NL/NT/II	12,000/↑	Coastal; long feeding trips	Juan Fernández and San Félix / San Ambrosio island groups off Chile
South African, Australian fur seals (*Arctocephalus pusillus*)	NL/LC/II	1.5–2 million (S Africa)/↑ 30,000–50,000 (Australia)	Coastal, rocky inshore islands	Namibian and South African coastlines; Kangaroo Island, SA to Tasmania and Port Macquarie, NSW
Subantarctic fur seal (*Arctocephalus tropicalis*)	NL/LC/II	>310,000/↑	Oceanic islands, pelagic to forage	Subantarctic breeding colonies in S Atlantic, Indian, Pacific; most breed on islands in S Atlantic, Amsterdam (Indian Ocean)
Guadalupe fur seal (*Arctocephalus townsendi*)	T/NT/I	~7408/↑	Coastal, shelf, pelagic to forage	NE Pacific off Calif. and Baja Calif.; breed almost exclusively on Guadalupe Island, Mexico
South American fur seal (*Arctocephalus australis*)	NL/LC/II	300,000–450,000/↑	Coastal	South America from central Peru and S Brazil to Tierra del Fuego and Falkland Islands
New Zealand fur seal (*Arctocephalus forsteri*)	NL/LC/II	>50,000/↑	Coastal, rocky coasts, islands	Western Australia, South Australia, Tasmania and New Zealand, subantarctic islands E and S of New Zealand
Galapagos fur seal (*Arctocephalus galapagoensis*)	NL/EN/II	40,000/↓	Rocky coasts	Galapagos Islands
Northern fur seal (*Callorhinus ursinus*) E Pacific stock San Miguel Isl. stock	 NL/VU/NL NL/VU/NL	1.2–4 million/↓ 888,120 ~7784	Pelagic	Temperate N Pacific, Bering Sea, Sea of Okhotsk; 1º breeding colonies Pribilof and Commander Isls.; in fall, M stay in Bering Sea, F migrate to central N Pacific and Calif. Coast. One breeding colony on San Miguel Isl., Calif.; maybe year-round
California sea lion (*Zalophus californianus*)	NL/LC/NL	~240,000/↑	Coastal, shelf	Temperate N Pacific; breed at Channel Islands, Calif. and Baja Calif. including Guadalupe Island
Steller sea lion (*Eumetopias jubatus*) Western U.S. stock Eastern U.S. stock	 E/E/NL T/E/NL	100,000/↓ 44,780 47,885	Coastal, shelf	Temperate N Pacific Ocean and S Bering Sea; W stock includes animals west of 144ºW, along Aleutian Islands, E stock includes animals east of 144ºW
Australian sea lion (*Neophoca cinerea*)	NL/EN/NL	10,000–12,000/↓	Offshore islands and coastal	Temperate, S Australia; largest colonies on offshore island in eastern S Australia
Galapagos sea lion (*Zalophus wollebaeki*)	NL/EN/NL	20,000–50,000/↓	On and near islands	Galapagos Islands
South American sea lion (*Otaria flavescens*)	NL/LC/NL	265,000/—	Coastal, wide-ranging	South America from northern Peru and SE Brazil to Tierra del Fuego and Falkland Islands
New Zealand sea lion (*Phocarctos hookeri*)	NL/VU/NL	12,000–14,000/↓	Coastal	South Island New Zealand, islands south of New Zealand

[1] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = not listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: CR = Critically Endangered, E = Endangered, DD = Data Deficient, VU – Vulnerable, NT = Near Threatened; LC = Least Concern / Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC 2009): Appendix I = Threatened with extinction; Appendix II = not necessarily now threatened with extinction but may become so unless trade is closely controlled; Appendix III: protected in at least one country, which has asked other CITES Parties for assistance in controlling the trade.
[2] Population estimates from various sources: NA = reliable data not available; Trends from IUCN (2010): ↑ = increasing, ↓ = decreasing, — = stable, ? = unknown
[3] Under consideration for listing under ESA
[4] Proposed threatened status for the southern distinct population segment (DPS), which occurs in the Yellow Sea and Sea of Japan, and not warranted status for the Okhotsk and Bering Sea SPSs

TABLE 3.7. Summary of the status, global population size and trends, habitat, and distribution and movements of sirenians.

Species	Status[1] ESA/ IUCN/CITES	Global Population Size/Trend[2]	Habitat	Distribution and Migratory Movements
Dugong (*Dugong dugon*)	NL/VU/I	NA/? >85,000? (Australia)	Highly coastal, tidal sandbanks, estuaries	Red Sea, Gulf of Aqaba, E coast of Africa, S coast of Asia, Madagascar, Indian Ocean, Australia
West African manatee (*Trichechus senegalensis*)	NL/VU/II	<10,000/?	Shallow coastal waters, freshwater rivers	Coastal waters and rivers from Senegal to Angola
W Indian manatee (*Trichechus manatus*)	E/VU/I	NA/↓	Subtropical, tropical freshwater systems, shallow nearshore	Florida, Greater Antilles, N and E South America, Central America, E Mexico; possible long-range migrations between population centers

[1] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = not listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: VU = Vulnerable / Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC 2009): Appendix I = Threatened with extinction; Appendix II = not necessarily now threatened with extinction but may become so unless trade is closely controlled.
[2] Population estimates from various sources: NA = reliable data not available; Trends from IUCN (2010): ↑ = increasing, ↓ = decreasing, — = stable, ? = unknown

3.9 CARNIVORA

In the order Carnivora are two species of marine mammals, the sea otter in the family Mustelidae and the polar bear in the family Ursidae. Their conservation status, populations, habitats, and distribution are given in Table 3.8.

TABLE 3.8. Summary of the status, global population size and trends, habitat, and general distribution and movements of the sea otter and polar bear.

Species	Status[1] ESA/ IUCN/CITES	Global Population Size/Trend[2]	Habitat	General Distribution/ Migratory Movements
Sea otter (*Enhydra lutris*)	T/E/II	107,000/—	Shallow, coastal, kelp forests	W North Pacific, central and SE Alaska, BC, Calif; non-migratory; local movements
Polar bear (*Ursus maritimus*)	T/VU/II	22,000–25,000/↓	Sea ice, marine	Circumpolar Arctic; Chukchi, Beaufort, East Siberia, Laptev, Kara, Barents, and Greenland seas, Baffin Bay, Canadian Arctic; long-distance movements, generally subpopulations

[1] U.S. Endangered Species Act (ESA): E = endangered, T = threatened, NL = not listed / International Union for Conservation of Nature and Natural Resources (IUCN) 2010 Red List of Threatened Species: T = Threatened / Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC 2009): Appendix II = not necessarily now threatened with extinction but may become so unless trade is closely controlled.

[2] Population estimates from Doroff and Burdin (2008) for sea otter and Schliebe et al (2008) for polar bear; Trends from IUCN (2010): ↑ = increasing, ↓ = decreasing, — = stable, ? = unknown

3.9.1 Sea Otter

No data are available on the hearing abilities of sea otters (Ketten 1998), although the in-air vocalizations of sea otters have most of their energy concentrated at 3–8 kHz (McShane et al. 1995; Thomson and Richardson 1995; Ghoul and Reichmuth in press). In-air audiograms for two river otters indicate that this related species has its best hearing sensitivity at the relatively high frequency of 16 kHz, with some sensitivity from ~460 Hz to 33 kHz (Gunn 1988). However, these data apply to a different species of otter, and to in-air rather than underwater hearing. Recent data for the sea otter suggest that in-air hearing extends from below 125 Hz to at least 32 kHz (Ghoul and Reichmuth in press).

3.9.2 Polar Bear

Data on the hearing capabilities of polar bears are limited. A recent study of the in-air hearing of polar bears applied the auditory evoked potential method while tone pips were played to anaesthetized bears (Nachtigall et al. 2007). Hearing was tested in ½-octave steps from 1 to 22.5 kHz, and best hearing sensitivity was found between 11.2 and 22.5 kHz. Other studies of captive polar bears suggested that they can detect sounds from 125 Hz to 14 kHz, with sensitivity declining rapidly above 20 kHz (Bowles et al. 2008). This indicates that polar bears could be able to detect low-frequency sounds. However, the polar bears' usual behaviour (e.g., remaining on the ice, at the water surface, or on land) reduces or avoids their exposure to underwater sounds.

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CHAPTER 4. AIRGUN AND MARINE VIBRATOR SOUNDS

Marine vibrators (MarVib) are quite different than airguns in many aspects of their design, operation, and typical use. As a result one must examine and evaluate a variety of system parameters in attempting to compare their characteristics.

Airguns create an acoustic signal by the release of a fixed volume of compressed air that evolves into an oscillating bubble. The amplitude and spectrum of the resultant acoustic field is governed by the array geometry, its depth relative to the ocean surface, the pressure of the compressed air, and the volume of air released by the individual array elements. Typically, array design is aimed at cancelling the oscillating bubble by using airguns of different volumes. Generally speaking, the larger the volume of an individual airgun, the greater is the amplitude and the lower the predominant frequency, with the output SPL of an individual element nominally increasing as the cube root of the volume (other factors being equal). However, the output from a single airgun is also dependent on port size and the characteristics of the lower air chamber. An airgun with large ports and a wide and short air chamber will have higher output than one with small ports and long narrow air chamber, if the volumes are equal. The overall output of an airgun array is generally related to the number of airgun elements in the array, but is also dependent on individual airgun volumes.

Existing MarVib devices are typically one of two types, both capable of creating coherent signals such as frequency sweeps. ***(1)*** The first existing type is a resonant device such as the PGS System MarVib [PGS 2005]. The peak source level of such a device will be at the resonant frequency of the transducer system, typically with a Q of 3 or less. (Q is the ratio of the bandwidth at the ½ power points divided by the center frequency.) Note that devices can be built with multiple resonances, thus achieving transmission over much broader bands as shown for the PGS system. ***(2)*** The second existing type is a mechanically driven piston-like device, usually hydraulically powered, that can produce a reasonably flat spectrum in the low frequency regime, but likely at lower levels (at any one frequency) than a resonant device produces at its resonant frequency. However, net energy in the overall transmit band may be roughly equivalent to that from a resonant device. Next generation MarVibs will likely aim toward greater energy in the frequency band <50 Hz, closer to the band now achievable with airguns, but with a reduction in the unwanted output at frequencies above the desired signal band.

Because both of the existing types of MarVib systems create sound by physically moving a surface in a harmonic manner, they are subject to both limitations and advantages in comparison with an impulsive device such as an airgun. The phenomenon of cavitation is relevant; it is usually described in concert with a term called the cavitation threshold, i.e., the point at which greater power cannot be generated. This threshold, and the potential radiated power, increase with increased source depth, frequency, and signal duration (Urick 1975). These are each design elements that must be taken into account in devising any next-generation MarVib. It should be noted that airguns also have some related limitations when operated near the surface. For the frequencies of interest to the oil industry, these can be dealt with by optimizing airgun array design and operating depth so as not to be a major issue.

When operating multiple coherent sources (such as MarVibs) in an array, there are other confounding issues to be addressed. For example, the net array cavitation threshold may be reduced because of the presence of hotspots within the array, i.e., locations where local pressure conditions vary from ideal. This issue is related to the equally problematic issue of accounting for the effective mutual impedance of individual units that varies depending on their location in an array. For a source array the size and scope of a low frequency MarVib design, such effects are best accounted for with individual amplifiers for each element allowing for individual control of phase and amplitude.

4.1 ARRAY BEAMFORMING

Arrays of sound sources are generally used for two purposes: (1) to increase the net sound level above that available with a single sound element (i.e., array gain), and (2) to direct the bulk of the sound energy in a desired direction and minimize the energy in other directions. The simplest type of array is a line array of elements spaced some distance, s, apart. If the array consists of N_E equivalent elements, one anticipates that the output transmit array gain on the main downward beam will be nominally proportional to $20\text{Log}(N_E)$, with the pressure transmitted by each element at some angle (broadside to the array) being in phase with the pressure from the other elements. A simple rule of thumb for the minimum distance required for this coherent addition (which occurs only in the far field) is that this distance must be greater than the array length squared divided by the acoustic wavelength of the frequency being transmitted.

By way of illustrating these array effects, we graphically compare the idealized results for a single point source of sound with an effective source level of 200 dB re 1 µPa @ 1 m, with the field from a horizontal linear array of seven such sources separated at 3 m intervals. In each instance, the source is located in an ideal half space submerged 7 m below the air/surface boundary (i.e., free surface or pressure release surface). The analytical technique used to create these results is to create a virtual array spaced at an equal distance above the free surface but operated at 180 degree phase shift, thereby simulating the free surface (Junger and Feit 1972). The result shown in Figure 4.1 below is for a single source, and that in Figure 4.2a,b is for the array of seven.

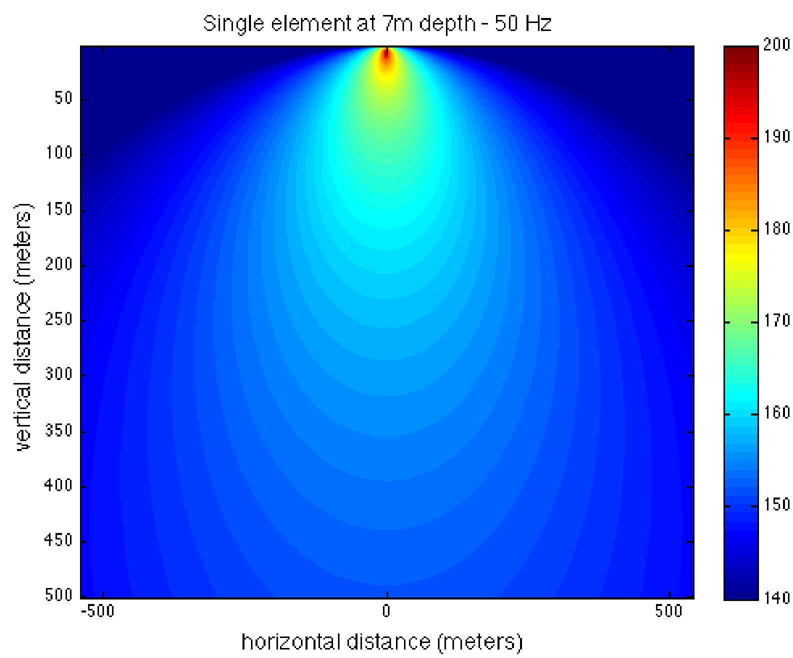
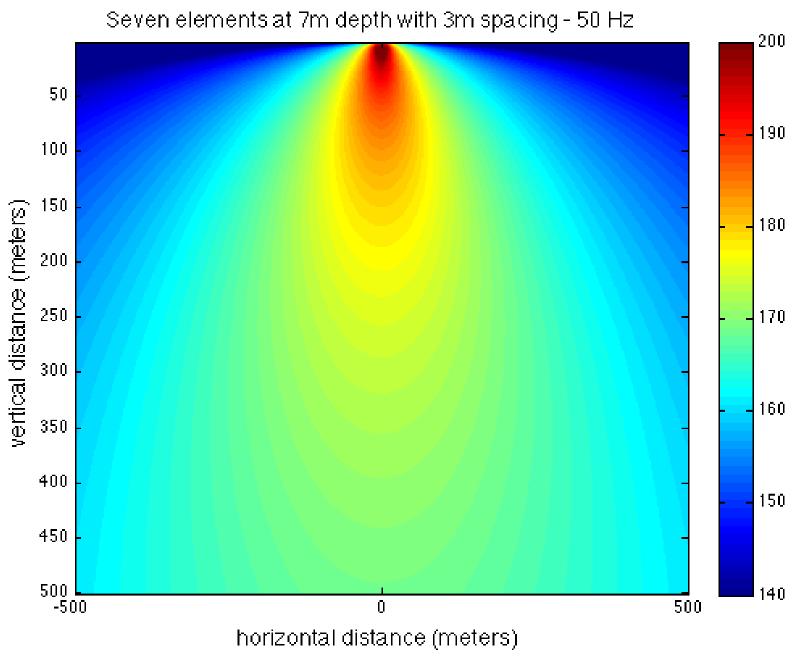


FIGURE 4.1. Propagation field (to 500 m) from an idealized 50-Hz point source at 7-m depth. Colour scale depicts received level in dB re 1 µPa. SL = 200 dB re 1 µPa @ 1m. (Note differing horizontal vs. vertical scales.)



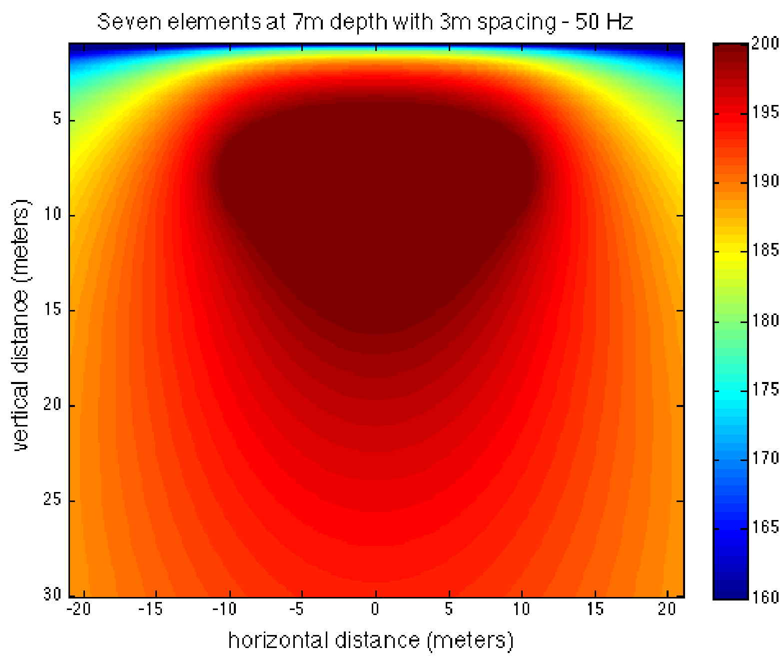


FIGURE 4.2. Propagation field to *(a)* 500 m (above) and *(b)* 30 m (below) from an idealized horizontal line array of 7 elements spaced at 3-m intervals. Each element is a 50-Hz point source at 7-m depth. Colour scale depicts received level in dB re 1 μPa. (Note differing horizontal vs. vertical scales.)

The effective source level of the 7-element array in the main downward beam is provided by

$$SL = SL_E + 20Log(N_E) \qquad (4\text{-}1)$$

where

SL_E = SL of an individual element

N_E = Number of elements in the array

In order to estimate the net received level at any point in the main beam from this source, several related terms must be identified:

d = depth in meters

$k = 2\pi f/c$ = acoustic wave number in m^{-1}

$\lambda = c/f$ = acoustic wavelength in m

f = frequency in Hz

c = sound speed in water in m/sec

R = distance from the array (on main beam) in meters

s = Array element spacing in meters

The following distance/spacing/frequency relationships apply to this simple modelling analysis:

$$kd,\ d/R \ll 1 \qquad (4\text{-}1a)$$

$$s = 3\ m$$

The received level, RL, along the main beam in a free space environment (i.e., no boundaries), can be estimated by

$$RL = [SL_E + 20Log(N_E)] - 20Log(R) \qquad (4\text{-}2a)$$

However, when the array is placed very near (kd<<1) the ocean surface (also called a free surface), the reflection process results in a doubling along the main axis (downwards in Fig. 4.1, 4.2) and an approximate addition of 20Log(2) is added to accommodate this effect:

$$RL = [SL_E + 20Log(N_E)] - 20Log(R) + 20Log(2) \qquad (4\text{-}2b)$$

This doubling factor is innately included in the complex modelling process used to generate Figures 4.1 and 4.2.

A graphic examination of Figures 4.1 and 4.2 serves to illustrate this result. Thus, for the single element at a distance of 500 m in the main downward beam we find a level of

$$RL(500\ m) = 200 + 20Log(1) + 6 - 20Log(500) = 152\ dB\text{ , single element}$$

and for the 7-element array, we find

$$RL(500\ m) = 200 + 20Log(7) + 6 - 20Log(500) = 169\ dB\text{, 7 element array}$$

Clearly both values (as they should) match the color pattern at these respective points on the propagation graphic. The purpose of this elementary illustrative exercise is to validate the utility of these types of graphics in describing the effects of frequency, distance, and array beamforming at frequencies and locations that are not so easily described by Eq's 4-1 and 4-2. If one examines our qualifying elements of Eq 4-1a and b, then it is clear that both the depth as a function of wavelength (inversely proportional to frequency) and spacing relative to wavelength will have more complicating effects on the result at higher frequencies. This is illustrated in a companion graphic for the same 7-element array now transmitting at a frequencies of 300 (Fig. 4.3a, b) and 1000 Hz (Fig. 4.4a, b).

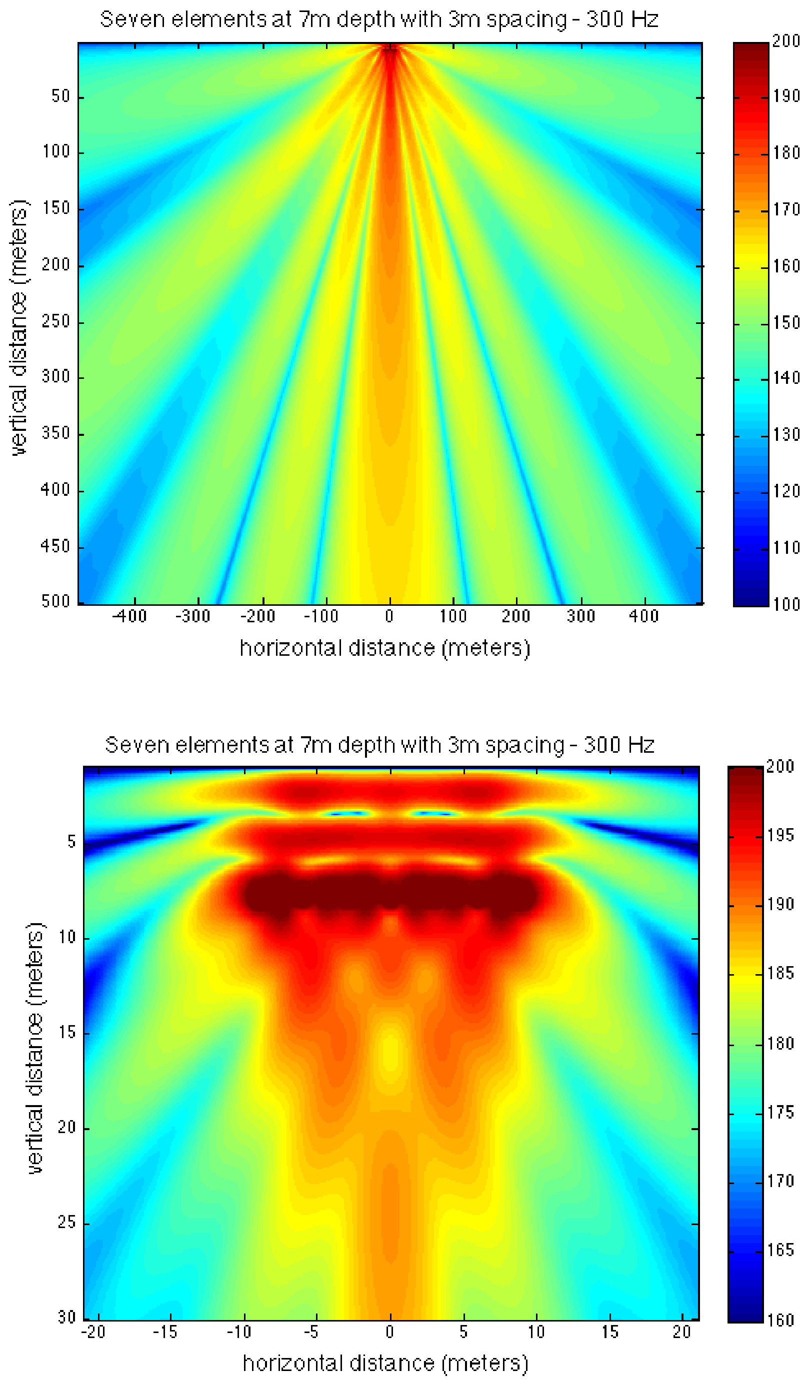


FIGURE 4.3. Propagation field to *(a)* 500 m (above) and *(b)* 30 m (below) from an idealized horizontal line array of 7 elements spaced at 3 m. Colour scale depicts received level in dB re 1 µPa. Each element is a 300-Hz point source at 7-m depth.

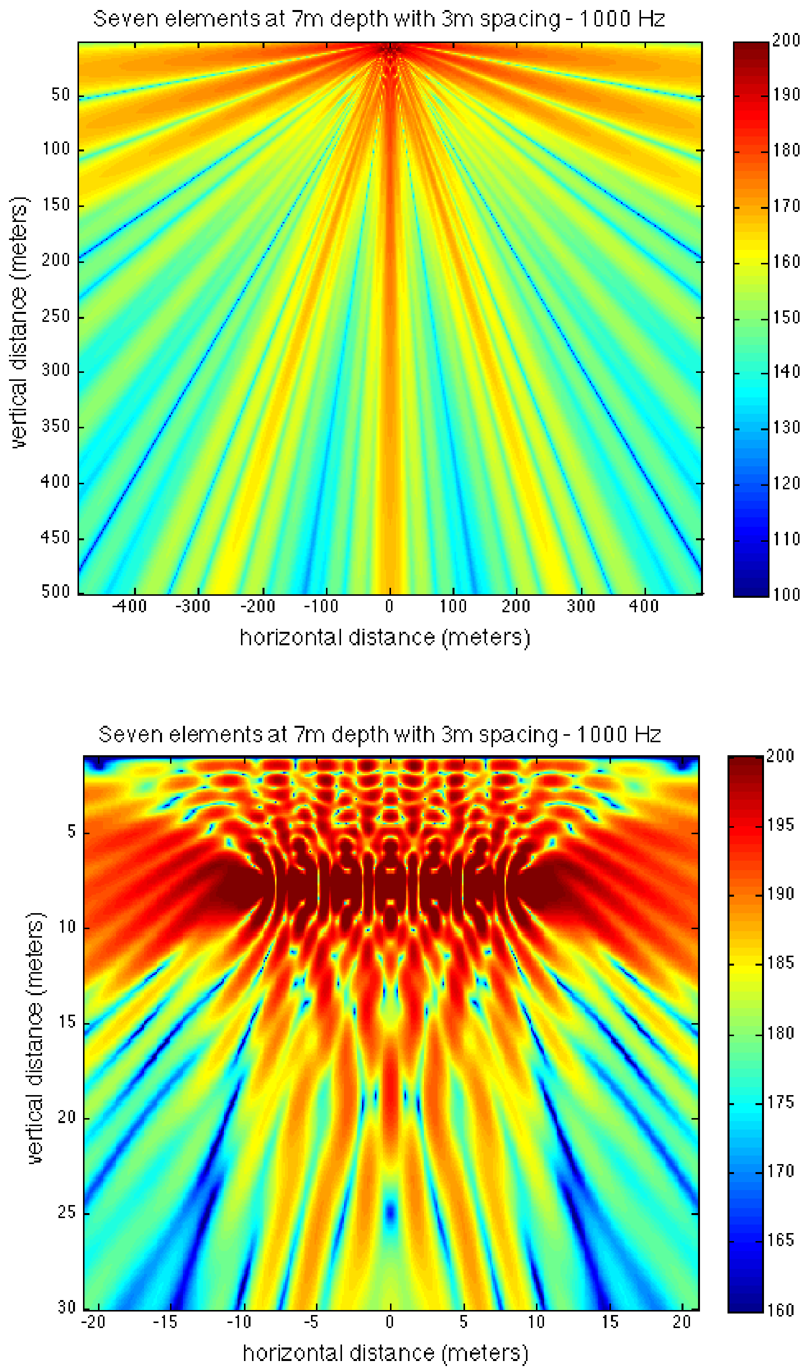


FIGURE 4.4. Propagation field to *(a)* 500 m (above) and *(b)* 30 m (below) from an idealized horizontal line array of 7 elements spaced at 3 m. Colour scale depicts received level in dB re 1 μPa. Each element is a 1000-Hz point source at 7-m depth.

At 1000 Hz the wavelength is 1.5 m and the 3-m spacing is now at 4 times the optimum, and could be termed a sparse array. The multiplicity of beams formed in this situation is shown. Although there is still a distinct downward main beam, there are almost equally strong beams at a number of other launch angles.

It should be noted that these model plots of the radiated pressure field from a horizontal array of 7 elements are based on a steady state solution. As a result, they provide a better representation for the pattern expected from a coherent array, such as a MarVib array, than they do for an impulsive airgun array.

4.2 ARRAY OUTPUT CHARACTERISTICS

Two interdependent aspects of the source array output are of interest. They are output acoustic energy and duty cycle, and output spectrum and beam pattern.

Output Acoustic Energy & Duty Cycle - The output energy of an acoustic source, as expressed in the classic SEL calculation (Southall et al. 2007), is

$$SEL = 10LOG_{10}\{\int(P/P_{REF})^2(t)dt\}, \quad (4\text{-}3a)$$

where the integral is taken over the extent of the radiated pulse. (See § 1.3 for description of SEL, i.e., Sound Exposure Level—a measure of total energy in a transient signal.)

The result for an airgun pulse can be visualized by integrating the modelled pulse shown below in Figure 4.5, which in turn was based on data from the Nucleus model simulating a 4140-in^3 airgun array with 30 guns in 21 positions at 7-m depth. One can see that virtually all of the energy will come during the period between the start of the positive pulse and the completion of the negative pulse, after ~15 or 20 msec ("Nucleus Gun Array" [PPT report] ExxonMobil Product for JIP Marine Source Modelling, 11 Feb. 2008). For a pulse as well defined as the one depicted here, the SEL value can be quite accurately estimated by

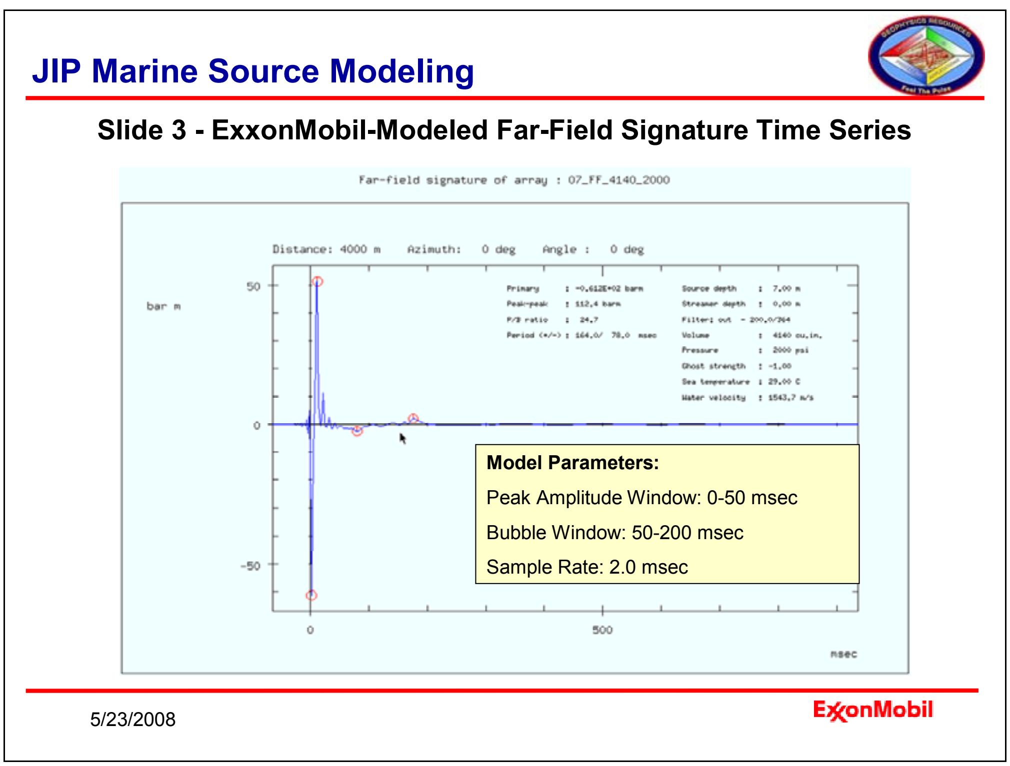


FIGURE 4.5. ExxonMobil-modelled far-field signature time series.

$$SEL \approx 10LOG_{10}\{[P_{P\text{-}P}/2]^2[T_P/2]\} \text{ in dB re } 1\ \mu Pa^2\cdot sec \quad (4\text{-}3b)$$

where

$P_{P\text{-}P}$ = Peak to Peak Pressure in the pulse, e.g. 112.4 bar-m in this example

T_P = The length of the dominant pulse, e.g. 20 msec in this example

With an idealized MarVib output,

$$P(t) = P_0e^{i\omega t},\ 0 < t < T_{SWEEP} \quad (4\text{-}4)$$

where P_0 stays relatively constant throughout the transmission, either as a frequency sweep or as discrete frequency, then the SEL value will be

$$SEL = 10Log_{10}[(P_0/P_{REF})^2] + 10Log_{10}[T_{SWEEP}(sec)] \quad (4\text{-}5)$$

and the energy of the signal will be directly proportional to the length of the sweep. Thus, the key differences between the two types of transmission are (1) with the airgun, the pressure pulse and duration are largely set by the volume of the gun and not controllable by the operator, and (2) with the MarVib the length and amplitude of the transmission are controllable and the energy can be grown by a factor of $10Log_{10}(T_{SWEEP})$.

For purposes of comparing the output sounds from MarVib and airgun systems, and resultant effects on marine animals, several decisions were made early in this analysis in consultation with the Project Support Group (PSG) appointed by the JIP. For example,

- The MarVib and airgun systems being compared should have source elements at the same number and geometry of locations, i.e., if there are *n* airguns or airgun-clusters, there should be *n* MarVib units at corresponding spacing;
- Tracklines and "shotpoints" should be the same for the MarVib and airgun systems;
- The total energy output at each shotpoint should be the same (though with MarVib systems the duration of emitted sounds at each shotpoint could vary).

A larger variety of design options could in theory be considered, but it was agreed that, for this evaluation, the above assumptions should be made to allow comparisons of results when only one factor was varied at a time.

Our comparisons of the MarVib vs. airgun approaches assume that the emitted signals would have the same SEL in dB re 1 $\mu Pa^2\cdot sec$ @ 1 m (i.e., equivalent energy level). For example, the SEL level for the airgun pulse shown in Figure 4.5 above is ~235 dB re 1 $\mu Pa^2\cdot sec$ at 1 m. If one were to create an equivalent MarVib source energy level with a sweep length of 5 sec, the MarVib source level (SL) would be 235 – 10Log(5) or 228 dB re 1 μPa @ 1 m. Thus, referring to SEL as defined in Eq. 4-3a, it can be seen that the SEL level grows as 10Log (T_{DUR}), or ~7 dB for a 5-sec transmission relative to an otherwise-similar 1-sec transmission.

If one wanted to do a direct comparison between the two systems it would be best (at least at the analysis outset) to standardize those properties that <u>could</u> be the same for both. The three most obvious are (1) the signal rate $T_{xmit,}$ i.e., interval from the start of the transmission of one signal to the start of the next signal, (2) the output frequency band desired, and (3) the effective band source level of a single element of the array. If this is done, then the primary variable to examine as a parameter is the duration of the MarVib sweep (T_{sweep} = time for the MarVib signal to sweep through the desired frequencies). (For now, we assume that the signals from a future MarVib system would be a form of frequency sweep, although use of other types of signals is considered in Chapter 6 on potential impacts.) Then T_{sweep} would have two effects:

- The total energy (dB re 1 $\mu Pa^2 \cdot sec$) in a MarVib frequency sweep would be directly proportional to $10Log(T_{sweep})$.
- The duty cycle defined as $[T_{sweep}/T_{xmit}]$ would also increase in direct proportion to T_{sweep}.

In actual practice during seismic surveys with airgun arrays, the standard transmit sequence appears to be a transmit data record (D_{DR}) every 25 m, and thus the resultant signal rate is dependent on vessel speed (V_V). Duty cycle would increase in direct proportion to vessel speed if the 25-m shot-spacing constraint were held to be standard:

- Duty Cycle = $T_{sweep} \times V_V/D_{DR}$

Obviously, if this industry 'standard' was relaxed or changed, then the duty cycle effect could change. In fact, changing the transmit cycle to a longer repetition interval would be one method of reducing both the resultant total number of exposures in any actual operation and the cumulative SEL values received at any specific location when accumulating across multiple pulses or transmissions:

The requested analysis of the effects of changing sweep length then becomes very straightforward both computationally and in comparison with the airgun result. The SEL value for a given MarVib transmission will grow as 10Log(Tp), and for constant range, the cumulative SEL (CSEL) over a series of transmissions will grow as SEL+ 10Log(N), where N is the number of pulses being considered. The only difference in these calculations from the CSEL of a sequence of airgun pulses is the possibility of control of Tp in MarVib operations. Obviously from an engineering view there may be significant constraints on the allowed duty cycle available for MarVib sources. As duty cycle involves shot spacing, Tp, and vessel speed, these are all potential variables in a parametric analysis of the optimum configuration. From an environmental impact viewpoint, a lower duty cycle (e.g., 10% vs. 20%) will engender less potential for masking, all else held constant. However, if source level must be increased or vessel speed reduced to offset lower duty cycle, that would to some degree offset the benefit of lower duty cycle.

4.3 Output Spectrum and Beampatterns

The shape of the resultant beam, i.e., the beampattern, will vary depending on frequency being broadcast and the element spacing within the array, as illustrated for our idealized line arrays in Figures 4.2, 4.3, and 4.4. For a horizontal array (broad in length and width, with all elements at similar depth), such as that typically used for airguns, the beampattern is purposely optimized for maximum downward gain in the frequency band <100 Hz. Thus, the sidelobes of these arrays, especially the sidelobes that transmit in the directions away from vertical, are dramatically affected by array configuration geometry, especially at higher frequencies away from the fundamental frequency band desired for seismic analysis.

4.4 Particle Velocity Field

Particle velocity (u), or particle displacement (ξ), is an integral component of any acoustic field. In the derivation of the wave equation for propagation of acoustic waves, one must consider the necessary elasticity (Bulk Modulus, B) and density (ρ) of the medium and the mechanical nature of the rarefaction and compression resulting from the presence of an acoustic field. Burdic (1984) summarized the family of pressure (p) and particle velocity (u) relationships that result from derivation of the one-dimensional (x direction) wave equation in an infinite medium as follows (terminology and equations as in Burdic 1984):

Differential Equation of Pressure:

$$d^2p/dt^2 = (B/\rho)\, d^2p/dx^2 \qquad (4\text{-}6a)$$

Plane Wave Velocity (c) of Propagation

$c = (B/\rho)^{1/2}$ (4-6b)

Characteristic Plane Wave Impedance (Z_o) of the Medium

$Z_o = \rho c$ (4-6c)

Relationship of Pressure to Particle Displacement

$p(t,x) = -Bd\xi(t,x)/dx$ (4-6d)

Relationship of Particle Displacement to Particle Velocity

$u(t,x) = d\xi(t,x)/dt$ (4-6e)

Note: $u = p/\rho c$ in the far field for a plane wave (4-6f)

Acoustic Intensity (I = Power/Unit Area):

Time average <*> of the Pressure and Particle Velocity product

$I = \langle pu \rangle = \langle p^2 \rangle / Z_o = Z_o \langle u^2 \rangle$ (4-6g)

In the partially restricted confines of a waveguide, further characteristics of particle velocity in relation to pressure can be explored in a setting where boundary conditions exist. Harris (1998; see his Fig. 14.1 included below) shows three conditions for a harmonic piston source on the left hand side of the wave-guide: ***(1)*** No boundary on right, equivalent to far field infinite medium, pressure and velocity in phase, and time average intensity as given by Eq. 4-6f above; ***(2)*** a partial reflection (finite impedance boundary) on right, pressure and velocity out of phase, lower net intensity (field is more reactive, i.e., low net power transfer), and ***(3)*** rigid boundary on right with complete reflection, pressure and velocity 90^o out of phase, and wholly reactive field with no time averaged intensity.

The more general relationship between pressure and velocity in both the near and far field of a source was provided by Siler (1969). In this benchmark paper he provided an early summary of the underlying theory of particle velocity in acoustic fields in the marine environment with reference to Harris and van Bergeijk (1962), Harris (1964), Cahn et al. (1967), Parvelescu (1967), Siler et al. (1967), and Banner (1968).

The summary he provides is repeated verbatim below:

- …both pressure and velocity are present in travelling sound waves. In the near field, velocity increases faster than pressure as the source is approached; in the far field, pressure and velocity (if expressed in microbars and microvars) are approximately equal. [Note: The microvar, nominally 6.7×10^{-6} cm/sec, is the velocity in water that accompanies 1 microbar or 1 dyne/cm^2 of pressure in the farfield.]
- For multipole sources, if one considers a far field crossover point to exist at a nominal distance of ($n/2\pi$) wavelengths from the source [where n=1 for a monopole, 2 for a dipole and 3 for a quadrupole], then for distances beyond the crossover point a planewave relationship exists, and for shorter distances the ratio (p/u) falls off as 6 dB per double distance in the source direction, i.e., the particle velocity increases.
- In the very near field the pressure and velocity are 90º out of phase, and in the crossover region they are 45º out of phase; in the far field of course they are in phase.

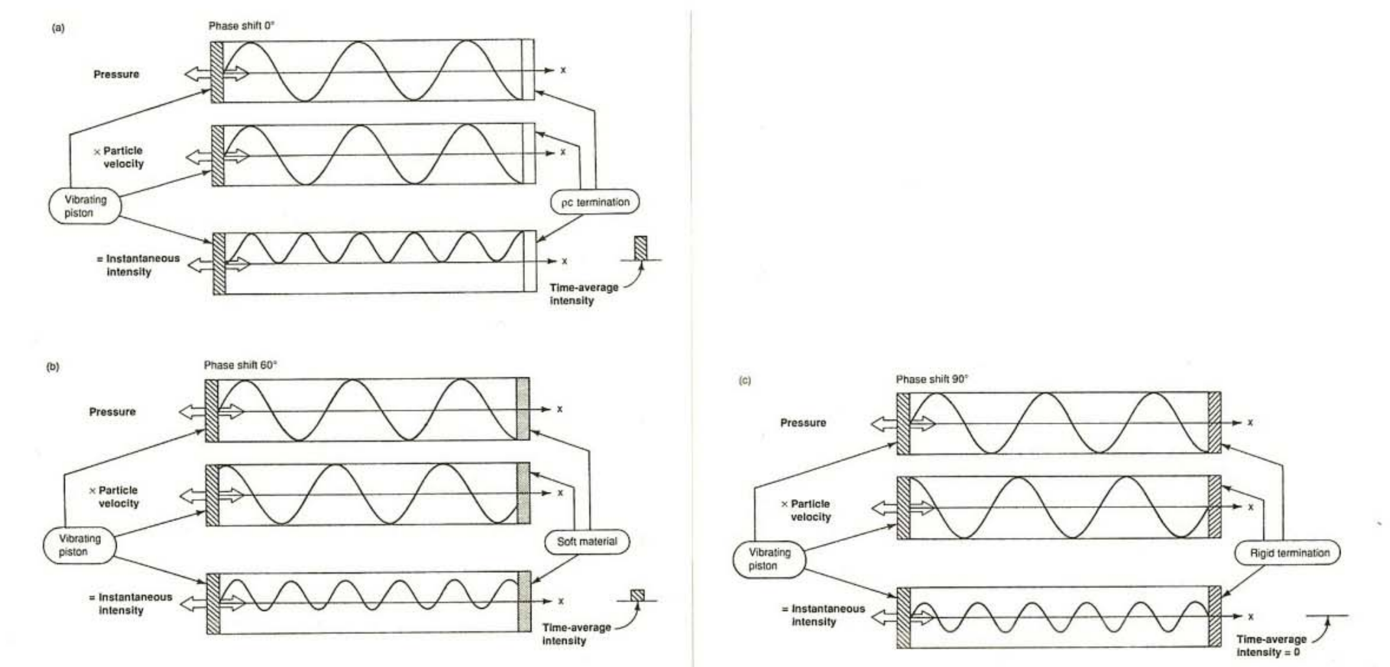


FIG. 14.1 Spatial distribution of instantaneous sound pressure, instantaneous particle velocity, instantaneous sound intensity, and time-average sound intensity for pure-tone one-dimensional plane wave in a tube. (*a*) Case with no reflection at right end of tube; sound pressure and particle velocity are in phase. (*b*) Case with partial reflection at right end of tube; sound pressure and particle velocity are 60° out of phase. (*c*) Case with rigid end at the right end of tube; there is a perfect reflection, and sound pressure and particle velocity are 90° out of phase; there is no time-average or *active* intensity—intensity is completely *reactive*.

Harris (1998) Handbook of Acoustical Measurements & Noise Control

4.5 PARTICLE VELOCITY FIELD OF A NEAR SURFACE SOURCE

The physical arrangement most applicable to many seismic airgun activities involves a source near the surface at a depth small in terms of wavelength. That may also be true of a future MarVib source, although a MarVib system might be designed to operate at deeper depths than possible with airguns. This arrangement can be viewed most simply in the form of a dipole formed by the pressure source and the nearby pressure release surface of the air/water interface. Thus, at low frequencies, the particle velocity field [$u_R\mathbf{i_R} + u_T\mathbf{i_T}$] of a dipole is given by Junger and Feit (1972, Eq. 3.10 et seq.), where $\mathbf{i_R}$ and $\mathbf{i_T}$ represent the unit vectors in the radial and tangential directions respectively:

$$|u_R| = (2Po/\rho c)(Ro/R)(1/kR)(1+(kR)^2)^{1/2}\sin(ke\cos(\Theta)) \quad (4\text{-}7)$$

$$|u_T| = (2Po/\rho c)(Ro/R)(1/kR)(ke\sin(\Theta)\cos(ke\cos(\Theta))) \quad (4\text{-}8)$$

Here

Po = SL of the source element in dB//Pref @ 1 m

R = Range in m

Ro = Reference range, 1 m

ρc = characteristic impedance (density × sound velocity)

k = acoustic wavenumber (2πf/c) in m^{-1}

e = source distance below the surface in m

Θ = angle from the vertical measured at the surface directly above the source, i.e., up =>0^o, down =>180^o.

Constraints: (ke^2/R) & (e/r) <<1, thus a farfield result.

The results for both radial and tangential particle velocity are illustrated for the single element source at 50 Hz (Fig. 4.6 and 4.7, respectively).

The following comparisons are relevant to these results:

- The U_R plots are minimized along the free surface boundary (Θ = π/2) as expected (Junger and Feit 1972).
- The U_T plots show the velocity gradients maximized along the free surface boundary.
- Along the main downward beam the U_R values closely match the expected plane wave result of u = p/ρc, i.e., for a transmitted pressure field with source level 200 dB re 1 μPa @ 1 m, as shown in Figure 4.1, the SPL value at 500 m directly below the source is 152 dB re 1 μPa. The corresponding plane wave velocity component in the direction of the source (U_R at Θ = π) should be 2.5 × 10^{-3} cm/sec. Given the color scale gradations, this is quite close to the result shown in Figure 4.6.
- Note that these plots are for an individual dipole source and thus are symmetric with regard to horizontal azimuth angle. Angles from horizontal can be calculated using the annotated horizontal and vertical distance scales, e.g. 45° would lie on the line from (0,0)m to (500,500)m.
- In summary, it is clear that the particle velocity component of greatest strength is the radial component, with the exception of a region very close to the source as predicted by Siler et al. (1967). At even moderate distances, on the order of a wavelength or more, the velocity is well represented by the plane wave approximation.

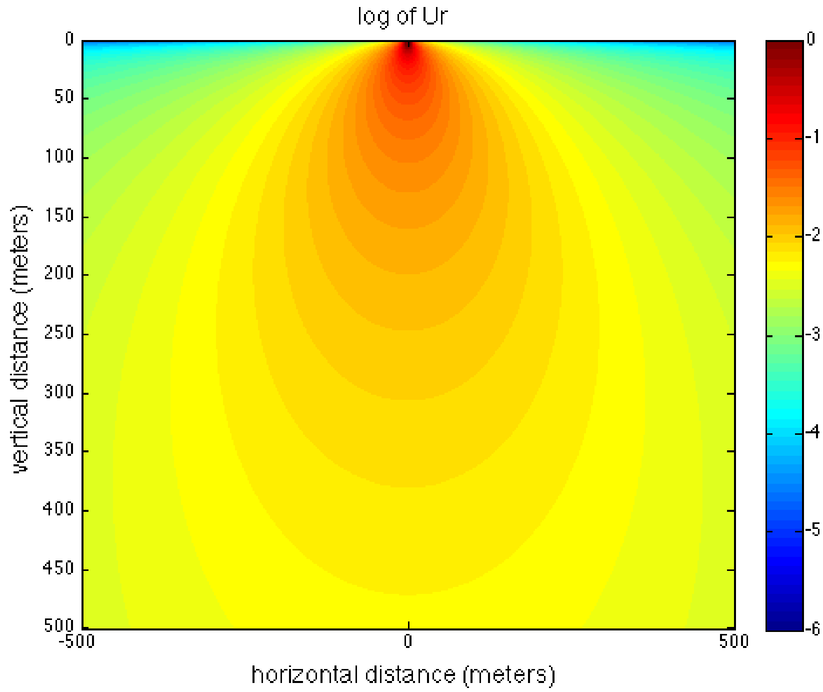


FIGURE 4.6. Particle velocity in the radial direction (U_R) for the 50-Hz source at 7-m depth, log scale in cm/sec, i.e., at color scale = –1, $U_R = 1{\times}10^{-1}$ cm/sec.

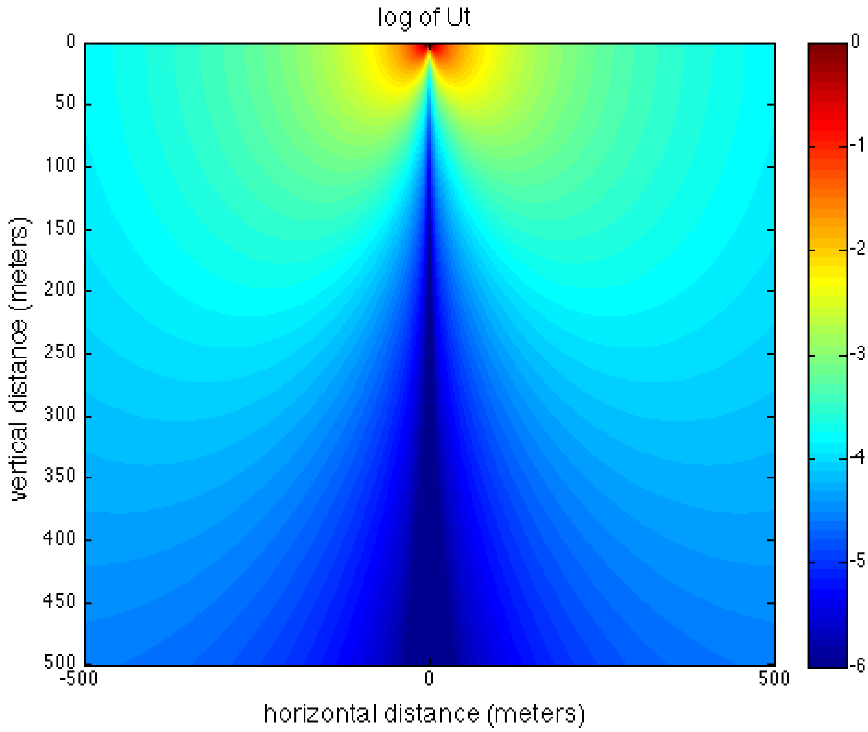


FIGURE 4.7. Particle velocity normal to the radial direction (U_T) for the 50-Hz source at 7-m depth, log scale in cm/sec, i.e., at color scale = –1, $U_T = 1{\times}10^{-1}$ cm/sec.

Figure 4.8 provides a point of comparison for the two particle velocity plots relative to the particle velocity threshold of Atlantic cod. With a best hearing threshold near 50 Hz of 1×10^{-6} cm/sec, the cod should clearly detect the values shown for the 200 dB monopole source. However, due to the scarcity of empirical data concerning effects of specific particle velocities on fish hearing or behaviour, the corresponding biological effects are difficult to assess (see Chapter 6).

From a layman's perspective, the model results depicted in Figures 4.6 and 4.7 can be interpreted as follows. Only in the very near field of the source (say at 50 m or less) are there any significant particle velocity components that are not radial in direction. Thus, outside of this relatively small region, the particle velocity field is well characterized by the plane wave convention with the amplitude given by Eq. 4.6f, and the direction being along the radial between the receiver and the source. In very shallow water, of course, such simple analogies do not hold and complex analysis or *in situ* measurements are needed to fully analyse the particle velocity field.

4.6 Mitigation of High Frequency Components

Given that higher frequency components (f>100 Hz) are not desired for geophysical exploration purposes, potential gains (from an environmental impact perspective) could be achieved by reducing these higher frequency components. This single factor could, for MarVib systems, be the most significant design feature with potential for reducing environmental impact, especially as it applies to the often-high population density of mid- and high-frequency odontocetes (see § 3.6 for species breakdown) in shallow and shelf waters.

To illustrate this potential, the following analysis parametrically examines the potential mitigation effects that could be gained by combining normal dropoff in high frequency amplitudes with the M-weighting curves proposed in Southall et al. (2007). These curves, shown in Figure 4.9 below, are based on the concept that species whose hearing is most sensitive at higher frequencies, and notably less so at frequencies below a few hundred hertz, are less affected by low frequency sounds. This is not the inverted hearing curve (audiogram) approach proposed by some (e.g., Nedwell et al. 2007), but rather a more conservative (precautionary) approach that flattens the marine mammal audiograms in a manner more consistent with C-weighting as often applied in quantifying sound exposure in humans exposed to strong sound.

Even so, the potential for impact minimization for mid- and high-frequency marine mammals is substantial if the levels of radiated sound above 100 Hz are reduced. For illustrative purposes, we have analyzed the potential effects of M weighting in combination with three different high-frequency roll-off curves: 10 dB, 20 dB and 30 dB per decade (Fig. 4.10). (Here, a decade is a 10-fold increase in frequency.) For purposes of comparison and simplicity, the baseline spectrum is a simplistic representation, and in the absence of other specific information about roll-off rates of likely future MarVib systems, an arbitrary linear (in dB relative to log-frequency) roll-off rate has been assumed.

Figures 4.11 through 4.14 clearly demonstrate the very substantial reductions in 'effective' received sound pressure level when higher frequencies can be attenuated, especially when combined with the M-weighting curves. The effect of attenuating the frequencies above 100 Hz is smallest for low-frequency cetaceans, notable for pinnipeds, and quite striking with both mid- and high-frequency odontocetes.

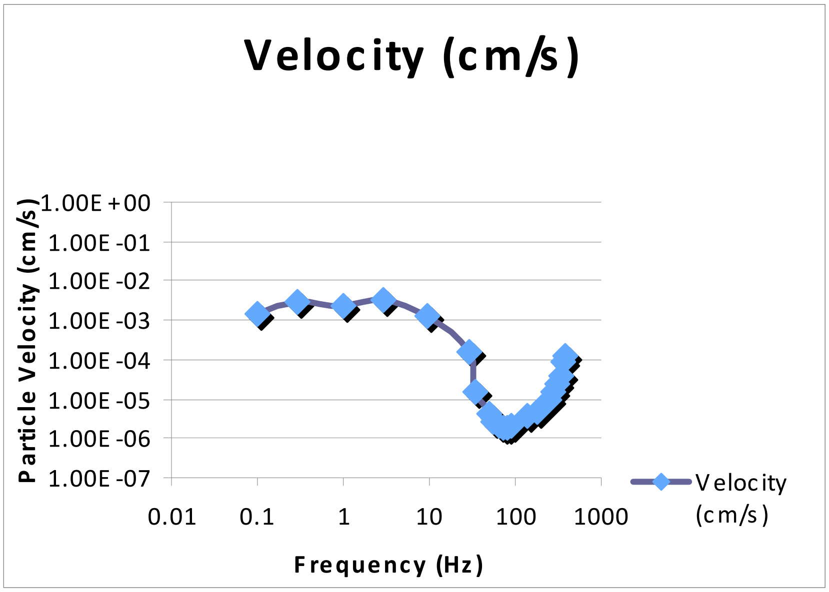


FIGURE 4.8. Particle velocity threshold values for Atlantic cod hearing; adapted from Sand and Karlsen (1986).

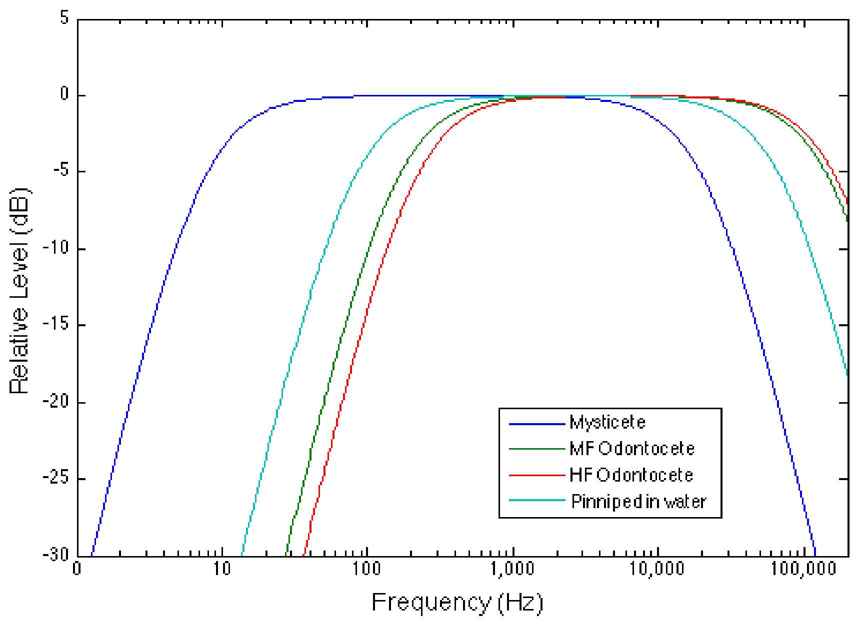


FIGURE 4.9. M-weighting functions normalized to unity at mid-frequencies (from Southall et al. 2007).

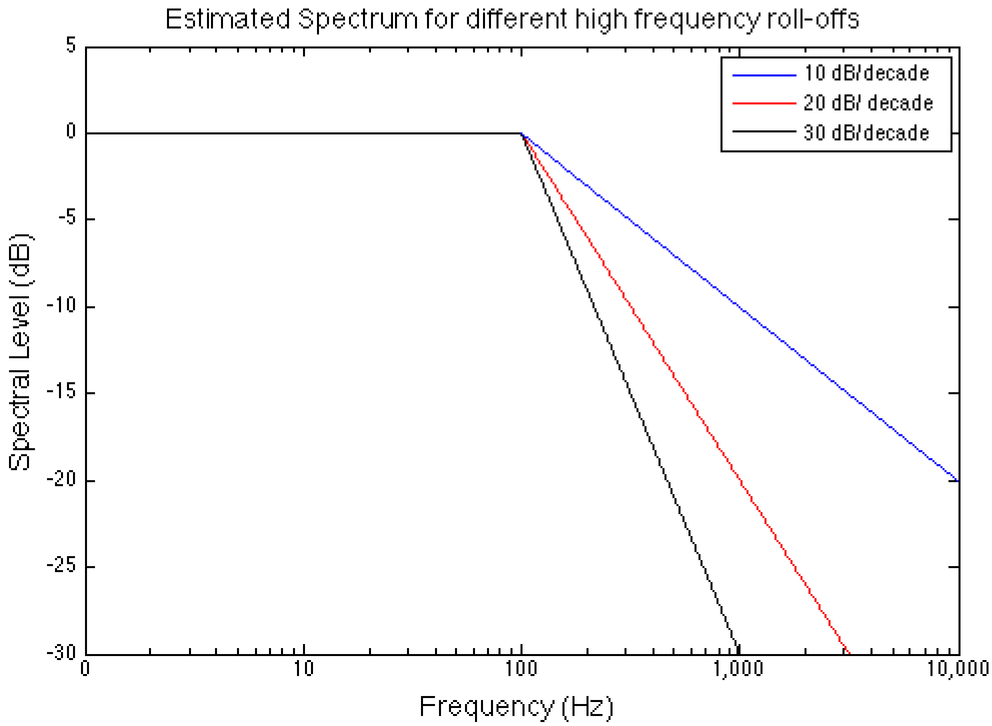


FIGURE 4.10. Nominal roll-off curves assuming a roll-off of 10, 20, or 30 dB/decade above 100 Hz.

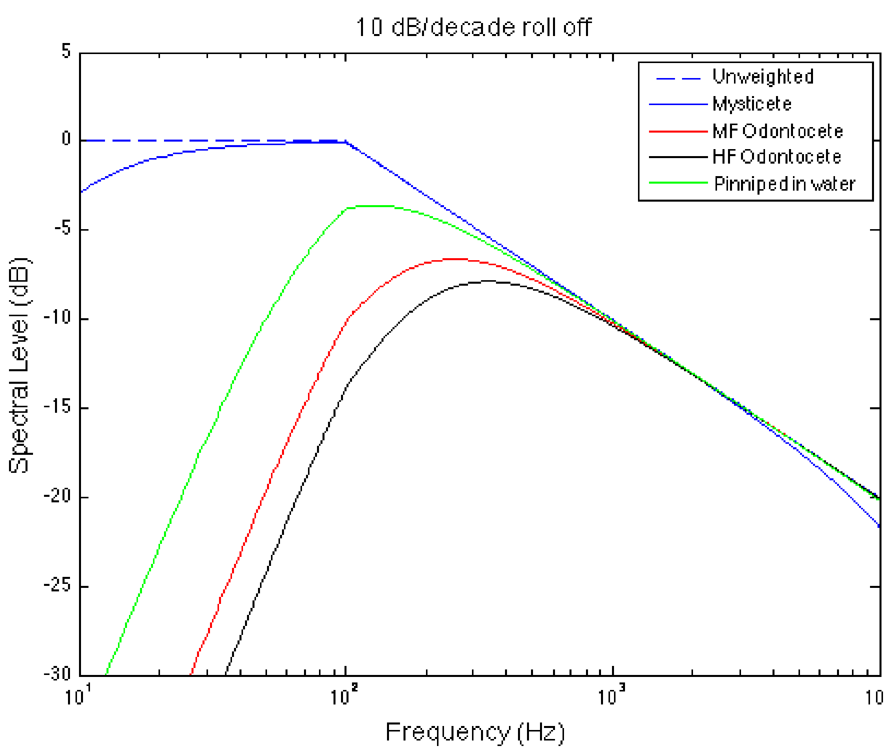


FIGURE 4.11. 10 dB/decade roll-off curve combined with M-weighting for each marine-mammal hearing group.

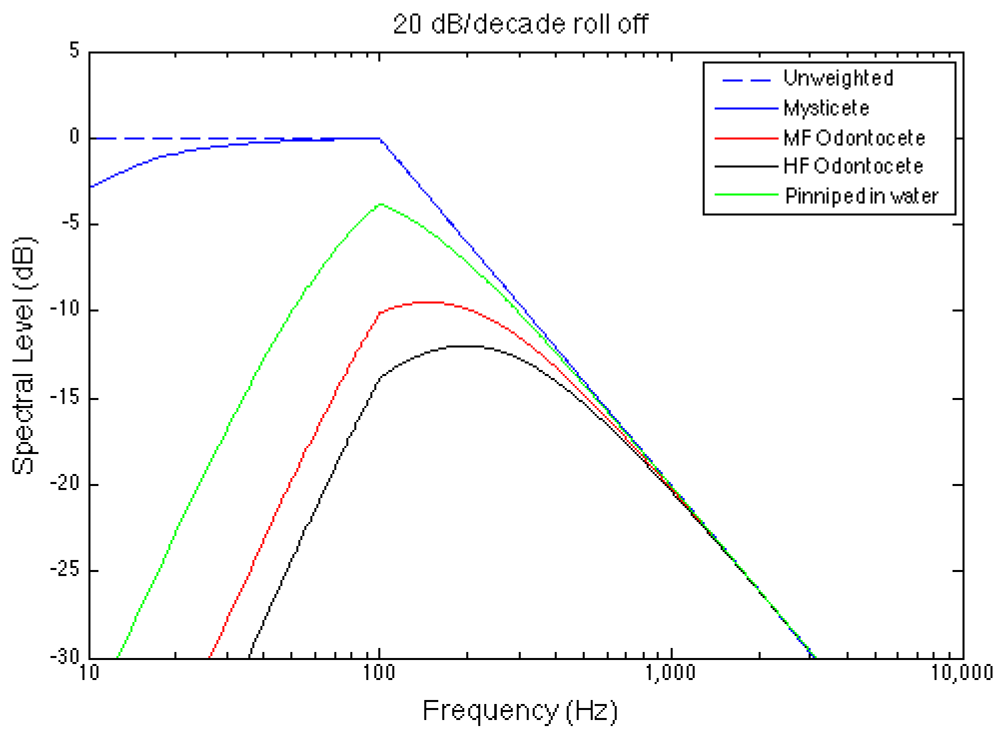


FIGURE 4.12. 20 dB/decade roll-off curve combined with M-weighting for each marine mammal hearing group.

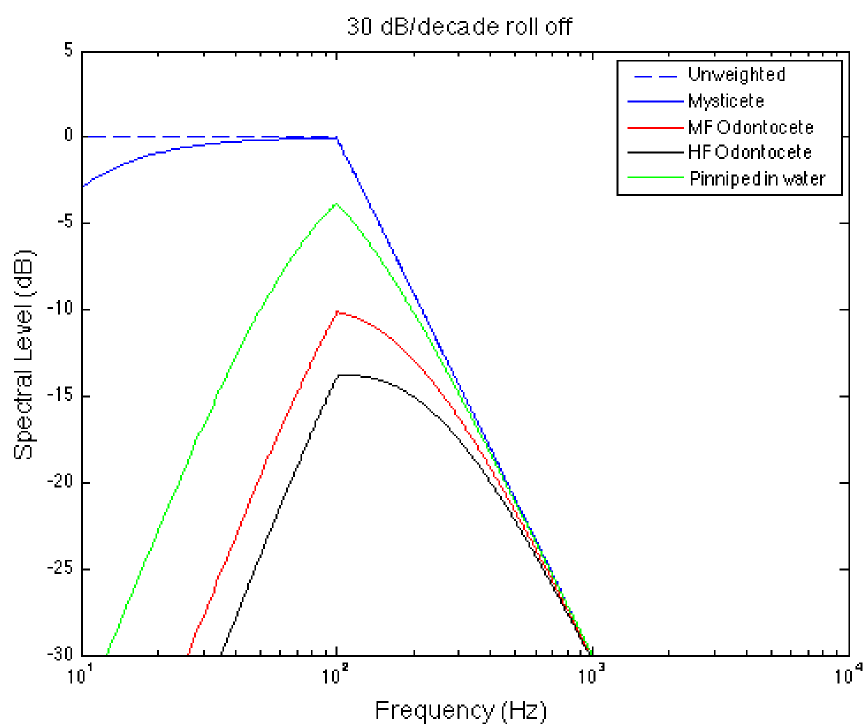


FIGURE 4.13. 30 dB/decade roll-off curve combined with M-weighting for each marine mammal hearing group.

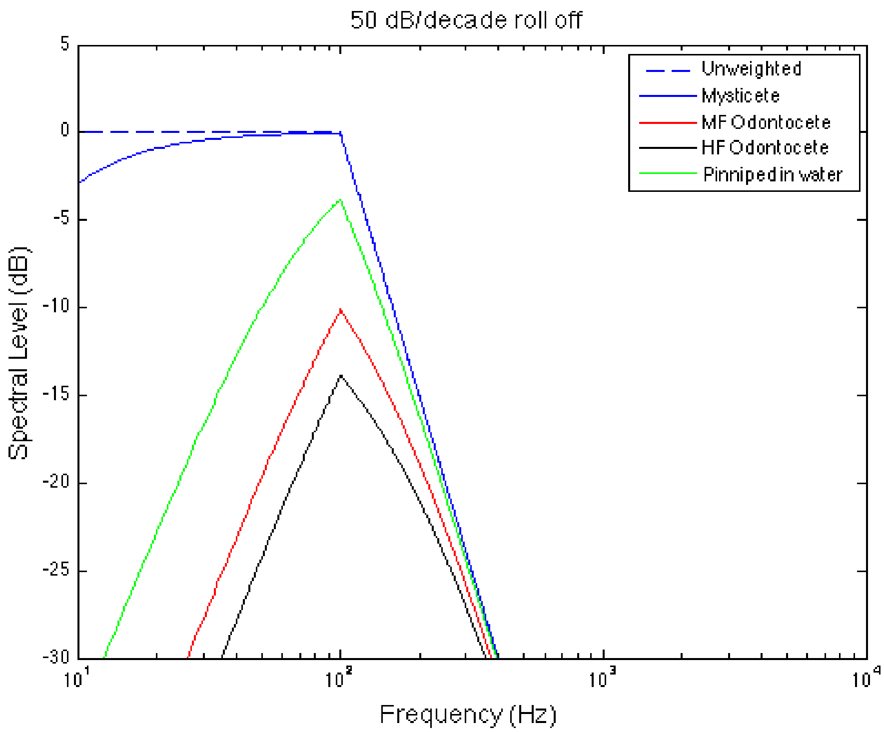


FIGURE 4.14. 50 dB/decade roll-off curve (not shown in Fig. 4.10) combined with M-weighting for each marine mammal hearing group.

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CHAPTER 5. ACOUSTIC MODELLING

5.1 APPROACH

The purpose of the acoustic modelling was to illustrate the comparative effects of MarVib and airgun source arrays on representative marine mammals, considering either of two specific sites in the Gulf of Mexico, one shallow site and one deep (§ 5.2, below; Fig. 5.1). The purpose was not to provide a definitive Environmental Assessment of these two system types, as the outcome would depend on the specific site, parameters of the seismic sources, and trackline design. Rather, the purpose here is to compare the anticipated effects of MarVib and airguns on numbers of marine mammals that might be affected by "comparable" MarVib vs. airgun operations, also considering the effects of water depth and of varying certain MarVib parameters, specifically signal duration and higher-frequency roll-off rate. Three representative species of marine mammals occurring in the Gulf of Mexico are considered: one toothed whale species (sperm whale), one dolphin species (bottlenose dolphin), and one baleen whale (Bryde's whale). The chapter considers numbers of these species that might receive sufficient MarVib or airgun sound for either behavioral effects or potential injurious effects (e.g., auditory damage). In estimating numbers of mammals exposed at relevant levels, this analysis considers both the RMS sound pressure criteria currently used by the U.S. National Marine Fisheries Service in regulating marine seismic operations (160 and 180 dB re 1 μPa for behavioral disturbance and potential injury, respectively) and the science-based injury criteria recommended by Southall et al. (2007). The latter mainly involve cumulative sound exposure level.

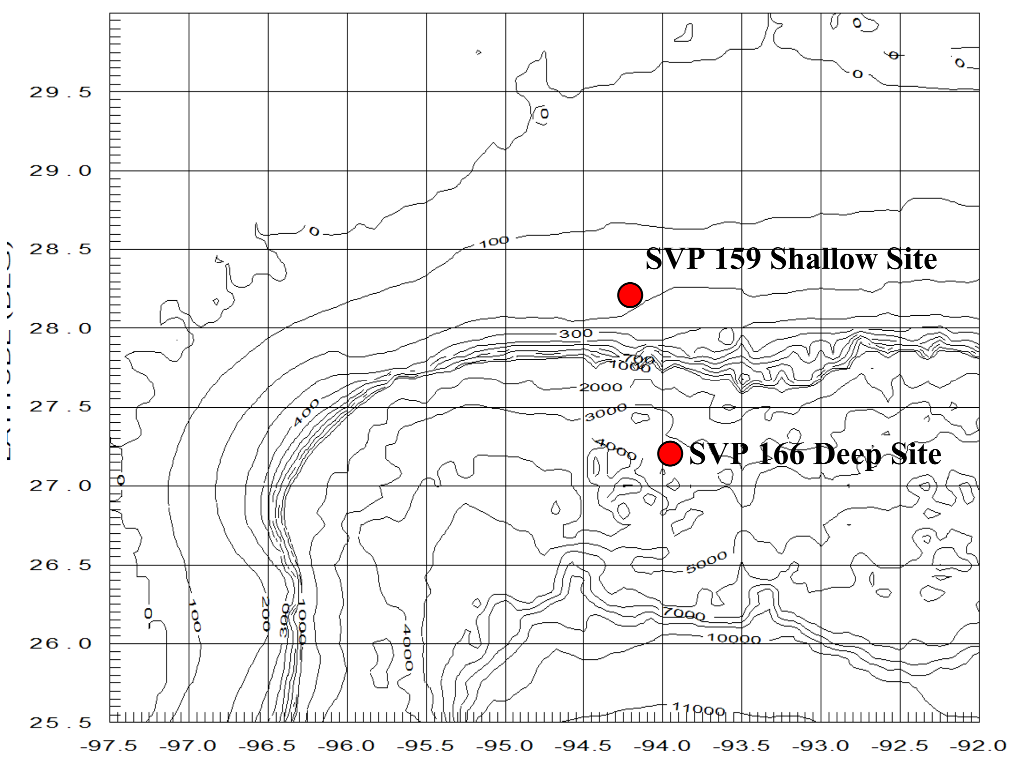

FIGURE 5.1. Modelling sites in the Gulf of Mexico, and DBDB-V bathymetry. Water depths are in feet.

This chapter describes the procedures and summarizes the modelling results. The marine mammal section within the subsequent Chapter 6, on anticipated impacts, uses results from this chapter as part of a more general assessment of potential impacts from MarVib vs. airgun systems as applied under different situations and with different MarVib parameters.

This modelling effort described in this chapter involved four main steps: (1) physical acoustic modelling to predict the underwater sound field generated by MarVib and airgun sources; (2) use of the Acoustic Integration Model (AIM; Frankel et al. 2002) to evaluate the interaction of the predicted sound field with three species of representative marine mammals; (3) use of a parametric approach to assess consequences of varying MarVib source spectrum and signal duration (other factors being held constant); and (4) evaluation of the number of animals that would be exposed to relevant sound levels including existing (in the U.S.) RMS pressure criteria for behaviour and injury, and the science-based criteria for auditory injury proposed in Southall et al. (2007).

Although the example problem undertaken here is not complete in the sense of matching all aspects of actual Environmental Assessment for a specific project, is does provide sufficient detail to show the level of complexity inherent in such a modelling scheme. It also illustrates the analytical decisions needed in both the development of the methods used and the analysis of the results.

5.1.1 Choice of Physical Acoustic Model

The overall approach to the acoustic modelling effort was to use available, well-adapted propagation models and databases to characterize the propagation for the two selected sites and for three specific frequencies within the stated frequency range of interest (i.e., 50, 300, and 1000 Hz). Propagation modelling for 50 Hz is here considered to be representative of that for frequencies 10–100 Hz. Propagation modelling at 300 Hz and 1000 Hz is considered representative of the 100–500 Hz and 500–1500 Hz bands, respectively.

It is important to note that seismic arrays are optimized for generating beamformed low frequency sound downwards into the earth's crust, yet the bulk of such an array's 'effects on marine wildlife' involve those propagation paths that lie more in the horizontal plane. It is the paths that lie closest to horizontal that propagate to any significant distance (Urick 1975), and thus the paths, or eigenrays, that would primarily contribute to the exposure of wildlife. Thus the model chosen for the 'effects' component must be well adapted for that purpose as discussed below. Because of this requirement to ensure that the frequency-dependent beamforming and source spectrum levels of the two source types was appropriately accounted for in the modelling, an eigenray propagation model (CASS/GRAB, described in §5.3.2) was selected as being most appropriate for this application.

Industry-standard source models are designed primarily to predict the properties of the downward-beamed energy, with no attention to the effects of the local environment (in particular, the vertical profile of sound velocity and bottom conditions) on propagation in near-horizontal directions. For the present application, it was essential to allow for the latter types of effects on propagation, and the sound propagation model chosen for use was appropriate for that as well. However, the model also had to account for a multi-element distributed source such as an array of seismic sources in much the same way that industry-standard source models do. Therefore, we verified, early in this analysis, that the chosen model did account for source properties in a manner comparable to industry standard models (see § 5.3.1, below).

5.1.2 Acoustic Modelling Frequency Issues

Three significant issues arise with modelling at the lowest frequency specifically considered here (50 Hz) at the shallow site. ***(1)*** The combination of the water depth and frequency are near the limit of the normal mode cut-off limitation of the physics upon which the model is based. ***(2)*** The second issue also involves the combination of the water depth and frequency of the transmitted signal. The eigenray model, as used here, assumes that the source is a sufficient distance from any boundaries, the ocean bottom in this instance, so that a far-field beam pattern can be superimposed on the calculated eigenrays as corrections to the source level. These corrections are a function of azimuthal bearing and angular difference from the main lobe or the vertical reference. In actuality, for the lowest frequencies examined, the beam pattern probably doesn't completely form before the acoustic energy interacts with the bottom. This complication is reduced somewhat by the fact that the main source of acoustic energy propagating from the source comes from the angles nearer to the horizontal plane and not the more vertical rays. The near-horizontal rays have a greater distance to travel before bottom interactions, consistent with their "slant" range to the bottom. However, with the generally downward refracting characteristic of the sound velocity profiles for this region, even the near-horizontal rays refract towards the bottom, causing the beam pattern to be less than ideal. The use of a winter sound velocity profile in this analysis minimizes this effect. ***(3)*** There are issues with the degree of accuracy to which the bottom parameters are known and modelled, especially for the lower frequencies (which are much more capable of penetrating into the sediment). For a "parametric" study like this one, this is not necessarily very critical, since both of the systems being compared (MarVibs and airguns) will have equal degree of bottom effects at the same frequency. This could be a more important modelling issue if an actual Environmental Assessment were the objective. At the highest frequency for which comparisons were made, 1000 Hz, the eigenray model and all databases used in this modelling effort are quite accurate.

5.2 ACOUSTIC MODELLING SITES

The two modelling sites (Fig. 5.1) were chosen to represent both shallow and deep water areas of the northern Gulf of Mexico, as the acoustic propagation can be quite different, especially at low frequencies (e.g., Tolstoy et al. 2004, 2009). The water depths at the chosen sites are 60 m and 1006 m. The shallow and deep sites are located on the Texas–Louisiana continental shelf and the Texas–Louisiana continental slope, respectively.

5.3 PHYSICAL ACOUSTIC MODELLING METHODOLOGY

5.3.1 Array Modelling: Gundalf – CASS/GRAB Comparison

Modelling the physical acoustics of airgun operations is a complex task that requires detailed knowledge of the source array characteristics as well as its physical location in the water column and supporting databases. This report must include proper modelling of the entire radiated field from the seismic arrays being modelled, including effects associated with the array source and effects of environmental conditions on long-distance propagation. Because of these requirements and to ensure that the frequency-dependent beamforming and source spectrum levels of the two source types were appropriately accounted for in the modelling, an eigenray propagation model, CASS/GRAB, was selected as being appropriate for this application. This model and its method of application are described in this section. However, it was also deemed important that this model be compared to industry standard models designed primarily to predict the highly beamformed downward looking source characteristics necessary for seismic exploration. Gundalf is one such program. It was chosen for comparison to CASS/GRAB since an existing Gundalf dataset for an industry array was available from the Gulf of Mexico Environmental Assessment (Minerals Management Service 2002).

The approach for this comparison was to duplicate the array characteristics of this specific industry array for input to CASS/GRAB, and then compare the resultant spectral and spatial beam forming and propagation results for both models. It is noted that Gundalf takes into account airgun interactions including non-linearities and interactions between sub-arrays as well as the effect of the nearby adjacent free surface, as further described by Hatton (2008), "No assumptions of linear superposition are made and the engine is capable of modelling airgun clusters down to the 'super-foam' region where the bubbles themselves collide and distort. Gundalf has been calibrated against both single and clustered guns for a number of different gun types under laboratory conditions and accurately predicts peak to peak and primary to bubble parameters across a very wide range of operating conditions."

CASS/GRAB is a limited-release, publicly available model that can be run internally and whose performance has been well documented (Weinberg 2004). Whereas CASS/GRAB does not model bubble interactions, it can (unlike Gundalf) model the propagation of acoustic energy out to long distances through a complex marine and sub-bottom environment—a necessary part of this study. However, as stated it was important to first determine how well the CASS/GRAB array beam generator model captures the important features of airgun array operation. Although Gundalf and CASS/GRAB may perform similar functions, they may follow a different order of computation. Most relevant here is that the beam pattern generator of Gundalf takes into account air/water surface interactions. The CASS/GRAB beam pattern generator model does not; it assumes a free field when calculating the beam pattern. Surface interactions and other environmental factors are taken into account in a subsequent step by CASS/GRAB, i.e., during the propagation modelling step.

5.3.1.1 Beam-Pattern Comparison

This section compares the beam patterns predicted by Gundalf vs. CASS/GRAB when applied to the same airgun array. The industry array that was modelled using both Gundalf and CASS/GRAB is shown in Figure 5.2 below. Note that the array used for the comparison of beam-patterns differs slightly from the array used for impact analysis. The values listed by each airgun unit are as follows: airgun number (above) and volume in cubic inches (below). The grid spacing is 1 m. The model was set for operation at a depth of 6 m.

Several methods of comparison are provided in this section. The first comparison is for both the inline directivity (oriented along the tow axis of the array, and looking downward where 0° is straight down toward the bottom) and the crossline directivity (oriented perpendicular to the tow axis, with 0° being straight down). These directivity patterns were modelled separately by Gundalf and by the CASS/GRAB volumetric array beam pattern model. Figures 5.3 and 5.5 show the inline and crossline beam patterns, respectively, produced by Gundalf. Figures 5.4 and 5.6 show the inline and crossline beam patterns from the CASS/GRAB array beam pattern model. The similarity demonstrates good agreement between beam patterns generated by Gundalf and by the CASS/GRAB array beam pattern generator.

A distinctive feature that is 'seemingly' missing from the CASS/GRAB beam patterns depicted in these Figures is destructive interference, or 'ghost' lines, that result from acoustic interaction with the air/water surface. As pointed out above, the CASS/GRAB beam pattern model does not take into account surface interactions at this stage, whereas they are included in Gundalf. CASS/GRAB is a more generally applied model for sound sources that could be arbitrarily operated anywhere in the water column, so its beam pattern model does not inherently assume that the source will be near the air/water surface.

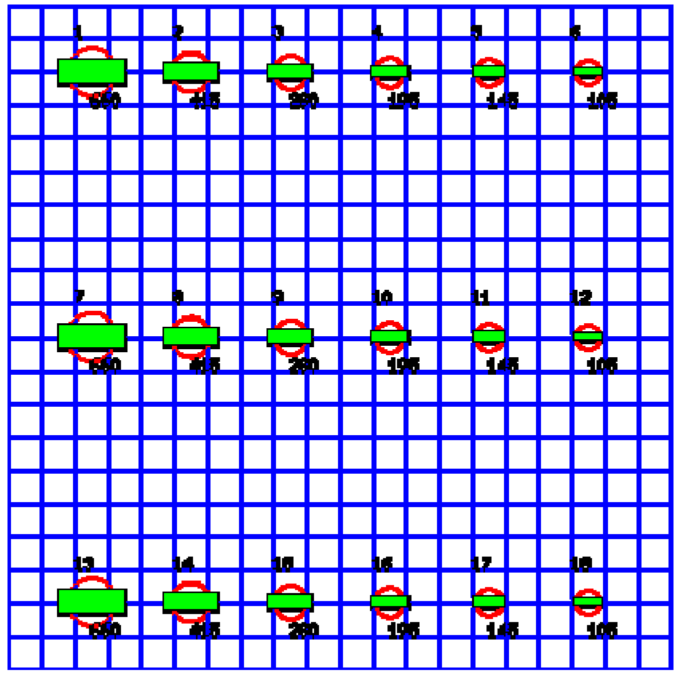

FIGURE 5.2. Airgun array used for Gundalf modelling and CASS-GRAB comparison. The element number is shown above each gun and the size of each gun is shown below in cubic inches.

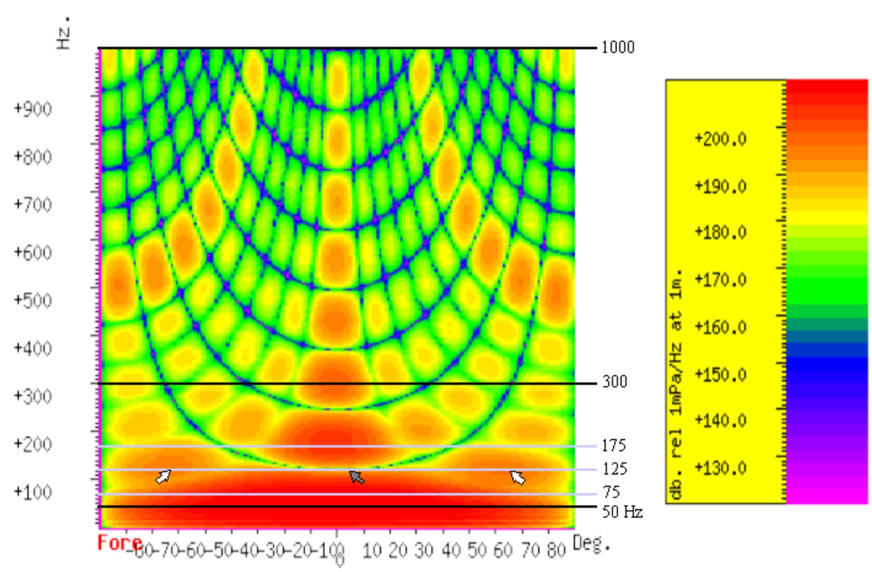

FIGURE 5.3. Airgun array beam pattern determined by Gundalf for inline directivity (i.e., along the tow axis of the array). Horizontal lines (black and gray) are the frequencies used for comparison with CASS / GRAB (see below). The dark gray arrowhead points out a null, or ghost, at 125 Hz and the white arrowheads point out nodes of sound energy at 125 Hz.

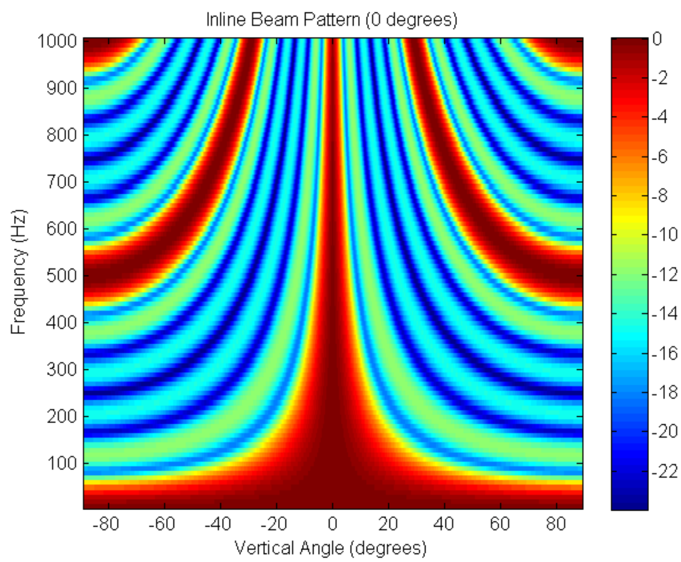

FIGURE 5.4. Inline directivity beam pattern determined by the volumetric array beam pattern model of CASS/GRAB for the array shown in Figure 5.2. The beam pattern is shown as attenuation in dB, as used in CASS/GRAB. The overall beam pattern is well accounted for by the beam pattern generator model of CASS. Note, however, that the 'ghosting' effects due to interaction with the air/water surface are not accounted for here. They are incorporated later in the modelling process when using CASS/GRAB. The important issue is the agreement of the overall beam pattern with that predicted by Gundalf (*cf.* Fig. 5.3).

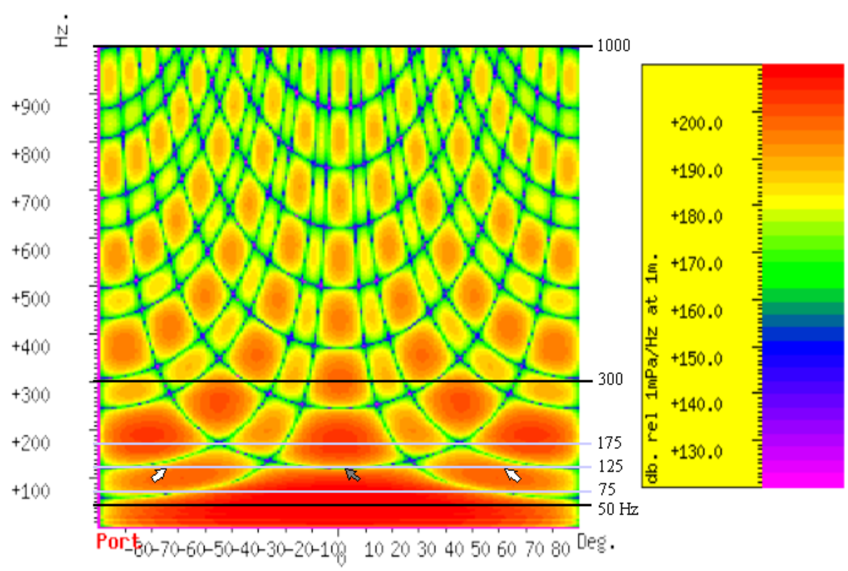

FIGURE 5.5. Airgun array beam pattern determined by Gundalf for crossline directivity (i.e., perpendicular to the tow axis of the array). Horizontal lines (black and gray) are the frequencies used for comparison with CASS/GRAB (see below). The gray arrowhead points out a null, or ghost, at 125 Hz and the white arrowheads point out nodes of sound energy at 125 Hz.

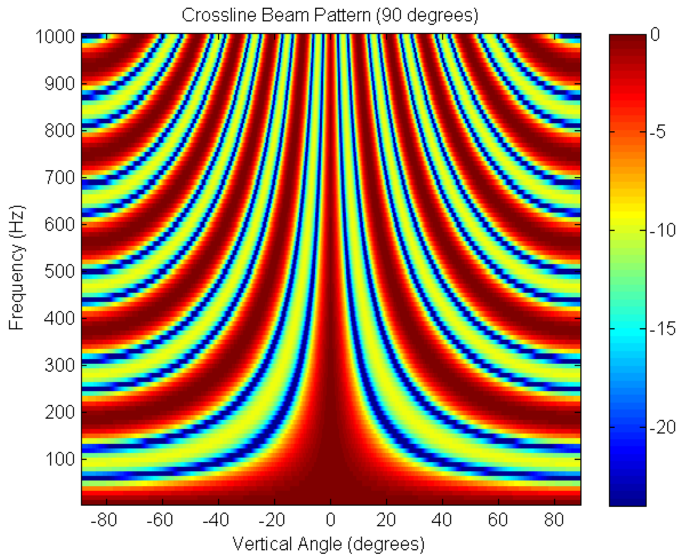

FIGURE 5.6. Crossline directivity beam pattern determined by the volumetric array beam pattern model of CASS/GRAB for the array shown in Figure 5.2. The beam pattern is shown as attenuation in dB, as used in CASS/GRAB. The overall beam pattern predicted by Gundalf (*cf.* Fig. 5.5) is well accounted for by beam pattern generator model of CASS. Again, note that the 'ghosting' effects caused by interaction with the air/water surface are not accounted for here. They are incorporated later in the modelling process when using CASS/GRAB.

5.3.1.2 Surface Interference Effects

As previously mentioned, the output of the Gundalf beam pattern generator includes interference effects due to the water/air boundary. The CASS/GRAB beam pattern generator model does not account for these effects at this step, but does account for such effects during propagation modelling. Therefore, the attenuated 'ghosting' lines do not appear in the beam pattern predicted by CASS/GRAB, but they do exist in the propagation prediction.

To demonstrate this aspect of the CASS/GRAB modelling, propagation runs were conducted at 125 Hz. For an array depth of 6 m there should be null at 125 Hz (dividing the sound speed of 1496 m/s by 12 m travel distance results in a frequency of 124.7 Hz or about 125 Hz). This first cancellation resulting from the out-of-phase surface reflection is seen in the Gundalf beam patterns shown in Figures 5.3 and 5.5. The pattern of constructive and destructive interference is a function of frequency and directivity. This results in continuous families of curves representing the destructive interference (ghost lines) and constructive interference. Figures 5.7 and 5.8 show a null in the inline and crossline propagation (respectively) for the airgun array using CASS/GRAB at 125 Hz, as well as beams directed roughly at 60°, all in concert with the Gundalf beam pattern models shown in Figures 5.3 and 5.5.

By way of further illustration, the beam patterns generated by the CASS/GRAB model at 75 Hz (Fig. 5.9 and 5.10) have no null at zero degrees. This agrees with the Gundalf prediction of beam pattern at the same frequency and direction.

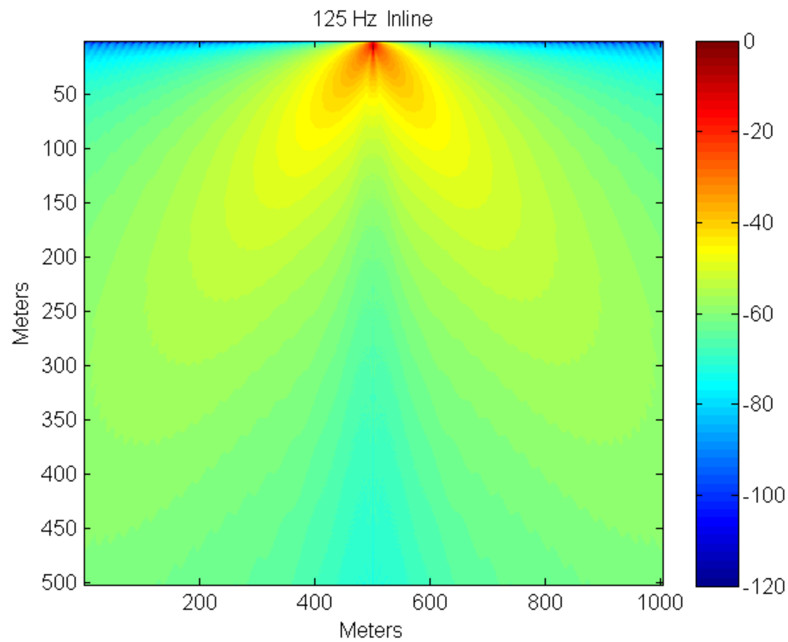

FIGURE 5.7. Inline propagation pattern for the airgun array at 125 Hz as predicted by CASS/GRAB, showing the lack of a strong downward beam and the presence of two strong beams directed at about 60º from vertical.

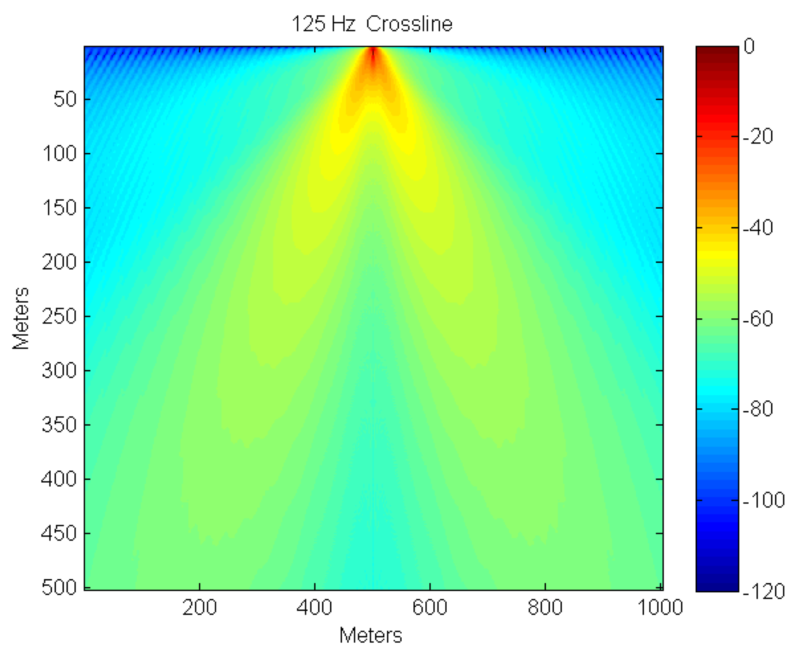

FIGURE 5.8. Crossline propagation pattern for array at 125 Hz as predicted by CASS/GRAB shows the lack of a strong downward beam and the presence of strong beams directed at about 50º from vertical.

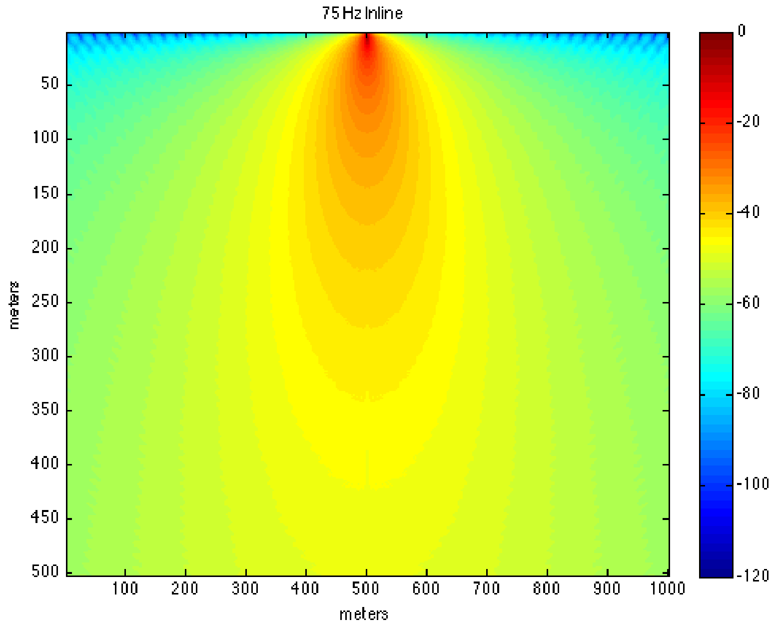

FIGURE 5.9. Inline propagation pattern for 75 Hz as predicted by CASS/ GRAB showing a strong downward beam pattern.

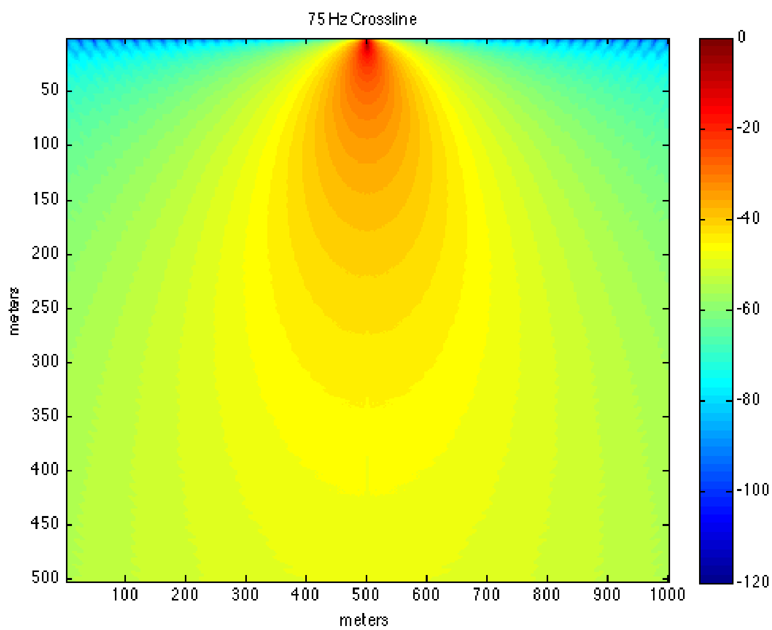

FIGURE 5.10. Crossline propagation pattern for 75 Hz as predicted by CASS/ GRAB showing a strong downward beam pattern.

5.3.2 CASS/GRAB Sound Propagation Model

The acoustic propagation model used to predict the acoustic propagation loss for both airgun and MarVib sources is the U.S. Navy standard Comprehensive Acoustic Simulation System (CASS) Model Version 4.0 and the Gaussian Ray Bundle (GRAB) version 2.0 (Naval Oceanographic Office 2006). CASS provides the interface to the various environmental, system, and propagation models available and already embedded in it, while GRAB (the default eigenray calculation model) was the actual eigenray calculation engine used for these calculations. CASS/GRAB is a range-dependent model capable of incorporating the specific beam patterns produced by the airgun array and the MarVib sources. It also can incorporate and allow for the historic environmental parameters for the ocean sound velocity profile, bathymetry, ocean surface conditions, and the characteristics of the ocean bottom. GRAB can accurately model active-source range-dependent propagation and reverberation for frequencies from 150 Hz to 100 kHz. However, additional testing of the model down to 50 Hz has been conducted satisfactorily and the official frequency range for this model is in process to be expanded in the future to recognize this fact (E. McCarthy, SAIC, pers. comm.).

5.3.3 Sound Propagation Supporting Databases

5.3.3.1 Sound Velocity Profiles

The ocean database used to supply the sound velocity profiles (SVPs) used in this study is the U.S. Navy standard Generalized Digital Environmental Model Variable Resolution (GDEM-V) Database, version 3.0 (Naval Oceanographic Office 2006). GEDM-V provides a global-gridded monthly mean (and standard deviation) of ocean salinity and temperature. For the region studied here, this database provides resolution of 15-arc min in both latitude and longitude. A plot of the GDEM-V province numbers for the Gulf of Mexico (Fig. 5.11) shows a total of 5 provinces, identified as 159, 166, 176, 183 and 181. The two that are specifically applicable to the two modelled sites are province 159 for the shallow site and province 166 for the deep site. A plot of the average monthly SVP values for each of these two provinces (Fig. 5.12 and 5.13) shows the monthly changes to the profiles, especially in the shallow area.

Propagation predictions were compared between summer and winter conditions because those two seasons have the largest differences in environmental conditions. In all cases, sound propagated better during the winter. Therefore we used the winter profiles for all modelling efforts to be conservative (i.e., precautionary). Actual operations during summer months will likely involve less-efficient sound propagation and therefore (for any given animal and location), reduced potential for environmental impact from any particular airgun or MarVib source configuration.[5]

5.3.3.2 Bottom Topography

The bathymetric database used for all modelling in this report is the U.S. Navy standard Ocean Floor Depth Digital Bathymetric Database Variable Resolution (DBDB-V), version 4.3 (level 0). This is an unclassified version of the database that provides 0.05 arc-min data resolution in the modelled region for both latitude and longitude.

[5] Seasonal changes in animal abundance would need to be considered in assessing whether overall population impact would be less in summer, winter, or some other season.

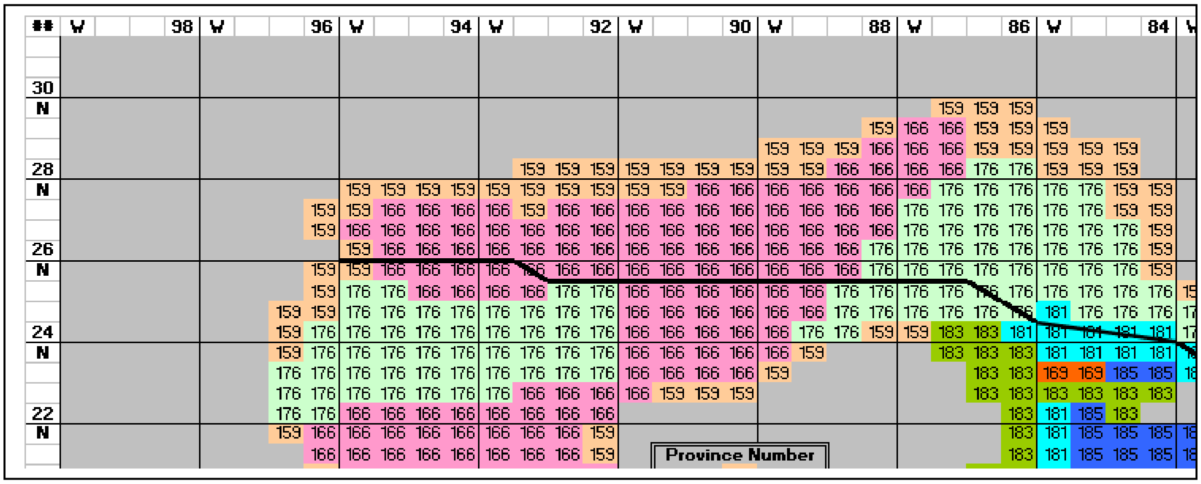

FIGURE 5.11. GDEM province numbers plotted for the Gulf of Mexico.

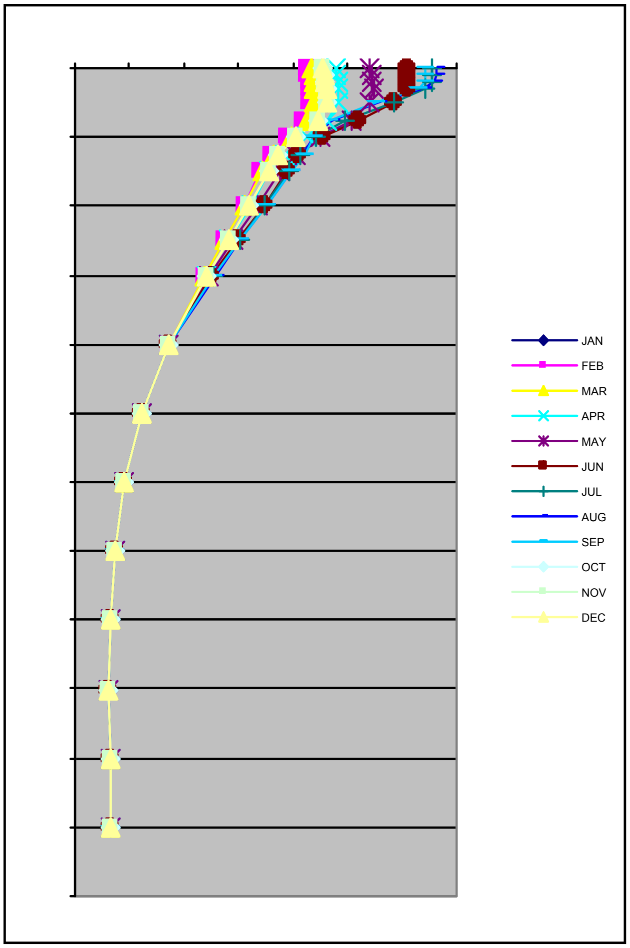

FIGURE 5.12. Average monthly SVPs for shallow site in the Gulf of Mexico (Province 159). Sound speeds (X-axis) are in m/sec. Water depths (Y-axis) are in m; depth at specific modelled site within Province 159 was 60 m.

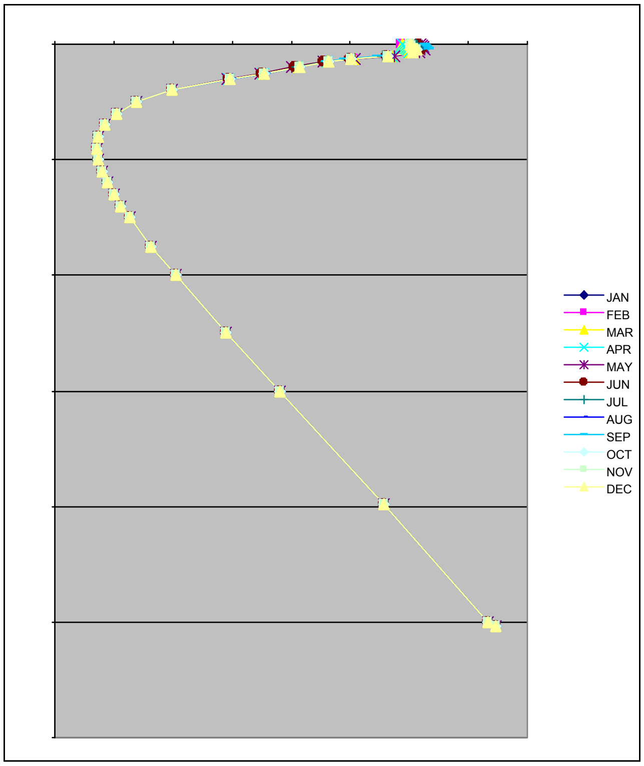

FIGURE 5.13. Average monthly SVPs for deep site in the Gulf of Mexico (Province 166). Axis units as in Figure 5.12.

5.3.3.3 Bottom Loss

The CASS/GRAB acoustic model (Weinberg 2004) was used to predict transmission loss at each site. Integral to the CASS/GRAB model is the Rayleigh bottom loss model (Officer 1958), which predicts the amount of acoustic energy loss due to reflection off the bottom. It does so as a function of incident angle of the acoustic propagation path to the bottom. The Rayleigh bottom loss model assumes that a simple harmonic plane-wave is reflected from an interface between two fluids that have different sound speeds and densities. The characteristics of the bottom sediment determine the sub-bottom sound speeds and densities. Bottom sediment characteristics were determined by using the NOAA National Coastal Data Development Center (NCDDC) Coastal Ecosystems Program database for the Gulf of Mexico (http://www.ncddc.noaa.gov/website/CHP/viewer.htm). The Gulf of Mexico sediment database depicts shelf sediment textures, hard banks, and gravel deposits on the continental shelf of the U. S. Gulf of Mexico as a map and is summarized from 16 different sources (U. S. Department of the Interior 1983, Visual No. 3). The sediment database was prepared from existing sources to accompany an Environmental Impact Statement, and displays general classification of bottom sediments (using the Shepard pyramid) throughout the Gulf of Mexico. It was provided by the Minerals Management Service (now Bureau of Ocean Energy Management, Regulation and Enforcement), Gulf of Mexico OCS Regional Office. Inputs to the Rayleigh bottom loss model, i.e., sound speed differences and sediment density, were inferred using the URL-UW method (Applied Physics Laboratory 1994); grain size was determined from the NCDDC database.

5.3.4 Modelled Array Configurations

This comparison of MarVib vs. airgun sources is based on a parametric approach for MarVib source properties of spectrum and duration, followed by an evaluation of the number of marine mammals predicted to be exposed to sound in excess of relevant impact criteria. These include pressure the thresholds above which NMFS considers behavioral responses likely and injury to be possible, as well as several variations of the recent science-based criteria proposed in Southall et al. (2007).

5.3.4.1 Array Geometry

The two dimensional configurations of the arrays analysed here are shown in Figure 5.14 for airguns and Figure 5.15 for MarVibs. All distances are in metres. The weighting values provide an effective source strength term (normalized to unity) for each element of the array. The JIP study airgun configuration was the one specified for consideration in this analysis; it consists of 30 airguns at 21 locations. The MarVib array was configured to be the same in dimensions but consisted of 21 equally weighted elements.

5.3.4.2 Array Spectrum and Duration Parameters

Our approach is to compare the anticipated biological effects of the airgun array described above with various parametric variations in the operation of the MarVib array, specifically various levels of unwanted high frequency components and varying pulse lengths. For both source arrays, the main downward beam is constrained to have a constant energy source level (in dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m) and a shot or transmission interval of ~25 m of along-track distance (Rodger Melton, ExxonMobil, pers. comm.).

The high frequency components were examined by comparison of hypothetical roll-off values for the spectrum of the MarVib system above 100 Hz, considering possible rates of 10, 30, and 50 dB/decade (i.e., per 10-fold increase in frequency). The term "roll-off" is used here to denote the frequency dependent reduction in the level of unwanted signal energy above 100 Hz generated by the source. This energy can derive a variety of mechanisms, but in general (for a MarVib) is related to higher harmonics of the generated signal. The roll-off metric is important as these unwanted higher frequency components are those that have the most potential for behavioral disturbance of mid- and high-frequency odontocetes. The duration aspect is discussed below, but MarVib transmissions of time duration (T_{DUR}) of 2, 5, and 8 sec were considered.

The modelling approach was to set a standard SEL (sound exposure level) source energy level of 235 dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m for all source configurations (airguns or MarVibs). This allows direct comparison of predicted impacts for airgun and MarVib sources emitting the same energy. The SPL (sound pressure level) for any given SEL can be approximated under an assumption of equal energy accrual as a function of duration, according to the relation

$$SEL = SPL + 10LOG_{10}(T_{DUR})$$

This relationship is illustrated in Figure 5.16.

Thus, the source level at different frequencies was adjusted in two ways: (1) by the spectral roll off for different sources; and (2) by the signal duration. These spectral roll-offs are shown in Figure 5.17. Three discrete frequencies of 50, 300, and 1000 Hz were selected as sample points at which to evaluate the roll-off effects, with 50 Hz being representative of the 10–100 Hz band, which contains the energy useful for seismic exploration. The pressure based source levels are listed in Table 5.1. The column with the 0.02 sec (20 msec) duration is representative of the airgun array. For the MarVib source, the source energy level in all cases is 235 dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m for the 10–100 Hz band. SPL in that band varies depending on signal duration, and SPL in higher-frequency bands varies with assumed roll-off rate.

x	y	z	Weighting
0	-5.5	0	0.4
0	-4.5	0	0.4
3	-5.5	0	0.343
3	-4.5	0	0.343
6	-5.5	0	0.286
6	-4.5	0	0.286
9	-5	0	0.343
12	-5	0	0.286
15	-5	0	0.2
18	-5	0	0.114
0	-0.5	0	1
0	0.5	0	1
3	-0.5	0	0.571
3	0.5	0	0.571
6	-0.5	0	0.443
6	0.5	0	0.443
9	0	0	0.343
12	0	0	0.286
15	0	0	0.229
18	0	0	0.229
0	4.5	0	0.714
0	5.5	0	0.714
3	4.5	0	0.343
3	5.5	0	0.343
6	4.5	0	0.286
6	5.5	0	0.286
9	5	0	0.343
12	5	0	0.286
15	5	0	0.2
18	5	0	0.2

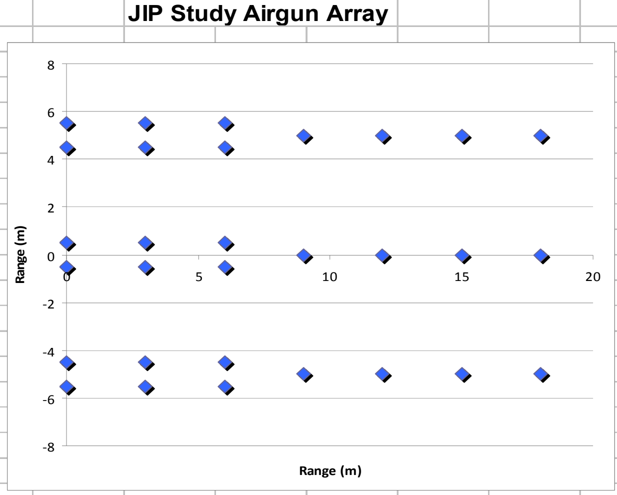

FIGURE 5.14. JIP study airgun array configuration and relative amplitude weighting.

x	y	z	Weighting
0	-5	0	1
3	-5	0	1
6	-5	0	1
9	-5	0	1
12	-5	0	1
15	-5	0	1
18	-5	0	1
0	0	0	1
3	0	0	1
6	0	0	1
9	0	0	1
12	0	0	1
15	0	0	1
18	0	0	1
0	5	0	1
3	5	0	1
6	5	0	1
9	5	0	1
12	5	0	1
15	5	0	1
18	5	0	1

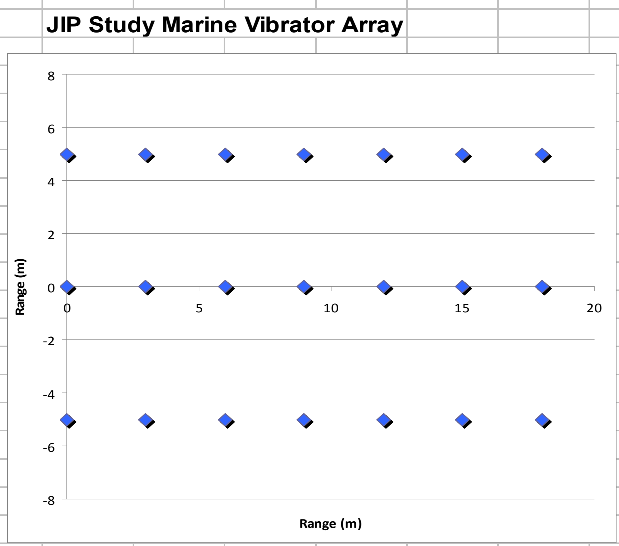

FIGURE 5.15. JIP Study Marine Vibrator Array configuration and relative amplitude weighting.

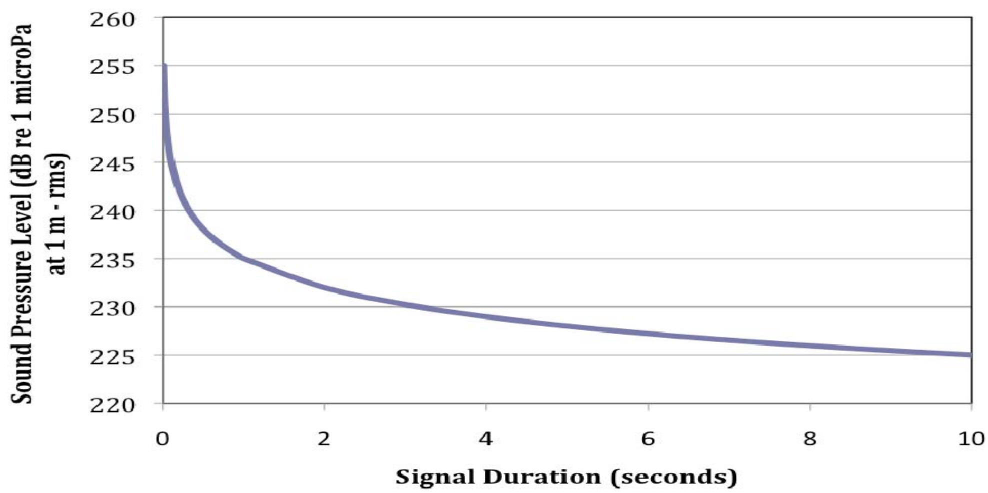

FIGURE 5.16. The relationship between duration and source sound pressure level, for a fixed source SEL value of 235 dB re 1 μPa^2·sec.

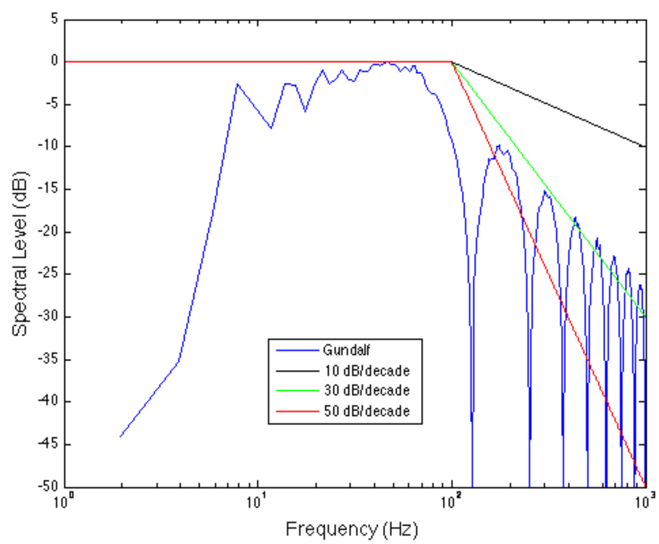

FIGURE 5.17. Spectral characteristics of airgun signals (predicted by Gundalf) and three theoretical MarVib sources. Above 100 Hz, the spectrum of the airgun most closely approximates that of the MarVib source with 30 dB/decade roll-off. Note that the MarVib spectrum at low frequencies is idealized; the actual spectrum would not be flat down to 1 Hz.

5.3.5 M-weighting

An additional spectral factor included in the analysis, and discussed in Chapter 4, is the potential amelioration of sound effects because of the varying hearing abilities of the marine mammals. This is addressed via the M-weighting approach outlined in Southall et al. (2007). Specifically, the received level at the animal in each of three frequency bands (centred at 50 Hz, 300 Hz, and 1 kHz) is adjusted based on a generalized function relating auditory response to frequency for the relevant species group. The M-weighting relationships are shown in Figure 4.9 for the four different in-water species groups. Of these, two groups (the low- and mid-frequency cetaceans) that occur in the Gulf of Mexico were

TABLE 5.1. Source Pressure Levels (dB re 1μPa @ 1 m) in each of three contiguous frequency bands for different seismic sources with equivalent source energy levels of 235 dB re 1 $\mu Pa^2 \cdot$ sec @ 1 m.

	Center Freq. [and Bandwidth] (Hz)	Band SPL (0.02-sec duration)	Band SPL (2-sec duration)	Band SPL (5-sec duration)	Band SPL (8-sec duration)
Airgun	50 [10–100]	252			
	300 [100–500]	238			
	1000 [500–1500]	225			
MarVib, 10 dB/decade	50 [10–100]		232	228	226
	300 [100–500]		227	223	221
	1000 [500–1500]		217	213	211
MarVib, 30 dB/decade	50 [10–100]		232	228	226
	300 [100–500]		218	214	212
	1000 [500–1500]		188	184	182
MarVib, 50 dB/decade	50 [10–100]		232	228	226
	300 [100–500]		208	204	202
	1000 [500–1500]		158	154	152

modelled. Figures 4.10 through 4.14 provide the combined effect of M-weighting and roll-off into a single curve for each combination of M-weighting and the three roll-off curves.

5.4 MODELLING SOURCE AND ANIMAL MOVEMENT

To estimate how changing the acoustic source characteristics affects the acoustic exposure of animals, the Acoustic Integration Model© (AIM) was used (Frankel et al. 2002). AIM is a Monte Carlo-based statistical model, strongly based on two earlier models, a whale movement and tracking model developed for a combined acoustic and visual census of bowhead whales (Ellison et al. 1987), and an underwater acoustic back-scattering model for a moving sound source in an under-ice arctic environment (Bishop et al. 1987). Because the exact positions of sound sources and animals (sound receivers for the purpose of this analysis) in any given simulation cannot be known, the movements and sound exposure of a large number of receivers are simulated to provide statistical validity. The movement and/or behavioral patterns of sources and receivers can be modelled based on measured field data; empirical data on movement patterns can be incorporated into the model. Each source and/or receiver is modelled via the "animat" concept, where each has parameters that control its speed and direction in three dimensions. In the case of the source, it is also imbued with the parameters describing its source operation over time (i.e., SL, signal duration, and spectral characteristics), and for this report also includes all of the MarVib parametric variations discussed in previous sections. It is possible to simulate the type of diving pattern that an animal shows in the real world. Furthermore, the movement of the animat can be programmed to respond to environmental factors, such as water depth and sound level (this latter feature was not used in this analysis). In this way, species that normally inhabit specific environments can be constrained in the model to stay within that habitat.

Once the behaviour of the animats has been programmed (see below), the model is run. The run consists of a user-specified number of steps forward in time. For each time step, each animat is moved according to the rules describing its behaviour. For each time step of the model run, the received sound level values at each receiver (i.e., each marine mammal) animat are calculated. For this analysis, AIM returns the movement patterns of the animats, and the received sound levels are calculated separately, using the acoustic propagation predictions provided by the CASS/GRAB model.

At the end of each time step, each animat "evaluates" its environment including its 3-D location. If an environmental variable has exceeded the user-specified boundary value (e.g., water too shallow), then the animat will alter its course to react to the environment. These responses to the environment are entitled 'aversions'. There are a number of potential aversion variables that can be used to build an animat's behavioral pattern.

5.4.1 Source Movement

For this assessment, each modelling simulation began with the creation of a movement pattern for the seismic source vessel (see Fig. 5.18). The assumed survey at either the deep or the shallow site consisted of thirty east–west lines each 47 km long and connected by a short north-south leg of 1.5 km. The sound source was assumed to be operating during the turns (short north–south legs). It is recognized that, for a real survey, sources would not normally be operational at full power during turns, and turns would be smooth with much larger radii. Also, adjacent lines would not be shot in sequence, given the limitations in turn radius when towing long streamers. However, these simplifications were applied to both the airguns and the MarVib sources so will not affect the relative results. The sequence in which the lines are assumed to be shot has negligible effect on the predicted sound exposures received by the animats.

The survey was modelled as if the vessel was shooting every ~25 m. The same trackline was assumed regardless whether the energy source was an airgun array or a MarVib array.

5.4.2 Animal Movement

Marine mammals were simulated by creating animats that were programmed with behavioral values describing typical dive depths, surfacing and dive durations, swimming speeds, and course change parameters. A minimum and maximum value for each of these parameters was specified. These data, extracted from the literature as summarized in the MAI behavioral database, were used to simulate movements and dive characteristics of individual animats for each species or species group relative to the simulated vessel source tracks at both modelling locations.

Animals move through four dimensions: three-dimensional space plus time. Several movement parameters are used in the model to produce a simulated movement pattern that approximates real animal movements. A typical dive pattern (depth vs. time) is shown below in Figure 5.19. It consists of two phases. The first is a shallow respiratory sequence. The second phase is a deeper, longer dive. The pattern concludes with another shallow respiratory sequence.

These two phases are represented in the model with several behavioral parameters; Figure 5.20 shows values for some of the key parameters as they would be input into model. The top row has the values for the shallow, respiratory dives. In this case, the animal dives from the surface to a maximum depth of 5 m. The second row describes the second phase of the dive. In this phase the animal dives to a depth between 50 and 75 m. In this example, the animal spends time at both 60 and 50 m before surfacing (Fig. 5.19). The pattern then repeats, although usually with minor variations.

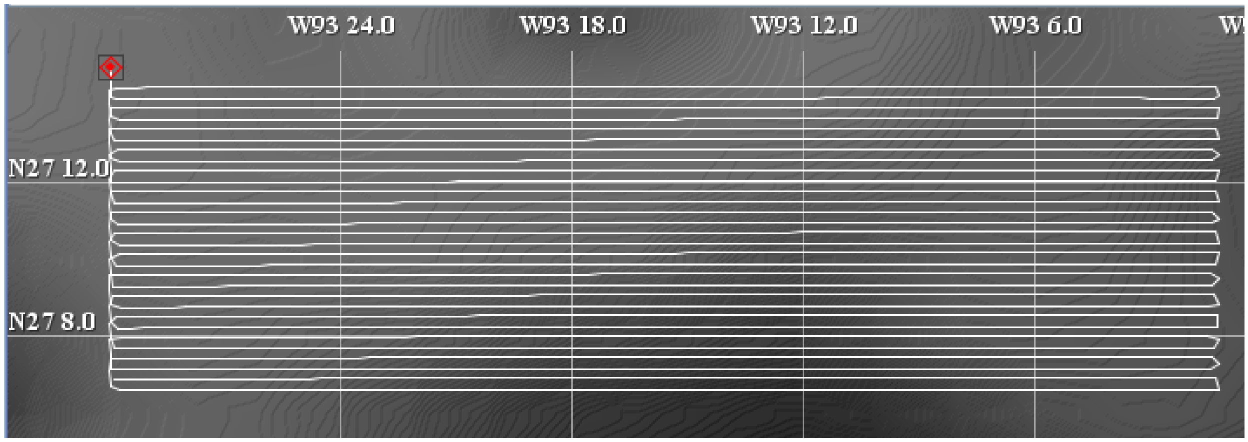

FIGURE 5.18. The assumed trackline for the seismic survey is shown for the deep water site. The same trackline pattern was assumed at the shallow water site. See text regarding assumptions about turns.

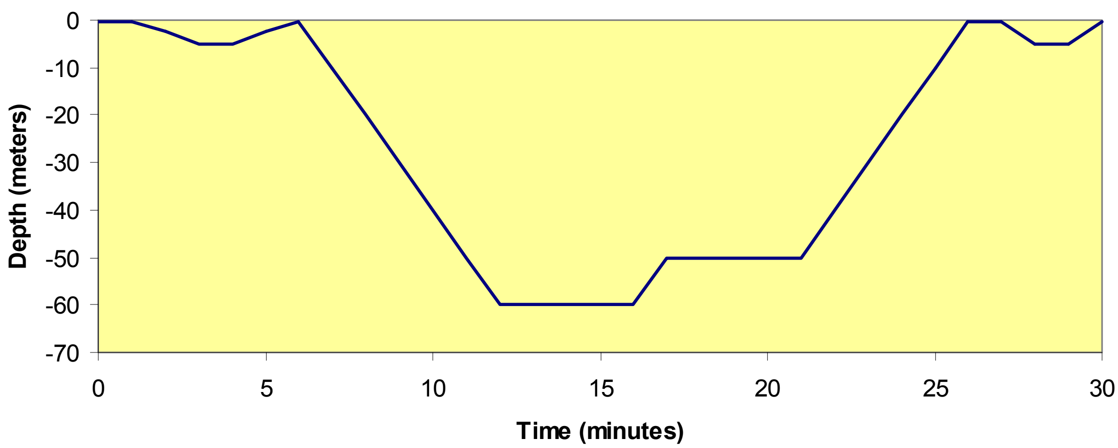

FIGURE 5.19. Typical dive pattern.

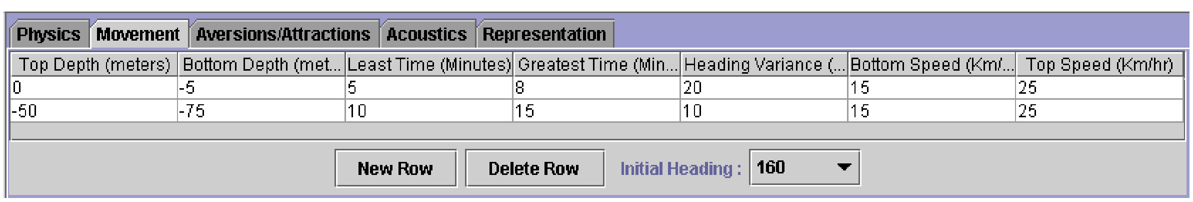

FIGURE 5.20. Some of the parameters used to specify the typical dive pattern illustrated in Figure 5.19.

The changes in course exhibited by the animats are handled with the 'heading variance' term. It specifies the number of degrees that the animat is programmed to turn up at each movement step. In the case specified in Figure 5.20, the animal can change course 20º on the surface, but only 10º underwater. This example involves a narrowly constrained set of variables, appropriate for a migrating animal. There are few published data that summarize marine mammal movement in terms of heading variance, or any other measure of course change per unit time. The default value used in the modelling is 30º. Exceptions are made for migratory animals, which tend to have more linear travel; these animals typically are assigned a value of 10º. Foraging animals tend to have less linear travel, as they often reorient to remain within a food patch. Therefore, foraging animals are assigned a higher heading variance value, typically 90º.

In addition to movement patterns, animats can be programmed to avoid certain environmental situations. For example, this option can be used to constrain an animal to a particular depth regime. The example below (Fig. 5.21) constrains the animal to waters between 2000 and 5000 m deep.

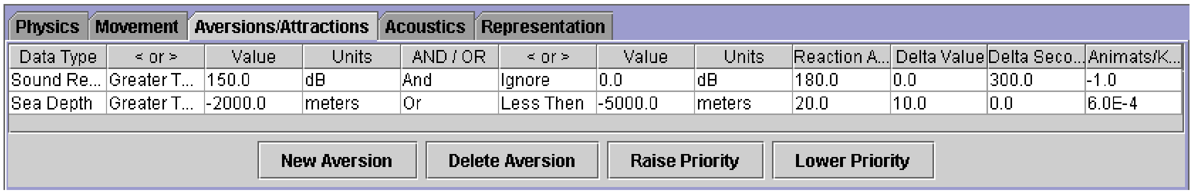

FIGURE 5.21. An example showing 'aversions' set to limit an animat to waters between 2000 and 5000 m.

After the animats were created, they were randomly distributed over each simulation area. The simulation area was delineated by four boundaries, composed of a combination of latitude and longitude lines. These boundaries extend at least 1º of latitude (60 n.mi.) or longitude (~53.5 n.mi.) beyond the outer extent of the vessel track to insure an adequate number of animats in all directions, and to ensure that the simulation areas extended beyond the area where substantial behavioral reactions might be anticipated. Each simulation had ~4000 animats representing each of the representative species. In all cases, this is a higher number and density of animats in the simulation than occurs in the real environment (see Table 5.2, later). This "over-population" allowed the calculation of smoother "tails" to the sound exposure distribution, and in the final analysis all results were normalized back to actual predicted population counts by species.

During the AIM modelling, animats were programmed to remain within the simulation area boundaries. This behaviour was incorporated to prevent the animats from diffusing out of the simulation, which (if allowed) would result in a systematic decrease in animat density over time. Thus, the simulations modelled the animals as a closed population with a high residency factor. This approach is clearly conservative in that it allows for more prolonged exposures (higher cumulative SEL values) than would be expected from species with a lower residency factor.

Also, for these simulations, animats were not programmed to show avoidance of the approaching source vessel (i.e., we assumed no "responsive movement"). This also tended to increase the sound exposures relative to those that would occur when some fraction of the animals show avoidance.

The duration of each simulation was determined by the length of the vessel track, divided by the modelled vessel speed of 6 km per hr (~3 knots). The duration of each simulation was 18,330 min (12.7 days).

5.4.3 Data Convolution to Create Animat Exposure Histories

The AIM simulations created a realistic animal movement track for each animat and were based on the best available animal behavioral data. It was assumed that, collectively, the ~4000 animat tracks derived for each simulation (area/species combination) were a reasonable representation of the movements of the animals in the population under consideration. Animat positions along each of these tracks were converted to polar coordinates (range and bearing) from the simulated source to the receivers. These data, along with the depth of the animat at the corresponding simulated time, were used to extract RL estimates from the acoustic propagation modelling results provided by CASS/GRAB. For each bearing, distance, and depth from the source when it was operating at a given site, the RL values were expressed as SPLs with units of dB re 1 μPa.

For each simulated animal, the received SPL values are calculated in two ways, in one case without frequency weighting, and in the other case with weighting related to the auditory sensitivity of the species-group in question. In the latter case, weighted SPL values are computed depending on whether the animat being simulated is a low-frequency (LF), mid-frequency (MF), or high-frequency (HF) cetacean, or a pinniped in water. (In the present analysis, only LF and MF cetaceans were considered.) The weighted SPLS are calculated based on the M-weighting functions described by Miller et al. (2005) and Southall et al. (2007). As noted earlier, M-weighting is a filter function (analogous to human C-weighting) that is applied to the acoustic signal to account for the differential auditory effects of high-level sound depending on its frequency and the species group (see Fig. 4.9).

The final result was a time history of acoustic exposures for each individual animat every 30 seconds, including both unweighted SPL values and M-weighted values.

5.5 Representative Species

Three species were chosen to represent both different diving behaviours and different hearing abilities. Bryde's whale is the most widely distributed baleen whale in the Gulf of Mexico and is a good example of a species with predominantly low-frequency hearing. Two odontocete species were modelled, both of which are considered mid-frequency specialists (Southall et al. 2007). The bottlenose dolphin was chosen to represent a "mid-frequency" species with a moderate range of diving depths and characteristics of the various dolphin species present in the Gulf of Mexico. The deep-diving odontocete species were represented by the sperm whale.

The overall estimated densities and associated variances for Bryde's whale, sperm whale and bottlenose dolphins from the Gulf of Mexico in spring (mid-April to early June) 1996, 1997, 1999, 2000, and 2001 (Mullin and Fulling 2004; Table 5.2) were used in establishing the likely number of individuals within the study areas.

Table 5.2. Density and its coefficient of variation (CV) for the representative modelled species in the northern Gulf of Mexico, from Mullin and Fulling (2004).

Species	Density (#/100/km^2)	CV
Bryde's whale	0.01	0.61
Sperm whale	0.35	0.23
Bottlenose dolphin	0.59	0.41

The behavioral parameters that were assumed for these species are presented below.

5.5.1 Bryde's Whale (*Balaenoptera edeni*)

There is a paucity of data on behaviour of Bryde's whales. Since Bryde's and sei whales are closely related and similar in size, data for both species have been pooled to derive parameters for the Bryde's whale. In addition, some fin whale behavioural parameters have been used where data are lacking for both the Bryde's and sei whales.

Fin whale values are used in Figure 5.22 for surface time and dive depth because no direct data are available for Bryde's or sei whales. Dive times ranged between 0.75 and 11 min, with a mean duration of 1.5 min (Schilling et al. 1992). Most of the dives were short in duration, presumably because they were associated with surface or near-surface foraging. Schilling et al. (1992) reported surface times that ranged between 2 sec and 15 min. Observations of foraging sei whales found that they had a very high reorientation rate, frequently resulting in minimal net movement (Schilling et al. 1992).

	Min/max surface time (min)	Surface/ dive angle	Dive depth (m) min/max (%)	Min/max dive time (min)	Heading variance (angle/time)	Min /max speed (km/hr)	Speed distri-bution	Depth limit / reaction angle
Sei/Bryde's whale	1/1	90/75	20/150	2/11	30	0/20	5/1	50/ reflect

FIGURE 5.22. Bryde's whale model parameters.

A tagging study found that the overall speed of advance for sei whales was 4.6 km/hr (Brown 1977). The highest speed reported for a Bryde's whale was 20 km/hr (Cummings 1985). A Bryde's whale being attacked by killer whales traveled ~9 km in 94 min, with most of the travel occurring in first 50 min, producing an estimated speed of 10.8 km/hr (Silber et al. 1990). The speed parameters used in AIM are 0–20 km/hr, with alpha and beta parameters of 5 and 1, which produces the distribution of animat speeds shown in Figure 5.23.

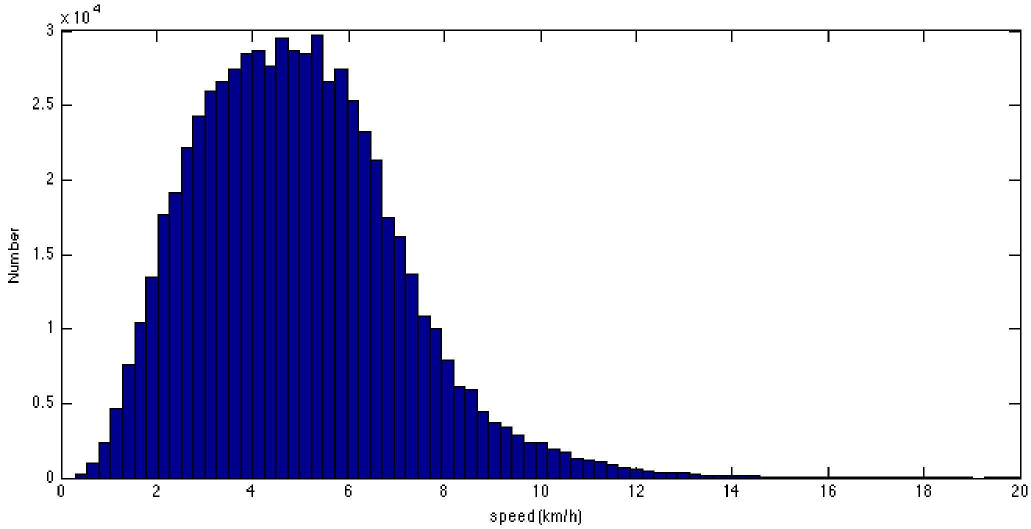

FIGURE 5.23. Assumed distribution of swimming speeds for Bryde's whales based on data-derived parameters.

Sei whales are known to feed on shallow banks, such as Stellwagen Bank (Kenney and Winn 1986). Therefore, simulated Bryde's whales are allowed to move into shallow water.

Sei whales in the Gulf of Maine were seen in groups of 1–6 animals with a mean group size of 1.8 whales (Schilling et al. 1992). Bryde's whales in the Gulf of California were seen in groups of 1–2 animals, with a mean group size of 1.2 whales (Silber et al. 1994)..

5.5.2 Sperm Whale (Physeter macrocephalus)

Currently, sperm whales are modelled with a single category of animat. In the future, it would be desirable to create separate animat categories for males and females, since their behaviour is quite different.

Male sperm whales in New Zealand had a mean duration on the surface of 9.1 min, with a range of 2–19 min (Jaquet et al. 2000). The distribution of surface times was non-normal, with 68% of the surface times falling between 8 and 11 min. These values were used for AIM modeling (Fig. 5.24).

	Min/max surface time (min)	Surface / dive angle	Dive depth (m) min/max (%)	Min/ max dive time (min)	Heading variance (angle / time)	Min /max speed (km/hr)	Speed distri-bution	Depth limit / reaction angle
Sperm Whale	8/11	90/75	600/1400 (90) 200/600 (10)	18/65	20	0.1 / 10	Norm.	200/ reflect

FIGURE 5.24. Sperm whale model parameters.

Surfacing angles of 90° and diving angles between 60° and 90° have been reported. The maximum accurately-measured sperm whale dive depth was 1330 m (Watkins et al. 2002), although there are indications that dives occasionally extend to deeper depths. During dives, foraging typically begins at depths of 300 m (Papastavrou et al. 1989).

Sperm whale diving is not considered uniform because different dive types have been reported (Amano & Yoshioka 2003). AIM can accommodate these different dive types, at different frequencies of use (Fig. 5.25).

		Depth		Time	
Type of Dive	N	AIM min	AIM max	AIM min	AIM max
Dives w/ active bottom period	65	606	1082	33.17	41.63
dives w/o active bottom period	4	417	567	31.29	33.71
V shaped dives	3	213	353	12.77	20.83
Total	74				

FIGURE 5.25. Sperm whale dive statistics.

Sperm whale dive times average 44.4 min in duration and range from 18.2 to 65.3 min (Watkins et al. 2002). Sperm whales are typically slow or motionless on the surface. Mean surface speeds of 1.25 km/hr were reported by Jaquet et al. (2000) and 3.42 km/hr by Whitehead et al. (1989). Their mean speed during dives ranges from 5.22 km/hr to 10.08 km/hr with a mean of 7.32 km/hr (Lockyer 1997). In Norway, horizontal swimming speeds varied between 0.2 and 2.6 m/s (0.72 and 9.36 km/hr) (Wahlberg 2002). Sperm whales in the Atlantic Ocean swam at speeds between 2.6 and 3.5 km/hr (Watkins et al. 1999). Based on these data, minimum and maximum speeds of 1 and 10 km/hr were set for sperm whales, specified with a normal distribution, so that mean speeds will be ~5 km/hr.

Sperm whales are widespread in the Gulf of Mexico, but they are usually in water deeper than 480 m (Davis et al. 1998). However, there have been sightings of animals in shallow water (40–100 m) (Whitehead et al. 1992; Scott & Sadove 1997). In the Gulf of California, there was no relationship between depth or bathymetric slope and abundance, and animals were seen in water as shallow as 100 m (Jaquet and Gendron 2002). Based on these reports, a compromise value of 200 m was used as the shallow water limit for sperm whales for the AIM model.

Social, female-centered groups of sperm whales in the Pacific have ‘typical’ group sizes of 25–30 animals, based on the more precise measurements in Coakes and Whitehead (2004), although less precise estimates are as high as 53 whales in a group.

5.5.3 Bottlenose dolphin (*Tursiops truncatus*)

In many environments there can be coastal and pelagic stocks of bottlenose dolphins. This is certainly the case off the east coast of the United States. However, defining the range of the offshore form is difficult (Wells et al. 1999). Regardless of the genetic differences that may exist between these two forms, they frequently occur at different densities, and so they are split into two animat categories (Fig. 5.26).

	Min/max surface time (min)	Surface / dive angle	Dive depth (m) min/max (%)	Min/ max dive time (min)	Heading variance (angle / time)	Min /max speed (km/hr)	Speed distri-bution	Depth limit / reaction angle
Bottlenose (Coastal)	1/1		15/98	1/3	30	2/16	Norm.	10/ reflect
Bottlenose (Pelagic)	1/1		15/200	1/3	30	2/16	Norm.	101/ 1226 reflect

FIGURE 5.26. Bottlenose dolphin model parameters.

The maximum recorded dive depth for wild bottlenose dolphins is 200 m (Kooyman and Andersen 1969). A satellite-tagged dolphin near Tampa Bay had a maximum dive depth of 98 m (Mate et al. 1995). This value was used as the maximum dive depth for the coastal form of bottlenose dolphin. Measured surface times ranged from 38 sec to 1.2 min (Lockyer and Morris 1986, 1987; Mate et al. 1995). Dive durations for a juvenile bottlenose dolphin had a mean value of 55.3 sec, although the distribution was skewed toward shorter dives (Lockyer and Morris 1987; Fig. 5.27).

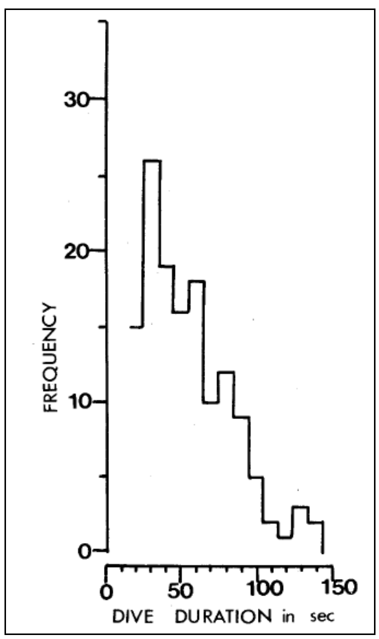

FIGURE 5.27. Dive duration for bottlenose dolphins from Lockyer and Morris (1987).

Bottlenose dolphins have been observed to swim, for extended period, at speeds of 4 to 20 km/hr, although they could (for ~20 sec) travel at up to 54 km/hr (Lockyer and Morris 1987). Dolphins in the Sado Estuary, Portugal, had a mean speed of 1.2 m/s (4.3 km/hr) and maximum speed of 3.2 m/s (11.2

km/hr) (Harzen 2002). A more recent analysis found that maximum speed of wild dolphins was 5.7 m/s (20.5 km/hr), although trained animals could double this speed when preparing to leap (Rohr et al. 2002). Maximum speed of wild dolphins in France was 4.8 m/sec (17.3 km/h), with an average speed (relative to water) of 2.2 m/sec (7.9 km/hr) (Ridoux et al. 1997). Bottlenose dolphins off Argentina swam much faster (3.9 m/sec, or 14 km/hr) when in water >10 m deep than while in shallow water (1.6 m/sec, or 5.8 km/hr) (Würsig and Würsig 1979).

In a deep-water study in the Gulf of Mexico, bottlenose dolphins were observed in water depths from 101 to 1226 m (Davis et al. 1998). Other studies show this species to be common in shallow water, and tagged animals have also been observed to swim into water 5000 m deep (Wells et al. 1999).

Bottlenose dolphins in the Gulf of California were seen in groups of 1–60 dolphins with a mean group size of 10.1 (Silber et al. 1994). In the Gulf of Mexico, they were seen in groups of 1–68 individuals (mean = 14.5, SE = 1.5, n = 83) (Mullin et al. 2004). Off the Pacific coast of Costa Rica, the mean group size was 21.5 (SD = 33.73, n = 176) (May-Collado et al. 2005).

5.6 EXPOSURE ASSESSMENT

In this section, we use the CASS/GRAB and AIM models to estimate the number of cetaceans of each representative species that would be expected to be exposed to sound levels exceeding various exposure criteria if the specified airgun array or MarVib array were to operate in each of the two study areas in winter. We also compare the expected numbers depending on the sweep duration and assumed rolloff rate of the MarVib spectrum above 100 Hz (source energy level held constant). We also examine the effect of applying vs. not applying frequency weighting (M-weighting). Results are summarized in Tables in this section, and are further illustrated and interpreted in Chapter 6, "Impact Assessment".

The animal movement patterns just described were used in the AIM modelling runs to establish the three dimensional location of each modelled animal at 30-sec intervals for the total period. These locations were then convolved with transmission loss estimates for each of the three frequency bands: 10–100 Hz, 100–500 Hz, and 500–1500 Hz to estimate received levels in those bands. These frequency bands were modelled at their center frequencies of 50, 300, and 1000 Hz. The received level values were calculated for the airgun array, and for the MarVib array operating with three possible signal durations and with three possible rolloff rates above 100 Hz. The source level in each of the three frequency bands was adjusted for the spectral quality of the source as per Table 5.1 (above, in § 5.3.4). The assumed airgun spectrum was based on an empirical airgun spectrum, whereas the MarVibs were modelled as flat to 100 Hz, and (above 100 Hz) assuming a roll-off of 10, 30, or 50 dB per decade to investigate the effect of roll-off rate on predicted impacts. In all cases, the overall source level was maintained at 235 dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m, so as to compare predicted impacts for a constant assumed source level.

The "exposures" were evaluated using several criteria. Potential physical injury was evaluated using the proposed criteria of Southall et al. (2007) and the older ≥180 dB re 1 μPa (RMS over pulse duration) pressure criterion.

Southall et al. (2007) estimated that permanent auditory injury in cetaceans might occur at a cumulative SEL level of

- 198 dB re 1 $\mu Pa^2 \cdot sec$ upon exposure to impulse sounds such as those from an airgun array, or
- 215 dB re 1 $\mu Pa^2 \cdot sec$ for a non-impulsive sound such as MarVib exposure.

Our accumulations of acoustic energy are over the entire duration of the simulated survey, which is a precautionary assumption. Southall et al. (2007) also indicate that auditory injury could occur upon exposure to a peak pressure of 230 dB re 1 μPa regardless of exposure duration, in the event that exposure to such a strong signal occurred without exposure to a cumulative energy level exceeding 198 or 215 dB re 1 $\mu Pa^2 \cdot$ sec.

Additionally, the more traditional pressure-based threshold criteria widely used by regulators in the U.S.A. were used. For impulse sources like airguns, we used the established (in the U.S.A.) criteria of 180 dB re 1 μPa (RMS over pulse duration) for potential injury, and 160 dB re 1 μPa (RMS) for potentially significant behavioral modification. The same approach was applied to the MarVib simulations, although there is no specific history of use of the 180 and 160 dB re 1 μPa (RMS) criteria for MarVib signals.

Received levels (both unweighted and M-weighted) were calculated for each of the three acoustic frequencies that were modelled, based on the band-specific source levels in Table 5.1 and a frequency-specific prediction of propagation loss from source to receiver. The number of exposures above the relevant criterion levels at each frequency was determined separately. The maximum number of animals for any one frequency was used to represent the number of exposures for that species, source and location combination.

For each animat, the maximum received sound pressure level at each modelled frequency was determined across the duration the simulation. For each animat, the maximum received level at any time during the simulated survey was the single value to be evaluated against the pressure-based criteria (180 and 160 dB re 1 μPa RMS).

A number of factors contributed to the uncertainty around these estimates of the numbers of exposures that would exceed the relevant criterion. The largest of these is the uncertainty of the density estimate for the population.

The AIM simulations used an overpopulation value of 10 animats/km^2 for each of the three species to ensure smooth variation in the tails of the distribution. However, the resulting values were scaled by the overpopulation factor to obtain real-world exposure estimates for the different sources.

5.6.1 Exposure Modelling Parametric Analysis

The illustrative modelling performed here was intended to be a basis for evaluating differences in numbers of marine mammals that could be exposed to specific sound levels during a seismic survey conducted with a MarVib array vs. airgun array operated in a similar fashion. To do this, it was necessary to set constant certain key features of both systems. The key design features set equal for both are

- the array geometry,
- tow speed, tow depth, and transmission rate, and
- the effective energy source level for a single transmission, which was held constant for all evaluations at a value of 235 dB re 1 $\mu Pa^2 \cdot$ sec @ 1 m.

When evaluating these results, one must take into consideration that—if energy exposure is a critical factor—then in an actual application the user would have the ability to operate either system at a higher or lower source energy level, as well as to operate the system at different depths and tow speeds. However, in this section, the operating features listed above have been set the same for the airgun and MarVib arrays to illustrate the effects of the variables evaluated. These variables included

- Sweep length of an individual MarVib transmission. In order to maintain equal energy transmissions (SEL), sound pressure level (SPL) for the MarVib array would be adjusted downwards as sweep length (T_{DUR}) increased:

  $SEL = SPL + 10Log(T_{DUR})$, or

  $SPL = SEL - 10Log(T_{DUR})$

- The use of M-Weighting as a modifier of exposure levels as discussed in Chapter 4.
- The level of higher frequency components in the MarVib transmit signal, modelled with different roll-off rates for frequencies above 100 Hz. In this case, the airgun roll-off rate was assumed to be 30 dB/decade. It is anticipated that an environmental design goal of future MarVib systems would be to reduce higher frequency components as much as possible.

The modelling provided in this section illustrates the effects of varying these three key parameters in a specific set of scenarios, one in deep water, and one in shallow water, as described above. For each situation, results are derived for the three representative species.

5.6.2 Estimated Numbers Exposed to Levels Exceeding Injury and Disturbance Criteria

Numbers of animals potentially subject to substantial disturbance (sometimes described as behavioral or Level B "takes") were estimated based solely on the behavioral harassment threshold recognized in the U.S.A.: 160 dB re 1 μPa (RMS). For each simulation, the number of individual animals expected to be exposed to various unweighted and M-weighted RMS levels were obtained from the AIM simulations. For the M-weighted results, the M-weighting function from Southall et al. (2007) was applied as appropriate for mysticetes and mid-frequency cetaceans. For the MarVib scenarios analyzed in this report, estimates of numbers that might be exposed to 160 dB re 1 μPa (RMS) are shown for all three representative species in Table 5.3, with and without M-weighting. Table 5.4 provides corresponding estimates for numbers that might be exposed to 180 dB re 1 μPa (RMS). Those Tables also list the estimates if the seismic survey were conducted with an airgun array having equivalent source energy level per pulse.

Detailed evaluation of these predictions is deferred to Chapter 6 where potential impacts are discussed. However, it is obvious from Tables 5.3 and 5.4 that predicted numbers of cetaceans exposed to these sound levels are notably lower for MarVib sources than for airguns. Also, with a MarVib source, there is a tendency for diminishing numbers of exposures to either 160 dB or 180 dB re 1 μPa (RMS) as the roll-off rate increases, and as the duration of the MarVib transmission increases (given that source energy level is assumed to be a constant 235 dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m). Use of the M-weighting procedure results in considerable reductions in estimated numbers of exposures of bottlenose dolphins and sperm whales (examples of mid-frequency cetaceans) to 160 or 180 dB (RMS), but much less change in estimates for the Bryde's whale (a low-frequency cetacean). As noted earlier, the AIM calculations used to develop these estimates do not allow for any avoidance responses of the cetaceans to a nearby airgun array or MarVib source. Thus, they are likely to overestimate numbers of animals that might be exposed to 160 dB and especially 180 dB re 1 μPa (RMS).

TABLE 5.3. Estimated numbers of representative cetacean species potentially exposed to **≥160 dB re 1 µPa (RMS)** during a simulated seismic survey in deep or shallow water of the northern Gulf of Mexico. Estimated separately for an airgun-based survey vs. MarVib surveys with varying signal duration (2, 5 or 8 sec) and varying roll-off rates for components above 100 Hz; also estimated separately including or excluding M-weighting (Southall et al. 2007). Assumes no avoidance reactions to nearby seismic vessel. For interpretation and discussion, see Chapter 6 (Fig. 6.2, Table 6.2, and associated text in §6.2.5).

M-Weighted

DEEP Bottlenose dolphin - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		16.52	6.785	3.54
5 sec	182.605	10.266	3.953	2.596
8 sec		8.732	3.068	2.36

DEEP Bryde's whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.379	0.281	0.281
5 sec	2.043	0.279	0.18	0.18
8 sec		0.238	0.16	0.16

DEEP Sperm whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		10.045	1.75	1.365
5 sec	37.17	5.04	0.7	0.665
8 sec		3.255	0.42	0.21

Shallow Bottlenose dolphin - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		17.169	10.679	5.133
5 sec	76.641	14.101	8.201	1.652
8 sec		13.275	7.316	1.18

Shallow Bryde's whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		1.083	0.892	0.892
5 sec	5.335	0.894	0.57	0.57
8 sec		0.819	0.517	0.517

Shallow Sperm whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		37.065	13.58	1.575
5 sec	96.145	26.355	5.425	0.35
8 sec		22.68	3.64	0.21

Unweighted

DEEP Bottlenose dolphin - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		22.184	19.824	19.824
5 sec	187.325	12.331	9.735	9.735
8 sec		10.207	8.496	8.496

DEEP Bryde's whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.379	0.288	0.288
5 sec	2.053	0.279	0.183	0.183
8 sec		0.238	0.162	0.162

DEEP Sperm whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		11.27	9.765	9.765
5 sec	38.71	8.085	8.085	8.085
8 sec		7.245	7.245	7.245

Shallow Bottlenose dolphin - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		18.821	14.809	14.809
5 sec	275.294	14.632	9.381	9.381
8 sec		14.101	8.85	8.85

Shallow Bryde's whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		1.083	0.899	0.899
5 sec	5.336	0.894	0.571	0.571
8 sec		0.819	0.522	0.522

Shallow Sperm whale - 160 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		41.93	36.365	36.365
5 sec	201.145	29.61	19.6	19.6
8 sec		26.32	14.385	14.385

TABLE 5.4. Estimated numbers of representative cetacean species potentially exposed to **≥180 dB re 1 µPa (RMS)** during a simulated seismic survey in deep or shallow water of the northern Gulf of Mexico. Otherwise as in Table 5.3. Assumes no avoidance reactions to nearby seismic vessel, and thus very likely overestimates numbers exposed to ≥180 dB RMS. For interpretation and discussion, see Chapter 6 (Fig. 6.3, Table 6.3, and associated text in §6.2.6).

M-Weighted

DEEP Bottlenose dolphin - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		1.475	0.708	0.59
5 sec	6.726	0.826	0.59	0.413
8 sec		0.826	0.531	0.354

DEEP Bryde's whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.073	0.067	0.067
5 sec	0.341	0.052	0.052	0.052
8 sec		0.043	0.043	0.043

DEEP Sperm whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.175	0.035	0
5 sec	1.54	0.14	0.035	0
8 sec		0.105	0.035	0

Shallow Bottlenose dolphin - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.885	0.767	0.767
5 sec	9.794	0.826	0.767	0.708
8 sec		0.826	0.708	0.708

Shallow Bryde's whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.102	0.063	0.063
5 sec	0.92	0.037	0.035	0.035
8 sec		0.02	0.02	0.02

Shallow Sperm whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.805	0.105	0.105
5 sec	10.43	0.21	0.105	0.105
8 sec		0.175	0.105	0.105

Unweighted

DEEP Bottlenose dolphin - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		3.54	3.54	3.54
5 sec	26.432	2.596	2.596	2.596
8 sec		2.36	2.36	2.36

DEEP Bryde's whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.073	0.067	0.067
5 sec	0.345	0.057	0.057	0.057
8 sec		0.043	0.043	0.043

DEEP Sperm whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		1.365	1.365	1.365
5 sec	10.15	0.665	0.665	0.665
8 sec		0.21	0.21	0.21

Shallow Bottlenose dolphin - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		2.537	2.537	2.537
5 sec	15.399	1.593	1.593	1.593
8 sec		1.416	1.416	1.416

Shallow Bryde's whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		0.102	0.065	0.065
5 sec	0.926	0.037	0.036	0.036
8 sec		0.02	0.02	0.02

Shallow Sperm whale - 180 dB	airgun	MV 10dB	MV 30dB	MV 50dB
2 sec		1.855	1.225	1.225
5 sec	39.725	0.42	0.35	0.35
8 sec		0.21	0.21	0.21

Numbers of representative animals potentially subject to injury were also estimated based on the SEL criteria of Southall et al. (2007) (see Table 5.5). Whereas the SEL source levels from all sources modeled here were arbitrarily preset to be equal for all parameter variations, the received SEL criteria proposed by Southall et al. (2007) differ for pulsed and non-pulsed sources (198 vs. 215 dB re 1 $\mu Pa^2 \cdot sec$), as discussed previously. This difference is an important consideration in that, for a specified source energy level, it leads to substantially reduced estimates of numbers of cetaceans that might be exposed to injurious levels when a MarVib source is used (Table 5.5). The results in Table 5.5 are all based on M-weighting as suggested by Southall et al. (2007).

The modelling predictions tabulated here are further summarized, evaluated, and discussed in the sections of Chapter 6 on predicted disturbance effects (§6.2.5) and predicted auditory effects (§6.2.6) on cetaceans.

TABLE 5.5. Estimated numbers of representative species receiving cumulative SEL in excess of criteria recommended by Southall et al. (2007), with M-weighting.

	Airgun (SEL ≥ 198)		**Marine Vibrator (SEL ≥ 215)**	
Species	**Deep**	**Shallow**	**Deep**	**Shallow**
Bottlenose dolphin	1.18	12.39	0.472	0.708
Bryde's whale	0.065	0.505	0.008	0.003
Sperm whale	0.14	5.04	0.035	0.07

	Numbers in Population			
Species	**Deep**	**Shallow**	**Deep**	**Shallow**
Bottlenose dolphin	2239	4191	2239	4191
Bryde's whale	32	32	32	32
Sperm whale	1315	1315	1315	1315

	Airgun (SEL ≥ 198)		**Marine Vibrator (SEL ≥ 215)**	
Species	**Deep**	**Shallow**	**Deep**	**Shallow**
Bottlenose dolphin	0.05%	0.30%	0.02%	0.02%
Bryde's whale	0.20%	1.58%	0.03%	0.01%
Sperm whale	0.01%	0.38%	0.00%	0.01%

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CHAPTER 6 ENVIRONMENTAL CONSEQUENCES

6.1 INTRODUCTION

6.1.1 Factors Relevant to Impact Assessment

The assessment of potential impacts of anthropogenic sound on marine animals requires consideration of many factors. These include the type of sound, how sounds should be measured (see § 1.3 in Chapter 1), major categories of marine animals of concern, the underwater hearing abilities of those animals, categories of sound impact, and what amounts of sound exposure will result in biological effects that are of concern (impact criteria).

The first of these factors, *type of sound,* is summarized in the next subsection. Airgun and MarVib sounds fall into two categories of sound: airgun sounds are "multiple pulses", whereas MarVib sounds are sequences of "non-pulses" (see § 6.1.2, below).

The most appropriate ways for *measuring sounds* are introduced in § 1.3 in Chapter 1. Because of the different characteristics of impulsive airgun sound vs. non-impulsive MarVib sound, there are difficulties in obtaining comparable measurements of the two sound types. Procedures for measuring impulse sounds, in particular, are problematic and not well standardized (Madsen 2005). The Joint Industry Programme has a separate initiative underway to strive for standardization of measurement procedures for underwater sounds so as to provide more consistent results that are both physically meaningful and biologically relevant.

The *types of marine animals* that are specifically addressed in this EA include marine mammals, sea turtles, fish, and invertebrates. These are the four main groups that spend much time underwater, are known to be sensitive to underwater sound to some degree, and are of concern to society. (This EA does not specifically address marine birds, for which virtually nothing is known about underwater hearing or about the disturbance effects of underwater sound [Dooling and Therrien in press].) In this EA, particular attention is given to impacts on marine mammals, given their known sensitivity to underwater sound, the larger amount of available information about acoustic effects on them as compared with other animals, and the high degree of public and regulatory concern about that group. We discuss marine mammals first (§ 6.2), with the expectation that some of the generalizations evident for that better-studied group may carry over to the less-well-studied groups that are discussed subsequently.

Underwater hearing abilities differ greatly among the various major groups of marine animals (summarized in Chapter 3). The situation is further complicated by variability among species within a given general category of animals, among individuals of a single species, and within a given individual over time (e.g., as it ages). Different categories of animals vary greatly in the frequencies to which they are sensitive. This is of much significance in assessing the biological effects of anthropogenic sounds at particular frequencies. Both airguns and MarVib systems produce most of their energy at low frequencies (below 100 Hz). Thus, to a first approximation, it is reasonable to expect that both types of sources would have stronger effects on species whose hearing is particularly sensitive at low frequencies (e.g., baleen whales, many fish, and probably sea turtles) than on species whose hearing is adapted mainly to detect high frequency sounds (e.g., porpoises, dolphins, and other toothed whales). However, at a finer scale, the frequency composition of airgun vs. MarVib sounds is expected to differ. It is assumed that the spectrum of future MarVib systems will be controlled to cut off rapidly as frequency increases above the maximum frequency useful for geophysical purposes. This could be important in reducing MarVib impacts on species affected by the higher frequency components (e.g., above 100 Hz) of airgun pulses or older-generation MarVib sound. For cetaceans, this possibility is addressed by application of modelling methods in § 5.5 and in this chapter (§ 6.2).

This EA focuses on four main *categories of biological effects (impacts)*: auditory masking, behavioral disturbance, hearing impairment (temporary and permanent), and non-auditory physical and physiological effects. The likelihood and severity of each of these effects is considered for each major category of marine animal. There are few empirical data concerning effects of airguns (let alone MarVib systems) on most groups of marine animals. Thus, for many combinations of animal type and effect type, conclusions about relative effects of MarVib vs. airgun systems are necessarily based on general principles in combination with analogies to or extrapolations from better-studied groups—most often, marine mammals. The resulting uncertainties lead us to identify various data gaps and recommended studies, as summarized in §8.11 of Chapter 8.

Acoustic impact criteria have been a subject of much interest, particularly for marine mammals and to some degree for fish. Acoustic impact criteria are sound exposure thresholds above which specified types of biological effects are considered likely, and below which those effects are considered unlikely. If realistic criteria can be identified, this would provide a more defensible and objective basis for impact prediction and for specification of mitigation requirements. Section 1.4 briefly summarized the historical development of such criteria for marine mammals, including the use in the U.S.A. of 180 or 190 dB re 1 μPa_{RMS} as a “do not exceed” criterion for pulsed sounds, and 160 re 1 μPa_{RMS} as the received level of pulsed sound above which disturbance is assumed to be likely. Section 1.4 also mentions the various Sound Exposure Levels (SEL) above which there is an expectation that temporary or permanent auditory impairment (temporary or permanent threshold shift, TTS or PTS) could occur in cetaceans and pinnipeds (Southall et al. 2007). Impact criteria for marine mammals are further described in subsequent § 6.2.2. In fish, there is an ongoing effort to develop noise impact criteria, but as yet, only interim criteria for exposure to pile driving have been proposed (Popper et al. 2007a; Rodkin et al. in press).

6.1.2 Sound Types

The properties of airgun and MarVib sound are discussed in Chapters 2 and 4. According to the sound classification scheme used in Southall et al. (2007), airgun(s) produce “multiple pulses” and MarVibs produce “nonpulses”. The distinction is important because, at least in marine mammals, the received sound levels above which there is risk of auditory damage are believed to be different for pulse and nonpulse sound (Southall et al. 2007). Airgun pulses are multiple discrete signals with rapid rise time. An unambiguous definition of impulse sound is difficult, as different types of sound can grade into one another rather than be entirely discrete. However, as outlined in Southall et al. (2007:428), an operational definition for pulse sounds (like those produced by airgun arrays) is that they result in a ≥3 dB difference in received level (RL) when measured via the “impulse” procedure as compared with procedures appropriate for continuous sound. Nonpulses such as those from MarVibs would typically produce multiple discrete events, but the difference in RL when using impulse vs. other time constants would be <3 dB. The rapid onset (rise time) of airgun sound, at least when measured near the airgun source, is a key consideration in determining potential impact. The slower onset of MarVib sound suggests that it will have less potential to cause damage (injury) to biological tissue.

In this EA, we recognize MarVib sound as being non-impulsive, and we generally consider airgun sound to be impulsive. However, as impulse sounds with rapid rise times propagate through a non-homogenous ocean, propagation effects act on the impulses to, effectively, stretch their durations. An airgun pulse that is several milliseconds in duration near the source becomes tens and sometimes hundreds of milliseconds in duration at distances of kilometres and tens of kilometres away. During this dispersion process, the onset of the pulse becomes less sudden, and beyond some variable distance the airgun pulse may no longer meet the "impulse" definition. In this EA, we generally adopt the precautionary practice of treating airgun sound, as received at any distance, as being impulsive. At the close ranges where there is a possibility of auditory impairment, airgun pulses are likely to retain at least some of the characteristics of true impulses, including rapid rise time. However, at the longer distances to which disturbance effects sometimes extend, airgun pulses will not always be truly impulsive. Thus, insofar as behavioral disturbance is concerned, the properties of MarVib and airgun sounds may not be quite as distinct as would occur closer to the source.

6.2 MARINE MAMMALS

6.2.1 Marine Mammal Functional Hearing Groups

Brief summaries of the hearing abilities of marine mammals were provided in Sections 3.5 (mysticetes), 3.6 (odontocetes), 3.7 (pinnipeds), 3.8 (sirenians), 3.9.1 (sea otter), and 3.9.2 (polar bear). For the purposes of this assessment, the functional hearing groups defined in Southall et al. (2007) will be used when appropriate. Those authors suggested that, considering cetaceans and pinnipeds only, thresholds for behavioral responses and injury induced by underwater sound should be examined separately for four functional hearing groups. Southall et al. did not discuss sirenians, the sea otter, or the polar bear, and those groups need to be considered here as well.

The four groups of marine mammals in water that were specifically discussed by Southall et al. are as follows:

Low-Frequency (LF) cetaceans: For baleen whales as a group, the functional hearing range is thought to be ~7 Hz to 22 kHz, and they constitute the LF cetacean hearing group (Southall et al. 2007). As noted in § 3.5, the U.S. regulatory procedures may amend the assumed upper frequency limit to 25 kHz (Scholik-Schlomer in press) based on indications that some baleen whales react to sounds up to about that frequency.

Mid-Frequency (MF) cetaceans: Most of the odontocete species have been classified as belonging to the MF cetacean hearing group, and the MF odontocetes (collectively) have functional hearing from ~150 Hz to 160 kHz (Southall et al. 2007).

High-Frequency (HF) cetaceans: The remaining odontocetes — the porpoises, river dolphins, and members of the genera *Cephalorhynchus* and *Kogia* — are distinguished as the HF cetacean hearing group. They have functional hearing from ~200 Hz to 180 kHz (Southall et al. 2007).

Pinnipeds in water: The functional hearing range for pinnipeds in water is considered to extend from 75 Hz to 75 kHz (Southall et al. 2007), although some individual species, especially the eared seals, do not have that broad an auditory range (Richardson et al. 1995; see § 3.7).

The frequency ranges noted above refer collectively to all species in the group. Individual species may not have quite so broad a functional frequency range. The pinnipeds are particularly variable in this regard, but some cetacean species may also have narrower functional hearing ranges than stated above for the overall cetacean group to which those species belong. Also, it should be noted that the functional hearing ranges do not have "sharp" cutoffs. Strong sounds at frequencies slightly outside the functional range may also be detectable, and weak sound just inside the range may be undetectable even though the same sound level would be detectable if it were at a frequency near the middle of the functional range.

Little is known about sound detection by sirenians, sea otters, and polar bears. Manatees can hear sound from 15 Hz to 46 kHz, and may have best sensitivity at frequencies as low as 1–1.5 kHz or as high as 6–

20 kHz (see § 3.8). There are no data on sea otter or polar bear hearing abilities in water. Their in-air hearing is summarized in § 3.9.

6.2.2 Acoustic Impact Criteria

Science-based auditory-damage criteria for pinnipeds and cetaceans have been proposed, albeit with many limitations and involving many assumptions. Disturbance criteria have been suggested for sequences of impulsive sounds like those from airguns, but responsiveness to such sounds varies widely among species and situations (see § 6.2.5, below). There is little guidance regarding appropriate disturbance criteria for nonpulse (but intermittent) sounds like those from MarVibs. Injury and disturbance criteria are discussed below for cetaceans and pinnipeds. Acoustic impact criteria applicable to other types of marine mammals are less well developed than are the criteria for cetaceans and pinnipeds.

6.2.2.1 TTS and PTS (Injury) Criteria

Since the mid 1990s, the U.S. NMFS has specified that marine mammals should not be exposed to pulsed sounds with received levels (RLs) exceeding 180 or 190 dB re 1 μPa_{RMS}. Since 2000, the "do-not-exceed" levels have been specified as 180 dB re 1 μPa_{RMS} for cetaceans and 190 dB re 1 μPa_{RMS} for pinnipeds (NMFS 2000; Table 6.1). When these criteria were first adopted in the 1990s, there was concern that, at higher RLs, the possibility of auditory damage or other noise-induced injuries could not be excluded.

TABLE 6.1. Acoustic exposure criteria for cetaceans and pinnipeds, as recognized by the U.S. National Marine Fisheries Service [Pressure columns] or proposed by Southall et al. (2007) [Energy columns]

	Level A Harassment (Possible Injury)			*Level B Harassment (Behavioral Disturbance)*
Group	*Pressure (dB re 1 μPa_{RMS})*[1]	*Energy (impulsive signals, e.g., airguns) (dB re 1 $\mu Pa^2 \cdot sec$)*[2]	*Energy (non-impulsive, e.g. MarVib) (dB re 1 $\mu Pa^2 \cdot sec$)*[2]	*Pressure (dB re 1 μPa_{RMS})*[1]
Cetaceans	180	198	215	160
Pinnipeds	190	186	203	160

Sources: [1] NMFS (2005); [2] Southall et al. (2007).

The 180- and 190-dB re 1 μPa_{RMS} "do-not-exceed" criteria were determined before there was any specific information about the received levels of underwater sound that would cause temporary or permanent hearing damage in marine mammals. Subsequently, data on RLs that cause the onset of TTS have been obtained for certain toothed whales and pinnipeds (e.g., Kastak et al. 1999, 2005; Finneran et al. 2002, 2005; see Southall et al. 2007 for review). A group of specialists in marine mammal acoustics, the "noise criteria group", has recommended new criteria, based on scientific knowledge available as of 2007, to replace the somewhat arbitrary 180 and 190 dB_{RMS} "do-not-exceed" criteria (Southall et al. 2007).

As of 2007, the available data indicated that TTS onset in marine mammals is more closely correlated with received energy levels (=sound exposure level or SEL) than with RMS pressure levels. Slight to moderate degrees of TTS are fully recoverable over time, and do not constitute injury. However, sound exposures eliciting slight TTS are considered to be an indicator that, with higher exposures, permanent auditory injury is a possibility. Therefore, studies to determine the sound exposure levels that elicit onset of TTS in cetaceans and pinnipeds have been an important step in the development of an understanding of the levels that might elicit permanent auditory injury in these marine mammals.

In odontocetes and in the more sensitive pinnipeds exposed to non-impulse sound, TTS onset was found to occur at SEL values near 195 and 183 dB re 1 $\mu Pa^2 \cdot sec$, respectively (Southall et al. 2007). In odontocetes exposed to impulsive sounds, the TTS threshold on an SEL basis can be as low as ~183 dB re 1 $\mu Pa^2 \cdot sec$. The corresponding value for pinnipeds exposed to impulse sound is less well defined. Based on the results for non-impulse sound (Kastak et al. 1999, 2005), plus the known tendency in other mammals for lower TTS thresholds with impulse than with non-impulse sound, the TTS thresholds for pinnipeds exposed to impulse sound may be as low as 171 dB re 1 $\mu Pa^2 \cdot sec$ in the more sensitive species such as the harbour seal. However, that estimate is based on assumptions and extrapolations, and does not apply to some other pinniped species (northern elephant seal and California sea lion) in which TTS thresholds, at least to non-impulse sound, are known to be higher (Kastak et al. 2005).

There are no specific data concerning the levels of underwater sound necessary to cause permanent hearing damage (permanent threshold shift or PTS) in any species of marine mammal. Direct empirical studies of this question have not been done and are not planned given the ethical, permitting, and other issues that would attend experiments causing permanent injury to marine mammals. However, PTS and TTS data from terrestrial mammals provide a basis for estimating the difference between the measured TTS thresholds of some marine mammals and their (unmeasured) PTS thresholds. A conservative (precautionary) estimate of this offset between TTS and PTS thresholds, when sound exposure is measured on an SEL basis (received energy levels), is 15 dB for impulsive sounds and 20 dB for non-impulse sounds (Southall et al. 2007). Thus, based on data reviewed by Southall et al. (2007), the lowest RLs of impulsive sounds (e.g., airgun pulses) that might elicit slight auditory injury (PTS) are 198 dB re 1 $\mu Pa^2 \cdot sec$ in cetaceans (i.e., 183 + 15 dB), and 186 dB re 1 $\mu Pa^2 \cdot sec$ in the more sensitive pinnipeds exemplified by the harbour seal (i.e., 171 + 15 dB). Corresponding values for non-impulse sounds (e.g., marine vibrator sweeps) are 215 re 1 $\mu Pa^2 \cdot sec$ in cetaceans (i.e., 195 + 20 dB) and 203 dB re 1 $\mu Pa^2 \cdot sec$ in the more sensitive pinnipeds (e.g., 183 + 20 dB) (Southall et al. 2007). These SEL measures are all assumed to incorporate M-weighting, i.e., somewhat downweighting the energy at frequencies near and especially beyond the lower and upper frequency limits of hearing in the relevant marine mammal group (J. Miller et al. 2005; Southall et al. 2007; see Fig. 4.9 and § 6.2.3, below).

Southall et al. (2007) also concluded that receipt of an instantaneous flat-weighted peak pressure exceeding 230 dB re 1 μPa_p by cetaceans or 218 dB re 1 μPa_p by pinnipeds might lead to auditory injury even if the aforementioned cumulative energy-based criterion was not exceeded.

The primary measure of sound used in the Southall et al. criteria is the received sound energy, not just in the single strongest pulse, but accumulated over time. The most appropriate interval over which the received airgun energy should be accumulated is not well defined. Pending the availability of additional relevant information, Southall et al. suggested that noise exposure be accumulated over 24-hr periods. However, the rationale for that is not well developed. In the acoustic exposure modelling described in Chapter 5 and in § 6.2.5–6.2.6 below, we adopted the precautionary approach of accumulationg over the full duration of the simulated seismic survey. Since most of the received energy comes from the few shotpoints closest to the simulated receiving animal, the duration of the accumulation does not make an appreciable difference to the total accumulated energy (i.e., to the cumulative SEL).

Following Southall et al. (2007), we have assumed, in some of the exposure modelling summarized in Chapter 5 and below, that the cumulative SEL necessary to elicit PTS (auditory injury) in any cetacean is 198 dB re 1 $\mu Pa^2 \cdot sec$ for impulsive sound (e.g., sequences of airgun pulses) and and 215 dB re

1 μPa^2·sec for non-impulse sound (e.g., sequences of MarVib signals). Corresponding criteria for any pinniped are assumed to be 186 dB and 203 dB re 1 μPa^2·sec.

These PTS criteria were based on extrapolation from TTS-onset measurements (Southall et al. 2007). However, there is increasing evidence that, in cetaceans, the SEL associated with TTS onset varies with the frequency and duration of sound, and occurrence of gaps (Mooney et al. 2009a; Finneran and Schlundt 2010; Finneran et al. 2010a,b; Finneran in press). TTS onset probably also varies among species both in cetaceans (Lucke et al. 2009) and in pinnipeds (Kastak et al. 2005). Given the linkages between TTS and PTS, it is likely that the (unmeasured) PTS thresholds also vary with those factors. The Southall et al. "noise criteria group" is presently considering the possibility of updating its 2007 recommendations based on the accumulating new information. For this reason, among others, acoustic exposure modelling based on the SEL criteria from Southall et al. (2007) should be considered a first approximation.

6.2.2.2 Disturbance Criteria

The existing U.S. NMFS criterion for potential disturbance to marine mammals from most airgun-based seismic surveys is 160 dB re 1 μPa (RMS, averaged over pulse duration). That is an RL above which, in NMFS' view, substantial behavioral disturbance is likely. It is well established that some individual cetaceans show avoidance or other behavioral reactions to airgun sound at RLs lower than 160 dB re 1 μPa$_{RMS}$ (McCauley et al. 2000a,b; G. Miller et al. 1999, 2005), so 160 dB should not be assumed to be the minimum level at which behavioral reactions occur. Conversely, at times, some marine mammals tolerate exposure to higher RLs without exhibiting overt behavioral responses. In at least one special case, in which migrating bowhead whales have shown avoidance at a substantially lower received level of airgun sounds, NMFS has adopted additional criteria acknowledging that significant disturbance may occur at a lower RL (e.g., NMFS 2006). Also, in other jurisdictions, alternative disturbance criteria for airgun sounds are sometimes recommended. However, the Southall et al. "noise criteria group" concluded that (as of late 2007) available data were insufficient as a basis for recommending any specific alternative disturbance criteria applicable to multiple-pulse sounds like airgun array sounds. For seismic surveys subject to U.S. regulatory procedures, the 160 dB re 1 μPa$_{RMS}$ exposure criterion is still widely used as an indicator of situations where substantial behavioral disturbance is likely, and we apply it in our exposure modelling (§ 5.4–5.5 and § 6.2.5). However, it should be recognized that there is much variability in responsiveness to airgun sounds. Occurrence of responses may depend as much or more on the species, the animals' activity and motivation at the time, their past history of exposure to the sound in question, and various other "context" factors as it does on the received sound level (Richardson et al. 1995; Southall et al. 2007; see also § 6.2.5).

No specific disturbance criterion applicable to marine vibrator sounds has been proposed previously. For some other non-impulse sounds, NMFS has concluded that RLs ≥120 dB re 1 μPa$_{RMS}$ are likely to elicit disturbance. The available information (see § 6.2.5) on the limited reactions of various cetaceans to intermittent low-frequency active (LFA) sonar sounds leads us to believe that cetaceans are unlikely to react strongly (if at all) to MarVib signals at RLs near 120 dB re 1 μPa$_{RMS}$. However, that is an assumption and needs to be verified by field studies. For LFA sonar sounds, NMFS has acknowledged that the probability of disturbance reactions increases from near 0 % at an RL of 120 dB re 1 μPa$_{RMS}$ to ~95 % at an RL of 180 dB re 1 μPa$_{RMS}$ (DoN 2001). That "risk continuum" concept also appears to be appropriate for MarVib signals, but the shape of the "probability of response" function at RLs between 120 and 180 dB re 1 μPa$_{RMS}$ is unknown. Our exposure modelling, which seeks to predict numbers of cetaceans that might be disturbed by a MarVib-based survey vs. an otherwise-comparable airgun survey (§ 5.4–5.5 and § 6.2.5), assumes a 160 dB re 1 μPa$_{RMS}$ disturbance criterion for both sources. However, we acknowledge that, at present, there is no information concerning the actual responses of cetaceans (or other marine mammals) to MarVib signals with various RLs, and there is a need for empirical data on this, as noted in the Recommended Studies section (§8.11.3).

6.2.3 Auditory Weighting Functions

A further recommendation from the "noise criteria group" was that allowance should be given to the differential frequency responsiveness of various marine mammal groups (J. Miller et al. 2005; Southall et al. 2007; see § 6.2.1, above). This is important when considering seismic survey sounds, as the energy in both airgun and MarVib sounds is mainly at low frequencies. With airguns, diminishing amounts of energy occur at progressively higher frequencies above ~100 Hz (Greene and Richardson 1988; Goold and Fish 1998; Goold and Coates 2006). However, airguns do, at some times and in some directions, emit sufficient energy in the 100 Hz to low kHz range for that energy to be detectable (and possibly disturbing) to animals that are relatively insensitive to the higher levels of airgun sound at ≤100 Hz (Richardson and Würsig 1997; Madsen et al. 2006). For future marine vibrator systems, the fall-off in amount of energy with increasing frequency is expected to be more rapid than for airguns (see § 4.6).

The "noise criteria group" proposed that, in calculating the effective SELs received by marine mammals, frequency-weighting functions should be applied (Southall et al. 2007). A separate weighting curve was proposed for each of the four marine mammal groups distinguished by Southall et al. (Fig. 4.9). The weighting curves de-emphasize the HF energy when dealing with baleen whales (LF cetaceans), and de-emphasize LF energy when dealing with MF and especially HF odontocetes. For pinnipeds in water, there is some de-emphasis of both the LF and HF energy, but the LF are weighted more heavily than for odontocetes and less heavily than for mysticetes. The shapes of the four M-weighting curves (i.e., M_{lf} for baleen whales, M_{mf} for most odontocetes, M_{hf} for the HF odontocetes, and M_{pw} for pinnipeds in water) are similar to those of C-weighting curves that are widely used when considering effects of strong pulsed sounds on human hearing. However, the M-weighting curves are shifted downward in frequency for baleen whales and upward in frequency for toothed whales relative to C-weighting, consistent with the frequency ranges of best hearing by baleen and toothed whales relative to the optimum range for humans.

The M-weighting curves have been defined in a precautionary manner that allows for the fact that, at least in terrestrial mammals, TTS and PTS are less strongly related to frequency than is audibility. Thus, M-weighting curves (and the C-weighting curve for humans) are "flatter" than the audiograms representing minimum detectable sound level at each frequency. Steeper frequency-weighting functions based on the shape of the audiogram have been recommended by some researchers (e.g., Nedwell et al. 2007). That may be appropriate when dealing with acoustic detection or any disturbance responses that occur at relatively low RLs. However, by analogy with the flatter C-weighting curves applied for humans exposed to high-level sounds, use of flatter M-weighting functions was considered more appropriate when dealing with auditory effects that occur at high RLs (Southall et al. 2007). A recent equal-loudness study in the bottlenose dolphin tends to confirm that, at least in that species, weighting curves tend to flatten when sound level increases (Schlundt and Finneran in press). That supports the idea that M-weighting curves are more appropriate than audiogram-based weighting when considering relatively high criterion values like 160 or 180 dB re 1 μPa_{RMS}.

Our exposure modelling comparing numbers of marine mammals likely to be exposed to specified levels of sound during MarVib-based surveys vs. airgun surveys considers both M-weighted received sound levels and unweighted (i.e., flat-weighted) sound levels. Following Southall et al., we believe that the M-weighted approach is more appropriate from a biological perspective, but in the U.S.A., the cognizant regulatory authority (NMFS) has generally required airgun exposures be calculated on a flat-weighted basis. However, it appears that NMFS may change its policy and recommend use of M-weighting in future (Scholik-Schlomer in press). We conducted the exposure modelling using both the flat-weighted and M-weighted approaches for completeness and for comparative purposes.

6.2.4 Masking

Masking is the obscuring of sounds of interest by interfering sounds, generally at similar frequencies (Richardson et al. 1995; Clark et al. 2009; Ellison 2010). Introduced underwater sound will, through "communication masking", reduce the effective communication distance of a marine mammal species if the frequency of the source is close to that of the marine mammal's calls, and if the anthropogenic sound is present for a significant fraction of the time (Richardson et al. 1995). Introduced underwater sound can also cause "informational masking", i.e., reduce the distances over which animals can hear other types of sounds important to them, including sounds from predators (killer whales) or sounds from other natural sources that may be used to find food, to navigate, or for other purposes. If little or no overlap occurs between the introduced sound and the frequencies used by the species, communication and information-gathering are not expected to be disrupted. Also, if the introduced sound is present only infrequently, communication and information gathering are not expected to be disrupted much if at all.

6.2.4.1 Airguns

Airgun sounds are pulsed, with relatively quiet periods between pulses, and with a relatively low duty cycle. In most situations, strong airgun sound will only be received for a brief period (<1 sec), with these sound pulses being separated by at least several seconds of relative silence (longer in the case of deep-penetration surveys or refraction surveys with long shot intervals). Cetaceans often continue to call in the presence of airgun pulses (see below). When the duty cycle of the interfering sound is low (as it is for airguns), most of the cetacean calls are received in the intervals between airgun pulses and are readily detectable on hydrophone recordings. Presumably they are also audible to other cetaceans.

A single airgun array might cause appreciable masking in only two situations: ***(1)*** When propagation conditions are such that sound from each airgun pulse reverberates strongly and persists at a substantial level for much or all of the interval up to the next airgun pulse (e.g., Simard et al. 2005). ***(2)*** When the water is deep and propagation conditions are good, sounds from several widely separated seismic ships sometimes arrive at a given location from long distances (e.g., Nieukirk et al. 2004; Clark and Gagnon 2006). In those situations the received seismic pulses might be sufficiently numerous and elongated (through propagation effects) such that significant masking could occur. In our experience, situations with prolonged strong reverberation do occur, but are relatively infrequent. However, it is common for reverberation to cause some lesser degree of elevation of the background level between pulses (e.g., Guerra et al. 2009; Gedamke and McCauley 2010), and this weaker reverberation presumably reduces the detection range of calls and other natural sounds.

Some *baleen whales* continue calling in the presence of seismic pulses, and whale calls often can be heard between the seismic pulses (e.g., Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999; Nieukirk et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b, 2006; Dunn and Hernandez 2009). However, one recent summary report indicated that calling fin whales distributed over a portion of the North Atlantic went silent for an extended period starting soon after the onset of a seismic survey in the area (Clark and Gagnon 2006). It is not clear from that preliminary paper whether the whales ceased calling because masking prevented them from hearing one another, or whether this was a behavioral response not directly involving masking. In contrast, Di Iorio and Clark (2010) found evidence of increased calling by blue whales during operations by a lower-energy seismic source―a sparker.

In *toothed whales* (odontocetes), masking effects of seismic pulses are expected to be negligible under most conditions, given the intermittent nature of seismic pulses plus the fact that sounds important to most odontocetes are predominantly at higher frequencies than are the dominant components of airgun sounds. Madsen et al. (2006) noted that airgun sounds would not be expected to mask sperm whale calls given the intermittent nature of airgun pulses. Hydrophones commonly detect calls from various species of odontocetes during the intervals between airgun pulses (e.g., Gordon et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b; Potter et al. 2007), and presumably those calls would also be detectable by other members of the same species. When strong reverberation continues between pulses, this would reduce detectability of odontocete calls to some degree, but this masking is expected to be less severe than for mysticetes given the much reduced overlap in frequencies of odontocete vs. airgun sounds as compared with mysticete vs. airgun sounds. Masking effects of airgun sound, to the extent that they occur in odontocetes, are likely to be less for the high-frequency odontocete group (porpoises, *Kogia*, *Cephalo-rhynchus*, and river dolphins) than for the "mid-frequency" odontocetes (see § 6.2.1, above).

Most *other marine mammals* (pinnipeds, sirenians, and sea otters) also have best hearing sensitivity and/or produce most of their sounds at frequencies higher than the dominant components of airgun sounds, but there is some overlap in the frequencies of the seismic sounds and calls. However, the intermittent nature of airgun pulses presumably reduces the potential for masking.

6.2.4.2 Marine Vibroseis

The signal duration for a source consisting of one or more marine vibrators is expected to be much longer than that for an airgun source, and the duty cycle would be higher. Thus, masking is more likely to be an issue for a MarVib source than for airguns, notwithstanding the lower peak pressure of the MarVib source.

***Relevant Empirical Information*.—**Masking effects of MarVib signals on marine mammal calls or other sounds important to marine mammals have not been studied directly. However, some potentially relevant information comes from observations of marine mammals exposed to other types of prolonged anthropogenic sounds.

Baleen whales that are exposed to other types of prolonged anthropogenic sounds adjust the characteristics of their calls in ways that would tend to reduce masking (e.g., Dahlheim 1987; P. Miller et al. 2000; Fristrup et al. 2003; Parks et al. 2007, 2010). Whether whales would make such adjustments to their calls in the presence of MarVib sounds is unknown. The fact that they sometimes do make such adjustments upon exposure to other anthropogenic sounds is, on the one hand, an indirect indication that masking can be an issue in baleen whales, and on the other hand, an indication that whales have mechanisms to compensate (to some unknown degree) for masking of their own calls. However, baleen whales seeking to detect other low-frequency environmental sounds that may be important to the whales, e.g., surf noise, could encounter increased masking in the presence of MarVib sounds, with no obvious way to compensate for that masking. Even so, MarVib signals are assumed to be discontinuous, and sounds of interest to baleen whales should be detectable in the intervals when MarVib signals are not being received. (If a MarVib system were operated with little or no gap between successive transmissions, or if propagation conditions resulted in strong reverberation of MarVib signals during the "gaps", masking effects would be greater.) Calls from predatory killer whales are not likely to be significantly masked by MarVib sounds because killer whale calls are at frequencies higher than than those of MarVib signals; masking mainly affects sounds at frequencies similar to those of the masking signal (here the MarVib sound). In summary, given the higher duty cycle, MarVib signals are likely to have a greater masking effect on sounds important to baleen whales than occurs with airgun pulses, but even for MarVib signals, the masking effect would be partial, not total, provided there are gaps between MarVib signals.

In *odontocetes*, as in mysticetes, masking effects of MarVib signals have not been studied. There is evidence that some odontocetes exposed to other types of prolonged or recurrent anthropogenic sounds also adjust characteristics of their calls in ways that would tend to reduce masking (Au 1993; Lesage et al. 1999; Scheifele et al. 2005; Holt et al. 2009). If MarVib signals had a masking effect on odontocete calls, then these compensatory mechanisms should reduce the masking effect on calls from conspecifics. Also, the fact that MarVib signals are predominantly at low frequencies whereas odontocete calls are mainly at higher frequencies means that masking of conspecific calls (or calls by predatory killer whales) by Mar-Vib signals should not be a major problem for odontocetes. Any limited masking effect that does exist would be further reduced if future MarVib systems can be designed with minimal acoustic output at frequencies above about 100 Hz.

Pinnipeds, sirenians, and *sea otters* also have best hearing sensitivity and/or produce most of their sounds at frequencies higher than the dominant components of MarVib sounds, but for some species there could be some overlap in the frequencies of the seismic sounds and calls. This overlap would be reduced or eliminated if future MarVib systems can be designed with minimal acoustic output above ~100 Hz.

Expected MarVib vs. Airgun Effects.—The several-second gaps that are expected to occur between marine vibrator signals will usually allow marine mammals to hear natural environmental sounds intermittently, including sounds from other marine mammals. However, the higher duty cycle of MarVib signals as compared with airguns means that, within the range around the source vessel where the vibrator signals are audible, masking of faint natural sounds will occur for a higher proportion of the time. Offsetting this, to some degree, is the lower source level of the vibrator signals. That will limit the radius within which masking can occur. Nonetheless, an array of marine vibrators will inevitably be a moderately strong source, presumably with a source level of 220 dB re 1 μPa or more. Under typical background noise conditions, a sound with that source level is often detectable above the natural background level up to at least a few tens of kilometres away, even when the source is within metres of the water surface. Any detectable sound signal, even a weak one, has the potential to reduce the detectability of other weak sounds. Thus, for baleen whales to which low frequency sound is particularly relevant, there could be at least a slight masking effect for a significant proportion of the time (depending on the MarVib duty cycle) at distances up to 10s of kilometres. Stronger sound signals would be masked only for receivers closer to the vibrators (Richardson et al. 1995:359).

Little is known about the effects of intermittent masking on marine mammals in the wild (Richardson et al. 1995), but this is a subject of increasing concern (Clark et al. 2009). It is not possible to predict with precision or assurance the consequences of the extra masking of low-frequency sounds that would occur as a result of using marine vibrators (which might have a duty cycle up to 50% or perhaps more) as compared with airguns (≤5% duty cycle). Given the mobility of any seismic source, the reduced source level of the marine vibrators as compared to airguns, and the assumption that the vibrators would not have a 100% duty cycle (i.e., there would be silent periods), the masking effect of the vibrator sounds may not have serious consequences for marine mammals. Provided that future MarVib systems can be designed to avoid emitting much sound above the frequencies useful for geophysicists, masking should not be a significant issue for odontocetes and perhaps not for other marine mammal groups aside from baleen whales. In relative sense, however, for marine mammals near the source, marine vibrators will cause more masking of low frequency sounds than usually occurs with airguns.

MarVib Design Alternatives.—To the extent that MarVib systems do cause some masking, especially for baleen whales that use low-frequency sounds, potential design decisions about future MarVib systems could affect and to a some degree mitigate the extent of masking.

Decreasing the duration of each MarVib signal and increasing the duration of the intervals between signals, thus reducing the duty cycle, would reduce the potential for overlap of MarVib sounds with biologically relevant sounds and reduce masking. Although that in itself would be desirable, a reduction in signal duration and duty cycle would probably require increasing the source level of each MarVib signal. If so, masking effects during receipt of the shorter but stronger MarVib signals would be somewhat increased. However, the lower duty cycle would allow detection of relevant sounds for a higher proportion of the time and might still be a useful tradeoff.

Conversely, increasing the duty cycle by increasing the duration of each MarVib signal or reducing (or especially eliminating) the gap between signals would increase the masking effect and potential impact.

Better suppression of harmonics or other unneeded higher-frequency components of the MarVib signals (e.g., above 100 Hz) would be desirable for several reasons, including reduction of masking. This would be especially so for species that call at (or pay attention to) the frequencies that might be suppressed through design changes (e.g., at 100–500 Hz). That includes many of the mysticetes and pinnipeds, and to a lesser degree odontocetes and other marine mammal groups.

Earlier MarVib designs used frequency-modulated (FM) signals, but geophysicists are interested in the possibility of using pseudo-random noise (PRN) signals. From the geophysicists' perspective, these may provide signal-processing advantages, allowing better detection of weak seismic signals and extraction of more geophysical information. If that, in turn, allowed a MarVib system to operate with a lower source level, shorter signal duration, or lower duty cycle than would be required with FM signals, that could be advantageous from an impact perspective.

However, if PRN MarVib signals would need to contain the same total energy as FM MarVib signals that would otherwise be used, then use of PRN signals might be disadvantageous from an environmental perspective, at least for baleen whales. Clark (2009) notes that baleen whales often adapt to and tolerate anthropogenic LF-FM sounds, whereas upon exposure to increased broadband noise they either compensate behaviorally (by adjusting their call characteristics) or they incur increased masking. Clark (2009) suggested that, for the same amount of energy in the relevant frequency band, a broadband signal will have a larger biological effect. Figure 6.1, from Ellison (2010), summarizes some key features of an FM signal (e.g., baleen whale call, depicted in green) received simultaneously with either another FM signal or a broadband signal (in red). The time (dt) and bandwidth (df) of overlap and potential masking are much reduced for the FM vs. FM case as compared with the FM vs. broadband case.

MarVib systems are expected to be useable at a wider range of depths in the water column than are airguns. The ability to operate at additional depths, as compared to airguns, could provide additional options for mitigation. If the MarVib system could be operated deeper than is practical with airguns, that could reduce the maximum received levels (and thus masking effects) that would be encountered by animals that generally remain close to the water's surface. Depending on the sound velocity profile and other factors affecting sound propagation, operating the source at a deeper depth could either increase or decrease the received levels (and masking effects) at various depths and distances. These tradeoffs would ideally need to be evaluated on a site- and season-specific basis. Choice of source depth would also affect the radii of potential disturbance and auditory effects for marine mammals and other biota, depending on their depth preferences (see subsequent sections). In selecting an optimum depth of operation for a MarVib system, disturbance, auditory effects, and other issues may be of greater direct relevance than the potential for masking.

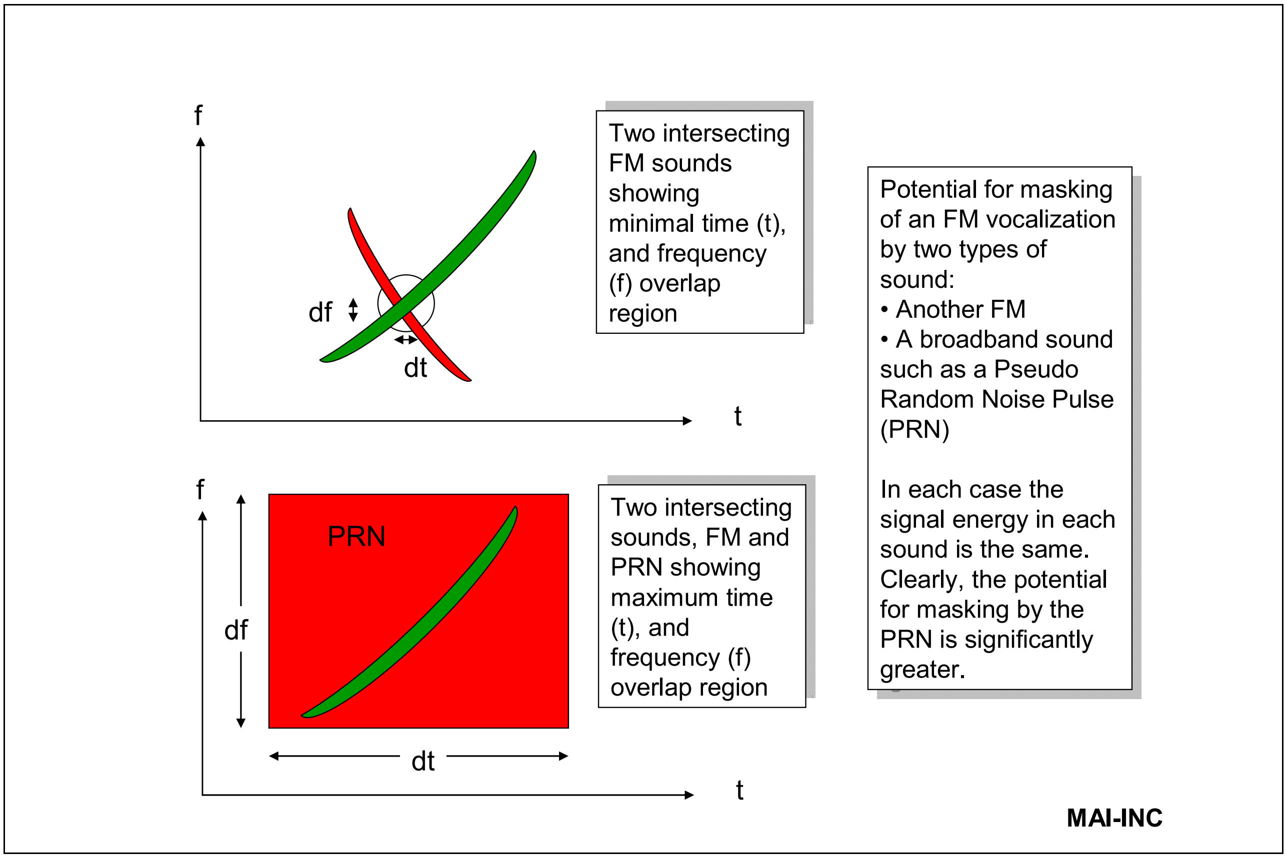

FIGURE 6.1. Comparison of an FM signal (in green, such as a baleen whale call) overlapped by another signal (in red) that is either FM (above) or broadband (below). df and dt refer to the ranges of frequency and of time where the two signals overlap. From Marine Acoustics,Inc. (Ellison 2010).

6.2.4.3 Summary for Masking

The longer signal duration and higher duty cycle of MarVib systems, as compared with airguns, provides greater potential for masking of animal calls and other ecologically-important sounds. Although some reverberation often persists during the intervals between airgun pulses, in many cases marine mammals will be able to hear one another, or other relevant sounds, during those intervals, whereas during a MarVib survey, the relatively quiet intervals will constitute a lower proportion of the total time. Masking during either airgun or MarVib surveys will be most significant for baleen whales, given the importance of low-frequency calls for communication in many baleen whales. For other marine mammal groups, especially odontocetes, there is less overlap in frequency between MarVib sounds and sounds important to the mammals, and masking by MarVib sounds is expected not to be a major issue to those animals. That will be especially so if the higher frequency components of MarVib sound that are of no value to geophysicists can be further suppressed. The implications of various other MarVib design considerations to masking potential are summarized immediately above.

6.2.5 Disturbance

Disturbance includes a variety of effects, including subtle to conspicuous changes in behaviour, movement, and displacement. Based on NMFS (2001, p. 9293), NRC (2005), and Southall et al. (2007), we assume that simple exposure to sound, or brief reactions that do not disrupt behavioral patterns in a potentially significant manner, do not constitute harassment or "taking". By potentially significant, we mean "in a manner that might have deleterious effects to the well-being of individual marine mammals or their populations".

Behavioral reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors, along with received sound level and (probably) background noise conditions (Richardson et al. 1995; Gordon et al. 2004; Wartzok et al. 2004; Nowacek et al. 2007; Southall et al. 2007; Weilgart 2007). There is no single received sound level above which all individuals react and below which they do not react. The occurrence of disturbance responses is a probabilistic and context-dependent phenomenon, and the probability of response depends on numerous factors in addition to sound exposure.

If a marine mammal does react briefly to an underwater sound by changing its behaviour or moving a small distance, the impacts of the change are unlikely to be significant to the individual, let alone the stock or population. However, if a sound source displaces marine mammals from an important feeding or breeding area for a prolonged period, impacts on individuals and populations could be significant (e.g., NRC 2005; Lusseau and Bejder 2007; Weilgart 2007). Given the many uncertainties in predicting the quantity and types of impacts of noise on marine mammals, it is common practice to estimate how many mammals would be present within a particular distance of industrial activities and/or exposed to a particular received level of industrial sound. In most cases, this approach likely overestimates the numbers of marine mammals that would be affected in some biologically-important manner.

The sound criteria used to estimate how many marine mammals might be disturbed to some biologically-important degree by a seismic programme are based primarily on behavioral observations of a few species exposed to airgun sounds. Detailed studies of responses to airgun sound have been done on humpback, gray, bowhead, and sperm whales. Less detailed data are available for some other species of baleen whales, small toothed whales, pinnipeds, and sea otters, but for many marine mammal species, there are no data on responses to marine seismic surveys involving airguns. Even for the well-studied species, it is important to recognize that the occurrence and nature of responses to a seismic survey can be difficult to predict given the inherently variable and context-dependent nature of behavioral responsiveness.

To our knowledge, there have been no studies of behavioral reactions by any marine mammal species to MarVib signals. In the absence of specific data on reactions to MarVib signals, reactions to other types of intermittent, strong, low-frequency sounds may have some relevance, and are summarized in § 6.2.5.2.

6.2.5.1 Airguns

This subsection summarizes the available empirical data on reactions (or lack of reactions) of the major groups of marine mammals to airguns. This is intended primarily as a starting point and basis of comparison for the subsequent assessment of anticipated reactions of those groups to MarVib signals. More extensive reviews of marine mammal reactions to airgun sounds can be found in Richardson et al. (1995), Gordon et al. (2004), Nowacek et al. (2007), and Richardson and Moulton (2010). Readers seeking a more detailed review than appears below are referred to Richardson and Moulton (2010), to which an internet link is provided in the Literature Cited section.

***Baleen Whales*.—**Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable. Whales are often reported to show no overt reactions to pulses from large arrays of airguns at distances beyond a few kilometres, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, as documented in the reviews cited above, baleen whales exposed to strong noise pulses from airguns often react by deviating from their normal migration route and/or interrupting their feeding and moving away. In the cases of migrating gray and bowhead whales, the observed changes in behaviour appeared to be of little or no biological consequence to the animals. They simply avoided the sound source by displacing their migration route to varying degrees, but within the natural boundaries of the migration corridors.

Studies of gray, bowhead, and humpback whales have shown that seismic pulses with received levels of 160–170 dB re 1 μPa_{RMS} seem to cause obvious avoidance behaviour in a substantial fraction of the animals exposed (Richardson et al. 1995). In many areas, seismic pulses from large arrays of airguns diminish to those levels at distances ranging from 4 to 15 km from the source. A considerable proportion of the baleen whales within those distances may show avoidance or other strong behavioral reactions to the airgun array. Subtle behavioral changes sometimes become evident at somewhat lower received levels, and studies summarized in the aforementioned reviews have shown that bowhead and humpback whales at times show strong avoidance at received levels lower than 160–170 dB re 1 μPa_{RMS}.

Responses of humpback whales to seismic surveys have been studied during migration, on summer feeding grounds, and on Angolan winter breeding grounds; there has also been discussion of effects on the Brazilian wintering grounds. McCauley et al. (1998, 2000a,b) studied the responses of humpback whales off Western Australia to a full-scale seismic survey with a 16-airgun, 2678-in^3 array, and to a single 20-in^3 airgun with source level 227 dB re 1 $\mu Pa \cdot m_{p-p}$. McCauley et al. (1998) documented that avoidance reactions began at 5–8 km from the array, and that those reactions kept most pods ~3–4 km from the operating seismic boat. McCauley et al. (2000a,b) noted localized displacement during migration of 4–5 km by travelling pods and 7–12 km by more sensitive resting pods of cow-calf pairs. Avoidance distances with respect to the single airgun were smaller but consistent with the results from the full array in terms of the received sound levels. The mean received level for initial avoidance of an approaching airgun was 140 dB re 1 μPa_{RMS} for humpback pods containing females, and at the mean closest point of approach (CPA) distance the received level was 143 dB re 1 μPa_{RMS}. The initial avoidance response generally occurred at distances of 5–8 km from the airgun array and 2 km from the single airgun. However, some individual humpback whales, especially males, approached within distances of 100–400 m, where the maximum received level was 179 dB re 1 μPa_{RMS}.

Humpback whales on their summer feeding grounds in southeast Alaska did not exhibit persistent avoidance when exposed to seismic pulses from a 1.64-L (100-in^3) airgun (Malme et al. 1985). Some humpbacks seemed “startled” at received levels of 150–169 dB re 1 μPa. Malme et al. (1985) concluded that there was no clear evidence of avoidance, despite the possibility of subtle effects, at received levels up to 172 re 1 μPa on an approximate RMS basis.

It has been suggested that South Atlantic humpback whales wintering off Brazil may be displaced or even strand upon exposure to seismic surveys (Engel et al. 2004). The evidence for this was circumstantial and subject to alternative explanations (IAGC 2004). Also, the evidence was not consistent with subsequent results from the same area of Brazil (Parente et al. 2006b), or with direct studies of humpbacks exposed to seismic surveys in other areas and seasons. After allowance for data from subsequent years, there was “no observable direct correlation” between strandings and seismic surveys (IWC 2007:236).

There are no data on reactions of right whales to seismic surveys, but results from the closely-related bowhead whale show that responsiveness of bowheads can be quite variable depending on their activity (migrating vs. feeding). Bowhead whales migrating west across the Alaskan Beaufort Sea in autumn, in particular, are unusually responsive, with substantial avoidance occurring out to distances of 20–30 km from a medium-sized airgun source at received sound levels of around 120–130 dB re 1 μPa_{RMS} (G. Miller et al. 1999; Richardson et al. 1999). However, more recent research on bowhead whales (G. Miller et al. 2005; Harris et al. 2007) corroborates earlier evidence that, during the summer feeding season, bowheads are not as sensitive to seismic sources. Nonetheless, subtle but statistically significant changes in surfacing–respiration–dive cycles were evident upon statistical analysis (Richardson et al. 1986). In summer, bowheads typically begin to show avoidance reactions at received levels of about 152–178 dB re 1 μPa_{RMS} (Richardson et al. 1986, 1995; Ljungblad et al. 1988; G. Miller et al. 2005).

Reactions of migrating and feeding (but not wintering) gray whales to seismic surveys have been studied. Malme et al. (1986, 1988) studied the responses of feeding eastern Pacific gray whales to pulses from a single 100-in^3 airgun off St. Lawrence Island in the northern Bering Sea. They estimated, based on small sample sizes, that 50% of feeding gray whales stopped feeding at an average received pressure level of 173 dB re 1 μPa on an (approximate) RMS basis, and that 10% of feeding whales interrupted feeding at received levels of 163 dB re 1 μPa_{RMS}. Those findings were generally consistent with the results of experiments conducted on larger numbers of gray whales that were migrating along the California coast (Malme et al. 1984; Malme and Miles 1985), and western Pacific gray whales feeding off Sakhalin Island, Russia (Würsig et al. 1999; Gailey et al. 2007; Johnson et al. 2007; Yazvenko et al. 2007a,b), along with data on gray whales off British Columbia, Canada (Bain and Williams 2006).

Various species of *Balaenoptera* (blue, sei, fin, and minke whales) have occasionally been seen in areas ensonified by airgun pulses (Stone 2003; MacLean and Haley 2004; Stone and Tasker 2006), and calls from blue and fin whales have been localized in areas with airgun operations (e.g., McDonald et al. 1995; Dunn and Hernandez 2009). Sightings by observers on seismic vessels off the United Kingdom from 1997 to 2000 suggest that, during times of good sightability, sighting rates for mysticetes (mainly fin and sei whales) were similar when large arrays of airguns were shooting vs. silent (Stone 2003; Stone and Tasker 2006). However, these whales tended to exhibit localized avoidance, remaining significantly farther (on average) from the airgun array during seismic operations compared with non-seismic periods (Stone and Tasker 2006). In a study off Nova Scotia, Moulton and Miller (2005) found little difference in sighting rates (after accounting for water depth) and initial sighting distances of balaenopterid whales when airguns were operating vs. silent. However, there were indications that these whales were more likely to be moving away when seen during airgun operations. Similarly, ship-based monitoring studies of blue, fin, sei, and minke whales offshore from Newfoundland found no more than small differences in sighting rates and swim directions during seismic vs. non-seismic periods (Moulton et al. 2005, 2006a,b). In contrast, a recent study in the Mediterranean Sea concluded that fin whales apparently left an area where a seismic survey was underway, and did not begin to return to their former distribution until ~2–3 weeks after airgun operations ended (Castellote et al. 2010). That study was based on detections of fin whale calls. It was shown that exposure to the airgun pulses had some type of behavioral effect, but it is unclear whether all fin whales moved away; some might have remained but ceased calling upon exposure to airgun pulses. Either reaction would be a type of disturbance response.

Data on short-term reactions by cetaceans to impulsive noises are not necessarily indicative of long-term or biologically significant effects. It is not known whether impulsive sounds affect reproductive rate or have long-term effects on distribution and habitat use. However, gray whales have continued to migrate annually along the west coast of North America with substantial increases in the population over recent decades despite intermittent seismic exploration (and much ship traffic) in that area (Appendix A *in* Malme et al. 1984). Western Pacific gray whales did not seem affected at the population level by a seismic survey in their main feeding ground during a previous year (Johnson et al. 2007). Similarly, bowhead whales continued to travel to the eastern Beaufort Sea each summer, and their numbers increased notably, despite seismic exploration in their summer and autumn range for many years (Richardson et al. 1987).

***Toothed Whales*.—**Little systematic information is available about reactions of odontocetes to noise pulses. Few studies similar to the more extensive baleen whale/seismic pulse work summarized above and (in more detail) in Richardson and Moulton (2010) have been reported for toothed whales. However, there are recent systematic studies on sperm whales (e.g., Gordon et al. 2006; Madsen et al. 2006; Winsor and Mate 2006; Jochens et al. 2008; P. Miller et al. 2009). There is also an increasing amount of information about responses of various odontocetes to seismic surveys based on monitoring studies (e.g., Stone 2003; Smultea et al. 2004; Moulton and Miller 2005; Bain and Williams 2006; Holst et al. 2006; Stone and Tasker 2006; Potter et al. 2007; Hauser et al. 2008; Holst and Smultea 2008; Weir 2008; Barkaszi et al. 2009; Richardson et al. 2009; Barry et al. in press).

Seismic operators and marine mammal observers on seismic vessels regularly see dolphins and other small toothed whales near operating airgun arrays, but in general there is a tendency for most delphinids to show some avoidance of operating seismic vessels (e.g., Goold 1996a,b,c; Calambokidis and Osmek 1998; Stone 2003; Moulton and Miller 2005; Holst et al. 2006; Stone and Tasker 2006; Weir 2008; Richardson et al. 2009; see also Barkaszi et al. 2009). Some dolphins seem to be attracted to the seismic vessel and floats, and some ride the bow wave of the seismic vessel even when large arrays of airguns are firing (e.g., Moulton and Miller 2005). Nonetheless, small toothed whales more often tend to head away, or to maintain a somewhat greater distance from the vessel, when a large array of airguns is operating than when it is silent (e.g., Stone and Tasker 2006; Weir 2008; Barry et al. in press). In most cases the avoidance radii for delphinids appear to be small, on the order of 1 km less, and some individuals show no apparent avoidance. The beluga is a species that (at least at times) shows long-distance avoidance of seismic vessels. Aerial surveys conducted in the southeastern Beaufort Sea during summer found that sighting rates of beluga whales were significantly lower at distances 10–20 km compared with 20–30 km from an operating airgun array, and observers on seismic boats in that area rarely see belugas (G. Miller et al. 2005; Harris et al. 2007).

Results for porpoises depend on species. The limited available data suggest that harbour porpoises show stronger avoidance of seismic operations than do Dall's porpoises (Stone 2003; MacLean and Koski 2005; Bain and Williams 2006; Stone and Tasker 2006). Dall's porpoises seem relatively tolerant of airgun operations (MacLean and Koski 2005; Bain and Williams 2006), although they too have been observed to avoid large arrays of operating airguns (Calambokidis and Osmek 1998; Bain and Williams 2006). This apparent difference in responses of harbour vs. Dall's porpoises is consistent with their relative responsiveness to boat traffic and some other acoustic sources (Richardson et al. 1995; Southall et al. 2007).

Most studies of sperm whales exposed to airgun sounds indicate that the sperm whale shows considerable tolerance of airgun pulses (e.g., Stone 2003; Moulton et al. 2005, 2006a; Stone and Tasker 2006; Weir 2008). In most cases the whales do not show strong avoidance, and they continue to call (see Richardson and Moulton [2010] for review). However, controlled exposure experiments in the Gulf of Mexico indicate (with small sample sizes) that foraging behaviour was altered upon exposure to airgun sound (Jochens et al. 2008; P. Miller et al. 2009; Tyack 2009).

There are almost no specific data on the behavioral reactions of beaked whales to seismic surveys. However, some northern bottlenose whales remained in the general area and continued to produce high-frequency clicks when exposed to sound pulses from distant seismic surveys (Gosselin and Lawson 2004; Laurinolli and Cochrane 2005; Simard et al. 2005). Most beaked whales tend to avoid approaching vessels of other types (e.g., Würsig et al. 1998). They may also dive for an extended period when approached by a vessel (e.g., Kasuya 1986), although it is uncertain how much longer such dives may be as compared to dives by undisturbed beaked whales, which also are often quite long (Baird et al. 2006;

Tyack et al. 2006). In any event, it is likely that most beaked whales would also show strong avoidance of an approaching seismic vessel, although this has not been documented explicitly.

There are increasing indications that some beaked whales tend to strand when naval exercises involving mid-frequency sonar operation are ongoing nearby (e.g., Cox et al. 2006; D'Spain et al. 2006; D'Amico et al. 2009; Filadelfo et al. 2009). These strandings are apparently at least in part a disturbance response, although auditory or other injuries or other physiological effects may also be involved. Seismic survey sounds are quite different from those of the military sonars in operation during the incidents noted above. Whether beaked whales would ever react similarly to seismic surveys is unknown. There is no conclusive evidence of cetacean strandings or deaths at sea as a result of exposure to seismic surveys, but a few cases of strandings in the general area where a seismic survey was ongoing have led to speculation about a possible link (see § 6.2.7, below).

In summary, odontocete reactions to large arrays of airguns are variable and, at least for delphinids and Dall's porpoises, seem to be confined to a smaller radius than has been observed for the more responsive of the mysticetes, belugas, and harbour porpoises. A ≥170 dB re 1 μPa_{RMS} disturbance criterion (rather than the ≥160 dB criterion recognized by NMFS—see § 6.2.2) may be appropriate for delphinids (and pinnipeds), which tend to be less responsive than the more responsive cetaceans.

Pinnipeds.—Pinnipeds usually do not show a strong avoidance reaction to sound pulses from an airgun array. Visual monitoring from seismic vessels has shown only slight (if any) avoidance of airguns by pinnipeds, and only slight (if any) changes in behaviour (see Richardson and Moulton 2010 for details). In the Beaufort Sea, some ringed seals avoided an area of 100 m to (at most) a few hundred metres around seismic vessels, but many seals remained within 100–200 m of the trackline as the operating airgun array passed by (e.g., Harris et al. 2001; Moulton and Lawson 2002; G. Miller et al. 2005). Ringed seal sightings averaged somewhat farther away from the seismic vessel when the airguns were operating than when they were not, but the difference was small (Moulton and Lawson 2002). Recent monitoring studies in Alaskan Arctic waters also found evidence of a tendency for phocid seals to exhibit localizaed avoidance of the seismic source when airguns were firing (Reiser et al. 2009). Similarly, in Puget Sound, sighting distances for harbour seals and California sea lions tended to be larger when airguns were operating (Calambokidis and Osmek 1998). A telemetry study of seals exposed to pulses from small airgun sources suggested that avoidance and other behavioral reactions may be stronger than evident to date from visual studies (Thompson et al. 1998).

In general, reactions to airgun sources are confined to relatively small distances and durations, with no evidence of long-term effects on pinniped individuals or populations. As noted above for delphinids, a ≥170 dB re 1 μPa_{RMS} disturbance criterion seems more appropriate for pinnipeds than the current NMFS criterion of 160 dB (*cf.* § 6.2.2). Pinnipeds are less responsive to airguns than are many cetaceans.

Other Marine Mammals.—There are few data on the behavioral responses of sirenians, sea otters, or polar bears to airgun sounds. We know of no specific studies of sirenians or polar bear responses. Polar bears are only infrequently encountered during marine seismic surveys in the Arctic given the tendency of polar bears to associate with ice, which seismic vessels generally avoid (Ireland et al. 2009). However, polar bears on the ice would be largely unaffected by underwater sound. Sound levels received by polar bears in the water would also be attenuated because polar bears generally do not dive much below the surface. Received levels of airgun sound are reduced just below the surface because of pressure release and interference (Lloyd's mirror) effects near the surface (Greene and Richardson 1988; Richardson et al. 1995).

Behaviour of sea otters along the California coast was monitored by Riedman (1983, 1984) while they were exposed to sound from a single 100-in^3 airgun and a 4089-in^3 airgun array. No disturbance reactions were evident when the airgun array was as close as 0.9 km. Sea otters also did not respond noticeably to the single airgun. The results suggest that sea otters are less responsive to marine seismic pulses than are some other marine mammals. Also, sea otters spend a great deal of time at the surface feeding and grooming. While at or near the surface, the potential noise exposure of sea otters would be much reduced by the aforementioned pressure release and interference effects.

6.2.5.2 Marine Vibroseis

***Relevant Empirical Information*.—**There have been no studies of the behavioral reactions of marine mammals to marine vibrator signals.

In the absence of specific data on reactions to MarVib signals, reactions to other types of intermittent, strong, low-frequency sounds may have some some relevance. Some data are available concerning reactions of some *baleen whales* to sounds produced by the U.S. Navy's Low-Frequency Active (LFA) sonar (e.g., Clark et al. 1999). The sound sources used in these studies had some limited degree of similarity to marine vibroseis, in that LFA sources were also low frequency (<500 Hz), intermittent, non-impulse sources that projected strong swept tones. However, the projected LFA sounds differed in frequency, duration, and duty cycle from anticipated MarVib sounds, and in certain cases were operated at lower source levels. The LFA sounds involved swept tones within the 100–500 Hz band (e.g., 160–330 Hz). The signals were longer in duration (often 42 s) than MarVib signals, and more widely separated (by several minutes of silence) than those emitted by a MarVib. When an array of LFA sources was used, the sources were in a vertical line, contrary to the horizontal layout that would be used with MarVibs. Observations of baleen whales exposed to LFA sounds are summarized below. Whether whale reactions to MarVib sounds would be similar is speculative; direct observations of whales exposed to MarVib sounds would be needed to assess this.

Humpback whale singing behaviour in Hawaii was compared during periods with and without LFA sonar sounds (160–330 Hz band; 42-sec tonal signal repeated every 6 min; source levels 170–200 dB re 1 μPa_{RMS}; Biassoni et al. 2000; P. Miller et al. 2000). LFA sound levels received by humpback whales had received levels 120–150 dB re 1 μPa_{RMS}. Whale response varied. Most humpbacks (n=9) continued calling in the presence of the LFA sonar signal, some whales (n=4) stopped singing when they joined other humpbacks (which is typical of a mysticete social interaction), and other whales (n=5) ceased singing during exposure without joining other whales. There tended to be an increase in song duration upon exposure to the LFA signal; this involved increased repetition of elements of the song. Subsequently, Fristrup et al. (2003) applied a multivariate approach to examine humpback whale song relative to LFA sonar signals. They also found that song duration increased in association with LF broadcasts. Statistically significant differences in song duration extended 2 hr beyond the last LF signal. Also, longer songs tended to occur with higher source levels of LFA sound. However, the fraction of the variability in song length associated with LFA signals was low, and the responses of the humpbacks to the LFA sound were well within the range of variation in song lengths in the absence of LF broadcasts (Fristrup et al. 2003).

The distribution of *blue and fin whales* off southern California during the fall feeding period did not change in any major way when they were exposed to LFA sonar transmissions with estimated RL as high as 150 dB re 1 μPa_{RMS} (Croll et al. 2001). The probability of fin whales vocalizing was slightly reduced during periods when the LFA sonar source was active than when it was inactive (Clark and Altman 2006). The authors suggested that this may have resulted from reduced vocal activity of the whales in response to LFA transmissions, the effect of mitigation measures, or a combination of both. Although fin and blue whales seemed relatively non-responsive to LFA sonar signals, it should be noted that the frequencies of the LFA sonar sounds were well above the very low frequencies at which fin and blue whales call.

Responses of migrating *gray whales* to LFA sonar signals were studied along the California coast. The LFA sonar signals were as described in the preceding paragraph, i.e., the signals were more complex, longer in duration, and more widely separated than those emitted by a marine vibrator. Avoidance thresholds to the LFA sonar sound were substantially lower than those found for a single airgun deployed in the same area during an earlier study. The 50% avoidance threshold was ~141 dB re 1 μPa_{RMS} (95% CI ± 3 dB) when the LFA sonar source was placed in the path of migrating gray whales (Buck and Tyack 2000; DoN 2001; Tyack 2009), as compared with ~170 dB re 1 µPa on an approximate RMS basis for the single airgun, and ~120 dB for playback of continuous industrial sound. (A subsequent reanalysis found that the median avoidance threshold for the LFA signals was 135 dB rather than 141 dB**—**Buck and Tyack [2003].) However, when the LFA sonar source was located offshore from the gray whale migration route, responsiveness was much reduced, and 50% avoidance was not found even at higher received sound levels.

These results from gray whales are noteworthy in at least two respects: ***(1)*** They showed that the responsiveness of migrating gray whales was strongly context-dependent, and much reduced when the sound source was not directly in the migration path (Buck and Tyack 2000; Tyack 2009). ***(2)*** They indicated that, for a sound source in the migration path, gray whale responsiveness to intermittent LFA sounds was higher than for pulses from a single airgun but lower than for playbacks of continuous industrial sound when the sound exposure was measured on an RMS basis averaged over the respective signal durations. These differences may have important implications with regard to the response threshold for MarVib vs. airguns. However, the finding that 50% avoidance occurred with a received level of LFA sound near 135–141 dB re 1 μPa_{RMS} came from a different study than did the finding of 50% avoidance for airgun sound with received level 170 dB re 1 μPa_{RMS}. In both studies, a single "subscale" sound source was used**—**smaller than the full-scale LFA source or a full-scale airgun array. For this reason, and because a MarVib source would differ in several respects from an LFA source, one should be very cautious in interpreting these data. It would be desirable to conduct further empirical testing of a variety of marine mammal species exposed to sounds from realistic sources (including an actual MarVib source).

There is no information about responses of *other types of marine mammals* (odontocetes, pinnipeds, sirenians, sea otters, or polar bears) to marine vibrator sounds. There is some information about arctic seals and polar bears on sea ice exposed to sounds and vibrations from on-ice vibroseis. However, those observations have limited relevance to marine mammals in the water and exposed to sound from an underwater MarVib source. Also, we are not aware of information on the responses of any of these groups of animals to similar types of sounds (e.g., LFA sonar transmissions).

Expected MarVib vs. Airgun Effects: General Considerations**.—**The responsiveness of various cetaceans and pinnipeds to airgun sounds is known to some degree, but there are no data on responsiveness of any marine mammals to MarVib sounds. Available data on responses (or lack of responses) of a few species of baleen whales to LFA sonar sounds are instructive, but the degree of similarity in baleen whale responses to MarVib vs. LFA sonar is speculative. Also, for groups other than baleen whales, responses to LFA are not documented. A further major complication is the fact that responsiveness of marine mammals to any type of underwater sound is quite variable and context dependent.

Notwithstanding these important caveats and limitations, airgun sounds have substantially higher source pressure levels, and higher received pressure levels at any given distance, than would MarVib signals. This has important consequences ***if*** marine mammal responsiveness to a given received pressure level of MarVib and airgun sounds is similar for a given context. With both sources, most of the energy is at low frequencies

(<100 Hz), and thus subject to similar propagation loss rates. Because of its higher received level (RL) at any given range, airgun sound is expected to remain above the ambient noise level to greater distances than MarVib sound. Airgun sound will remain detectable (at least by baleen whales and other animals with sensitive low-frequency hearing) out to greater distances than MarVib sound.

If a MarVib system had (for example) a source level 20 dB lower than an airgun array useable in the corresponding situation, then the distance to a given RL or signal-to-ambient ratio, and the maximum detection distance, would all be much lower with MarVib than for the airgun system. Propagation loss rates are complex, but as a first approximation, with a nominal spreading loss of 20 log (range), i.e., spherical spreading, a 20-dB difference in source level translates into a 10-fold difference in distance. The difference becomes even greater if the loss rate is closer to 15 log (range) or lower, as can occur in ducting conditions. Furthermore, a 10-fold reduction in the radius of ensonification to a given RL represents a 100-fold reduction in the area ensonified to that level, assuming (as a first approximation) omnidirectional propagation of the dominant low-frequency components in near-horizontal planes.

Thus, if the probability of a disturbance response is the same for a MarVib and airgun signal with a given RL, the response distance would be much lower for MarVib, and the number of animals expected to be disturbed would be much reduced with MarVib. The effects of anticipated differences in RLs of MarVib vs. airgun sounds (assuming the same 160 dB re 1 μPa_{RMS} response criterion in each case) are shown quantitatively in the following subsection on results of exposure modelling.

However, MarVib and airgun signals have other differences aside from their source levels and their RLs at a given distance. In particular, MarVib signals are longer than airgun pulses, with higher duty cycle. Total energy content of a MarVib signal may be similar to that of an airgun pulse appropriate for the same application. If behavioral responses are better correlated with energy content than with RL, then response distances of animals sensitive to low frequencies might be similar for MarVib to those for an airgun array.

Southall et al. (2007) reviewed then-available behavioral response data for cetaceans and pinnipeds seeking to determine if disturbance responses were better correlated with received sound level or with received sound energy. Given the wide variability in responsiveness within and between species, and other limitations of the available data, Southall et al. concluded that it was not possible to answer this question. That answer would be important in predicting responsiveness to MarVib sound, and the lack of data on this point is an important data gap.

One potentially relevant empirical observation is the evidence that migrating gray whales reacted to a sound source within their migration path at a lower received sound level when receiving LFA sonar sounds than when receiving airgun pulses. As noted above, 50% avoidance was determined to occur at a RL of ~135–141 dB re 1 µPa for LFA sound (Buck and Tyack 2000, 2003; Tyack 2009) as compared with ~170 dB re 1 µPa on an approximate "RMS over pulse duration" basis for airgun sound (Malme et al. 1984). The LFA sonar sounds were even more different from airgun pulses than are anticipated MarVib signals. (The LFA signals were more complex, longer, higher in frequency, and with much longer intervals between successive signals.) Thus, it is not at all certain that there would be a similar difference in the avoidance thresholds for MarVib vs. airgun sounds as there was for LFA vs. airgun sounds. However, *the LFA vs. airgun results do indicate the possibility of lower avoidance thresholds (on a received pressure level basis) for MarVib vs. airguns*. The lack of specific data on this is another important data gap.

It is expected that future MarVib systems would produce less "unnecessary" energy at frequencies above those relevant for geophysical purposes (e.g., above 100 Hz). This might not make much difference to baleen whales, for which the predominant energy below ~100 Hz is presumably a prominent part of the received sound. However, for toothed whales and (to a lesser degree) pinnipeds whose hearing sensitivity is much reduced at low frequencies, the components of airgun sounds above 100 Hz are probably the most prominent components. For example, Richardson and Würsig (1997) showed that, for beluga whales in the Alaskan Arctic, the components of airgun sounds from 100 or 200 Hz to ~1600 Hz are likely to be the most prominent components. If components at those frequencies can be much reduced with future MarVib systems as compared to airgun sources, disturbance responses of toothed whales and perhaps pinnipeds to MarVib should be reduced relative to their responses to airguns. This question is addressed in the *Design Alternatives* subsection, below, via modelling methods.

***Expected MarVib vs. Airgun Effects: Exposure Modelling*.—**Chapter 5 of this document describes application of modelling methods to predict the numbers of cetaceans (of three representative species) that might receive MarVib and airgun sounds with RLs above 160 dB re 1 μPa_{RMS} during seismic surveys in the northern Gulf of Mexico. The assumed characteristics of the MarVib and airgun systems were chosen (in consultation with the JIP's Project Support Group for this project) so as to represent systems that might substitute for one another. In each case, it was assumed that there would be a source element [MarVib or airgun(s)] at 21 locations within a 3-string array, and that the overall source energy level would be a constant 235 dB re 1 $\mu Pa^2 \cdot$ sec per transmission. The CASS/GRAB propagation model was used to predict the received sound levels in three dimensions around these sources if they operated at either of two sites in the northern Gulf of Mexico—one shallow site (~60 m deep) and one deep site (~1000 m) (see Fig. 5.1 for map). Details about the characteristics of the assumed source arrays, and about the propagation modelling, are provided in § 5.3.

Numbers of cetaceans that might be exposed to seismic signals with RLs ≥160 dB re 1 μPa_{RMS} (and also ≥180 dB re 1 μPa_{RMS}) were calculated assuming that either the MarVib system or the airgun system was used for a 3-D seismic survey around each site (shallow or deep). For these calculations, we used the Acoustic Integration Model, AIM, which was developed by Marine Acoustics, Inc. (Frankel et al. 2002). AIM is a Monte Carlo-based statistical model that takes account of biologically appropriate assumptions about the movement and diving behaviour of the animal population being simulated. Among AIM's many previous applications have been assessments of numbers of cetaceans that might be exposed to various received sound pressure levels and received sound exposure levels of airgun sound during seismic surveys in several regions within and outside U.S. waters (e.g., Appendix B *in* NSF and USGS 2010, plus other as-yet-unreleased assessments of the impacts of airgun-based seismic-surveys).

In the present application of AIM, we considered three cetacean species representative of the broader range of cetaceans occurring in the Gulf of Mexico: one dolphin species (bottlenose dolphin), one species of deep-diving toothed whale (sperm whale), and one species of baleen whale (Bryde's whale). The AIM model took account of the relative densities of these three species in the northern Gulf of Mexico: low for the Bryde's whale, intermediate for the sperm whale, and higher for the bottlenose dolphin (Table 5.2). In the calculations summarized here, we assumed the same density of animals at the deep and shallow water sites. That may not be biologically appropriate, especially for the sperm whale, but it allows direct evaluation of the relative numbers of individuals potentially exposed to RLs ≥160 dB re 1 μPa_{RMS} under different circumstances, other factors (e.g., population density) being equal. We assumed that the animals did not change their movement patterns in response to the approaching (simulated) seismic vessel, and that there were no shutdowns of the source if cetaceans were sighted nearby. Thus, our estimates of numbers that might be exposed to ≥160 dB (and especially to ≥180 dB) are probably overestimates, given the likelihood of some avoidance by the animals, and some shutdowns of the source when animals are detected nearby. In predicting the numbers of cetaceans (of the three representative species) that might receive ≥160 dB (or ≥180 dB), we did the calculations twice. One set of calculations assumed that received sound levels should incorporate the M-weighting functions that allow for frequency-related differences in sensitivity of the various cetacean groups (Southall et al. 2007; § 6.2.3), and once without frequency weighting. Additional details concerning the assumptions and AIM modelling procedures are given in § 5.4–5.5. Predicted numbers of animals that might be exposed to ≥160 (and ≥180) dB re 1 μPa_{RMS} are summarized in § 5.5 and further summarized and interpreted here.

Table 6.2A shows some of the key results of the AIM modelling with respect to the numbers of cetaceans that could be exposed to RLs ≥160 dB re 1 μPa_{RMS} during otherwise-comparable MarVib-based vs. airgun-based seismic surveys. For the model runs summarized here, the MarVib system was assumed to emit signals 5 sec in duration with a frequency rolloff rate above 100 Hz of 30 dB per octave (i.e., per doubling of frequency). (Comparative results with different assumptions about signal duration and rolloff rate are described in the following subsection.)

The number of individual cetaceans predicted to be exposed to ≥160 dB re 1 μPa_{RMS} on one or more occasions during the simulated seismic survey was always much lower during the MarVib-based survey than during the corresponding airgun-based survey. The estimates for MarVib ranged from 1.9% to 20.9% of those for airguns, depending on the species, site (deep or shallow), and whether or not M-weighting was applied (Table 6.2A). Actual numbers of animals predicted to receive ≥160 dB at some point during the simulated airgun survey ranged from ~77 to 275 for the bottlenose dolphin, ~2 to 5 for the Bryde's whale, and 37 to 201 for the sperm whale, again depending site and whether M-weighting was applied. Corresponding predictions for the MarVib survey ranged from 4 to 10 for the bottlenose dolphin, 0.2 to 0.6 for the Bryde's whale, and 0.7 to 20 for the sperm whale.

When M-weighting was applied, estimates for the MarVib survey ranged from 1.9% to 10.7% of those for the corresponding airgun survey, depending on species and site (deep or shallow; Table 6.2A). When unweighted RLs were considered, the corresponding percentages were 3.4% to 20.9%. As expected, M-weighting made little difference to the results for the Bryde's whale, as the M_{lf}-weighting curve applicable to a baleen whale (e.g., Bryde's whale) has very little effect for sounds that are predominantly at low frequency. Application of M-weighting had a considerable effect on the predicted number of exposures of bottlenose dolphins and sperm whales at the shallow site, but not at the deep site (Table 6.2A).

These model predictions are instructive in estimating, for representative species of cetaceans, the proportional reduction in numbers of animals that might be exposed to ≥160 dB re 1 μPa_{RMS} during a MarVib survey vs. an otherwise-comparable airgun survey. That reduction is very substantial (Table 6.2A). The ≥160 dB criterion is the one currently applied by the U.S. NMFS in judging, for a project involving airguns or other impulsive sources, how many animals might be "taken by harassment" under the provisions of the U.S. Marine Mammal Protection Act (MMPA; see § 6.2.2).

We emphasize that it is uncertain whether the ≥160 dB re 1 μPa_{RMS} criterion is appropriate for MarVib sources, given the lack of empirical data on responses of any marine mammals to MarVib sounds. Disturbance responses of marine mammals might be more closely related to received signal energy than to received pressure level. If so, the numbers of marine mammals expected to be disturbed by a MarVib vs. airgun survey would be more similar than predicted by AIM on the assumption that the same pressure threshold (e.g., 160 dB re 1 μPa_{RMS}) applies to both sources.

Comparison of AIM results for MarVib surveys at the deep vs. shallow site shows that, for all three representative species of cetaceans, predicted numbers exposed to M-weighted RLs ≥160 dB re 1 μPa_{RMS} were higher in shallow than in deep water (Table 6.2A) if the same population density was assumed for

TABLE 6.2. Estimated numbers of representative cetacean species potentially exposed to sounds with received levels ***(A)*** ≥160 dB and ***(B)*** ≥180 dB re 1 μPa$_{RMS}$ (M-weighted or unweighted) during otherwise-comparable airgun-based or MarVib-based seismic surveys in the northern Gulf of Mexico. The MarVib source was assumed to produce signals 5 sec in duration and with a rolloff rate (above 100 Hz) of 30 dB per octave. See preceding paragraphs for summary of modelling methods, and Chapter 5 for details. Assumed cetacean densities are given in Table 5.2.

		M-Weighted			Unweighted		
		Airguns	**MarVib**	**MV as % of Airgun**	**Airguns**	**MarVib**	**MV as % of Airgun**
A. Number Exposed to ≥160 dB re 1 μPa$_{RMS}$							
Deep Site							
	Bottlenose dolphin	182.61	3.95	2.2	187.33	9.74	5.2
	Bryde's whale	2.04	0.18	8.8	2.05	0.18	8.9
	Sperm whale	37.17	0.70	1.9	38.71	8.09	20.9
Shallow Site							
	Bottlenose dolphin	76.64	8.20	10.7	275.29	9.38	3.4
	Bryde's whale	5.34	0.57	10.7	5.34	0.57	10.7
	Sperm whale	96.15	5.43	5.6	201.15	19.60	9.7
B. Number Exposed to ≥180 dB re 1 μPa$_{RMS}$							
Deep Site							
	Bottlenose dolphin	6.73	0.59	8.8	26.43	2.60	9.8
	Bryde's whale	0.34	0.05	15.2	0.35	0.06	16.5
	Sperm Whale	1.54	0.04	2.3	10.15	0.67	6.6
Shallow Site							
	Bottlenose dolphin	9.79	0.77	7.8	15.40	1.59	10.3
	Bryde's whale	0.92	0.04	3.8	0.93	0.04	3.9
	Sperm whale	10.43	0.11	1.0	39.73	0.35	0.9

each site.[6] This result was a consequence of differing sound propagation conditions at the two sites and (especially near the shallow site) constraints on dive-depths imposed by limited water depth. The shallow vs. deep pattern was not as consistent for airgun sound, or when the RLs were unweighted (Table 6.2A).

[6] To facilitate comparisons, the same population densities were assumed for the shallow and deep sites, though that may not be realistic for species with pronounced depth preferences, such as the sperm whale.

***MarVib Design Alternatives*.**—To the extent that MarVib systems do cause disturbance, especially for baleen whales that use low-frequency sounds, potential design decisions about future MarVib systems could affect and to some degree mitigate the extent of disturbance.

Decreasing the duration of each MarVib signal and/or increasing the duration of the intervals between signals, thus reducing the duty cycle, would expose the animals to similar peak levels of sound but less sound energy if these changes could be done without necessitating an offsetting increase in the source level. However, AIM modelling showed that, if it were necessary to increase the source level to compensate for reduced signal duration, use of signals 2 sec rather than 5 sec in duration would increase the number of animals predicted to be exposed to ≥160 dB re 1 μPa_{RMS} (M-weighted) at some point during the seismic survey (Fig. 6.2, blue vs. red bars). Conversely, if duration were extended from 5 to 8 sec, with a commensurate decrease in source pressure level so as to maintain the same source energy level, numbers exposed to ≥160 dB (M-weighted) would tend to decrease (Fig. 6.2, green vs. red bars). Thus, if numbers of cetaceans exposed to ≥160 dB re 1 μPa_{RMS} is the relevant measure and a certain signal energy is required, then lengthening the MarVib transmissions could have some benefit, and shortening them could be counterproductive. However, as noted in §6.2.4, increasing the signal duration and duty cycle, and/or reducing or eliminating the gaps between MarVib transmissions, would increase the masking effect, so lengthening the transmissions could also be counterproductive.

Better suppression of harmonics or other unneeded higher-frequency components of the MarVib signals (e.g., above 100 Hz) would, qualitatively, be expected to have relatively little benefit for baleen whales, which hear the predominant low-frequency components well, but substantial benefit for toothed whales, which are more sensitive to the higher-frequency components. AIM modelling confirmed these expectations (Fig. 6.2). The predicted numbers of bottlenose dolphins and sperm whales (toothed whales) receiving ≥160 dB re 1 μPa_{RMS} (M_{mf}-weighted) during the MarVib survey are notably lower if the rolloff rate above 100 Hz is assumed to be 50 dB per octave than for 30 dB per octave. With a rolloff rate of only 10 dB per octave, the numbers of dolphins and sperm whales exposed to ≥160 dB (M_{mf}-weighted) would be considerably higher. In contrast, for the one species of baleen whale considered (Bryde's whale), the predicted effect of changes in rolloff rate on numbers exposed to ≥160 dB (M_{lf}-weighted) is considerably reduced as compared to the two representative odontocete species.

If MarVib system could be engineered such that the rolloff begins at a frequency lower than 100 Hz, and if this can be done without increasing the source level below that frequency, that should further reduce the numbers exposed to ≥160 dB (or any other relevant level). Among marine mammals, this benefit is likely to be most pronounced for some baleen whales and perhaps to some degree pinnipeds, given their assumed or (for some pinnipeds) known sensitivity to sounds at frequencies just below 100 Hz. However, in the absence of specific data on the auditory sensitivity or behavioral responsiveness of baleen whales as a function of frequency, it is not possible to predict quantitatively how much advantage (reduced disturbance effect) there would be if the rolloff could begin at any specific frequency somewhat below 100 Hz. The degree of advantage would presumably depend on species. Whales that call at very low frequencies (≤20 Hz), and presumably are sensitive to such frequencies, e.g., fin and blue whales, probably would not benefit much from a reduction in the rolloff frequency from 100 Hz to (for example) 80 or 90 Hz. Species whose hearing is less sensitive at 80 Hz than at 100 Hz (possibly some other baleen whale species as well as pinnipeds) might benefit from such a reduction in the rolloff frequency. Specific data on marine mammal responsiveness vs. frequency would be needed to verify these general predicttions.

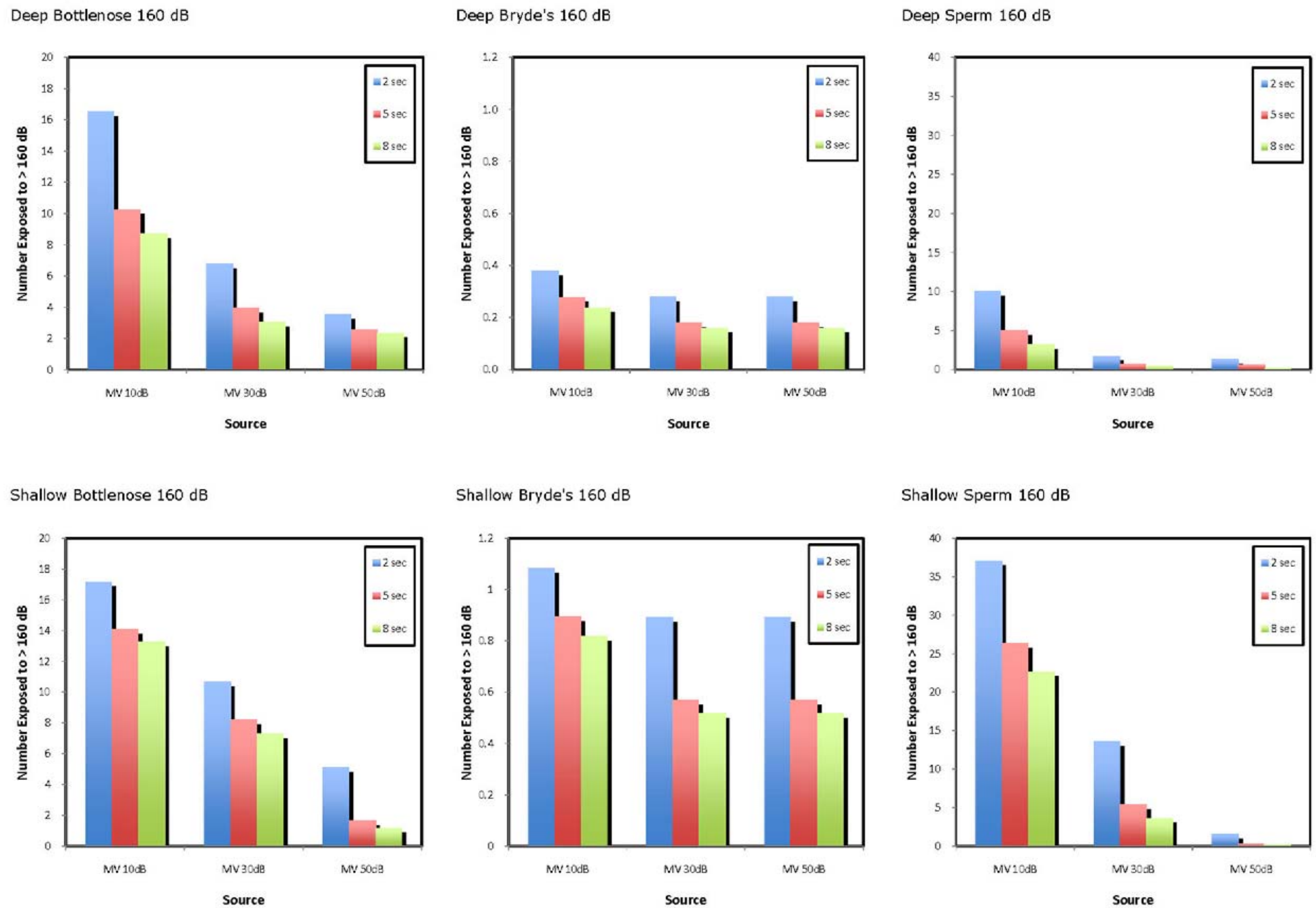

FIGURE 6.2. Effects of MarVib signal-duration and rolloff rate above 100 Hz on estimated numbers of representative cetacean species potentially exposed to sounds with received levels ≥160 dB re 1 μPa$_{RMS}$ (M-weighted) during otherwise-comparable seismic surveys in the northern Gulf of Mexico. Signal durations 2, 5 and 8 sec are evaluated, assuming the same source energy level would be required regardless of signal duration (i.e., higher source pressure level is assumed for short signals; lower source pressure level for long signals). Rolloff rates of 10, 30 and 50 dB per octave (at frequencies above 100 Hz) are assumed. See §5.6 for details.

Earlier MarVib designs used frequency-modulated (FM) signals, but geophysicists are interested in the possibility of using pseudo-random noise (PRN) signals. If that allowed a MarVib system to operate with a lower source level, shorter signal duration, or lower duty cycle than would be required with FM signals, that could be advantageous from an impact perspective. However, if PRN MarVib signals would need to contain the same total energy as FM MarVib signals that would otherwise be used, then use of PRN signals might be disadvantageous from both a masking perspective (§ 6.2.4.2) and a disturbance perspective. Clark (2009) and Ellison (2010) concluded that baleen whales tend to be more responsive to PRN signals than to FM signals. To our knowledge, there has been no direct comparison of behavioral responsiveness of marine mammals to FM vs. PRN signals that are otherwise consistent in level, duration, bandwidth, etc. It would be desirable to obtain empirical data on that to help in deciding about the relative merits of the two types of signals.

MarVib systems are expected to be useable at a wider range of depths in the water column than are airguns. The ability to operate at additional depths, as compared to airguns, could provide additional options for mitigation, as noted earlier with respect to masking (§ 6.2.4.2). If the MarVib system could be operated deeper than is practical with airguns, that could reduce the maximum received levels (and thus disturbance effects) that would be encountered by animals that generally remain close to the water's surface. Depending on the sound velocity profile and other factors affecting sound propagation, operating the source at a deeper depth could either increase or decrease the received levels (and disturbance effects) at various depths and distances. These tradeoffs would ideally need to be evaluated on a site- and season-specific basis.

6.2.5.3 Summary for Disturbance

Short-term behavioral reactions (or lack therof) of various marine mammals to airgun-based seismic surveys have been described, but there are no data on their reactions to MarVib sounds. For a MarVib system, source level and RL at any given distance would be considerably lower than for airguns. If NMFS' 160 dB re 1 μPa_{RMS} criterion of disturbance applies (at least approximately) to MarVib, the radius of disturbance would be much lower with MarVib, and the number of animals disturbed by a survey of a given seismic line would be much reduced (probably to ≤10%; see M-weighted section of Table 6.2A).

However, it is unknown whether the the onset of significant disturbance responses would occur at a similar sound pressure level for MarVib signals as for airgun sounds, with their shorter durations and lower duty-cycle. If behavioral response is significantly influenced by received signal energy (which is unproven but in our view likely), then the reaction distance for MarVib signals (and the number of animals disturbed) would both be higher than predicted based on pressure levels alone. Results from migrating gray whales exposed to airgun sound vs. LFA sonar sound are consistent with the possibility that the longer duration of LFA signals might elicit disturbance responses when the received pressure level is lower than would be necessary for airgun sounds. However, other interpretations are possible, and in any case, the gray whale comparison involves airgun sound vs. LFA sonar sound, not MarVib sound. Also, Southall et al. (2007) concluded that disturbance response data for marine mammals were so variable and context dependent that it was not possible to determine (from then-existing data) whether responsiveness is better correlated with received pressure levels (lower for MarVib) or received signal energy (probably similar for airguns and MarVibs). Lack of specific data on marine mammal responsiveness to MarVib sound is a *key data gap* that needs to be addressed before it will be possible to determine how much reduction in disturbance could be achieved by using a MarVib rather than an airgun source.

Regarding MarVib design alternatives that could reduce disturbance to marine mammals, • better suppression of higher frequency components (e.g., above 100 Hz or, even better, above some lower cutoff frequency) would be beneficial, mainly for odontocetes, less so for pinnipeds, and least for baleen whales. • Depending on the specific situation, changes in the operating depth of the MarVib might reduce sound exposure to animals that frequent particular depths; this would need to be evaluated on a case-by-case basis. For other possible design alternatives, lack of data on responsiveness to MarVib signals hampers discussion. • If mammal responses are a function of received pressure levels, then numbers of animals disturbed should be less if source and received levels are reduced, even if signal duration must be longer or the duty cycle higher to compensate for lower signal levels. However, if responses are more a function of received energy than of received pressure, then reducing source level at the "expense" of extending signal duration may make little difference to the number of animals disturbed. • There is reason to suspect that PRN MarVib signals might elicit stronger disturbance responses than would FM sweep signals, but specific data are lacking. Again, to resolve these questions, *empirical data are needed* concerning responsiveness of marine mammals to MarVib sounds.

6.2.6 Hearing Impairment

6.2.6.1 Introduction

***Temporary and Permanent Threshold Shift*.—**The possibility that marine mammal hearing might be impaired by exposure to strong sounds from seismic surveys has been discussed since the 1980s (e.g., Richardson et al. 1989). More specifically, it has been suspected at least since the early 1990s that some marine mammals close to airguns might receive sufficient sound to cause temporary or possibly even permanent hearing impairment, i.e., temporary or permanent threshold shift, TTS or PTS (NMFS 1995; Richardson et al. 1995). There are now relevant experimental data on the received sound levels necessary to cause TTS in a few species of captive odontocetes and pinnipeds exposed to pulsed and non-pulsed sound (reviewed in Southall et al. 2007). However, there are no specific data documenting that, in realistic field conditions, airgun or marine vibrator sounds can cause TTS, and there have been no direct studies of PTS in any marine mammals. Nonetheless, as described in this section, it is likely that TTS does sometimes occur in marine mammals close to an operating airgun array, and PTS is a possibility.

TTS is the mildest form of hearing impairment that can occur during exposure to a strong sound (Kryter 1985). While experiencing TTS, the hearing threshold rises and a sound must be stronger in order to be heard. It is a temporary phenomenon, and (at least when mild) is not considered to represent physical damage or "injury" (Southall et al. 2007; Le Prell in press). Rather, the onset of TTS is an indicator that, if the animal is exposed to higher levels of that sound, physical damage is ultimately a possibility. While an animal's hearing is temporarily impaired, it would (in theory) be less able to detect relevant sounds in its environment—specifically, sounds with received levels that would normally be slightly above the detection threshold but (because of the TTS) are below the now-elevated threshold and undetectable. To the extent that detection of faint sounds from conspecifics, predators (killer whales), prey, or physical phenomena is important to the marine mammal, it could be at least mildly disadvantaged for the duration of the TTS.

The magnitude of TTS depends on the level and duration of noise exposure, and to some degree on frequency, among other considerations (Kryter 1985; Richardson et al. 1995; Southall et al. 2007). For sound exposures at or somewhat above the TTS threshold, hearing sensitivity recovers rapidly after exposure to the noise ends. Extensive studies of terrestrial mammal hearing in air show that TTS can last from minutes or hours to (in cases of strong TTS) days. More limited data from odontocetes and pinnipeds show similar patterns (e.g., Mooney et al. 2009a,b; Finneran et al. 2010a). At least in terrestrial animals, exposure to sounds sufficiently strong to elicit a large TTS induces physiological and structural changes in the inner ear, and at some high level of sound exposure, these phenomena become non-recoverable (Le Prell in press). At this level of sound exposure, TTS grades into PTS.

PTS is, by definition, a permanent, non-recoverable impairment of hearing. When PTS occurs, there is physical damage to the sound receptors in the ear. In some cases, there can be total or partial deafness, whereas in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges (Kryter 1985). PTS in terrestrial animals and humans often results from prolonged exposure to levels of sound well above the levels that elicit TTS. PTS can also develop rapidly if an animal or human is exposed to sound impulses that have very high peak pressures, especially if they have very short rise times. (PTS can also occur for other reasons aside from exposure to intense sound.) As noted in § 6.2.2, no experiments have been done to measure the sound exposure necessary to elicit PTS in marine mammals, and no such experiments are likely to be done. Therefore, exposures that might cause PTS must be estimated indirectly using data on relationships between sound exposure and TTS in marine mammals, and between sound exposures eliciting PTS and TTS in laboratory mammals (Southall et al. 2007).

***Noise Criteria in Relation to TTS and PTS*.—**For projects under U.S. jurisdiction, current NMFS policy is that cetaceans and pinnipeds should not be exposed to impulsive sounds (e.g., airgun pulses) with received levels ≥180 and 190 dB re 1 μPa_{RMS}, respectively (NMFS 2000; §6.2.2.1). Those criteria have been used in establishing the safety (=shut-down) radii planned and implemented for numerous airgun-based seismic surveys conducted under U.S. procedures. However, those criteria were established in the mid-1990s before there was any information about the minimum received levels of sounds necessary to cause auditory impairment (TTS or PTS) in marine mammals. As introduced in § 6.2.2 and discussed in this section,

- the 180 dB re 1 μPa_{RMS} do-not-exceed criterion for cetaceans is probably precautionary for at least some species including the bottlenose dolphin and beluga, i.e., lower than necessary to avoid temporary auditory impairment let alone permanent auditory injury.
- the 180 dB re 1 μPa_{RMS} do-not-exceed criterion may not be precautionary with regard to TTS in some other cetacean species, including the harbour porpoise. Likewise, the 190 dB re 1 μPa_{RMS} criterion for pinnipeds may not be precautionary for all pinnipeds, although for pinnipeds the underlying data are indirect and quite variable among species.
- the likelihood of TTS (and probably also PTS) upon exposure to high-level sound appears to be better correlated with the amount of acoustic energy received by the animal, measured by the cumulative sound exposure level (SEL) in dB re 1 $\mu Pa^2 \cdot sec$, than it is with maximum received RMS pressure level in dB re 1 $\mu Pa_{RMS.}$. SEL allows for exposure duration and/or number of exposures; the maximum RMS level does not. In other words, the current U.S. do-not-exceed criteria do not appear to be expressed in the most appropriate acoustic units.
- low and moderate degrees of TTS, up to at least 30 dB of elevation of the threshold, are not injury and do not constitute "Level A harassment" in U.S. MMPA terminology. Beyond that level, TTS may grade into PTS (Le Prell in press).
- the minimum sound level necessary to cause permanent hearing impairment (which is "Level A harassment") is higher, by a variable and speculative amount, than the level that induces barely-detectable TTS.
- the level associated with the onset of TTS is often considered to be a level below which there is no danger of permanent damage. The actual PTS threshold is likely to be well above the level causing onset of TTS (Southall et al. 2007).

Recommendations for new science-based noise exposure criteria for marine mammals, frequency-weighting procedures, and related matters were published by a group of specialists in marine mammal acoustics (Southall et al. 2007). Those recommendations have not, as of late 2010, been formally adopted by NMFS for use in U.S. regulatory processes and during mitigation programs associated with seismic surveys. However, some aspects of the recommendations have been taken into account in certain EISs and small-take authorizations, and NMFS is moving toward adoption of new procedures taking at least some of the Southall et al. recommendations into account (Scholik-Schlomer in press).

Several aspects of the monitoring and mitigation measures that are often implemented during seismic survey projects are designed to detect marine mammals occurring near the sound source, and to avoid exposing them to sound pulses that might, at least in theory, cause hearing impairment (see Chapter 7). In addition, many cetaceans and (to a limited degree) pinnipeds show some avoidance of the area where received levels of airgun sound are high enough such that hearing impairment could potentially occur (§ 6.2.5.1, above). In those cases, the avoidance responses of the animals themselves will reduce (and will often avoid) the possibility of hearing impairment.

6.2.6.2 Airguns

TTS.—Very few data are available on levels of impulse sound necessary to elicit TTS in any marine mammals. Insofar as we know, the only specific data are from two species of small and medium-sized odontocetes.

Toothed Whales: Finneran et al. (2002) found that, upon exposure of a beluga whale to a single impulse from a watergun, the onset of mild TTS occurred when the received SEL (unweighted) was ~186 dB re 1 $\mu Pa^2 \cdot sec$. That corresponded to an M_{mf}-weighted SEL of 183 dB re 1 $\mu Pa^2 \cdot sec$ (Southall et al. 2007). The corresponding peak-to-peak pressure was 226 dB re 1 µPa. The beluga's measured TTS threshold for single impulses was lower than the TTS threshold for non-impulse sound, which on an SEL basis was about 195 dB re 1 $\mu Pa^2 \cdot sec$ (Schlundt et al. 2000). This difference was expected, based on evidence from terrestrial mammals showing that broadband pulsed sounds with rapid rise times have greater auditory effect than do non-impulse sounds (Southall et al. 2007).

The RMS level of an airgun pulse (in dB re 1 µPa measured over the duration of the pulse) is typically 10–20 dB higher than the SEL (in dB re 1 $\mu Pa^2 \cdot sec$) for the same pulse when received within a few kilometres of the airguns. Results from numerous recent "sound-source verification" studies (most unpublished) show that the RMS–SEL difference tends to be highest at close range and to diminish with increasing range, as expected from the typical "temporal stretching" of pulses as they propagate. Given a TTS threshold of 186 dB re 1 $\mu Pa^2 \cdot sec$, a single airgun pulse might need to have a received level of ~196–206 dB re 1 μPa_{RMS} (186 plus 10–20) in order to produce brief, mild TTS.

Insofar as we are aware, there are no published data confirming that the auditory effect of a sequence of airgun pulses received by an odontocete is a function of their cumulative energy. Southall et al. (2007) consider that to be a reasonable, but probably somewhat precautionary, assumption. It is precautionary because, based on data from terrestrial mammals, one would expect that a given energy exposure would have somewhat less effect if separated into discrete pulses, with potential opportunity for partial auditory recovery between pulses. Southall et al. (2007) concluded that, until relevant data on recovery are available from marine mammals, it is appropriate not to allow for any assumed recovery during the intervals between pulses within a pulse sequence.

At a location close enough to the seismic trackline to receive a cumulative SEL ≥186 dB, most of the received energy comes from the closest few airgun shots. This is evident both from empirical data and modelling studies—again largely unpublished, but see Erbe and King (2009) and Laws (in press). Exposure to a sequence of airgun pulses in which the strongest has a flat-weighted received level near 180 dB SEL (190–200 dB RMS, depending on the RMS–SEL difference) could result in cumulative exposure of ~186 dB SEL (flat-weighted) or ~183 dB SEL (M_{mf}-weighted), and thus slight TTS in a beluga. That assumes that the TTS threshold upon exposure to multiple pulses is (to a first approximation) a function of the total received pulse energy, without allowance for any recovery between pulses. A recent TTS study exposed a bottlenose dolphin to a sequence of tonal sounds (not impulses) separated by 3.7-min gaps (Finneran et al. 2010b). That study confirmed that the TTS effect increased upon exposure to subsequent sounds even with 3.7-min gaps between signals, although some auditory recovery did occur within those gaps. Presumably there would be less (if any) recovery within the shorter intervals between airgun signals, and the net auditory effect would be a more direct function of cumulative SEL across all received pulses.

The sound exposure necessary to elicit slight TTS in a harbour porpoise exposed to single airgun pulses has also been tested, and (as compared to the above beluga study) the received level that elicited onset of TTS was lower (Lucke et al. 2009). The animal was exposed to single pulses from a small (20-in^3) airgun, and auditory evoked potential methods were used to test the animal's hearing sensitivity at frequencies of 4, 32, or 100 kHz after each exposure (Lucke et al. 2009). Based on the measurements at 4 kHz, TTS occurred upon exposure to one airgun pulse with received level ~200 dB re 1 μPa_{pk-pk} or an SEL of 164.3 dB re 1 $\mu Pa^2 \cdot sec$ (vs. 186 dB for the beluga). If these results from a single animal of each species are representative, it is inappropriate to assume that onset of TTS occurs at similar received levels in all odontocete and mysticete species (*cf.* Southall et al. 2007). Some cetaceans may incur TTS at lower sound exposures than are necessary to elicit TTS in the beluga. Given the implications concerning the possible PTS threshold in harbour porpoises (and perhaps some other cetaceans) exposed to impulse noise, it would be *important to replicate* the Lucke et al. (2009) study.

Baleen Whales: There are no data, direct or indirect, on levels or properties of sound that are required to induce TTS in any baleen whale. The frequencies to which mysticetes are most sensitive are assumed to be lower than those to which odontocetes are most sensitive, and natural background noise levels at those low frequencies tend to be higher. As a result, auditory thresholds of baleen whales within their frequency band of best hearing are believed to be higher (less sensitive) than are those of odontocetes at their best frequencies (Clark and Ellison 2004). From this, it is suspected that received levels causing TTS onset may also be higher in mysticetes (Southall et al. 2007). However, based on preliminary simulation modelling that attempted to allow for various uncertainties in assumptions and variability around population means, Gedamke et al. (2008) suggested that some baleen whales whose closest point of approach to a seismic vessel is 1 km or more could experience TTS or even PTS.

In practice during seismic surveys, few if any cases of TTS in baleen whales are expected given the strong likelihood that they would avoid the approaching airguns (or vessel) (see § 6.2.5) before being exposed to levels high enough for there to be any possibility of TTS.[7]

[7] This assumes that the ramp-up (soft-start) procedure is used when commencing airgun operations, to give whales near the vessel the opportunity to move away before they are exposed to sound levels that might be strong enough to elicit TTS (see Chapter 7, "Mitigation"). Single-airgun experiments with bowhead, gray, and humpback whales (reviewed in Richardson et al. 1995) have shown that those species do tend to move away when a single airgun starts firing nearby, which simulates the onset of a ramp up.

Pinnipeds: In pinnipeds, TTS thresholds associated with exposure to brief pulses (single or multiple) of underwater sound have not been measured directly. Two California sea lions did not incur TTS when exposed to single brief pulses with RLs of ~178 and 183 dB re 1 μPa_{RMS} and total energy fluxes (SELs) of 161 and 163 dB re 1 $\mu Pa^2 \cdot sec$ (Finneran et al. 2003).

The threshold for onset of mild TTS upon exposure of a harbour seal to impulse sounds has been estimated indirectly as being an SEL of ~171 dB re 1 $\mu Pa^2 \cdot sec$ (Southall et al. 2007). If that indirect estimate is validated when specific TTS data become available for pinnipeds exposed to impulse sounds, the TTS threshold would be approximately equivalent to a single pulse with RL ~181–191 dB re 1 μPa_{RMS} (171 dB + 10–20 dB) or a series of pulses for which the highest RMS values are a few dB lower. In other words, if this estimate is correct, the TTS threshold for some pinnipeds exposed to airgun pulses may be *lower* than the 190 dB re 1 μPa_{RMS} "do-not-exceed" criterion established by NMFS for pinnipeds (§ 6.2.2).

At least for non-impulse sounds, TTS onset occurs at appreciably higher received levels in California sea lions and northern elephant seals than in harbour seals (Kastak et al. 2005). Thus, the former two species would presumably need to be closer to an airgun array than would a harbour seal before TTS is a possibility. Insofar as we are aware, there are as yet no data to indicate whether the TTS thresholds of other pinniped species are more similar to those of the harbour seal or to those of the two less-sensitive species. The lack of any direct measurements of TTS thresholds in pinnipeds exposed to impulse sound is a *significant data gap*, given the implications if (in some pinnipeds) that threshold is as low as estimated indirectly by Southall et al. (2007) for the harbour seal.

Sirenians, Sea Otter and Polar Bear: There are no available data on TTS in sea otters and polar bears. However, TTS is unlikely to occur in sea otters or polar bears if they are on the water surface, given the pressure release and Lloyd's mirror effects at the water's surface. Furthermore, sea otters tend to inhabit shallow coastal habitats where large seismic survey vessels towing large spreads of streamers may be unable to operate. TTS is also considered unlikely to occur in sirenians as a result of exposure to sounds from a seismic survey. They, like sea otters, tend to inhabit shallow coastal habitats and rarely range far from shore, whereas seismic survey vessels towing large arrays of airguns and (usually) streamers normally must remain farther offshore.

Likelihood of Incurring TTS from Airgun Sound: Most cetaceans show some degree of avoidance of seismic vessels operating an airgun array (§ 6.2.5). It is unlikely that these cetaceans would be exposed to airgun pulses at a high enough level for a sufficiently long period to cause more than mild TTS, given the relative movement of the vessel and the marine mammal. TTS would be more likely in any odontocetes that bow- or wake-ride or otherwise linger near the airguns. However, while bow- or wake-riding, odontocetes would be at the surface and thus not exposed to strong sound pulses given the pressure-release and Lloyd Mirror effects at the surface. But if bow- or wake-riding animals were to dive intermittently near airguns, they would be exposed to strong sound pulses, possibly repeatedly.

Some pinnipeds show avoidance reactions to airguns, but their avoidance reactions are generally not as strong or consistent as those of cetaceans (§ 6.2.5). Pinnipeds occasionally seem to be attracted to operating seismic vessels. There are no specific data on TTS thresholds of pinnipeds exposed to single or multiple low-frequency pulses. However, given the indirect indications of a lower TTS threshold for the harbour seal than for odontocetes exposed to impulse sound (see above), it is possible that some pinnipeds close to a large airgun array could incur TTS.

Although TTS is by definition a temporary and reversible phenomenon, it could be deleterious in the event that, during that a period of reduced sensitivity, a marine mammal needed its full hearing sensitivity to detect approaching predators, or for some other reason.

NMFS (1995, 2000) concluded that cetaceans should not be exposed to pulsed underwater noise at received levels >180 dB re 1 μPa_{RMS}. The corresponding limit for pinnipeds has been set by NMFS at 190 dB (§ 6.2.2), although the HESS Team (HESS 1999) recommended a 180-dB limit for pinnipeds in California. The 180 and 190 dB re 1 μPa_{RMS} criteria were not originally considered to be the RLs above which TTS might occur. Rather, they were the levels above which, in the professional judgement of expert panels convened by NMFS and HESS before TTS measurements for marine mammals started to become available, one could not be certain that there would be no injurious effects, auditory or otherwise, to marine mammals (see §1.4 and §6.2.2.1). Data that are now available imply that TTS is unlikely to occur in some odontocetes (and probably mysticetes as well) unless they are exposed to a sequence of airgun pulses in which the maximum RL is ≥190 dB re 1 μPa_{RMS}. On the other hand, for the harbour porpoise, harbour seal, and perhaps some other species, slight TTS may occur upon exposure to one or more airgun pulses whose received level equals the NMFS "do not exceed" values of 180 or 190 dB re 1 μPa_{RMS}. Those criteria correspond to a single-pulse SEL of (respectively) ~160–170 or ~170–180 dB re 1 $\mu Pa^2 \cdot$sec in typical conditions, whereas slight TTS may occur in harbour porpoises and harbour seals upon exposure to a cumulative SEL of ~164 and ~171 dB re 1 $\mu Pa^2 \cdot$sec, respectively.

***PTS*.—**There is no specific evidence that exposure to pulses of airgun sound can cause PTS in any marine mammal, even with large arrays of airguns. However, given the likelihood that some mammals close to an airgun array could incur at least mild TTS (see above), there has been further speculation that some individuals occurring very close to airguns might incur PTS (e.g., Richardson et al. 1995:372*ff*; Gedamke et al. 2008). Single or occasional occurrences of mild TTS are not indicative of PTS, but exposures to a level well above that causing TTS onset might elicit PTS.

Relationships between TTS and PTS thresholds have not been studied in marine mammals, but are assumed to be similar to those in humans and other terrestrial mammals (Southall et al. 2007). Based on data from terrestrial mammals, a precautionary assumption is that the PTS threshold for impulse sounds (such as airgun pulses as received close to the source) is at least 6 dB higher than the TTS threshold on a peak-pressure basis, and probably >6 dB higher (Southall et al. 2007). They also estimated that RLs would need to exceed the TTS threshold by at least 15 dB, on an SEL basis, for there to be risk of PTS.

- for *cetaceans* exposed to impulse sound, Southall et al. estimated that the PTS threshold might be an M-weighted SEL (for the pulse sequence) of ~198 dB re 1 $\mu Pa^2 \cdot$sec (15 dB higher than the M_{mf}-weighted TTS threshold, in a beluga, for a watergun impulse).
- for *pinnipeds*, additional assumptions had to be made, as the only available TTS data pertained to non-impulse sound (see above). Southall et al. (2007) estimated that the PTS threshold could be a cumulative M_{pw}-weighted SEL of ~186 dB re 1 $\mu Pa^2 \cdot$sec for a harbour seal exposed to impulse sound. The PTS thresholds for the California sea lion and northern elephant seal would probably be higher given the higher non-pulse TTS thresholds in those species than in the harbour seal.
- for *sirenians, sea otters,* and *polar bears*, there are no data on TTS and thus there is no basis for estimating the PTS thresholds.

Southall et al. (2007) also noted that, regardless of the SEL, there is concern about the possibility of PTS if a cetacean or pinniped received one or more pulses with peak pressure (unweighted) exceeding 230 or 218 dB re 1 µPa, respectively. Thus, PTS might be expected upon exposure of cetaceans to airgun pulses with either cumulative SEL ≥198 dB re 1 $\mu Pa^2 \cdot$s or peak pressure ≥230 dB re 1 µPa. Corresponding proposed dual criteria for pinnipeds (at least harbour seals) are ≥186 dB SEL or ≥ 218 dB peak pressure.

These estimates are all first approximations, given the very limited underlying data, numerous assumptions, and species differences. Also, data have been published subsequent to Southall et al. (2007) indicating that, at least for non-pulse sounds, the "equal energy" model is not entirely correct—TTS and presumably PTS thresholds may depend somewhat on the duration over which sound energy is accumulated, the frequency of the sound, whether or not there are gaps, and probably other factors (§ 6.2.2.1; see also Ketten 1994, in press).

The TTS section (above) concludes that, in a beluga or similar odontocete, exposure to a sequence of seismic pulses in which the strongest pulse has a flat-weighted RL near 180 dB SEL (190–200 dB re 1 μPa_{RMS}) could result in cumulative exposure of ~186 dB SEL (flat-weighted) or ~183 dB SEL (M_{mf}-weighted), and thus slight TTS. Allowing for the assumed 15 dB offset between PTS and TTS thresholds, expressed on an SEL basis, exposure to a sequence of pulses in which the strongest has a flat-weighted RL near 190–195 dB SEL (200–215 dB re 1 μPa_{RMS}) could result in cumulative exposure of ~198 dB SEL (M_{mf}-weighted), and thus slight PTS in a beluga or similar odontocete. However, the levels of successive pulses that would be received by a marine mammal that is below the surface as a seismic vessel approaches, passes, and moves away will tend to increase gradually and then decrease gradually, with periodic decreases superimposed on this pattern when the animal comes to the surface to breathe. To estimate how close an odontocete's CPA distance would have to be for the cumulative SEL to exceed 198 dB SEL (M_{mf}-weighted), one would (as a minimum) need to allow for the sequence of distances at which airgun shots would occur, and for the dependence of received SEL on distance in the region of the seismic operation (e.g., Erbe and King 2009; Laws in press). For a more refined analysis, the AIM model can be applied to allow for animal movement patterns in 3 D (see § 6.2.6.3, below, and Frankel et al. 2002).

Likelihood of Incurring PTS from Airgun Sound: It is unlikely that an odontocete would remain close enough to a large airgun array for sufficiently long to incur PTS. There is some concern about bow-riding odontocetes, but for animals at or near the surface, auditory effects are reduced by Lloyd's mirror and surface release effects. The presence of the vessel between the airgun array and bow-riding odontocetes could also, in some but probably not all cases, reduce the levels received by bow-riding animals (e.g., Gabriele and Kipple 2009). The TTS (and thus PTS) thresholds of baleen whales are unknown but, as an interim measure, assumed to be no lower than those of odontocetes. Also, baleen whales generally avoid the immediate area around operating seismic vessels, so it is unlikely that a baleen whale could incur PTS from exposure to airgun pulses. The TTS (and thus PTS) thresholds of some pinnipeds (e.g., harbour seal) as well as the harbour porpoise may be lower (Kastak et al. 2005; Southall et al. 2007; Lucke et al. 2009). If so, those animals might incur TTS and potentially PTS at a greater distance from the source. Again, Lloyd's mirror and surface release effects will ameliorate effects for animals at or near the surface.

Although it is unlikely that airgun operations during most seismic surveys would cause PTS in many marine mammals, caution is warranted given

- the limited knowledge about noise-induced hearing damage in marine mammals, particularly baleen whales, pinnipeds, and sea otters;
- the seemingly greater susceptibility of certain species (e.g., harbour porpoise and harbour seal) to TTS and presumably also PTS; and
- the lack of knowledge about TTS and PTS thresholds in many species, including various species closely related to the harbour porpoise and harbour seal.

The avoidance reactions of many marine mammals, along with commonly-applied monitoring and mitigation measures (Chapter 7) would reduce but not eliminate the probability of exposure of marine mammals to airgun sounds strong enough to induce PTS.

6.2.6.3 Marine Vibroseis

***TTS*.—**There are, to our knowledge, no specific data on the levels and durations of MarVib sound necessary to cause TTS in any marine mammal. However, there are experimental data from several species of captive odontocetes and pinnipeds concerning TTS as a function of received level and duration of other types of non-impulse sound. The characteristics of the sounds used in those tests differ in various ways from MarVib signals, including differences in frequency, bandwidth, signal duration, and (usually) lack of repetition. Even so, the experimental results are informative as a basis for predicting the possibility of TTS and (by implication) PTS in response to MarVib signals.

Toothed Whales: Of particular importance, TTS tests using both impulse sound (see above) and non-pulse sound have been done on the beluga and bottlenose dolphin. These confirm the expectation (from terrestrial mammal studies) that a higher sound exposure level is necessary to elicit mild TTS when the sound is non-pulse in character (Schlundt et al. 2000; Finneran et al. 2005) than when it is impulsive (Finneran et al. 2002). Southall et al. (2009) considered this to be a general principle broadly applicable across marine mammals, and that generalization is important in assessing the degree to which MarVibs might cause TTS and PTS. For the beluga, the difference between the sound exposure level necessary to elicit mild TTS with non-pulse sound vs. impulse sound (~195 vs. 183–186 dB re 1 $\mu Pa^2 \cdot$sec, respecttively) is quite substantial. Some other studies have reported that the onset of TTS in dolphins does not occur with non-impulse sound unless the received level is even higher (e.g., Mooney et al. 2009b).

The common assumption that, in marine mammals, the occurrence and magnitude of TTS is a function of cumulative acoustic energy (SEL) is probably an oversimplification (Finneran in press). For example, Mooney et al. (2009a) showed that, in a bottlenose dolphin exposed to octave-band non-impulse noise, higher SELs were required to induce a given TTS if exposure duration was short than if it was longer. Also, exposure of the aforementioned bottlenose dolphin to a sequence of brief sonar signals showed that, with those brief (but non-impulse) sounds, the received energy (SEL) necessary to elicit TTS was higher than was the case with exposure to the more prolonged octave-band noise (Mooney et al. 2009b). Those authors concluded that, when using (non-impulse) acoustic signals of duration ~0.5 sec, SEL must be at least 210–214 dB re 1 $\mu Pa^2 \cdot$sec to induce TTS in the bottlenose dolphin.

As a cautionary point, the conclusion that the TTS (and by implication PTS) threshold is higher for non-impulse sound (like MarVib) than for impulse sound is somewhat speculative. The available TTS data for a beluga exposed to impulse sound are extremely limited, and the TTS data from the beluga and bottlenose dolphin exposed to non-pulse sound pertain to sounds at 3 kHz and above. Follow-on work has shown that the SEL necessary to elicit TTS can depend substantially on frequency (Finneran and Schlundt 2010; Finneran in press). The data for 3 kHz and above pertain to frequencies far above those of anticipated MarVib sounds (<100 Hz). The lack of specific TTS measurements at the low frequencies that would be used by MarVib systems is a *significant data gap*. Also, we are not aware of any TTS measurements for the harbour porpoise exposed to non-impulse sound, which would be of interest given the data showing a relatively low TTS threshold when that species is exposed to airgun sound.

Baleen Whales: There are no TTS data from any baleen whale. It is likely that the TTS threshold (on an SEL basis) would be higher for non-pulse sounds such as MarVib than for impulse sounds such as airgun pulses, as that trend occurs in toothed whales and in terrestrial mammals.

Pinnipeds: TTS experiments with captive pinnipeds exposed to non-pulse sounds for extended periods (22–50 min) showed that some pinnipeds, the harbour seal in particular, incur TTS at lower sound exposure levels than do the beluga or bottlenose dolphin (Kastak et al. 1999, 2005). Kastak et al. found that, for non-impulse sound, SELs resulting in TTS onset in three species of pinnipeds ranged from 183 to 206 dB re 1 $\mu Pa^2 \cdot$ sec, with the lowest value occurring in the harbour seal. The 183 dB SEL value for that species is lower than the level of non-pulse sound eliciting mild TTS in the beluga or bottlenose dolphin (~195 dB SEL).

Sirenians, Sea Otter and Polar Bear: There are no TTS data for these groups. See the "Airguns" subsection, above, for some general considerations associated with the possibility of TTS in these groups.

***PTS*.—** There is no specific information about occurrence of auditory injury in marine mammals exposed to MarVib sounds. In general, the auditory effects of non-pulse sounds such as MarVib signals are expected to be lower than would occur upon exposure to the corresponding received energy level (SEL) of impulse sound. Southall et al. (2007) estimated that PTS onset in marine mammals would not occur unless the received SEL were at least 20 dB higher than that necessary to cause TTS, i.e.,

- In cetaceans, PTS onset at ≥215 dB SEL vs. TTS onset at ≥195 dB SEL;
- In pinnipeds, PTS onset at ≥203 dB SEL vs. TTS onset at ≥183 dB SEL

***Likelihood of Incurring TTS and PTS from MarVib Sound*.—**The estimated PTS-onset values for MarVib and other non-impulse sounds, expressed as sound exposure levels, are very high. These SELs could only occur for an animal whose closest point of approach to the moving MarVib system was very close. The CPA distances within which the PTS and TTS criteria could be exceeded would depend on specific source characteristics, the animal's 3-D position relative to the source at the time of the closest MarVib transmission, etc. However, at close distances from a moving MarVib source, received level would be near maximum for only 1 or 2 transmissions, and notably lower for all other transmissions; i.e., most of the received sound energy would be received from the closest few "shotpoints". Given that, and an assumed source energy level of ~235 dB re 1 $\mu Pa^2 \cdot$ sec @ 1 m for each transmission (§ 4.2, §5.3), it is apparent that an animal's CPA position would have to be within (at most) 10s of metres to receive ≥215 or ≥203 dB SEL (Southall et al.'s PTS criteria for non-pulse sources like MarVib). The estimated TTS onset values for non-pulse sounds like MarVib are 20 dB lower than PTS onset values, and animals within a larger (but still relatively small) distance could theoretically incur TTS.

It is uncertain to what degree various types of marine mammals will avoid an approaching seismic vessel operating a MarVib system (and thus reduce their exposure to MarVib sounds). Avoidance reactions to MarVib could be notably less than those to seismic vessels operating airguns, or they could be similar; specific data are lacking (§6.2.5.2). If there is strong avoidance, that will much reduce the likelihood of incurring TTS and PTS (given that TTS and PTS will only be possible for animals close to the source). If avoidance is reduced relative to that with an airgun array, then there might theoretically be more occurrences of TTS and PTS, assuming that received energy levels of MarVib transmissions and airgun pulses are about the same at a given distance. Even in that case, however, the higher exposure level believed necessary to incur TTS or PTS from a non-pulse source than from an impulse source should act to reduce the likelihood of TTS or PTS.

When assessing effects of exposure to multiple signals on either TTS or PTS, the equal energy concept is likely to overestimate the effect; some auditory recovery is expected during the silent periods between signals (Ward 1997; Finneran et al. 2010b). The relative magnitude of this recovery with MarVib vs. airgun signals is not predictable with any confidence. In any case, the size of this recovery effect is likely to be quite small; the intervals between seismic signals will be short, affording little opportunity for auditory recovery).

Insofar as effects on hearing are concerned, the mitigative effect of the marine vibrator's reduced peak pressure at any given range will undoubtedly be at least partly offset by the longer signal duration and similar total energy.

***Expected MarVib vs. Airgun Effects: General Considerations*.—**Earlier subsections have at least introduced, in a qualitative way, several of the considerations relevant here:

- TTS and especially PTS would only occur upon exposure to high cumulative levels of airgun or MarVib sound. For either type of source, such levels could only occur for animals that are, at some point, quite close to the operating source.
- Although MarVib systems (as compared to airguns) would have notably lower source pressure levels, and lower received pressure levels at any specific distance, the source and received energy levels for MarVib and airgun systems are likely to be similar given the longer anticipated duration of MarVib signals. Occurrence and extent of TTS and PTS are, to a first approximation, a function of received energy level. Thus, with regard to TTS or PTS, the lower pressure level of a MarVib system would not be as much of an advantage as might be expected.
- In any type of marine mammal, the sound exposure levels necessary to cause onset of TTS or PTS are assumed to be lower for impulse sounds (like airgun pulses) than for non-pulse sounds such as MarVib (Southall et al. 2007). For example, the proposed PTS onset criteria for exposure to pulsed vs. non-pulse sound are, respectively, 198 dB vs. 215 dB re 1 $\mu Pa^2 \cdot sec$ for cetaceans, and 186 dB vs. 203 dB for pinnipeds. Thus, TTS and PTS would extend to greater distances from the trackline during an airgun survey than during a MarVib survey, despite the similar received energy levels (at any given location) from the two types of sources.
- To the extent that marine mammals avoid the approaching seismic vessel, occurrence of TTS and especially PTS will be reduced. For airgun surveys, considerable information is available about the relative tendencies of various marine mammal groups to avoid a nearby seismic vessel (§ 6.2.5.1). The data show substantial avoidance by baleen whales, generally less avoidance by toothed whales (and some attraction of bow- or wake-riders), and still less avoidance by most pinnipeds. In contrast, the degree to which marine mammals would avoid an operating MarVib source is uncertain—some avoidance is expected, but it could be less pronounced than for airguns (§6.2.5.2). Reduced avoidance of MarVib sources could at least partially offset the benefits afforded by the higher SEL required for occurrence of TTS or PTS with a non-pulse source.

***Expected MarVib vs. Airgun Effects: Exposure Modelling.*—**As part of the evaluation of expected disturbance effects from MarVib vs. airgun sources, we used the Acoustic Integration Model (AIM) to estimate the numbers of cetaceans that might receive sounds with RLs above 180 dB re 1 μPa_{RMS} if either type of source was used for a specific seismic survey in the northern Gulf of Mexico (Table 6.2B *in* § 6.2.5.2).

180 dB re 1 µPa (RMS) Estimates: An RL of 180 dB re 1 μPa_{RMS} is the "do-not-exceed" criterion recognized by NMFS for cetaceans. At least in the 1990s, when that criterion was first established, NMFS had concerns that, upon exposure to levels above 180 dB re 1 μPa_{RMS}, the possibility of injurious effects could not be excluded (§ 6.2.2). That criterion is still widely used by NMFS in regulating exposure of marine mammals under U.S. jurisdiction to high-level sounds, and is sometimes described as the "Level A Harassment" criterion. Three representative species of cetaceans were considered with AIM: bottlenose dolphin and sperm whale (both mid-frequency odontocetes), and Bryde's whale (a baleen whale). Chapter 5 and § 6.2.5.2 explain the assumptions and procedures used in the AIM modelling for both the 160 dB and the 180 dB (RMS) criteria; those explanations are not repeated here.

Table 6.2B shows some of the key results of the AIM modelling with respect to the numbers of cetaceans that could be exposed to received levels ≥180 dB re 1 μPa_{RMS} during otherwise-comparable MarVib-based vs. airgun-based seismic surveys. For the model runs summarized in Table 6.2B, the MarVib system was assumed to emit signals 5 sec in duration with a frequency rolloff rate above 100 Hz of 30 dB per octave (i.e., per doubling of frequency). (Comparative results with different assumptions about signal duration and rolloff rate are shown in Figure 6.3.)

The number of individual cetaceans predicted to be exposed to ≥180 dB re 1 μPa_{RMS} on one or more occasions during the simulated seismic survey was always much lower during the MarVib-based survey than during the corresponding airgun-based survey. The estimates for MarVib ranged from 1.0 % to 16.5 % of those for airguns, depending on the species, site (deep or shallow), and whether or not M-weighting was applied (Table 6.2B). With airguns, actual numbers of animals predicted to receive ≥180 dB at some point during the simulated airgun survey ranged from ~7 to 26 for the bottlenose dolphin, ~0.3 to 0.9 for the Bryde's whale, and 2 to 40 for the sperm whale, again depending site and whether M-weighting was applied. Corresponding predictions for the MarVib survey ranged from only 0.6 to 2.5 for the bottlenose dolphin, 0.04 to 0.06 for the Bryde's whale, and 0.04 to 0.7 for the sperm whale.

As expected, all of these predicted numbers were considerably reduced relative to the corresponding estimates of numbers that might receive ≥160 dB RMS during the same survey (*cf.* Table 6.2A). Furthermore, the predicted numbers that might be exposed to ≥180 dB RMS are probably overestimates, at least for the Bryde's whale and sperm whale, as these predictions assume no avoidance of the approaching seismic vessel by the cetaceans. Some proportion of the whales are expected to begin avoidance reactions before the received level from the approaching seismic source reaches 180 dB re 1 μPa_{RMS}. With an airgun array, the 180 dB RMS isopleth is usually within several hundred metres of the source, and that isopleth would be much closer to a MarVib source.

In cases where the prediction was that <0.5 animals would be exposed to ≥180 dB RMS, e.g., for Bryde's or sperm whales during a MarVib-based survey, the implication is that (if the model is realistic), most likely no animals of that species would be exposed to ≥180 dB RMS during such a survey.

These model predictions are instructive in estimating, for representative species of cetaceans, the proportional reduction in numbers of animals that might be exposed to ≥180 dB re 1 μPa_{RMS} during a MarVib survey vs. an otherwise-comparable airgun survey. That reduction is very substantial (Table 6.2B). The ≥180 dB criterion is the one currently applied by the U.S. NMFS in setting safety ("exclusion") radii for cetaceans in projects involving airguns or other impulsive sources (see § 6.2.2).

We note that it is uncertain whether the same RMS pressure criterion is appropriate for MarVib sources, given their non-pulse nature and higher duty cycle. Auditory impairment and possible non-auditory injuries (§ 6.2.7) are likely to be more closely related to received signal energy than to received pressure level.

Comparison of AIM results for simulated airgun surveys at the deep vs. shallow site shows that, for all three representative species of cetaceans, predicted numbers exposed to M-weighted RLs ≥180 dB re 1 μPa_{RMS} were higher in shallow than in deep water (Table 6.2B).[8] This result was a consequence of differing sound propagation conditions at the two sites and (especially near the shallow site) constraints on dive-depths imposed by limited water depth.

[8] To facilitate comparisons, the same population densities were assumed for the shallow and deep sites, though that may not be realistic for species with pronounced depth preferences, such as the sperm whale.

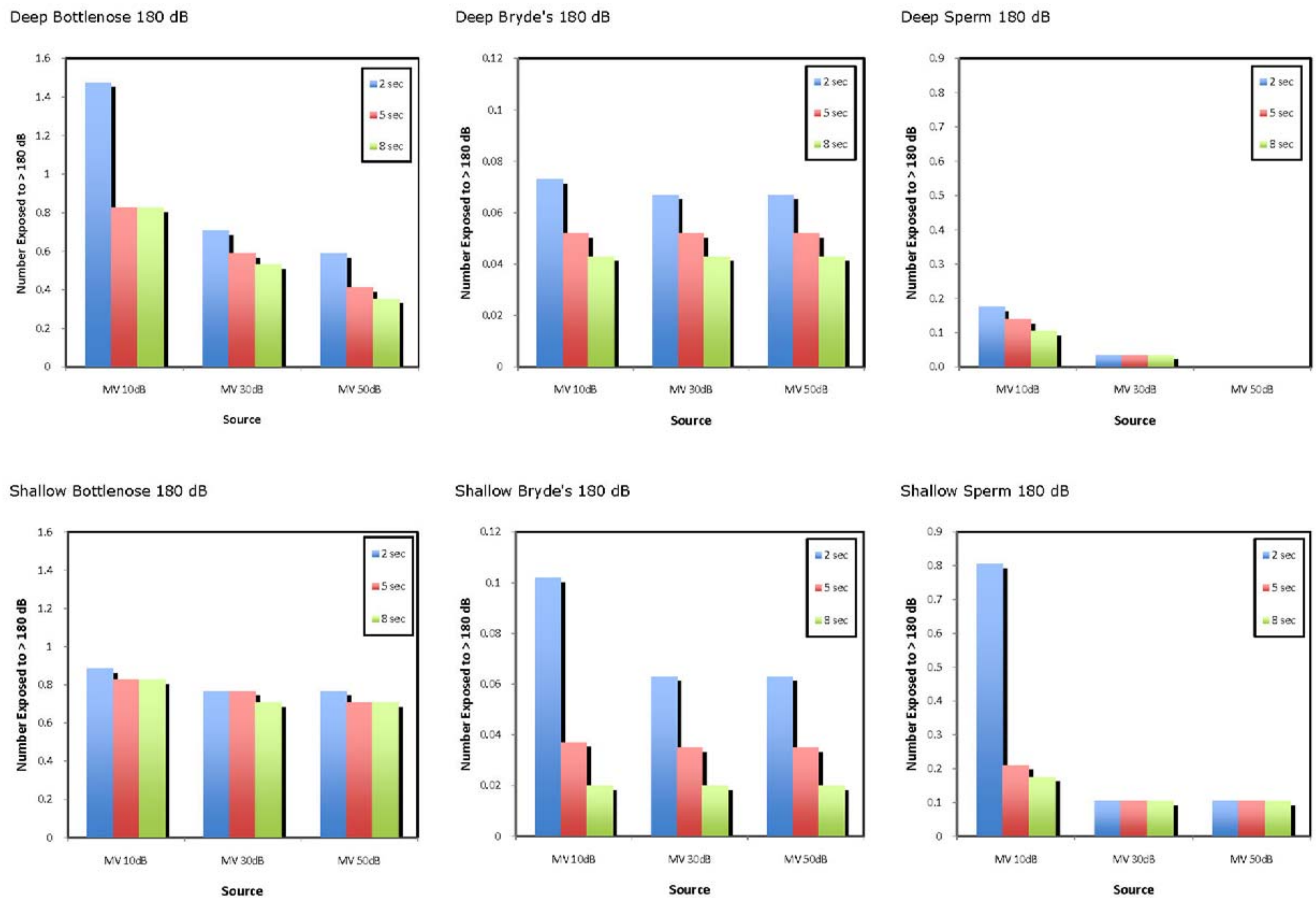

FIGURE 6.3. Effects of MarVib signal-duration and rolloff rate above 100 Hz on estimated numbers of representative cetacean species potentially exposed to sounds with received levels ≥180 dB re 1 μPa_{RMS} (M-weighted) during otherwise-comparable seismic surveys in the northern Gulf of Mexico. Signal durations 2, 5 and 8 sec are evaluated, assuming the same source energy level would be required regardless of signal duration (i.e., higher source pressure level is assumed for short signals; lower source pressure level for long signals). Rolloff rates of 10, 30 and 50 dB per octave (at frequencies above 100 Hz) are assumed. No allowance was made for likely avoidance responses by some animals before the received level reached 180 dB, or for possible shutdowns of the source when cetaceans are detected nearby. See §5.6 for details.

Estimates Based on SEL Injury Criteria: Additional AIM model runs were done to assess the numbers of the three representative species expected to be exposed to cumulative SEL values in excess of the "injury" criteria proposed by Southall et al. (2007), i.e., 198 dB re 1 μPa^2·sec for impulsive signals (airguns) vs. 215 dB for non-pulses (MarVib). The predictions are summarized in Table 6.3. For all three representative species in both water depths, the predicted numbers exposed to an M-weighted SEL in excess of the applicable criterion were lower for the MarVib survey. Depending on species and site (deep vs. shallow), the estimated numbers exposed to ≥215 dB SEL during the MarVib survey ranged from 1 % to 40 % of the estimated numbers exposed to ≥198 dB SEL during an otherwise comparable airgun survey. The differences were greater for shallow water (Table 6.3). *Thus, for both environments, but particularly in shallow water, use of a MarVib source was predicted to result in a reduction in the numbers of cetaceans of all three representative species that could be exposed to sounds in excess of the auditory injury criterion proposed by Southall et al. (2007).*

It is also useful to compare the absolute numbers of cetaceans predicted to be exposed to a cumulative SEL in excess of the injury criteria proposed by Southall et al. (198 dB for airgun surveys vs. 215 dB for MarVibs) with the corresponding predictions of numbers that would be exposed to RMS pressures ≥180 dB re 1 μPa. For every combination of source type (airgun vs. MarVib), environment (deep vs. shallow), and representative species, *the absolute numbers of cetaceans predicted to receive a cumulative SEL in excess of the Southall et al. injury criteria (Table 6.3B) were considerably lower than the numbers predicted to be exposed to RMS pressures ≥180 dB re 1 μPa (Table 6.3A).* None of these predictions allow for the likely avoidance reactions of some animals, especially the two whale species. Thus, the low numbers of animals predicted to be exposed to these high levels are probably overestimates, with actual numbers exposed to potentially injurious sound levels being lower than suggested in Table 6.3.

MarVib Design Alternatives.—To the extent that MarVib systems do have any potential to cause auditory effects in marine mammals, especially for baleen whales that use low-frequency sounds, potential design decisions about future MarVib systems could affect and to some degree mitigate the auditory effects.

Adjustments to signal duration and to the rolloff rate for unnecessary components above 100 Hz would have similar types of benefits with respect to numbers of animals predicted (via AIM) to receive ≥180 dB re 1 μPa_{RMS} (Fig. 6.3) as they did with respect to numbers receiving ≥160 dB RMS (Fig. 6.2). However, regardless of the assumed conditions, the numbers of cetaceans predicted to be exposed to ≥180 dB re 1 μPa_{RMS} during the simulated MarVib surveys were low (Fig. 6.3). Note that the vertical scales in Figure 6.3 extend only up to 1.6 animals in the case of the bottlenose dolphin, and to <1 animal for the other two species. Given the low numbers of animals at risk, it may not be necessary to optimize pulse duration or suppression of higher-frequency components specifically for the purpose of reducing auditory effects, at least for a survey in the northern Gulf of Mexico. However, Figure 6.2 *in* §6.2.5.2 shows that the same mitigation options do have the potential to reduce numbers of cetaceans exposed to the NMFS disturbance criterion (≥160 dB RMS), and that may justify efforts to refine the MarVib design.

Earlier MarVib designs used frequency-modulated (FM) signals, but geophysicists are interested in the possibility of using pseudo-random noise (PRN) signals. If that allowed a MarVib system to operate with lower source level, shorter signal duration, or lower duty cycle than required with FM signals, that could be advantageous from an impact perspective. However, if PRN MarVib signals would need to contain the same total energy as FM MarVib signals that would otherwise be used, then use of PRN vs. FM signals would probably make little difference with regard to numbers of animals at risk of auditory effects.

TABLE 6.3. Estimated numbers of representative cetacean species potentially exposed to sounds with received levels ***(A)*** ≥180 dB re 1 μPa_{RMS} and ***(B)*** ≥198 or ≥215 dB re 1 μ$Pa^2 \cdot$sec (M-weighted) during otherwise-comparable airgun-based or MarVib-based seismic surveys in the northern Gulf of Mexico. The MarVib source was assumed to produce signals 5 sec in duration and with a rolloff rate (above 100 Hz) of 30 dB per octave. See text for details.

	(A) ≥180 dB RMS			***(B)*** ≥Southall et al. ('07) Criteria		
	Airguns	MarVib	MV as % of Airgun	Airgun ≥198 dB SEL	MarVib ≥215 dB SEL	MV as % of Airgun
Deep Site						
Bottlenose dolphin	6.73	0.59	8.8	1.18	0.472	40
Bryde's whale	0.34	0.05	15.2	0.065	0.008	12
Sperm whale	1.54	0.04	2.3	0.14	0.035	25
Shallow Site						
Bottlenose dolphin	9.79	0.77	7.8	12.39	0.708	6
Bryde's whale	0.92	0.04	3.8	0.505	0.003	1
Sperm whale	10.43	0.11	1.0	5.04	0.07	1

Note: values in (A) are from Table 6.2; values in (B) are from Table 5.5.

The ability of MarVib systems to operate at additional depths, as compared to airguns, could provide additional options for mitigation, as noted earlier with respect to masking and disturbance. Given the low numbers of animals at risk of auditory effects, it is not likely to be a priority to adjust the depth of the MarVibs for purposes reduction of further reducing those numbers.

6.2.5.3 Summary for Hearing Impairment

It is believed that exposure of belugas and probably various other cetaceans to high levels of impulse sound (such as *airgun pulses*) can elicit the onset of temporarily impaired hearing if the received energy level is ≥183 dB re 1 μ$Pa^2 \cdot$sec (M_{mf}-weighted). This conclusion is based on very limited data. In terrestrial mammals exposed to impulse noise, the threshold for permanent hearing damage (PTS) is about 15 dB above that for temporary hearing impairment (TTS). Based on that, Southall et al. (2007) proposed that exposure of cetaceans to ≥198 dB re 1 μ$Pa^2 \cdot$sec could elicit PTS. In determining whether sound from a sequence of pulses is sufficient to elicit TTS or PTS, Southall et al. (and others) have concluded that, as a first approximation, it is appropriate to cumulate the energy received in the pulses. Recently, new data have suggested that some cetaceans, specifically the harbour porpoise, may incur TTS (and presumably PTS) upon exposure to underwater impulses with lower received energy levels.

Though there are no specific TTS measurements for pinnipeds exposed to impulse sound, Finneran et al. (2003) found that two California sea lions did not incur TTS when exposed to single brief pulses with RLs of ~178 and 183 dB re 1 μPa_{RMS} and total energy fluxes (SELs) of 161 and 163 dB re 1 $\mu Pa^2 \cdot sec$. Southall et al. estimated from other related data that the thresholds for TTS and PTS onset in the harbour seal are about 171 and 186 dB re 1 $\mu Pa^2 \cdot sec$, i.e., lower than in the beluga. Some other pinnipeds are less susceptible to auditory impairment than is the harbour seal.

Based on these concepts and meagre data, it appears that TTS could occur in cetaceans and especially some pinnipeds that fail to avoid an approaching airgun array if their CPA distances are within 10s or possibly 100s of metres of the operating airguns. PTS is probably quite uncommon, but theoretically could occur. Caution (and further study) is warranted, especially in animals whose hearing is as susceptible to TTS as the harbour seal and harbour porpoise.

There are no data on the auditory effects of *MarVib sound*. However, for some other types of non-impulse sound, exposure levels necessary to elicit TTS in odontocetes and pinnipeds have been measured, and found to be about 195 and 183 dB re 1 $\mu Pa^2 \cdot sec$, respectively. With non-impulse sound, the PTS threshold in terrestrial mammals is at least 20 dB above the TTS threshold. Therefore, PTS thresholds for non-impulse sound (e.g., MarVib sound) in cetaceans and pinnipeds have been estimated as about 215 and 203 dB re 1 $\mu Pa^2 \cdot sec$. Although MarVib signals have much lower source and received levels than airgun pulses, the duration of MarVib signals is longer and their total energy content may not be much different than for airgun pulses. However, the higher exposure levels required to elicit TTS and PTS with non-impulse sound mean that auditory effects would be confined to very short distances around a MarVib source, if they occur at all.

Acoustic modelling confirms that the number of individual cetaceans predicted to be exposed to ≥180 dB re 1 μPa_{RMS} (do-not-exceed criterion specified by NMFS) is much lower during a MarVib survey than during a survey with airguns. Also, numbers of cetaceans predicted to be exposed to ≥215 dB re 1 $\mu Pa^2 \cdot sec$ during simulated surveys with MarVibs were lower than the numbers predicted to be exposed to ≥198 dB re 1 $\mu Pa^2 \cdot sec$ during comparable simulated surveys with airguns. In the scenarios analyzed, MarVibs had advantages over airguns from the perspective of minimizing auditory effects on cetaceans; the advantage was larger in shallow than in deep water.

Adjustments to the signal duration, high-frequency rolloff rate, and operating depth may affect numbers of marine mammals that would incur auditory impairment from a MarVib survey. However, predicted numbers were sufficiently low with the baseline MarVib design that refinements to the design may be better directed toward reduction of masking or disturbance rather than hearing impairment.

6.2.7 Other Injury or Physiological Effects

Non-auditory physical or physiological effects may also occur in marine mammals exposed to strong underwater sound. Possible types of noise-induced non-auditory effects that might (at least in theory) occur under certain conditions include physiological stress, bubble formation in blood or other tissue, resonance of body cavities, and perhaps other types of organ or tissue damage. The possibility of occasional whale strandings as a result of seismic surveys has been debated. Some marine mammal species, particularly beaked whales, may be especially susceptible to injury and/or stranding when exposed to strong transient sounds, especially from mid-frequency naval sonar. The possibility that any of these non-auditory or stranding effects might occur upon exposure to airgun or MarVib sound is discussed briefly here.

6.2.7.1 Airguns

There is no specific evidence that airgun pulses can cause non-auditory injury, death, or stranding even in the case of large airgun arrays. However, the spatial and temporal association of mass strandings of beaked whales with naval exercises involving use of high-power mid-frequency sonar (Cox et al. 2006; D'Amico et al. 2009; Filadelfo et al. 2009) and, in one case, with a seismic survey (Malakoff 2002; Hildebrand 2005) has raised concern that beaked whales exposed to strong airgun sounds might be susceptible to injury and/or behavioral reactions that can lead to stranding (e.g., Hildebrand 2005).

There is no conclusive evidence of cetacean strandings or deaths at sea as a result of exposure to airgun-based seismic surveys. However, a few cases of strandings in the general area where airguns were in use have led to speculation concerning a possible link between seismic surveys and strandings. • Suggestions that there was a link between seismic surveys and strandings of humpback whales in Brazil (Engel et al. 2004) were not well founded (IAGC 2004; IWC 2007). • In Sept. 2002, there was a stranding of two Cuvier's beaked whales in the Gulf of California, Mexico, when the academic seismic vessel R/V *Maurice Ewing* was operating a 20-airgun, 8490-in^3 airgun array in the general area. The evidence linking the stranding to the *Mauice Ewing*'s operations was inconclusive (Hogarth 2002; Yoder 2002). The ship was also operating its multibeam echosounder at the same time, but this had much less potential than the aforementioned naval sonars to affect beaked whales, given its generally downward-directed beams (narrow in the along-track direction), much shorter pulse durations, and lower duty cycle. Nonetheless, the Gulf of California incident plus the beaked whale strandings near naval exercises involving use of mid-frequency sonar suggest a need for caution in conducting seismic surveys in areas occupied by beaked whales until more is known about effects of seismic surveys on those species (Hildebrand 2005).

Specific sound-related processes that lead to strandings and mortality of beaked whales in association with mid-frequency naval sonars are not well documented, but may include (1) swimming into shallow water when avoiding sonar sound; (2) a change in behaviour (especially diving behaviour) that might contribute to gas bubble formation ("the bends"), hypoxia, or other forms of trauma; (3) some other physiological change leading to tissue damage; and (4) tissue damage directly from sound exposure, such as through acoustically mediated bubble formation and growth or acoustic resonance of tissues. Some of these mechanisms are unlikely to apply in the case of impulse sounds. However, there are increasing indications that gas-bubble disease (analogous to "the bends"), induced in supersaturated tissue by a behavioral response to acoustic exposure, could be a mechanism for the strandings and mortality of some deep-diving cetaceans exposed to mid-frequency naval sonar. The evidence for this remains circumstantial and associated with exposure to naval mid-frequency sonar, not seismic surveys.

Airgun pulses and mid-frequency sonar signals are quite different, and some mechanisms by which sonar sounds have been hypothesized to affect beaked whales are unlikely to apply to airgun pulses. Sounds produced by airgun arrays are broadband brief impulses with most of the energy below 1 kHz. Typical military mid-frequency sonars emit non-impulse transient sounds at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time (although the frequency may change over time). Thus, it is not appropriate to assume that the effects of airgun pulses on beaked whales or other species would be the same as the apparent effects of military sonar. For example, resonance effects (Gentry 2002) and acoustically-mediated bubble growth (Crum et al. 2005) are implausible in the case of exposure to broadband airgun pulses. Nonetheless, evidence that sonar signals can, in special circumstances, lead (at least indirectly) to physical damage and mortality (e.g., Balcomb and Claridge 2001; NOAA and USN 2001; Jepson et al. 2003; Fernández et al. 2004, 2005; Hildebrand 2005; Cox et al. 2006) suggests that caution is warranted when dealing with exposure of marine mammals to any high-intensity transient sound. One of the hypothesized mechanisms by which naval sonars lead to strandings might, in theory, also apply to seismic surveys: If the strong sounds sometimes cause deep-diving species to alter their surfacing–dive cycles in a way that causes bubble formation in tissue, that hypothesized mechanism might apply to seismic surveys as well as mid-frequency naval sonars. However, there is no specific evidence of this upon exposure to airgun pulses.

Based on evidence from terrestrial mammals and humans, sound is a potential source of stress (Wright and Kuczaj 2007; Wright et al. 2007a,b, 2009). However, almost no information is available on sound-induced stress in marine mammals, or on its potential (alone or in combination with other stressors) to affect the long-term well-being or reproductive success of marine mammals (Fair and Becker 2000; Hildebrand 2005; Wright et al. 2007a,b). Such long-term effects, if they occur, presumably would be mainly associated with chronic noise exposure, which is characteristic of some seismic surveys and exposure situations (McCauley et al. 2000b; Nieukirk et al. 2009) but not of some others.

Available data on potential stress-related impacts of anthropogenic noise on marine mammals are extremely limited. We know of only two specific studies of noise-induced stress in marine mammals exposed to oil-industry sounds: ***(1)*** Romano et al. (2004) examined the effects of single underwater impulse sounds from a seismic water gun (source level up to 228 dB re 1 µPa @ 1 m, pk–pk) and single short-duration pure tones (sound pressure level up to 201 dB re 1 µPa) on the nervous and immune systems of a beluga and a bottlenose dolphin. They found that neural-immune changes to noise exposure were minimal. Although levels of some stress-released substances (e.g., catecholamines) changed significantly with exposure to sound, levels returned to baseline after 24 hr. ***(2)*** During playbacks of recorded drilling noise to four captive beluga whales, Thomas et al. (1990) found no changes in blood levels of stress-related hormones. Long-term effects were not measured, and no short-term effects were detected. For both studies, caution is necessary when extrapolating these results to wild animals and to real-world situations given the small sample sizes, use of captive animals, and other technical limitations of the two studies.

In summary, very little is known about the potential for airgun-based seismic survey sounds to cause non-auditory injury or physiological effects in marine mammals. No such effects have been demonstrated conclusively. The available data do not allow identification of any specific exposure level above which such effects can be expected (Southall et al. 2007). Such effects, if they occur at all, would presumably be limited to short distances and to activities that extend over a prolonged period.

6.2.7.2 Marine Vibroseis

There are no data concerning MarVib effects (injurious, physiological, or otherwise) on marine mammals. Therefore, any discussion of the possibility that exposure to high levels of MarVib sound could lead to non-auditory injury or physiological effects is necessarily very speculative.

Because MarVib sounds would be non-pulse in nature, they would not have the rapid rise time of airgun pulses. That factor, along with their lower anticipated sound pressure levels, suggests that — in at least some respects — MarVib sounds have less potential to cause direct non-auditory injury than do airgun sounds. Such effects have not been demonstrated for airgun sounds, and it seems unlikely that they would occur upon exposure to lower-level MarVib sounds.

In the absence of any information about behavioral responses of marine mammals to MarVib sounds (§ 6.2.5.2), it remains a possibility that behavioral responses to MarVib sound might lead to physiological problems, e.g., disruption of diving cycles in beaked whales leading to bubble formation and “the bends”. However, even if this phenomenon does occasionally occur upon exposure of beaked whales to mid-frequency naval sonar sounds, it seems much less likely upon exposure to MarVib sounds. Beaked whale hearing appears to be similar to that of other odontocetes (§ 3.6), i.e., attuned to mid- and high-frequency sounds but quite insensitive to low-frequency sounds (of which MarVib sound is one example). Strong behavioral reactions by beaked whales to the predominant low-frequency components of MarVib sounds seem unlikely. To the extent that MarVib systems can be designed to suppress higher frequency (e.g., >100 Hz) components of sound, the likelihood of behavioral reactions that might lead to physiological problems should be even lower.

One additional concern is that MarVib sound might tend to elicit resonance of air-filled body cavities or other structures. This is a greater concern for MarVib than for airguns because of the more prolonged nature of MarVib signals. There are few specific data on resonance-induced damage to marine animals (see Gentry [ed.] 2002 for review; see also Finneran 2003). However, natural resonant frequency varies with the size of the lungs, and that depends on body size and on depth in the water column. The natural resonant frequencies of marine mammal lungs are in the low-frequency range where MarVib systems are likely to operate. There is some concern about the possibility that, depending on the signal type used and circumstances, MarVib sources might elicit resonance in marine mammals. In theory, resonance of a body cavity or structure tends to occur when the wavelength of the sound signal is an integer multiple of a principal dimension of the cavity or structure, and when the sound continues for long enough to excite oscillation. A PRN signal, if that were used in a MarVib system, does not have any one predominant wavelength and would not be expected to elicit resonance. An FM sweep signal might start to elicit resonance as the frequency sweeps past the resonant frequency of the body cavity, but resonance is unlikely to be fully established or sustained given the constantly changing frequency. The most problematic type of signal, from the perspective of resonance, would presumably be a constant-frequency (CF) signal sustained at a resonant frequency, if a low-frequency CF signal were ever used in a MarVib system. However, our understanding is that CF signals would not be useful for geophysical purposes. We emphasize that these comments about resonance are speculative. Research on resonance effects of proposed MarVib signals would be desirable, especially if (contrary to our expectation) CF signals are considered for use in MarVib systems.

6.3 Sea Turtles

6.3.1 Masking

There is no information available on the potential masking effect of introduced underwater sound on the ability of sea turtles to detect relevant environmental sounds and social signals. There are limited data to indicate that sea turtles can hear moderately low-frequency sounds, including some of the frequencies that are prominent in airgun pulses and expected to predominate in MarVib signals (see § 3.4.1). There have been (to our knowledge) no reports of sea turtles producing sound underwater, although female sea turtles do emit in-air sounds in the 300–500 Hz range during nesting (Mrosovksy 1972). Other senses—vision, detection of wave direction, magnetic orientation, and perhaps smell—are known to be important in orientation, navigation, and natal beach homing (Lohmann et al. 1997), but the importance of underwater sound (and thus of potential masking) to sea turtles is not known.

6.3.1.1 Airguns

There is no empirical information indicating that sounds relevant to sea turtles can be masked by seismic airgun sound, but there is some potential for this effect. However, as for other types of marine animals, that potential is reduced by the intermittent nature and low duty cycle of airgun pulses, in most situations with much less (or no) airgun sound during the intervals between shots (see § 6.2.4.1 for the corresponding discussion with regard to marine mammals).

6.3.1.2 Marine Vibroseis

Relevant Empirical Information.—There is no empirical information with regard to masking of sounds relevant to sea turtles by MarVib sound, but this effect would inevitably occur to some degree (see below).

Expected MarVib vs. Airgun Effects.— Regardless of the lack of empirical information on masking by MarVib sound, there is potential for the occurrence of this effect if there is overlap in time and frequency between the MarVib sound and sea turtle sounds, if any, or other sounds relevant to sea turtles. Compared to seismic airgun sound, the likelihood of masking is higher with MarVib sound given its longer signal duration and higher duty cycle. The amplitude of the MarVib sound received by sea turtles would have to be (to a first approximation) equal to or greater than the amplitude of the sound relevant to turtles, and at similar frequencies, for masking to occur. If signals from airguns and marine vibrators have equal source SELs, the received signals from the airguns would have higher peak amplitude given their lower duty cycle. However, except in the unusual case of strong reverberation throughout the interval between pulses, the masking effect by airgun sound will be brief and intermittent. Therefore, in the absence of strong reverberation, masking of sounds relevant to sea turtles will likely be more of a problem with MarVib. Sea turtles are capable of hearing relatively low frequencies, supporting the idea that masking by MarVib sound will at times occur. However, in the absence of much information as to whether and how sea turtles actually use underwater sound, the consequences of masking cannot be predicted.

MarVib Design Alternatives.—Design changes to certain aspects of a MarVib system could potentially decrease the extent of masking of any sounds that are ecologically relevant to sea turtles. The rationale for the following predictions is similar to that for other animals sensitive to low-frequency sound, e.g., baleen whales (§6.2.4), and some details given in §6.2.4 are not repeated here. It is also noted that there is no information about the occurrence or importance of masking in sea turtles, so this is a theoretical discussion.

Decreasing the duration of each MarVib signal or increasing the duration of the intervals between signals (or both), thereby decreasing duty cycle, would lower the probability of temporal overlap of the MarVib sound and the sounds ecologically relevant to turtles. On the other hand, decreasing the signal duration might necessitate increasing the peak and RMS sound pressure levels (SPL) of the signal, which would tend to increase the size the area around the MarVib system within which a given level of masking would occur. As noted in §6.2.4.2 for marine mammals, increasing the duty cycle and (especially) eliminating gaps between MarVib transmissions would increase masking, if masking by MarVib signals would in fact be an issue for sea turtles.

Suppression of the components of MarVib sound occurring above 100 Hz (see § 5.3.4.2) could decrease the potential of masking for sea turtles. Sea turtles exhibit maximal sensitivity at frequencies between 100 Hz and 800 Hz with less sensitivity below 50–80 Hz. Better suppression of the higher frequency components of MarVib signals would result in fewer sea turtles being subject to masking.

A sweep signal would likely have less potential to mask ecologically relevant sounds of any particular sea turtle species than a pseudo-random noise (PRN) signal. With sweep signals, the masking of sound at a particular frequency or in a particular frequency range could happen for a fraction of each sweep, but with a PRN signal, masking could occur more continuously throughout the signal duration.

Adjusting the depth at which the MarVib is operated could be beneficial to sea turtles if masking is an issue. The degree of benefit would depend on the species in the area and their depth preferences at that time. The sound-velocity profile (SVP) of the water could affect the source depth from which sea turtles at long horizontal distances would receive lowest or highest received levels of MarVib sound.

6.3.2 Disturbance

6.3.2.1 Airgun

***Directed Studies*.—**Few studies have examined the effects of airgun noise on sea turtles; to our knowledge, only four studies have been reported, all focused on short-term behavioral responses of sea turtles in enclosures to single airguns. Comparisons of results among studies are difficult because experimental designs and reporting procedures varied greatly, and some of the studies did not provide specific information about the levels of the airgun pulses received by the turtles. Although monitoring studies are now providing some information on responses (or lack of responses) of free-ranging sea turtles to seismic surveys, we are not aware of any systematic studies on responses of free-ranging sea turtles to seismic sounds or on the long-term effects of seismic or other sounds on sea turtles.

McCauley et al. (2000a,b) exposed caged green and loggerhead sea turtles (one of each) off Western Australia to pulses from an approaching and then receding 20-in^3 airgun operating at 1500 psi and 5-m airgun depth. The single airgun fired every 10 sec. There were two trials separated by two days; the first trial involved ~2 hr of airgun exposure and the second ~1 hr. The results from the two trials showed that, above a received level of 166 dB re 1 μPa_{RMS}, the turtles noticeably increased their speed of swimming relative to periods when no airguns were operating. The behaviour of the sea turtles became more erratic when received levels exceeded 175 dB re 1 μPa_{RMS}. The authors suggested that the erratic behaviour exhibited by the caged sea turtles would likely, in unrestrained turtles, be expressed as an avoidance response (McCauley et al. 2000a,b).

O'Hara and Wilcox (1990) tested the reactions to airguns of loggerhead sea turtles held in a 300 × 45 m area of a canal 10 m deep in Florida. Nine turtles were tested at different times. The sound source consisted of one 10-in^3 airgun plus two 0.8-in^3 "poppers" operating at 2000 psi [9] at depth 2 m for prolonged periods of 20–36 hr. The turtles maintained a standoff range of ~30 m when exposed to airgun pulses every 15 sec or 7.5 sec. It was also possible that some turtles remained on the bottom of the enclosure when exposed to airgun pulses. O'Hara and Wilcox (1990) did not measure the received airgun sound levels. McCauley et al. (2000a,b) estimated that "the level at which O'Hara saw avoidance was around 175–176 dB re 1 μPa_{RMS}". The levels received by the turtles in the Florida study probably were actually a few dB less than 175–176 dB because the calculations by McCauley et al. apparently did not allow for the shallow 2-m airgun depth in the Florida study. The effective source level of airguns is less when they are near 2-m depth than at 5 m (Greene and Burgess 2000).

Moein et al. (1994) investigated the avoidance behaviour and physiological responses of loggerhead turtles exposed to an operating airgun, as well as the effects on their hearing. The turtles were held in a netted enclosure ~18 m × 61 m and 3.6 m deep, with an airgun of unspecified size at each end. Only one airgun was operated at any one time; firing rate was one shot every 5–6 sec. Ten turtles were tested individually, and seven of these were retested several days later. The airgun was initially discharged when the turtles were near the centre of the enclosure and the subsequent movements of the turtles were

[9] There was no significant reaction by five turtles during an initial series of tests with the airguns operating at the unusually low pressure of 1000 psi. The source and received levels of airgun sounds would have been substantially lower when the air pressure was only 1000 psi than when it was at the more typical operating pressure of 2000 psi.

documented. The turtles exhibited avoidance during the first presentation of airgun sounds at a mean range of 24 m, but the avoidance response waned quickly. Additional trials conducted on the same turtles several days later did not show statistically significant avoidance reactions, although there was an indication of slight initial avoidance followed by rapid waning of the avoidance response. The authors described the rapid waning of the avoidance response as "habituation".

Once again, inconsistencies in reporting procedures and experimental design prevent direct comparison of this study with either McCauley et al. (2000a,b) or O'Hara and Wilcox (1990). Moein et al. (1994) stated, without further details, that "three different decibel levels (175, 177, 179) were utilized" during each test. These figures probably are received levels in dB re 1 μPa, and probably relate to the initial exposure distance (mean 24 m), but these details were not specified. Also, it was not specified whether these values were measured or estimated, or whether they are expressed in peak-peak, peak, RMS, SEL, or some other units. Given the shallow water in the enclosure (3.6 m), any estimates based on simple assumptions about propagation would be suspect.

Lenhardt (2002) exposed captive loggerhead sea turtles to seismic airgun (Bolt 600) sounds in a large net enclosure. At received levels of 151–161 dB, turtles were found to increase their swimming speeds. Similar to the McCauley et al. studies (2000a,b—see above), at a received level of ~175 dB, an avoidance reaction was common in initial trials, but habituation then appeared to occur. Lenhardt (2002) suggested that exposure of sea turtles to airguns at water depths >10 m may result in exposure to more energy at low frequencies with unknown biological effects.

Despite the problems in comparing these studies, they are consistent in showing that, at some received level, sea turtles show avoidance of an operating airgun. McCauley et al. (2000a,b) found evidence of behavioral responses when the received level from a single small airgun was 166 dB re 1 μPa_{RMS}, and avoidance responses at 175 dB re 1 μPa_{RMS}. Based on these data, McCauley et al. estimated that, for a typical airgun array (2678 in^3, 12 elements) operating in 100–120 m water depth, sea turtles may exhibit behavioral changes at ~2 km and avoidance around 1 km. These estimates are subject to great variation, depending on the seismic source and local propagation conditions. Also, estimates of reaction thresholds and distances for full-scale sources that are based on upward scaling of results from experiments with small sources are subject to additional uncertainties.

A further potential complication is that sea turtles on or near the bottom may receive sediment-borne "headwave" signals from the airguns (McCauley et al. 2000a,b). It is believed that sea turtles use bone conduction to hear and it is unknown how sea turtles might respond to the headwave component of an airgun impulse, or to bottom vibrations.

Monitoring Results.—Sea turtle behaviour near airgun operations has also been observed during marine mammal and sea turtle monitoring and mitigation programmes associated with various seismic operations around the world. Although the primary objectives usually concerned marine mammals, sea turtle sightings have also been documented in some of monitoring projects. Results suggest that some sea turtles exhibit behavioral changes and/or avoidance within an area of unknown size near a seismic vessel. However, avoidance of approaching seismic vessels is sufficiently limited and small-scale such that sea turtles are often seen from operating seismic vessels. Also, average distances from the airguns to these sea turtles are usually not greatly increased when the airguns are operating as compared with times when airguns are silent.

For example, during six large-source surveys (10–20 airguns; total airgun volume 3050–8760 in^3) and various small-source surveys (up to six airguns or three GI guns; 75–1350 in^3) conducted during 2003–

2005, the mean closest observed point of approach (CPA) for turtles was closer during non-seismic than seismic periods: 139 m vs. 228 m and 120 m vs. 285 m, respectively (Holst et al. 2006). During a large-source seismic survey off the Pacific coast of Central America in 2008, the turtle sighting rate during non-seismic periods was seven times greater than that during seismic periods (Holst and Smultea 2008). In addition, sturtles seen from the seismic vessel were significantly farther from the airgun array when it was operating (mean 159 m, n = 77) than when the airguns were off (mean 118 m, n = 69; Mann-Whitney U test, P<0.001) (Holst and Smultea 2008). During another survey in the Eastern Tropical Pacific in 2008, the turtle sighting rate during non-seismic periods was 1.5× that during seismic periods; however, turtles tended to be seen closer to the airgun array when it was operating, but this difference was not statistically significant (Hauser et al. 2008).

Weir (2007) reported on the behaviour of sea turtles near seismic exploration operations off Angola, West Africa. A total of 240 sea turtles were seen during 676 hr of vessel-based monitoring, mainly directed to marine mammals. Airgun arrays with total volumes of 5085 and 3147 in^3 were used at different times during the seismic programme. Sea turtles tended to be seen slightly closer to the seismic source, and at sighting rates twice as high, during non-seismic vs. seismic periods (Weir 2007). However, there was no significant difference in the median distance of turtle sightings from the array during non-seismic vs. seismic periods, with means of 743 m (n = 112) and 779 m (n = 57).

Off northeastern Brazil, 46 sea turtles were seen during 2028 hr of vessel-based monitoring of seismic exploration using 4–8 GI airguns (Parente et al. 2006a). There were no apparent differences in turtle sighting rates during seismic and non-seismic periods, but detailed behavioral data during seismic operations were lacking.

6.3.2.2 Marine Vibroseis

Relevant Empirical Information.—This section provides some empirical information that is at least indirectly relevant to disturbance of sea turtles by MarVibs.

Studies involving stimuli other than airguns may be relevant to MarVibs. ***(1)*** Two loggerhead turtles resting on the bottom of shallow tanks responded repeatedly to low-frequency (20–80 Hz) tones emitted by a Vibra-Coustics speaker coupled by its water bladder to the tank. The turtles became active and swam to the surface. They remained at the surface or only slightly submerged for the remainder of the 1-min trial (Lenhardt 1994). Although no detailed data on sound levels at the bottom vs. surface were reported, the surfacing response probably reduced the levels of underwater sound to which the turtles were exposed. ***(2)*** In a separate study, a loggerhead and an Atlantic ridley sea turtle responded similarly when vibratory stimuli at 250 or 500 Hz were applied to the head for 1 sec (Lenhardt et al. 1983). There appeared to be rapid habituation to these vibratory stimuli. ***(3)*** Turtles in tanks showed agitated behaviour when exposed to simulated boat noise and, perhaps of more relevance to MarVibs, recorded sound from the U.S. Navy's Low Frequency Active (LFA) sonar (Samuel et al. 2005, 2006).

Expected MarVib vs. Airgun Effects.—The likelihood that sea turtles will be disturbed by marine seismic surveys is probably lower for MarVib sound than for airgun sound given that the airguns would create higher peak pressures and higher particle displacement values at any given distance. However, this difference in peak amplitude is somewhat offset by the longer signal duration/higher duty cycle of typical MarVib sound. Either the MarVib or airgun array would need to produce received sound pressure or particle displacement levels equal to or greater than the disturbance thresholds of receiving turtles to cause any effect. However, it is unknown whether the disturbance threshold would be the same for the two types of sound, given the differences in signal duration, duty cycle, and other properties. MarVib sound might cause either more or less disturbance effect; the data are insufficient to determine this. A greater degree of suppression of upper frequency components is expected with MarVib sound than with airgun sound. This could make MarVib sound less likely to cause disturbance to sea turtles, particularly if the transmitted frequencies are well below the frequency range of highest sensitivity.

MarVib Design Alternatives.—If MarVib sound does cause disturbance effects in sea turtles, then changes to certain aspects of MarVib could potentially decrease those effects.

Decreasing the duration of each signal and increasing the interval between signals, thereby decreasing duty cycle, would likely lower the probability of MarVibs sound disturbing sea turtles, other factors being equal. However, decreasing the signal duration would probably require an increase in the peak SPL of the signal in order to emit sufficient energy per signal. This would potentially increase the probability of disturbance at a given distance from the source, and increase the radius of disturbance.

Suppression of the components of marine vibroseis sound occurring above 100 Hz or some such frequency (see § 5.3.4.2) could decrease the potential disturbance of sea turtles. Available sea turtle audiograms indicate that sea turtles exhibit highest sensitivity to sound pressure at frequencies between 100 Hz and 800 Hz, although some sea turtles have been shown to react to frequencies as low as 20 Hz.

There is no specific information concerning the relative degree of disturbance or radius of disturbance for sea turtles exposed to a sweep signal as compared with a PRN signal with similar energy content and bandwidth. An FM sweep would probably be more prominent against the natural background noise than would a PRN signal. Thus, there is a possibility that the latter might have less disturbance effect.

Adjusting the depth at which the MarVib is operated could be beneficial to sea turtles from a disturbance perspective but the optimal depth of operation would likely vary by location, time, and species, as well as the age class of the exposed individuals: young individuals spend more time at the surface than adults. The degree of benefit to sea turtles achievable by adjusting the depth of a MarVib would be most related to which species and age-classes of sea turtles occur in the area, and what behaviours (especially depth preferences, for example while feeding) they are exhibiting at that time.

6.3.3 Hearing Impairment

6.3.3.1 Airguns

Few studies have directly investigated hearing or noise-induced hearing loss in sea turtles. Moein et al. (1994) used an evoked potential method to test the hearing of loggerhead sea turtles exposed to a few hundred pulses from a single airgun. Turtle hearing was tested before, within 24 h after, and two weeks after exposure to pulses of airgun sound. Levels of airgun sound to which the turtles were exposed were not specifically reported. The authors concluded that five turtles exhibited some change in their hearing when tested within 24 h after exposure relative to pre-exposure hearing, and that hearing had reverted to normal when tested two weeks after exposure. The results are consistent with the occurrence of TTS upon exposure of the turtles to airgun pulses. Unfortunately, the report did not state the size of the airgun used, or the received sound levels at various distances. The distances of the turtles from the airgun were also variable during the tests; the turtle was about 30 m from the airgun at the start of each trial, but it could then either approach the airgun or move away to a maximum of about 65 m during subsequent airgun pulses. Thus, the levels of airgun sounds that apparently elicited TTS are not known. Nonetheless, it is noteworthy that there was evidence of TTS from exposure to pulses from a single airgun. However, the turtles were confined and unable to move more than about 65 m away. Similarly, Lenhardt (2002) exposed loggerhead turtles in a large net enclosure to airgun pulses. A TTS of >15 dB was evident for one loggerhead turtle, with recovery occurring in two weeks. Turtles in the open sea might have moved away from an airgun operating at a fixed location, and in the more typical case of a towed airgun or airgun array, very few shots would occur at or around one location. Thus, exposure to underwater sound during net-enclosure experiments was not typical of that expected during an operational seismic survey.

Studies with terrestrial reptiles have demonstrated that exposure to airborne impulse noise can cause hearing loss. For example, desert tortoises (*Gopherus agassizii*) exhibited TTS after exposure to repeated high-intensity sonic booms (Bowles et al. 1999). Recovery from these temporary hearing losses was usually rapid (<1 hr), which suggested that tortoises can tolerate these exposures without permanent injury (Bowles et al. 1999).

The results from captive, restrained sea turtles exposed repeatedly to seismic sounds in enclosed areas indicate that TTS is possible under these artificial conditions. However, there are no data to indicate whether there are any plausible field situations in which exposure to repeated airgun pulses at close range could cause permanent threshold shift (PTS) or hearing impairment in sea turtles. Hearing impairment (whether temporary or permanent) from seismic sounds is considered unlikely to occur at sea; turtles are unlikely to be exposed to more than a few strong pulses close to the sound source, as individuals are mobile and the vessel travels relatively quickly compared to the swimming speed of a sea turtle. However, in the absence of specific information on received levels of impulse sound necessary to elicit TTS and PTS in sea turtles, it is uncertain whether there are circumstances where these effects could occur in the field. If sea turtles exhibit little or no behavioral avoidance, or if they acclimate to seismic noise to the extent that avoidance reactions cease, sea turtles might sustain hearing loss if they are close enough to seismic sources.

6.3.3.2 Marine Vibroseis

Relevant Empirical Information.—We are not aware of any empirical data on the specific effects of MarVib sound or any similar sound on sea turtle hearing.

Expected MarVib vs. Airgun Effects.—Airgun sound signals have more rapid rise times than do MarVib sound signals. Based on this difference in rise time as well as airgun sound's higher peak pressures and particle displacement values, airguns likely have more potential to cause hearing impairment in sea turtles than do MarVibs. However, the anticipated lesser auditory effects of MarVib sound may be partially offset by the longer durations and duty cycles of MarVib signals.

It should be noted that auditory impairment as a result of exposure to either airgun sound or (theoretically) MarVib signals would require exposure to high received levels, which will be limited to distances close to the sound source. It has not been demonstrated that, in field conditions, MarVib sound would cause significant auditory impairment, either temporary or permanent, in sea turtles.

MarVib Design Alternatives.—If hearing impairment upon exposure of sea turtles to MarVib sound is ever a possibility in field conditions, design changes to certain aspects of MarVib could potentially decrease the probability and severity of the auditory effects.

Decreasing the duration of the signal and increasing the duration of the interval between signals, thereby decreasing duty cycle, would be expected to lower the probability of hearing impairment in sea turtles. On the other hand, if a decrease in signal duration would require an increase in the peak sound pressure level (SPL) of the signal in order to achieve the geophysical objectives, that would very likely offset the benefit of the shorter duration to some degree.

Suppression of the components of MarVib sound occurring above 100 Hz or some such frequency (see Section 5.3.4.2) could decrease the potential for hearing impairment in sea turtles.

We are not aware of specific information about the relative auditory effects on sea turtles of sweep signals and pseudo-random signals. However, if signals of those two types had similar energy and bandwidth, it seems likely that there would be similar potential to cause hearing impairment.

As was the case for masking and disturbance effects, adjusting the depth at which the MarVib is operated could be beneficial to sea turtles from a hearing impairment perspective. The optimal depth of operation would likely vary by location, time, species, age class, and behaviour.

6.3.4 Other Injury or Physiological Effects

We are not aware of any studies of non-auditory physical injury in sea turtles, or of physiological effects, as a result of exposure to any type of noise.

It is possible that airgun sound signals, given their more rapid rise time compared with MarVib sounds, might have more potential to cause non-auditory injury or physiological effects in sea turtles as compared to MarVibs. However, there are no relevant experimental or observational data.

Changes to certain design features of MarVibs could potentially decrease the probability that MarVib sound would cause non-auditory injury or physiological effects in sea turtles, should such effects ever occur. The tradeoffs would probably be similar to those for auditory effects (see § 6.3.3, above).

6.3.5 Summary for Sea Turtles

There is little information on sea turtle hearing, whether sea turtles produce underwater sounds, or what environmental sounds may be important to them. The data that are available suggest that they can hear moderately low-frequency sounds, including those frequencies that are prominent in airgun pulses and in MarVib signals. Experimental studies have determined that, for several species of sea turtles, maximal sensitivity is at 100–800 Hz, with reduced sensitivity below ~50–80 Hz. However, some species react to sounds at frequencies as low as 20 Hz.

It is possible that low-frequency sounds of potential importance to sea turtles could be masked by MarVib sounds, and that the longer signal duration and higher duty cycle of MarVib sounds could result in a greater potential for masking than occurs with airgun pulses.

There is little information on the behavioral responses of sea turtles to either airguns or MarVib-like sounds. On general principles, it is expected that MarVib impacts could be smaller due to the potential suppression of high-frequency components and the lower peak pressure compared to airgun pulses. There are limited data on whether TTS would result from exposure to either type of seismic survey, although it is presumed that animals at close range could suffer reduced hearing sensitivity. There are no data concerning whether airgun or MarVib sounds could ever result in PTS. As noted above, the potential for both TTS and PTS, should either occur, is expected to be greater with exposure to airgun pulses than for MarVib sounds due to the rapid rise times and higher peak pressures of airgun signals. However, the longer signal duration and higher duty cycle of MarVib signals would presumably, to some degree, offset their lower peak pressure.

Decreasing the components of MarVib sounds above 100 Hz, using sweep rather than PRN signals, and adjusting the depth of a MarVib array may partially mitigate masking, disturbance, and auditory effects on sea turtles, depending on the behaviour of the turtles (particularly their dive profiles) and the local sound-propagation conditions.

6.4 FISHES

6.4.1 Masking

The scientific literature includes studies on the potential masking effect of introduced underwater sound on the ability of particular fishes to detect and broadcast key environmental sounds and social signals. However, none of these studies pertain directly to either seismic airguns or marine vibroseis. Many of the studies relate to the potential masking effects of vessel noise (Vasconelos et al. 2007; Codarin et al. 2009; Fisher-Pool et al. in press; Luczkovich et al. in press; Wall et al. in press) or of ambient noise (Amoser and Ladich 2005, 2010; Wysocki et al. 2007; Lugli 2010).

6.4.1.1 Airguns

There is no empirical information indicating that sounds relevant to fish can be masked by seismic airgun sound, but there is some potential for this effect. However, that potential is reduced by the intermittent nature and low duty cycle of airgun pulses, in most situations with much less (or no) airgun sound during the intervals between shots (see § 6.2.4.1 for the corresponding discussion with regard to marine mammals).

6.4.1.2 Marine Vibroseis

Relevant Empirical Information.—There is no empirical information with regard to masking of sounds relevant to fish by MarVib sound, but this effect would inevitably occur to some degree (see below).

Expected MarVib vs. Airgun Effects.—Regardless of the lack of empirical information on masking by MarVib sound, there is potential for the occurrence of this effect if there is overlap in time and frequency between the MarVib sound and the relevant fish sounds. Compared to seismic airgun sound, the likelihood of masking is higher with MarVib sound given its longer signal duration and higher duty cycle. The amplitude of the MarVib sound received by fishes would have to be (to a first approximation) equal to or greater than the amplitude of the relevant fish sound, and at similar frequencies, for masking to occur. Assuming that signals from airguns and marine vibrators would have equal source SELs, the received signals from the airguns would have higher peak amplitude given their lower duty cycle. However, except in the unusual case of strong reverberation throughout the interval between pulses, the masking effect by airgun sound will be brief and intermittent. Therefore, in the absence of strong reverberation, masking of sounds relevant to fish will likely be more of a problem with MarVib. This masking would occur when the sounds relevant to fish overlap in frequency with the sounds produced by the MarVib. Hearing in many fish species is relatively sensitive at low frequencies, and many fish sounds are at low frequencies, further supporting the idea that masking by MarVib sound will at times occur.

MarVib Design Alternatives.—Design changes to certain aspects of a MarVib system could potentially decrease the extent of masking of ecologically relevant fish sounds.

Decreasing the duration of each MarVib signal or increasing the duration of the intervals between signals (or both), thereby decreasing duty cycle, would lower the probability of temporal overlap of the MarVib sound and the sounds ecologically relevant to fishes. On the other hand, decreasing the signal duration might necessitate increasing the peak and RMS sound pressure levels (SPL) of the signal, which would tend to increase the size of the area around the MarVib system within which a given level of masking would occur. As noted earlier for marine mammals and sea turtles, increasing the duty cycle and (especially) eliminating gaps between MarVib transmissions would increase masking, if masking by MarVib signals would in fact be an issue for fish.

Suppression of the components of MarVib sound occurring above 100 Hz (see Section 5.3.4.2) could decrease the potential of masking for some but not all fish species. Available fish audiograms indicate that some fish species exhibit highest sound pressure and particle displacement sensitivity at frequencies between 100 Hz and 1000 Hz whereas others appear to be most sensitive at or below 100 Hz. There is substantial inter-specific and intra-specific variability in sound detection thresholds and frequency ranges in fishes. In general, better suppression of the higher frequency components of MarVib signals would result in fewer fish species being subject to significant masking.

A sweep signal would likely have less potential to mask ecologically relevant sounds of any particular fish species than a pseudo-random noise (PRN) signal. With sweep signals, the masking of sound at a particular frequency or in a particular frequency range could happen for a fraction of each sweep, but with a PRN signal, masking could occur more continuously throughout the signal duration.

Adjusting the depth at which the marine vibrator is operated could be beneficial to some fishes from a masking perspective, but the optimal depth of operation (with regard to fish) would likely vary by location and/or time. In other words, for fishes (and other animals as well), the degree of benefit from adjusting the depth of a marine vibrator would depend on the species in the area, and their depth preferences at that time. The sound-velocity profile (SVP) of the water could also affect the source depth from which fish at long horizontal distances would receive lowest or highest received levels of MarVib sound.

6.4.2 Disturbance

6.4.2.1 Airguns

Disturbance effects of airgun sound on fishes have been investigated using two methods: direct and indirect observation. The former method includes direct observation of behavioral changes by individual fish and schools of fish, as reported for captive rockfishes *Sebastes* spp. (Pearson et al. 1992), captive European sea bass *Dicentrarchus labrax* (Santulli et al. 1999), captive reef fishes, herring *Clupea harengus*, silver bream *Acanthopagrus buthcheri*, mullet *Mugil cephalus* (McCauley et al. 2000a,b), captive reef fishes (Boeger et al. 2006), captive lesser sandeel *Ammodytes marinus* (Hassel et al. 2003, 2004), captive salmonids (Thomsen 2002), and unfettered juvenile and adult saithe *Pollachius virens*, juvenile cod *Gadus morhua*, and adult mackerel *Scomber scombrus* (Wardle et al. 2001). Observed disturbance effects were temporary and included startle and alarm responses, changes in schooling density, and distributional shifts. Ranges of received sound pressure levels associated with directly-observed behavioral responses by fishes include 156–161 dB re 1 μPa_{RMS} (McCauley et al. 2000a,b), 161–180 dB re 1 $\mu Pa_{0\text{-}p}$ (Pearson et al. 1992), and 195–218 dB re 1 $\mu Pa_{0\text{-}p}$ (Wardle et al. 2001). The distances from the airgun source at which these types of behavioral effects have been directly observed are variable and dependent on factors that include airgun source SPL, fish species, and sound propagation characteristics of an area.

Indirect observation includes monitoring of unfettered fishes through either the use of acoustic survey equipment or fishing. Indirect observation has been used in studies involving Greenland halibut *Reinhardtius hippoglossoides*, redfishes *Sebastes* sp., haddock and saithe (Løkkeborg et al. 2010), cod and haddock (Dalen and Knutsen 1986; Løkkeborg 1991; Engås et al. 1993, 1996; Løkkeborg and Soldal 1993; Thomsen 2002), rockfishes (Skalski et al. 1992), whiting *Merlangius merlangus* (Chapman and Hawkins 1969), herring and blue whiting *Micromesistius poutassou* (Slotte et al. 2004), lesser sandeel

(Hassel et al. 2003, 2004), and hake *Merluccius merluccius* (La Bella et al. 1996), as well as various freshwater and estuarine species (Jorgenson and Gyselman 2009). Observed disturbance effects included vertical and horizontal avoidance behaviour, changes in schooling density, reduced catch rates that might suggest avoidance behaviour, and increased catch rates that might suggest increased swimming activity. In general, disturbance effects noted through indirect observation were temporary and their occurrence lessened with increasing distance from the airguns and, in some cases, prolonged exposure (i.e., habituation). The distances from the airgun source at which these types of behavioral effects have been reported through indirect observation are as great as 18 n.mi. (Engås et al. 1996). Løkkeborg et al. (2010) were unable to determine the maximum distances from an airgun array at which various species reacted to the airgun sound. As shown by the studies using direct observation, fishes will certainly react to airgun sound but the extent of reaction, especially as it relates to effects on fishery catch rate, is extremely variable and dependent on numerous factors.

6.4.2.2 Marine Vibroseis

Relevant Empirical Information.—This section provides some empirical information that is either directly or indirectly relevant to MarVib.

Linton (1995) described the results of field tests intended to investigate the effects of marine vibrator sound on mud minnows *Fundulus grandis* (6–8 cm length) in the marine environment, and on white sturgeon *Acipenser tramsmontanus* (10–12 cm length) and channel catfish *Ictalurus punctatus* (11–13 cm length) in the freshwater environment. All captive fishes were placed immediately next to the marine vibrator (hydraulically-driven loudspeaker) during the five sweep exposures (duration 6–12 sec; 5–200 Hz frequency range) in order to test the effects of the highest pressure level possible. The approximate peak acoustic pressure produced at source was 214 dB re 1 μPa. The sequential sweeps were delivered on a normal acquisition cycle with a normal listen time but no other interruption (M.R. Jenkerson, Exxon-Mobil, pers. comm.). No changes in activity level or swimming patterns were observed in

- the 20 exposed mud minnows during the 24-hr period following exposure,
- the 20 exposed channel catfish immediately after their exposure, or
- the 10 exposed white sturgeon either immediately after exposure or during the next two weeks.

Anecdotal observations from fisheries observers during a MarVib test in the southern Norwegian Sea suggested that MarVib did not have noticeable effects on a sandeel fishery, unlike the experience with airguns (M.R. Jenkerson, pers. comm.).

Arctic char *Salvlinus alpinus* were exposed to underwater sound produced by on-ice vibrators (source <u>not</u> in the water). Received pressure levels were 180–190 dB re 1 μPa_{RMS} at 10 m from the source (Nyland 2002; Morris and Winters 2005). Through extrapolation, the sound pressure level immediately below the ice was estimated to be 201 dB re 1 μPa_{RMS}. Fish were positioned 0 to 1 m and 3 to 5 m below the ice, both immediately below the source and offset from the source by 3 to 5 m. The fish were exposed to five 6-sec sweeps with bandwidth 6–106 Hz. The duration of the behavioral responses to the vibroseis sound was not measured but fish reactions recorded by video camera were noted to be immediate and intense.

Another Alaskan experiment reported by Morris and Winters (2005) was conducted to investigate potential behavioral effects in broad whitefish *Coregonus nasus* when energy was imparted to a water body by on-ice vibroseis equipment. Non-captive wintering fish were exposed to four energy bursts from a single vibrator rig. Received SPLs for the broad whitefish are unknown. Responses of the whitefish to the initial energy burst were immediate and intense as they attempted to flee the area at the onset of exposure of the vibroseis sounds. However, swimming speeds slowed quickly and, within 1–2 min, the fish swimming speeds had returned to the pre-exposure level and the fish had schooled back to the area beneath the vibrator. The whitefish response decreased with subsequent exposure to vibroseis sound, indicating an apparent habituation. Within 2–6 min of cessation of the final vibroseis exposure, fish were either moving very slowly or had returned to a sedentary posture. A single slimy sculpin *Cottus cognatus* observed during the fourth vibroseis burst did not show any response to the sound.

Doksaeter et al. (2009; in press) report the results of their study of the disturbance effects of exposure to sound from a sonar source on penned Atlantic herring. The sonar signal was a 1–1.6 kHz hyperbolic frequency modulated (FM) up-sweep emitted from a moving frigate with a 500 m closest point of approach. Although these signals differed in frequency and other characteristics from MarVib signals, the reactions of the fish may be of some relevance. The FM signals were introduced to the herring in two ways; gradual and sudden. Gradual introduction involved the onset of transmissions 1 n.mi. away from the pen whereas the sudden introduction involved onset of transmission of the signal at the closest point of approach (i.e., 500 m). The highest measured received sound pressure level was 168 dB re 1 μPa_{RMS} during one of the sudden introductions of the FM signal. Herring behaviour was monitored with both an echosounder and an underwater video camera. Only minor startle responses were observed and these occurred during only 3 of the 14 sudden exposures to the FM signal.

Expected MarVib vs. Airgun Effects.—The likelihood that fishes will be disturbed by marine seismic surveys is probably lower for MarVib sound than for airgun sound given that the signal SEL for each source is expected to be similar but the airgun sound signals would likely have a higher peak pressure and particle displacement. However, this difference in peak amplitude is somewhat offset by the longer signal duration/higher duty cycle of typical MarVib sound. Either the MarVib or airgun array would need to produce received sound pressure or particle displacement levels equal to or greater than the disturbance thresholds of receiving fishes to cause any effect. However, it is unknown whether the disturbance threshold would be the same for the two types of sound, given the differences in signal duration, duty cycle, and other properties. MarVib sound might cause either more or less disturbance effect; the data are insufficient to determine this. However, a greater degree of suppression of upper frequency components is expected with MarVib sound than with airgun sound. This could make MarVib sound less likely to cause disturbance to fishes, particularly to species that are especially sensitive to frequencies present to a significant degree in airgun sound but potentially much reduced in MarVib sound. The relative degree of disturbance for each sound source would depend on the audiogram shape for the fishes receiving the signals.

MarVib Design Alternatives.—Changes to certain aspects of MarVib could potentially decrease the probability of its sound causing disturbance effects on fishes.

Decreasing the duration of each signal and increasing the interval between signals, thereby decreasing duty cycle, would likely lower the probability of MarVib sound disturbing fishes, other factors being equal. However, decreasing the signal duration would probably require an increase in the peak SPL and particle displacement associated with the signal. This would potentially increase the probability of disturbance at a given distance from the source, and increase the radius of disturbance.

Suppression of the components of MarVib sound occurring above 100 Hz or some such frequency (see Section 5.3.4.2) could decrease the potential disturbance of some but not all fish species. Available fish audiograms indicate that some fish species exhibit highest sensitivity to sound pressure and particle displacement at frequencies between 100 Hz and 1000 Hz, whereas others appear to be most sensitive at or below 100 Hz. There is substantial inter-specific and intra-specific variability in the frequencies to which fish are most sensitive. In general, the higher the degree of suppression of the higher frequency components, the lower the number of fish species that would exhibit disturbance, and (for many species) the smaller the radius of disturbance effects.

There is no specific information concerning the relative degree of disturbance or radius of disturbance for fish exposed to a frequency-modulated sweep signal as compared with a pseudo-random noise signal with similar energy content and bandwidth. An FM sweep would probably be more prominent against the natural background noise than would a PRN signal. Thus, there is a possibility that the latter might have less disturbance effect.

Adjusting the depth at which the marine vibrator is operated could be beneficial to fishes from a disturbance perspective but the optimal depth of operation would likely vary by location, time and species. The degree of benefit to fishes achievable by adjusting the depth of a marine vibrator would be most related to which fish species occur in the area and what behaviours (especially depth preferences) they are exhibiting at that time. If the major concern were about effects on benthic species, then one should presumably avoid having the MarVib source close to the bottom.

6.4.3 Hearing Impairment

6.4.3.1 Airguns

There have been some studies of temporary threshold shift (TTS) in fishes exposed to strong underwater sounds. Almost all of these studies used sound sources other than seismic airguns (Scholik and Yan 2001, 2002a,b; Amoser and Ladich 2003; Smith et al. 2004a,b; Wysocki and Ladich 2005; Popper et al. 2007b; Jørgensen et al. in press; Oestman and Earle in press). These studies confirmed the occurrence of TTS upon exposure to sufficient underwater sound, and also indicated that there is inter-specific variability in susceptibility to TTS.

One study of TTS in fishes that did involve exposure to airgun sound investigated airgun effects on the hearing of three fish species in northern Canada's Mackenzie River Delta (Popper et al. 2005). The fishes included young-of-the year (YOY) and adult northern pike *Esox lucius*, adult broad whitefish *Coregonus nasus*, and adult lake chub *Couesius plumbeus*. The caged fish were exposed to either 5 or 20 discharges from an airgun array, receiving approximate mean SPLs of 205–210 dB re 1 $\mu Pa_{0\text{-}p}$. Both adult northern pike and lake chub exhibited hearing threshold shifts but thresholds returned to normal 18 hr post-exposure. The greatest threshold shift for northern pike exposed to five discharges was about 20 dB at 400 Hz, whereas the shift for lake chub exposed to 5 and 20 discharges was 25 dB at 200 Hz and 35 dB at 400 Hz, respectively. Neither adult broad whitefish nor YOY northern pike exhibited any hearing threshold shifts. The same animals were also examined to determine whether there were observable effects on the sensory cells of the inner ear as a result of exposure to seismic sound (Song et al. 2008). No damage to the ears of the fishes was found, including those that exhibited TTS.

One additional study tested for but did not find TTS in fish exposed to airgun pulses. Captive tropical reef fishes were exposed to multiple sound pulses from a moving airgun array, resulting in cumulative sound exposure levels as high as 190 dB re 1 $\mu Pa^2 \cdot sec$ (Hastings and Miksis-Olds in press). Those authors did not find evidence of TTS resulting from the sound exposure in any of the four fish species.

Evidence for airgun-induced damage to fish ears has been provided by a study involving pink snapper *Pagrus auratus* (McCauley et al. 2000a,b, 2003). In that study, fish were caged and exposed to the sound of a single moving airgun that discharged every 10 sec over a period of 1.7 hr. The source SPL was about 223 dB re 1 $\mu Pa \cdot m_{p\text{-}p}$, and the received SPLs were 165–209 dB re 1 $\mu Pa_{p\text{-}p}$. The pink snapper were exposed to more than 600 airgun discharges during the study. In some individual fish, the sensory epithelium of the inner ear sustained extensive damage as indicated by ablated hair cells. Damage was more extensive in fish examined 58 days post-exposure compared to those examined 18 hr post-exposure. There was no evidence of repair or replacement of damaged sensory cells up to 58 days post-exposure. McCauley et al. (2000a,b, 2003) included the following caveats in the study reports: ***(1)*** fish were caged and unable to swim away from the seismic source, ***(2)*** only one species of fish was examined, ***(3)*** the impact on the ultimate survival of the fish is unclear, and ***(4)*** specific sound exposures required to cause the observed damage were not determined. (That is, it was not determined whether the effects were attributable to a few high SPL signals or to the cumulative effect of many low to moderate SPL signals.)

6.4.3.2 Marine Vibroseis

Relevant Empirical Information.—We are not aware of any empirical data on the specific effects of MarVib sound on fish hearing. However, one study of the effects of low-frequency sonar sound may be of some relevance.

Popper et al. (2007b) investigated the effects of exposure to high intensity, low-frequency sonar on hearing in rainbow trout *Oncorhynchus mykiss*. Each exposure consisted of three hyperbolic frequency-modulated sweeps, each sweep with a frequency range from 170 to 320 Hz. The trout were exposed to a maximum received RMS sound pressure level of 193 dB re 1 μPa for 324 or 648 sec. These exposures were far in excess of any exposure that a wild fish would normally encounter near either a low-frequency sonar or a MarVib system (and the frequency was considerably higher than would be involved with MarVib). A significant 20 dB TTS at 400 Hz was observed, but not for all groups of trout. Sensory tissue of the inner ears did not show any morphological damage, even after several days post-exposure.

Expected MarVib vs. Airgun Effects.—Rise time is one of the critical aspects of a sound signal affecting its potential to cause tissue injury to fishes, in this case tissue associated with the auditory system. Airgun sound signals (at least in the close vicinity of the source) have more rapid rise times than do MarVib sound signals. Based on this difference in rise time as well as airgun sound's higher peak pressures and particle displacement values, airguns very likely have more potential to cause hearing impairment in fishes than do marine vibrators. The lesser auditory effects of MarVib sound may be somewhat offset by the longer durations and duty cycles of MarVib signals. Even so, both TTS and PTS are more likely with airguns given the rapid rise times and higher peak amplitudes of airgun signals.

It should be noted, however, that auditory impairment as a result of exposure to either airgun sound or (theoretically) MarVib signals requires exposure to high received levels, which will be limited to distances close to the sound source. It has not been demonstrated that, in field conditions, MarVib sound would cause significant auditory impairment, either temporary or permanent.

MarVib Design Alternatives.—Design changes to certain aspects of MarVib could potentially decrease the probability of its sound causing hearing impairment in fishes.

Decreasing the duration of the signal and increasing the duration of the interval between signals, thereby decreasing duty cycle (other factors being unchanged), would be expected to lower the probability of MarVib hearing impairment in fishes. On the other hand, if a decrease in signal duration would require an increase in the peak amplitude of the signal in order to achieve the geophysical objectives, that would very likely offset the benefit of the shorter duration to some degree. Auditory impairment in fishes (as in other animals) is expected to be, to a first approximation, a function of the total acoustic energy received. If a particular signal energy is required for geophysical purposes, then the auditory effect on fish would probably be similar for various combinations of signal duration and level that have similar total energy.

Suppression of the components of MarVib sound occurring above 100 Hz or some such frequency (see Section 5.3.4.2) could decrease the potential for hearing impairment in fishes. The greater the degree of suppression of higher frequency components, the lower the number of fish species that could potentially suffer hearing impairment if present close to the sound source.

We are not aware of specific information about the relative auditory effects on fishes of FM sweep vs. pseudo-random signals. However, if signals of those two types had similar energy and bandwidth, it seems likely that there would be similar potential to cause hearing impairment in fish.

As was the case for masking and disturbance effects, adjusting the depth at which the marine vibrator is operated could be beneficial to fishes from a hearing impairment perspective, but the optimal depth of operation would likely vary by location, time, and species. The degree of benefit to fishes achievable by adjusting the depth of a marine vibrator would be most related to which fish species occur in the area and what behaviours (especially depth preferences) they are exhibiting at that time. If the major concern were about effects on benthic species, then one should presumably avoid having the MarVib source close to the bottom.

6.4.4 Other Injury or Physiological Effects

6.4.4.1 Airguns

Non-auditory Physical Injury.—The potential for airgun sound to cause non-auditory physical injury to eggs and larvae of fishes has had limited study (Kostyuchenko 1973; Holliday et al. 1987; Saetre and Ona 1996; Booman et al. 1996; Payne et al. 2009). In general, results of these studies indicated that eggs and larvae located immediately next to an airgun source have some potential to suffer injury while those more than 5 m away do not appear to be significantly impacted. In the studies mentioned above, the highest reported sound pressure level was 242 dB re 1 µPa (unspecified metric) (Booman et al. 1996). It is not clear whether that SPL was a source or received level. Regardless, the exposed eggs and larvae were, at most, 5 m from the source.

The potential for airgun sound to cause non-auditory physical injury to juvenile and adult stages of fishes has also had only limited study (Weinhold and Weaver 1972; Falk and Lawrence 1973; Santulli et al. 1999; Thomsen 2002; Hassel et al. 2003, 2004; Popper et al. 2005; Boeger et al. 2006). The species involved in these studies included marine reef and non-reef fishes, freshwater fishes, and anadromous salmonids. No apparent non-auditory physical injury was observed in any of the studies. Although received sound pressure levels usually were not reported, Popper et al. (2005) reported approximate mean received SPLs ranging from 205 to 210 dB re 1 $\mu Pa_{0\text{-}p}$.

Physiological Effects.—Santulli et al. (1999) reported results of blood biochemical analyses after the exposure of European sea bass to multiple discharges from an airgun array. Levels of cortisol, glucose, and lactate were significantly higher in the sera of exposed fish compared to control fish. However, all three chemicals returned to normal levels within 72 hr of exposure.

6.4.4.2 Marine Vibroseis

Relevant Empirical Information.—This section provides some empirical information directly associated with an early MarVib system, and some other information that may be indirectly relevant.

Linton (1995) described observations from field tests intended to determine the effects of MarVib sound on mud minnows in the marine environment, and on white sturgeon and channel catfish in the freshwater environment. All captive fishes were placed immediately next to the marine vibrator (hydraulically-driven loudspeaker) during the five sweep exposures (duration 6–12 sec; 5–200 Hz frequency range) in order to test the effects of the highest pressure level possible. The approximate peak SPL at source was 214 dB re 1 µPa. Neither acute nor chronic non-auditory physical injury was observed in any of the fish.

More recently, Arctic char were exposed to underwater sound produced by <u>on-ice</u> vibrators; received pressure levels were 180–190 dB re 1 µPa$_{RMS}$ at 10 m from the source (Nyland 2002; Morris and Winters 2005). Through extrapolation, the sound pressure level immediately below the ice was estimated to be 201 dB re 1 µPa$_{RMS}$. Fish used in the exposure experiment were positioned 0 to 1 m and 3 to 5 m below the ice, both immediately below the source and offset from the source by 3–5 m. The fish were exposed to five 6-sec sweeps with bandwidth 6–106 Hz. Subsequent necropsy indicated several types of injury, including haemorrhaging within the musculature and body cavity, and in the eyes. No damage to the swim bladder was observed. However, the level of injury in exposed fish was not significantly different from that observed in the control fish, so the significance and proper interpretation of these results is uncertain.

Popper et al. (2007b) also investigated the non-auditory physical injury effects of exposure to high intensity, low-frequency sonar sound on rainbow trout. Each exposure consisted of three hyperbolic frequency-modulated sweeps, each sweep with a frequency range 170–320 Hz. The trout were exposed to a maximum received RMS sound pressure level of 193 dB re 1 µPa for 324 or 648 sec — far in excess of any exposure that a wild fish would normally encounter near either a low-frequency sonar or a MarVib system. The frequency was considerably higher than would be involved with MarVib. No fish mortality was observed during or after exposure. Gross and histopathological observations did not detect any injurious effects on non-auditory tissues.

Expected MarVib vs. Airgun Effects.—Non-auditory effects are more likely with airguns than with MarVib, for the same reasons that auditory effects are more likely with airguns than with MarVib (see § 6.4.3.2). These reasons involve the rapid rise times and higher peak amplitudes of airgun signals. However, it should again be noted that non-auditory physical injury as a result of exposure to either airgun sound or (theoretically) MarVib signals requires exposure to high received levels, which will be limited to distances very close to the sound source. It has not been demonstrated that, in field conditions, MarVib sound would cause significant non-auditory physical injury.

MarVib signals are expected to be either frequency-modulated sweeps or perhaps pseudo-random noise signals. Neither of these signal types would be expected to cause prolonged resonance in an air-filled cavity, e.g., swim bladder.

MarVib Design Alternatives.—Design changes to certain aspects of MarVib could potentially decrease the probability of its sound causing non-auditory physical injury in fishes (if that ever would occur with MarVib). In most if not all respects, design changes that would be optimum with regard to reducing auditory effects (§ 6.4.3.2, above) are also likely to be optimum in reducing non-auditory injury and physiological effects.

With regard to the possibility of swim-bladder resonance, it may be important to avoid using constant-frequency tonal sounds as MarVib signals. However, such sounds would probably not be desirable for geophysical purposes either, so are not expected to be an issue.

6.4.5 Summary for Fishes

Direct empirical information on how exposure to MarVib sound affects fishes is limited to data from a single study involving exposure of fishes to sound from an early design of MarVib, supplemented by data from two studies involving exposure of fishes to sound somewhat similar to MarVib sound. Neither disturbance nor non-auditory injury was detected by Linton (1995) in mud minnows, white sturgeon, or channel catfish during the one MarVib study. Morris and Winters (2005) exposed fishes to sound produced by on-ice vibrators and reported temporary disturbance effects on Arctic char and broad whitefish but no non-auditory injury effects on the char. High-intensity low-frequency sound used by Popper et al. (2007b) caused temporary threshold shifts in rainbow trout but neither acute auditory injury nor non-auditory injury was noted in the fish. Received sound pressure levels reported in the latter two studies were 180–201 dB re 1 μPa_{RMS}. Linton (1995) reported a source SPL only. We know of no empirical information relating to masking effects of MarVib sound on fishes. All types of effects except masking have also been observed in exposure studies using airgun sound.

For fishes, the potential for masking is higher with MarVib sound compared to airgun sound because of the longer signal duration and higher duty cycle for MarVib sound. However, the likelihood that MarVib sound would cause disturbance, hearing impairment, or non-auditory injury/physiological effects is presumably lower with MarVib than for airgun sound because of MarVib's lower signal amplitude. Altering some specific design features of MarVib systems, where possible, could also lower their potential to cause effects on fishes. Desirable features would be to decrease signal duration and/or to increase the intervals between signals (i.e., decrease duty cycle), if this could be done without increasing source level, and to suppress higher frequency components. It is possible that use of FM sweeps would (for fish) be preferable to use of a pseudo-random noise signal, but it would be desirable to test that before making a choice. Adjustment of the operating depth of the marine vibrator might also be helpful, but the optimum depth would depend on the specific circumstances of the planned seismic survey. Overall, MarVib sound would likely have less effect on fishes compared with airgun sound.

Effects of MarVib sound on the prey and predators of fishes would, to the extent they occur, be indirect effects. The potential effects of exposure to MarVib on prey of fishes (i.e., on other fishes and on invertebrates) have been partially addressed in this section and in the next section (on invertebrates). Similarly, discussion of the potential effects of exposure to MarVib on predators of fishes (marine mammals, sea turtles, and other fishes) is provided in the preceding sections on marine mammals and sea turtles, and in the current section.

6.5 MARINE INVERTEBRATES

6.5.1 Masking

As indicated in § 3.2.1, there is scientific evidence supporting the ability of certain groups of marine crustaceans and molluscs to detect and/or produce low-frequency sound. However, there is no scientific evidence concerning acoustic masking in invertebrates.

Research has indicated that ambient underwater sound produced in coastal habitats in many parts of the world is important to the early recruitment processes of a wide range of coastal organisms, including crabs. Stanley et al. (in press) discuss the possibility that introduced anthropogenic noise could interfere with recruitment processes by masking important settlement cues and subsequently causing premature or reduced settlement.

6.5.1.1 Airguns

There is no empirical information concerning masking of sounds relevant to invertebrates by airgun sound but there is at least a slight potential for this effect. However, as in other types of animals, the potential for masking is reduced by the intermittent nature and low duty cycle of airgun pulses, in most situations with much less (or no) airgun sound during the intervals between shots.

6.5.1.2 Marine Vibroseis

There is no empirical information concerning masking of sounds relevant to invertebrates by MarVib sound, but there is potential for this effect. As with other organisms, there is potential for masking if there is overlap in time and frequency between the MarVib sound and the sounds relevant to marine invertebrates. The likelihood of masking is higher with MarVib sound than with airgun sound, given the longer signal duration and higher duty cycle of MarVib sound.

Changes to certain aspects of MarVib could potentially decrease the extent of masking of sounds relevant to marine invertebrates. Given the limited information about invertebrate acoustics, the situation is especially speculative for invertebrates, but in general, the design choices that are optimum for fish (§ 6.4.1.2) would probably also be optimum for invertebrates.

6.5.2 Disturbance

6.5.2.1 Airguns

As with fishes, disturbance effects of airgun sound on marine invertebrates have been investigated using two methods: direct and indirect observation. The former method included direct observation of behavioral changes in captive snow crab *Chionoecetes opilio* (Christian et al. 2003, 2004), captive American lobster *Homarus americanus* (Payne et al. 2007), and captive squid *Sepioteuthis australis* (McCauley et al. 2000a,b). Although snow crab and lobster did not exhibit any behavioral reactions to airgun sound, the squid did exhibit startle responses after exposure to sound pressure levels ranging from 168 to more than 200 dB re 1 $\mu Pa_{0\text{-}p}$.

Indirect observation has included monitoring of marine invertebrate fisheries. There have been anecdotal reports of reduced catch rates of shrimp shortly after exposure to seismic survey sound. However, one published study reported no significant changes in catch rates of various shrimp species (*Litopenaeus schmitti*, *Farfantepenaeus subtilis*, and *Xyphopenaeus kroyeri*) from before to after exposure to a seismic survey employing four 635-in^3 airguns (Andriguetto-Filho et al. 2005). They also reported no significant difference in catch rate as a function of distance from the operating source, but there was a tendency toward lower catch rates close to the source. A study conducted in Australia indicated an apparent lack of effect of seismic surveys on catch rates of rock lobsters *Jasus* spp. (Parry and Gason 2006). This study used historical seismic survey and fishery data for a particular area where maximum water depth was 150 m. Effects of airgun sound on crustacean and cephalopod fisheries are likely specific to the species in question and aspects of its fishery, including seasonality, duration, and fishing method.

6.5.2.2 Marine Vibroseis

Linton (1995) tested the effects of MarVib sound on Gulf white shrimp *Penaeus setiferus*. The marine vibrator used in the field tests was an early hydraulically-driven design that generated a fundamental frequency range of 5–200 Hz. The approximate peak sound pressure level at source was 214 dB re 1 µPa. The captive shrimp (5–8 cm length) were placed immediately next to the marine vibrator and exposed to five sweeps, each 6–12 sec in duration. Immediately after exposure, the shrimp were observed for any changes in activity level and swimming pattern. Further observations were made during the following 24-hr period. No changes in activity level or swimming patterns were observed.

The likelihood that marine invertebrates will be disturbed by marine seismic surveys is probably lower for MarVib sound than for airgun sound given that the signal SEL for each source is expected to be similar but the airgun sound signals would likely have a higher amplitude. The basis for this statement is the same as that provided for fishes (see § 6.4.2.2).

Changes to certain aspects of MarVib could potentially decrease the probability of its sound causing disturbance effects on marine invertebrates. In most if not all respects, design changes that would be optimum with regard to reducing disturbance effects in fishes (§ 6.4.2.2) are also likely to be optimum in reducing disturbance effects in marine invertebrates. If the major concern were about effects on benthic invertebrates, then one should presumably avoid having the MarVib source close to the bottom.

6.5.3 Hearing Impairment and Injury

6.5.3.1 Airguns

There is no empirical information to support the idea that exposure to airgun sound would impair the capability of marine invertebrates to detect underwater sound.

6.5.3.2 Marine Vibroseis

There is no direct evidence that exposure to MarVib sound would impair the capability of marine invertebrates to detect underwater sound. However, a paper released as this report was being finalized describes injury to the auditory organs (statocysts) in four species of cephalopods exposed to moderately high levels of 50–400 Hz FM sound for 2 hr (André et al. in press). Similarly-handled control animals did not show this damage. Received levels averaged 157 dB re 1 µPa, with peak levels 175 dB. The sound exposure conditions differed in potentially important ways (e.g., enclosed tank; different frequency range, sweep pattern, duty cycle) from exposures that would occur during MarVib operations. However, given the new results, effects of MarVib sound on cephalopod hearing deserve specific study.

As with fishes (see § 6.4.3.2), rise time likely affects the potential for tissue injury to marine invertebrates. Airgun sound signals (at least in the close vicinity of the source) have more rapid rise times and higher peak amplitudes than do MarVib signals, and therefore are more likely to cause auditory impairment despite the longer durations and duty cycles of MarVib signals.

Changes to certain aspects of MarVib could potentially decrease the probability that MarVib sound would impair sound detection by marine invertebrates. In most if not all respects, design changes that would be optimum with regard to reducing auditory impairment in fishes (§ 6.4.3.2) are also likely to be optimum in reducing sound detection effects in marine invertebrates.

6.5.4 Other Injury or Physiological Effects

6.5.4.1 Airguns

Non-auditory Physical Injury.—To date, only the early life stages of snow crab and Dungeness crab (*Cancer magister)* have been studied. Christian et al. (2003) reported that multiple exposures to strong sound from a 7-airgun array affected the development rate of snow crab embryos. Significantly more of the exposed embryos exhibited delayed development compared with the control embryos. In addition, a significantly higher mortality rate was observed in the exposed embryos compared with the control embryos. The received SPL was 221 dB re 1 $\mu Pa_{0\text{-}p}$. However, this study was limited by the fact that all fertilized eggs were taken from a single female crab. Another study involved multiple exposures of egg-bearing female snow crabs to airgun sound produced during a full commercial seismic survey (DFOC 2004a,b). The received SPL was considerably lower, 190 dB re $1\mu Pa_{RMS}$. Subsequent analyses of the snow crab embryos and resulting larvae did not indicate any significant impact from the exposure. Also, stage II Dungeness crab larvae exposed at close range to single discharges from an airgun array did not exhibit either acute or chronic mortality, or changes to development rate, relative to control eggs and larvae (Pearson et al. 1994). In that study, the mean received SPL was 234 dB re $1\mu Pa_{0\text{-}p}$.

The potential for airgun sound to cause non-auditory physical injury to *juvenile and adult stages* of marine invertebrates has also had only limited study. Only snow crab, American lobster, and squid have been studied to date. Adult male snow crabs were exposed to multiple discharges from a 7-airgun array, with some crabs as close as 2 m to an airgun and with a received SPL of 221 dB re 1µPa_{0-p} (Christian et al. 2003, 2004). No acute or chronic sub-lethal injury or mortality was observed. Female snow crabs exposed to multiple discharges from an airgun array used during a full commercial seismic survey (received SPL of 190 dB re 1µPa_{RMS}) also did not exhibit acute or chronic sub-lethal injury or mortality that could be attributed to exposure to airgun sound (DFOC 2004a,b). Adult American lobsters exposed to multiple airgun discharges (received SPL of 227 dB re 1µPa_{p-p}) did not exhibit any acute or chronic mortality effects or damage to the mechanosensory systems (Payne et al. 2007). McCauley et al. (2000a,b) exposed caged squid and cuttlefish to multiple exposures from a single airgun (received SPLs of 156–174 dB re 1µPa_{RMS}) and did not observe sub-lethal injury or mortality as a result of the exposures. However, the possibility that airgun sounds might affect cephalopods warrants further consideration given circumstantial reports of increased mortality and tissue damage in giant squid when airgun-based seismic surveys were underway in the area (A. Guerra et al., *in* André et al. in press).

In summary, most studies to date on the potential for airgun sound to cause physical injury to either eggs and larvae or to juvenile and adult life stages of marine invertebrates have found little (if any) effect, even upon close exposure to airguns.

Physiological Effects.—Serum biochemistry analyses have been performed on snow crabs and American lobsters exposed at close range to multiple discharges from airguns (received SPLs 221–227 dB re 1µPa_{0-p}). Christian et al. (2003, 2004) measured changes in the haemolymph refractive index (measure of solutes), serum levels of proteins and enzymes, and relative numbers of haemocyte types in adult snow crabs exposed to airgun sound. No acute or chronic effects were observed. Similar biochemical analyses were conducted on adult lobsters exposed to airgun sound (Payne et al. 2007). Subtle sub-lethal effects were observed but these primary and secondary stress responses were temporary.

6.5.4.2 Marine Vibroseis

Linton (1995) examined Gulf white shrimp exposed to marine vibrator sound for any signs of injury. The MarVib used in the field tests was a hydraulically-driven loudspeaker that generated a fundamental frequency range of 5–200 Hz. The approximate peak SPL produced by the marine vibrator near the source was 214 dB re 1 µPa. Neither mortality nor physical damage was observed immediately following the 5-sweep exposure. At 1-hr post-exposure, 10 of the 60 exposed shrimp had died but the mortality could not be definitively linked to MarVib as there was also mortality in control shrimp. No further mortality was noted during the remainder of the 24-hr observation period.

As with fishes (see § 6.4.4.2), rise time is likely critical in affecting the potential for a seismic signal to cause tissue injury to marine invertebrates. Airgun sounds (at least in the close vicinity of the source) have more rapid rise times and higher peak amplitudes than do MarVib sounds. Therefore, airgun sounds likely have more potential than MarVib to cause non-auditory injury or physiological effects in marine invertebrates despite the longer durations and duty cycles of MarVib signals.

In most if not all respects, design changes that would be optimum with regard to reducing non-auditory injury or physiological effects in fishes (§ 6.4.4.2) are also likely to be optimum in reducing similar effects in marine invertebrates.

6.5.5 Summary for Invertebrates

Available empirical information on how exposure to MarVib sound affects marine invertebrates is even more limited than that for fishes. The only specific data are from a single study involving exposure of marine invertebrates to sound from an early design of MarVib. Linton (1995) subjected Gulf white shrimp to multiple exposures of MarVib sound and did not observe either disturbance effects or non-auditory injury. The reported source sound pressure level in this study was 214 dB re 1 μPa$_{0\text{-}p}$. No empirical information is available concerning either masking or sensory impairment in marine invertebrates exposed to MarVib sound. For airguns, as for MarVib, only disturbance effects and non-auditory injury/physiological effects have been observed in exposure studies of invertebrates. However, the possibility of auditory damage in cephalopods exposed to MarVib sound deserves study given a recent report of auditory injury in captive cephalopods exposed to prolonged low-frequency FM sound (André et al. in press).

In general, MarVib sound might theoretically cause more masking of sounds relevant to marine invertebrates than would airgun sound (because of the longer signal duration and higher duty cycle of MarVib sound). However, MarVib sound is less likely to cause disturbance of marine invertebrates, impairment of their sound detection abilities, or non-auditory injury/physiological effects. Altering some specific design features of MarVib systems, where possible, could also lower their potential to cause effects on marine invertebrates (insofar as these might occur with any MarVib system). Desirable changes would be to decrease signal duration and/or increase the intervals between signals (i.e., decrease duty cycle), if that can be done without increasing source level, and to suppress higher frequency components. Adjustment of the operating depth of the marine vibrator might also be helpful, but the optimum depth would depend on the specific circumstances of the planned seismic survey. Overall, MarVib sound would likely have less effect on marine invertebrates as compared with airgun sound.

Effects of MarVib sound on the prey and predators of marine invertebrates would, to the extent they occur, be indirect effects. The potential effects of exposure to MarVib on prey of marine invertebrates (i.e., on fishes and other marine invertebrates) is addressed in the preceding section on fishes and in this current section. Similarly, discussion of the potential effects of exposure to MarVib on predators of marine invertebrates (on marine mammals, sea turtles, fishes, and other marine invertebrates) is provided in preceding sections on marine mammals, sea turtles and fishes, and in the current section.

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CHAPTER 7. MITIGATION MEASURES

7.1 INTRODUCTION

Measures to reduce the effects of seismic survey sound (usually airgun sound) on marine animals are employed by many seismic operators and are required in various jurisdictions. These measures are most commonly designed to reduce known or presumed effects on marine mammals, but measures to reduce effects on sea turtles and fish (or fishing) are sometimes applied.

The specific objectives of mitigation vary from one operator and jurisdiction to another, and can include measures intended to accomplish one or more of the following:

- reduce or avoid the number of animals close to the sound source that are subject to possible physical injury (auditory or otherwise);
- reduce the number of animals that are disturbed (or displaced) to some degree, e.g., disturbed sufficiently to have a negative effect on important biological activities such as feeding or breeding;
- reduce or avoid negative effects on the number of fish or economically-important invertebrates caught in fisheries.

The objectives of this chapter are

- to outline and evaluate mitigation measures specific to MarVib systems that could be adopted to minimise impacts from "next generation" marine vibrators;
- briefly describe mitigation measures that are currently used during airgun-based seismic programs and comment on their effectiveness in mitigating airgun effects and (potentially) MarVib effects;
- evaluate the need for mitigation during "next generation" marine vibroseis projects compared to that during airgun-based projects; and
- discuss possible combinations of mitigation measures that might be appropriate and effective in reducing impacts well below those with airguns without incorporating techniques of marginal benefit.

7.2 POSSIBLE MITIGATION MEASURES SPECIFIC TO MARINE VIBROSEIS

7.2.1 Source and Received Pressure Levels

As discussed in Chapters 4 and 6 and summarized above, an inherent benefit of any MarVib system is that its source pressure level would be lower than that of an airgun array. The concept of source level is somewhat abstract and complex when dealing with a distributed source such as an array of airguns or an array of MarVib units (see Chapter 1). Also, source level is normally quoted on a peak or peak-to-peak basis for an impulsive source like an airgun array, but on an RMS basis for a non-pulse source such as marine vibroseis. A further complication is that the required RMS source level of the MarVib array would depend on the selected signal duration and other factors. However, for purposes of this assessment, we assume that a typical airgun array (as described in § 4.2) would have a pk–pk source level of about 112 bar-m or 261 dB re 1 μPa @ 1 m and a peak pressure level of ~256 dB re 1 μPa @ 1 m. In contrast, a MarVib array with comparable source energy level of ~235 dB re 1 $\mu Pa^2 \cdot sec$ @ 1 m would have a nominal source level 226–232 dB re 1 μPa_{RMS}, depending on signal duration (within the 2–8 sec range). The corresponding nominal pk–pk source levels for the MarVib would be 235–241 dB re 1 µPa @ 1 m (RMS + 9 dB), or 229–235 dB peak (RMS + 3 dB), as compared with the aforementioned 261 dB pk-pk and 256 dB peak for the airgun array.

As compared with an airgun array, a MarVib source would (at any specific distance) produce a lower peak pressure level and a lower RMS pressure level as measured over the durations of the respective signals. To the extent that biological effects are a function of received sound pressure level, effects of the MarVib system should (for that reason alone) be substantially reduced with a MarVib source relative to airguns. At least for auditory effects, the effects of MarVib relative to airgun signals would be further reduced because of the slower rise time.

However, in marine mammals (and probably at least some other animals), auditory impairment effects that occur at high exposure levels (close distances) are expected to be more directly a function of cumulative sound exposure level, i.e., total amount of acoustic energy received, than of received pressure level (Southall et al. 2007). To meet the geophysical objectives, MarVib transmissions at a given location would be longer in duration than is a single airgun shot (seconds vs. milliseconds). To a first approximation, the MarVib may emit a similar amount of energy per "shotpoint" as would an airgun system. Some reduction in the required energy per location may be possible if signal processing is more efficient for MarVib signals than for airguns and if signal components above ~100 Hz can be better suppressed with MarVib systems. It will be beneficial for MarVib designers to incorporate both of these mitigation measures to the extent possible. Even so, the longer duration of each transmission with MarVib than with airguns would reduce the environmental benefits of a MarVib source relative to those that might be expected on a pressure basis alone if (as expected) received energy is a key indicator of some biological effects.

Although auditory effects in marine mammals are believed to be more directly related to received energy than to received pressure, and by extension the same might be true in some other types of marine animals, there is little evidence one way or the other for most types of animals. Also, for marine mammals, there is little available information about the relative importance of received energy vs. pressure in eliciting disturbance (behavioral) effects or masking effects (Chapter 6). Particularly for masking, it would be reasonable to expect the received pressure level to be the key variable.

These uncertainties regarding the most relevant metric are important, as the need for additional mitigation measures (beyond the lower pressure levels and slower rise times inherent with MarVib) would be greater if some biological effects are more directly related to received energy. If pressure is the relevant measure, MarVib systems have an immediate and large benefit given their lower source pressure level and lower received level at any given distance, and there is likely to be less need for specific mitigation measures than is true with airguns. If energy is the key metric, then MarVib systems have less immediate advantage over airguns. However, even if received acoustic energy is considered to be the relevant metric for at least some biological effects, such as auditory effects on marine mammals, a MarVib system would have advantages related to the non-impulsive nature of MarVib sound, reduction in higher-frequency components, and (if possible) a somewhat reduced source energy level.

7.2.2 Impact Criteria for Non-Pulsed Sound

MarVib sound is "non-pulse" in nature, whereas airgun sound is impulsive, at least near the source (§ 1.3). In cetaceans, the onset of Temporary Threshold Shift (TTS), i.e., temporary hearing impairment, has been found to occur at a higher sound exposure level if the sound is non-pulse than if it is impulsive. Although the data (especially for impulsive sound) are limited, TTS onset in some odontocetes appears to occur at a received energy level about 12 dB higher for non-pulse than for impulse sound (195 vs. 183 dB re 1 μPa^2•sec; Finneran et al. 2002, 2005; Southall et al. 2007). Similar differences are known to occur in terrestrial animals. Also, based on data from terrestrial animals, the onset of Permanent Threshold Shift (PTS), i.e., permanent hearing impairment (auditory injury) in cetaceans, is believed to occur at a received level ~17 dB higher for non-pulse than for impulse sound (215 vs. 198 dB re 1 μPa^2•sec; Southall et al. 2007). This ~17 dB difference in the assumed cumulative energy level required for onset of PTS means that, for a given source energy level, a marine mammal would need to be much closer to the trackline to incur auditory injury from a MarVib source than from an airgun source if the source energy level is the same for MarVib and airgun systems. Therefore, the number of marine mammals that might incur auditory injury from a MarVib survey would be substantially lower than that expected from a corresponding airgun survey in any situation where the latter (airgun) number is sufficiently high to be of concern. To the extent that MarVib systems can be design to operate at source energy levels lower than required with airguns, the impacts of the MarVib systems would be further reduced relative to airguns.

This issue was addressed quantitatively via acoustic and exposure modelling in § 5.6.2 and in Table 6.3. The modelling results show that, for seismic survey scenarios in the northern Gulf of Mexico, numbers of cetaceans (of three representative species) that might receive sufficient sound energy to have some potential to cause hearing damage were predicted to be very low for MarVib: <1 bottlenose dolphin, for example. With an airgun array producing the same source energy level per shotpoint, the corresponding numbers were also low, but higher than for MarVib: 1–12 bottlenose dolphins, depending on the assumed site. The difference was the result of the different auditory injury criterion assumed for cetaceans exposed to non-pulse vs. impulse sound: a cumulative sound exposure level of 215 vs. 198 dB re 1 μPa^2•sec. These predictions do not allow for either avoidance effects, which would reduce the predicted numbers, or for attraction effects (e.g., bowriding), which might increase those numbers.

Another way to express the general point is that the mitigation radius for a MarVib survey would be significantly less than that for a corresponding airgun survey even if received acoustic energy is the relevant metric, as is likely for auditory impairment. For any biological effect that is more closely related to received sound pressure than to received energy, the reduction in mitigation radius with a MarVib system would be larger.

7.2.3 Signal Duration and Duty Cycle

A MarVib survey would employ signals of longer duration (but lower source pressure level) than would a corresponding airgun survey. As noted above, the total energy per signal is expected to be generally similar during MarVib and airgun surveys, although perhaps somewhat lower with MarVibs if unnecessary components above ~100 Hz are better suppressed by MarVib systems, and if enhanced signal processing applicable with MarVib allow extraction of the required geophysical data with less signal energy.

It is assumed that MarVib signal duration could be adjusted, within limits, to shorter signals with higher source levels or to longer signals with lower source levels, maintaining a more-or-less constant signal energy. The potential advantages and disadvantages of shorter (but higher-level) signals as compared with longer (but lower-level) signals were summarized in Chapter 6 for various possible categories of effect (masking, disturbance, auditory impairment) in each of four types of marine animals (marine mammals, sea turtles, fish, invertebrates). The interpretations summarized there are speculative, given the lack of specific data on MarVib effects and the generally limited data on airgun effects. However, those sections provide some indication of the tradeoffs that should be considered in setting the signal duration, and are drawn together here:

Masking: Reduction of signal duration and of duty cycle would reduce masking, and could be beneficial to low-frequency specialists such as baleen whales, sea turtles, and many fish. However, if the source level must be increased during the shorter transmissions (to maintain constant total signal energy), this would increase the severity and extent of the masking effect during the reduced-duration transmissions, and would partially offset the advantage of shorter transmissions. Until more data are available, short or at most medium duration signals seem preferable with regard to masking.

Disturbance: If the signal level would be increased upward if duration were reduced, or downward if duration were increased, then the implications for disturbance would depend whether responsiveness is a function of received sound level or some combination of level and duration (e.g., received sound energy). If responsiveness is more closely related to received pressure level, then disturbance (especially of low-frequency specialists) would be reduced if the signals were longer and lower in level (e.g., Fig. 6.2). If responsiveness is more closely related to received signal energy, then adjustments to signal duration (with offsetting changes in signal level) would have little effect on responsiveness. Until more data are available, medium or long duration signals seem preferable with regard to disturbance (assuming source level will be reduced if duration is increased). If source level would be the same regardless of duration, then short duration would be preferable.

Auditory Impairment: Assuming that signal level would be inversely related to signal duration, and that auditory impairment (at least in marine mammals) is more directly related to received signal energy than to duration, upward or downward adjustments in signal duration and duty cycle probably would make little difference to the auditory effects. Also, because close proximity to the source is necessary for there to be auditory effects, numbers of animals that might incur these effects would be small (e.g., § 6.2.5), and mitigation for auditory effects may be a lower priority than mitigation for masking or disturbance. Notwithstanding this, if do-not-exceed requirements specified by regulators are expressed as sound pressure levels (e.g., the U.S. 180 and 190 dB re 1 μPa_{RMS} criteria for cetaceans and pinnipeds, respectively), there will be some <u>apparent</u> advantage to operating with longer, lower-level signals. That will result in fewer animals being exposed to ≥180 or 190 dB (e.g., Fig. 6.3), even though received energy levels and actual auditory effects are expected to be little different than would occur with shorter, higher-level signals.

Other Injury or Physiological Effects: In the unlikely event that the type of MarVib signal selected for use tends to induce resonance in some animals, shorter signals with lower duty cycle would be preferable—particularly if source level can be kept constant without regard to signal duration. However, selecting a signal type that does not induce resonance will be important (see §7.2.5, below). Also, source level probably will need to be increased if signal duration is reduced. Thus, reduced signal duration and duty cycle may convey no strong advantage with regard to non-auditory injury or physiological effects.

Summary: Reduced signal duration and duty cycle would be beneficial in reducing masking; increased signal duration (with associated lower source pressure level) might or might not be beneficial in reducing disturbance. Until specific data about the dependence of the various types of biological effects on MarVib design parameters are available, it would probably be best to operate with a moderate signal duration and with the lowest practical source level and duty cycle.

7.2.4 Signal Frequency

As compared with an airgun array, a next-generation MarVib source is expected to emit less energy (both proportionally and in absolute terms) at frequencies above those useful for geophysical purposes (§ 4.6). The frequency above which the output of a future MarVib source would start to diminish is somewhat uncertain as yet. However, in consultation with the JIP's Project Support Group for this project, we assumed a nominal inflection point of 100 Hz, above which MarVib output was considered to diminish progressively. Better suppression of components above 100 Hz (or some similar frequency) is expected to have relatively little benefit to species most sensitive to the strong MarVib (or airgun) components below 100 Hz, but considerable benefit to species relatively insensitive to low frequencies, such as toothed whales (§ 4.6). There would be an intermediate benefit to species with "intermediate" hearing, such as pinnipeds (§ 4.6). For the modelling work summarized in § 5.6 and § 6.2.5–6.2.7, we compared numbers of marine mammals that might be exposed to specified amounts of sound if the MarVib output above 100 Hz diminished at (alternatively) 10 dB, 30 dB, or 50 dB per octave (doubling of frequency). It is assumed that a future MarVib system would have a rolloff rate of at least 30 dB per octave, and possibly more.

The likely effects of reduced source output above 100 Hz (or a similar cutoff frequency) for the four major taxonomic groups considered in this analysis are summarized in § 6.2–6.5. Although specific empirical data concerning the effect of rolloff rate on the biological effects are lacking, a higher rolloff rate has the potential for substantial benefits (especially for "high frequency" specialists), and there are no known negative effects of a higher rolloff rate. Even the low- and intermediate-frequency specialists (e.g., baleen whales; pinnipeds; sea turtles, most fish and invertebrates) would benefit if signal components in the 100–1000 Hz band were reduced in strength, either by changing from airguns to a modern MarVib system with high rolloff rate above ~100 Hz, or by designing the MarVib to have a higher rolloff rate. The 100–1000 Hz band is within the band of optimum hearing for most low- and intermediate-frequency specialists, so better suppression of sound components within that band would be expected to reduce masking, disturbance, and auditory effects of a seismic survey on those animals. For the high-frequency specialists, most of the effect of a seismic survey is likely attributable to the components above 100 Hz, and better suppression of those components would be especially advantageous for them. The strong benefits of a higher rolloff rate to high-frequency specialists like the toothed whales (and the lesser benefits to low-frequency specialists like baleen whales) are illustrated quantitatively by the AIM modelling summarized in § 6.2.5 and § 6.2.6.

If the MarVib system could be designed such that the rolloff begins at a frequency lower than 100 Hz, that would further reduce the numbers of animals that would receive an effective (frequency-weighted) sound level above any specific level of concern. The degree of benefit would depend on the species. The benefit would presumably be least (and possibly zero) for species that use very low frequency (in some cases infrasonic) sounds, e.g., blue or fin whales. The greatest benefits from shifting the inflection point downward from 100 Hz to some lower frequency would presumably accrue to other low-frequency specialists whose calls and hearing are tuned to frequencies that are low by most standards, but above the inflection point in the MarVib spectrum (e.g., most other baleen whales, sea turtles, various fish, etc.).

7.2.5 Signal Type

Earlier MarVib designs used frequency-modulated (FM) signals, i.e., upsweeps, but geophysicists are interested in the possibility of using pseudo-random noise (PRN) signals or other similar coded signals in future MarVib designs. Although it is beyond the scope of this assessment to address the advantages and disadvantages of different signal types for geophysical purposes, PRN signals may provide some signal-processing advantages. That, in turn, might allow a MarVib system to operate with a lower source level, shorter signal duration, or lower duty cycle, any of which could be advantageous from an environmental impact perspective. However, in animals sensitive to low-frequency sound (e.g., baleen whales), masking and disturbance effects of low-frequency PRN signals may be greater than corresponding effects from FM signals (see § 6.2.4.2 and § 6.2.5.2, summarizing Clark 2009; Ellison 2010). In the absence of

- specific empirical data on the effects of signal type (and level) on masking and disturbance, and
- information about relative source levels and duty cycles that would be necessary with PRN vs. FM signals,

it is not possible to provide a definitive assessment as to which signal type (PRN or FM) would have less masking, disturbance, or auditory effect. If MarVib designers have the option of using either PRN or FM signals, then before they choose which signal type to use, it would be desirable to obtain empirical data on the relative biological effects associated with each of these signal types.

Any signal type that might tend to elicit resonance of air-filled body cavities or other structures should be avoided. There are few specific data on resonance-induced damage to marine animals (see Gentry [ed.] 2002 for review). However, natural resonant frequency varies with the size of the lungs (in mammals) or swim bladder (in certain fish), and that depends on body size and on depth in the water column. The natural resonant frequencies of marine mammal lungs are in the low frequency range. There is some concern about the possibility that, depending on the signal type used, MarVib sources might elicit resonance in marine mammals (and perhaps large fishes) under some conditions (§ 6.5.4). There are very few specific data on resonance in marine animals. In theory, resonance tends to occur when the wavelength of the sound signal is an integer multiple of a principal dimension of the cavity, and when the sound continues for long enough to excite oscillation of the cavity and nearby tissue. A PRN signal does not have any one predominant wavelength and it would not be expected to elicit resonance. An FM sweep signal might start to elicit resonance as the frequency sweeps past the resonant frequency of the body cavity, but resonance is unlikely to be fully established or sustained given the constantly changing frequency. The most problematic type of signal, from the perspective of resonance, would presumably be a constant-frequency (CF) signal that is sustained at a resonant frequency. We emphasize that these comments about resonance are speculative. Research on resonance effects of proposed MarVib signals would be desirable, especially if CF signals are considered for use in MarVib systems.

7.2.6 Source Depth

The range of possible deployment depths for a MarVib source appears to be greater than that for airguns (Tenghamn *in* Okeanos 2010). Airguns must, for physical reasons, be operated within a fairly narrow range of near-surface depths. If a MarVib source could be operated effectively at deeper depths, this would provide additional options to consider in attempting to minimize the impact of a specific seismic survey. This is discussed briefly in § 6.2.4.2 in the context of marine mammals and masking, but similar considerations apply for other types of biological effects and other types of marine animals.

Depending on the sound propagation conditions at the location and time of the seismic survey, and on the depth distribution of the animals of concern, a change in operating depth could result in increased, decreased, or unchanged biological effects. To optimize the source depth for minimal biological effects (within the range of practical source depths), a site- and season-specific evaluation would be needed, probably with the aid of sound propagation modelling allowing for local conditions. No specific operating depth will be optimum for all places and seasons. Also, different types of animals have varying depth distributions, so it is to be expected that the optimum source depths for the various important species will vary. In that case, it would be necessary to consider the relative benefits and costs of different potential operating depths. At this time it is unclear how beneficial it would be to adjust source depth within the range that is practical. Again, this would probably depend on the specific location and time, and in particular on the degree of variation in the depth distributions of the main species of concern.

7.3 APPLICATION OF MITIGATION MEASURES CURRENTLY USED WITH AIRGUNS

7.3.1 Pre-Project Planning

Pre-project planning, in terms of seasonal timing, line locations and orientations (when flexible), source array design, etc., is considered a standard approach to mitigate potential impacts of seismic surveys prior to full commitment of resources to a specific project. The geophysics requirements obviously limit the adjustments that can be made. However, it is usually possible to make adjustments of some of these types if the need for them is recognized sufficiently early in the planning process. Pre-project planning measures often considered in advance of *airgun-based surveys* include the following:

- select the smallest source array that can meet the geophysical objectives, and employ only a subset of the source elements (airguns in present surveys) if and when the full array is not required;
- minimise the number of lines, shots, and line repetition; increase shot spacing when possible;
- deploy the source array at as shallow a depth as possible;
- identify the locations and timing of use of sensitive biological areas (e.g., areas where marine mammals breed and calve or where fish congregate to spawn), and schedule the survey to avoid periods of intensive or sensitive use; and
- establish mitigation distances using appropriate impact criteria and a well-accepted and validated propagation model that takes account of empirical site-specific environmental data (e.g., vertical sound speed profile for the planned season of operation, bathymetry, and bottom composition) to predict expected received sound levels as a function of distance and direction from the array.

At least in theory, all of these measures (or somewhat amended versions of them) could also be considered in planning a *MarVib-based seismic survey*. However, the best way to implement some of these measures is likely to differ somewhat for MarVib vs. airgun sources, or to be unclear until certain data gaps are filled:

- Depending on the range of depths at which MarVib source could be operated, it is possible that (in some situations) impacts might be reduced by operating the MarVib source at a deeper-than-standard rather than shallower-than-standard depth (see § 7.2.6, above).
- To guard against the possibility of auditory impairment to marine mammals, it is reasonable (as an initial approach) to apply the energy-based injury criteria recommended by Southall et al. (2007). That approach will predict considerably shorter mitigation distances for MarVib than for airguns given the different criteria proposed for non-pulse sound vs. impulsive sound (see Table 6.1 *in* § 6.2.2.1).
- The present uncertainty about levels of MarVib sound that would elicit significant disturbance in marine mammals (§ 6.2.5.2) is problematic if, in some jurisdictions, there is a requirement to limit numbers of animals that would be disturbed. There is a need for research concerning animal reactions to MarVib sound as a function of received sound level and context.

7.3.2 Measures Applied During Operations

7.3.2.1 Sound Source Verification

In some seismic surveys using airgun arrays, there is a regulatory requirement to obtain site- and season-specific measurements of sound levels at various distances and directions from the sound source immediately before or during the early stages of the project. These measurements are often used to supplement and verify earlier model predictions of sound levels vs. distance, and to verify or refine mitigation distances. Assuming that specific mitigation criteria will eventually be specified by regulators for MarVib surveys, there may be a similar requirement to measure MarVib sound levels and to verify or refine mitigation distances. If these distances are based on an auditory impairment criterion, then they are expected to be smaller than corresponding distances for airgun-based surveys.

Given the costs and time required to conduct sound source verification work, and the smaller mitigation radii anticipated to occur with MarVib sources, MarVib operators might sometimes find it advantageous to accept mitigation radii with built-in precautionary factors if (by doing so) they did not need to perform sound source verification. For example, with a MarVib project, it might be acceptable to all concerned to use mitigation radii 2× the (presumably) short distances predicted by a model. In contrast, with an airgun project, mitigation radii with that safety factor might be too large to be practical, making it important to conduct the sound source verification.

7.3.2.2 Visual Observations

Visual observations are essential as a basis for implementing real-time mitigation measures (e.g., shut downs and power downs, as often applied during airgun-based surveys). Visual observation protocol generally includes

- one or two trained or experienced observers on watch before and during all daylight seismic operations, and preferably during non-seismic periods to provide comparative data on sighting rates, behaviour, etc., at times with and without airgun operations;
- an unobstructed or minimally obstructed 360º view around the vessel from the highest suitable vantage point available (e.g., the flying bridge or bridge), and in particular, a clear view of the area immediately around the airgun array and in front of the bow if the latter area is within the mitigation distance
- use of handheld reticle binoculars, and
- in some cases use of Big Eye (25×) or similar high-power binoculars, especially during large-source surveys and/or if the mitigation distance is ≥1 km.

The same methods could be applied during a MarVib-based survey. However, the mitigation distance is expected to be substantially reduced during a MarVib survey, and the number of animals potentially susceptible to hearing impairment would be considerably lower with MarVibs (e.g., Table 6.3 *in* § 6.2.6.3). Therefore, it would be logical for visual observation requirements to be reduced during at least some MarVib surveys relative to those needed during a corresponding airgun survey. For example, with a notably shorter mitigation distance, there could be more situations where it could be deemed sufficient to have one rather than two observers on watch, or to employ only handheld reticle binoculars and not Big-Eye binoculars.

For the same reasons, there should be fewer situations (during a MarVib survey) when additional special restrictions would be considered necessary. For example, in some airgun projects where poor visibility triggers a requirement for PAM or restrictions on startups (see below), these restrictions might be reduced or eliminated if a MarVib system with shorter mitigation distances and fewer projected 'takes' were used.

7.3.2.3 Passive Acoustic Monitoring (PAM)

Passive Acoustic Monitoring (PAM) is increasingly used on seimic vessels or associated scout vessels to monitor for calling cetaceans. The utility of basic PAM systems applied aboard some seismic ships is limited because it is difficult and generally not possible to obtain specific location information via a single linear and typically short hydrophone array towed from a non-manoeuvrable vessel. These limitations can be resolved with more elaborate equipment and procedures, but in practice this has not normally (to date) been done. However, using visual observations and even a basic PAM system in combination can increase the number of detections of many species of cetaceans, particularly odontocetes. The main real-time value of PAM, as currently implemented, is in cueing the visual observer to the presence (and sometimes bearing) of the cetacean. During periods of darkness, fog, or heavy rain, when visual observation is not effective, PAM is the only method of detecting cetaceans beyond a very few hundred metres from the seismic vessel. In some situations, regulators have required that PAM be used if source operations are to continue during times of poor visibility, or before airguns can be started up (from a full shut-down) during times of poor visibility. The value of PAM could be enhanced if more capable PAM systems were used.

The basic PAM equipment sometimes deployed from seismic vessels, while valuable in detecting some odontocetes that would be missed by visual observers, rarely detects baleen whale calls. That is probably attributable to • avoidance of the operating seismic vessel by some baleen whales (§ 6.2.5.1), • masking of weak low-frequency calls by continuous low-frequency propulsion noise from the seismic vessel, and • (to a lesser extent) masking of some calls by the intermittent airgun pulses. PAM also does not commonly detect pinniped calls, and it is not effective in detecting sea turtles or other types of biota.

PAM could (within limits) have the same role in detecting odontocetes during a MarVib-based seismic survey as with airguns. Mid- and high-frequency calls from odontocetes should be detectable even during transmission of low-frequency MarVib signals. PAM is likely to be even less effective in detecting baleen whale calls during a MarVib survey than it is during an airgun survey given that the low-frequency calls or call-components from baleen whales will be masked by low-frequency sounds for a higher proportion of the time during a MarVib survey. In practice, this may not make much difference as the basic PAM equipment currently deployed from some seismic vessels rarely detects baleen whale calls even during an airgun survey. The value of PAM during a MarVib survey will depend primarily on its usefulness in detecting and (ideally) localising odontocetes.

In general, during a MarVib-based survey as compared with an airgun survey, there will be less need for detection of marine mammals at long distances and there will be fewer occasions when undetected animals would be at risk of auditory injury (Table 6.3). Hence, the need for PAM should be reduced if a MarVib source is used.

7.3.2.4 Scout Vessels

During some seismic surveys with airguns, one or more scout (support) vessels are used to help mitigate acoustic effects (among other purposes). • In some cases, the scout vessel(s) travel ahead of (or ahead and to the side of) the source vessel to extend the area of visual monitoring coverage and to increase the probability of detecting marine animals of concern before they are exposed to high-level sounds (e.g., Johnson et al. 2007; Ireland et al. 2009). This would be most appropriate during seismic surveys involving some combination of large sound source, environmental conditions where sound propagation is efficient (and thus mitigation distances are large), and where there are special environmental sensitivities. • A scout vessel can also tow a PAM system while stationed ahead of the source vessel (or elsewhere) to improve detectability of calling cetaceans (e.g. Goold 1996). Besides providing acoustic coverage of an area somewhat farther from from the source vessel (e.g., well ahead), operating the PAM system from a separate vessel should improve detectability of cetacean calls. This is likely because of reduced masking by seismic signals (or their reverberations) when the PAM system is deployed farther from the seismic source, and potentially also through reduced masking by vessel noise (if the scout vessel's propulsion noise is quieter than that of the source vessel). • Another use of a vessel aside from the source vessel is to implement sound source verification measurements (see § 7.3.2.1, above), or to record received sound levels in sensitive habitats and to ensure that they are below designated thresholds (e.g., Johnson et al. 2007; Holst 2009:13). • Finally, a separate vessel also provides enhanced opportunities to obtain comparative data on densities and behaviour of animals in the general area but not in the immediate vicinity of the seismic source (e.g., Smultea et al. 2004; Ireland et al. 2009).

A scout vessel could fulfil the same functions during a seismic survey using MarVibs as the source. However, there is likely to be less need for a scout vessel during a MarVib survey given the reduced mitigation radii with MarVibs as opposed to airguns. Aside from the possible need for a support vessel to facilitate sound source verification work, the main reasons for using a scout vessel during an airgun-based project involve the potentially large mitigation radii during some airgun projects. With smaller mitigation radii during a MarVib project, there should be less need for a scout vessel.

7.3.2.5 Speed or Course Alteration

Regulatory authorities often state that, if a marine mammal or sea turtle is detected outside the mitigation radius but, based on its position and the relative motion, is likely to enter the mitigation distance as the seismic vessel advances, the vessel's speed and/or direct course should (if possible) be changed if this can be done with minimal effects on the geophysical objectives. However, aside from the loss of geophysical data that would result from diversion, seismic vessels are generally difficult to manoeuver on short notice, and sharp turns cannot usually be done because of the risk of entangling and damaging the airguns and/or streamers. Therefore, this commonly-specified mitigation measure is not widely applied during airgun-based surveys. It is likely to be similarly impractical during a MarVib-based survey.

7.3.2.6 Ramp-up Procedures

Ramp ups (also known as "soft starts), as applied during airgun-based seismic surveys, are intended • to alert animals to the presence of airguns, and • if airgun sound is aversive to those animals, to provide sufficient time for them to move away prior to exposure to high-level sounds. During an airgun-based survey, a ramp up generally begins by starting the smallest airgun in the array and subsequently starting other airguns sequentially. The ramp-up may be required to be over a specified period (usually 20–30 min) or such that the source level of the array increases in steps not exceeding ~6 dB per 5-min period until all airguns are firing. Before a ramp up, a pre-ramp-up observation period of specified duration (often 30 min) is implemented seeking to detect any marine mammals or sea turtles that may be in the mitigation zone.

The effectiveness of the ramp-up procedure in avoiding exposure to high-level airgun sound depends on the responsiveness of the animals to the onset of lower-level airgun sound. Single-airgun experiments with bowhead, gray, and humpback whales (reviewed in Richardson et al. 1995) have shown that those species do tend to move away when a single airgun starts firing nearby, which simulates the onset of a ramp up. For odontocetes, pinnipeds, and other marine animals, there is less evidence of avoidance in such conditions. The effectiveness of ramp-up as a mitigation method for species other than baleen whales exposed to airgun pulses is uncertain and probably quite variable.

With MarVib sources, ramp-up is technically possible at the start of a seismic line or in other situations when the sources have been silent for some extended period. Depending on the design of the MarVib source, ramp up could be achieved by adding source elements in sequence (as during a project using an airgun array). Alternatively or additionally, if the source level of each element is adjustable, as is likely, ramp up could be achieved via a gradual or stepwise increase in the power level being transmitted via individual MarVib sources.

One key question is whether ramp-up of a MarVib source would be useful in reducing auditory impairment or other biological effects. Given the considerably reduced radius of auditory effects anticipated during a MarVib survey and the lower numbers of animals (if any) that might incur auditory impairment, the need for and benefits of ramp up would be lower than during an airgun-based seismic survey. At least for initial MarVib projects, it might be advisable to apply a modelling approach similar to that in § 5.4–5.6 to predict, using project-specific information, the numbers of marine mammals and (if relevant) sea turtles that might be exposed to high-level MarVib sounds without and with use of ramp-up. Those predictions could be informative as a basis for discussions about the need for ramp-up procedures. Subsequent observations by on-board observers, and comparison with the model predictions, would be helpful in checking whether accurate predictions had been made, and in helping to make decisions about the need for ramp-up during subsequent MarVib surveys.

Another question is whether ramp-up of a MarVib source would be *effective* in reducing auditory impairment or other biological effects. Even for airgun arrays, relatively little is known about the effectiveness of ramp-up of as a mitigation measure, and there is no specific information of this type for MarVibs. Data on responsiveness of marine animals to other types of non-pulse sources somewhat similar to MarVibs are also very limited. However, those data suggest that―at least for baleen whales―there may be considerable tolerance (§ 6.2.5.2). The lack of specific data on marine mammal responsiveness to MarVib sound was previously identified as a key data gap insofar as disturbance effects of MarVibs are concerned (§ 6.2.5.3). It is also a data gap with regard to judging the effectiveness of ramp-up of MarVib sound as a mitigation measure.

7.3.2.7 Power-down and Shut-down Procedures

During airgun-based surveys in some jurisdictions, when a marine mammal or sea turtle is detected approaching a specified mitigation distance, visual observers call for airgun operations to be reduced to a smaller source ("power down") or suspended entirely ("shut down").

A power down involves decreasing the number of airguns in use, typically to one airgun.

- When a power down is initiated upon detecting a protected marine mammal or sea turtle nearby, the radius of the mitigation zone around the smaller source is much decreased relative to that around the full-size source. Marine mammals or turtles that might otherwise have been in or about to enter the mitigation zone around the full-size source will (in most cases) remain outside this smaller zone. In these cases, the power-down procedure either avoids or curtails exposure of a protected animal to a sound level in excess of a "do not exceed" criterion, without entirely suspending airgun operations. (A full shut down can cause operational problems; for example, in some jurisdictions, airgun operations cannot resume after a full shut down unless visibility is good or PAM is in use, whereas operations may be allowed to resume if a single airgun has operated throughout.)

- A power down can also occur when the vessel is moving from one seismic line to another (i.e., during a turn). In this case, the power down reduces ensonification of animals relative to what would occur if all airguns operated (unnecessarily) during the turn, but again avoids entirely shutting down the airguns and the operational restrictions that can ensue with a full shut down.

One or both of these types of power downs are employed as mitigation measures during airgun-based seismic surveys in some jurisdictions. Following a power down initiated because of proximity to a protected species of marine animal, airgun activity is not resumed until the animal is outside the mitigation zone.

Shut downs occur when all airguns are turned off to avoid further high-level exposure of marine mammals or sea turtles detected within (or about to enter) the mitigation zone. In some jurisdictions, there is no provision for power downs, and a full shut down is required whether or not powering down to a single airgun could avoid exposure to a sound level in excess of the do-not-exceed level. In jurisdictions where both procedures are used, the shut-down procedure is used in conjunction with power downs. If, either before or after a power down, an animal is detected within or about to enter the mitigation zone around the small source in use during a power down, a shut down is required.

The same procedures could, in theory, be applied during a seismic survey with a MarVib source. The appropriate mitigation radius around a MarVib source will be smaller than that around an airgun source suitable for the same situation. This is a consequence of the higher injury threshold with a non-pulse source like MarVib—see Table 6.1 and Southall et al. (2007). That being so, fewer power downs and/or shut downs should be necessary with MarVibs than with airguns. Also, in jurisdictions where power downs are acceptable in lieu of shut downs, very few (or no) shutdowns are likely to be needed. Even with airguns, only a low proportion of the encounters requiring a power down or shut down are close enough to need a shut down. Given the smaller mitigation radii with MarVibs, a shut down of a MarVib source should rarely be necessary if the power down procedure is allowed.

7.4 Relative Need for Mitigation with MarVib vs. Airguns

Many researchers and industry representatives have noted the need for scientific studies to establish the efficacy of mitigation measures employed during airgun-based seismic surveys (e.g., Barlow and Gisiner 2006; Dolman 2007; Weir and Dolman 2007). Given the scarcity of empirical data on mitigation effectiveness, there is much uncertainty regarding the efficacy of mitigation measures designed to minimize impacts of airgun sound on marine fauna. The uncertainties are compounded when dealing with MarVib sound, for which there is almost no operational experience. Further complicating the situation are the uncertainties about the amount of airgun and MarVib sound that would elicit specific biological effects, e.g., onset of TTS or PTS, or some level of disturbance, and about how best to quantify this sound, e.g., based on sound pressure level, cumulative energy (SEL), or some other measure.

Preceding sections assume that the injury criteria proposed by Southall et al. (2007) on an SEL basis provide meaningful guidance concerning levels of impulse (airgun) and non-pulse (MarVib) sound that could elicit onset of auditory impairment in cetaceans and pinnipeds. Those proposed criteria have their own substantial uncertainties. However, because of the physical differences between MarVib and airgun sound, it is reasonable to assume that animals can tolerate a higher SEL of MarVib sound than of airgun sound without incurring auditory impairment. Also, if some biological effects (e.g., disturbance) are more a function of received pressure than of cumulative received energy, a MarVib source would have a further advantage over airguns in causing less biological effects.

The acoustic modelling summarized in § 5.4–5.6 and in § 6.2.6.3 illustrates, for northern Gulf of Mexico scenarios, that even without specific mitigation measures, the number of marine mammals that might incur auditory damage from a MarVib survey is quite low in an absolute sense — fewer than one individual of any of the three representative cetacean species considered (Table 6.3). That was true with the 180 dB re 1 μPa_{RMS} do-not-exceed pressure criterion recognized by NMFS as well as with the more justifiable 215 dB re 1 $\mu Pa^2 \cdot sec$ SEL criterion recommended by Southall et al. (2007). With either criterion, the predicted numbers were higher during an airgun survey than with MarVibs (Table 6.3). The modelling results should not be interpreted to mean that specific mitigation of MarVib surveys would be unnecessary. The modelling involved many assumptions and uncertainties, and numbers affected would very likely be higher during some "larger" seismic surveys or during surveys in areas with more marine mammals. However, the modelling did support the intuitive indications that at least some of the effects of a MarVib survey may be low enough that there would be less need for specific mitigation than with airgun surveys.

One exception to this generalization is the matter of masking, which is expected to be more of a problem during MarVib surveys because the duty cycle is higher with MarVibs than with airguns (§ 6.2.4.2). The main concern would be for baleen whales and perhaps sea turtles and various fish — animals for which the most important sounds tend to be at low frequencies. MarVib operating and design procedures that would reduce masking may be important. General operating procedures that could be beneficial are for the most part the same as during an airgun survey (§ 7.3.1). Specific MarVib design considerations that might be helpful in reducing masking are addressed in § 6.2.4.2 and in §7.2. They include • reduce duty cycle (unless this would necessitate increasing source pressure level substantially); • suppress MarVib sound components outside the bandwidth relevant for geophysical purposes, e.g., those above 100 Hz, or a lower cutoff frequency if practical; • (tentatively) use FM signals rather than pseudo-random noise signals unless use of the latter allows a considerably lower source level; and • assess (probably via modelling) whether some practical adjustment of operating depth might reduce exposure of key species to MarVib sound in the circumstances of the planned survey.

7.5 Appropriate Combinations of Mitigation Measures

Although the need for mitigation measures may be somewhat reduced (in most respects) with MarVibs as compared with airguns, and specific biological effects of MarVib operations are largely unknown, it is reasonable and prudent to assume that some mitigation will be needed (and required by regulators).

The first (and arguably the most important) two categories of mitigation measures to consider should be those inherent to the design of the MarVib system (§ 7.2), and those that can be implemented during pre-project planning (§ 7.3.1). These measures have been addressed in previous sections and that discussion is not repeated here.

For some MarVib projects, those general measures, even without additional real-time monitoring and mitigation measures (§ 7.3.2), may reduce most biological effects to a level no higher than occurs during an airgun-based survey that incorporates real-time monitoring and mitigation. (Masking may be an exception to this generalization, given the possibility that it will be more of a problem with MarVib than with airgun sources, at least for baleen whales and perhaps sea turtles.) Nonetheless, it will be prudent to include (and regulators are likely to require) some real-time monitoring and mitigation as part of MarVib surveys at least until empirical data verifying the reduced biological effects with MarVibs become available from monitoring and/or systematic scientific studies. Even so, the expectation that auditory impairment and probably disturbance effects will be reduced with MarVib relative to airguns makes it reasonable to propose some reduction in real-time monitoring and mitigation effort relative to that expected for an otherwise-comparable airgun survey. Possible reductions could depend on the types of monitoring and mitigation that would currently be required for a corresponding airgun survey in that jurisdiction. However, most of the "measures applied during operations" (§ 7.3.2, above) could be considered for reduction or possibly elimination. For example, • the number of on-board observers might be reduced; • requirements for Big Eye binoculars, PAM, or observers on a scout vessel might be dropped (given the more limited mitigation radii); and • restrictions on starting up under limited visibility conditions might be relaxed (again given the limited mitigation radii).

Although there may in fact be less need for mitigation measures during a MarVib-based survey than during the type of airgun-based survey that would otherwise be needed, the scientific data needed to verify that are very incomplete at present. It will be in the interests of all concern to verify that MarVib surveys do have reduced biological effects. To do that, a two-pronged approach will probably be necessary. Some questions will be most effectively resolved by directed and systematic scientific investigations, with good scientific control, either under field conditions or with captive animals. Other questions will be most effectively resolved by systematic monitoring during actual MarVib operations. In order to acquire monitoring data suitable to address questions about biological effects as part of early MarVib projects, there will probably be situations where it will be advisable to provide for more intensive monitoring that might be needed if the only objective was the normal real-time mitigation. For example, during those early MarVib surveys, it might be desirable to include one or more extra observers, or to provide BigEye binoculars for long-distance observations even though they might not be necessary to meet the narrow mitigation objectives. More specific recommendations are provided in the following "Conclusions and Recommendations" chapter.

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CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

This chapter is intended to summarize the major findings of this assessment concerning the potential use of new-generation Marine Vibroseis as a seismic survey method. It also seeks to identify key data gaps that create important uncertainties concerning the effects of MarVib methods. The chapter begins with a brief summary of the conclusions with respect to four key questions listed in § 1.2, "Objectives and Need". It then summarizes the conclusions concerning a longer list of questions about MarVib, including the 12 topics specified by the JIP, listed in § 1.2 as items (a) through (l), as requiring consideration in this analysis. It concludes with a discussion concerning data gaps and recommended studies. Most of the topics addressed in this chapter have been treated in greater detail in earlier chapters, and the preceding detailed discussion is often cross-referenced rather than repeating the details here.

Four key questions identified early in the report were as follows:

(1) Is marine vibroseis—especially new-generation marine vibroseis—an environmentally viable and beneficial method of obtaining seismic data?

> Information included in Chapter 6, "Environmental Consequences", shows that MarVib methods implemented in the manner now anticipated, e.g., with unwanted higher-frequency components strongly suppressed, should in most respects have less environmental impact than surveys using airgun arrays. It is acknowledged that, given the scarcity of direct information on biological effects of MarVib (and similar) sounds, this conclusion depends strongly on indirect evidence. Also, one type of biological effect, masking, could be more of a problem with MarVib than with airguns. Masking and other effects of MarVib can be reduced through application of mitigation methods, in some cases closely related to those often applied during airgun-based surveys, and in other cases unique to MarVib (Chapter 7).

(2) Under what circumstances does marine vibroseis offer reduced environmental impact compared to airguns?

> Use of MarVib sources rather than airguns is expected to reduce most types of environmental impacts in all habitats and environments. Behavioral effects, auditory effects, and other physiological effects are all expected to be less with MarVib, regardless of water depth or other environmental conditions (Chapter 6). Masking of natural environmental sounds is the one type of effect that could at times be more problematic with MarVib if, as expected, the MarVib system operates at a higher duty cycle than applies with airgun arrays.

(3) Are the available data sufficient to determine whether marine vibroseis is environmentally beneficial?

> There have been almost no direct studies of the biological effects of MarVib operations. As a result, there are some key data gaps concerning possible biological effects, and several tentative conclusions about MarVib effects are supported by very meagre data. It is nonetheless possible to conclude that MarVib will (in most respects, masking being the likely exception) have reduced environmental impacts as compared to airguns. It is likely (and reasonable) that MarVib projects will, when first implemented, be subject to close scrutiny and to precautionary requirements. As scientific and monitoring data on the environmental effects of MarVib projects accumulate, some of these concerns and precautionary measures probably will be relaxed.

(4) If the data are not sufficient, what information needs to be gathered? What field tests will need to be conducted?

This topic is addressed in § 8.11, "Recommendations", later in this chapter.

Subsequent sections summarize the major conclusions in a more specific way. These sections include conclusions about each of the 12 topics of concern to the JIP, as listed as items (a), (b), (c), …, (l) in § 1.2. However, the sequence of those 12 topics has been reorganized, and conclusions concerning additional related topics are included.

8.2 Acoustic Footprint

The nominal source pressure levels of anticipated MarVib sources are expected to be substantially less than the nominal source pressure levels of airguns and airgun arrays that would currently be used in the same situation (Chapter 4). This will be possible because signal duration will be longer for a MarVib source, allowing the necessary geophysical data to be acquired with a lower source pressure level. Improvements in signal processing that may be achievable when using a well-controlled, coherently-operated MarVib source may also allow the use of a lower source level.

The source energy levels of anticipated MarVib sources are expected to be similar to those of airgun sources. For a given "shotpoint", roughly the same total energy output is expected to be necessary with a MarVib source as with an airgun source. For each "shotpoint", it is assumed that one or more signals with lower source level than an airgun pulse will be transmitted for a longer duration. Improvements in signal processing that may be achievable with a well-controlled MarVib source or via other MarVib design considerations may allow use of a somewhat lower source energy level than would be used with airguns, and this is desirable from an environmental impact perspective. However, the other conclusions in this assessment assume that the source energy level with MarVib will be generally similar to those with airguns. To the extent that a lower source energy level can be used, this would further reduce the environmental effects.

It is expected that received levels in various directions and and at various distances will follow a similar pattern – i.e., a lower received pressure level and similar (or only slightly lower) received energy level with MarVib as compared with airguns at a given distance and 3-D bearing. Both sources emit most of their energy at low frequencies, and we assume that propagation loss rates for the dominant low-frequency components will be similar for the two sources. Also, this assumes that those predominant low-frequency components will have relatively low directionality with both MarVib and airguns (§ 5.3). That is less certain, given present uncertainties about the specific configuration of source elements in a MarVib array.

The strongest components of future-generation MarVib sounds are expected to be at low frequencies — below 100 Hz, and possibly below some lower inflection frequency. Above that inflection point, it is expected that the spectrum levels of future-generation MarVib sounds will diminish (with increasing frequency) at a higher rate than occurs with airgun sound. A rolloff rate of at least 30 dB per octave (i.e., 30 dB per doubling of frequency) is expected, and it is hoped that a higher rolloff rate can be achieved. This would substantially reduce the biological effects, particularly on species that are most sensitive to higher frequency sounds, e.g., the odontocete cetaceans (§ 4.6; see also Fig. 6.2 and 6.3).

8.3 Overlap Between Hearing and MarVib Sounds

Baleen whales, sea turtles, many fish, and some invertebrates are believed to be most sensitive to relatively low-frequency (LF) sounds, including sounds at or near the predominant frequencies emitted by both airguns and anticipated MarVib systems (Chapter 3). Toothed whales (odontocetes) and some other fish and invertebrates are known or expected to be relatively insensitive to LF sounds. Pinniped sensitivity to LF sounds is intermediate, though the lack of specific data on hearing sensitivity in baleen whales makes the specific relationship of LF sensitivity in pinnipeds vs. baleen whales somewhat speculative. Sirenians (manatees, dugongs) may also have moderate sensitivity to LF sound. Underwater hearing sensitivity in polar bears and sea otters has not been measured. Based on this, it is expected that baleen whales, sea turtles, many fish species, and some invertebrate species are inherently more likely to be affected by either airgun or MarVib sounds than are other groups — especially odontocetes.

Better suppression of harmonics or other unneeded higher-frequency components of the MarVib signals (e.g., above 100 Hz) is expected to have relatively little benefit for baleen whales and other animals with sensitive low-frequency hearing, assuming that most of the effect on those animals is attributable to the predominant low-frequency components. (However, the lower levels of the MarVib signals at low frequencies would be a benefit.)

In contrast, better suppression of components above ~100 Hz would reduce effects on animals that are relatively insensitive to low frequencies but somewhat sensitive to frequencies in the 100–1000 Hz band. Airgun sounds include sufficient energy in that band such that odontocetes can hear (and at least potentially might be affected by) airgun sounds out to distances >10 km despite their relative insensitivity to the predominant low-frequency components of airgun sounds (§ 3.6). For example, there is empirical evidence that beluga whales sometimes show avoidance reactions out to distances beyond 10 km (Miller et al. 2005). Therefore, a reduction in the proportion of the sound output above 100 Hz, which is expected to be possible with a MarVib source, should reduce the effects on odontocetes and other animals sensitive to components of airgun sounds above ~100 Hz. This reduction in effect would be over and above any reduction achieved with the lower received pressure levels with a MarVib source.

8.4 Expected MarVib vs. Airgun Impacts, by Categories of Impact

Chapter 6 assessed relative effects of future-generation MarVib systems as compared with airgun arrays for each major type of biological effect (masking, disturbance, auditory, other injury, or physiological), considering marine mammals, sea turtles, marine fishes, and (more generally) invertebrates. For cetaceans, anticipated behavioral and auditory effects of MarVib vs. airgun surveys were examined in a more quantitative way by applying an acoustic modelling approach to deep and shallow water scenarios in the northern Gulf of Mexico (§ 6.2.5, 6.2.6). It should be kept in mind that there are no specific data concerning the effects of MarVib sounds on any marine animals aside from some very limited data for fish and shrimp. The following paragraphs summarize *predicted* MarVib effects and associated comparisons with airgun effects as described in Chapter 6.

Masking: This is the one type of biological effect that could be more of a problem with MarVib than with airguns (§ 6.2.4). Because of the expected higher duty cycle of MarVib signals, MarVib sounds will mask faint natural sounds for a higher proportion of the time than would occur with airguns, potentially out to a few tens of kilometres away at some times. Stronger sound signals would be masked only for receivers closer to the vibrators, and even the weaker sounds would be masked only when MarVib signals are being received, and then only when the spectra of the two overlap. Because of the instantaneous narrowband nature of FM sweeps, masking effects of MarVib should be limited if the MarVib signals are

FM in nature. Little is known about the effects of intermittent masking by low-frequency anthropogenic sounds on marine animals in the wild. However, this is a subject of increasing concern, at least for baleen whales (Clark et al. 2009) and perhaps for other animals whose hearing is most sensitive to low frequencies (e.g., sea turtles and many fish). Provided that future MarVib systems do not emit much sound above the frequencies useful for geophysicists, masking should not be a significant issue for odontocetes and perhaps not for other marine mammal groups aside from baleen whales. In a relative sense, however, for marine animals near the source, marine vibrators could potentially cause more masking of low-frequency sounds than would occur with airguns.

Disturbance: Behavioral disturbance effects from MarVib operations are expected to be no greater than those during airgun operations, and quite possibly less. There are no specific data on the responses of any of the main types of marine animals to MarVib signals, and for most types of animals data on responses to airgun signals are also sparse. If animal responses are most directly related to received pressure level, then reactions to MarVib surveys (with lower source pressure levels) should be considerably reduced relative to reactions to airguns. If animal responses are more directly related to received energy level than to pressure level, then responses to MarVib and airgun sources might extend to similar distances. Arguments for either possibility can be proposed (see Chapter 6), but the lack of data on behavioral responses of marine animals to MarVib sound is a data gap that needs to be filled before this will be resolved.

A further unknown in assessing potential disturbance is whether received sound levels should be frequency-weighted, e.g., using the M-weighting curves (Fig. 4.9; Southall et al. 2007) or possibly using the audiograms of the species concerned (Nedwell et al. 2007). If so, expected disturbance effects would be reduced for pinnipeds and especially odontocetes relative to baleen whales, and stronger suppression of components above ~100 Hz during MarVib surveys would reduce the expected effects from MarVibs vs. airguns. We expect that some form of frequency weighting is appropriate in predicting behavioral effects in marine mammals and probably also in other taxa. However, to date, the U.S. regulatory authority (NMFS) has required flat-weighting when predicting numbers of marine mammals that would be exposed to sufficient airgun sound to elicit behavioral disturbance.

Auditory Impairment: At least in marine mammals, temporary and permanent auditory impairment (TTS and PTS) are assumed to be mainly a function of cumulative received energy level. If so, the higher pressure levels of airgun sounds are largely offset by the longer signal duration of MarVib sounds. However, MarVib sounds would be non-pulse sounds whereas airgun sounds are impulsive, at least in the region close to the source where received levels are high. For a given received energy level, impulsive sounds are expected to have larger auditory and (in theory) tissue-damage effects, primarily because of the very rapid changes in pressure that occur at the onset of an impulse. Thus, even after allowing for the longer durations and higher duty cycles of MarVib sounds, auditory effects are expected to be reduced with MarVib, and to extend a lesser distance, as compared with a corresponding airgun source. For cetaceans and pinnipeds, the impulse vs. non-pulse difference has been quantified in the recommendations of Southall et al. (2007). They concluded that, to cause the same auditory effect in cetaceans, the cumulative received energy level of a non-pulse sound (e.g., MarVib) must be about 12–17 dB higher as compared with impulse (e.g., airgun) sound. Therefore, during a MarVib survey, a cetacean would have to be several times closer to the sound source in order to incur the same auditory effect (TTS or PTS) as might occur during an airgun survey emitting the same signal energy per “shotpoint”.

The specific distances out to which TTS or PTS might extend would depend on the circumstances. However, for the MarVib scenarios in the northern Gulf of Mexico examined in this assessment (§ 6.2.6.3), PTS would be limited to very close distances, if it occurs at all, and the number of individual animals that might incur PTS would be very small or zero. In the modelled scenarios, PTS is expected in <1 individual of each of the three representative species that were considered (sperm whale, bottlenose dolphin, Bryde's whale). In an actual seismic survey in which • some animals avoid the approaching seismic source and • real-time mitigation measures are implemented, even fewer cases of hearing impairment would be expected.

It has not been demonstrated that, in realistic field conditions, a MarVib source (or airguns) would cause TTS or PTS in any type of marine animal. For cetaceans and perhaps pinnipeds, it can be inferred from available data that TTS and (less likely) PTS might occur in the occasional animal that is very close to a MarVib source during at least one transmission. For sea turtles, fish, and invertebrates, it is unknown whether these auditory effects could occur in animals close to a MarVib source. If hearing impairment is possible, it would be limited to close distances. In the case of benthic-dwelling animals, this would mean that these theoretical auditory effects would only be possible in shallow water or if the source were towed close to the bottom.

Other Injury or Physiological Effects:

Of the various types of non-auditory injury or physiological problems that have been suggested, resonance effects are perhaps of most relevance. Given the longer duration of MarVib signals than of airgun pulses, there would be some concern about resonance of body cavities or structures in large animals if constant-frequency (CF) signals were used. However, MarVib signals are expected to be either FM sweeps or frequency-coded signals (pseudo-random noise, PRN). CF signals are unlikely to be suitable for use in a MarVib system, and in any case should be avoided if possible given the concern about resonance.

8.5 IMPACTS BY TYPE OF MARINE ANIMAL

There are no specific data concerning the effects of MarVib sounds on any marine animals aside from some very limited data for fish and shrimp. However, some of the likely effects of MarVib on various categories of animals can be predicted based on other related data and general biological and acoustic principles. The following paragraphs summarize the assessments described in Chapter 6.

Low-Frequency Cetaceans: The term "low-frequency (LF) cetaceans" is synonymous with baleen whales, which are assumed to be the marine mammals that are most reliant on LF sounds. As a group, their functional hearing range is believed to extend down to about 7 Hz (Southall et al. 2007), although specific audiometric data for any baleen whale remain lacking. Some species (e.g., blue and fin whales) emit many of their calls at frequencies around 16–20 Hz, and are presumably sensitive to those infrasonic frequencies. Although there are no specific data, effects of LF MarVib signals on baleen whales are expected to be stronger than for other marine mammals that are less well attuned to LF sound. MarVib operations are more likely to cause masking, behavioral disturbance, and (perhaps) auditory impairment in baleen whales than in other marine mammals. Masking and disturbance effects, in particular, may extend to greater distances in baleen whales than in other groups. The longer signal duration and higher duty cycle of MarVib than of airgun sounds could cause increased masking with MarVib. Suppression of the higher frequency components of MarVib sound (e.g., above 100 kHz) will provide little advantage to these whales, as most of the MarVib effect on them is expected to be attributable to the predominant LF components.

Mid-Frequency Cetaceans: This term is applied to most of the odontocetes or toothed whales, including sperm whales, beaked whales, most dolphins, and various others (see § 3.6). This term is to some degree a misnomer, as all members of this group are believed to be highly sensitive not only to mid-frequency but also to high-frequency sounds, extending upward to 100 kHz or above. The predominant low-frequency (<100 Hz) components of MarVib signals are expected to have relatively little masking, disturbance, or auditory effect on these animals, as their lower limit of functional hearing is considered to be ~150 Hz (Southall et al. 2007). It is the weaker components of the seismic signals above 100–150 Hz that will account for most of the (presumably limited) MarVib effect. Further suppression of unneeded components of MarVib sound above ~100 Hz would substantially reduce the limited MarVib effects on this group.

High-Frequency Cetaceans: These are a minority of the odontocete species (§ 3.6) whose functional hearing range has even higher low- and high-frequency limits, extending from about 200 Hz to 180 kHz. This group includes the porpoises, river dolphins, and members of the genera *Cephalorhynchus* and *Kogia.* The above comments concerning anticipated minimal effects of MarVib on mid-frequency cetaceans are also expected to apply to this group. However, behavioral responses of some porpoises to other types of anthropogenic sounds are especially strong, and their TTS and presumably PTS thresholds may be relatively low (Lucke et al. 2009). Therefore, effects of MarVib (and airgun) sounds on this group may be no less than on the mid-frequency cetaceans.

Pinnipeds in Water: Seals and sea lions are intermediate between baleen whales and odontocetes in terms of the frequencies to which they are most sensitive. There are no data on the effects of MarVib sounds on pinnipeds. Although there are relatively few data on the behavioral responses of pinnipeds to airgun pulses, pinnipeds (as compared with cetaceans) seem to be relatively non-responsive to airgun sounds (§ 6.2.5.1). However, at least one species of seal, the harbour seal, appears to incur TTS with less exposure to underwater sound than is necessary to cause TTS in odontocetes such as the bottlenose dolphin and beluga.

Other Marine Mammals: There are either no or few available data concerning effects of airguns, and no data concerning effects of MarVibs, on any of the "other marine mammals": sirenians (manatees and dugongs), polar bears, and sea otters (§ 6.2). Sirenians and sea otters tend to occur in relatively shallow, coastal waters, and polar bears are usually on ice or land or swimming at the surface of the water. Thus, none of these animals is expected to be much affected by either airgun or MarVib signals.

Sea Turtles: Auditory data show that sea turtles are sensitive to low frequency sounds, so they could potentially be affected by MarVib as well as airgun signals. However, the ways in which sea turtles use underwater sound are unknown. It is possible that MarVib sounds could cause some masking, in which case the longer signal duration and higher duty cycle of MarVib than of airgun sounds could cause increased masking with MarVib. If so, better suppression of MarVib components above 100 Hz could be beneficial to sea turtles. There is some limited information indicating that exposure of sea turtles to high levels of airgun sound can elicit avoidance effects and auditory impairment (TTS). If so, then use of MarVib instead of airguns might (hypothetically) somewhat reduce these effects, for the same reasons that apply in marine mammals.

Fishes: Direct empirical information on how exposure to MarVib sound affects fishes is limited to data from a single study involving an early design of MarVib, supplemented by data from studies involving exposure of fishes to somewhat similar sounds. Neither disturbance nor non-auditory injury was detected during the one MarVib study. The sensitivity of fishes to sound is quite variable, but many fish species are most sensitive to relatively low frequencies, potentially including frequencies emitted by next-generation MarVib systems. In many species, it is the particle velocity component rather than pressure to which fishes are most sensitive. The potential for masking is higher with MarVib signals compared to airgun pulses because of the longer signal duration and higher duty cycle for MarVib signals. However, the likelihood that seismic surveys would cause disturbance, hearing impairment, or non-auditory injury / physiological effects may be lower with MarVib than for airgun sound because of MarVib's lower signal amplitude and/or non-pulse characteristics.

Invertebrates: The only specific data are from a single study involving exposure of shrimp to high-level sound from an early design of MarVib; no disturbance effects or non-auditory injury were detected. No empirical information is available concerning either masking or sensory impairment in marine invertebrates exposed to MarVib sound. As with fishes, MarVib sound might theoretically cause more masking than would airgun sound (because of the longer signal duration and higher duty cycle of MarVib sound), but MarVib sound is less likely to cause disturbance, impairment of sound detection abilities, or non-auditory injury/physiological effects. Overall, MarVib sound would likely have less effect on marine invertebrates as compared with airgun sound. However, the possibility of auditory damage in cephalopods exposed to MarVib sound deserves study given a recent report of auditory injury in captive cephalopods exposed to prolonged low-frequency FM sound (André et al. in press).

8.6 IMPACT OF ALTERED SIGNAL PROPERTIES

The sound signals expected to be emitted by next-generation MarVib systems will differ in important ways from airgun signals. Differences include being non-pulse rather than impulsive in character, having reduced peak pressure but increased signal duration and probably increased duty cycle, and having well-controlled spectral properties.

Non-Pulse Signals: The non-pulse character of MarVib signals relative to airgun pulses is expected to be an important mitigating factor, as the rapid pressure changes ("rise time") of impulses contribute to their potential to cause auditory impairment and perhaps injury. The non-pulse character of MarVib signals means that marine mammals could tolerate exposure to higher cumulative energy levels from MarVib than from airguns before auditory impairment would be expected (Southall et al. 2007). The same is probably true for at least some other types of marine animals. Southall et al. estimated that the cumulative energy exposure would need to be ~17 dB higher with non-pulse sound than with impulse sound before PTS (auditory injury) would be expected.

Reduced Peak Pressure: The reduced peak pressure with MarVib would mean that (other factors being equal) any biological effect that is primarily a function of received pressure level would be expected to be lower than during an airgun-based survey.

If disturbance effects in some types of marine animals are mainly a function of received sound level and not much affected by signal duration, disturbance would be limited to smaller distances around a MarVib source than around an airgun array, and fewer individual animals might be disturbed during a MarVib survey. However, it is not known to what extent disturbance would also be affected by the increased duration and duty cycle of MarVib signals.

Increased Signal Duration and Duty Cycle: The likely increase in signal duration and duty cycle with MarVib would probably offset, to varying degrees, the benefits of the lower pressure level with MarVib.

- For disturbance, the lower pressure level with MarVib might provide some benefit (less disturbance) even if received energy level is the same as with airguns. However, specific data on this are lacking.
- For auditory impairment, the likely increase in signal duration and duty cycle of MarVib signals are expected to largely offset the advantage of the lower pressure level (see § 8.4, above). Even so, MarVib would still be expected to have notably reduced potential to cause auditory impair-

ment because of its non-pulse nature and the higher cumulative sound exposure level necessary to cause auditory effects when the sound is non-pulse.

- For masking, the increased signal duration and duty cycle of MarVib signals are expected to cause a stronger effect in low-frequency specialists (e.g., baleen whales) than would occur with the more intermittent airgun signals (§ 8.4).

Well-controlled Spectral Properties: The more precise control over signal characteristics anticipated with future-generation MarVib than with airguns should allow some reduction in environmental impacts. With MarVib, less energy is expected to be emitted at frequencies above those relevant to geophysicists, e.g., at >100 Hz. (If if is possible for the inflection point to be at a frequency lower than 100 Hz, that would be better.) This will reduce effects on animals that have relatively low sensitivity to the predominant low-frequency components and higher sensitivity to the components above 100 Hz that can be better suppressed with MarVib than with airguns.

8.7 MarVib Usefulness by Habitat and Geographic Area

This assessment has not found any habitats or geographic areas where there is a reversal of the pattern for MarVib to have advantages (in most respects) relative to airguns. It was beyond the scope of this assessment to investigate the relative benefits in a wide variety of situations. However, acoustic and exposure modelling techniques were applied to make specific comparisons of the numbers of cetaceans occupying shallow and deep waters of the northern Gulf of Mexico that might be disturbed or subjected to auditory effects during MarVib vs. airgun surveys. That analysis showed that, in both shallow continental shelf waters and deeper slope waters, disturbance and auditory effects would be reduced substantially by use of MarVib rather than airguns. However, the extent of the predicted reduction with MarVib varied considerably depending not only on location / depth but also on the type of effect (disturbance vs. auditory), species of cetacean, and whether or not frequency-weighting was applied (Table 6.2). There was no consistent tendency for the "MarVib benefit" to be greater or less in continental shelf waters than in deeper water within the limited range of situations examined.

8.8 Mitigation Measures for MarVib vs. Airguns

Available information indicates that animals can tolerate the receipt of more acoustic energy (measured on an SEL basis) from a non-pulse MarVib source than from impulsive airgun sound without incurring auditory impairment — either TTS or PTS (Southall et al. 2007). Therefore, mitigation radii are expected to be smaller during MarVib surveys than during airgun surveys. Also, some biological effects such as disturbance may be more a function of received pressure than of cumulative received energy. If so, disturbance radii may be further reduced (relative to those during airgun surveys), and a MarVib source could have a further advantage over airguns in causing less biological effects of most types (aside from masking). However, available data are not sufficient to show whether disturbance radii are more directly related to received energy level or to received sound pressure level, and this is an important data gap.

Acoustic modelling applied to northern Gulf of Mexico scenarios § (5.4–5.6; § 6.2.6.3) indicated that, even without specific mitigation measures, the number of marine mammals that might incur auditory damage from a MarVib survey is low — fewer than one individual of any of the three representative cetacean species considered (Table 6.3). That was true with the 180 dB re 1 μPa_{RMS} do-not-exceed pressure criterion recognized by NMFS as well as with the more justifiable 215 dB re 1 $\mu Pa^2 \cdot sec$ SEL criterion recommended by Southall et al. (2007). With either criterion, predicted numbers were higher during an airgun survey than with MarVibs (Table 6.3). The modelling results do not mean that specific mitigation of MarVib surveys would be unnecessary, but did imply that some MarVib effects may be sufficiently limited that there would be less need for specific mitigation than with airgun surveys.

One exception to this generalization is the matter of masking, which is expected to be more of a problem because of the higher duty cycle with MarVibs than with airguns (§ 6.2.4.2). The main concern would be for baleen whales and perhaps sea turtles and various fish — animals for which the most important sounds are at low frequencies. MarVib operating and design procedures that would reduce masking, as discussed in Chapter 7, may be important.

General operating procedures that could be beneficial for mitigation during MarVib surveys are, for the most part, the same as during an airgun survey (§ 7.3). Specific MarVib design considerations that might be helpful in reducing masking and other biological effects include • reduce duty cycle (unless this would necessitate increasing source pressure level substantially); • suppress MarVib sound components outside the bandwidth relevant for geophysical purposes, e.g., those above 100 Hz, or a lower cutoff frequency if practical; • (tentatively) use FM signals rather than PRN signals unless use of the latter allows a considerably lower source level (see §8.10, below); and • assess (probably via modelling) whether some practical adjustment of operating depth might reduce exposure of key species to MarVib sound in the circumstances of the planned survey (see § 7.2 for details).

8.9 PREFERABLE MARVIB SIGNAL TYPES TO REDUCE IMPACT

Earlier MarVib designs used FM signals, i.e., upsweeps, but geophysicists are interested in the possibility of using PRN signals or other similar coded signals in future MarVib designs, as these signals may provide signal-processing advantages. That, in turn, might allow a MarVib system to operate with a lower source level, shorter signal duration, or lower duty cycle, any of which could be advantageous from an environmental impact perspective. However, in animals sensitive to low-frequency sound (e.g., baleen whales), masking and disturbance effects of LF PRN signals may be greater than corresponding effects from FM signals (§ 7.2.5, summarizing Clark 2009; Ellison 2010). If MarVib designers have the option to use either PRN or FM signals, then before they choose which signal type to use, it would be desirable to obtain empirical data on the relative biological effects associated with each of these signal types.

Any signal type that might elicit resonance of air-filled body cavities or other structures should be avoided. The most problematic type of signal might be a constant-frequency (CF) signal sustained at a resonant frequency. If there is some requirement to consider the use of CF signals (not currently expected), directed research on their resonance effects would be desirable.

8.10 RECOMMENDED STUDIES

The major underlying question addressed in this report is, “what are the key differences between airguns and marine vibrators with regard to their environmental impact?” The principal objective is to determine if there are significant differences between the two approaches that would or would not support further engineering development of the MarVib approach.

Because there are almost no empirical data concerning the environmental effects of MarVib systems, a large number of data gaps and recommended studies could be identified. However, it is probably more useful to identify a smaller number of recommendations that are of particular importance. That is the approach in this section.

Before a major research program concerning the biological effects of MarVib systems is launched, it would be beneficial to have more specific information about the design options available to MarVib developers. For the present assessment, it was necessary to consider a wide range of potential alternative

MarVib configurations, and to make numerous assumptions about the likely characteristics of future-generation MarVib systems. If the range of design options can be narrowed before beginning direct research on biological effects, those biological studies can be better focussed on the most relevant questions and MarVib design options.

8.10.1 Weighting Functions

The sound frequencies to which different groups of marine animals are most sensitive vary widely (Chapter 3). A given amount of sound energy at a particular frequency is assumed to have more biological effect if it is within or near the frequency range of best hearing sensitivity than if it is at a frequency to which the animal is relatively insensitive. However, the degree to which sound at frequencies outside the range of best hearing should be downweighted is controversial, and probably depends on the type of biological effect under consideration (masking, disturbance, or auditory impairment). For various groups of marine mammals, relatively shallow "M-weighting" curves have been proposed (Southall et al. 2007; see Fig. 4.9 *in* Chapter 4). These are presumed to be most appropriate when dealing with effects of high-level sounds on auditory impairment, but are not fully accepted as applicable even to that situation. Alternatively, steeper weighting curves derived through inversion of the audiogram have been proposed as weighting curves for marine mammals and fish (e.g., Nedwell et al. 2007). Steeper audiogram-based curves might be more relevant than the flatter "M-weighting" curves when dealing with masking and disturbance, but Nedwell et al. recommended that the audiogram-based curves also be applied when assessing auditory effects. Uncertainty about the most appropriate weighting functions is important because the type of weighting curve (if any) that is applied can make a large difference in predicted masking, disturbance, or auditory effects, and associated mitigation radii. Very little direct empirical testing has been done to determine the most appropriate weighting functions in any marine animal (but see Schlundt and Finneran [in press] for odontocetes). Research on this topic is warranted, at least in the various major groups of marine mammals, sea turtles, and fish.

Impact and mitigation radii for an animal whose frequency weighting significantly discounts the expected LF transmissions of a MarVib source (e.g., an odontocete cetacean) would be considerably reduced for both airguns and especially for MarVib sources. MarVib sources would have advantages over airguns if the falloff rate above ~100 Hz (or some lower frequency) was also improved, e.g., to 50 or even 100 dB/decade for MarVib vs. 30 dB/decade for airguns. Determining whether such gains are achievable with new MarVib designs, and whether the regulatory processes in various jurisdictions will adopt scientifically-appropriate weighting functions, must be a critical issue for discussion. This will affect the estimated numbers of animals subject to both disturbance and auditory impairment from future MarVib systems.

8.10.2 Masking

Masking is one type of biological effect that might be greater with MarVib than with airguns. Therefore, there is a particular need to have specific data on the effects of exposure to realistic MarVib sounds on emission of animal calls, detection of those calls by conspecifics, and detection of other sounds relevant to those animals (see Chapter 6). No specific data of these types currently exist for MarVib sounds, and there are few relevant data for other similar types of sounds.

Some progress concerning potential masking issues could be made through quantitative modelling approaches, analogous to those recently applied in assessing the masking effects of shipping noise (Clark et al. 2009). However, well-controlled empirical studies are also needed for representative species that are particularly dependent on low-frequency sound, i.e., baleen whales, many fish, and possibly sea turtles. Those studies should assess the extent to which emission and detection of relevant sounds depend on the properties of MarVib sound, including received level, duty cycle / intermittency, signal type (FM vs. PRN), and spectral properties (suppression of higher-frequency components). As noted above, it would be desirable to begin by narrowing down the range of options being considered by MarVib designers; otherwise the number of potential options for which masking effects would need to be studied is impractically large.

8.10.3 Disturbance

Disturbance effects, like masking, have the potential to extend to considerably longer distances than auditory impairment might extend. Therefore, much larger numbers of animals could potentially be affected by disturbance (or masking) than might incur auditory effects. This may be particularly the case with MarVib, where the potential for auditory effects appears to be limited to quite short distances (if they occur at all). It will be important to develop a better understanding and predictive capacity for disturbance effects of MarVib than we currently possess.

There are essentially no existing data concerning the disturbance effects of MarVib sounds on any type of marine animal, and the limited data from studies of behavioral responses to other types of intermittent non-pulse sounds are of questionable applicability to MarVib (Chapter 6). Therefore, there is a strong need for systematic, well-controlled studies of behavioral reactions of key marine taxa to MarVib sounds, with emphasis on taxa most sensitive to LF sounds (baleen whales, sea turtles, and some fish).

One important question is whether, when other factors are held constant, behavioral responses are more directly related to received sound pressure levels or received sound energy levels. If disturbance is most closely related to pressure level, then disturbance radii will be much reduced with MarVib than with airguns, given the lower pressure levels for MarVib than for airgun sources. However, if duty cycle as well as pressure is a consideration, i.e., if disturbance is most closely related to received energy level than to received pressure level, then the difference in disturbance radii around MarVib vs. airgun sources would be much less. The results of this study would bear directly on whether existing pressure-based disturbance criteria for airgun-based surveys (e.g., the 160 dB re 1 μPa_{RMS} criterion that is often applied in the U.S. for marine mammals) can be applied to MarVib projects, or whether a different (and probably more restrictive) criterion is appropriate for MarVib. If the airgun vs. LFA sonar results for gray whales (summarized in § 6.2.5.2) are even approximately relevant to the airgun vs. MarVib comparison, then a more restrictive (i.e., lower) pressure-based criterion may be appropriate for MarVib than for airguns. In that case, benefits of MarVib would be less than predicted when the same pressure criterion is assumed for MarVib and airguns. This can only be resolved by conducting controlled exposure testing of relevant marine animals.

If multiple signal types (e.g., FM and PRN) remain as viable options for MarVib systems, then it would be valuable to compare the behavioral responses of representative LF-sensitive marine animals to those types of signals via controlled exposure experiments. Behavioral responses to FM signals may be less than those to PRN signals (Ellison 2010), but this needs to be tested if both signal types are under active consideration by MarVib developers.

Similarly, if varying degrees of suppression of “higher”-frequency signal components remain as alternatives, or if varying signal durations or duty cycles remain as options, then it would be desirable to test the behavioral responses of representative LF-sensitive marine animals to MarVib sounds with those alternative signal properties.

In planning this research, close attention should be given to developing an appropriate research design and optimum methodology. For example, it will be important to obtain accurate data on the actual sound levels received by the test animals. In field studies of marine mammals or other large animals, it will be desirable to have calibrated sound-recording devices directly attached to the test animals to obtain a continuous record of received sounds throughout the test. If it is not practical to have sound monitoring "tags" attached to the animals themselves, then other methods will need to be applied in order to obtain reasonably accurate and reliable information about sound exposure while behavioral responses are being documented. It will also be important to control or match the circumstances of the test exposures as closely as possible, given the high degree of variability and strong context-dependence of animal behaviour in general and of disturbance responses in particular. Close attention will need to be given to the sample sizes necessary for statistically reliable results when substantial inter-individual variability in responses is expected. Other procedural recommendations for controlled exposure experiments can be found in Gordon et al. (2003) and Tyack (2009). The ongoing efforts by the JIP to conduct full-scale tests of the responses of tagged whales to sounds from airgun arrays will provide experience with many of the procedures needed for this type of research.

8.10.4 Auditory Impairment

Regulatory requirements associated with use of airguns, sonars, and other relatively high-energy sound sources are usually tied directly or indirectly to assumptions about potential noise-induced auditory impairment, and it is very likely that this will also apply to MarVib operations if and when these are proposed. Data on sound levels necessary to elicit temporary hearing impairment (TTS) are the key data used in assessing potential auditory impairment, at least in marine mammals. Sound levels necessary to cause permanent hearing impairment (PTS) are of more direct relevance, but experiments to determine PTS thresholds are not done with marine mammals or sea turtles, and TTS data are used as a proxy for PTS data. (In fish and invertebrates, direct studies of PTS could be done.) Although some data on sound exposures necessary to elicit TTS have been obtained from marine mammals and fish, these data do not apply directly to MarVib-type sounds. There is a need for TTS information from more species of marine animals sensitive to LF sounds, including data on the effects of intermittent LF sounds with received signal levels that gradually increase and then decrease in a manner representative of a passing MarVib source.

Currently, there are limited TTS data for a few species of odontocetes exposed to impulse and non-pulse sounds, and for a few species of pinnipeds exposed to non-pulse (but not impulse) sounds. However, the non-pulse sounds used in these tests were at considerably higher frequencies than would be expected with MarVib systems, and were not repeated in intermittent sequences similar to those that a passing MarVib source would create. There is recent evidence that, in odontocetes, the frequency of the received sound can have an important influence on the occurrence of auditory impairment (Finneran and Schlundt 2010). There are also preliminary indications that intermittency / duty cycle can affect TTS (Mooney et al. 2009; Finneran et al. 2010). The few available data show that there are substantial interspecific differences within the odontocetes and within the pinnipeds in sound exposure levels necessary to cause onset of TTS. To better assess the auditory effects of MarVib systems, and to determine which MarVib design concepts would produce lesser and greater auditory effects, there is a need for data on the effects of key MarVib parameters such as received level and energy, frequency content, and intermittency / duty cycle on TTS onset and rate of growth of TTS with increasing exposure.

Ideally, it would be desirable to have data on sound exposures necessary to cause permanent auditory damage (PTS). Such studies are not possible with marine mammals or sea turtles for ethical and legal reasons. However, data on TTS as a function of sound exposure can provide an indirect way to estimate the potential for PTS. In most species of fish, direct studies of PTS presumably could be done.

8.10.5 Other Injury or Physiological Effects

Resonance effects in marine mammals are not well documented or understood (e.g., Gentry 2002). However, there is some concern that exposure to high level LF sounds, especially if sustained over time, could cause resonance of body cavities or other body structures (§ 6.2.7). This could be an issue with regard to human divers as well as marine mammals and other marine biota. The likelihood of this with MarVib signals is largely unknown. Particularly if MarVib designers are considering the use of constant-frequency tonal signals, resonance deserves consideration, perhaps initially via a modelling approach.

8.10.6 New Regulatory Tools: Risk Continuum

Historically, acoustic exposure thresholds have been just that, fixed thresholds or step functions. While heuristically convenient, step functions are poor models of most animal behaviour, given its wide variability and context dependence.

One early attempt to deal with some of the problems associated with the step function approach was taken by Malme et al. (1984), who estimated the probability of avoidance by migrating gray whales as a function of the received level of industrial sound. This approach attempted to address the fact that, with increasing received levels of sound, the probability of a disturbance response increases. They did not address other factors that could affect probability of response, but did apply their approach to data collected in one particular season and situation. The probabilities of avoidance by gray whales might be different in other situations, as is now known (e.g., Tyack 2009).

A further development of the probabilistic approach was described and implemented in the SURTASS LFA EIS (DoN 2001). The approach undertaken was to distribute the associated risk using a Feller risk continuum function

The continuum is defined as
$$R = \frac{1 - \left[(\mathrm{L} - \mathrm{B})/\mathrm{K}\right]^{-\mathrm{A}}}{1 - \left[(\mathrm{L} - \mathrm{B})/\mathrm{K}\right]^{-2\mathrm{A}}}$$

Thus the original risk continuum for SURTASS-LFA was built upon four parameters:

1) The basement sound exposure level (B), at which there was a negligible probability of a behavioral response. The original B value chosen for LFA was 120 dB re 1 μPa_{RMS}.
2) The midpoint (K), at which there is a 50% probability of a behavioral response (i.e., when L–B = K, R = 0.5). The value originally selected for LFA was K = 45 dB above the basement level. This was based upon an interpretation of the behavioral observation results of the LFA Scientific Research Program (Croll et al. 2001; Tyack 2009).
3) The transition parameter (A), which controls the shape of the curve. When the original risk continuum was created, it was assumed that 180 dB re 1 μPa was the threshold for potential injurious effect (HESS 1999). In order to tune the risk continuum function to create a 95% probability of response at a received level of 180 dB, a transition parameter value of A = 10 was specified.
4) With values of A, B, and K set, the received sound level at the animal (L) then determines the amount of risk (R) associated with that sound level. The cumulative risk values can then be

statistically allocated to estimate such values as net risk assessment to a regional population from a sound-producing activity such as seismic exploration.

In a recent (2008) letter, this approach was proposed by NMFS for evaluating the effects of mid-frequency sonar signals, with the following specified values for cetaceans:

- The basement value, B, is 120 dB re 1 μPa.
- The midpoint was specified as K = 45.
- The transition parameter was specified as A=10 for odontocetes and pinnipeds whereas a value of A=8 was specified for mysticetes.

The parameters specified by NMFS result in the 98.4% probability of response occurring at 195 dB re 1 μPa_{RMS} for mysticetes and a 99.4% probability of response occurring at 195 dB re 1μPa_{RMS} for other cetacean species. These exposure levels approximately correspond to the SEL value for temporary threshold shift (TTS) for an exposure of 1 sec as identified in Southall et al. (2007).

If one now considers applying this "risk continuum" methodology to an assessment of behavioral response to MarVib, then the same four parameters can in theory be used, with appropriately revised parameter values. It will be apparent that the parameters listed above for cetaceans exposed to LFA or mid-frequency sonar are based on limited data, and the overall approach involves a number of assumptions even for those sound sources, whose effects on marine mammals have been studied to some limited degree. At present, the data necessary to estimate corresponding parameters for marine mammals (or other marine animals) exposed to MarVib are entirely lacking. However, because of the inherent parametric nature of the Feller function, the risk continuum approach for behavioral effects should be adaptable to other sound sources such as MarVib, with specific parameters appropriate to the various species groups. Studies of behavioral responsiveness to MarVib, along the lines suggested above (§ 8.11.3), would be needed to provide the new observational data required to implement a risk continuum approach for MarVib.

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Overall, this assessment has found that new-generation MarVib systems show potential for allowing marine seismic surveys to occur with reduced impacts on marine life relative to the impacts of airgun-based seismic surveys. However, this conclusion is based largely on indirect evidence. There is almost no direct empirical information concerning the effects of MarVib operations on marine animals. Knowledge of the biological effects of other types of high-level non-pulse sounds somewhat similar to MarVib sounds is also quite limited. Furthermore, in at least one respect (masking), effects of MarVib-based seismic surveys may at times be greater than the effects of airguns. Given that MarVib systems show promise as being able to reduce the overall effects of marine seismic surveys, it would be useful to undertake carefully-planned empirical studies to document the biological effects of MarVib operations. Notwithstanding the difficulties inherent in such studies, it would be valuable to obtain specific data on MarVib effects on masking, disturbance, auditory impairment, and perhaps resonance in key types of marine animals known to be sensitive to low-frequency sound, which include baleen whales, sea turtles, many fish, and perhaps some invertebrates. Besides being useful in further assessing MarVib impacts relative to airgun impacts, these data would be valuable in optimizing MarVib design features for minimal environmental impact, beyond the level that can be done from the present assessment of existing information. These new data might also demonstrate that MarVib-based seismic surveys could at times go ahead with reduced need for mitigation measures, or in circumstances where airgun-based surveys are not allowed or are more seriously restricted.

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