

**Environmental Assessment of a Marine Geophysical Survey
by the R/V *Marcus G. Langseth* in the Arctic Ocean,
September–October 2011**

Prepared for

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TABLE OF CONTENTS

ABSTRACT.....	vi
LIST OF ACRONYMS	viii
I. PURPOSE AND NEED.....	1
II. ALTERNATIVES INCLUDING PROPOSED ACTION	2
Proposed Action	2
(1) Project Objectives and Context	2
(2) Proposed Activities.....	2
(3) Mitigation Measures.....	6
Alternative Action: Another Time.....	13
No Action Alternative	14
III. AFFECTED ENVIRONMENT.....	14
Physical Environment.....	14
Biological Environment.....	15
Fish and Fisheries	15
Essential Fish Habitat.....	16
Seabirds	17
(1) Spectacled Eider	17
(2) Steller’s Eider	17
(3) Kittlitz’s Murrelet.....	18
(4) Yellow-billed Loon	18
(5) Other Seabirds, Shorebirds, and Waterfowl	18
Marine Mammals.....	19
(1) Mysticetes.....	21
(2) Odontocetes	24
(3) Pinnipeds	27
(4) Carnivora.....	30
IV. ENVIRONMENTAL CONSEQUENCES.....	31
Proposed Action	31
(1) Direct Effects on Marine Mammals and Their Significance	31
(2) Mitigation Measures for Marine Mammals.....	45
(3) Numbers of Marine Mammals that Could be “Taken by Harassment”.....	45
(4) Conclusions	51
(5) Direct Effects on Fish, EFH, and Fisheries, and Their Significance.....	52
(6) Direct Effects on Invertebrates and Their Significance.....	55
(7) Direct Effects on Seabirds and Their Significance.....	56
(8) Indirect Effects on Marine Mammals, Seabirds, and Their Significance.....	57
(9) Possible Effects on Subsistence Hunting and Fishing.....	58
(10) Cumulative Effects	62
(11) Unavoidable Impacts of Noise	66

(12) Coordination with Other Agencies and Processes.....	66
Alternative Action: Another Time.....	67
No Action Alternative	68
V. LIST OF PREPARERS	69
VI.LITERATURE CITED.....	70
APPENDIX A1: PROPAGATION MODELING FOR A SEISMIC SURVEY IN THE ARCTIC OCEAN, SEPTEMBER– OCTOBER 2011	93
APPENDIX A2: L-DEO MODELING FOR MARINE SEISMIC SOURCE ARRAYS FOR SPECIES MITIGATION.....	94
1. Summary.....	94
2. Introduction	94
3. Modeling.....	95
4. Units	98
5. Calculating the exclusion zone	99
6. Literature Cited.....	108
APPENDIX B: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE MAMMALS	109
1. Categories of Noise Effects	109
2. Hearing Abilities of Marine Mammals.....	109
2.1 Toothed Whales	110
2.2 Baleen Whales.....	111
2.3 Seals and Sea Lions.....	111
2.4 Manatees and Dugong.....	112
2.5 Sea Otter and Polar Bear	112
3. Characteristics of Airgun Sounds	112
4. Masking Effects of Airgun Sounds	114
5. Disturbance by Seismic Surveys	116
5.1 Baleen Whales.....	117
5.2 Toothed Whales	123
5.3 Pinnipeds.....	129
5.4 Sirenians, Sea Otter and Polar Bear	131
6. Hearing Impairment and Other Physical Effects of Seismic Surveys	131
6.1 Temporary Threshold Shift	132
6.2 Permanent Threshold Shift.....	137
6.3 Strandings and Mortality.....	139
6.4 Non-Auditory Physiological Effects	141
7. Literature Cited.....	141
APPENDIX C: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON FISHES	158
1. Acoustic Capabilities.....	158
2. Potential Effects on Fishes	160
2.1 Marine Fishes	160

2.2 Freshwater Fishes.....	163
2.3 Anadromous Fishes.....	164
3. Indirect Effects on Fisheries.....	164
4. Literature Cited.....	165
APPENDIX D: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES.....	169
Sound Production.....	169
Sound Detection.....	170
Potential Seismic Effects.....	170
Literature Cited.....	174

ABSTRACT

The University of Alaska Geophysics Institute (UAGI), with research funding from the National Science Foundation (NSF), plans to conduct a marine seismic survey in the Arctic Ocean during September–October 2011. This project will include collection of seismic reflection data across the transition from the Chukchi Shelf to the Chukchi Borderland to define the apparent change in structure between two large continental blocks. This study will test existing tectonic models and develop new constraints on the development of the Amerasian Basin. The project will substantially advance our understanding of the Mesozoic history of this basin. In addition, these data will enable the formulation of new tectonic models for the history of this region, which will substantially expand our understanding of the surrounding continents. As its energy source, the seismic survey will employ a 10-airgun array with a discharge volume of 1830 in³. The survey will also include collection of gravity anomaly, sonobuoy refraction, multibeam bathymetry and backscatter, and sub-bottom profiler data. The seismic survey will take place in water depths ranging from ~30 to 3800 m.

UAGI is requesting that the National Marine Fisheries Service (NMFS) issue an Incidental Harassment Authorization (IHA) to authorize the incidental, i.e., not intentional, harassment of small numbers of cetaceans and pinnipeds should this occur during the seismic survey. NSF and UAGI are also consulting with the U.S. Fish & Wildlife Service (USFWS) regarding concerns about potential, although unlikely, disturbance to walrus and polar bears. The information in this Environmental Assessment (EA) supports the IHA Application process, provides information on marine species that are not addressed by the IHA Application to NMFS, and addresses the requirements of the National Environmental Policy Act (NEPA) and Executive Order 12114, “Environmental Effects Abroad of Major Federal Actions”. Alternatives addressed in this EA consist of a corresponding program at a different time, along with issuance of an associated IHA; and the no action alternative, with no IHA and no seismic survey.

Several species of cetaceans and pinnipeds inhabit the Arctic Ocean. Few species that may be found in the study area are listed as *endangered* under the U.S. Endangered Species Act (ESA). The bowhead whale is the only *endangered* species of marine mammal that is likely to occur within the survey area; however, it is possible that the *endangered* fin or humpback whale may also be encountered there. The survey has been scheduled specifically to avoid the spring bowhead whale migration north of Barrow and to be well north of the migration route during the fall migration. Two additional species of special concern that might be encountered are the *threatened* spectacled and Steller’s eiders.

Potential impacts on the environment due to the seismic survey would be primarily a result of the operation of the airgun source. A multibeam echosounder, sub-bottom profiler, and possibly acoustic Doppler current profilers will also be operated. Potential impacts would be associated with increased underwater noise, which may result in avoidance behavior by some marine mammals, seabirds, and fish; and other forms of disturbance. An integral part of the planned survey is a monitoring and mitigation program to minimize impacts of the proposed activities on marine species present, and on fishing and subsistence activities, and to document the nature and extent of any effects. Injurious impacts to marine mammals have not been demonstrated to occur near airgun arrays, and the planned monitoring and mitigation measures would minimize the possibility of such effects should they otherwise occur.

Protection measures designed to mitigate the potential environmental impacts will include the following: ramp ups; typically two, however a minimum of one, dedicated protected species observer (PSO) maintaining a visual watch during all daytime airgun operations; two observers on watch 30 min

before and during ramp ups during the day and at night; no start ups during poor visibility or at night unless at least one airgun has been operating; passive acoustic monitoring (PAM) via towed hydrophones during both day and night to complement visual monitoring (unless the system and back-up systems are damaged during operations); and, power downs (or if necessary shut downs) when marine mammals are detected in or about to enter designated exclusion zones. UAGI and its contractors are committed to apply these measures in order to minimize effects on marine mammals and other environmental impacts.

With the planned monitoring and mitigation measures, unavoidable impacts to each of the species of marine mammal that might be encountered are expected to be limited to short-term localized changes in behavior and distribution near the seismic vessel. At most, such effects may be interpreted as falling within the Marine Mammal Protection Act (MMPA) definition of “Level B Harassment”. No long-term or significant effects are expected on individual marine mammals, seabirds, the populations to which they belong, or their habitats.

LIST OF ACRONYMS

~	approximately
ACP	Arctic Coastal Plain
ADCP™	Acoustic Doppler Current Profiler
ADFG	Alaska Department of Fish and Game
AEWC	Alaska Eskimo Whaling Commission
BASC	Barrow Arctic Science Consortium
BCB	Bering–Chukchi–Beaufort
BLM	Bureau of Land Management
CI	Confidence Interval
CITES	Convention on International Trade in Endangered Species
COMIDA	Chukchi Offshore Monitoring in Drilling Area
CPA	Closest Point of Approach
CPUE	Catch per Unit Effort
dB re 1 μ Pa	decibels in relation to a reference pressure of 1 micropascal
DPS	Distinct Population Segment
EA	Environmental Assessment
EEZ	Exclusive Economic Zone
EFH	Essential Fish Habitat
ESA	(U.S.) Endangered Species Act
$f(0)$	sighting probability density at zero perpendicular distance from survey track line
FMP	Fishery Management Plan
ft	feet
$g(0)$	probability of seeing a group located directly on the survey trackline
h	hour
ICES	International Council for the Exploration of the Sea
IHA	Incidental Harassment Authorization (under MMPA)
in	inch
IUCN	International Union for the Conservation of Nature and Natural Resources
IWC	International Whaling Commission
kHz	kilohertz
kW	kilowatt
LT	Long ton = 1016 kg
L-DEO	Lamont-Doherty Earth Observatory of Columbia University
LME	Large Marine Ecosystem
m	meter
MAI	Marine Acoustics, Inc.
MCS	Multi-Channel Seismic
min	minute
MMPA	(U.S.) Marine Mammal Protection Act
MMS	Minerals Management Service
ms	millisecond
MTTS	Masked Temporary Threshold Shift
MW	Megawatt
n.mi.	nautical mile

NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NMML	National Marine Mammal Laboratory
NOAA	National Oceanic and Atmospheric Administration
NPFMC	North Pacific Fisheries Management Council
NSB	North Slope Borough
NSF	National Science Foundation
OCS	Outer Continental Shelf
PAM	Passive Acoustic Monitoring
PI	Principal Investigator
pk	peak
psi	pounds per square inch
PSO	Protected Species Observer
PTS	Permanent Threshold Shift
RAM	Range-Dependent Acoustic Model
rms	root-mean-square
s	second
SE	Southeast
SEL	sound energy level
SIS	sea ice seismometer
SPL	sound pressure level
T	ton = 907.18 kg
TTS	Temporary Threshold Shift
UAGI	University of Alaska Geophysics Institute
U.K.	United Kingdom
UNEP	United Nations Environment Program
U.S.	United States of America
USCG	United States Coast Guard
USDI	United States Department of the Interior
USFWS	U.S. Fish and Wildlife Service
USN	U.S. Navy
USGS	United States Geological Survey
UAGI	University of Alaska Geophysics Institute
WCMC	World Conservation Monitoring Centre

I. PURPOSE AND NEED

The University of Alaska Geophysics Institute (UAGI) plans to conduct a marine seismic survey from the *R/V Marcus G. Langseth* in the Arctic Ocean from 5 September to 9 October 2011. The *Langseth* is operated by Lamont-Doherty Earth Observatory (L-DEO), a part of Columbia University, under a cooperative agreement with the U.S. National Science Foundation (NSF). The survey will take place in International Waters and in the Exclusive Economic Zone (EEZ) of the U.S.

NSF, as the funding and action agency, has a mission to “promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense...”. The proposed seismic survey is part of a research proposal recommended for funding by an expert review panel. This project will include collection of seismic reflection data across the transition from the Chukchi Shelf to the Chukchi Borderland to define the apparent change in structure between two large continental blocks. This study will test existing tectonic models and develop new constraints on the development of the Amerasian Basin, and will substantially advance our understanding of the Mesozoic history of this basin. In addition, these data will enable the formulation of new tectonic models for the history of this region, which will improve our understanding of the surrounding continents.

The purpose of this Environmental Assessment (EA) is to provide information needed to assess potential environmental impacts associated with use of a 10-airgun array. The EA was prepared under the National Environmental Policy Act (NEPA) and Executive Order 12114, “Environmental Effects Abroad of Major Federal Actions”. The EA addresses potential impacts of the proposed seismic survey from the *Langseth* on marine mammals, fisheries, and subsistence harvesting in the Arctic Ocean. The EA will also provide useful information in support of the application for an Incidental Harassment Authorization (IHA) from the National Marine Fisheries Service (NMFS). This EA also provides information on marine species that are not addressed by the IHA Application, including seabirds that are listed under the U.S. Endangered Species Act (ESA), fish, Essential Fish Habitat (EFH), and two marine mammal species (polar bear and Pacific walrus) that are managed by the U.S. Fish and Wildlife Service (USFWS) rather than by NMFS.

The requested IHA would, if issued, allow the non-intentional, non-injurious “take by harassment” of small numbers of marine mammals during the proposed seismic survey. To be eligible for an IHA, the proposed “taking” (with mitigation measures in place) must not cause serious physical injury or death of marine mammals, must have negligible impacts on the species and stocks, must “take” no more than small numbers of those species or stocks, and must not have an unmitigable adverse impact on the availability of the species or stocks for legitimate subsistence uses.

Several species of cetaceans and pinnipeds inhabit the parts of the Arctic Ocean where this cruise is proposed to occur. Species listed as *endangered* under the U.S. Endangered Species Act (ESA) and managed by NMFS may occur in certain portions of the survey area, most notably the bowhead whale, and (although very unlikely) the fin and humpback whale. Other species of concern that might occur in the area are the *threatened* spectacled and Steller’s eiders.

Protection measures designed to mitigate the potential environmental impacts are also described in this EA as an integral part of the planned activities. With the mitigation measures in place, any impacts on marine mammals and other species of concern are expected to be limited to short-term, localized changes in behavior of small numbers of animals. No long-term or significant effects are expected on individual marine mammals or their populations, on the subsistence harvest of marine mammals, on marine mammal habitat, or on the individuals and populations of other species. The proposed project

would also have little impact on fish resources, and the only effect on fish habitat would be short-term disturbance that could lead to temporary relocation of pelagic fish species or their food. Impacts of seismic sounds on some pelagic seabirds are possible, although none are expected to be significant to individual birds or their populations.

II. ALTERNATIVES INCLUDING PROPOSED ACTION

Three alternatives are addressed: (1) the proposed seismic survey and issuance of an associated IHA, (2) a corresponding seismic survey program at an alternative time, along with issuance of an associated IHA, (3) the no-action alternative, with no IHA and no seismic survey.

Proposed Action

The project objectives and context, activities, and mitigation measures for the proposed activities planned by UAGI are described in the following subsections.

(1) Project Objectives and Context

UAGI plans to conduct a geophysical and seismic survey in the Arctic Ocean north of the Chukchi Sea. The purpose of the proposed study is to collect seismic reflection data across the transition from the Chukchi Shelf to the Chukchi Borderland to image the structures that separate these two large continental blocks. This study will test existing tectonic models and develop new constraints on the development of the Amerasian Basin, and will substantially advance our understanding of the Mesozoic history of this basin. In addition, these data will enable the formulation of new tectonic models for the history of this region, which will improve our understanding of the surrounding continents.

(2) Proposed Activities

(a) Location of the Activities

The seismic survey will take place in the Arctic Ocean, encompassing the area 72.5–77°N, 160–175°W (Fig. 1). The bulk of the seismic survey will not be conducted in International Waters. However, the southeastern segments of the proposed survey lines are within the EEZ of the U.S.A.

(b) Description of the Activities

The procedures to be used for the survey will be similar to those used during previous seismic surveys by L-DEO and will use conventional seismic methodology. The survey will involve one source vessel, the R/V *Marcus G. Langseth*. The *Langseth* will deploy an array of 10 airguns as an energy source. The receiving system will consist of one 2-km long hydrophone streamer. As the airgun array is towed along the survey lines, the hydrophone streamer will receive the returning acoustic signals and transfer the data to the on-board processing system. In addition, at least 72 sonobuoys will be deployed in order to record seismic refraction data.

The program will consist of a total of ~5502 km of survey lines, not including transits to and from the survey area when airguns will not be in use (Fig. 1). Water depths within the study area range from ~30–3800 m. Just over half of the survey effort (55%) will occur in water 100–1000 m deep, 32% will take place in water >1000 m deep, and 13% will occur in water depths <100 m. There will be additional seismic operations in the survey area associated with turns, airgun testing, and repeat coverage of any areas where initial data quality is sub-standard. In our calculations (see § IV(3)), 25% has been added for

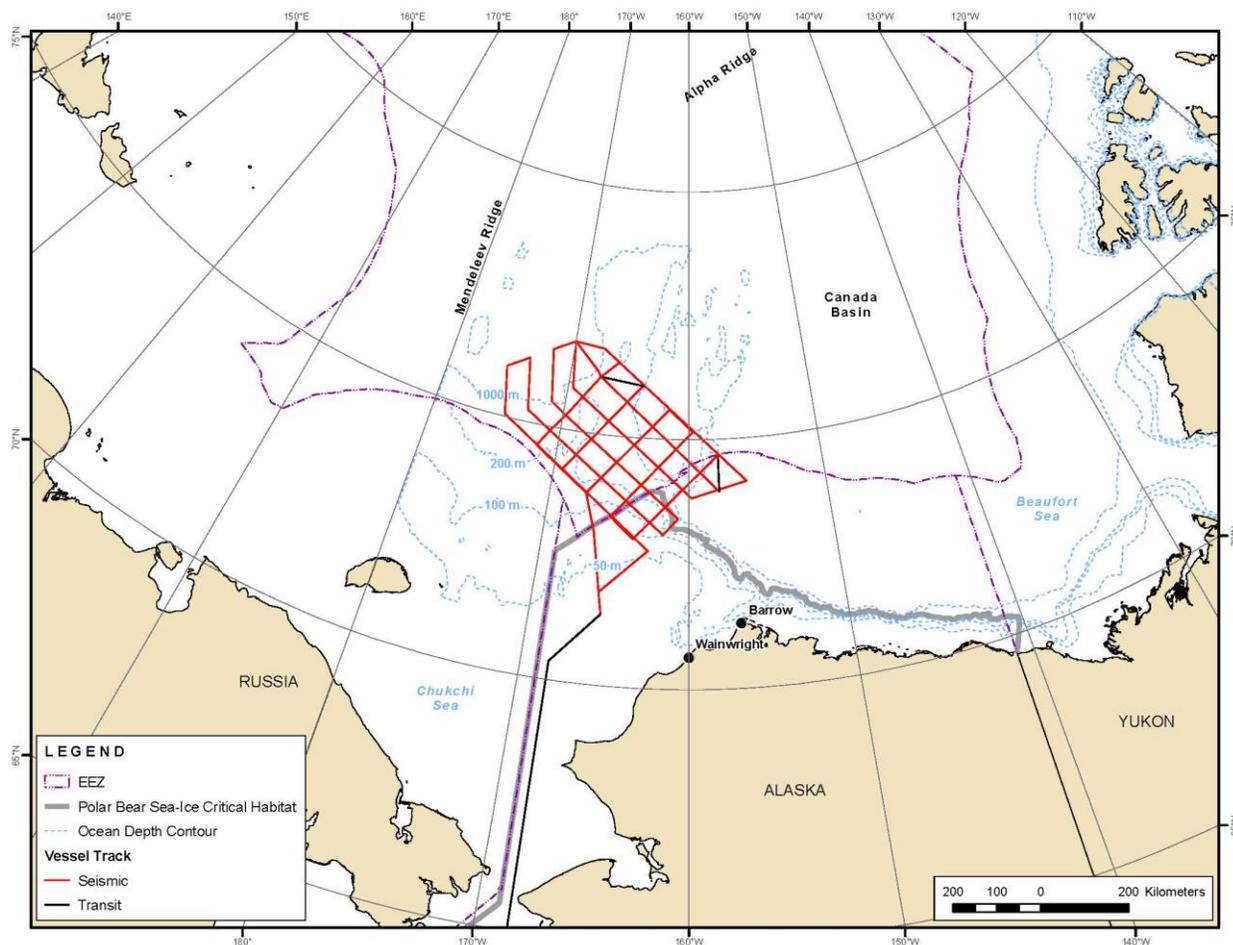


FIGURE 1. Proposed location of UAGI's September–October 2011 Arctic Ocean seismic survey lines. The precise track may vary somewhat from this proposed version depending on ice conditions.

those additional operations. The *Langseth* will be avoiding the ice edge, and an ice expert will be available to provide daily guidance and predict ice movements.

In addition to the operations of the airgun array, a multibeam echosounder (MBES) and a sub-bottom profiler (SBP) will also be operated from the *Langseth* continuously throughout the cruise. Acoustic Doppler current profilers (75-kHz and 150-kHz) may also be used. All planned geophysical data acquisition activities will be conducted by L-DEO with on-board assistance by the scientists who have proposed the study. The Principal Investigator (PI) is Dr. Bernard Coakley of UAGI. The vessel will be self-contained, and the crew will live aboard the vessel for the entire cruise.

(c) Schedule

The *Langseth* will depart from Dutch Harbor on ~5 September 2011 and sail northeast to arrive at ~72.5°N, 162°W, where the seismic survey will begin, >200 km from Barrow. The entire cruise will last for ~34 days, and it is estimated that the total seismic survey time will be ~25 days depending on ice conditions. Seismic survey work is scheduled to terminate near the starting point at ~72.4°N, 164°W on ~6 October; the vessel will then sail south to Dutch Harbor for arrival on 9 October.

(d) Vessel Specifications

The R/V *Marcus G. Langseth* will be used as the source vessel. The *Langseth* will tow the 10-airgun array, as well as the hydrophone streamer, along predetermined lines (Fig. 1). The *Langseth* will also deploy sonobuoys for collection of reflection data. When the *Langseth* is towing the airgun array and the hydrophone streamer, the turning rate of the vessel is limited. Thus, the maneuverability of the vessel is limited during operations with the streamer.

The *Langseth* has a length of 71.5 m, a beam of 17.0 m, and a maximum draft of 5.9 m. The *Langseth* was designed as a seismic research vessel, with a propulsion system designed to be as quiet as possible to avoid interference with the seismic signals. The ship is powered by two Bergen BRG-6 diesel engines, each producing 3550 horsepower (hp), which drive the two propellers directly. Each propeller has four blades, and the engine typically rotates at 600 or 750 revolutions per minute (rpm). The vessel also has an 800 hp bowthruster, which is not used during seismic acquisition. The operation speed during seismic acquisition is typically 7.4–9.3 km/h. When not towing seismic survey gear, the *Langseth* typically cruises at 18.5 km/h. The *Langseth* has a range of 25,000 km (the distance the vessel can travel without refueling).

The *Langseth* will also serve as the platform from which protected species observers (PSOs) will watch for marine mammals before and during airgun operations, as described in § II(3), below.

Other details of the *Langseth* include the following:

Owner:	National Science Foundation
Operator:	Lamont-Doherty Earth Observatory of Columbia University
Flag:	United States of America
Date Built:	1991 (Refitted in 2006)
Gross Tonnage:	3834
Accommodation Capacity:	55 including ~35 scientists

(e) Airgun Description

During the survey, the airgun array to be used will consist of 10 airguns, with a total volume of ~1830 in³. The airgun array will consist of a mixture of Bolt 1500LL and Bolt 1900LLX airguns, set in a typical configuration of one of the *Langseth*'s four linear arrays or "strings" (Fig. 2) with the first and last airguns in the strings spaced 16 m apart. The airgun array will be towed ~100 m behind the *Langseth*. The shot interval will be 15 s. The firing pressure of the array is 1950 psi. During firing, a brief (~0.1 s) pulse of sound is emitted. The airguns will be silent during the intervening periods.

The tow depth of the array will be 6 m. Because the actual source is a distributed sound source (10 airguns) rather than a single point source, the highest sound levels measurable at any location in the water will be less than the nominal source level. In addition, the effective source level for sound propagating in near-horizontal directions will be substantially lower than the nominal source level applicable to downward propagation because of the directional nature of the sound from the airgun array.

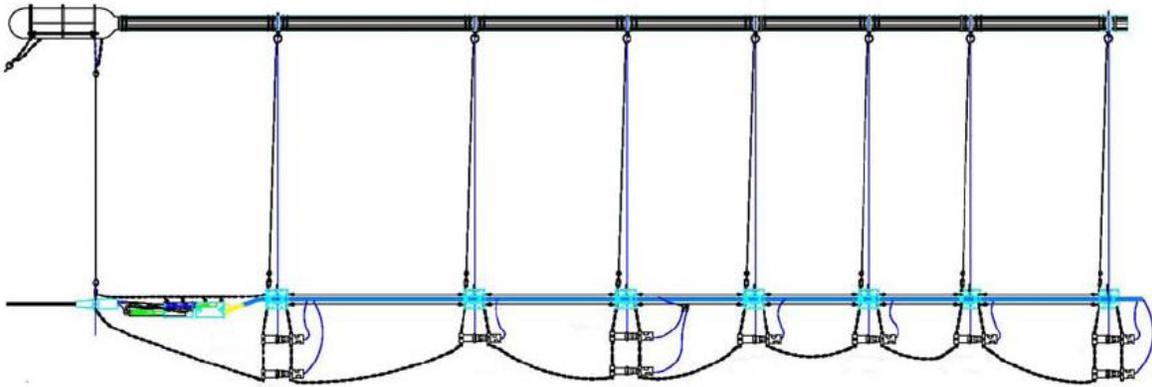


FIGURE 2. One linear airgun array or string with ten airguns.

10-Airgun Array Specifications

Energy Source	Ten 1950 psi Bolt airguns; 40–360 in ³
Source output (downward)	0-pk is 19.6 bar·m (246 dB re 1 μPa·m); pk-pk is 39.4 bar·m (252 dB)
Air discharge volume	~1830 in ³
Dominant frequency components	2–188 Hz

(f) Other Acoustical Systems

Along with the airgun operations, additional acoustical systems will be operated during the cruise. The ocean floor will be mapped with the Kongsberg EM 122 MBES and a Knudsen 320B SBP. These sound sources will be operated from the *Langseth* continuously throughout the cruise. An Acoustic Doppler Current Profiler (RDI OS75-kHz) may also be used.

Multibeam Echosounder

The Kongsberg EM 122 MBES operates at 10.5–13 (usually 12) kHz and is hull-mounted on the *Langseth*. The transmitting beamwidth is 1° fore–aft and 150° athwartship. The maximum source level is 242 dB re 1 μPa·m_{rms}. Each “ping” consists of eight (in water >1000 m deep) or four (<1000 m) successive fan-shaped transmissions, each ensonifying a sector that extends 1° fore–aft. Continuous-wave (CW) pulses increase from 2 to 15 ms long in water depths up to 2600 m, and frequency-modulated (FM) chirp pulses up to 100 ms long are used in water >2600 m. The successive transmissions span an overall cross-track angular extent of about 150°, with 2-ms gaps between the pulses for successive sectors.

Hydrographic Sub-bottom Profiler (Knudsen 320B)

The Knudsen 320B SBP is normally operated to provide information about the sedimentary features and the bottom topography that is being mapped simultaneously by the MBES. The beam is transmitted as a 27° cone, which is directed downward by a 3.5-kHz transducer in the hull of the *Langseth*. The maximum output is 1000 watts (204 dB), but in practice, the output varies with water depth. The ping interval is 1 s, but a common mode of operation is to broadcast five pings at 1-s intervals followed by a 5-s pause.

Langseth Sub-bottom Profiler Specifications

Maximum source output (downward)	204 dB re 1 μ Pa \cdot m; 800 watts
Dominant frequency components	3.5 kHz
Bandwidth	1.0 kHz with ping duration 4 ms 0.5 kHz with ping duration 2 ms 0.25 kHz with ping duration 1 ms
Nominal beam width	30 degrees
Ping duration	1, 2, or 4 ms

Acoustic Doppler Current Profiler (R D Instruments Ocean Surveyor 150 kHz)

The 150-kHz acoustic Doppler current profiler (ADCP™) has a minimum ping rate of 0.65 ms. There are four beam sectors and each beamwidth is 3°. The pointing angle for each beam is 30° off from vertical with one each to port, starboard, forward, and aft. The four beams do not overlap. The 150-kHz ADCP's maximum depth range is 300 m.

(3) Mitigation Measures

Several species of marine mammals are known to occur in the proposed study area. However, the number of individual animals expected to be approached closely during the proposed activities will be relatively small in relation to regional population sizes. With the proposed monitoring and mitigation provisions, potential effects on most if not all individuals are expected to be limited to minor behavioral disturbance. Those potential effects are expected to have negligible impacts both on individual marine mammals and on the associated species and stocks.

To minimize the likelihood that potential impacts could occur to the species and stocks, airgun operations will be conducted in accordance with all applicable U.S. federal regulations and IHA requirements.

The following subsections provide more detailed information about the monitoring and mitigation measures that are an integral part of the planned activities. The procedures described here are based on protocols used during previous L-DEO seismic research cruises as approved by NMFS, and on best practices recommended in Richardson et al (1995), Pierson et al. (1998), and Weir and Dolman (2007).

(a) Planning Phase

This survey was originally proposed to be scheduled in 2010 on the icebreaker USCGC *Healy*. Appropriate seismic equipment to meet the scientific requirements however could not be obtained in time for a survey to be conducted in 2010. The seismic equipment is integral to the success of the science mission; faulty or undependable equipment would put the mission at risk and a significant amount of funding would be lost. As a consequence, the survey was postponed until appropriate and reliable equipment could be obtained.

The R/V *Langseth*, the primary seismic vessel in the academic fleet, had a proposed 2011 schedule which included several surveys in the Alaska region. Given its proximity, the vessel operator and technicians, UNOLS schedulers, and NSF considered the possibility of the *Langseth* supporting the proposed action. The *Langseth* is not an ice-strengthened vessel and must especially consider safety-of-operations while towing a significant amount of equipment behind the vessel; it therefore cannot operate in ice conditions that would pose serious hazards to the vessel and crew. After consideration of the operational challenges, however, it was concluded that the *Langseth* would be able to support the activity

if it remained in ice-free waters. An ice expert would be available to help provide guidance during any operations. An additional aspect of using the *Langseth* to support the activity would be that another research vessel would not need to be moved into the area to support the activity, thereby reducing vessel presence in the region.

The PI worked with L-DEO and NSF to identify potential time periods to carry out the survey in 2011, taking into consideration key factors such as environmental conditions (i.e., ice conditions, the seasonal presence of marine mammals and sea birds), weather conditions, and equipment. The project's proposed timeframe avoids the eastward (spring) bowhead migration, but overlaps with that of the westward fall migration and the subsistence bowhead hunt along the north shore of Alaska near Barrow. To avoid disturbance, the seismic survey has been scheduled to depart from Dutch Harbor in early September and remain at least 200 km from Barrow during transit to and from the survey area, which is ~250–800 km northeast of Barrow. Also, to reduce potential effects, the size of the energy source was reduced from the *Langseth*'s 36-airgun, 6600-in³ array to a 10-gun, 1830-in³ array.

(b) Visual Monitoring

PSOs observations will take place during daytime airgun operations and nighttime start ups of the airguns. Airgun operations will be suspended when marine mammals are observed within, or about to enter, designated exclusion zones [see subsection (e) below] where there is concern about potential effects on hearing or other physical effects. PSOs will also watch for marine mammals near the seismic vessel for at least 30 min prior to the planned start of airgun operations after an extended shut down of the airguns. When feasible, observations will also be made during daytime periods when the *Langseth* is underway without seismic operations, such as during transits.

During seismic operations, at least five PSOs will be based aboard the *Langseth*. PSOs will be appointed by L-DEO with NMFS concurrence. During the majority of seismic operations, two PSOs will monitor for marine mammals around the seismic vessel. Use of two simultaneous observers will increase the effectiveness of detecting animals around the source vessel. However, during meal times, only one PSO may be on duty. PSO(s) will be on duty in shifts of duration no longer than 4 h. Other crew will also be instructed to assist in detecting marine mammals and implementing mitigation requirements. Before the start of the seismic survey, the crew will be given additional instruction on how to do so.

The *Langseth* is a suitable platform for marine mammal observations. When stationed on the observation platform, the eye level will be ~21.5 m above sea level, and the observer will have a good view around the entire vessel. During daytime, the PSO(s) will scan the area around the vessel systematically with reticle binoculars (e.g., 7×50 Fujinon), Big-eye binoculars (25×150), and with the naked eye. During darkness, night vision devices (NVDs) will be available (ITT F500 Series Generation 3 binocular-image intensifier or equivalent), when required. Laser rangefinding binoculars (Leica LRF 1200 laser rangefinder or equivalent) will be available to assist with distance estimation. Those are useful in training observers to estimate distances visually, but are generally not useful in measuring distances to animals directly; that is done primarily with the reticles in the binoculars.

When mammals are detected within or about to enter the designated exclusion zone, the airguns will immediately be powered down or shut down if necessary. The PSO(s) will continue to maintain watch to determine when the animal(s) are outside the exclusion zone. Airgun operations will not resume until the animal has left the exclusion zone.

The vessel-based monitoring will provide data to estimate the numbers of marine mammals exposed to various received sound levels, to document any apparent disturbance reactions or lack thereof,

and thus to estimate the numbers of mammals potentially “taken” by harassment. It will also provide the information needed in order to power down or shut down the airguns at times when mammals are present in or near the exclusion zone. When a sighting is made, the following information about the sighting will be recorded:

1. Species, group size, age/size/sex categories (if determinable), behavior when first sighted and after initial sighting, heading (if consistent), bearing and distance from seismic vessel, sighting cue, apparent reaction to the airguns or vessel (e.g., none, avoidance, approach, paralleling, etc.), and behavioral pace.
2. Time, location, heading, speed, activity of the vessel, sea state, visibility, and sun glare.

The data listed under (2) will also be recorded at the start and end of each observation watch, and during a watch whenever there is a change in one or more of the variables.

All observations and power downs or shut downs will be recorded in a standardized format. Data will be entered into an electronic database. The accuracy of the data entry will be verified by computerized data validity checks as the data are entered and by subsequent manual checking of the database. These procedures will allow initial summaries of data to be prepared during and shortly after the field program, and will facilitate transfer of the data to statistical, graphical, and other programs for further processing and archiving.

Results from the vessel-based observations will provide

1. The basis for real-time mitigation (airgun power down or shut down).
2. Information needed to estimate the number of marine mammals potentially taken by harassment, which must be reported to NMFS.
3. Data on the occurrence, distribution, and activities of marine mammals in the area where the seismic study is conducted.
4. Information to compare the distance and distribution of marine mammals relative to the source vessel at times with and without seismic activity.
5. Data on the behavior and movement patterns of marine mammals seen at times with and without seismic activity.

(c) Passive Acoustic Monitoring

Passive acoustic monitoring (PAM) will take place to complement the visual monitoring program. Visual monitoring typically is not effective during periods of poor visibility or at night, and even with good visibility, is unable to detect marine mammals when they are below the surface or beyond visual range. Acoustical monitoring can be used in addition to visual observations to improve detection, identification, and localization of marine mammals. The acoustic monitoring will serve to alert visual observers (if on duty) when vocalizing cetaceans are detected. It is only useful when marine mammals call, but it can be effective either by day or by night, and does not depend on good visibility. It will be monitored in real time so that the visual observers can be advised when marine mammals are detected.

The PAM system consists of hardware (i.e., hydrophones) and software. The “wet end” of the system consists of a towed hydrophone array that is connected to the vessel by a tow cable. The tow cable is 250 m long, and the hydrophones are fitted in the last 10 m of cable. A depth gauge is attached to the free end of the cable, and the cable is typically towed at depths <20 m. The array will be deployed from a

winch located on the back deck. A deck cable will connect the tow cable to the electronics unit in the main computer lab where the acoustic station, signal conditioning, and processing system will be located. The acoustic signals received by the hydrophones are amplified, digitized, and then processed by the Pamguard software. The system can detect marine mammal vocalizations at frequencies up to 250 kHz.

The towed hydrophones will ideally be monitored 24 h per day while at the seismic survey area during airgun operations, and during most periods when the *Langseth* is underway while the airguns are not operating. However, PAM may not be possible if damage occurs to the array or back-up systems during operations. One PSO will monitor the acoustic detection system at any one time, by listening to the signals from two channels via headphones and/or speakers and watching the real-time spectrographic display for frequency ranges produced by cetaceans. PSOs monitoring the acoustical data will be on shift for 1–6 h at a time. All PSOs are expected to rotate through the PAM position, although the most experienced with acoustics will be on PAM duty more frequently.

When a vocalization is detected while visual observations are in progress, the acoustic PSO will contact the visual PSO immediately, to alert him/her to the presence of cetaceans (if they have not already been seen), and to allow a power down or shut down to be initiated, if required. The information regarding the call will be entered into a database. The data to be entered include an acoustic encounter identification number, whether it was linked with a visual sighting, date, time when first and last heard and whenever any additional information was recorded, position and water depth when first detected, bearing if determinable, species or species group (e.g., unidentified dolphin, sperm whale), types and nature of sounds heard (e.g., clicks, continuous, sporadic, whistles, creaks, burst pulses, strength of signal, etc.), and any other notable information. The acoustic detection can also be recorded for further analysis.

(d) Proposed Exclusion Zones

Received sound levels have been predicted by Marine Acoustics, Inc. (MAI), in relation to distance and direction from the airguns, for the 10-airgun array. The MAI model was site specific; sound velocity profiles, bathymetry, and bottom composition were used to model propagation at seven sites 120–2727 m deep in the survey area that represented different physiographic provinces described by Jakobsson et al. (2003). The source model used was the CASS/GRAB model, and propagation was modeled using the Range-Dependent Acoustic Model (RAM) (Zingarelli and King 2005). The detailed modeling report can be found in Appendix A1.

Received sound levels for a single 40-in³ airgun were modeled by L-DEO. Figure 3 illustrates modeled received sound levels for a single airgun operating in deep water. The tow depth has minimal effect on the maximum near-field output and the shape of the frequency spectrum for the single airgun; thus, the predicted safety radii are essentially the same at different tow depths. As the L-DEO model does not allow for bottom interactions, and thus is most directly applicable to deep water and to relatively short ranges, correction factors were used to estimate safety radii in shallow and intermediate-depth water as was done for previous L-DEO surveys from the *Langseth*. A detailed description of the L-DEO modeling effort is provided in Appendix A2. The predicted sound contours for the 40-in³ mitigation airgun are shown as sound exposure levels (SEL) in decibels (dB) re 1 $\mu\text{Pa}^2 \cdot \text{s}$. SEL is a measure of the received energy in the pulse and represents the sound pressure level (SPL) that would be measured if the pulse energy were spread evenly across a 1-s period. Because actual seismic pulses are less than 1 s in duration in most situations, this means that the SEL value for a given pulse is usually lower than the SPL calculated for the actual duration of the pulse (see Appendix B). The advantage of working with SEL is that the SEL measure accounts for the total received energy in the pulse, and biological effects of pulsed sounds are believed to depend mainly on pulse energy (Southall et al. 2007). In contrast, SPL for a given pulse depends greatly on pulse duration.

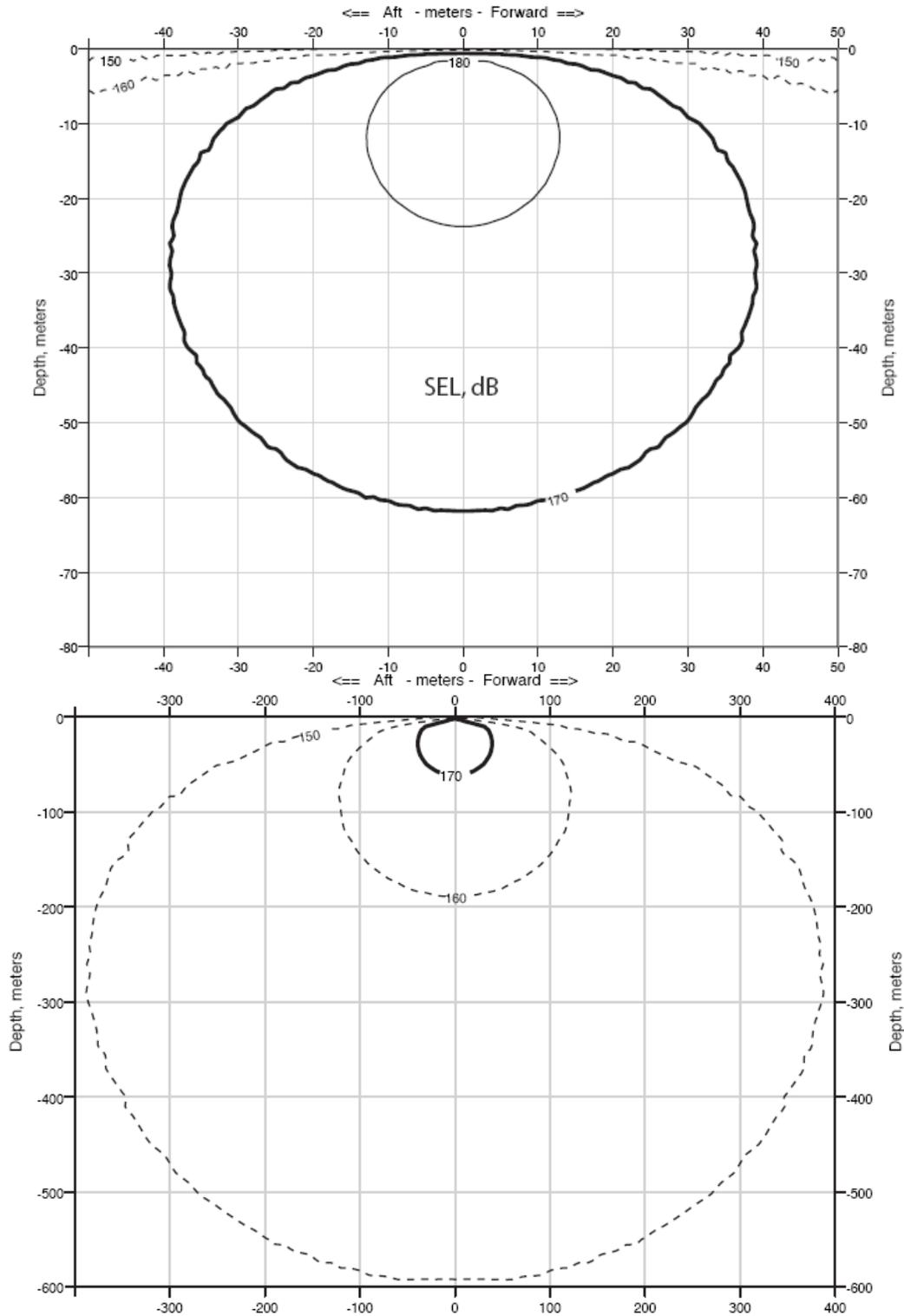


FIGURE 3. Modeled received sound levels (SELs) from a single 40-in³ airgun operating in deep water, which is planned for use as a mitigation airgun. Received rms levels (SPLs) are expected to be ~10 dB higher.

A pulse with a given SEL can be long or short depending on the extent to which propagation effects have “stretched” the pulse duration. The SPL will be low if the duration is long and higher if the duration is short, even though the pulse energy (and presumably the biological effects) are the same.

Although SEL is now believed to be a better measure than SPL when dealing with biological effects of pulsed sound, SPL is the measure that has been most commonly used in studies of marine mammal reactions to airgun sounds and in NMFS guidelines concerning levels above which “taking” might occur. SPL is often referred to as rms or “root mean square” pressure, averaged over the pulse duration. As noted above, the rms received levels that are used as impact criteria for marine mammals are not directly comparable to pulse energy (SEL). At the distances where rms levels are 160–190 dB re 1 μPa , the difference between the SEL and SPL values for the same pulse measured at the same location usually average ~10–15 dB, depending on the propagation characteristics of the location (Greene 1997; McCauley et al. 1998, 2000a; Appendix B). In this EA, we assume that rms pressure levels of received seismic pulses will be 10 dB higher than the SEL values predicted by L-DEO’s model. Thus, we assume that 170 dB SEL \approx 180 dB re 1 $\mu\text{Pa}_{\text{rms}}$. It should be noted that neither the SEL nor the SPL (=rms) measure is directly comparable to the peak or peak-to-peak pressure levels normally used by geophysicists to characterize source levels of airguns. Peak and peak-to-peak pressure levels for airgun pulses are always higher than the rms dB referred to in much of the biological literature (Greene 1997; McCauley et al. 1998, 2000a). For example, a measured received level of 160 dB re 1 $\mu\text{Pa}_{\text{rms}}$ in the far field typically would correspond to a peak measurement of ~170–172 dB re 1 μPa , and to a peak-to-peak measurement of ~176–178 dB re 1 μPa , as measured for the same pulse received at the same location (Greene 1997; McCauley et al. 1998, 2000a). (The SEL value for the same pulse would normally be 145–150 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$). The precise difference between rms and peak or peak-to-peak values for a given pulse depends on the frequency content and duration of the pulse, among other factors. However, the rms level is always lower than the peak or peak-to-peak level and (for an airgun-type source at the ranges relevant here) higher than the SEL value.

Table 1 shows the distances at which four rms sound levels are expected to be received from the 10-airgun array and a single airgun. For the 10-gun array, distances were modeled at seven sites; the distances in Table 1 are the averages from the sites in each depth range. The 180- and 190-dB re 1 $\mu\text{Pa}_{\text{rms}}$ distances are the safety criteria as specified by NMFS (2000) and are applicable to cetaceans and pinnipeds, respectively. If marine mammals are detected within or about to enter the appropriate exclusion zone, the airguns will be powered down (or shut down if necessary) immediately.

Southall et al. (2007) made detailed recommendations for new science-based noise exposure criteria. UAIG will be prepared to revise their procedures for estimating numbers of mammals “taken”, exclusion zones, etc., as may be required by any new guidelines established by NMFS as a result of these recommendations. However, currently the procedures are based on best practices noted by Pierson et al. (1998) and Weir and Dolman (2007) as NMFS has not yet specified a new procedure for determining exclusion zones.

(e) Mitigation During Operations

Mitigation measures that will be adopted during the survey include (1) power-down procedures, (2) shut-down procedures, and (3) ramp-up procedures.

Power-down Procedures.—A power down involves decreasing the number of airguns in use to one, such that the radius of the 180-dB (or 190-dB) zone is decreased to the extent that marine mammals are no longer in or about to enter the exclusion zone. A power down of the airgun array can also occur when the vessel is moving from one seismic line to another. During a power down for mitigation, one airgun will be operated. The continued operation of one airgun is intended to alert marine mammals to

TABLE 1. Maximum predicted distances to which sound levels ≥ 190 , 180, 170, and 160 dB re 1 $\mu\text{Pa}_{\text{rms}}$ could be received in various water-depth categories during the proposed survey in the Arctic Ocean. The distances for the 10-airgun array are the averages of modeled 95% percentile distances at modeling sites in each depth range (see text and Appendix A1).

Source and Volume	Tow Depth (m)	Water Depth	Predicted RMS Radii (m)			
			190 dB	180 dB	170 dB	160 dB
Single Bolt airgun 40 in ³	6 ¹	Deep (>1000 m)	12	40	120	385
		Intermediate (100–1000 m)	18	60	180	578
		Shallow (<100)	150	296	500	1050
1 string		Deep (>1000 m)	130	425	3180	14,070
10 airguns 1830 in ³	6 ¹	Intermediate (200–1000 m)	130	1400	5570	13,980
		Shallow (<200)	190	1870	5510	14,730

¹Although tow depth is listed as 6m, actual tow depth is irrelevant for this source level

the presence of the seismic vessel in the area. In contrast, a shut down occurs when all airgun activity is suspended.

If a marine mammal is detected outside the exclusion zone but is likely to enter the exclusion zone, the airguns will be powered down before the animal is within the exclusion zone. Likewise, if a mammal is already within the safety zone when first detected, the airguns will be powered down immediately. During a power down of the airgun array, the 40-in³ airgun will be operated. If a marine mammal is detected within or near the smaller exclusion zone around that single airgun (Table 1), it will be shut down (see next subsection).

Following a power down, airgun activity will not resume until the marine mammal has cleared the safety zone. The animal will be considered to have cleared the safety zone if

- it is visually observed to have left the exclusion zone, or
- it has not been seen within the zone for 15 min in the case of small odontocetes (or pinnipeds), or
- it has not been seen within the zone for 30 min in the case of mysticetes and large odontocetes, including sperm, pygmy sperm, dwarf sperm, and beaked whales.

During airgun operations following a power down (or shut down) whose duration has exceeded the limits specified above, the airgun array will be ramped up gradually. Ramp-up procedures are described below.

Shut-down Procedures.—The operating airgun(s) will be shut down if a marine mammal is seen within or approaching the exclusion zone for the single airgun. Shut downs will be implemented (1) if an animal enters the exclusion zone of the single airgun after a power down has been initiated, or (2) if an animal is initially seen within the exclusion zone of the single airgun when more than one airgun (typically the full array) is operating. Airgun activity will not resume until the marine mammal has cleared the safety zone, or until the PSO is confident that the animal has left the vicinity of the vessel. Criteria for judging that the animal has cleared the safety zone will be as described in the preceding subsection.

Ramp-up Procedures.—A ramp-up procedure will be followed when the airgun array begins operating after a specified period without airgun operations or when a power down has exceeded that

period. It is proposed that, for the present cruise, this period would be ~8 min. Similar periods (~8–10 min) were used during previous L-DEO surveys.

Ramp up will begin with the smallest airgun in the array (40 in³). Airguns will be added in a sequence such that the source level of the array will increase in steps not exceeding 6 dB per 5-min period over a total duration of ~15–20 min. During ramp up, the PSOs will monitor the exclusion zone, and if marine mammals are sighted, a power down or shut down will be implemented as though the full array were operational.

If the complete exclusion zone has not been visible for at least 30 min prior to the start of operations in either daylight or nighttime, ramp up will not commence unless at least one airgun (40 in³ or similar) has been operating during the interruption of seismic survey operations. Given these provisions, it is likely that the airgun array will not be ramped up from a complete shut down at night or in thick fog, because the outer part of the safety zone for that array will not be visible during those conditions. If one airgun has operated during a power-down period, ramp up to full power will be permissible at night or in poor visibility, on the assumption that marine mammals will be alerted to the approaching seismic vessel by the sounds from the single airgun and could move away. Ramp up of the airguns will not be initiated if a marine mammal is sighted within or near the applicable exclusion zones during the day or at night.

(f) Reporting

A report will be submitted to NMFS and NSF (with a copy to USFWS) within 90 days after the end of the cruise. The report will describe the operations that were conducted and the marine mammals that were detected near the operations. The report will provide full documentation of methods, results, and interpretation pertaining to all monitoring. The 90-day report will summarize the dates and locations of seismic operations, and all marine mammal sightings (dates, times, locations, activities, associated seismic survey activities). The report will also include estimates of the amount and nature of potential “takes” of marine mammals by harassment or in other ways.

Alternative Action: Another Time

In theory, an alternative to issuing the IHA for the period requested, and to conducting the project then, is to issue the IHA for another time, and to conduct the project at that alternative time. However, the window of opportunity for an Arctic Ocean cruise is extremely narrow because of the dependence on ice conditions and requirements of the *Langseth* to operate in ice-free waters. Late summer–early fall is by far the most suitable time, offering the least amount of ice pack and the most favorable weather conditions. Delaying the cruise could make it impractical and unsafe or impossible because of seasonal ice conditions.

A major scheduling consideration is the timing of bowhead whale migration in the Beaufort Sea, and the timing of the associated subsistence hunt for bowheads by Inupiat whalers. The project’s time-frame avoids the eastward bowhead migration. The whales typically pass westward through the Barrow area in September and October, and subsistence bowhead hunting along the north shore of Alaska near Barrow typically takes place from mid-September through mid-October. In consideration of the fall subsistence bowhead whale hunt, the seismic survey has been scheduled to depart northward from Dutch Harbor in early September, and the *Langseth* will remain at least 200 km from Barrow during transit to and from the survey area, which is ~250–800 km northeast of Barrow. A significant delay in the start of the cruise would reduce or eliminate the planned separation of the cruise from the bowheads (and bowhead hunt) and, as previously noted, result in potential operational issues with ice and poor weather conditions.

The overall schedule for the *Langseth* has been established to accomplish this cruise and other objectives in a coordinated and optimized manner. Likewise, the scientific personnel and specialized equipment to be deployed on the *Langseth* are available for the planned period but not necessarily for other periods. If the IHA was issued for a substantially different range of dates, that would very likely result in the need to cancel the 2011 cruise, given the probable inability to amend the schedules for all of the required project components. Also, any major change in dates would mean that the cruise could not occur during the optimum weather-and-ice period, which could also make the project impractical.

No Action Alternative

An alternative to conducting the proposed activities is the “No Action” alternative, i.e., do not issue an IHA and do not conduct the operations. If the planned geophysical research were not conducted, the “No Action” alternative would result in no disturbance to marine mammals attributable to the proposed activities, and no impacts of other types.

The purpose of the proposed study is to collect seismic reflection data across the transition from the Chukchi Shelf to the Chukchi Borderland to define the apparent change in structure between two large continental blocks. This study will test existing tectonic models and develop new constraints on the development of the Amerasian Basin, and will substantially advance our understanding of the Mesozoic history of this basin. In addition, these data will enable the formulation of new tectonic models for the history of this region, which will substantially expand our understanding of the surrounding continents. The “No Action” alternative, through forcing cancellation of the planned seismic survey in the Arctic Ocean, would result in a loss of important scientific data and knowledge relevant to a number of research fields. The “No Action” alternative could also, in some circumstances, result in significant delay of other geophysical studies that are proposed for the *Langseth* in 2011, depending on the timing of the decision. The entire proposal, based on the premise of collecting these data, would be compromised.

III. AFFECTED ENVIRONMENT

Physical Environment

The Arctic Ocean is the smallest of the world’s oceans, covering 14,090,000 km². The arctic region contains a number of the world’s 64 Large Marine Ecosystems¹ (LME), including three near the proposed survey area: the Chukchi Sea, Beaufort Sea, and Arctic Ocean LMEs (UN 2011). The proposed project is active entirely within the Arctic Ocean, based on boundaries defined by the International Hydrographic Commission.

There are three main water layers in the Arctic Ocean: (1) relatively fresh, low-salinity surface water, (2) an intermediate layer that is composed of warmer, saltier Atlantic water, which enters north of Spitzbergen, and (3) cold, deep water which flows in across the submarine ridge between Spitzbergen and Greenland (Sverdrup et al. 1942; McLaughlin et al. 1996).

Surface water enters the Arctic Ocean mainly from the Pacific Ocean through the shallow Bering Straits and from the Atlantic Ocean through the eastern part of Fram Strait. These source waters are

¹ LMEs are organizational units that facilitate management and governance strategies; they are relatively large regions that have been “delineated based on continuities in their physical and biological characteristics, including *inter alia* bathymetry, hydrography, productivity and trophically dependent populations” (UN 2011).

modified by river runoff and meltwater in summer and by salt rejection during freezing in winter, resulting in a characteristic surface brackish layer (lower salinity) that can reach ~30–50 m in thickness. A smaller quantity of water is transported southward through the Barents and Kara seas and the Canadian Archipelago. Approximately 2% of the water entering the Arctic Ocean is fresh water, and precipitation in the region is ~10 times greater than loss by evaporation.

The core of the intermediate layer occurs at ~300 m and extends to a depth of ~400 m. Two water masses are evident within the bottom layer: (1) Eurasian Basin deep water, and (2) Canadian Basin deep water, separated by the Lomonosov Ridge (Woodgate et al. 2001). Warmer Atlantic water underlies the Arctic surface waters to a depth of ~900 m. As this water cools it becomes so dense that it slips below the surface layer as it enters the Arctic Basin. Cold bottom water extends beneath the Atlantic layer to the ocean floor.

Arctic surface waters are driven by wind and density differences and by a clockwise surface circulation pattern that reaches speeds of 15–40 cm/sec. The deep boundary current in the Arctic Ocean appears to be characterized by weak mean flows and strong, isolated eddies (Aagaard 1989; Woodgate et al. 2001).

The Arctic is dominated by ice cover that opens significantly during summer only in the coastal seas to the north of Asia, Alaska, and northern Canada. Sea ice rarely forms in the open ocean below 60°N. Between 60°N and 75°N it is present seasonally. Above 75°N, ice cover is present on a largely permanent basis. The Arctic has notable year-to-year variations in ice cover although an increasing trend in the retreat of the pack ice in recent years has been documented (Stroeve et al. 2008). When ice is present it suppresses wind stress and wind mixing and also reflects solar radiation, thereby lowering surface temperature and impeding evaporation. Wind and surface stresses keep the ice pack in constant motion, resulting in the formation of leads, polynyas, pressure ridges, shear zones, and other features.

The deepest sounding made in the Arctic Ocean is 5502 m, although the average depth is 972 m. The Arctic Ocean consists of two main deep basins that can be subdivided into four smaller basins by three transoceanic submarine ridges. The Lomonosov Ridge is the centermost of these ridges and extends from the continental shelf off Ellesmere Island to the New Siberian Islands. The Lomonosov Ridge has an average relief of about 3000 m and divides the Arctic Ocean into two basins: the Eurasia Basin and the Amerasia Basin. The Amerasia Basin is further divided by the Mendeleev Ridge–Alpha Ridge complex into the Makarov Basin and the Canada Basin. The proposed survey will start just north of the boundary between the Chukchi Sea and the Arctic Ocean and extend northward to the Chukchi Borderland (Fig. 1).

Biological Environment

The Arctic Ocean is classified as a low productivity ecosystem, a consequence of the extensive seasonal ice cover and extreme weather conditions. The Arctic plankton show weak diurnal vertical migrations but pronounced seasonal ones. The Arctic fauna is impoverished and consists mainly of organisms derived from the Atlantic Ocean. The biomass is low, often dominated by one of only a few species. Because of the extensive areas of sediments, the Arctic benthic fauna is mainly an infauna. Specialized endemic fish are not present in the Arctic. Marine mammals are diverse.

Fish and Fisheries

FishBase, a global information system on fishes available electronically, lists 123 species for the Arctic Ocean, including bays and gulfs (Froese and Pauly 2010). The total includes 18 salmonid species that likely would not occur in the offshore waters of the survey area.

Fisheries catches in the Arctic Ocean LME during 1950–2006 are given in Figure 4. The vast majority of the fish caught are small (<30 cm) demersals caught in bottom trawls; in 2006, most catches were taken by Sweden (68%), Norway (25%), and Japan (5%) (Sea Around Us Project 2010). However, there is no fishing activity along most of the planned seismic survey route.

Essential Fish Habitat

The *Magnuson-Stevens Fishery Conservation and Management Act* (16 U.S.C. §1801-1882) established Regional Fishery Management Councils and mandated that Fishery Management Plans (FMPs) be developed to manage exploited fish and invertebrate species responsibly in federal waters of the U.S. Congress reauthorized the act in 1996 as the *Sustainable Fisheries Act* to require the description and identification of EFH and FMPs, adverse impacts on EFH, and actions to conserve and enhance EFH. Guidelines were developed by NMFS to assist fishery management councils in fulfilling the requirements set forth by the MSA.

The North Pacific Fisheries Management Council (NPFMC) was tasked with preparation of an FMP for the Arctic Management Area, which includes all marine waters in the U.S. EEZ of the Chukchi and Beaufort seas from 3 n.mi. offshore of the Alaska coast to 200 n.mi. (370 km) offshore. The FMP was approved by the Secretary of Commerce in August 2009 and governs commercial fishing for all stocks of fish including all finfish, shellfish, or other marine living resources, except commercial fishing for Pacific salmon and Pacific halibut. EFH established in the FMP includes all waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity. Identification of EFH is based on the historical range of target species but may expand or contract based on a variety of factors including changes in environmental variables, population size, and predator/prey distribution. EFH may be specific to a specific life stage such as egg, larval, juvenile, etc. EFH is described for only one target species, arctic cod (*Boreogadus saida*), including late juveniles and adults, that is likely to occur in the proposed survey area (NPFMC 2009).

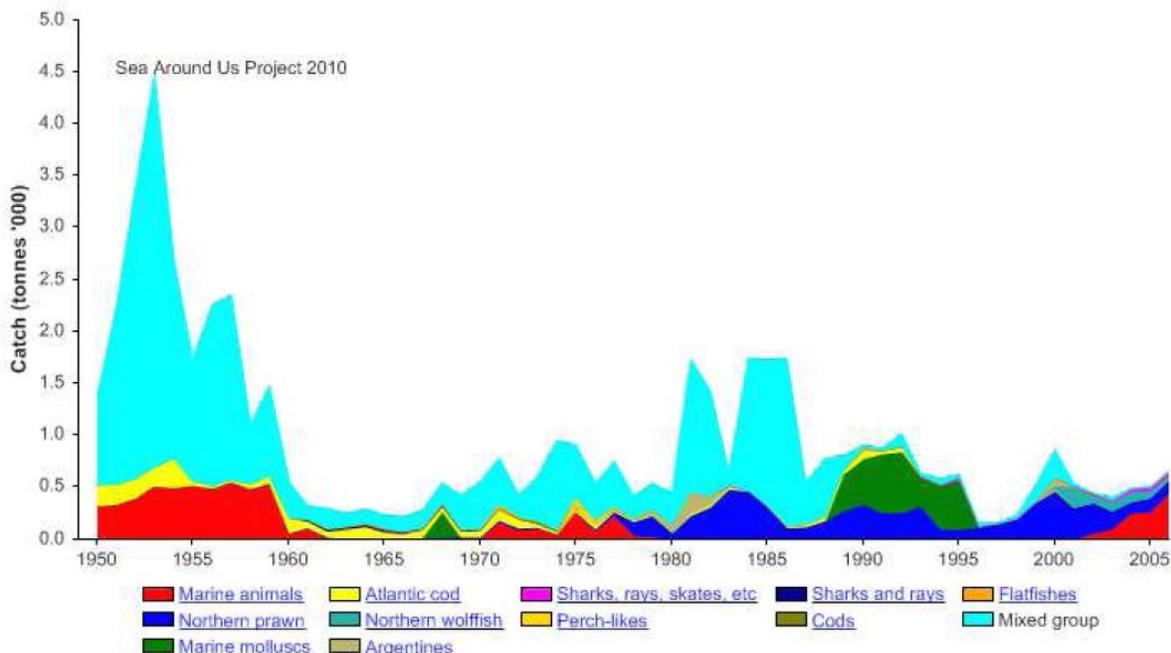


FIGURE 4. Fisheries landings for the Arctic Ocean LME, Source: Sea Around Us Project (2010).

Seabirds

Four bird species of special concern may be encountered during transits off the coast of Alaska, but not likely during the seismic component of the survey as that would be >200 km from the coast. Spectacled eiders (*Somateria fischeri*) travel west along the arctic coast after breeding across the Arctic Coastal Plain (ACP) of northern Alaska. Both marine and terrestrial (for males in particular) routes are used during migration (Troy 2003). Steller's eiders (*Polysticta stelleri*) also breed on the ACP and move to marine habitats after breeding (Fredrickson 2001), but occur in much lower densities than spectacled eiders and would be less likely to be encountered by transiting vessels. Spectacled and Steller's eiders were listed as **threatened** in the U.S. under the U.S. Endangered Species Act in May 1993 and July 1997, respectively. In addition, the Kittlitz's murrelet (*Brachyramphus brevirostris*) and yellow-billed loon (*Gavia adamsii*) are candidate species for ESA listing and may be encountered during transits off the coast of Alaska.

(1) Spectacled Eider

The spectacled eider is a medium-sized sea duck that breeds along coastal areas of western and northern Alaska and eastern Russia, and winters in the Bering Sea (Petersen et al. 2000). Three breeding populations have been described: one in the Yukon-Kuskokwim (Y-K) delta in western Alaska, a second on the North Slope of Alaska, and the third in northeastern Russia. The spectacled eider was listed as a **threatened** species because of declines in the breeding population in the Y-K delta (Stehn et al. 1993; Ely et al. 1994). The North Slope spectacled eider population seems to be stable, although surveys have been conducted only since 1992 (Larned et al. 2009a).

Males leave the breeding grounds along the coastal plain earlier than females. Male and female spectacled eiders have been documented migrating west along the Alaska coast as far as 24 and 40 km offshore, respectively (TERA 1999). The *Langseth* survey will begin and end seismic operations >200 km offshore, beyond the known range of spectacled eiders.

(2) Steller's Eider

Steller's eiders breed across coastal eastern Siberia and the ACP of Alaska. A smaller population also breeds in western Russia and winters in northern Europe (Fredrickson 2001). Steller's eiders were formerly common breeders in the Y-K delta, but numbers there declined drastically, and Steller's eider is now apparently rare or extinct as a breeding species on the Y-K delta (Kertell 1991; Flint and Herzog 1999). Steller's eider density on the ACP is low, with the highest densities reported near Barrow; the largest population, located in eastern Russia, may number >128,000 birds (Hodges and Eldridge 2001).

Steller's eiders have been observed east of Barrow in the Prudhoe Bay area where they are considered rare (TERA 1997). Although Steller's eiders may breed in a relatively large area of the ACP as far east as the Prudhoe Bay area, densities are low. Steller's eiders apparently do not breed every year, and breeding may be tied to the lemming cycle (Quakenbush et al. 2004). After the breeding season Steller's eiders move to nearshore marine habitats, using lagoon systems and coastal bays along the coast of Alaska to molt (USFWS 2002). The young Steller's eiders hatch in late June. Male departure from the breeding grounds begins in late June or early July. Females that fail in breeding attempts may remain in the Barrow area into late summer. Females and fledged young depart the breeding grounds in early to mid-September.

(3) Kittlitz's Murrelet

Kittlitz's murrelet breeds only in Alaska and the Russian Far East. In Alaska, it is found from just east of Cape Lisburne south to the Aleutian Islands and east to LeConte Bay. Kittlitz's murrelet has the smallest population of any seabird breeding in Alaska, and populations have been declining in recent years. The reasons for the declining populations are not well known but may be related to global climate changes that cause glacial retreat (Kuletz et al. 2003) and loss of breeding and/or foraging habitat. Kittlitz's murrelet may also be at risk from the effects of oil spills (e.g., Van Vliet and McAllister 1994) and gillnet fishing for salmon. Kittlitz's murrelet is a candidate for listing under the ESA as threatened or endangered (USFWS 2004), but it is not currently listed. It is listed as critically endangered on the 2010 IUCN Red List of Threatened Species (IUCN 2010). The population is estimated at 13,000–35,000 birds, with ~9000–25,000 in Alaska (BirdLife International 2011).

Unlike many seabirds that nest in large colonies, Kittlitz's murrelets nest singly in dispersed locations. Nests are located on the ground, primarily in unvegetated scree associated with previously glaciated areas, or on cliff faces (Day et al. 1999). A single egg is laid in an open scrape, but little is known about the incubation or fledging periods.

(4) Yellow-billed Loon

In Alaska, the yellow-billed loon is the least abundant of the loon species. As the yellow-billed loon's restricted range, small population size, habitat requirements, and threats to breeding habitat are of concern (Earnst 2004), this species is currently designated as a candidate species under the ESA. Although the USFWS has determined that listing the yellow-billed loon as a threatened or endangered species is warranted under the ESA, that listing is currently precluded by other higher priority species. The "warranted but precluded" finding was published in the Federal Register on 25 March 2009 (USFWS 2009b).

Yellow-billed loons breed on arctic and subarctic tundra of northern Alaska, Canada, and Eurasia from June through September. The Russian population is estimated at ~5000 (Fair 2002 in Earnst 2004); the North American population is estimated at ~16,000, with 6024 in Alaska (Earnst et al. 2005) and 9975 in Canada (Earnst 2004). Less than 1000 nesting pairs are thought to occur in northern Alaska annually (Earnst 2004; Earnst et al. 2005). Based on aerial surveys, the yellow-billed loon population on the Arctic Coastal Plain of Alaska has been stable since at least 1986, with a slightly increasing growth trend during the last 10 years (Larned et al. 2009b).

(5) Other Seabirds, Shorebirds, and Waterfowl

In addition to the two eider species described above, a portion of the project area is within the range of a number of other seabird, shorebird, and waterfowl species. Most of these species would be found mainly within 30 km of shore where no seismic activities will take place. Summer bird densities in offshore marine waters of the Beaufort Sea are considered to be lower than in other marine areas adjacent to Alaska (USACE 1999). There is a general absence of diving seabirds in the offshore waters, with the exception of small numbers of thick-billed murres (*Uria lomvia*), horned puffins (*Fratercula corniculata*), and black guillemots (*Cephus grylle*). A few species of surface-feeding birds also make use of offshore waters, including red and red-necked phalaropes (*Phalaropus fulicaria* and *P. lobatus*), pomarine, parasitic and long-tailed jaegers (*Stercorarius pomarinus*, *S. parasiticus*, and *S. longicaudus*), Arctic tern (*Sterna paradisaea*), and glaucous gulls (*Larus hyperboreus*). Divoky (1979) reported a bird density during the open water season in offshore waters >18 m at <10 birds/km².

Divoky (1983) conducted extensive boat-based surveys in the Beaufort Sea during early August through mid-September. The primary species observed during pelagic surveys were surface-feeding species including gulls, terns, phalaropes, and jaegers. Long-tailed ducks, loons, and migrant eiders as well as low densities of surface-feeding species were reported during nearshore surveys. Pelagic birds were feeding primarily on arctic cod while nearshore birds were feeding on epibenthic crustaceans and zooplankton.

Frame (1973) conducted seabird observations from an icebreaker in the Beaufort Sea during August 1969 and reported black-legged kittiwake (*Rissa tridactyla*) as the most abundant species, followed by Sabine's gull (*Xema sabini*). Pomarine and long-tailed jaegers were the other two most commonly observed species along with unidentified shorebirds.

Fischer and Larned (2004) conducted more recent aerial surveys of marine birds in 1999 and 2000 in areas up to 100 km offshore of the Alaskan Beaufort Sea. Approximately 90% of birds observed were sea ducks, primarily long-tailed ducks (*Clangula hyemalis*), king eiders (*Somateria spectabilis*), and scoters (*Melanitta* spp.). Densities of most species decrease with distance offshore although king eiders densities were higher in deeper, offshore waters.

Harwood et al. (2005) recorded the distribution of birds during oceanographic studies through the Canadian Basin, Beaufort Sea, and Chukchi Sea. Between 16 August and 6 October 2002, they recorded 16 bird species and a total of 1213 birds. The birds were found in greater density in areas where oceanographic features such as a shelf break, or an area of coastal upwelling, heightened productivity.

Marine Mammals

A total of nine cetacean species, five species of pinnipeds, and one marine carnivore are known to or may occur in or near the proposed study area (Table 2). Three of these species, the bowhead whale, humpback whale, and fin whale, are listed as *endangered* under the ESA, and the polar bear is listed as *threatened* under the ESA.

The marine mammals that occur in the proposed survey area belong to three taxonomic groups: odontocetes (toothed cetaceans, such as beluga whale and narwhal), mysticetes (baleen whales), and carnivora (pinnipeds and polar bears). Cetaceans and pinnipeds (except walrus) are the subject of the IHA Application to NMFS; in the U.S., the walrus and polar bear are managed by USFWS.

The marine mammal species most likely to be encountered during the seismic survey include two cetacean species (beluga and bowhead whale) and two pinniped species (ringed and bearded seal). However, most of these species will occur in low numbers and are most common within 100 km of shore, where no seismic work is planned to take place. The marine mammal most likely to be encountered throughout the cruise is the ringed seal.

Seven additional cetacean species—narwhal, killer whale, harbor porpoise, gray whale, minke whale, fin whale, and humpback whale—could occur in the project area but are unlikely to be encountered during the survey because they are primarily coastal species or rare because they are outside of their normal range in the survey area in the Arctic Ocean. The gray whale is a coastal species that occurs regularly in continental shelf waters along the Chukchi Sea coast in summer and to a lesser extent along the Beaufort Sea coast. Recent evidence from monitoring activities in the Chukchi and Beaufort seas during industry seismic surveys suggests that the harbor porpoise, also a coastal species, and the minke whale, both of which have been considered uncommon or rare in the Chukchi and Beaufort seas, may be increasing in numbers in these areas (Funk et al. 2010). Small numbers of killer whales have also been recorded during recent industry surveys, along with a few sightings of fin and humpback whales.

TABLE 2. The habitat, abundance, and conservation status of marine mammals that could occur in or near the proposed study area in the Arctic Ocean.

Species	Habitat	Regional abundance	ESA ¹	IUCN ²	CITES ³
Mysticetes					
Bowhead whale, <i>Balaena mysticetus</i>	Pack ice, coastal	11,836 ⁴	EN	LC	I
Gray whale, <i>Eschrichtius robustus</i>	Coastal, lagoons	19,126 ⁵	DL	LC	I
Humpback whale, <i>Megaptera novaeangliae</i>	Shelf, coastal	20,800 ⁶	EN	LC	I
Minke whale, <i>Balaenoptera acutorostrata</i>	Shelf, coastal	810 ⁷	NL	LC	I
Fin whale, <i>Balaenoptera physalus</i>	Slope, mostly pelagic	13,620-18,680 ⁸	EN	EN	I
Odontocetes					
Beluga whale, <i>Delphinapterus leucas</i>	Offshore, coastal, Ice edges	42,968 ⁹	NL	NT	II
Narwhal, <i>Monodon monoceros</i>	Offshore, Ice edge	N.A. ¹⁰	NL	NT	II
Killer whale, <i>Orcinus orca</i>	Widely distributed	N.A.	NL	DD	II
Harbor porpoise, <i>Phocoena phocoena</i>	Coastal, inland waters, shallow offshore waters	48,215 ¹¹	NL	LC	II
Pinnipeds					
Pacific walrus, <i>Odobenus rosmarus</i>	Coastal, pack ice, ice floes	~200,00-246,000 ¹⁶	R	DD	III
Bearded seal, <i>Erignathus barbatus</i>	Pack ice, open water	250,000-300,000 ¹²	R	LC	–
Spotted seal, <i>Phoca largha</i>	Pack ice, open water, coastal haulouts	~59,214 ¹³	NL	DD	–
Ringed seal, <i>Pusa hispida</i>	Landfast ice, pack ice, open water	>249,000 ¹⁴	R	LC	–
Ribbon seal, <i>Histiophoca fasciata</i>	Pack ice, open water	90,000–100,000 ¹⁵	NL	DD	–
Ursids					
Polar bear, <i>Ursus maritimus</i>	Pack ice	4700 ¹⁷	T	VU	II

N.A. = Not available

¹ U.S. Endangered Species Act: EN = Endangered, T = Threatened, NL = Not listed, R = In review for listing; DL = Delisted.

² Classifications are from the IUCN *Red List of Threatened Species* (IUCN 2010): EN = Endangered; VU = Vulnerable; NT = Near Threatened; LC = Least Concern; DD = Data Deficient.

³ Convention on International Trade in Endangered Species of Wild Fauna and Flora (UNEP-WCMC 2011): 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.

⁴ Based on 2003-2004 surveys (Koski et al. 2008).

⁵ Eastern North Pacific gray whale population (Allen and Angliss 2010).

⁶ North Pacific Ocean (Barlow et al. 2009).

⁷ Central-eastern Bering Sea (Allen and Angliss 2010).

⁸ North Pacific (Ohsumi and Wada 1974).

⁹ Sum of Eastern Chukchi Sea and Beaufort Sea stocks (Allen and Angliss 2010)

¹⁰ Baffin Bay and Canadian Arctic archipelago population (COSEWIC 2004).

¹¹ Bering Sea stock (Allen and Angliss 2010).

¹² Based on early estimates of the Bering-Chukchi Sea population (see Allen and Angliss 2010)

¹³ Alaska stock based on aerial surveys in 1992 (Allen and Angliss 2010).

¹⁴ Minimum estimate for Beaufort and Eastern Chukchi Sea populations (Allen and Angliss 2010)

¹⁵ Bering Sea population in the mid 1970s (Allen and Angliss 2010).

¹⁶ 1975-1990 (Allen and Angliss 2010).

¹⁷ Chukchi Sea and northern and southern Beaufort Sea populations combined (Aars et al. 2006).

The narwhal occurs in Canadian waters and occasionally in the Beaufort Sea, but is rare there and not expected to be encountered.

Additional pinniped species that could be encountered during the proposed survey include the spotted seal, ribbon seal, and Pacific walrus. Spotted seals are more abundant in the Chukchi Sea and occur in small numbers in the Beaufort Sea. The ribbon seal is uncommon in the Chukchi Sea, and there are few sightings in the Beaufort Sea. The Pacific walrus is common in the Chukchi Sea but uncommon in the Beaufort Sea, and not likely to occur in the far offshore waters of the proposed survey area in the Arctic Ocean. None of these species would likely be encountered during the proposed cruise other than perhaps during transit periods to or from the survey area.

Polar bears occur on the pack ice in low densities. As the vessel will avoid the ice edge, it is unlikely that many polar bears would be encountered in the open-water study area.

(1) Mysticetes

Bowhead Whale

The bowhead whale only occurs at high latitudes in the northern hemisphere and has a disjunct circumpolar distribution (Reeves 1980). It is one of only three whale species that spends its entire life in the Arctic. The bowhead whale is listed as *endangered* under the ESA, *least concern* on the IUCN Red List of Threatened Species (IUCN 2010), and it is listed in CITES Appendix I (UNEP-WCMC 2011) (Table 2). Of four or five stocks recognized worldwide by the International Whaling Commission (IWC), the Bering–Chukchi–Beaufort (BCB) Stock is the one that occurs in Alaskan waters. The latest, and preliminary, abundance estimate for 2003–2004 is 11,836 (95% CI = 6795–20,618), based on a photographic survey conducted in spring 2003 (Koski et al. 2008). Between 1978 and 2001, the population is estimated to have increased at a rate of ~3.4% per year (George et al. 2004; Zeh and Punt 2005).

The BCB Stock winters in the central and western Bering Sea and summers in the Canadian Beaufort Sea and Amundsen Gulf (Moore and Reeves 1993). Spring migration through the western Beaufort Sea occurs through offshore ice leads, generally from mid-April through mid-June (Braham et al. 1984; Moore and Reeves 1993). In recent years, whale migration has occurred in early April and at times in late March (Quakenbush and Huntington 2010). The whales make the return migration west through the Alaskan Beaufort Sea in the fall to wintering areas in the Bering Sea. Satellite tracking data indicate that some bowhead whales continue migrating west past Barrow and through the Chukchi Sea to Russian waters before turning south toward the Bering Sea (Quakenbush 2007). Some bowheads may reach ~75°N latitude during the westward fall migration (Quakenbush et al. 2010a). Other researchers have also reported a westward movement of bowhead whales through the northern Chukchi Sea during fall migration (Moore et al. 1995, 2000b; Mate et al. 2000).

Fall migration into Alaskan waters is primarily during September and October. However, in recent years a small number of bowheads have been seen or heard offshore from the Prudhoe Bay region during the last week of August (Treacy 1993; LGL and Greeneridge 1996; Greene 1997; Greene et al. 1999a, 2007; Blackwell et al. 2004, 2010). Consistent with this, Nuiqsut whalers have stated that the earliest arriving bowheads have apparently reached the Cross Island area earlier in recent years than formerly (T. Napageak, pers. comm.).

Bowheads tend to migrate west in deeper water (farther offshore) during years with higher-than-average ice coverage than in years with less ice (Moore 2000; Treacy et al. 2006). The migration corridor ranged from ~30 km offshore during light ice years to ~80 km offshore during heavy ice years (Treacy et

al. 2006). In addition, the sighting rate tends to be lower in heavy ice years (Treacy 1997:67). During fall migration, most bowheads migrate west in water ranging from 15 to 200 m deep (Miller et al. 2002). Some individuals enter shallower water, particularly in light ice years, but very few whales are ever seen shoreward of the barrier islands in the Alaskan Beaufort Sea. Survey coverage far offshore in deep water is usually limited, and offshore movements may have been underestimated. However, the main migration corridor is over the continental shelf.

Westbound bowheads typically reach the Barrow area in mid-September, and are in that area until late October (e.g., Brower 1996). In recent years bowhead whales have been seen near Barrow in late August and, if ice conditions are favorable, in early August (Huntington and Quakenbush 2009). Whaling near Barrow can continue into October, depending on the quota and conditions.

Sekiguchi et al. (2008) reported one sighting of an aggregation of ~30 bowheads during vessel-based operations ~130 km north of Cape Lisburne on 9 August 2007. Bowhead whales were not reported by vessel-based observers during cruises in the Arctic Ocean north of Barrow in August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). One bowhead whale that was satellite-tagged in Barrow on 23 September 2008 traveled 330 km northwest of Barrow (~73°N; 163°W), just south of and near the southern extent of the proposed survey area in water depths ~200 m. One whale tagged in late August 2007 traveled further northwest (~75°N; 176°W), near of the western extent of the proposed survey area in water depths of 600 m (Quakenbush et al. 2010a). One whale tagged in the fall of 2009 traveled as far as ~76°N; 179°W, its path intersecting with the proposed survey area (Quakenbush et al. 2010b).

Given the recent telemetry data (Quakenbush et al. 2010a,b), some bowheads are expected to be encountered during the proposed survey >200 km offshore in the Arctic Ocean.

Gray Whale

There are two extant populations of gray whales—the Eastern North Pacific Stock that ranges between summer grounds in the Chukchi and Beaufort seas to wintering lagoons in Baja, California, and the remnant Western North Pacific Stock that summers mainly in the Sea of Okhotsk, particularly in the waters off northeastern Sakhalin Island. The larger eastern Pacific or California gray whale population recovered significantly from commercial whaling during its protection under the ESA; the population was delisted from the ESA in 1994. The latest (2006–2007) population size estimate is 19,126 (Allen and Angliss 2010).

Eastern Pacific gray whales breed and calve in the protected waters along the west coast of Baja, California, and the east coast of the Gulf of California from January to April (Swartz and Jones 1981; Jones and Swartz 1984). At the end of the breeding and calving season, most of these gray whales migrate ~8000 km, generally along the west coast, to the main summer feeding grounds in the northern Bering and Chukchi seas (Tomilin 1957; Rice and Wolman 1971; Braham 1984; Nerini 1984; Moore et al. 2003; Bluhm et al. 2007).

Most summering gray whales congregate in the northern Bering Sea, particularly off St. Lawrence Island and in the Chirikov Basin (Moore et al. 2000a), and in the southern Chukchi Sea. More recently, Moore et al. (2003) suggested that gray whale use of Chirikov Basin has decreased, likely as a result of the combined effects of changing currents resulting in altered secondary productivity dominated by lower quality food. The northeastern-most of the recurring feeding areas is in the northeastern Chukchi Sea southwest of Barrow (Clarke et al. 1989). Moore et al. (2000b) reported that during the summer, gray

whales in the Chukchi Sea were clustered along the shore primarily between Cape Lisburne and Point Barrow and were associated with shallow, coastal shoal habitat. In autumn, gray whales were clustered near shore at Point Hope and between Icy Cape and Point Barrow, and in offshore waters northwest of Point Barrow at Hanna Shoal and southwest of Point Hope. Based on aerial surveys of nearshore waters of the eastern Chukchi Sea, Thomas et al. (2010) reported that gray whale sighting rates and abundance were greater in the 0–5 km offshore band in 2006, and in the 25–30 km band in 2007 and 2008; they suggested that the difference in distribution may have been attributable to differences in food availability and perhaps ice conditions.

Only a small number of gray whales enter the Beaufort Sea east of Point Barrow. In recent years, ice conditions have become lighter near Barrow, and gray whales may have become more common. Several gray whale sightings were reported during both vessel-based and aerial surveys in the Beaufort Sea during 2006–2008 (Funk et al. 2010) and in 2010 (Beland and Ireland 2010). Several single gray whales have been seen farther east in the Canadian Beaufort Sea (Rugh and Fraker 1981; LGL Ltd., unpubl. data), indicating that small numbers must travel through the Alaskan Beaufort during some summers. However, no gray whales were sighted during cruises north of Barrow in 2002, August–September 2005, July–August 2006, or August–September 2009 (Harwood et al. 2005; Haley 2006; Haley and Ireland 2006; Mosher et al. 2009). Given that most gray whales are typically seen nearshore, and the seismic survey is proposed to occur far offshore, no more than a few gray whales are expected to be in the region at the time of the proposed survey.

Humpback Whale

The humpback whale is found throughout all of the oceans of the world (Clapham 2002). The species is listed as *endangered* under the ESA, *least concern* on the IUCN Red List of Threatened Species (IUCN 2010), and it is listed in CITES Appendix I (UNEP-WCMC 2011) (Table 2). The worldwide population of humpback whales is divided into northern and southern ocean populations, but genetic analyses suggest some gene flow (either past or present) between the North and South Pacific oceans (e.g., Baker et al. 1993; Caballero et al. 2001). Based on a collaborative study involving numerous jurisdictions, the North Pacific stock has been recently estimated at 18,302 whales (excluding calves; Calambokidis et al. 2008). Barlow et al. (2009) provided a bias-corrected abundance estimate of 20,800. Overall, the North Pacific stock is considered to be increasing.

In the Bering Sea, humpback whales have been sighted southwest of St. Lawrence Island, in the southeastern Bering Sea, and north of the central Aleutian Islands (Moore et al. 2002; Allen and Angliss 2010). Recently there have been sightings of humpback whales in the Chukchi Sea and a single sighting in the Beaufort Sea (Greene et al. 2007; Funk et al. 2010). Haley et al. (2010) reported three humpback whales during vessel-based surveys in the Chukchi Sea in 2007 and one sighting in 2008. A humpback whale sighting was also made during the 2009 Chukchi Offshore Monitoring in Drilling Area (COMIDA) aerial surveys (COMIDA 2011). Greene et al. (2007) reported and photographed a humpback whale cow/calf pair east of Barrow near Smith Bay in 2007. No humpback whales were reported during cruises in the Arctic Ocean north of Barrow in August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). Humpback whales could occur in the Chukchi Sea and possibly in the Beaufort Sea but would be unlikely to occur in the offshore waters of the proposed survey area in the Arctic Ocean.

Minke Whale

The minke whale has a cosmopolitan distribution that spans polar, temperate, and tropical regions (Jefferson et al. 2008). In the Northern Hemisphere, minke whales are usually seen in coastal areas, but

can also be seen in pelagic waters during northward migrations in spring and summer, and southward migration in autumn (Stewart and Leatherwood 1985).

The minke whale's range extends into the Chukchi Sea. During recent vessel-based surveys in the Chukchi Sea, three, three, and 10 minke whales were sighted in 2006, 2007, and 2008, respectively (Haley et al. 2010); another minke whale was detected in the Chukchi Sea in 2008 by Brueggeman (2009). Savarese et al. (2010) reported one minke whale in the Beaufort Sea during vessel-based operations in 2007. However, no minke whales were sighted during cruises in the Arctic Ocean north of Barrow in August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). Minke whales sometimes occur in areas with minimal ice cover, but it is unlikely that minke whales would be encountered during the proposed survey in the Arctic Ocean.

Fin Whale

The fin whale is widely distributed in all the world's oceans (Gambell 1985), but typically occurs in temperate and polar regions from 20° to 70° north and south of the equator (Perry et al. 1999). It is listed as *endangered* under the ESA and on the IUCN Red List of Threatened Species (IUCN 2010), and it is listed in CITES Appendix I (UNEP-WCMC 2011).

The North Pacific fin whale population summers from the Chukchi Sea to California (Gambell 1985), but does not range into the Alaskan Beaufort Sea or waters of the northern Chukchi Sea. Recently a fin whale was recorded in the southern Chukchi Sea during vessel-based surveys in 2006 (LGL Ltd. unpubl. data), and four fin whales were sighted in the Chukchi Sea in 2008 (Haley et al. 2010). National Marine Mammal Laboratory (NMML) observers also saw and photographed a fin whale off Point Lay in 2008 during aerial surveys (COMIDA 2011). Fin whales were not recorded during vessel-based or aerial surveys in the Beaufort Sea in 2006–2008 (Funk et al. 2010) and were not sighted from during surveys in the Arctic Ocean during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). Fin whales likely would not be encountered in the proposed survey area in the Arctic Ocean.

(2) Odontocetes

Beluga

The beluga whale is an arctic and subarctic species that includes several populations in Alaska and northern European waters. It has a circumpolar distribution in the Northern Hemisphere and occurs between 50° and 80°N (Reeves et al. 2002). It is distributed in seasonally ice-covered seas and migrates to warmer coastal estuaries, bays, and rivers in summer for molting (Finley 1982). Of five distinct beluga stocks recognized in Alaska (O'Corry-Crowe et al. 1997), only the Beaufort Sea and Eastern Chukchi Sea stocks could be encountered during the proposed survey. Based on a partial survey in 1992 of the known range of the Beaufort Sea Stock, the population was estimated at 39,258 (Allen and Angliss 2010). Based on 1989–1991 surveys concentrated on the 170-km long Kasegaluk Lagoon where belugas are known to occur during the open-water season, a minimum population size of 3710 was estimated; the surveys on which it was based did not include offshore areas where belugas are also likely to occur.

Both stocks of belugas may share common wintering grounds in the pack ice of the central Bering Sea (O'Corry-Crowe et al. 1997). In summer, whales from the Eastern Chukchi Sea Stock are known to congregate in Kasegaluk Lagoon, but evidence from a small number of satellite-tagged animals suggests that some of these whales may subsequently range into the Arctic Ocean north of the Beaufort Sea. Suydam et al. (2005a) put satellite tags on 23 beluga whales captured in Kasegaluk Lagoon in late June

and early July 1998–2002. Five of these whales moved far into the Arctic Ocean and into the pack ice to 79–80°N. These and other whales moved to areas as far as 1100 km offshore between Barrow and the Mackenzie River Delta, spending time in water with 90% ice coverage.

Belugas from the Beaufort Sea Stock migrate from the Bering Sea through offshore waters of western and northern Alaska and summer in the eastern Beaufort Sea. Most whales migrate into the Beaufort Sea in April or May, although some whales may pass Point Barrow as early as late March and as late as July (Braham et al. 1984; Ljungblad et al. 1984). Much of the population enters the Mackenzie River estuary for a short period during July–August to molt their epidermis, but they spend most of the summer in offshore waters of the eastern Beaufort Sea, Amundsen Gulf, and more northerly areas (Davis and Evans 1982; Harwood et al. 1996; Richard et al. 2001). Belugas are rarely seen in the central Alaskan Beaufort Sea during the early summer. During late summer and autumn, most belugas migrate westward far offshore near the pack ice (Frost et al. 1988; Hazard 1988; Clarke et al. 1993; Miller et al. 1999).

Moore (2000) and Moore et al. (2000b) suggested that beluga whales select deeper slope water independent of ice cover. However, during the westward migration in late summer and autumn, small numbers of belugas are sometimes seen near the north coast of Alaska (e.g., Johnson 1979). The main fall migration corridor of beluga whales is ~100+ km north of the coast. Satellite-linked telemetry data show that some belugas of this population migrate west considerably farther offshore, as far north as 76–78°N (Richard et al. 1997, 2001). Belugas were not recorded, however, during arctic cruises in August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010).

Beluga whales from the eastern Chukchi Sea Stock are an important subsistence resource for residents of the village of Point Lay, adjacent to Kasegaluk Lagoon, and other villages in northwest Alaska. Each year, hunters from Point Lay drive belugas into the lagoon to a traditional hunting location. The belugas have been predictably sighted near the lagoon from late June through mid- to late July (Suydam et al. 2001). In 2007, ~70 belugas were harvested at Kivalina located southeast of Point Hope.

The beluga whale is the most likely cetacean species to occur in the proposed project area.

Narwhal

The narwhal has a discontinuous arctic distribution (Hay and Mansfield 1989; Reeves et al. 2002). A large population inhabits Baffin Bay, West Greenland, and the eastern part of the Canadian Arctic archipelago, and much smaller numbers inhabit the Northeast Atlantic/East Greenland area. Narwhals are associated with sea ice. In the spring, as the ice breaks up, they follow the receding ice edge and enter deep sounds and fjords, where they remain during the summer and early fall (Reeves et al. 2002). As the ice reforms, narwhals move to offshore areas in the pack ice (Reeves et al. 2002), living in leads in the heavy pack ice throughout the winter.

Innes et al. (2002) estimated a population size of 45,358 narwhals in the Canadian Arctic, although little of the area was surveyed. There are scattered records of narwhal in Alaskan waters, where the species is considered extralimital (Reeves et al. 2002). Narwhals were not recorded during cruises in the Arctic Ocean during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). Narwhals are unlikely to be encountered during the proposed survey.

Killer Whale

The killer whale is cosmopolitan and globally fairly abundant. It is very common in temperate waters, but also frequents the tropics and waters at high latitudes; it appears to prefer coastal areas, but is also known to occur in deep water (Dahlheim and Heyning 1999). The greatest abundance is thought to occur within 800 km of major continents (Mitchell 1975), and the highest densities occur in areas with abundant prey. Both resident and transient stocks have been described as well as an “offshore” ecotype. The resident and transient types are believed to differ in several aspects of morphology, ecology, and behavior (Allen and Angliss 2010).

Killer whales are known to inhabit almost all coastal waters of Alaska, extending from southeast Alaska through the Aleutian Islands to the Bering and Chukchi seas (Allen and Angliss 2010). Killer whales probably do not occur regularly in the Beaufort Sea although sightings have been reported there (Leatherwood et al. 1986; Lowry et al. 1987). George et al. (1994) reported that they and local hunters see a few killer whales at Point Barrow each year. Killer whales are more common southwest of Barrow in the southern Chukchi Sea and the Bering Sea. Killer whales from either the North Pacific resident or transient stock could occur in the Chukchi Sea. Observers onboard industry vessels in the Chukchi Sea recorded two killer whales in 2006 and one killer whale in 2008 (Haley et al. 2010). No killer whales were seen during aerial or vessel surveys in the Beaufort Sea during 2006–2008 (Funk et al. 2010). The killer whale was not sighted during cruises in the Arctic Ocean during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010).

Killer whales are unlikely to be encountered during the proposed seismic survey.

Harbor Porpoise

The harbor porpoise is a small odontocete that inhabits shallow, coastal waters—temperate, subarctic, and arctic—in the Northern Hemisphere (Read 1999). Harbor porpoises occur mainly in shelf areas where they can dive to depths of at least 220 m and stay submerged for more than 5 min (Harwood and Wilson 2001). Harbor porpoises typically occur in small groups of only a few individuals and tend to avoid vessels (Richardson et al. 1995).

The subspecies *P. p. vomerina* ranges from the Chukchi Sea, Pribilof Islands, Unimak Island, and the southeastern shore of Bristol Bay south to San Luis Obispo Bay, California. During recent vessel-based surveys in the Chukchi Sea, the harbor porpoise was one of the most abundant cetaceans sighted during summer and fall 2006–2008 (Haley et al. 2010). Point Barrow, Alaska, is the approximate northeastern extent of its regular range (Suydam and George 1992), though there are extralimital records east to the mouth of the Mackenzie River in Canada and recent sightings in the Beaufort Sea near Prudhoe Bay during aerial surveys in 2006–2008 (Christie et al. 2010; LGL Limited, unpubl. data). Observers onboard industry vessels reported one sighting in the Beaufort Sea in 2006 but none in 2007 or 2008 (Savarese et al. 2010). Harbor porpoises were not recorded during aerial surveys in the Beaufort Sea in 2002–2004 (Monnett and Treacy 2005), nor during cruises in the Arctic Ocean during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010).

Given that the harbor porpoise is mainly a shallow-water species, no encounters with this species are expected in the far offshore waters where the seismic survey is to occur.

(3) Pinnipeds

Pacific Walrus

The walrus occurs in moving pack ice over shallow water of the circumpolar arctic coast (King 1983). There are two recognized subspecies of walrus: the Pacific walrus and Atlantic walrus (*O. r. divergens* and *O. r. rosmarus*, respectively.). Only the Pacific subspecies may potentially occur in the proposed seismic survey area. The Pacific walrus is not listed under the ESA, but the Center for Biological Diversity petitioned the Secretary of Interior to list Pacific walrus as a threatened or endangered species under the ESA primarily as a result of potential impacts from global climate change and associated retreat of the pack ice (CBD 2008). In September 2009, the USFWS announced that a full status review was being launched. A 1990 survey produced a conservative population estimate of ~200,000, but no current estimate is available (USFWS 2009a). The estimated average annual walrus mortality from the average subsistence harvest in Russia and the U.S. during 1996–2009 was 5789, which included animals wounded but not retrieved (Allen and Angliss 2010).

Walrus are most commonly found near the southern margins of the pack ice as opposed to deep in the pack where few open leads (polynyas) exist to afford access to the sea for foraging (Estes and Gilbert 1978; Fay 1982; Gilbert 1989). Walrus are not typically found in areas of >80% ice cover (Fay 1982). Ice serves as an important mobile platform providing walrus with a place to rest and nurse their young that is safe from predators and near feeding grounds. Pacific walrus feed primarily on benthic invertebrates, occasionally fish and cephalopods, and more rarely, some adult males may prey on other pinnipeds (Riedman 1990). Walrus typically feed in depths of 10–80 m (Vibe 1950, Fay 1982; Reeves et al. 2002). In Bristol Bay, 98% of satellite locations of tagged walrus were in water depths of 60 m or less (Chadwick and Hills 2005).

The Pacific walrus ranges from the Bering Sea to the Chukchi Sea, occasionally moving into the East Siberian and Beaufort seas. Walrus are migratory, moving south with the advancing ice in autumn and north as the ice recedes in spring (Fay 1981). In the summer, most of the population of Pacific walrus moves to the Chukchi Sea, but several thousands aggregate in the Gulf of Anadyr and in Bristol Bay (Allen and Angliss 2010). Limited numbers of walrus inhabit the Beaufort Sea during the open water season, and they are considered extralimital east of Point Barrow (Sease and Chapman 1988). The northeast Chukchi Sea west of Barrow is the northeastern extent of the main summer range of the walrus, and only a few individuals are seen farther east in the Beaufort Sea (e.g., Harwood et al. 2005; Funk et al. 2010). During a survey through the northern Chukchi Sea/Arctic Ocean in August–September 2005, two sightings of a total of seven walrus were made between 71.5 and 73°N, 164°W, just south of and near the southern extent of the proposed survey area in water depths <70 m (Haley and Ireland 2006). No walrus were sighted during surveys in the Arctic Ocean during July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Mosher et al. 2009; Beland and Ireland 2010).

Walrus are not expected to be encountered in the survey area because they occur in pack ice and the *Langseth* will completely avoid ice during the entire cruise.

Bearded Seal

The bearded seal is associated with sea ice and has a circumpolar distribution, generally south of 80°N (Jefferson et al. 2008). In waters around Alaska, it occurs over the continental shelves of the Bering, Chukchi, and Beaufort seas and Arctic Ocean. An early estimate of the Bering-Chukchi Sea population was ~300,000, but there is no reliable estimate of the current population size (Allen and Angliss 2010). The bearded seal is not listed under the ESA. In September 2008, NMFS published a

finding that a petitioned action to list it and other ice seals as *threatened* or *endangered* might be warranted; NMFS initiated a status review (NMFS 2008a).

During the open-water period, bearded seals occur mainly in relatively shallow areas, because they are predominantly benthic feeders (Burns 1981). They prefer areas of water no deeper than 200 m (e.g., Harwood et al. 2005). Bearded seals have occasionally been reported to maintain breathing holes in sea ice and broken areas within the pack ice, particularly if the water depth is <200 m. Bearded seals apparently also feed on ice-associated organisms when they are present, and this allows a few bearded seals to live in areas considerably deeper than 200 m.

Seasonal movements of bearded seals are directly related to the advance and retreat of sea ice and to water depth (Kelly 1988). During winter, most bearded seals in Alaskan waters are found in the Bering Sea. In the Chukchi and Beaufort seas, favorable conditions are more limited, and consequently, bearded seals are less abundant there during winter. From mid-April to June, as the ice recedes, some of the bearded seals that overwintered in the Bering Sea migrate northward through the Bering Strait. During the summer, they are found near the widely fragmented margin of multi-year ice covering the continental shelf of the Chukchi Sea and in nearshore areas of the central and western Beaufort Sea. In the Beaufort Sea, bearded seals rarely use coastal haulouts.

In some areas, bearded seals are associated with the ice year-round; however, they usually move shoreward into open water areas when the pack ice retreats to areas with water depths greater than 200 m. During the summer, when the Bering Sea is ice-free, the most favorable bearded seal habitat is found in the central or northern Chukchi Sea/Arctic Ocean along the margin of the pack ice. Suitable habitat is more limited in the Beaufort Sea where the continental shelf is narrower and the pack ice edge frequently occurs seaward of the shelf and over water too deep for benthic feeding. The preferred habitat in the western and central Beaufort Sea during the open water period is the continental shelf seaward of the scour zone. Vessel surveys in the Arctic Ocean have reported much lower percentages of bearded compared to ringed seals during cruises in the Arctic Ocean in 2005, 2006, and 2010 (Haley 2006; Haley and Ireland 2006; Beland and Ireland 2010). One bearded seal was sighted in the Arctic Ocean during August–September 2009 (Mosher et al. 2009).

Small numbers of bearded seals would likely be encountered at tracklines in shallow (<200-m) water in the southern part of the proposed survey area.

Spotted Seal

The spotted seal (also known as largha seal) occurs in the Beaufort, Chukchi, Bering, and Okhotsk seas, and south to the northern Yellow Sea and western Sea of Japan (Shaughnessy and Fay 1977). The spotted seal is not listed under the ESA. However, in September 2008, NMFS published a finding that a petitioned action to list it and other ice seals as *threatened* or *endangered* might be warranted and initiated a status review (NMFS 2008a). In October 2009, 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 DPSs (NMFS 2008b). Based on an actual minimum count of 4145 hauled out seals, Allen and Angliss (2010) estimated the Alaskan population at 59,214.

During summer, spotted seals are found primarily in the Bering and Chukchi seas, but some range into the Beaufort Sea (Rugh et al. 1997; Lowry et al. 1998). At this time of year, spotted seals haul out on land part of the time, but also spend extended periods at sea. The seals are commonly seen in bays, lagoons and estuaries, but also range far offshore as far north as 69–72°N. In summer, they are rarely seen on the

pack ice, except when the ice is very near to shore. As the ice cover thickens with the onset of winter, spotted seals leave the northern portions of their range and move into the Bering Sea (Lowry et al. 1998).

Spotted seals have been sighted during open-water seismic programs and barge operations in the Alaskan Beaufort Sea (Moulton and Lawson 2002; Greene et al. 2007; Savarese et al. 2010) and during vessel-based seismic surveys and aerial surveys in the Chukchi Sea during 2006–2008 (Brueggeman 2009; Funk et al. 2010). No spotted seals were recorded on arctic cruises during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010). Spotted seals would be unlikely to occur in the proposed survey area although some spotted seals could be encountered during transit periods.

Ribbon Seal

The ribbon seal is found along the pack-ice margin in the southern Bering Sea during late winter and early spring, and it moves north as the pack ice recedes during late spring to early summer (Burns 1970; Burns et al. 1981). The ribbon seal is not listed under the ESA. In December 2008, NMFS published a finding that a petition to list the ribbon seal as *threatened* or *endangered* was not warranted at that time (NMFS 2008c).

Little is known about ribbon seal summer and fall distribution, but a review of sightings during the summer suggested that they move into the southern Chukchi Sea (Kelly 1988). During a recent satellite telemetry program, a number of ribbon seals tagged in the Bering Sea in May had moved to the Chukchi Sea by July (NMML 2009). However, ribbon seals appeared to be relatively rare in the northern Chukchi Sea during recent vessel and aerial surveys in summer and fall of 2006–2008 (Brueggeman 2009; Funk et al. 2010). Ribbon seals do not normally occur in the Beaufort Sea, although three recent ribbon seal sightings were reported during vessel-based surveys in the Beaufort Sea in 2008 (Savarese et al. 2010). No ribbon seals were recorded on cruises in the Arctic Ocean during August–September 2005, July–August 2006, August–September 2009, or August–September 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010).

Ringed Seal

The ringed seal has a circumpolar distribution and occurs in all seas of the Arctic Ocean (King 1983). The ringed seal is not listed under the ESA. In September 2008, NMFS published a finding that a petitioned action to list it and other ice seals as *threatened* or *endangered* might be warranted and initiated a status review (NMFS 2008a). Past population estimates in the Bering-Chukchi-Beaufort area ranged from 1–1.5 million (Frost 1985) to 3.3–3.6 million (Frost et al. 1988), but a current estimate is not available (Allen and Angliss 2010).

Ringed seals are closely associated with ice, and in summer they often occur along the receding ice edges or farther north in the pack ice. During winter, ringed seals occupy landfast ice and offshore pack ice, maintaining breathing holes in the ice and occupying lairs in accumulated snow where they give birth and nurse their pups (Smith and Stirling 1975). In winter and spring, the highest densities of ringed seals are found on stable shorefast ice. However, in some areas where there is limited fast ice but wide expanses of pack ice, including the Beaufort Sea, Chukchi Sea, and Baffin Bay, total numbers of ringed seals on pack ice may exceed those on shorefast ice (Burns 1970; Stirling et al. 1982; Finley et al. 1983).

Ringed seals are year-round residents in the northern Chukchi and Beaufort seas and are the most frequently encountered seal species in the area. In the Chukchi Sea, the ringed seal was the most abundant seal species sighted during vessel-based surveys in 2006–2008, with densities up to 0.129/km² in the fall (Haley et al. 2010). In the Beaufort Sea, the ringed seal was also the most abundant seal species

during similar fall vessel-based surveys, with densities up to 0.103/km² (Savarese et al. 2010). Many unidentified seals during these surveys may have also been ringed seals, thus actual densities may have been higher. In the Arctic Ocean, the ringed seal was also the most frequently sighted marine mammal species during Arctic cruises in August–September 2005 (35 sightings; Haley and Ireland 2006), July–August 2006 (48 sightings; Haley 2006), August–September 2009 (30 sightings; Mosher et al. 2009), and August–September 2010 (29 sightings; Beland and Ireland 2010).

The ringed seal is the marine mammal most likely to be encountered during the proposed survey.

(4) Carnivora

Polar Bear

The polar bear has a circumpolar distribution throughout the northern hemisphere (Amstrup et al. 1986); it occurs in relatively low densities throughout most ice-covered areas (DeMaster and Stirling 1981). It is listed as *threatened* under the ESA, *vulnerable* on the IUCN Red List of Threatened Species (IUCN 2010), and it is listed in CITES Appendix II (UNEP-WCMC 2011). In addition to the U.S. Marine Mammal Protection Act (MMPA) of 1973, the polar bear is protected by the International Agreement on the Conservation of Polar Bears, ratified in 1976 by Canada, Denmark, Norway, Russia (former USSR), and the U.S. Article II of the agreement states, “Each contracting party...shall manage polar bear populations in accordance with sound conservation practices based on the best scientific data.” Current world population estimates are ~20,000–30,000 (Derocher et al. 1998; Aars et al. 2006). On 7 December 2010, Federally Designated Critical Habitat for polar bear was listed (50 CFR Part 17). The critical habitat is designated in three units: sea-ice critical habitat, terrestrial denning critical habitat, and barrier island critical habitat (USFWS 2010). Sea-ice critical habitat within the U.S. EEZ is shown in Figure 1.

Polar bears are divided into 19 relatively distinct populations or management units although there may be overlap of some individuals among populations (Aars et al. 2006; USFWS 2008). Individuals from three populations could occur in the proposed survey area: the Southern Beaufort Sea population (~1500), ranging from the Baillie Islands, Canada, to near Point Lay, Alaska; the Chukchi Sea population (~2000), from most of the Chukchi Sea and the northern Bering Sea; and the Northern Beaufort Sea population (~1200), located in Canadian waters primarily north of the Southern Beaufort Sea and extending into Amundsen Gulf. USFWS (2008) designated the Northern Beaufort Sea population as stable, the Southern Beaufort Sea population as declining, and the Chukchi Sea population as data deficient. Data from tracking studies indicate wide-ranging movements of individual bears and overlap among polar bear populations (Garner et al. 1990; Amstrup 1995; Durner and Amstrup 1995).

Polar bears usually forage in areas where there are high concentrations of ringed seals which is their primary prey, and bearded seals (Larsen 1985; Stirling and McEwan 1975). This includes areas of landfast ice, as well as moving pack ice. They typically range as far north as 88°N (Ray 1971; Durner and Amstrup 1995) where the population thins dramatically. However, polar bears have been observed across the Arctic, including close to the North Pole (van Meurs and Splettstoesser 2003). During a cruise in the Arctic Ocean in August–September 2005, there were 21 sightings of 27 polar bears, most between ~80 and 82°N with one at ~87°N (Haley and Ireland 2006). During a cruise in the Arctic Ocean in July–August 2006, there were three sightings of nine polar bears at ~73 and 78°N, all on ice (Haley 2006). During a cruise in the Arctic Ocean in August–September 2009, there were nine sightings of 11 polar bears between ~79 and 82°N (Mosher et al. 2009). Sixteen polar bears were seen on the ice during a seismic survey in the Arctic Ocean in August–September 2010 (Beland and Ireland 2010).

Although the proposed survey area appears to overlap sea-ice critical habitat within the U.S. EEZ, this would only occur if sea ice was present in the area where the *Langseth* will be operating. However, as the *Langseth* will be avoiding the pack ice, neither polar bears or their critical habitat are expected to be encountered in the survey area.

IV. ENVIRONMENTAL CONSEQUENCES

Proposed Action

(1) Direct Effects on Marine Mammals and Their Significance

The material in this section includes a summary of the anticipated effects (or lack thereof) on marine mammals of the airgun system to be used by UAGI. A more detailed review of airgun effects on marine mammals appears in Appendix B. That Appendix is similar to corresponding parts of previous EAs and associated IHA applications concerning other NSF-funded seismic surveys since 2003, but was updated in 2009. This section (along with Appendix B) also includes a discussion of the potential impacts of operations by UAGI's echosounders and ADCP.

Finally, this section includes estimates of the numbers of marine mammals that could be affected by the activities during the proposed seismic survey. A description of the rationale for UAGI's estimates of the numbers of exposures to various received sound levels that could occur during the planned seismic program is also provided.

(a) Summary of Potential Effects of Airgun Sounds

The effects of sounds from airguns could include one or more of the following: tolerance, masking of natural sounds, behavioral disturbance, and at least in theory, temporary or permanent hearing impairment, or non-auditory physical or physiological effects (Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Southall et al. 2007). Permanent hearing impairment, in the unlikely event that it occurred, would constitute injury, but temporary threshold shift (TTS) is not an injury (Southall et al. 2007). Although the possibility cannot be entirely excluded, it is unlikely that the project would result in any cases of temporary or especially permanent hearing impairment, or any significant non-auditory physical or physiological effects. Some behavioral disturbance is expected, but this would be localized and short-term.

Tolerance.—Numerous studies have shown that pulsed sounds from airguns are often readily detectable in the water at distances of many kilometers. For a summary of the characteristics of airgun pulses, see Appendix B (3). Several studies have shown that marine mammals at distances more than a few kilometers from operating seismic vessels often show no apparent response—see Appendix B (5). That is often true even in cases when the pulsed sounds must be readily audible to the animals based on measured received levels and the hearing sensitivity of that mammal group. Although various baleen whales, toothed whales, and (less frequently) pinnipeds have been shown to react behaviorally to airgun pulses under some conditions, at other times mammals of all three types have shown no overt reactions. In general, pinnipeds usually seem to be more tolerant of exposure to airgun pulses than are cetaceans, with the relative responsiveness of baleen and toothed whales being variable.

Masking.—Masking effects of pulsed sounds (even from large arrays of airguns) on marine mammal calls and other natural sounds are expected to be limited, although there are very few specific data on this. Because of the intermittent nature and low duty cycle of seismic pulses, animals can emit

and receive sounds in the relatively quiet intervals between pulses. However, in exceptional situations, reverberation occurs for much or all of the interval between pulses (e.g., Simard et al. 2005; Clark and Gagnon 2006) which could mask calls. Some baleen and toothed whales are known to continue calling in the presence of seismic pulses, and their calls usually can be heard between the seismic pulses (e.g., Richardson et al. 1986; McDonald et al. 1995; Greene et al. 1999a,b; Nieukirk et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b, 2006; Dunn and Hernandez 2009). However, Clark and Gagnon (2006) reported that fin whales in the northeast Pacific Ocean went silent for an extended period starting soon after the onset of a seismic survey in the area. Similarly, there has been one report that sperm whales ceased calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994). However, more recent studies found that sperm whales continued calling in the presence of seismic pulses (Madsen et al. 2002; Tyack et al. 2003; Smultea et al. 2004; Holst et al. 2006; Jochens et al. 2008). Dolphins and porpoises commonly are heard calling while airguns are operating (e.g., Gordon et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b; Potter et al. 2007). The sounds important to small odontocetes are predominantly at much higher frequencies than are the dominant components of airgun sounds, thus limiting the potential for masking. In general, masking effects of seismic pulses are expected to be minor, given the normally intermittent nature of seismic pulses. Masking effects on marine mammals are discussed further in Appendix B (4).

Disturbance Reactions.—Disturbance includes a variety of effects, including subtle to conspicuous changes in behavior, 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”.

Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors (Richardson et al. 1995; Wartzok et al. 2004; Southall et al. 2007; Weilgart 2007). If a marine mammal does react briefly to an underwater sound by changing its behavior 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., 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 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 program are based primarily on behavioral observations of a few species. Detailed studies 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, and sea otters, but for many species there are no data on responses to marine seismic surveys.

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 kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, as reviewed in Appendix B (5), 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 behavior 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 $\mu\text{Pa}_{\text{rms}}$ seem to cause obvious avoidance behavior 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 substantial 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 Appendix B (5) have shown that some species of baleen whales, notably bowhead and humpback whales, at times show strong avoidance at received levels lower than 160–170 dB re 1 $\mu\text{Pa}_{\text{rms}}$.

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) studied the responses of humpback whales off Western Australia to a full-scale seismic survey with a 16-airgun, 2678-in³ array, and to a single 20-in³ airgun with source level 227 dB re 1 $\mu\text{Pa}\cdot\text{m}_{\text{p-p}}$. 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) noted localized displacement during migration of 4–5 km by traveling 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 $\mu\text{Pa}_{\text{rms}}$ for humpback pods containing females, and at the mean closest point of approach (CPA) distance the received level was 143 dB re 1 $\mu\text{Pa}_{\text{rms}}$. 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 $\mu\text{Pa}_{\text{rms}}$.

Data collected by observers during several seismic surveys in the Northwest Atlantic showed that sighting rates of humpback whales were significantly greater during periods of no seismic compared with periods when a full array was operating (Moulton and Holst 2010). In addition, humpback whales were more likely to swim away and less likely to swim towards a vessel during seismic vs. non-seismic periods (Moulton and Holst 2010).

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-in³) 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. However, Moulton and Holst (2010) reported that humpback whales monitored during seismic surveys in the Northwest Atlantic had lower sighting rates and were most often seen swimming away from the vessel during seismic periods compared with periods when airguns were silent.

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 circum-

stantial 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. 2006), 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 their responsiveness 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 $\mu\text{Pa}_{\text{rms}}$ [Miller et al. 1999; Richardson et al. 1999; see Appendix B (5)]. However, more recent research on bowhead whales (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 analysis (Richardson et al. 1986). In summer, bowheads typically begin to show avoidance reactions at received levels of about 152–178 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (Richardson et al. 1986, 1995; Ljungblad et al. 1988; 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-in³ 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 $\mu\text{Pa}_{\text{rms}}$. 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 B.C., Canada (Bain and Williams 2006).

Various species of *Balaenoptera* (blue, sei, fin, and minke whales) have occasionally been seen in areas ensounded by airgun pulses (e.g., Stone 2003; MacLean and Haley 2004; Stone and Tasker 2006; Moulton and Holst 2010), 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; Castellote et al. 2010). 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 further (on average) from the airgun array during seismic operations compared with non-seismic periods (Stone and Tasker 2006). Castellote et al. (2010) reported that singing fin whales in the Mediterranean moved away from an operating airgun array.

Ship-based monitoring studies of baleen whales (including blue, fin, sei, minke, and humpback whales) in the Northwest Atlantic found that overall, this group had lower sighting rates during seismic vs. non-seismic periods (Moulton and Holst 2010). Baleen whales as a group were also seen significantly farther from the vessel during seismic compared with non-seismic periods, and they were more often seen to be swimming away from the operating seismic vessel (Moulton and Holst 2010). Blue and minke whales were initially sighted significantly farther from the vessel during seismic operations compared to non-seismic periods; the same trend was observed for fin whales (Moulton and Holst 2010). Minke whales were most often observed to be swimming away from the vessel when seismic operations were underway (Moulton and Holst 2010).

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 distribution and habitat use in subsequent days or years. However, gray whales have continued to migrate annually along the west coast of North America with substantial increases in the population over recent years, despite intermittent seismic exploration (and much ship traffic) in that area for decades (Appendix A *in* Malme et al. 1984; Richardson et al. 1995; Allen and Angliss 2010). The western Pacific gray whale population did not seem affected by a seismic survey in its feeding ground during a previous year (Johnson et al. 2007). Similarly, bowhead whales have continued to travel to the eastern Beaufort Sea each summer, and their numbers have increased notably, despite seismic exploration in their summer and autumn range for many years (Richardson et al. 1987; Allen and Angliss 2010).

Toothed Whales

Little systematic information is available about reactions of toothed whales to noise pulses. Few studies similar to the more extensive baleen whale/seismic pulse work summarized above and (in more detail) in Appendix B 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; Miller et al. 2009). There is 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; Moulton and Holst 2010).

Seismic operators and PSOs 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; Barkaszi et al. 2009; Richardson et al. 2009; Moulton and Holst 2010). 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. 2010; Moulton and Holst 2010). 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 (Miller et al. 2005; Harris et al. 2007).

Captive bottlenose dolphins and beluga whales exhibited changes in behavior when exposed to strong pulsed sounds similar in duration to those typically used in seismic surveys (Finneran et al. 2000, 2002, 2005). However, the animals tolerated high received levels of sound before exhibiting aversive behaviors.

Results for porpoises depend on species. The limited available data suggest that harbor 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 responsiveness of these two porpoise species 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; Stone and Tasker 2006; Weir 2008; Moulton and Holst 2010). In most cases the whales do not show strong avoidance, and they continue to call (see Appendix B for review). However, controlled exposure experiments in the Gulf of Mexico indicate that foraging behavior was altered upon exposure to airgun sound (Jochens et al. 2008; 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. In fact, Moulton and Holst (2010) reported 15 sightings of beaked whales during seismic studies in the Northwest Atlantic; seven of those sightings were made at times when at least one airgun was operating. There was little evidence to indicate that beaked whale behavior was affected by airgun operations; sighting rates and distances were similar during seismic and non-seismic periods (Moulton and Holst 2010).

There are increasing indications that some beaked whales tend to strand when naval exercises involving mid-frequency sonar operation are ongoing nearby (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; NOAA and USN 2001; Jepson et al. 2003; Hildebrand 2005; Barlow and Gisiner 2006; see also the “Strandings and Mortality” subsection, later). These strandings are apparently at least in part a disturbance response, although auditory or other injuries or other physiological effects may also be involved. Whether beaked whales would ever react similarly to seismic surveys is unknown (see “Strandings and Mortality”, below). Seismic survey sounds are quite different from those of the sonars in operation during the above-cited incidents.

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 harbor porpoises (Appendix B). A ≥ 170 dB re 1 μ Pa disturbance criterion (rather than ≥ 160 dB) is considered appropriate for delphinids (and pinnipeds), which tend to be less responsive than the more responsive cetaceans.

Pinnipeds

Pinnipeds are not likely to show a strong avoidance reaction to the 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 behavior—see Appendix B (5). In the Beaufort Sea, some ringed seals avoided an area of 100 m to (at most) a few hundred meters 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; 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). Similarly, in Puget Sound, sighting distances for harbor seals and

California sea lions tended to be larger when airguns were operating (Calambokidis and Osmek 1998). Previous telemetry work suggests that avoidance and other behavioral reactions may be stronger than evident to date from visual studies (Thompson et al. 1998). Even if reactions of any pinnipeds that might be encountered in the present study area are as strong as those evident in the telemetry study, reactions are expected to be confined to relatively small distances and durations, with no long-term effects on pinniped individuals or populations. As for delphinids, a ≥ 170 dB disturbance criterion is considered appropriate for pinnipeds, which tend to be less responsive than many cetaceans.

Polar Bears

Airgun effects on polar bears have not been studied. However, polar bears on the ice would be unaffected by underwater sound. Sound levels received by polar bears in the water would be attenuated because polar bears generally do not dive much below the surface. Received levels of airgun sounds are reduced near the surface because of the pressure release effect at the water's surface (Greene and Richardson 1988; Richardson et al. 1995).

Additional details on the behavioral reactions (or the lack thereof) by all types of marine mammals to seismic vessels can be found in Appendix B (5).

Hearing Impairment and Other Physical Effects.—Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds. TTS has been demonstrated and studied in certain captive odontocetes and pinnipeds exposed to strong sounds (reviewed in Southall et al. 2007). However, there has been no specific documentation of TTS let alone permanent hearing damage, i.e., permanent threshold shift (PTS), in free-ranging marine mammals exposed to sequences of airgun pulses during realistic field conditions. Current NMFS policy regarding exposure of marine mammals to high-level sounds is that cetaceans and pinnipeds should not be exposed to impulsive sounds with received levels ≥ 180 dB and 190 dB re $1 \mu\text{Pa}_{\text{rms}}$, respectively (NMFS 2000). Those criteria have been used in establishing the exclusion (=shut-down) zones planned for the proposed seismic survey. However, those criteria were established before there was any information about minimum received levels of sounds necessary to cause auditory impairment in marine mammals. As discussed in Appendix B (6) and summarized here,

- the 180-dB criterion for cetaceans is probably quite precautionary, i.e., lower than necessary to avoid temporary auditory impairment let alone permanent auditory injury, at least for delphinids.
- TTS is not injury and does not constitute “Level A harassment” in U.S. MMPA terminology.
- the minimum sound level necessary to cause permanent hearing impairment (“Level A harassment”) is higher, by a variable and generally unknown 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 recently (Southall et al. 2007). Those recommendations have not, as of early 2011, been formally adopted by NMFS for use in regulatory processes and during mitigation programs associated with seismic surveys. However, some aspects of the recommendations have been taken into account in certain environmental impact statements and small-take authorizations. NMFS has indicated that it may issue new noise exposure criteria for marine mammals

that account for the now-available scientific data on TTS, the expected offset between the TTS and PTS thresholds, differences in the acoustic frequencies to which different marine mammal groups are sensitive (e.g., M-weighting or generalized frequency weightings for various groups of marine mammals, allowing for their functional bandwidths), and other relevant factors. Preliminary information about possible changes in the regulatory and mitigation requirements, and about the possible structure of new criteria, was given by Wieting (2004) and NMFS (2005).

Several aspects of the planned monitoring and mitigation measures for this project are designed to detect marine mammals occurring near the airgun array, and to avoid exposing them to sound pulses that might, at least in theory, cause hearing impairment (see § II, “Monitoring and Mitigation Measures”). In addition, many marine mammals show some avoidance of the area where received levels of airgun sound are high enough such that hearing impairment could potentially occur. In those cases, the avoidance responses of the animals themselves will reduce or (most likely) avoid any possibility of hearing impairment.

Non-auditory physical effects may also occur in marine mammals exposed to strong underwater pulsed sound. Possible types of non-auditory physiological effects or injuries that might (in theory) occur in mammals close to a strong sound source include stress, neurological effects, bubble formation, and other types of organ or tissue damage. It is possible that some marine mammal species (i.e., beaked whales) may be especially susceptible to injury and/or stranding when exposed to strong transient sounds. However, as discussed below, there is no definitive evidence that any of these effects occur even for marine mammals in close proximity to large arrays of airguns. It is unlikely that any effects of these types would occur during the present project given the brief duration of exposure of any given mammal and the planned monitoring and mitigation measures (see below). The following subsections discuss in somewhat more detail the possibilities of TTS, PTS, and non-auditory physical effects.

Temporary Threshold Shift

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. At least in terrestrial mammals, TTS can last from minutes or hours to (in cases of strong TTS) days. For sound exposures at or somewhat above the TTS threshold, hearing sensitivity in both terrestrial and marine mammals recovers rapidly after exposure to the noise ends. Few data on sound levels and durations necessary to elicit mild TTS have been obtained for marine mammals, and none of the published data concern TTS elicited by exposure to multiple pulses of sound. Available data on TTS in marine mammals are summarized in Southall et al. (2007). Based on these data, the received energy level of a single seismic pulse (with no frequency weighting) might need to be ~186 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (i.e., 186 dB SEL or ~196–201 dB re 1 $\mu\text{Pa}_{\text{rms}}$) in order to produce brief, mild TTS². Exposure to several strong seismic pulses that each have received levels near 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$ might result in cumulative exposure of ~186 dB SEL and thus slight TTS in a small odontocete assuming the TTS threshold is (to a first approximation) a function of the total received pulse energy; however, this ‘equal-energy’ concept is an oversimplification. The distances from the *Langseth*’s airguns at which the received energy level (per pulse, flat-weighted) would be expected to be ≥ 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$ are estimated in Table 1. Levels ≥ 190

² If the low frequency components of the wateregun sound used in the experiments of Finneran et al. (2002) are downweighted as recommended by Miller et al. (2005) and Southall et al. (2007) using their M_{mf} -weighting curve, the effective exposure level for onset of mild TTS was 183 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (Southall et al. 2007).

dB re 1 $\mu\text{Pa}_{\text{rms}}$ are expected to be restricted to radii no more than 190 m (Table 1). For an odontocete closer to the surface, the maximum radius with ≥ 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$ would be smaller.

The above TTS information for odontocetes is derived from studies on the bottlenose dolphin and beluga. For the one harbor porpoise tested, the received level of airgun sound that elicited onset of TTS was lower (Lucke et al. 2009). If these results from a single animal are representative, it is inappropriate to assume that onset of TTS occurs at similar received levels in all odontocetes (*cf.* Southall et al. 2007). Some cetaceans apparently can incur TTS at considerably lower sound exposures than are necessary to elicit TTS in the beluga or bottlenose dolphin.

For baleen whales, there are no data, direct or indirect, on levels or properties of sound that are required to induce TTS. The frequencies to which baleen whales 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 baleen whales (Southall et al. 2007). In any event, no cases of TTS are expected given the strong likelihood that baleen whales would avoid the approaching airguns (or vessel) before being exposed to levels high enough for TTS to occur, as well as the mitigation measures that are planned.

In pinnipeds, TTS thresholds associated with exposure to brief pulses (single or multiple) of underwater sound have not been measured. Initial evidence from more prolonged (non-pulse) exposures suggested that some pinnipeds (harbor seals in particular) incur TTS at somewhat lower received levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001). The TTS threshold for pulsed sounds has been indirectly estimated as being an SEL of ~ 171 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (Southall et al. 2007), which would be equivalent to a single pulse with received level ~ 181 – 186 dB re 1 $\mu\text{Pa}_{\text{rms}}$, or a series of pulses for which the highest rms values are a few dB lower. Corresponding values for California sea lions and northern elephant seals are likely to be higher (Kastak et al. 2005).

NMFS (1995, 2000) concluded that cetaceans and pinnipeds should not be exposed to pulsed underwater noise at received levels exceeding, respectively, 180 and 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$. Those sound levels are *not* considered to be the level above which TTS might occur. Rather, they were the received levels above which, in the view of a panel of bioacoustics specialists convened by NMFS 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. As summarized above and in Southall et al. (2007), data that are now available imply that TTS is unlikely to occur in most odontocetes (and probably mysticetes as well) unless they are exposed to a sequence of several airgun pulses stronger than 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$. For the harbor seal and any species with similarly low TTS thresholds, TTS may occur upon exposure to one or more airgun pulses whose received level equals the NMFS “do not exceed” value of 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$. That criterion corresponds to a single-pulse SEL of 175–180 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ in typical conditions, whereas TTS is suspected to be possible (in harbor seals) with a cumulative SEL of ~ 171 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$.

Permanent Threshold Shift

When PTS occurs, there is physical damage to the sound receptors in the ear. In severe 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).

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 possibility that mammals close to an airgun array might incur at least mild TTS, there has been further speculation about the possibility that some individuals occurring very close to airguns might incur PTS (e.g., Richardson et al. 1995, p. 372ff; Gedamke et al. 2008). Single or occasional occurrences of mild TTS are not indicative of permanent auditory damage, but repeated or (in some cases) single 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. PTS might occur at a received sound level at least several decibels above that inducing mild TTS if the animal were exposed to strong sound pulses with rapid rise time—see Appendix B (6). 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 (Southall et al. 2007). On an SEL basis, Southall et al. (2007:441-4) estimated that received levels would need to exceed the TTS threshold by at least 15 dB for there to be risk of PTS. Thus, for cetaceans they estimate that the PTS threshold might be an M-weighted SEL (for the sequence of received pulses) of ~198 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (15 dB higher than the M_{mf} -weighted TTS threshold, in a beluga, for a waterygun impulse), where the SEL value is cumulated over the sequence of pulses. Additional assumptions had to be made to derive a corresponding estimate for pinnipeds, as the only available data on TTS-thresholds in pinnipeds pertain to non-impulse sound. Southall et al. (2007) estimate that the PTS threshold could be a cumulative M_{pw} -weighted SEL of ~186 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ in the harbor seal exposed to impulse sound. The PTS threshold for the California sea lion and northern elephant seal the PTS threshold would probably be higher, given the higher TTS thresholds in those species.

Southall et al. (2007) also note 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 exceeding 230 or 218 dB re 1 μPa (peak), respectively. Thus, PTS might be expected upon exposure of cetaceans to either SEL ≥ 198 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ or peak pressure ≥ 230 dB re 1 μPa . Corresponding proposed dual criteria for pinnipeds (at least harbor seals) are ≥ 186 dB SEL and ≥ 218 dB peak pressure (Southall et al. 2007). These estimates are all first approximations, given the limited underlying data, assumptions, species differences, and evidence that the “equal energy” model is not be entirely correct. A peak pressure of 230 dB re 1 μPa (3.2 bar \cdot m, 0-pk) would only be found within a few meters of the largest airguns in the planned airgun array (e.g., Caldwell and Dragoset 2000). A peak pressure of 218 dB re 1 μPa could be received somewhat farther away; to estimate that specific distance, one would need to apply a model that accurately calculates peak pressures in the near-field around an array of airguns.

Given the higher level of sound necessary to cause PTS as compared with TTS, it is considerably less likely that PTS would occur. Baleen whales generally avoid the immediate area around operating seismic vessels, as do some other marine mammals. The planned monitoring and mitigation measures, including visual monitoring, PAM, power downs, and shut downs of the airguns when mammals are seen within or approaching the “exclusion zones”, will further reduce the probability of exposure of marine mammals to sounds strong enough to induce PTS.

Strandings and Mortality

Marine mammals close to underwater detonations of high explosives can be killed or severely injured, and the auditory organs are especially susceptible to injury (Ketten et al. 1993; Ketten 1995). However, explosives are no longer used for marine waters for commercial seismic surveys or (with rare

exceptions) for seismic research; they have been replaced entirely by airguns or related non-explosive pulse generators. Airgun pulses are less energetic and have slower rise times, and there is no specific evidence that they can cause serious injury, death, or stranding even in the case of large airgun arrays. However, the association of strandings of beaked whales with naval exercises and, in one case, an L-DEO seismic survey (Malakoff 2002; Cox et al. 2006), has raised the possibility that beaked whales exposed to strong “pulsed” sounds may be especially susceptible to injury and/or behavioral reactions that can lead to stranding (e.g., Hildebrand 2005; Southall et al. 2007). Appendix B (6) provides additional details.

Specific sound-related processes that lead to strandings and mortality are not well documented, but may include (1) swimming in avoidance of a sound into shallow water; (2) a change in behavior (such as a change in diving behavior) that might contribute to tissue damage, gas bubble formation, hypoxia, cardiac arrhythmia, hypertensive hemorrhage or other forms of trauma; (3) a physiological change such as a vestibular response leading to a behavioral change or stress-induced hemorrhagic diathesis, leading in turn 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 pathologic mechanism for the strandings and mortality of some deep-diving cetaceans exposed to sonar. The evidence for this remains circumstantial and associated with exposure to naval mid-frequency sonar, not seismic surveys (Cox et al. 2006; Southall et al. 2007).

Seismic 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 impulses with most of the energy below 1 kHz. Typical military mid-frequency sonars emit non-impulse sounds at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time. A further difference between seismic surveys and naval exercises is that naval exercises can involve sound sources on more than one vessel. Thus, it is not appropriate to assume that there is a direct connection between the effects of military sonar and seismic surveys on marine mammals. However, 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 “pulsed” sound.

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 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 L-DEO vessel R/V *Maurice Ewing* was operating a 20-airgun, 8490-in³ airgun array in the general area. The link between the stranding and the seismic surveys was inconclusive and not based on any physical evidence (Hogarth 2002; Yoder 2002). Nonetheless, the Gulf of California incident plus the beaked whale strandings near naval exercises involving use of mid-frequency sonar suggests 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). Beaked whales do not occur in the proposed study area. However, even if beaked whales were to occur in the vicinity of the seismic survey, no injuries would be anticipated because of (1) the high likelihood that any beaked whales nearby would avoid the approaching vessel before being

exposed to high sound levels, (2) the proposed monitoring and mitigation measures, and (3) differences between the sound sources operated by the seismic vessel and those involved in the naval exercises associated with strandings.

Non-auditory Physiological Effects

Non-auditory physiological effects or injuries that theoretically might occur in marine mammals exposed to strong underwater sound include stress, neurological effects, bubble formation, resonance, and other types of organ or tissue damage (Cox et al. 2006; Southall et al. 2007). Studies examining such effects are limited. However, resonance effects (Gentry 2002) and direct noise-induced bubble formation (Crum et al. 2005) are implausible in the case of exposure to an impulsive broadband source like an air-gun array. If seismic surveys disrupt diving patterns of deep-diving species, this might perhaps result in bubble formation and a form of “the bends”, as speculated to occur in beaked whales exposed to sonar. However, there is no specific evidence of this upon exposure to airgun pulses.

In general, very little is known about the potential for seismic survey sounds (or other types of strong underwater sounds) to cause non-auditory physical effects in marine mammals. Such effects, if they occur at all, would presumably be limited to short distances and to activities that extend over a prolonged period. The available data do not allow identification of a specific exposure level above which non-auditory effects can be expected (Southall et al. 2007), or any meaningful quantitative predictions of the numbers (if any) of marine mammals that might be affected in those ways. Marine mammals that show behavioral avoidance of seismic vessels, including most baleen whales, some odontocetes, and some pinnipeds, are especially unlikely to incur non-auditory physical effects. Also, the planned mitigation measures [§ II (3)], including shut downs of the airguns, will reduce any such effects that might otherwise occur.

(b) Possible Effects of Multibeam Echosounder Signals

The Kongsberg EM 122 MBES will be operated during the planned study. Information about this equipment was provided in § II. Sounds from the MBES are very short pings, occurring for 2–15 ms once every 5–20 s, depending on water depth. Most of the energy in the sound emitted by this MBES is at frequencies near 12 kHz, and the maximum source level is 242 dB re 1 $\mu\text{Pa}_{\text{rms}}$. The beam is narrow (1°) in the fore-aft extent and wide (150°) in the cross-track extent. Each ping consists of eight (in water >1000 m deep) or four (<1000 m deep) successive fan-shaped transmissions (segments) at different cross-track angles. Any given mammal at depth near the trackline would be in the main beam for only one or two of the eight segments. Also, marine mammals that encounter the Kongsberg EM 122 are unlikely to be subjected to repeated pings because of the narrow fore-aft width of the beam and will receive only limited amounts of energy because of the short pings. Animals close to the ship (where the beam is narrowest) are especially unlikely to be ensonified for more than one 2–15 ms ping (or two pings if in the overlap area). Similarly, Kremser et al. (2005) noted that the probability of a cetacean swimming through the area of exposure when an MBES emits a ping is small. The animal would have to pass the transducer at close range and be swimming at speeds similar to the vessel in order to receive the multiple pings that might result in sufficient exposure to cause TTS.

Navy sonars that have been linked to avoidance reactions and stranding of cetaceans (1) generally have a longer signal duration than the Kongsberg EM 122, and (2) are often directed close to horizontally vs. more downward for the MBES. The area of possible influence of the MBES is much smaller—a narrow band below the source vessel. The duration of exposure for a given marine mammal can be much longer for a naval sonar. During UAGI’s operations, the individual pings will be very short, and a given

mammal would not receive many of the downward-directed pings as the vessel passes by. Possible effects of an MBES on marine mammals are outlined below.

Masking.—Marine mammal communications will not be masked appreciably by the MBES signals given the low duty cycle of the echosounder and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of baleen whales, the MBES signals (12 kHz) do not overlap with the predominant frequencies in the calls, which would avoid any significant masking.

Behavioral Responses.—Behavioral reactions of free-ranging marine mammals to sonars, echosounders, and other sound sources appear to vary by species and circumstance. Observed reactions have included silencing and dispersal by sperm whales (Watkins et al. 1985), increased vocalizations and no dispersal by pilot whales (Rendell and Gordon 1999), and the previously mentioned beachings by beaked whales. During exposure to a 21–25 kHz “whale-finding” sonar with a source level of 215 dB re 1 $\mu\text{Pa} \cdot \text{m}$, gray whales reacted by orienting slightly away from the source and being deflected from their course by ~200 m (Frankel 2005). When a 38-kHz echosounder and a 150-kHz ADCP were transmitting during studies in the Eastern Tropical Pacific, baleen whales showed no significant responses, while spotted and spinner dolphins were detected slightly more often and beaked whales less often during visual surveys (Gerrodette and Pettis 2005).

Captive bottlenose dolphins and a white whale exhibited changes in behavior when exposed to 1-s tonal signals at frequencies similar to those that will be emitted by the MBES used by UAGI, and to shorter broadband pulsed signals. Behavioral changes typically involved what appeared to be deliberate attempts to avoid the sound exposure (Schlundt et al. 2000; Finneran et al. 2002; Finneran and Schlundt 2004). The relevance of those data to free-ranging odontocetes is uncertain, and in any case, the test sounds were quite different in duration as compared with those from an MBES.

Very few data are available on the reactions of pinnipeds to echosounder sounds at frequencies similar to those used during seismic operations. Hastie and Janik (2007) conducted a series of behavioral response tests on two captive gray seals to determine their reactions to underwater operation of a 375-kHz multibeam imaging echosounder that included significant signal components down to 6 kHz. Results indicated that the two seals reacted to the signal by significantly increasing their dive durations. Because of the likely brevity of exposure to the MBES sounds, pinniped reactions are expected to be limited to startle or otherwise brief responses of no lasting consequence to the animals.

Hearing Impairment and Other Physical Effects.—Given recent stranding events that have been associated with the operation of naval sonar, there is concern that mid-frequency sonar sounds can cause serious impacts to marine mammals (see above). However, the MBES proposed for use by UAGI is quite different than sonars used for navy operations. Ping duration of the MBES is very short relative to the naval sonars. Also, at any given location, an individual marine mammal would be in the beam of the MBES for much less time given the generally downward orientation of the beam and its narrow fore-aft beamwidth; navy sonars often use near-horizontally-directed sound. Those factors would all reduce the sound energy received from the MBES rather drastically relative to that from the sonars used by the navy.

Given the maximum source level of 242 dB re 1 $\mu\text{Pa} \cdot \text{m}_{\text{rms}}$ (see § II), the received level for an animal within the MBES beam 100 m below the ship would be ~202 dB re 1 $\mu\text{Pa}_{\text{rms}}$, assuming 40 dB of spreading loss over 100 m (circular spreading). Given the narrow beam, only one ping is likely to be received by a given animal as the ship passes overhead. The received energy level from a single ping of duration 15 ms would be about 184 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$, i.e., 202 dB + 10 log (0.015 s). That is below the TTS threshold for a cetacean receiving a single non-impulse sound (195 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$) and even further

below the anticipated PTS threshold (215 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$) (Southall et al. 2007). In contrast, an animal that was only 10 m below the MBES when a ping is emitted would be expected to receive a level ~20 dB higher, i.e., 204 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ in the case of the EM 122. That animal might incur some TTS (which would be fully recoverable), but the exposure would still be below the anticipated PTS threshold for cetaceans. As noted by Burkhardt et al. (2008), cetaceans are very unlikely to incur PTS from operation of scientific sonars on a ship that is underway.

In the harbor seal, the TTS threshold for non-impulse sounds is about 183 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$, as compared with ~195 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ in odontocetes (Kastak et al. 2005; Southall et al. 2007). TTS onset occurs at higher received energy levels in the California sea lion and northern elephant seal than in the harbor seal. A harbor seal as much as 100 m below the *Langseth* could receive a single MBES ping with received energy level of ≥ 184 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (as calculated in the toothed whale subsection above) and thus could incur slight TTS. Species of pinnipeds with higher TTS thresholds would not incur TTS unless they were closer to the transducers when a ping was emitted. However, the SEL criterion for PTS in pinnipeds (203 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$) might be exceeded for a ping received within a few meters of the transducers, although the risk of PTS is higher for certain species (e.g., harbor seal). Given the intermittent nature of the signals and the narrow MBES beam, only a small fraction of the pinnipeds below (and close to) the ship would receive a ping as the ship passed overhead.

(c) Possible Effects of the Sub-bottom Profiler Signals

An SBP will also be operated from the source vessel during the planned study. Details about this equipment were provided in § II. Sounds from the SBP are very short signals, occurring for 1–4 ms once every second. Most of the energy in the sound emitted by the SBP is at 3.5 kHz, and the beam is directed downward. The sub-bottom profiler on the *Langseth* has a maximum source level of 221 dB re 1 $\mu\text{Pa} \cdot \text{m}$ (see § II). Kremser et al. (2005) noted that the probability of a cetacean swimming through the area of exposure when a bottom profiler emits a ping is small—even for an SBP more powerful than that on the *Langseth*—if the animal was in the area, it would have to pass the transducer at close range and in order to be subjected to sound levels that could cause TTS.

Masking.—Marine mammal communications will not be masked appreciably by the SBP sounds given the directionality of the signal and the brief period when an individual mammal is likely to be within its beam. Furthermore, in the case of most baleen whales, the SBP signals do not overlap with the predominant frequencies in the calls, which would avoid significant masking.

Behavioral Responses.—Marine mammal behavioral reactions to other sound sources are discussed above, and responses to the SBP are likely to be similar to those for other non-impulse sources if received at the same levels. However, the signals from the SBP are considerably weaker than those from the MBES. Therefore, behavioral responses are not expected unless marine mammals are very close to the source.

Hearing Impairment and Other Physical Effects.—It is unlikely that the SBP produces sound levels strong enough to cause hearing impairment or other physical injuries even in an animal that is (briefly) in a position near the source. The SBP is usually operated simultaneously with other higher-power acoustic sources. Many marine mammals will move away in response to the approaching higher-power sources or the vessel itself before the mammals would be close enough for there to be any possibility of effects from the less intense sounds from the SBP. In the case of mammals that do not avoid the approaching vessel and its various sound sources, mitigation measures that would be applied to minimize effects of other sources [see § II(3)] would further reduce or eliminate any minor effects of the SBP.

(d) Possible Effects of the Acoustic Doppler Current Profiler Signals

An ADCP will be operated during the proposed program. Sounds from the ADCP are very short, occurring every 0.65 ms to 1.4 s. Most of the energy in the sound emitted is at high frequencies (~75 kHz). The ADCP produces sounds that are within the range of frequencies used by odontocetes that occur or may occur in the area of the planned survey.

Masking.—Whereas the ADCP produces sounds within the frequency range used by odontocetes that may be present in the survey area, marine mammal communications will not be masked appreciably by the signals. This is a consequence of the relatively low power output, low duty cycle, and brief period when an individual mammal is likely to be within the area of potential effects. In the case of mysticetes, the pulses do not overlap with the predominant frequencies in the calls, which would avoid significant masking.

Behavioral Responses.—When a 38-kHz echosounder and a 150-kHz ADCP were transmitting during studies in the Eastern Tropical Pacific, baleen whales showed no significant responses, while spotted and spinner dolphins were detected slightly more often and beaked whales less often during visual surveys (Gerrodette and Pettis 2005). Marine mammal behavioral reactions to other sound sources are discussed above. Responses to the ADCP are likely to be similar to those for other sources if received at the same levels. The signals from the ADCP are weaker than those from the echosounders and the airguns. Therefore, behavioral responses are not expected unless marine mammals are very close to the source.

Hearing Impairment and Other Physical Effects.—Source levels of the ADCP are lower than those of the airguns, which are discussed above. It is unlikely that the ADCP produce sound levels strong enough to cause temporary hearing impairment or (especially) physical injuries even in an animal that is (briefly) in a position near the source.

(2) Mitigation Measures for Marine Mammals

Several mitigation measures are built into the proposed seismic survey as an integral part of the planned activities. These measures include the following: ramp ups; typically two, however a minimum of one dedicated observer maintaining a visual watch during all daytime airgun operations; two observers for 30 min before and during ramp ups during the day and at night; PAM during the day and night to complement visual monitoring (unless the system and back-up systems are damaged during operations; and, power downs (or if necessary shut downs) when mammals are detected in or about to enter designated exclusion zones. These mitigation measures are described earlier in this document, in § II(3). The fact that the airgun array, as a result of its design, directs the majority of the energy downward, and less energy laterally, is also an inherent mitigation measure.

Previous and subsequent analysis of the potential impacts take account of these planned mitigation measures. It would not be meaningful to analyze the effects of the planned activities without mitigation, as the mitigation (and associated monitoring) measures are a basic part of the activities.

(3) Numbers of Marine Mammals that Could be “Taken by Harassment”

All anticipated takes would be “takes by harassment”, involving temporary changes in behavior; the mitigation measures to be applied will minimize the possibility of injurious takes. In the sections below, we describe the methods used to estimate the number of potential exposures to various received sound levels and present estimates of the numbers of marine mammals that could be affected during the proposed seismic program. The estimates are based on a consideration of the number of marine mammals that could be disturbed appreciably by operations with the 10-airgun array to be used during ~5500 km of

seismic surveys in the Arctic Ocean north of the Chukchi Sea. The sources of distributional and numerical data used in deriving the estimates are described in the next subsection.

The anticipated radii of influence of the echosounders and ADCP are less than those for the airgun array. It is assumed that, during simultaneous operations of the echosounders, ADCP, and the airguns, any marine mammals close enough to be affected by the other sound sources would already be affected by the airguns. However, whether or not the airguns are operating simultaneously with the echosounders or ADCP, marine mammals are expected to exhibit no more than short-term and inconsequential responses to the echosounders and ADCP given their characteristics and other considerations described in § II and in § IV (1) (b,c) above. Such reactions are not considered to constitute “taking” (NMFS 2001). Therefore, no additional allowance is included for animals that might be affected by the sound sources other than the airguns.

(a) Basis for Estimating “Take by Harassment” for the Arctic Ocean Cruise

Moore et al. (2000b) did not report densities, but reported sightings and effort data for belugas, bowhead whales, and gray whales from aerial surveys in the Beaufort and Chukchi seas during summer (July–August) and fall (September–October) 1982–1991. We calculated densities using data for the fall in Chukchi Sea depth strata 35–50 m, 51–200 m, and >200 m, mean group sizes from the Beaufort Whale Aerial Survey Project (BWASP) database, and values for detectability bias and availability bias, $f(0)$ and $g(0)$ ³, from Harwood et al. (1996) for belugas, Thomas et al. (2002) for bowhead whales, and Forney and Barlow (1998) for gray whales. Most Moore et al. (2000b) sightings were south of the proposed seismic survey area. Based on the lack of any beluga whale sightings and very low densities of bowheads (0.0003–0.0044/km²) and gray whales (0.0026–0.0042/km²) during non-seismic periods of industry vessel operations in the Chukchi Sea during September–October 2006–2008 (Haley et al. 2010), and the lack of beluga, bowhead, or gray whale sightings during arctic cruises by the *Healy* in August–September 2005 or July–August 2006 (Haley 2006; Haley and Ireland 2006), the calculated densities are likely considerable overestimates. Accordingly, they were reduced by an order of magnitude. Densities were calculated for depths >200 m and <200 m; in the latter case, the densities were effort-weighted averages of the 35–50 m and 51–200 m densities.

Six other cetacean species were included in Table 2 and described in § III. Because the harbor porpoise is mainly a shallow-water species, it is not expected to occur in the survey area. Narwhals are considered extralimital in Alaska, and any vagrants likely would be associated with sea ice. The *Langseth* is not ice-strengthened and will completely avoid ice, so encounters with narwhals are not expected. There is evidence of the occasional occurrence of humpback, minke, fin, and killer whales in the northern Chukchi Sea, but because they occur so infrequently in the Chukchi Sea, little to no data are available for the calculation of densities. Minimal, arbitrary densities have therefore been assigned to these species to allow for chance encounters.

The Pacific walrus, under USFWS jurisdiction, is not expected to be encountered in the survey area because it occurs in pack ice and the *Langseth* will completely avoid ice during the entire cruise. Four species of pinnipeds under NMFS jurisdiction could be encountered in the proposed seismic survey area: ringed seal, bearded seal, ribbon seal, and spotted seal. Bengtson et al. (2005) reported ringed and

³ Detectability bias is associated with diminishing sightability with increasing lateral distance from the trackline [$f(0)$]. Availability bias refers to the fact that there is less-than-100% probability of sighting an animal that is present along the survey trackline, and it is measured by $g(0)$.

bearded seal densities in nearshore fast ice and pack ice and offshore pack ice based on aerial surveys in May–June 1999 and May 2000; ringed seal but not bearded seal densities were corrected for haulout behavior. We used densities from the offshore stratum (12P). Bearded seal densities were used for water depths <200 m and were assumed to be 0 in water depths >200 m because they are predominantly benthic feeders. The fall densities of ringed seals in the open water of the offshore survey area have been estimated as $1/10$ of the spring pack ice densities because ringed seals are strongly associated with sea ice and begin to reoccupy nearshore fast ice areas as it forms in the fall. The resulting densities (.081/km² in 1999 and .023/km² in 2000) are similar to ringed seal density estimates (0.016/km² to 0.069/km²) from industry vessel operations during summer 2006–2008 (Haley et al. 2010).

Little information is available on spotted seal or ribbon seal densities in offshore areas of the Chukchi Sea. Spotted seal density in the summer were estimated by multiplying the ringed seal density by 0.02. This calculation was based on the ratio of the estimated Chukchi populations of the two species: 8% of the Alaskan population of spotted seals is present in the Chukchi Sea during the summer and fall (Rugh et al. 1997), the Alaskan population of spotted seals is 59,214 (Allen and Angliss 2010), and the population of ringed seals in the Alaskan Chukchi Sea is >208,000 (Bengtson et al. 2005). The ribbon seal density that we used is based on two ribbon seal sightings reported during industry vessel operations in the Chukchi Sea in 2006–2008 (Haley et al. 2010).

The polar bear, under USFWS jurisdiction, is not expected to be encountered in the survey area because it occurs on fast or pack ice and the *Langseth* will completely avoid ice during the entire cruise. However, as a precautionary measure, we have requested a small number of takes.

Table 3 gives the estimated average and maximum densities of marine mammals expected to occur in the proposed survey area. As noted above, there is some uncertainty about the representativeness of the data and assumptions used in the calculations. Because few data were available for the survey area, we calculated densities based on densities observed in adjacent areas of the northern Chukchi Sea, adjusted downward by various assumed factors (see above). For species seen only rarely in the northern Chukchi Sea, we arbitrarily assigned low densities. It is not known how closely the densities that were used reflect the actual densities that will be encountered; however, the approach used here is believed to be the best available at this time.

To provide some allowance for the uncertainties, “maximum estimates” as well as “best estimates” of the numbers potentially affected have been derived (Table 3). For a few marine mammal species, several density estimates were available, and in those cases, the mean estimates were calculated from the survey data, weighted by survey effort. Maximum estimates are 1.5× the best estimates.

The estimated numbers of individuals potentially exposed are presented below based on the 160-dB re 1 $\mu\text{Pa}_{\text{rms}}$ criterion for all marine mammals, and the 170-dB re 1 $\mu\text{Pa}_{\text{rms}}$ criterion for delphinids and pinnipeds. It is assumed that marine mammals exposed to airgun sounds this strong might change their behavior sufficiently to be considered “taken by harassment”.

It should be noted that the following estimates of “takes by harassment” assume that the surveys will be fully completed; in fact, the ensonified areas calculated using the planned number of line-kilometers *have been increased by 25%* to accommodate turns, lines that may need to be repeated, equipment testing, etc. As is typical during offshore ship surveys, inclement weather and equipment malfunctions are likely to cause delays and may limit the number of useful line-kilometers of seismic operations that can be undertaken. The *Langseth* is not ice-strengthened and will completely avoid ice, so it is very likely that the survey will not be completed because ice likely will be present. Furthermore, any marine mammal sightings within or near the designated exclusion zone will result in the shut down of seismic operations as a

TABLE 3. Expected densities of marine mammals in the offshore survey area of the Arctic Ocean north of the Chukchi Sea in September–October 2011. Cetacean densities are corrected for f(0) and g(0) biases. Species listed as endangered are in italics.

Species	Density (#/1000 km ²) in depths <200 m		Density (#/1000 km ²) in depths >200 m	
	Mean	Maximum	Mean	Maximum
Mysticetes				
<i>Bowhead Whale</i>	1.87	2.80	0	0
Gray Whale	1.48	2.22	0	0
<i>Fin Whale</i>	0.01	0.02	0.01	0.02
<i>Humpback Whale</i>	0.01	0.02	0.01	0.02
Minke Whale	0.01	0.02	0.01	0.02
Odontocetes				
Beluga	1.65	2.48	6.78	10.17
Narwhal	0	0	0	0
Killer whale	0.01	0.02	0.01	0.02
Harbor Porpoise	0	0	0	0
Pinnipeds				
Walrus	0	0	0	0
Bearded Seal	14.18	21.27	0	0
Spotted Seal	0.98	1.47	0.98	1.47
Ringed Seal	48.92	73.38	48.92	73.38
Ribbon Seal	0.27	0.41	0.27	0.41
Carnivora				
Polar bear	0	0	0	0

mitigation measure. Thus, the following estimates of the numbers of marine mammals potentially exposed to 160- or 170-dB sounds are precautionary, and probably overestimate the actual numbers of marine mammals that might be involved. These estimates assume that there will be no ice, weather, equipment, or mitigation delays, which is highly unlikely.

Number of Cetaceans that could be Exposed to ≥160 dB.—The number of different individuals that could be exposed to airgun sounds with received levels ≥160 dB re 1 μPa_{rms} on one or more occasions can be estimated by considering the expected density of animals in the area along with the total marine area that would be within the 160-dB radius around the operating airgun array on at least one occasion. The number of possible exposures (including repeated exposures of the same individuals) can be estimated by considering the total marine area that would be within the 160-dB radius around the operating airguns, including areas of overlap. In the proposed survey, the seismic lines are widely spaced in the survey area, so few individual mammals would be exposed more than once during the survey; the area including overlap is only 1.31× the area excluding overlap. Thus, few individual marine mammals would be exposed more than once during the survey. Moreover, it is unlikely that a particular animal would stay in the area during the entire survey.

The numbers of different individuals potentially exposed to ≥160 dB re 1 μPa_{rms} were calculated by multiplying

- the expected species density, either “mean” (i.e., best estimate) or “maximum”, times
- the anticipated area to be ensonified to that level during airgun operations in each depth stratum excluding overlap.

The area expected to be ensonified was determined by entering the planned survey lines into a MapInfo Geographic Information System (GIS), using the GIS to identify the relevant areas by “drawing” the applicable 160-dB (or, in the next subsection, 170-dB) buffer (see Table 1) around each seismic line, and then calculating the total area within the buffers. Areas of overlap (because of lines being closer together than the 160 dB radius) were limited and included only once when estimating the number of individuals exposed.

For species whose densities were the same regardless of water depth, we used ensonified areas for all water depths to calculate numbers exposed. For species whose densities were different in water depths <200 m and >200 m (see Table 3), we used ensonified areas for tracklines in water depths <200 m and the sum of the ensonified areas in water depths 200–1000 and >1000 m and applied them to the different densities.

Table 4 shows the best and maximum estimates of the number of different individual marine mammals that potentially could be exposed to ≥ 160 dB re $1 \mu\text{Pa}_{\text{rms}}$ during the seismic survey if no animals moved away from the survey vessel. The *Requested Take Authorization*, given in the far right column of Table 4, is based on the best estimates of the numbers exposed.

Applying the approach described above, $\sim 122,530 \text{ km}^2$ ($\sim 153,163 \text{ km}^2$ including the 25% contingency) would be within the 160-dB isopleth on one or more occasions during the survey. For <200 m and >200 m depth ranges, the areas are $38,188 \text{ km}^2$ ($47,736 \text{ km}^2$ including the 25% contingency) and $84,342 \text{ km}^2$ ($105,427 \text{ km}^2$ including the 25% contingency), respectively. Because this approach does not allow for turnover in the mammal populations in the study area during the course of the survey, the actual number of individuals exposed could be underestimated in some cases. However, the approach assumes that no marine mammals will move away from or toward the trackline as the Langseth approaches in response to increasing sound levels prior to the time the levels reach 160 dB, which will result in overestimates for those species known to avoid seismic vessels (see § IV a).

The ‘best estimate’ of the number of individual cetaceans that could be exposed to seismic sounds with received levels ≥ 160 dB re $1 \mu\text{Pa}_{\text{rms}}$ during the proposed survey is 962 (Table 4). That total includes 93 **endangered** whales (89 bowheads, 2 humpbacks, and 2 fin whales), which (if realistic) would represent 0.85%, 0.01%, and 0.01%, respectively, of the regional populations (Table 4). The beluga is expected to be the most common cetacean species in the study area; the best estimate of the number of belugas that could be exposed is 794 or 1.85% of the regional population (Table 4). The ‘maximum estimate’ column in Table 4 shows estimates totaling 1438 cetaceans.

Number of Delphinids that could be Exposed to ≥ 170 dB.—The 160-dB criterion, on which the preceding estimates are based, was derived from studies of baleen whales. Odontocete hearing at low frequencies is relatively insensitive, and delphinids generally appear to be more tolerant of strong low-frequency sounds than are many baleen whales. As summarized in Appendix B (5), delphinids commonly occur within distances where received levels would be expected to exceed 160 dB re $1 \mu\text{Pa}_{\text{rms}}$. There is no generally accepted alternative “take” criterion for delphinids exposed to airgun sounds. However, the estimates in this subsection assume that only those delphinids exposed to ≥ 170 dB re $1 \mu\text{Pa}_{\text{rms}}$, on average, would be affected sufficiently to be considered “taken by harassment”. (“On average” means that some individuals might react significantly upon exposure to levels somewhat <170 dB, but others would not do so even upon exposure to levels somewhat >170 dB.)

TABLE 4. Estimates of the possible numbers of marine mammals exposed to ≥ 160 dB and (for delphinids and pinnipeds) ≥ 170 dB during UAGI's proposed seismic program in the Arctic Ocean north of the Chukchi Sea, 5 September–9 October 2011. The proposed sound source is a 10-gun array with a total discharge volume of 1830 in³. Received levels of airgun sounds are expressed in dB re 1 μ Pa (rms, averaged over pulse duration). Not all marine mammals will change their behavior when exposed to these sound levels, but some may alter their behavior when levels are lower (see text). Delphinids and pinnipeds are unlikely to react to levels below 170 dB. Species in italics are listed under the U.S. ESA as endangered. The rightmost column of numbers (in boldface) shows the numbers of "harassment takes" for which authorization is requested.

Species	Best Estimate ¹		Maximum Estimate ¹	Requested Take Authorization
	Number	% Regional Pop'n ²		
Mysticetes				
<i>Bowhead whale</i>	89	0.85	134	89
Gray whale	71	0.35	106	71
<i>Humpback whale</i>	2	0.01	2	2
Minke whale	2	0.02	2	2
<i>Fin whale</i>	2	0.01	2	2
Odontocetes				
Beluga whale	794	1.85	1190	794
Narwhal	0	0	0	0
Killer whale	2 (1)	NA	2 (1)	2
Harbor porpoise	0	0	0	0
Pinnipeds				
Pacific walrus	0	0	0	0
Bearded seal	677 (277)	0.25	1015 (415)	677
Spotted seal	150 (58)	0.25	225 (87)	150
Ringed seal	7492 (2899)	3.01	11,239 (4349)	7492
Ribbon Seal	42 (16)	0.04	63 (24)	42
Carnivora				
Polar bear	0	0	0	5

¹ Best and maximum estimates are based on densities from Table 3 and ensonified areas (including 25% contingency) for 160 dB of 47,736 km² in water depths <200m and 105,427 km² in water depths >200 m, and for 170 dB (identified in parentheses) of 19,523 km² in water depths <200m and 39,741 km² in water depths >200 m.

² Regional population size estimates are from Table 2.

The area ensonified by levels ≥ 170 dB was estimated to be $\sim 47,411$ km² (59,264 km² including the 25% contingency). For <200 m and >200 m depth ranges, the areas are 15,619 km² (19,523 km² including the 25% contingency) and 31,793 km² (39,741 km² including the 25% contingency), respectively. The best and maximum estimates of the numbers of individuals exposed to ≥ 170 dB for the killer whale, the only delphinid expected to be encountered during the survey, are both 2 (Table 4). These values are based on the predicted 170-dB radii around the array to be used during the study and are considered to be more realistic estimates of the number of individual killer whales that could be affected.

Number of Pinnipeds that might be Exposed to ≥ 160 dB and ≥ 170 dB.—The methods described previously for cetaceans were also used to calculate numbers of pinnipeds that could be exposed to airgun sounds with received levels ≥ 160 dB re 1 μ Pa_{rms}. As summarized in § IV(1)(a) and Appendix B, most pinnipeds, like delphinids, seem to be less responsive to airgun sounds than are some mysticetes. Thus, the numbers of pinnipeds that could be exposed to received levels ≥ 170 dB re 1 μ Pa_{rms} were also

calculated, based on the estimated 170-dB radii (Table 1). Based on the “best” densities, 8361 pinnipeds, mostly (89.6%) ringed seals, could be exposed to airgun sounds ≥ 160 dB re 1 $\mu\text{Pa}_{\text{rms}}$; the corresponding numbers that could be exposed to airgun sounds ≥ 170 dB re 1 $\mu\text{Pa}_{\text{rms}}$ are 3250 pinnipeds including 2899 ringed seals. The ‘maximum estimate’ column in Table 4 shows an estimated 12,542 and 4875 pinnipeds that could be exposed to airgun sounds ≥ 160 dB or ≥ 170 dB re 1 $\mu\text{Pa}_{\text{rms}}$, respectively.

Number of Polar Bear that might be Exposed to ≥ 160 dB.— The polar bear, under USFWS jurisdiction, is not expected to be encountered in the survey area because it occurs on fast or pack ice and the *Langseth* will completely avoid ice during the entire cruise. However, as a precautionary measure, we have requested a small number of takes.

(4) Conclusions

The proposed survey in the Arctic Ocean will involve towing an airgun array that will introduce pulsed sounds into the ocean, along with simultaneous operation of an MBES, an SBP, and ADCP. Routine vessel operations, other than the proposed operations by the airguns, are conventionally assumed not to affect marine mammals sufficiently to constitute “taking”. No “taking” of marine mammals is expected in association with operations of the other acoustic sources given the considerations discussed in § II and § IV (b), i.e., such sounds are beamed downward, the beam is narrow, at least in the fore-aft direction, and the pulses are extremely short.

(a) Cetaceans

Strong avoidance reactions by several species of mysticetes to seismic vessels operating large arrays of airguns have been observed at ranges up to 6–8 km and occasionally as far as 20–30 km from the source vessel. However, reactions at the longer distances appear to be atypical of most species and situations, particularly when feeding whales are involved (Miller et al. 2005). During autumn seismic surveys in the Beaufort Sea, some bowhead whales displayed avoidance upon exposure to received sound levels ≥ 130 dB (rms) while migrating west (Richardson et al. 1986, 1999). It is possible that a larger number of bowhead whales than estimated may be disturbed if reactions occur at ≥ 130 dB (rms).

Odontocete reactions to seismic pulses are usually assumed to be limited to lesser distances from the airgun(s) than are those of mysticetes, probably in part because odontocete low-frequency hearing is less sensitive than that of mysticetes. However, at least when in the Canadian Beaufort Sea in summer, belugas appear to be fairly responsive to seismic surveys, with few being sighted within 10–20 km during aerial surveys (Miller et al. 2005).

Taking into account the moderately-sized airgun array to be used and mitigation measures that are planned, effects on cetaceans are generally expected to be restricted to avoidance of a limited area around the seismic operation and short-term changes in behavior, falling within the MMPA definition of “Level B harassment”. Furthermore, the estimated numbers of animals potentially exposed to sound levels sufficient to cause appreciable disturbance are relatively low percentages of the population sizes in the Arctic Ocean, as described below.

Based on the 160-dB criterion, the *best estimates* of the numbers of *individual* cetaceans that may be exposed to sounds ≥ 160 dB re 1 μPa (rms) represent varying proportions of the populations of each species in the Arctic Ocean and adjacent waters (Table 4). For species listed as *Endangered* under the ESA, our estimates include two fin whales, two humpback whales, and ~0.85% of the Bering-Chukchi-Beaufort bowhead whale population of >10,545+ (Table 4).

Varying estimates of the numbers of marine mammals that might be exposed to strong airgun sounds during the proposed program have been presented, depending on the specific exposure criteria (≥ 160 or ≥ 170 dB) and density criterion used (best or maximum). The requested “take authorization” of the number of individuals that could be exposed to ≥ 160 dB re $1 \mu\text{Pa}_{\text{rms}}$ likely overestimates the actual number of animals that will be exposed to and will react to the seismic sounds. The reasons for that conclusion are outlined above. The relatively short-term exposures are unlikely to result in any long-term negative consequences for the individuals or their populations.

The many cases of apparent tolerance by cetaceans of seismic exploration, vessel traffic, and some other human activities show that co-existence is possible. Mitigation measures such as look outs, ramp ups, and power downs or shut downs when marine mammals are seen within defined ranges, should further reduce short-term reactions, and avoid or minimize any effects on hearing sensitivity. In all cases, the effects are expected to be short-term, with no lasting biological consequence.

(b) Pinnipeds

A few pinniped species are likely to be encountered in the study area, but the ringed seal is by far the most abundant marine mammal that will be encountered during the seismic survey. An estimated 7492 ringed seals, 677 bearded seals, 150 spotted seals, and 42 ribbon seals may be exposed to airgun sounds at received levels ≥ 160 dB re $1 \mu\text{Pa}_{\text{rms}}$ during the seismic survey. It is probable that only a small percentage of those would actually be disturbed. The Pacific walrus, under USFWS jurisdiction, is not expected to be encountered in the survey area because it occurs in pack ice and the *Langseth* will completely avoid ice during the entire cruise.

As for cetaceans, the short-term exposures of pinnipeds to airgun sounds are not expected to result in any long-term negative consequences for the individuals or their populations.

(c) Polar Bears

The polar bear, under USFWS jurisdiction, is not expected to be encountered in the survey area because it occurs on fast or pack ice and the *Langseth* will completely avoid ice during the entire cruise. However, as a precautionary measure, we have requested a small number of takes.

(5) Direct Effects on Fish, EFH, and Fisheries, and Their Significance

(a) Effects on Fish

One reason for the adoption of airguns as the standard energy source for marine seismic surveys is that, unlike explosives, they have not been associated with large-scale fish kills. However, existing information on the impacts of seismic surveys on marine fish populations is limited (see Appendix D). There are three types of potential effects of exposure to seismic surveys: (1) pathological, (2) physiological, and (3) behavioral. Pathological effects involve lethal and temporary or permanent sub-lethal injury. Physiological effects involve temporary and permanent primary and secondary stress responses, such as changes in levels of enzymes and proteins. Behavioral effects refer to temporary and (if they occur) permanent changes in exhibited behavior (e.g., startle and avoidance behavior). The three categories are interrelated in complex ways. For example, it is possible that certain physiological and behavioral changes could potentially lead to an ultimate pathological effect on individuals (i.e., mortality).

The specific received sound levels at which permanent adverse effects to fish potentially could occur are little studied and largely unknown. Furthermore, the available information on the impacts of

seismic surveys on marine fish is from studies of individuals or portions of a population; there have been no studies at the population scale. The studies of individual fish have often been on caged fish that were exposed to airgun pulses in situations not representative of an actual seismic survey. Thus, available information provides limited insight on possible real-world effects at the ocean or population scale. This makes drawing conclusions about impacts on fish problematic because, ultimately, the most important issues concern effects on marine fish populations, their viability, and their availability to fisheries.

Hastings and Popper (2005), Popper (2009), and Popper and Hastings (2009a,b) provided recent critical reviews of the known effects of sound on fish. The following sections provide a general synopsis of the available information on the effects of exposure to seismic and other anthropogenic sound as relevant to fish. The information comprises results from scientific studies of varying degrees of rigor plus some anecdotal information. Some of the data sources may have serious shortcomings in methods, analysis, interpretation, and reproducibility that must be considered when interpreting their results (see Hastings and Popper 2005). Potential adverse effects of the program's sound sources on marine fish are then noted.

Pathological Effects.—The potential for pathological damage to hearing structures in fish depends on the energy level of the received sound and the physiology and hearing capability of the species in question (see Appendix C). For a given sound to result in hearing loss, the sound must exceed, by some substantial amount, the hearing threshold of the fish for that sound (Popper 2005). The consequences of temporary or permanent hearing loss in individual fish or a fish population are unknown; however, they likely depend on the number of individuals affected and whether critical behaviors involving sound (e.g., predator avoidance, prey capture, orientation and navigation, reproduction, etc.) are adversely affected.

Little is known about the mechanisms and characteristics of damage to fish that may be inflicted by exposure to seismic survey sounds. Few data have been presented in the peer-reviewed scientific literature. As far as we know, there are only two papers with proper experimental methods, controls, and careful pathological investigation implicating sounds produced by actual seismic survey airguns in causing adverse anatomical effects. One such study indicated anatomical damage, and the second indicated TTS in fish hearing. The anatomical case is McCauley et al. (2003), who found that exposure to airgun sound caused observable anatomical damage to the auditory maculae of “pink snapper” (*Pagrus auratus*). This damage in the ears had not been repaired in fish sacrificed and examined almost two months after exposure. On the other hand, Popper et al. (2005) documented only TTS (as determined by auditory brainstem response) in two of three fish species from the Mackenzie River Delta. This study found that broad whitefish (*Coregonus nasus*) that received a sound exposure level of 177 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ showed no hearing loss. During both studies, the repetitive exposure to sound was greater than would have occurred during a typical seismic survey. However, the substantial low-frequency energy produced by the airguns [less than ~400 Hz in the study by McCauley et al. (2003) and less than ~200 Hz in Popper et al. (2005)] likely did not propagate to the fish because the water in the study areas was very shallow (~9 m in the former case and <2 m in the latter). Water depth sets a lower limit on the lowest sound frequency that will propagate (the “cutoff frequency”) at about one-quarter wavelength (Urlick 1983; Rogers and Cox 1988).

Wardle et al. (2001) suggested that in water, acute injury and death of organisms exposed to seismic energy depends primarily on two features of the sound source: (1) the received peak pressure and (2) the time required for the pressure to rise and decay. Generally, as received pressure increases, the period for the pressure to rise and decay decreases, and the chance of acute pathological effects increases. According to Buchanan et al. (2004), for the types of seismic airguns and arrays involved with the

proposed program, the pathological (mortality) zone for fish would be expected to be within a few meters of the seismic source. Numerous other studies provide examples of no fish mortality upon exposure to seismic sources (Falk and Lawrence 1973; Holliday et al. 1987; La Bella et al. 1996; Santulli et al. 1999; McCauley et al. 2000a,b, 2003; Bjarti 2002; Thomsen 2002; Hassel et al. 2003; Popper et al. 2005; Boeger et al. 2006).

Some studies have reported, some equivocally, that mortality of fish, fish eggs, or larvae can occur close to seismic sources (Kostyuchenko 1973; Dalen and Knutsen 1986; Booman et al. 1996; Dalen et al. 1996). Some of the reports claimed seismic effects from treatments quite different from actual seismic survey sounds or even reasonable surrogates. However, Payne et al. (2009) reported no statistical differences in mortality/morbidity between control and exposed groups of capelin eggs or monkfish larvae. Saetre and Ona (1996) applied a ‘worst-case scenario’ mathematical model to investigate the effects of seismic energy on fish eggs and larvae. They concluded that mortality rates caused by exposure to seismic surveys are so low, as compared to natural mortality rates, that the impact of seismic surveying on recruitment to a fish stock must be regarded as insignificant.

Physiological Effects.—Physiological effects refer to cellular and/or biochemical responses of fish to acoustic stress. Such stress potentially could affect fish populations by increasing mortality or reducing reproductive success. Primary and secondary stress responses of fish after exposure to seismic survey sound appear to be temporary in all studies done to date (Sverdrup et al. 1994; Santulli et al. 1999; McCauley et al. 2000a,b). The periods necessary for the biochemical changes to return to normal are variable and depend on numerous aspects of the biology of the species and of the sound stimulus (see Appendix C).

Behavioral Effects.—Behavioral effects include changes in the distribution, migration, mating, and catchability of fish populations. Studies investigating the possible effects of sound (including seismic survey sound) on fish behavior have been conducted on both uncaged and caged individuals (e.g., Chapman and Hawkins 1969; Pearson et al. 1992; Santulli et al. 1999; Wardle et al. 2001; Hassel et al. 2003). Typically, in these studies fish exhibited a sharp “startle” response at the onset of a sound followed by habituation and a return to normal behavior after the sound ceased.

In general, any adverse effects on fish behavior or fisheries attributable to seismic testing may depend on the species in question and the nature of the fishery (season, duration, fishing method). They may also depend on the age of the fish, its motivational state, its size, and numerous other factors that are difficult, if not impossible, to quantify at this point, given such limited data on effects of airguns on fish, particularly under realistic at-sea conditions.

(b) EFH

A small proportion of the proposed survey in the Arctic Ocean off northern Alaska will be conducted in an area designated as EFH, i.e. the U.S. EEZ (NPFMC 2009). Seismic sound should not have any direct effect on EFH, given that the definition of EFH includes only chemical and physical criteria, not biological criteria (e.g., prey species).

(c) Fisheries

There is general concern about potential adverse effects of seismic operations on fisheries, namely a potential reduction in the “catchability” of fish involved in fisheries. Although reduced catch rates have been observed in some marine fisheries during seismic testing, in a number of cases the findings are confounded by other sources of disturbance (Dalen and Raknes 1985; Dalen and Knutsen 1986; Løkkeborg 1991; Skalski et al. 1992; Engås et al. 1996). In other airgun experiments, there was no

change in catch per unit effort (CPUE) of fish when airgun pulses were emitted, particularly in the immediate vicinity of the seismic survey (Pickett et al. 1994; La Bella et al. 1996). For some species, reductions in catch may have resulted from a change in behavior of the fish, e.g., a change in vertical or horizontal distribution, as reported in Slotte et al. (2004).

No active fishing is expected to be conducted within the study area during the time of the survey. Any on-going fisheries near the project area would be subsistence, and much closer to shore than the actual survey.

(6) Direct Effects on Invertebrates and Their Significance

The existing body of information on the impacts of seismic survey sound on marine invertebrates is very limited. However, there is some unpublished and very limited evidence of the potential for adverse effects on invertebrates, thereby justifying further discussion and analysis of this issue. The three types of potential effects of exposure to seismic surveys on marine invertebrates are pathological, physiological, and behavioral. Based on the physical structure of their sensory organs, marine invertebrates appear to be specialized to respond to particle displacement components of an impinging sound field and not to the pressure component (Popper et al. 2001; see also Appendix D).

The only information available on the impacts of seismic surveys on marine invertebrates involves studies of individuals; there have been no studies at the population scale. Thus, available information provides limited insight on possible real-world effects at the regional or ocean scale. The most important aspect of potential impacts concerns how exposure to seismic survey sound ultimately affects invertebrate populations and their viability, including availability to fisheries.

Literature reviews of the effects of seismic and other underwater sound on invertebrates were provided by Moriyasu et al. (2004) and Payne et al. (2008). The following sections provide a synopsis of available information on the effects of exposure to seismic survey sound on species of decapod crustaceans and cephalopods, the two taxonomic groups of invertebrates on which most such studies have been conducted. The available information is from studies with variable degrees of scientific soundness and from anecdotal information. A more detailed review of the literature on the effects of seismic survey sound on invertebrates is provided in Appendix D.

(a) Pathological Effects

In water, lethal and sub-lethal injury to organisms exposed to seismic survey sound appears to depend on at least two features of the sound source: (1) the received peak pressure, and (2) the time required for the pressure to rise and decay. Generally, as received pressure increases, the period for the pressure to rise and decay decreases, and the chance of acute pathological effects increases. For the type of airgun array planned for the proposed program, the pathological (mortality) zone for crustaceans and cephalopods is expected to be within a few meters of the seismic source, at most; however, very few specific data are available on levels of seismic signals that might damage these animals. This premise is based on the peak pressure and rise/decay time characteristics of seismic airgun arrays currently in use around the world.

Some studies have suggested that seismic survey sound has a limited pathological impact on early developmental stages of crustaceans (Pearson et al. 1994; Christian et al. 2003; DFO 2004). However, the impacts appear to be either temporary or insignificant compared to what occurs under natural conditions. Controlled field experiments on adult crustaceans (Christian et al. 2003, 2004; DFO 2004) and adult cephalopods (McCauley et al. 2000a,b) exposed to seismic survey sound have not resulted in

any significant pathological impacts on the animals. It has been suggested that exposure to commercial seismic survey activities has injured giant squid (Guerra et al. 2004), but there is no evidence to support such claims.

(b) Physiological Effects

Physiological effects refer mainly to biochemical responses by marine invertebrates to acoustic stress. Such stress potentially could affect invertebrate populations by increasing mortality or reducing reproductive success. Primary and secondary stress responses (i.e., changes in haemolymph levels of enzymes, proteins, etc.) of crustaceans have been noted several days or months after exposure to seismic survey sounds (Payne et al. 2007). The periods necessary for these biochemical changes to return to normal are variable and depend on numerous aspects of the biology of the species and of the sound stimulus.

(c) Behavioral Effects

There is increasing interest in assessing the possible direct and indirect effects of seismic and other sounds on invertebrate behavior, particularly in relation to the consequences for fisheries. Changes in behavior could potentially affect such aspects as reproductive success, distribution, susceptibility to predation, and catchability by fisheries. Studies investigating the possible behavioral effects of exposure to seismic survey sound on crustaceans and cephalopods have been conducted on both uncaged and caged animals. In some cases, invertebrates exhibited startle responses (e.g., squid in McCauley et al. 2000a,b). In other cases, no behavioral impacts were noted (e.g., crustaceans in Christian et al. 2003, 2004; DFO 2004). There have been anecdotal reports of reduced catch rates of shrimp shortly after exposure to seismic surveys; however, other studies have not observed any significant changes in shrimp catch rate (Andrighetto-Filho et al. 2005). Similarly, Parry and Gason (2006) did not find any evidence that lobster catch rates were affected by seismic surveys. Any adverse effects on crustacean and cephalopod behavior or fisheries attributable to seismic survey sound depend on the species in question and the nature of the fishery (season, duration, fishing method).

(7) Direct Effects on Seabirds and Their Significance

Investigations into the effects of airguns on seabirds are extremely limited. Stemp (1985) conducted opportunistic observations on the effects of seismic exploration on seabirds, and Lacroix et al. (2003) investigated the effect of seismic surveys on molting long-tailed ducks in the Beaufort Sea, Alaska. Stemp (1985) did not observe any effects of seismic testing, although he warned that his observations should not be extrapolated to areas with large concentrations of feeding or molting birds. In a more intensive and directed study, Lacroix et al. (2003) did not detect any effects of seismic exploration on molting long-tailed ducks in the inshore lagoon systems of Alaska's North Slope. Both aerial surveys and radio-tracking indicated that the proportion of ducks that stayed near their marking location from before to after seismic exploration was unaffected by nearby seismic survey activities. Seismic activity also did not appear to change the diving intensity of long-tailed ducks significantly.

Birds might be affected slightly by seismic sounds from the proposed study, but the impacts are not expected to be significant to individual birds or their populations. The types of impacts that are possible are summarized below.

Localized, temporary displacement and disruption of feeding.—Such displacements would be similar to those caused by other large vessels that passed through the area. Agness et al. (2008) reported changes in behavior of Kittlitz's murrelets in the presence of large, fast-moving vessels, and suggested the possibility of biological effects due to increased energy expenditure. However, the *Langseth* travels at a

relatively slow speed (~7–9 km/h) during seismic acquisition. Any adverse effects are expected to be negligible.

Modified prey abundance.—It is unlikely that prey species for birds will be affected by seismic activities to a degree that affects the foraging success of birds. If prey species exhibit avoidance of the ship, the avoidance is expected to be transitory and limited to a very small portion of a bird's foraging range.

Disturbance to breeding birds on island colonies.—A vessel (seismic or otherwise) that approaches too close to a breeding colony could disturb adult birds from nests in response either to sonic or to visual stimuli. This is not applicable to the proposed Arctic Ocean survey, which will be in offshore waters.

Egg and nestling mortality.—Disturbance of adult birds from nests can lead to egg or nestling mortality *via* temperature stress or predation. There is no potential for this considering the distance that the seismic survey will occur from nesting colonies.

Chance injury or mortality.—Many species of marine birds feed by diving to depths of several meters or more. Flocks of feeding birds may consist of hundreds or even thousands of individuals. Also, some species of seabirds (particularly alcids) escape from boats by diving when the boat gets too close. It is possible that, during the course of normal feeding or escape behavior, some birds could be near enough to an airgun to be injured by a pulse. Although no specific information is available about the circumstances (if any) where this might occur, the negligible aversive reactions of birds to airguns (see above) suggest that a bird would have to be very close to any airgun to receive a pulse with sufficient energy to cause injury, if that is possible at all.

Induced injury or mortality.—If it disorients, injures, or kills prey species, or otherwise increases the availability of prey species to marine birds, a seismic survey could attract birds. Birds drawn too close to an airgun may be at risk of injury. However, available evidence from other seismic surveys utilizing airguns has not shown a pattern of fish (or other prey) kills from airguns [see § IV(5), above]. Thus, the potential that birds would be attracted and subsequently injured by the proposed seismic survey appears very low.

Consultation with the USFWS is required when activities may impact threatened or endangered bird species. An informal consultation was conducted with Ted Swem of the USFWS on 16 February 2010. His conclusion was that there would be no harmful effects to any bird species of concern in the survey area, notably spectacled or Steller's eiders.

(8) Indirect Effects on Marine Mammals, Seabirds, and Their Significance

The proposed airgun operations will not result in any permanent impact on habitats used by marine mammals, seabirds, or to the food sources they use. The main impact issue associated with the proposed activities will be temporarily elevated noise levels and the associated direct effects on marine mammals and seabirds as discussed above.

During the seismic study only a small fraction of the available habitat would be strongly ensonified at any given time. Disturbance to fish species would be short-term and fish would return to their pre-disturbance behavior once the seismic activity ceased [§ IV(5)(a), above]. Thus, the proposed survey would have little, if any, impact on the abilities of marine mammals to feed in the area where seismic work is planned.

Some mysticetes, including bowhead whales, feed on concentrations of zooplankton. Although the main summering area for bowheads is in the Canadian Beaufort Sea, at least a few feeding bowhead whales may occur in offshore waters of the western Beaufort Sea and northern Chukchi Sea while migrating westward in September and October, when the *Langseth* will be in the area. A reaction by zooplankton to a seismic impulse would only be relevant to whales if it caused a concentration of zooplankton to scatter. Pressure changes of sufficient magnitude to cause that type of reaction would probably occur only very close to the source. Impacts on zooplankton behavior are predicted to be negligible, and that would translate into negligible impacts on feeding mysticetes.

(9) Possible Effects on Subsistence Hunting and Fishing

Subsistence hunting and fishing continue to be prominent in the household economies and social welfare of some Alaskan residents, particularly among those living in small, rural villages (Wolfe and Walker 1987). Subsistence remains the basis for Alaska Native culture and community. In rural Alaska, subsistence activities are often central to many aspects of human existence, including patterns of family life, artistic expression, and community religious and celebratory activities. Because of the importance of subsistence, NSF offers guidelines for science coordination with native Alaskans (see <http://www.arcus.org/guidelines/>).

(a) Subsistence Hunting for Marine Mammals

Marine mammals are legally hunted along the north coast of Alaska near Barrow, Nuiqsut, and Kaktovik by coastal Alaska Natives; species hunted include bowhead whales, beluga whales, ringed, spotted, and bearded seals, walrus, and polar bears.

Bowhead whale hunting is the key activity in the subsistence economies of Barrow and two smaller communities to the east, Nuiqsut and Kaktovik. Whale harvests have a great influence on social relations by strengthening the sense of Inupiat culture and heritage in addition to reinforcing family and community ties.

An overall quota system for the hunting of bowhead whales was established by the International Whaling Commission in 1977; the quota is now regulated through an agreement between NMFS and the Alaska Eskimo Whaling Commission (AEWC). The AEWC allots the number of bowhead whales that each whaling community may harvest annually (USDI/BLM 2005; NMFS 2008d).

The community of Barrow hunts bowhead whales in both the spring and fall during the whales' seasonal migrations along the coast. Often, the bulk of the Barrow bowhead harvest is taken during the spring hunt. However, with larger quotas in recent years, it is common for a substantial fraction of the annual Barrow quota to remain available for the fall hunt (Table 5). The communities of Nuiqsut and Kaktovik participate only in the fall bowhead harvest. The spring hunt at Barrow occurs after leads open because of the deterioration of pack ice; the spring hunt typically occurs from early April until the first week of June. The fall migration of bowhead whales that summer in the eastern Beaufort Sea typically begins in late August or September. The location of the fall subsistence hunt depends on ice conditions and (in some years) industrial activities that influence the bowheads movements as they move west (Brower 1996). In the fall, subsistence hunters use aluminum or fiberglass boats with outboards. Hunters prefer to take bowheads close to shore to avoid a long tow during which the meat can spoil, but Braund and Moorehead (1995) report that crews may (rarely) pursue whales as far as 80 km offshore. The autumn hunt at Barrow usually begins in mid September, and mainly occurs in the waters east and northeast of Point Barrow. The whales have usually left the Beaufort Sea by late October (Treacy 2002a,b).

Table 5. Number of bowhead whale landing by year at Barrow, Cross Island (Nuiqsut), and Kaktovik, 1993–2008. Barrow numbers include the total number of whales landed for the year followed by the numbers landed during the fall hunt in parenthesis. Cross Isl. (Nuiqsut) and Kaktovik landings are in autumn.

Year	Point Hope	Wainwright	Barrow	Cross Island	Kaktovik
1993	2	5	23 (7)	3	3
1994	5	4	16 (1)	0	3
1995	1	5	19 (11)	4	4
1996	3	3	24 (19)	2	1
1997	4	3	30 (21)	3	4
1998	3	3	25 (16)	4	3
1999	2	5	24 (6)	3	3
2000	3	5	18 (13)	4	3
2001	4	6	27 (7)	3	4
2002	0	1	22 (17)	4	3
2003	4	5	16 (6)	4	3
2004	3	4	21 (14)	3	3
2005	7	4	29 (13)	1	3
2006	0	2	22 (19)	4	3
2007	3	4	20 (7)	3	3
2008	2	2	21(12)	4	3

Sources:USDI/BLM and references therein; Burns et al. (1993); Koski et al. (2005); Suydam et al. 2004, 2005, 2006, 2007, 2008, 2009.

The scheduling and location far (>200 km) offshore of this seismic survey has been discussed with representatives of those concerned with the subsistence bowhead hunt, most notably the AEWK and the Barrow Whaling Captains’ Association. No major concerns were expressed (see further in § IV(11c), below).

Beluga whales are available to subsistence hunters at Barrow in the spring when pack-ice conditions deteriorate and leads open up. Belugas may remain in the area through June and sometimes into July and August in ice-free waters. Hunters usually wait until after the spring bowhead whale hunt is finished before turning their attention to hunting belugas. During 2002–2006, Alaska Native subsistence hunters took a mean annual number of 25.4 beluga whales from the Beaufort Sea stock and 59 from the eastern Chukchi Sea stock. The average annual harvest of beluga whales taken by Barrow for 1962–1982 was five (MMS 1996). The Alaska Beluga Whale Committee recorded that 23 beluga whales had been harvested by Barrow hunters from 1987 to 2002, ranging from 0 in 1987, 1988, and 1995 to the high of 8 in 1997 (Fuller and George 1999; Alaska Beluga Whale Committee 2002 in USDI/BLM 2005). The timing of the proposed survey is after the beluga harvest, and the survey initiates >200 km offshore, which would be well outside the area where seismic surveys would influence any late beluga hunting by Barrow hunters.

Ringed seals are hunted by villagers along the Alaskan north coast mainly from October through June. Hunting for these smaller mammals is concentrated during winter because bowhead whales, bear-ded seals, and caribou are available through other seasons. Winter leads in the area off Point Barrow and along the barrier islands of Elson Lagoon to the east are used for hunting ringed seals. The average annual ringed seal harvest by the community of Barrow from the 1960s through much of the 1980s has been estimated as 394 (Table 6). Although ringed seals are available year-round, the seismic survey will not occur during the primary period when these seals are harvested. Also the seismic survey in offshore waters will not influence ringed seals in the nearshore areas where they are hunted.

The *spotted seal* subsistence hunt peaked in July and August, at least in 1987–1990, but involves few animals. Spotted seals typically migrate south by October to overwinter in the Bering Sea. Admiralty Bay, <60 km to the east of Barrow, is a location where spotted seals are harvested. Spotted seals are also occasionally hunted in the area off Point Barrow and along the barrier islands of Elson Lagoon to the east (USDI/BLM 2005). The average annual spotted seal harvest by the community of Barrow from 1987–1990 was one (Braund et al. 1993; Table 6). Spotted seals become less abundant at Nuiqsut and Kaktovik, and few if any spotted seals are harvested at these villages. The seismic survey will commence at least 200 km offshore from the preferred nearshore harvest area of these seals.

Bearded seals, although not favored for their meat, are important to subsistence activities in Barrow because of their skins. Six to nine bearded seal hides are used by whalers to cover each of the skin-covered boats traditionally used for spring whaling. Because of their valuable hides and large size, bearded seals are specifically sought. Bearded seals are harvested during the summer months in the Beaufort Sea (USDI/BLM 2005). The animals inhabit the environment around the ice floes in the drifting ice pack, so hunting usually occurs from boats in the drift ice. Braund et al. (1993) estimated that 174 bearded seals were harvested annually at Barrow from 1987 to 1990 (Table 6). The majority of bearded seal harvest sites from 1987 to 1990 was within ~24 km of Point Barrow (Braund et al. 1993), well inshore of the proposed survey, which is to take place >200 km offshore.

USFWS has monitored the harvest of *polar bears* in Alaska using a mandatory marking, tagging, and reporting program implemented in 1988. Polar bears are harvested in the winter and spring, but comprise a small percentage of the annual Native subsistence harvest. Braund et al. (1993) reported that ~2% of the total edible pounds harvested by Barrow residents from 1987 to 1989 involved polar bears. USFWS estimated that, from 2003 to 2007, the average annual harvest of polar bears in Alaska was ~37 (Allen and Angliss 2010). That would include harvests at other smaller communities besides Barrow. It is not expected that the seismic survey will interfere with polar bear subsistence hunting because of the limited annual harvest documented by USFWS and the fact that the subsistence hunt typically takes place in the winter and spring, either well after or well before the scheduled survey.

*Walrus*es are hunted primarily from June through mid August to the west of Point Barrow and southwest to Peard Bay. Walrus rarely occur in the Beaufort Sea north and east of Barrow and become less abundant farther east. The harvest effort peaks in July. The annual walrus harvest by Barrow residents was 7–206 during 1990–2002 (Fuller and George 1999; Schliebe 2002 in USDI/BLM 2005). It is unlikely that accessibility to walrus during the subsistence hunt could be impaired during the *Langseth*'s traverse north of Barrow to the starting point of the seismic survey in September and October. The area affected, in any case, would be an area in close proximity to the ship. The airguns would not be operating at this time.

TABLE 6. Average annual take of marine mammals other than bowhead whales harvested by the community of Barrow (as compiled by LGL Alaska 2004).

Beluga Whales	Ringed Seals	Bearded Seals	Spotted Seals
5 **	394 *	174*	1*

* Average annual harvest for years 1987-90 (Braund et al. 1993).

** Average annual harvest for years 1962-82 (MMS 1996).

In the event that both marine mammals and hunters were near the *Langseth* when it begins operating north of Barrow, the proposed project potentially could impact the availability of marine mammals for the harvest in a very small area immediately around the *Langseth*. However, the majority of marine mammals are taken by hunters within ~33 km off shore (Braund et al. 1993), and the *Langseth* will not commence the seismic survey until it is >200 km offshore.

Operations in the Arctic Ocean are scheduled to occur in early September–early October, and most hunting does not occur at that time of year. The bowhead hunt near Barrow could be underway, but the *Langseth* will be >200 km offshore in transit and when conducting seismic operations. Thus, the proposed project is not expected to have any significant impacts to the availability of marine mammals for subsistence harvest.

(b) Subsistence Fishing

Subsistence fishing is conducted by Alaska Natives through the year, but most actively during the summer and fall months. On average, subsistence fishing provides ~230 pounds of food per person per year in rural Alaska (Wolfe 2000). Of the estimated 43.7 million pounds of wild foods harvested in rural Alaska communities annually, subsistence fisheries contribute ~60–62% from finfish and 2% from shellfish (ADF&G 2005). Barrow residents often fish for camp food while hunting, so the range of subsistence fishing is widespread. Marine subsistence fishing occurs during the harvest of other subsistence resources in the summer. Fishing occurs in areas much closer to shore than where the survey will be conducted (MMS 1996), thus subsistence fishing activity will not be affected by the proposed survey.

Seismic surveys can, at times, cause changes in the catchability of fish. Airgun operations are not planned to occur within 200 km of shore. However, in the highly unlikely event that subsistence fishing (or hunting) is occurring within 5 km of the *Langseth's* trackline, the airgun operations will be suspended until the *Langseth* is >5 km away.

(c) Consultation with the Barrow Community

UAGI has worked with the people of Barrow to identify and avoid areas of potential conflict. The project's (PI) contacted Dr. Glenn Sheehan of the Barrow Arctic Science Consortium and North Slope Borough (NSB) biologist, Dr. Robert Suydam, on 7 January 2010 to inform them of the proposed study and the elements intended to minimize potential subsistence conflict. The PI presented the proposed UAGI survey at a meeting of the AEWG in Barrow on 11 February 2010. He explained the survey plans to the local residents, including NSB Department of Wildlife Management biologists, Craig George and Robert Suydam, consulted with stakeholders about their concerns, and discussed the aspects of the survey designed to mitigate impacts. No major concerns were expressed. The PI also attended the 2011 AEWG meeting on 17–18 February, and the only concern expressed was that AEWG would like a good communication link with the *Langseth* during the survey.

A Barrow resident knowledgeable about the mammals and fish of the area is expected to be included as a PSO aboard the *Langseth*. Although her/his primary duties will be as a member of the PSO team responsible for implementing the monitoring and mitigation requirements [see Section II(3)(a)], s/he will also be able to act as liaison with hunters and fishers if they are encountered at sea. However, the proposed activity has been timed so as to avoid overlap with the main harvests of marine mammals (especially bowhead whales), and is not expected to affect the success of subsistence fishers.

(10) Cumulative Effects

Cumulative effects refer to the impacts on the environment that result from a combination of past, existing, and imminent projects and human activities. Agents of cumulative effects can include multiple causes, multiple effects, effects of activities in more than one locale, and recurring events.

Human activities in the Arctic Ocean include commercial fishing, oil and gas development, and vessel traffic. These activities, when conducted separately or in combination with other activities, can affect marine mammals in the study area and potentially their overall well being. Any cumulative effects caused by the addition of the seismic survey impacts on marine mammals will be extremely limited, especially considering the timeframe of the proposed activities and the relatively small area involved.

(a) Commercial Fishing

In the Alaskan Beaufort Sea, commercial fisheries are very limited. The Helmericks family operates an under-ice commercial gill net fishery during fall in the Colville River Delta, about 470 km southeast of the closest part of the proposed study area (Gallaway et al. 1983, 1989). The fishery typically operates from early October through the end of November. Fishing effort is concentrated in the Main (Kupiguak) and East Channels of the river near Anachilik Island. The three principal species targeted in the fishery are Arctic cisco, least cisco, and humpback whitefish. During 2006, most commercial fishing in the Arctic Ocean was conducted by Sweden, Norway, and Japan (Sea Around Us Project 2010), and likely would not take place near the seismic survey area.

As noted above, the proposed survey will have a negligible impact on the marine mammals in the study area. Whereas bycatch may occur during commercial fisheries, no injuries or deaths of marine mammals are anticipated during the proposed seismic survey. The combination of UAGI's activities with those of fisheries will not result in any detectable increment in impacts on marine mammals over and above the impacts from the fisheries alone.

(b) Oil and Gas Development

The first lease sale in the Chukchi Sea was held in 1988, and offshore wells were drilled in 1989–1991. Interest in the Chukchi Sea declined after 1991, and between 1991 and 2005 there was virtually no petroleum exploration in the region. Following the four lease sales held between 1988 and 1991, a total of 483 tracts were leased (~1.1 ha). All blocks leased before the most recent lease sale (193) had either been relinquished or expired, and there were no active leases between 1998 and 2008. Lease Sale 193 was held on 6 February 2008. Of the 5354 blocks offered, 488 received bids and leases were issued (Fig. 5). The validity of the lease sale has been challenged in court, and no further sales are planned at present.

Exploration associated with the Chukchi lease sales has included ~203,000 line-km of 2-D seismic operations from the 1960s to 2005 (Virginia Hoffman, MMS, pers. comm. 2008), and ~30,000 line-km of seismic operations during 2006–2008 (see Funk et al. 2010). In the 1970s (21.2% of total), all of the seismic activity was during 1970–1975; in the 1980s (62.1%), there was seismic activity in all years except 1988; in the 1990s (0.6%), there was seismic activity only in 1990; and in the 2000s (11.7%) there was no seismic activity during 2000–2005. Seismic surveys covered most of the Chukchi Sea Planning Area (Fig. 6 illustrates the location of 2-D seismic surveys in the 1980s). There was little seismic activity during 2009 (~2477 km) and 2010 (~8073 km).

Five large prospects were drilled in July–September 1989, August–October 1990, and August–October 1991: the Burger, Klondike, Crackerjack, Popcorn, and Diamond prospects, in water depths 42–46 m (Fig. 7). Although most of the five wells encountered favorable geology, commercial quantities of

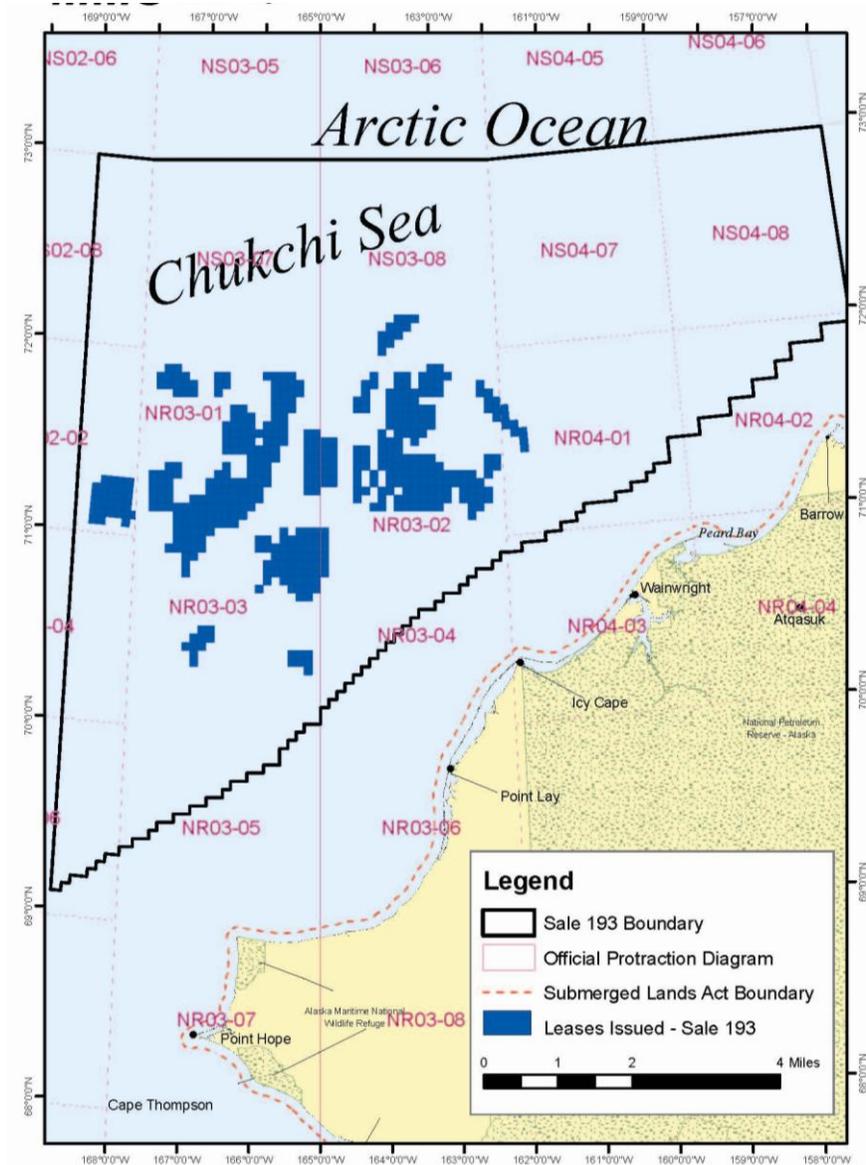


Figure 5. Leases issued in Lease Sale 193 in the Chukchi Sea Planning Area, 2008. Source: MMS.

oil or gas were not discovered, and exploration of Chukchi shelf was discontinued. Through successive rounds of relinquishments, industry lease holdings gradually diminished, and of the 483 leases active on Chukchi shelf in 1992, all subsequently expired. No drilling associated with Lease Sale 193 has yet occurred. There has been no development or production in the Chukchi Sea.

Open-water industry seismic and shallow hazards surveys took place in the Chukchi Sea each year from 2006-2010 and in the Alaskan Beaufort Sea in 2006, 2007, 2008, and 2010; surveys are also planned for 2011. These surveys take place much closer to shore than the majority of the proposed *Langseth* activities. However, the final leg of the *Langseth* project that extends south may overlap spatially and temporally with some industry shallow hazards seismic surveys planned for 2011. Non-industry seismic

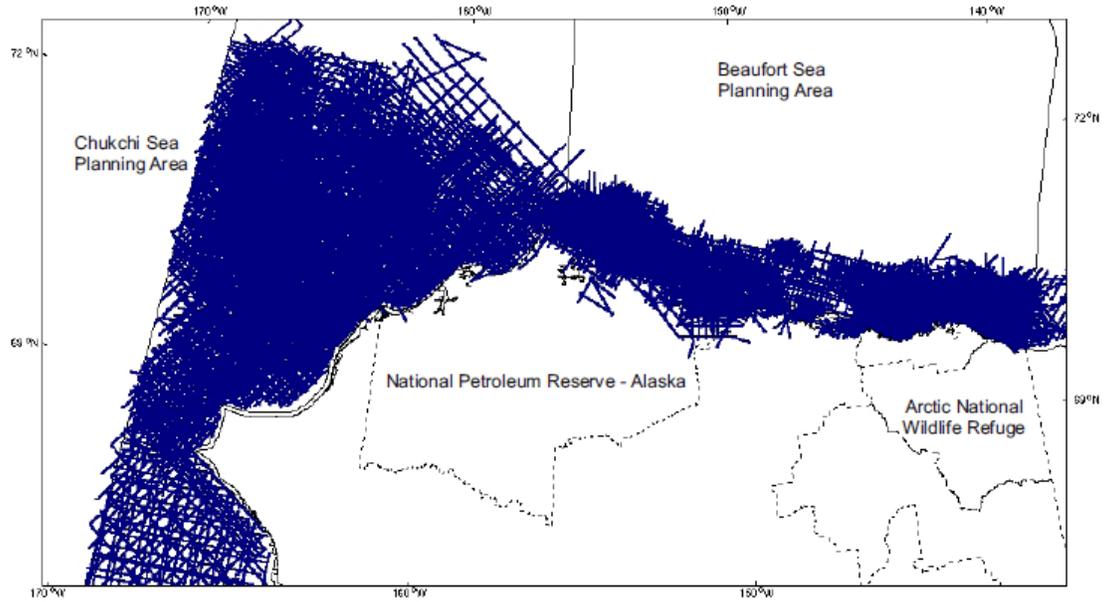


Figure 6. 2-D seismic survey lines shot in the Chukchi Sea and Beaufort Sea planning areas during 1980–1989. Source: MMS.

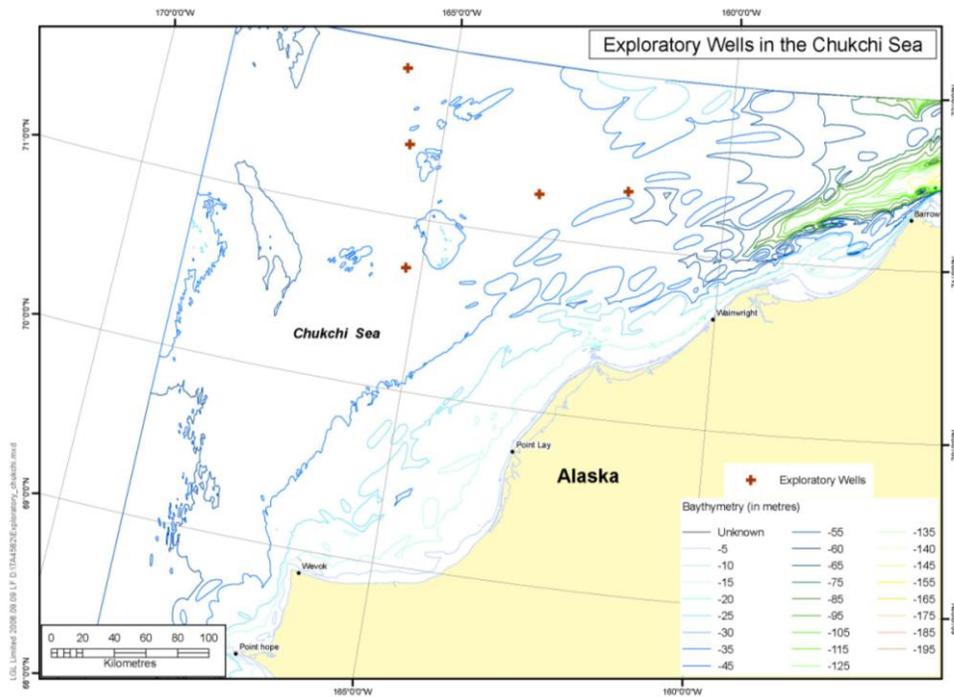


Figure 7. Exploratory wells drilled in the Chukchi Sea during 1989–1991. Source: MMS.

surveys also took place off the north coast of Alaska and in the Arctic Ocean during the open-water season in 2005, 2006, 2009, and 2010 (Haley 2006; Haley and Ireland 2006; Mosher et al. 2009; Beland and Ireland 2010).

Oil industry activities will be ongoing in the central part of Alaska's Beaufort Sea coast during the proposed seismic survey, but such activities are located >150 km from the beginning of the proposed survey, and no overlap is expected. Noise generated by oil industry activities in the nearshore zone, such as at Northstar, generally is not detectable underwater more than 10 km from the island-based facilities (Richardson and Williams [eds.] 2004). Underwater sounds from vessels supporting oil industry activities are often detectable farther away. However, the proposed survey route will take the *Langseth* due north of Barrow and there will be no encounters with any vessels servicing the oil fields. Also, few if any members of the species for which disturbance effects are of most concern, the bowhead whale, will occur in the survey area until the *Langseth* cruise approaches its completion ~160 km west of Barrow. No cumulative impacts of Alaskan oil industry activities and *Langseth* operations on bowheads or other species are anticipated.

(c) Vessel Traffic

In heavily-traveled areas, shipping noise generally dominates ambient noise at frequencies from 20 to 300 Hz, although that is not the case in most of the Arctic (Richardson et al. 1995). Baleen whales are likely more sensitive to sound at low frequencies than are toothed whales. There may be some avoidance by marine mammals of ships and boats operating in and near the proposed seismic survey area. Bowhead whales, in particular, often move away when vessels approach within several kilometers (Richardson and Malme 1993). Hunters at Barrow believe that vessel traffic near the coast southeast of Barrow can cause larger-scale displacement of bowheads. However, the proposed study area is located mostly northwest of where bowheads are expected to occur.

Responses of belugas to vessel traffic are highly variable (Richardson et al. 1995), and can extend to tens of kilometers in special circumstances (Finley et al. 1990). However, large-scale effects on belugas are not known to occur in the Beaufort Sea.

The existing oil fields on land and in the Beaufort Sea are serviced by land, air, and sea. Marine activities associated with the on-land oil developments in northern Alaska consist mainly of tug and barge traffic, mainly in nearshore waters along the north coast. In the past there has been crew boat traffic to Northstar Island during the open-water season, but that has been largely replaced by hovercraft and helicopter traffic, neither of which introduces much noise into the sea (Richardson and Williams 2004). Several supply vessels travel along the Beaufort Sea coast, transporting fuel and construction materials to communities and industrial centers. Two or three supply vessels routinely travel between Barrow and Kaktovik during the summer, with two additional vessels operating out of Prudhoe Bay.

Aside from vessels supporting the oil industry, vessel traffic in the proposed study area is limited. The majority of the other vessels will be within 20 km of the coast, and will include native vessels used for fishing and hunting, cruise ships, icebreakers, Coast Guard vessels, and supply ships. Several supply vessels are also scheduled to visit the North Slope communities from Barrow to Kaktovik, delivering fuel and construction equipment. An unknown number of trips by U.S. and Canadian Coast Guard vessels are also likely.

The addition of vessel traffic associated with the proposed survey activities will be mostly well offshore, away from other vessel traffic, and the negligible increase in overall vessel traffic will result in negligible cumulative effects to marine mammals. It is not anticipated that the *Langseth* would be in this part of the Arctic region within the foreseeable future.

(d) Oil Spills

There is always the risk of an oil spill in the study area. However, the *Langseth* is a U.S.-registered vessel, certified, maintained and operated to high standards, with dual engines and dual props. It is highly unlikely that the *Langseth* will be the source of an oil spill of any significant impact. The *Langseth*'s fuel capacity is relatively trivial when compared to the amount of oil produced from the offshore fields in the Beaufort Sea.

(e) Hunting

Marine mammals are legally hunted in Alaskan waters by coastal Alaska Natives. In the Alaskan Beaufort and Chukchi seas, bowhead whales, beluga whales, Pacific walruses, ringed, spotted, and bearded seals, and polar bears are hunted (see § IV[8]). The hunting communities within the area of the proposed survey are Barrow, Nuiqsut, and Kaktovik in the Alaskan Beaufort Sea and Wainwright in the Chukchi Sea. The planned project (unlike subsistence hunting activities) will not result in directed or lethal takes of marine mammals. Also, the direct disturbance-related impacts of the project on individuals are anticipated to be short-term and inconsequential to the long-term well being of those individuals and their populations. Thus, the combined effects of the project and of subsistence hunting on marine mammal stocks are not expected to differ appreciably from those of subsistence hunting alone.

(f) Summary of Cumulative Impacts

For the majority of the proposed trackline, the *Langseth* is unlikely to encounter any additional human activities, and thus the degree of cumulative impact will be minimal. Any such effects related to of human activities near the start and end of the trackline will have no more than a negligible impact on the marine mammal populations encountered.

(11) Unavoidable Impacts of Noise

Unavoidable impacts to marine mammals, seabirds, or fish occurring in the proposed study area in the Arctic Ocean will be limited to short-term changes in behavior and local distribution. For cetaceans and pinnipeds, some of the changes in behavior may be sufficient to fall within the MMPA definition of "Level B Harassment" (behavioral disturbance; no serious injury or mortality). No long-term or significant impacts are expected on any individual marine mammals, seabirds, or on the populations to which they belong. Effects on recruitment or survival are expected to be (at most) negligible. Also, any effects on accessibility of marine mammals for subsistence hunting and effects on commercial fishing are expected to be (at most) negligible.

(12) Coordination with Other Agencies and Processes

This EA has been prepared by LGL on behalf of NSF pursuant to NEPA and E.O. 12114. Potential impacts to endangered species and critical habitat have also been assessed in the document; therefore, it will be used to support the ESA Section 7 consultation process with NMFS and USFWS. This document will also be used as supporting documentation for an IHA application submitted by L-DEO to NMFS, under the U.S. MMPA, for "taking by harassment" (disturbance) of small numbers of marine mammals during UAGI's proposed seismic survey. Potential impacts on polar bears, walruses, and seabirds, which are managed by USFWS, are addressed. In addition, information has been included as documentation for an EFH consultation with NMFS.

UAGI and NSF will coordinate the planned marine mammal monitoring program associated with the seismic survey in the Arctic Ocean with other parties that may have interest in this area and/or be

conducting marine mammal studies in the same region during operations. No other marine mammal studies are expected to occur in the study area at the proposed time. However, other industry-funded seismic surveys may be occurring in the northeast Chukchi and/or western Beaufort Sea closer to shore, and those projects are likely to involve marine mammal monitoring. Coordination of monitoring programs can occur during and after the planned open-water peer review meeting in Anchorage during 7–8 March 2011.

UAGI and NSF have coordinated, and will continue to coordinate, with other applicable Federal, State and Borough agencies, and will comply with their requirements. The cruise was initially scheduled for 2010, and consultations were held then. Actions of this type that occurred in 2010 and are underway in 2011 in parallel with the ongoing request to NMFS for issuance of an IHA include the following:

- In compliance with the *Principles for Conduct of Research in the Arctic* (OPP 2008), the project PI initiated contact with community authorities of Barrow to foster understanding of, cooperation with, and consent to the proposed survey. The PI contacted Dr. Glenn Sheehan of the Barrow Arctic Science Consortium and NSB biologist, Dr. Robert Suydam, on 7 January 2010 to inform them of the proposed study and the elements intended to minimize potential subsistence conflict.
- LGL has had contact in 2010 with USFWS biologists of the Office of Marine Mammal Management, Anchorage, on NSF's behalf regarding potential interactions with polar bears and walrus, and will do so again in 2011.
- A consultation with USFWS is required when activities may impact threatened or endangered bird species. On behalf of NSF and UAGI, LGL contacted the USFWS avian biologist Ted Swem on 16 February 2010 regarding potential interaction with spectacled and Steller's eiders, birds of "concern". He agreed with LGL's conclusion that this survey will not present a threat to spectacled or Steller's eiders because of its timing and distance offshore in higher latitudes. Contact will be made again in 2011 to provide an update on the survey.
- To assure that the proposed survey poses no conflict with the Alaska Coastal Zone Management Program (ACZMP), on behalf of NSF and UAGI, LGL consulted with Kim Kruse, ACZMP's Operations Manager, on 11 February 2010. Ms. Kruse concluded that the project is in compliance with state and local programs. Contact will be made again in 2011 to provide an update on the survey.
- To further promote cooperation between the project researchers and the community, the PI presented the proposed UAGI survey at a meeting of the AEW in Barrow on 11 February 2010. He explained the survey plans to the local residents, including NSB Department of Wildlife Management biologists, Craig George and Robert Suydam, consulted with stakeholders about their concerns, and discussed the aspects of the survey designed to mitigate impacts. No major concerns were expressed. The PI attended the AEW meeting on 17 February 2011, and the only concern expressed was that AEW would like a good communication link with the Langseth during the survey.
- The PI is scheduled to present the project at the Arctic Open-water Meeting in Anchorage during 7–8 March 2011.
- UAGI has prepared a "Plan of Cooperation".

Alternative Action: Another Time

The proposed project is expected to occur from ~5 September to 9 October 2011. An alternative to issuing the IHA for the period requested, and to conducting the project within that period, is to issue the IHA for another period, and to conduct the project during that alternative period. However, conducting

the project at some other time of year outside the summer/fall period could result in impracticalities related to ice conditions. In addition, the proposed period for the cruise is the period when the ship and all of the personnel and equipment essential to meet the overall project objectives are available. Postponing or changing the project period will delay this and potentially other projects proposed for the *Langseth* during the rest of 2011 and in 2012, or it would need to be scheduled on another vessel and appropriate seismic equipment obtained.

A few marine mammals are expected to be found throughout the proposed study area and throughout the time period during which the project may occur. Ringed seals, the most abundant marine mammal in the area of the survey, are year-round residents in Alaska (see § III, above), so altering the timing of the proposed project likely would result in no net benefits for that species. The bowhead, beluga, and gray whale, as well as the walrus, are migratory, moving through the area in spring and fall (see § III, above), primarily south of the survey area, which is >200 km offshore at ~72–77°N. Conducting a summer cruise would increase the likelihood of encountering gray whales in the study area. For other marine mammal species there are insufficient data to predict when their abundance may be highest.

Subsistence harvests of ringed seals, bearded seals and bowhead whales occur near Barrow, far south and east of the survey area. Marine mammal harvests take place year-round, but subsistence harvest peaks during the bowhead whale hunts in the spring and fall. The harvest is of great value to the Inupiat people, both culturally and for the animals. As the harvests take place primarily within ~30 km of shore, the survey is not expected to have any effects on the subsistence harvest.

No Action Alternative

An alternative to conducting the proposed activities is the “No Action” alternative, i.e., do not issue an IHA and do not conduct the operations. If the research were not conducted, the “No Action” alternative would result in no disturbance to marine mammals attributable to the proposed seismic activities. Likewise, there would then be no possibility of effects on fisheries or on accessibility of marine mammals for subsistence hunting. However, cancellation of this project would result in a loss of important scientific data and knowledge relevant to a number of research fields. Also, there would be little reduction in impacts if the project did not go ahead, given the negligible effects on marine mammals, seabirds, fish, subsistence hunting, and fisheries that are anticipated if the project goes ahead as planned.

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**APPENDIX A1:
PROPAGATION MODELING FOR A SEISMIC SURVEY IN THE
ARCTIC OCEAN, SEPTEMBER–OCTOBER 2011**

This Appendix is being completed.

APPENDIX A2: L-DEO MODELING FOR MARINE SEISMIC SOURCE ARRAYS FOR SPECIES MITIGATION⁴

1. Summary

To ensure that U.S. academic marine seismic activity does not adversely affect marine wildlife stocks, federal regulations controlling the levels of sound to which those stocks may be exposed are closely followed. These regulations include the establishment of various exclusion zones, which are defined by a priori modeling of the propagation of sound from the proposed seismic source array. To provide realistic results, modeling must include free surface and array effects. This is best accomplished when the near field signature of each airgun array element is propagated separately to the far field and the results summed there. The far field signatures are analyzed to provide measurements that characterize the source's energy as a function of distance and direction. The measure currently required for marine wildlife mitigation is root-mean-square [RMS]. While RMS is an appropriate measure for lengthy signals, it may not accurately represent the energy and impact of a short, impulsive signal. When a comparison is made between RMS and several other metrics, it is apparent that RMS is the least consistent.

2. Introduction

Modern marine seismic profiling is typically carried out using arrays of airguns as the acoustic source. Unlike single airguns or explosive sources, the physical extent and distributed quality of these arrays produce an asymmetric pressure field, which cannot be described accurately by a simple, rule-of-thumb approach.

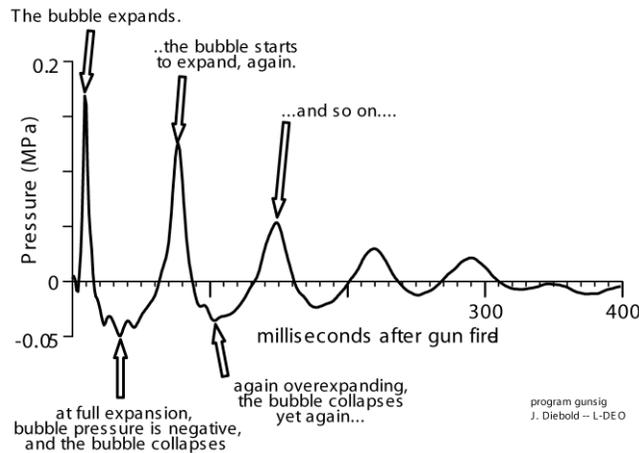


FIGURE A-1. Recording of a single airgun pulse made during R/V *EWING* tests, 1990.

⁴ By **John Diebold**, L-DEO, revised May 2006.

This wavetrain can be seen in its true form only very close to the airgun and it is called the “near field” signal. Airguns are usually towed at a shallow depth (3–9 m) beneath the sea surface, from which sound waves are negatively reflected, and at any significant distance from the airgun, both the direct and its negatively reflected “ghost” are seen, one right after the other. This ghosting imposes a strong and very predictable filter on the received arrivals.

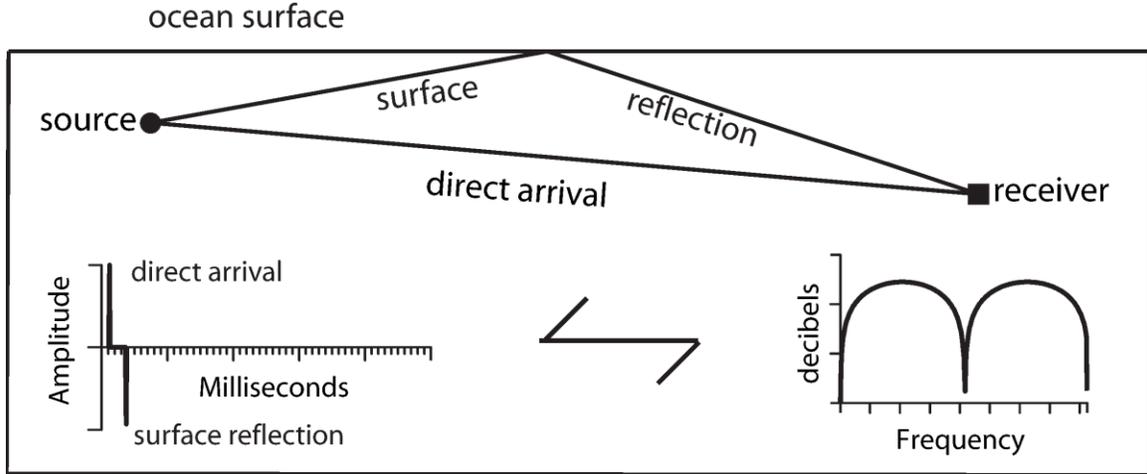


FIGURE A-2. Top: pathways for direct and surface-reflected arrivals used in modeling. Bottom: direct and ghosted arrival amplitudes in the time domain can be considered an operator whose spectrum is predictable, and which acts as a filter on the spectrum of the intrinsic near field source, whatever that may be.

The time interval between the arrivals of the direct and surface-reflected signals depends on the position of observation; it is greatest at any position directly beneath the source. Depending on the location of the point of observation relative to the source array, the appearance and strength of the signal can be extremely variable. In the comparison below, two observation points were chosen, equally distant from a 20-airgun array.

The differences here are caused by two effects. One is directionality resulting from the physical dimensions of the array. The other effect is that the surface ghosting imposes a strong filter on the near field source signatures, and the shape of this filter is controlled by the relative positions of sources and receivers.

3. Modeling

Since the sum of the direct and the surface-reflected signals varies according to position, modeling can only be carried out correctly when near-field source signatures are used, and propagation along all of the pathways between the source and the receiver is considered separately. In the simple half-space model illustrated above (Fig. 3), there are only two pathways. When an array of sources is used, travel time, spreading and reflection losses are calculated for each pathway and for each source element separately. According to the exact distance between the point of observation and the particular airgun, each element’s near-field signal is appropriately scaled in amplitude and shifted in time. Then the process is repeated to produce the free surface “ghost” signal of each airgun, and the results are summed.

For R/V *EWING* mitigation, the near-field signatures were calculated by extrapolation from a set of measured signals received from Teledyne in 1981. Results of this modeling have been compared to a great number of published signals, and the amplitudes of the library’s signals adjusted to provide a close match. Since peak values are highly dependent on an impulsive signal’s high frequency content, the comparisons are most accurately made in the spectral domain.

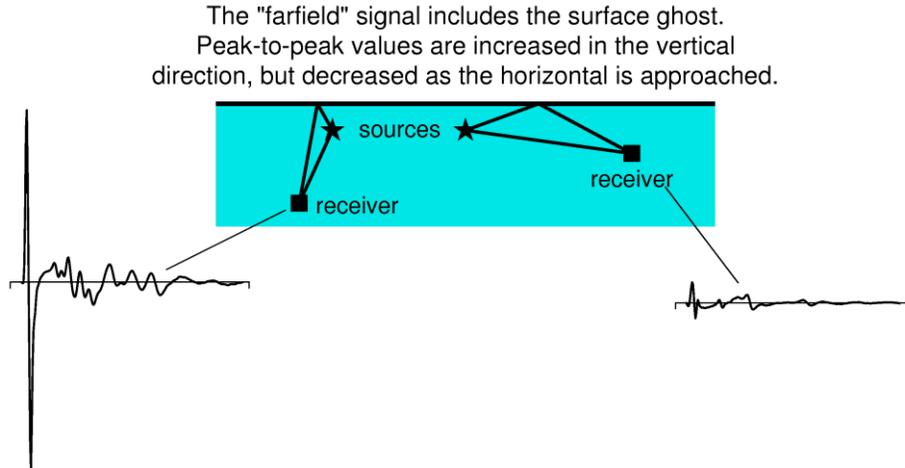


FIGURE A-3. The far field signature of a 20-airgun array modeled at two receiver positions equidistant from the center of the array. Differences are due to array directivity and surface ghosting effects.

Few, if any, of the published examples include airguns with volumes as large as those often included in *EWING*'s source arrays. There are several very good reasons for this (and for the inclusion of such sizes in *EWING* arrays.) Principal among these was the observation by W. Dragoset of Western Geophysical [pers. comm., 1990] that the characteristics of the Bolt 1500C air exhaust ports are such that throttling occurs when air chambers above a certain size are used. The result of this is that peak amplitudes increase only slightly, so that the efficiency of these airguns diminishes with increasing volume. On the other hand, bubble pulse periods do increase according to theory, so that the benefit of larger sizes in array tuning is undiminished. The decrease in efficiency was borne out during testing of *EWING*'s airguns during the 1990 shakedown legs (Fig. 4).

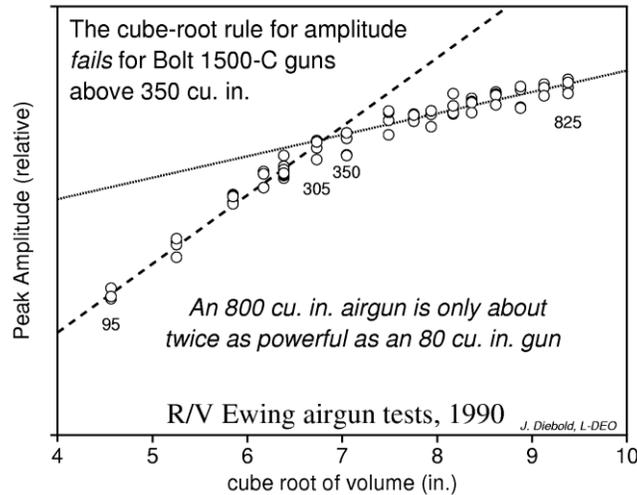


FIGURE A-4. R/V *EWING* test results, 1990.

Near-field signatures can be created by a number of commercially available modeling packages, all based in part on the work of Ziolkowski (1978). Those packages were not used for *EWING* modeling for two reasons: cost and accuracy. As Figure 5 demonstrates, PGS' Nucleus/Masomo software does not accurately model the large Bolt airguns used in *EWING* arrays:

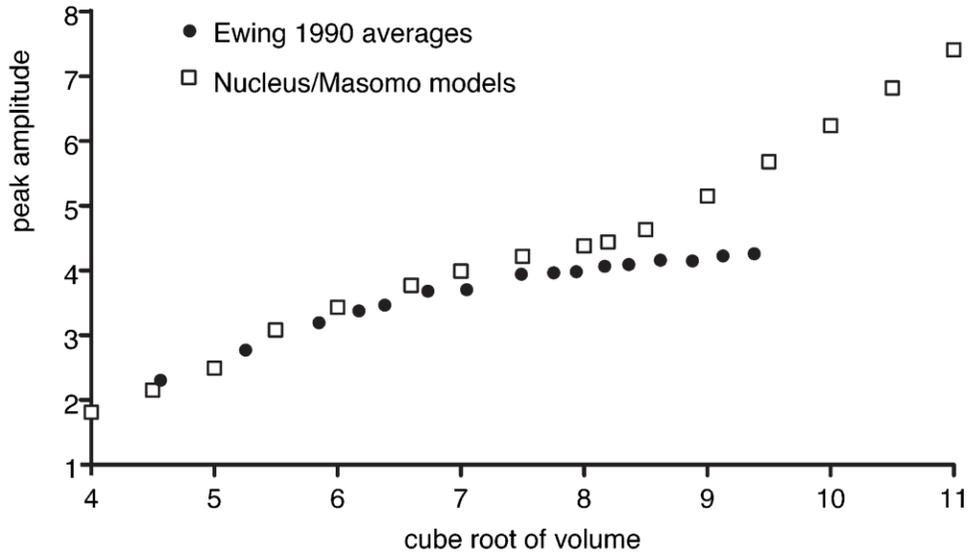


FIGURE A-5. Nucleus/Masomo overestimates peak values for large Bolt airguns.

The R/V *LANGSETH* will have source arrays that are quite different than *EWING*'s: (1) maximum airgun volume will be much smaller, (2) two different kinds of airguns will be combined, (3) airguns will be towed closer together, and (4) two-element "clusters" will be included. The latter three of these features are unsupported by the homebrew modeling used for *EWING* arrays, and we are currently using PGS' Nucleus/Masomo software for this purpose [<http://www.pgs.com/business/products/nucleus/>]. Some of the examples below have been created using the simpler *EWING* models, however.

The modeling procedure can be summarized as follows:

- 1) Define the airgun array in terms of the size and relative location of each airgun [X, Y, Z].
- 2) Create near field ["notional"] signatures for each airgun.
- 3) Decide upon a 2D mesh of points, for example within a plane intersecting the center of the airgun array. A typical mesh is 100 x 50.
- 4) For each of the points in the mesh, create the signal that would be observed there when every airgun in the array was fired simultaneously.
- 5) For that signal, determine the desired statistic: Peak-to-peak dB, Peak dB, RMS dB, maximum psi, etc.
- 6) Contour the mesh.

Most of the work lies in step 4) which has steps of its own:

- a) For each of the airguns in the array, determine the distances, and thus the time-of-flight between the airgun and the mesh point, as well as the free surface ghost "image" of the airgun and the mesh point.
- b) Scale and shift this airgun's near-field signal, dividing by the point-to-point distance and moving forward in time according to time-of-flight.
- c) Scale and shift the near-field signal's ghost image, as above, in addition multiplying by the free surface reflection coefficient [typically between -.9 and -.95].

- d) Sum the results. For the *EWING* 20-airgun array, 40 scaled and shifted signals were created and summed for each mesh point.

4. Units

Exploration industry standard units for seismic source pressures are Bar-meters; an intuitively attractive measure in atmospheres [bars] at one meter from the center of the source array. In SI units, 10 Bar = 1 megaPascal = 10^{-12} μ Pascal. To convert Bar-m to decibels with respect to μ Pascal–m we use this formula:

$$\text{dB [wrt } \mu\text{Pascal -m]} = 220 + 20 \log^{10}(\text{B-m})$$

RMS dB and the exclusion zone

A variety of means are used to characterize the strength of seismic source signals. Peak, peak-to-peak, and total energy levels are easy to measure, but historically, all of the research on acoustic avoidance behavior of marine mammals has quantified the sound levels in terms of RMS, a measure which is entirely appropriate for many acoustic signals found in the marine environment (e.g., shipping noise, Navy sonar, etc.). Although it is less appropriate for impulsive airgun signals, the RMS measure has been used in most published studies anyway (cf. Malme et al. 1983a,b), so that meaningful comparisons could be made. The protocols used for the RMS calculation in most published research are diagrammed below (Fig. 6), applied to the signal predicted by our modeling for a point 4000 m aft of *EWING*'s 20 airgun array, at a depth of 1200 m.

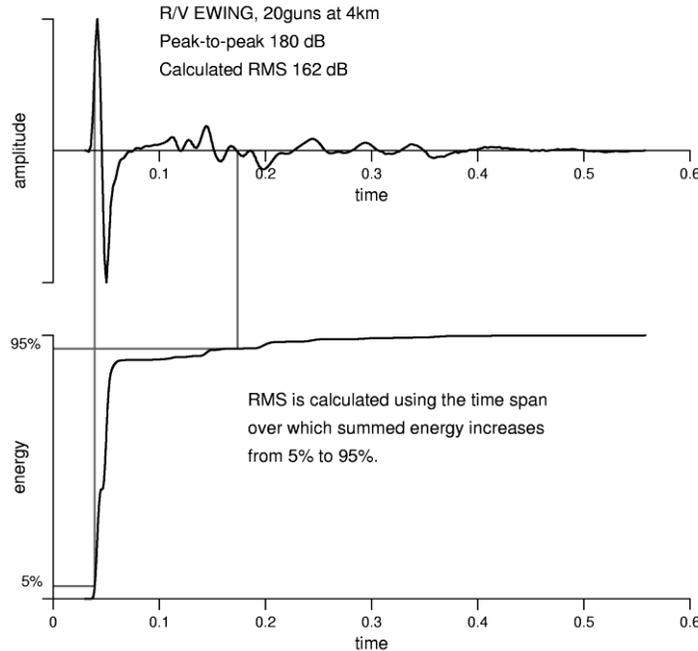


FIGURE A-6. The “standard” 90% RMS calculation. Energy is summed as a function of time for the entire signal. From this result, the times at which 5% and 95% of the total energy are attained define the RMS integration window.

This difference between the peak-to-peak and RMS dB levels for the same signal falls within the 16-18 dB averages reported for impulsive airgun signals by Greene (1997) and McCauley (1998).

5. Calculating the exclusion zone

R/V *EWING* source arrays were intended and designed for 2D seismic reflection and refraction work, and were, consequentially, highly directional, focusing energy downwards and in line with the ship's track direction.

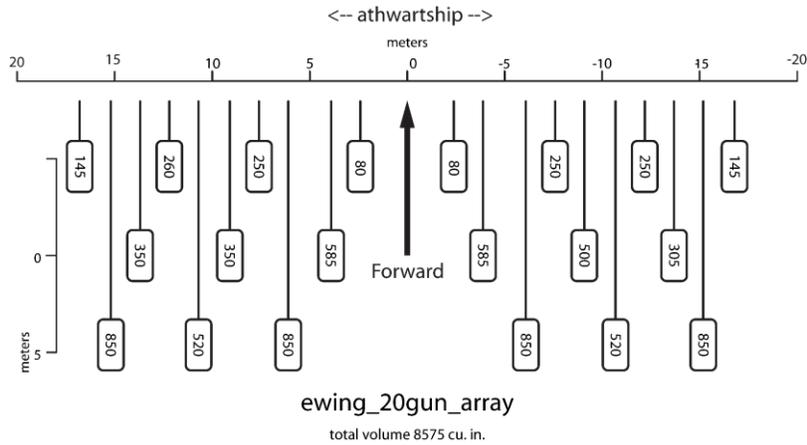


FIGURE A-7. Plan view of the 20-airgun array used to calculate Fig. 3, 4, and 6. Tow depth is 7.5 m.

The RMS calculation is applied to the mesh point signatures resulting from the modeling process described above. When the 90% RMS levels are contoured, the directional nature of the standard R/V *EWING* source array is obvious (Fig. 8).

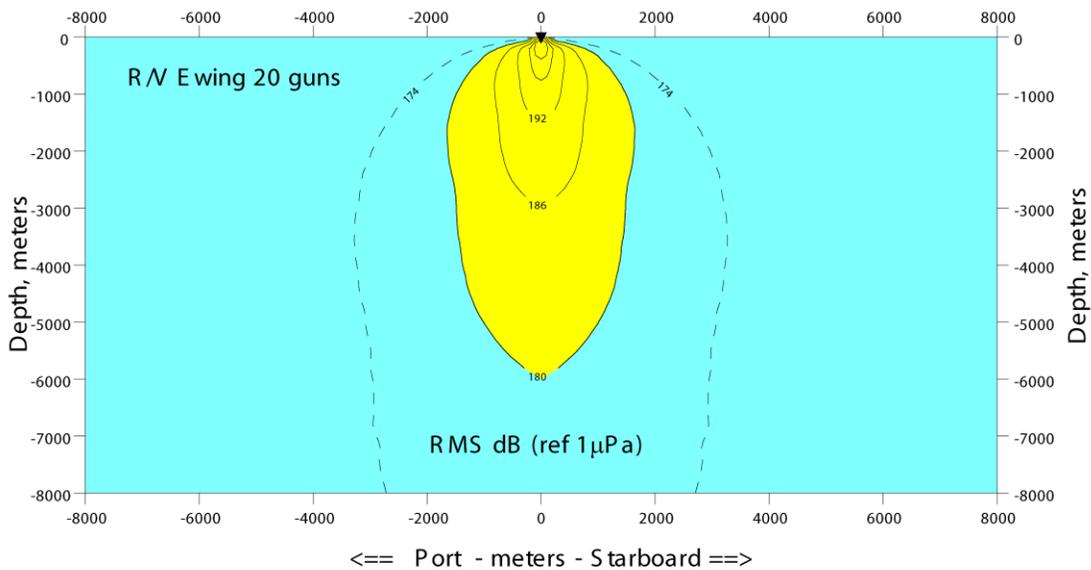


FIGURE A-8a. 90% RMS isopleths calculated in the cross-track direction for a 20-airgun array. Yellow denotes RMS values >180 dB.

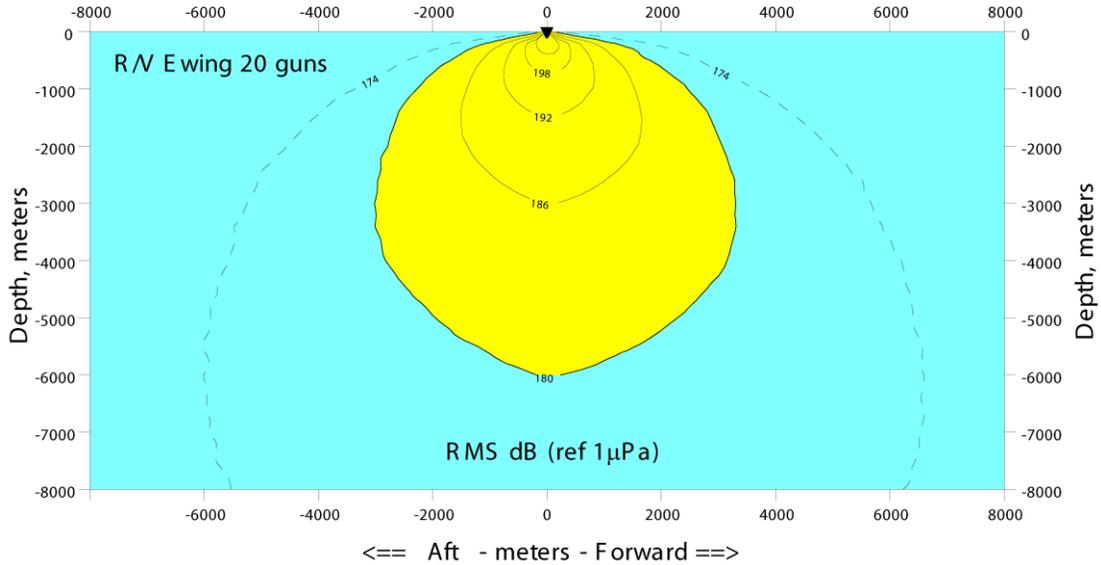


FIGURE A-8b. 90% RMS isopleths calculated in the along track direction for a 20-airun array. Yellow denotes RMS values >180 dB.

Since the fore-and-aft extent of *EWING*'s array is smaller than the athwartship dimension, directionality is less marked in front of and behind the array. The distances therefore to the 180 dB contours, or isopleths, are greater in the fore-and-aft than athwartship directions, and we use these worst case distances to determine exclusion zones.

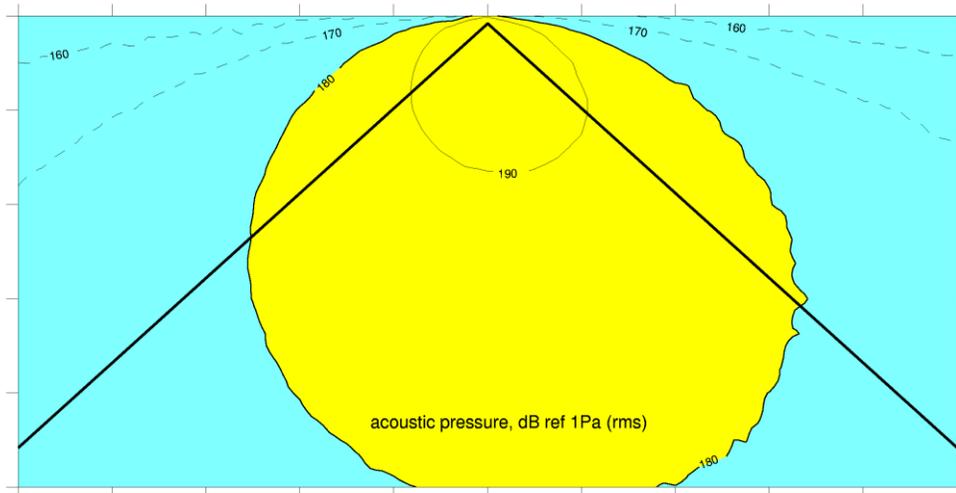


FIGURE A-9. The pathways in offset and depth which intersect maximum-radius isopleths. These are used to calculate radii for various 90% RMS levels.

This modeling approach includes two important simplifications: (1) the assumption of a homogeneous water column (i.e., raypaths are linear), and (2) that interactions with the seafloor are not included. In deep water (i.e., 1000 m and greater) our predicted exclusion zones are conservatively greater than those determined by actual calibration (Tolstoy et al. 2004). In shallow water (100 m and

less) water column reverberations and constructive interference contribute to increase actual levels over those predicted by the modeling techniques described here.

Problems with 90% RMS

The biggest pitfall in the 90% RMS measure is that the RMS value can vary tremendously for signals having similar energy content. If the signal is only a little less “ringy” than the *EWING* 20 gun example shown above, the 90% energy time span will be much smaller, which greatly increases the RMS value. The better the “tuning” of a seismic source array, the more impulsive its signature and the shorter its 90% energy window. The resulting problems can be illustrated using a simple source – a two-gun “cluster” as modeled by Nucleus/Masomo. Signals are calculated at hundreds of mesh points, 90% RMS is calculated for each signal, and the resulting levels were contoured (Fig. 10).

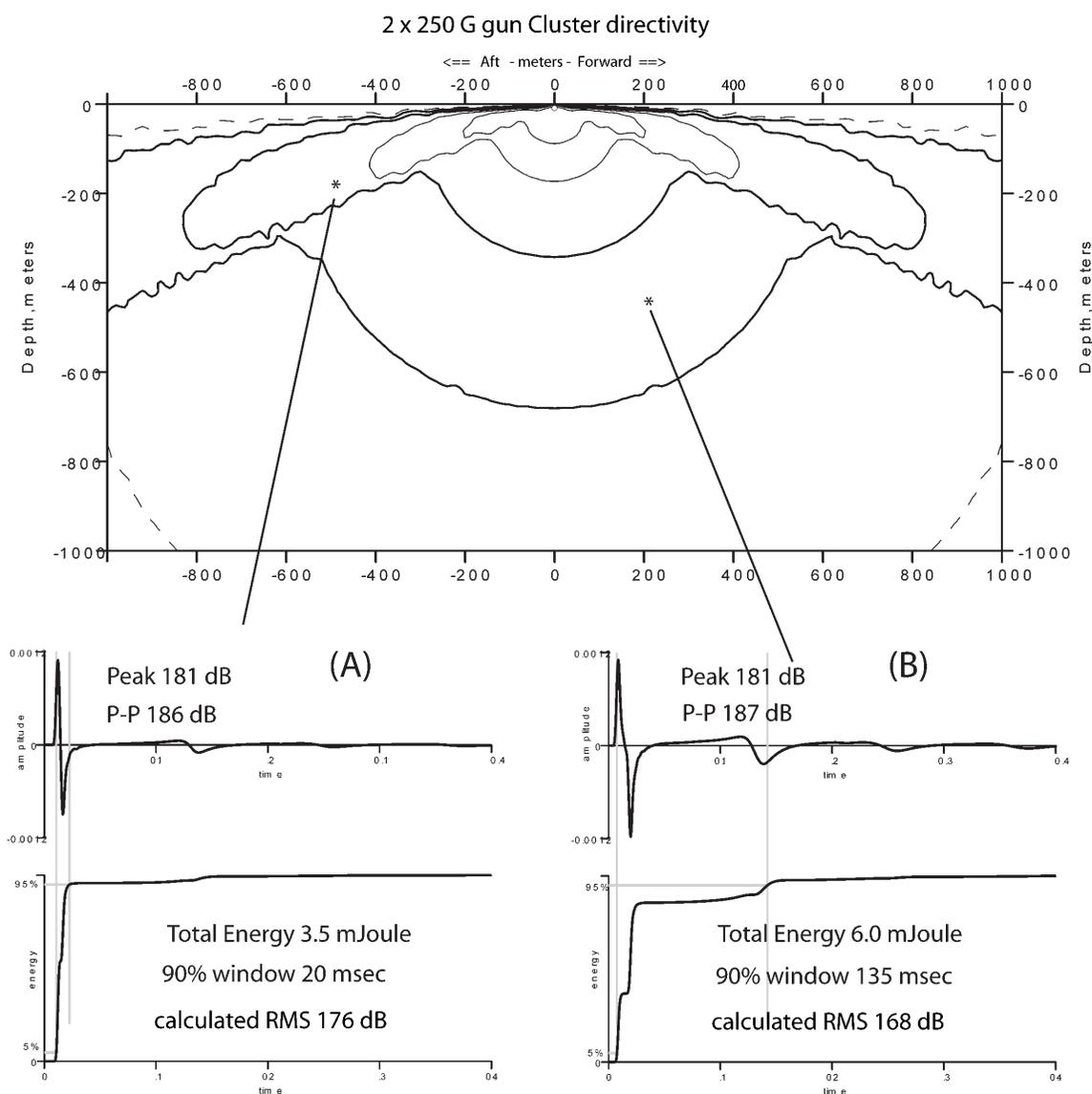


FIGURE A-10. Modeled results from a simple 2-airgun cluster source.

Unlike the *EWING* example presented earlier, the RMS contours for this source are pathologically variable. To investigate the reason for this, two signatures, (A) and (B), were calculated at equal distances from the source array, but in high and low RMS zones, respectively. These signals have identical peak levels, but greatly different RMS values. The difference is almost entirely due to the varying length of the automatically determined 90% RMS integration window. This change in window length is in turn due to the effects of surface ghosting, which diminish the bubble pulse in the left-hand signal (A), thus reducing the 90% energy time span. Paradoxically, the right-hand signal (B), which has higher peak-to-peak and total energy levels, has a greatly lower RMS value. This is almost entirely due to large variations in the automatically calculated 90% RMS window length. A contour plot of 90% RMS window length shows that for this source, they vary between 5 and 137 milliseconds (Fig. 11).

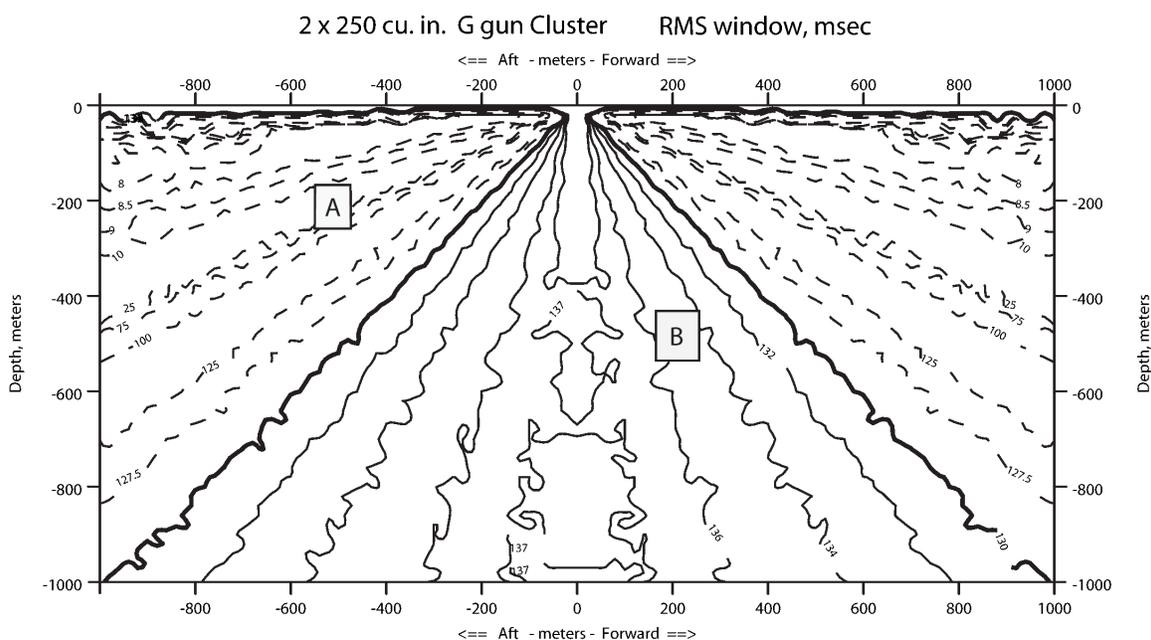


Figure A-11. The locations from which signals (A) and (B) were extracted are shown for reference.

Other measures may be far more appropriate for quantifying airgun signal levels and predicting their effect on marine creatures.

Sound exposure level [SEL] is equal to RMS but with an added factor which is intended to minimize the time windowing effect, and to produce a measure more meaningful for the effects of noise on mammalian ears:

$$DB_{SEL} = dB_{RMS} + 10 * \text{Log}_{10}(\text{window}), \text{ where the window has units of seconds.}$$

For RMS window lengths less than one second, this additive factor varies between -30 dB for a RMS window length of 1 millisecond, to zero, for a window length of one second.

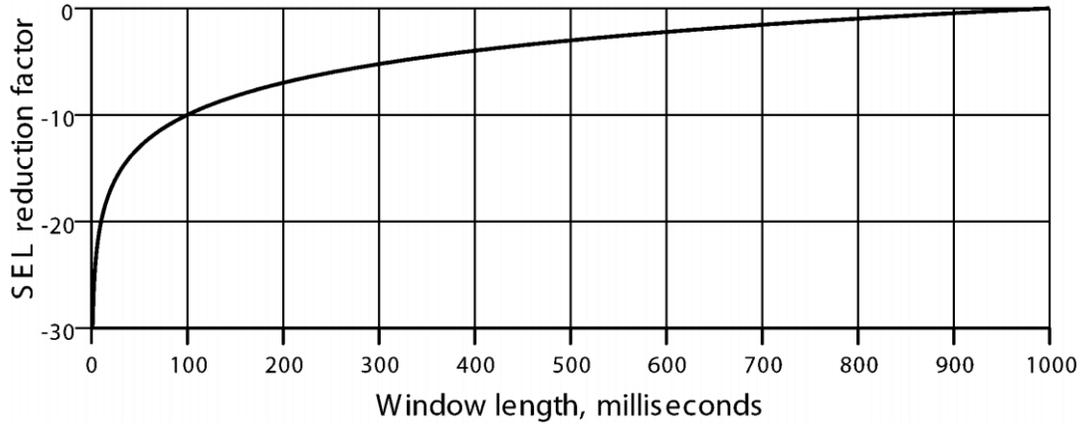


Figure A-12.

Calculation of SEL for the two cluster signatures shown above shows the effect of the calculation's window length correction factor:

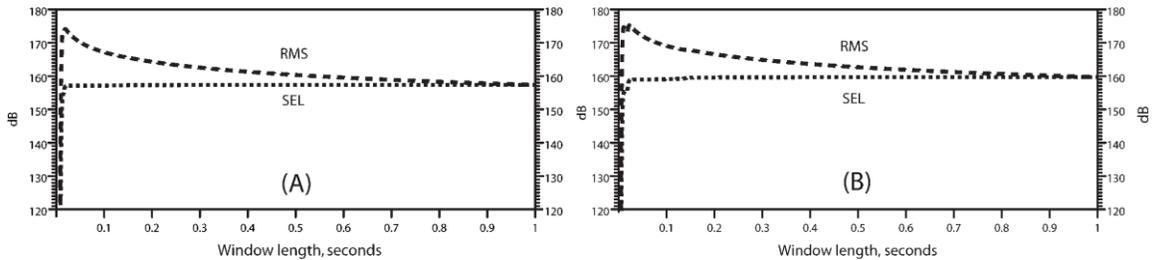


Figure A-13.

While RMS varies continually with window length, SEL tends to approach a stationary level; in this case 157 dB for signal (A), and 160 dB for (B). The effect is to eliminate the dependence of the determined level upon window size; as long as the entire signal is captured, the calculated SEL will be pretty much the same. SEL is considered by many researchers (cf. Patterson 1991) to be a better predictor of hearing threshold shifts than is RMS or peak level.

Neither RMS nor SEL include frequency content, and there are many ways to look at this. Within the exploration seismic community, the cumulative energy flux is a standard measure (Johnston et al. 1988).

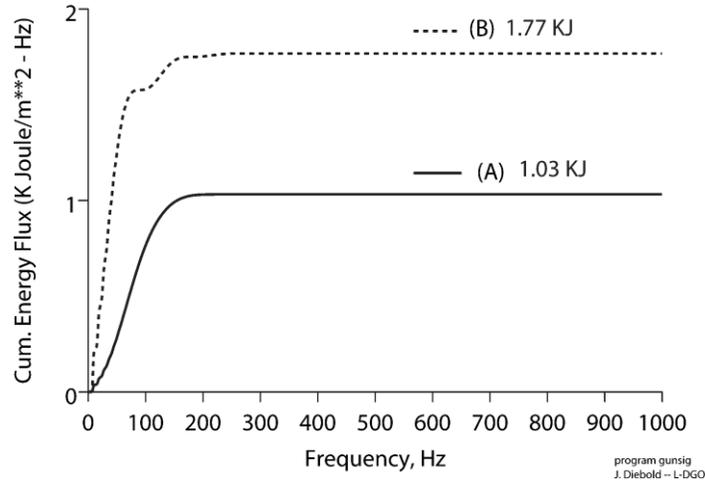


FIGURE A-14.

Two features are immediately apparent from this plot: first, most of the energy in both signals is present at frequencies below several hundred Hz, and second, signal (B) whose 90% RMS level is less than half that of signal (A), actually contains appreciably more total energy. When the total energy of a short, impulsive signal, such as that created by an airgun array in deep water, is expressed in terms of dB, the result is usually equal to SEL.

The 90% RMS measure currently used to characterize possible impact on marine mammals may be severely flawed, especially when marine seismic source arrays are physically compact and/or well-tuned. An energy-based metric would produce more consistent results, and can be implemented in either time or frequency domains.

TABLE A-1.

	A	B	%, A/B
RMS	176	168	166.67%
Peak	181	181	100.00%
P-P	186	187	91.67%
SEL	157	160	75.00%
Energy	3.5	6	58.33%
Energy	1.03	1.77	58.19%

The seismic sources planned and under construction for R/V *LANGSETH* are much more highly tuned than those deployed by R/V *EWING*. Although the total energy content in the signal produced by *LANGSETH*'s largest array is smaller than that of the "standard" *EWING* 20-airgun array, 90% RMS values of modeled signatures are much higher, due entirely to the RMS window length imposed by the improved tuning. Therefore, we propose to use SEL values, at least until new metrics are imposed. The question is: how to convert from SEL to equivalent RMS?

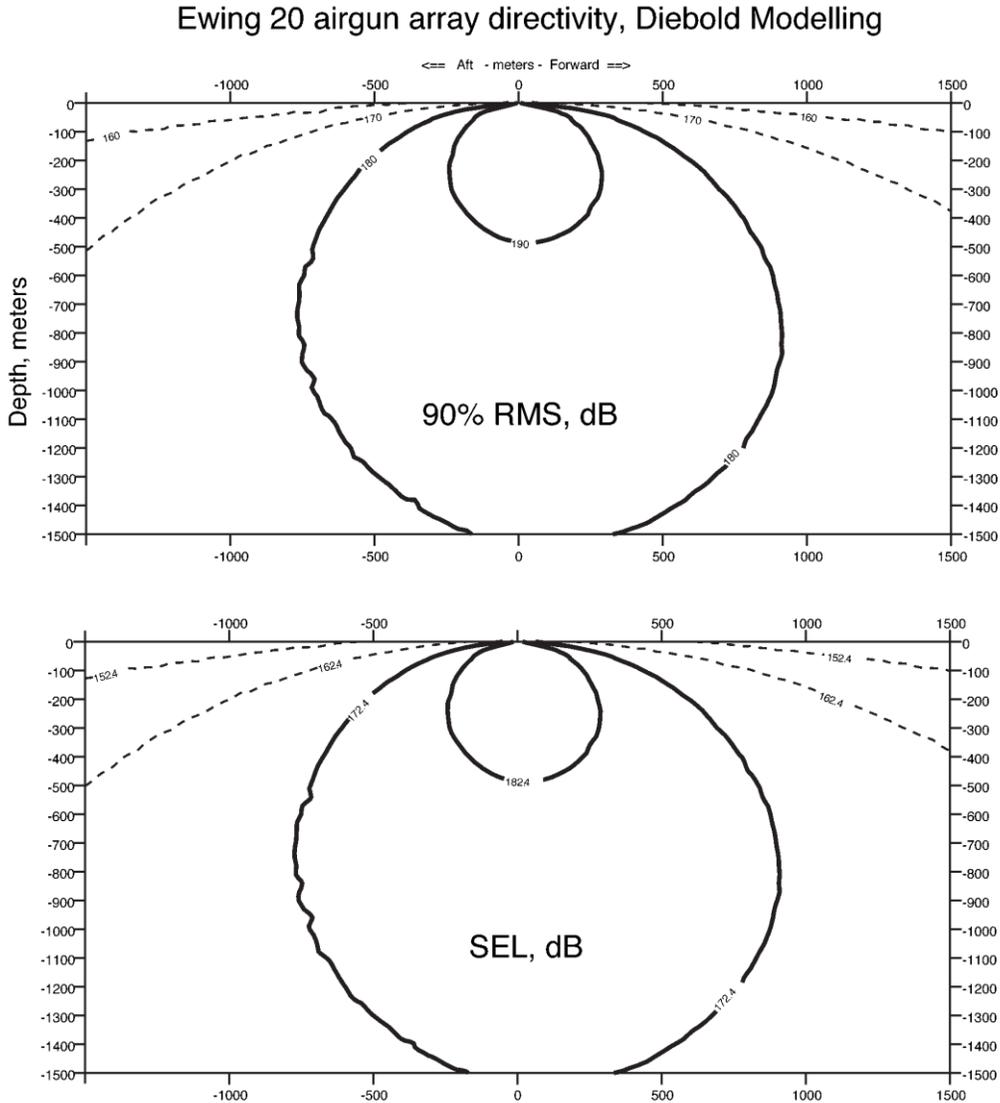


FIGURE A-15. Here we have matched the RMS and SEL contours nearly perfectly by using an SEL value equal to RMS – 7.6 dB, an offset corresponding to the normal 90% energy window length of about 174 msec. Current IHA applications have used an SEL “discount” of 15 dB, which is equivalent to an RMS window of about 32 msec. It might be more appropriate to use a discount factor which corresponds to the natural mammal hearing integration time – it has been suggested, for example [Peter Tyack, pers. comm.] that this is about 200 msec for dolphins. This would be equivalent to an RMS – SEL discount of 7 dB.

Other metrics

When geophysicists investigate signal quality, they are likely to plot spectral energy on a linear frequency scale, as specified in Johnston et al. (1988):

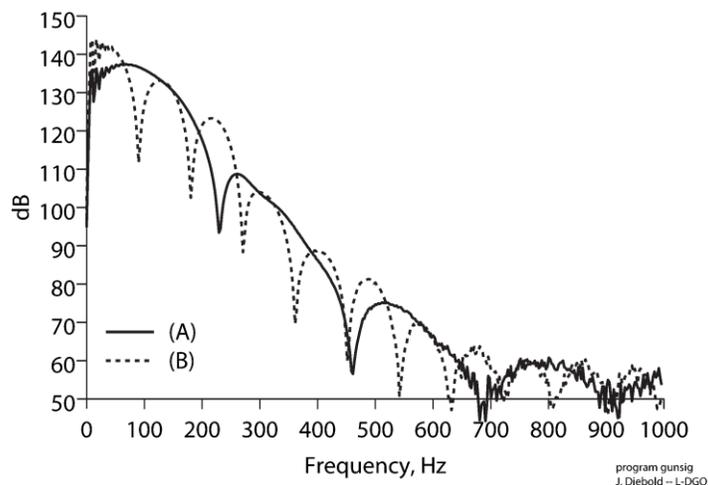


FIGURE A-16.

In studies of noise and its effect on marine animals, a spectral display in terms of 1/3 octave energy levels is often preferred. To obtain such a display, spectral power is integrated within specified bands whose width increases logarithmically with frequency.

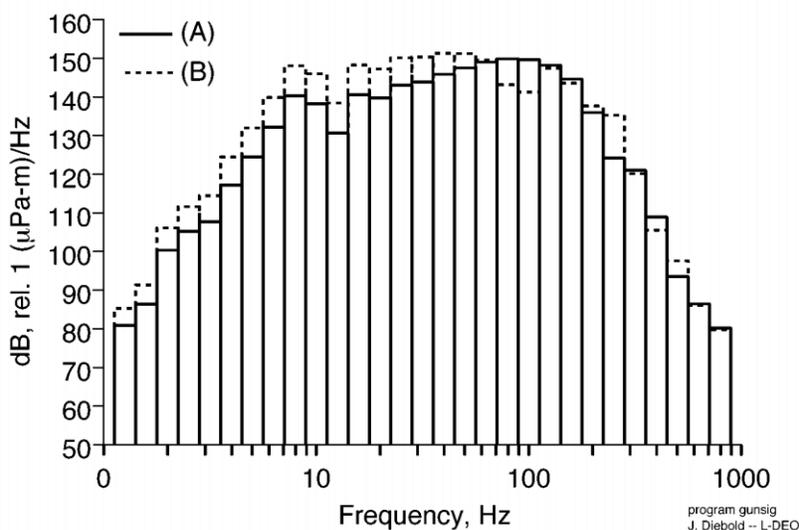


FIGURE A-17.

It is clear from this display that despite its higher calculated 90% RMS level, signal (A) has lower energy than (B) at most frequencies, especially between zero and 100 Hz, where ghosting effects play a major role.

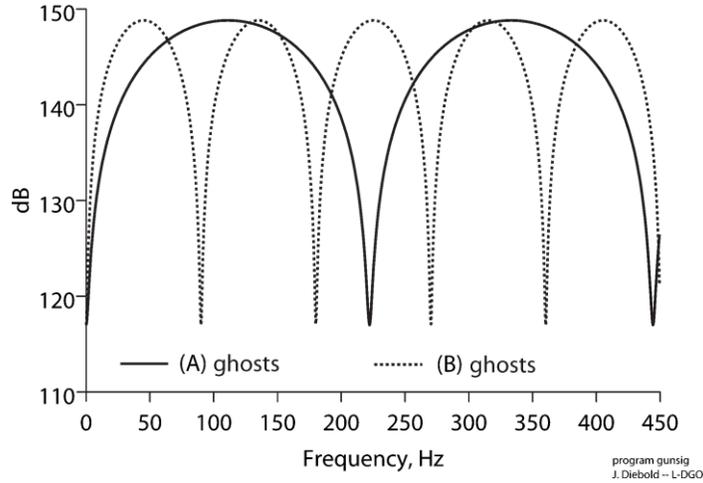


Figure A-18.

The time lag between direct and surface-reflected paths for signal (A) is much smaller than that for signal (B). Therefore the ghost-induced shaping filter superimposed on signal (A) cuts out much of the low-frequency energy seen in signal (B).

If we plot the ghost shaping filters in the third-octave display described above, it is readily apparent that most of the differences between (A) and (B) in the previous third-octave plot are due to ghosting effects:

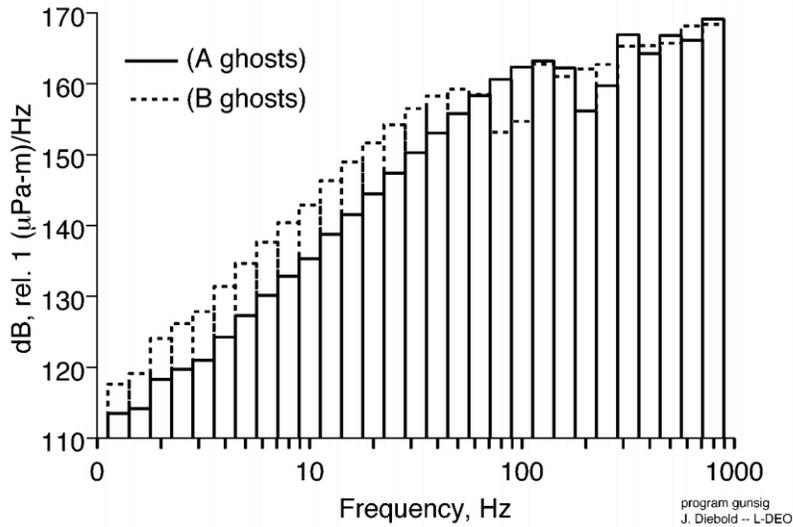


Figure A-19.

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APPENDIX B: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE MAMMALS⁵

The following subsections review relevant information concerning the potential effects of airguns on marine mammals. Because this review is intended to be of general usefulness, it includes references to types of marine mammals that will not be found in some specific regions.

1. Categories of Noise Effects

The effects of noise on marine mammals are highly variable, and can be categorized as follows (adapted from Richardson et al. 1995):

1. The noise may be too weak to be heard at the location of the animal, i.e., lower than the prevailing ambient noise level, the hearing threshold of the animal at relevant frequencies, or both;
2. The noise may be audible but not strong enough to elicit any overt behavioral response, i.e., the mammal may tolerate it, either without or with some deleterious effects (e.g., masking, stress);
3. The noise may elicit behavioral reactions of variable conspicuousness and variable relevance to the well being of the animal; these can range from subtle effects on respiration or other behaviors (detectable only by statistical analysis) to active avoidance reactions;
4. Upon repeated exposure, animals may exhibit diminishing responsiveness (habituation), or disturbance effects may persist; the latter is most likely with sounds that are highly variable in characteristics, unpredictable in occurrence, and associated with situations that the animal perceives as a threat;
5. Any man-made noise that is strong enough to be heard has the potential to reduce (mask) the ability of marine mammals to hear natural sounds at similar frequencies, including calls from conspecifics, echolocation sounds of odontocetes, and environmental sounds such as surf noise or (at high latitudes) ice noise. However, intermittent airgun or sonar pulses could cause strong masking for only a small proportion of the time, given the short duration of these pulses relative to the inter-pulse intervals;
6. Very strong sounds have the potential to cause temporary or permanent reduction in hearing sensitivity, or other physical or physiological effects. Received sound levels must far exceed the animal's hearing threshold for any temporary threshold shift to occur. Received levels must be even higher for a risk of permanent hearing impairment.

2. Hearing Abilities of Marine Mammals

The hearing abilities of marine mammals are functions of the following (Richardson et al. 1995; Au et al. 2000):

1. Absolute hearing threshold at the frequency in question (the level of sound barely audible in the absence of ambient noise). The "best frequency" is the frequency with the lowest absolute threshold.

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2. Critical ratio (the signal-to-noise ratio required to detect a sound at a specific frequency in the presence of background noise around that frequency).
3. The ability to determine sound direction at the frequencies under consideration.
4. The ability to discriminate among sounds of different frequencies and intensities.

Marine mammals rely heavily on the use of underwater sounds to communicate and to gain information about their surroundings. Experiments and monitoring studies also show that they hear and may react to many man-made sounds including sounds made during seismic exploration (Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Tyack 2008).

2.1 Toothed Whales (*Odontocetes*)

Hearing abilities of some toothed whales (odontocetes) have been studied in detail (reviewed in Chapter 8 of Richardson et al. [1995] and in Au et al. [2000]). Hearing sensitivity of several species has been determined as a function of frequency. 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 stranded juvenile Gervais' beaked whale showed evoked potentials from 5 kHz up to 80 kHz (the entire frequency range that was tested), with best sensitivity at 40–80 kHz. An adult Gervais' beaked whale had a similar upper cutoff frequency (80–90 kHz; Finneran et al. 2009).

Most of the odontocete species have been classified as belonging to the “mid-frequency” (MF) hearing group, and the MF odontocetes (collectively) have functional hearing from about 150 Hz to 160 kHz (Southall et al. 2007). However, individual species may not have quite so broad a functional frequency range. Very strong sounds at frequencies slightly outside the functional range may 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. They have functional hearing from about 200 Hz to 180 kHz (Southall et al. 2007).

Airguns produce a small proportion of their sound at mid- and high-frequencies, although at progressively lower levels with increasing frequency. In general, most of the energy in the sound pulses emitted by airgun arrays is at low frequencies; strongest spectrum levels are below 200 Hz, with considerably lower spectrum levels above 1000 Hz, and smaller amounts of energy emitted up to ~150 kHz (Goold and Fish 1998; Sodal 1999; Goold and Coates 2006; Potter et al. 2007).

Despite the relatively poor sensitivity of small odontocetes at the low frequencies that contribute most of the energy in pulses of sound from airgun arrays, airgun sounds are sufficiently strong, and contain sufficient mid- and high-frequency energy, that their received levels sometimes remain above the hearing thresholds of odontocetes at distances out to several tens of kilometers (Richardson and Würsig 1997). There is no evidence that most small odontocetes react to airgun pulses at such long distances. However, beluga whales do seem quite responsive at intermediate distances (10–20 km) where sound levels are well above the ambient noise level (see below).

In summary, even though odontocete hearing is relatively insensitive to the predominant low frequencies produced by airguns, sounds from airgun arrays are audible to odontocetes, sometimes to distances of 10s of kilometers.

2.2 Baleen Whales (*Mysticetes*)

The hearing abilities of baleen whales (mysticetes) have not been studied directly. Behavioral and anatomical evidence indicates that they hear well at frequencies below 1 kHz (Richardson et al. 1995; Ketten 2000). Frankel (2005) noted that gray whales reacted to a 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; Parks et al. 2007b). Although humpbacks and minke whales (Berta et al. 2009) may have some auditory sensitivity to frequencies above 22 kHz, for baleen whales as a group, the functional hearing range is thought to be about 7 Hz to 22 kHz and they are said to constitute the “low-frequency” (LF) hearing group (Southall et al. 2007). The absolute sound levels that they can detect below 1 kHz are probably limited by increasing levels of natural ambient noise at decreasing frequencies (Clark and Ellison 2004). Ambient noise levels are higher at low frequencies than at mid frequencies. At frequencies below 1 kHz, natural ambient levels tend to increase with decreasing frequency.

The hearing systems of baleen whales are undoubtedly more sensitive to low-frequency sounds than are the ears of the small toothed whales that have been studied directly. Thus, baleen whales are likely to hear airgun pulses farther away than can small toothed whales and, at closer distances, airgun sounds may seem more prominent to baleen than to toothed whales. However, baleen whales have commonly been seen well within the distances where seismic (or other source) sounds would be detectable and often show no overt reaction to those sounds. Behavioral responses by baleen whales to seismic pulses have been documented, but received levels of pulsed sounds necessary to elicit behavioral reactions are typically well above the minimum levels that the whales are assumed to detect (see below).

2.3 Seals and Sea Lions (*Pinnipeds*)

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: 211ff; Kastak and Schusterman 1998, 1999; Kastelein et al. 2002, 2009). 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 μ Pa. Measurements for harbor seals indicate that, below 1 kHz, their thresholds under quiet background conditions deteriorate gradually with decreasing frequency to ~75 dB re 1 μ Pa at 125 Hz (Kastelein et al. 2009).

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).

2.4 Manatees and Dugong (Sirenians)

The West Indian manatee can apparently detect sounds and low-frequency vibrations from 15 Hz to 46 kHz, based on a study involving behavioral testing methods (Gerstein et al. 1999, 2004). A more recent study found that, in one Florida manatee, auditory sensitivity extended up to 90.5 kHz (Bauer et al. 2009). Thus, manatees may hear, or at least detect, sounds in the low-frequency range where most seismic energy is released. It is possible that they are able to feel these low-frequency sounds using vibrotactile receptors or because of resonance in body cavities or bone conduction.

Based on measurements of evoked potentials, manatee hearing is apparently best around 1–1.5 kHz (Bullock et al. 1982). However, behavioral tests suggest that best sensitivities are at 6–20 kHz (Gerstein et al. 1999) or 8–32 kHz (Bauer et al. 2009). The ability to detect high frequencies may be an adaptation to shallow water, where the propagation of low frequency sound is limited (Gerstein et al. 1999, 2004).

2.5 Sea Otter and Polar Bear

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 3–5 kHz (McShane et al. 1995; Thomson and Richardson 1995). Sea otter vocalizations are considered to be most suitable for short-range communication among individuals (McShane et al. 1995). However, Ghoul et al. (2009) noted that the in-air “screams” of sea otters are loud signals (source level of 93–118 dB re 20 μPa_{pk}) that may be used over larger distances; screams have a frequency of maximum energy ranging from 2 to 8 kHz. 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 about 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.

Data on the specific 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 anesthetized bears (Nachtigall et al. 2007). Hearing was tested in $\frac{1}{2}$ octave steps from 1 to 22.5 kHz, and best hearing sensitivity was found between 11.2 and 22.5 kHz. Although low-frequency hearing was not studied, the data suggested that medium- and some high-frequency sounds may be audible to polar bears. However, polar bears’ usual behavior (e.g., remaining on the ice, at the water surface, or on land) reduces or avoids exposure to underwater sounds.

3. Characteristics of Airgun Sounds

Airguns function by venting high-pressure air into the water. The pressure signature of an individual airgun consists of a sharp rise and then fall in pressure, followed by several positive and negative pressure excursions caused by oscillation of the resulting air bubble. The sizes, arrangement, and firing times of the individual airguns in an array are designed and synchronized to suppress the pressure oscillations subsequent to the first cycle. The resulting downward-directed pulse has a duration of only 10–20 ms, with only one strong positive and one strong negative peak pressure (Caldwell and Dragoset 2000). Most energy emitted from airguns is at relatively low frequencies. For example, typical high-energy airgun arrays emit most energy at 10–120 Hz. However, the pulses contain significant energy up to 500–1000 Hz and some energy at higher frequencies (Goold and Fish 1998; Potter et al. 2007). Studies in the Gulf of Mexico have shown that the horizontally-propagating sound can contain significant energy above the frequencies that airgun arrays are designed to emit (DeRuiter et al. 2006; Madsen et al. 2006; Tyack et al. 2006a). Energy at frequencies up to 150 kHz was found in tests of single 60-in³ and 250-in³ airguns (Goold and Coates 2006). Nonetheless, the predominant energy is at low frequencies.

The pulsed sounds associated with seismic exploration have higher peak levels than other industrial sounds (except those from explosions) to which whales and other marine mammals are routinely exposed. The nominal source levels of the 2- to 36-airgun arrays used by Lamont-Doherty Earth Observatory (L-DEO) from the R/V *Maurice Ewing* (now retired) and R/V *Marcus G. Langseth* (36 airguns) are 236–265 dB re 1 $\mu\text{Pa}_{\text{p-p}}$. These are the nominal source levels applicable to downward propagation. The effective source levels for horizontal propagation are lower than those for downward propagation when the source consists of numerous airguns spaced apart from one another. Explosions are the only man-made sources with effective source levels as high as (or higher than) a large array of airguns. However, high-power sonars can have source pressure levels as high as a small array of airguns, and signal duration can be longer for a sonar than for an airgun array, making the source energy levels of some sonars more comparable to those of airgun arrays.

Several important mitigating factors need to be kept in mind. (1) Airgun arrays produce intermittent sounds, involving emission of a strong sound pulse for a small fraction of a second followed by several seconds of near silence. In contrast, some other sources produce sounds with lower peak levels, but their sounds are continuous or discontinuous but continuing for longer durations than seismic pulses. (2) Airgun arrays are designed to transmit strong sounds downward through the seafloor, and the amount of sound transmitted in near-horizontal directions is considerably reduced. Nonetheless, they also emit sounds that travel horizontally toward non-target areas. (3) An airgun array is a distributed source, not a point source. The nominal source level is an estimate of the sound that would be measured from a theoretical point source emitting the same total energy as the airgun array. That figure is useful in calculating the expected received levels in the far field, i.e., at moderate and long distances, but not in the near field. Because the airgun array is not a single point source, there is no one location within the near field (or anywhere else) where the received level is as high as the nominal source level.

The strengths of airgun pulses can be measured in different ways, and it is important to know which method is being used when interpreting quoted source or received levels. Geophysicists usually quote peak-to-peak (p-p) levels, in bar-meters or (less often) dB re 1 $\mu\text{Pa} \cdot \text{m}$. The peak (= zero-to-peak, or 0-p) level for the same pulse is typically ~ 6 dB less. In the biological literature, levels of received airgun pulses are often described based on the “average” or “root-mean-square” (rms) level, where the average is calculated over the duration of the pulse. The rms value for a given airgun pulse is typically ~ 10 dB lower than the peak level, and 16 dB lower than the peak-to-peak value (Greene 1997; McCauley et al. 1998, 2000a). A fourth measure that is increasingly used is the energy, or Sound Exposure Level (SEL), in dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$. Because the pulses, even when stretched by propagation effects (see below), are usually < 1 s in duration, the numerical value of the energy is usually lower than the rms pressure level. However, the units are different.⁶ Because the level of a given pulse will differ substantially depending on which of these measures is being applied, it is important to be aware which measure is in use when interpreting any quoted pulse level. In the past, the U.S. National Marine Fisheries Service

⁶ The rms value for a given airgun array pulse, as measured at a horizontal distance on the order of 0.1 km to 1–10 km in the units dB re 1 μPa , usually averages 10–15 dB higher than the SEL value for the same pulse measured in dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (e.g., Greene 1997). However, there is considerable variation, and the difference tends to be larger close to the airgun array, and less at long distances (Blackwell et al. 2007; MacGillivray and Hannay 2007a,b). In some cases, generally at longer distances, pulses are “stretched” by propagation effects to the extent that the rms and SEL values (in the respective units mentioned above) become very similar (e.g., MacGillivray and Hannay 2007a,b).

(NMFS) has commonly referred to rms levels when discussing levels of pulsed sounds that might “harass” marine mammals.

Seismic sound pulses received at any given point will arrive via a direct path, indirect paths that include reflection from the sea surface and bottom, and often indirect paths including segments through the 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.) 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 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 at 20 km, and 850 ms at 73 km (Greene and Richardson 1988).

The rms level for a given 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. There is increasing 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 (Urlick 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 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 μ Pa 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, low-frequency airgun signals sometimes can be detected thousands of kilometers from their source. For example, sound from seismic surveys conducted offshore of Nova Scotia, the coast of western Africa, and northeast of Brazil were reported as a dominant feature of the underwater noise field recorded along the mid-Atlantic ridge (Nieukirk et al. 2004).

4. Masking Effects of Airgun Sounds

Masking is the obscuring of sounds of interest by interfering sounds, generally at similar frequencies (Richardson et al. 1995). Introduced underwater sound will, through masking, reduce the effective communication distance of a marine mammal species if the frequency of the source is close to that used as a signal by the marine mammal, and if the anthropogenic sound is present for a significant fraction of the time (Richardson et al. 1995). If little or no overlap occurs between the introduced sound and the frequencies used by the species, communication is not expected to be disrupted. Also, if the

introduced sound is present only infrequently, communication is not expected to be disrupted much if at all. The duty cycle of airguns is low; the airgun sounds are pulsed, with relatively quiet periods between pulses. In most situations, strong airgun sound will only be received for a brief period (<1 s), with these sound pulses being separated by at least several seconds of relative silence, and longer in the case of deep-penetration surveys or refraction surveys. A single airgun array might cause appreciable masking in only one situation: When propagation conditions are such that sound from each airgun pulse reverberates strongly and persists for much or all of the interval up to the next airgun pulse (e.g., Simard et al. 2005; Clark and Gagnon 2006). Situations with prolonged strong reverberation are infrequent, in our experience. However, it is common for reverberation to cause some lesser degree of elevation of the background level between airgun pulses (e.g., Guerra et al. 2009), and this weaker reverberation presumably reduces the detection range of calls and other natural sounds to some degree.

Although masking effects of pulsed sounds on marine mammal calls and other natural sounds are expected to be limited, there are few specific studies on this. Some 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. 1999a,b; Nieu Kirk et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b, 2006; Dunn and Hernandez 2009). However, there is one recent summary report indicating that calling fin whales distributed in one part 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 of masking, or whether this was a behavioral response not directly involving masking. Also, bowhead whales in the Beaufort Sea may decrease their call rates in response to seismic operations, although movement out of the area might also have contributed to the lower call detection rate (Blackwell et al. 2009a,b). In contrast, Di Iorio and Clark (2009) found evidence of *increased* calling by blue whales during operations by a lower-energy seismic source—a sparker.

Among the odontocetes, there has been one report that sperm whales ceased calling when exposed to pulses from a very distant seismic ship (Bowles et al. 1994). However, more recent studies of sperm whales found that they continued calling in the presence of seismic pulses (Madsen et al. 2002; Tyack et al. 2003; Smultea et al. 2004; Holst et al. 2006; Jochens et al. 2008). Madsen et al. (2006) noted that airgun sounds would not be expected to mask sperm whale calls given the intermittent nature of airgun pulses. Dolphins and porpoises are also commonly heard calling while airguns are operating (Gordon et al. 2004; Smultea et al. 2004; Holst et al. 2005a,b; Potter et al. 2007). Masking effects of seismic pulses are expected to be negligible in the case of the smaller odontocetes, given the intermittent nature of seismic pulses plus the fact that sounds important to them are predominantly at much higher frequencies than are the dominant components of airgun sounds.

Pinnipeds, sirenians and sea otters have best hearing sensitivity and/or produce most of their sounds at frequencies higher than the dominant components of airgun sound, but there is some overlap in the frequencies of the airgun pulses and the calls. However, the intermittent nature of airgun pulses presumably reduces the potential for masking.

A few cetaceans are known to increase the source levels of their calls in the presence of elevated sound levels, shift their peak frequencies in response to strong sound signals, or otherwise modify their vocal behavior in response to increased noise (Dahlheim 1987; Au 1993; reviewed in Richardson et al. 1995:233ff, 364ff; Lesage et al. 1999; Terhune 1999; Nieu Kirk et al. 2005; Scheifele et al. 2005; Parks et al. 2007a, 2009; Di Iorio and Clark 2009; Hanser et al. 2009). It is not known how often these types of responses occur upon exposure to airgun sounds. However, blue whales in the St. Lawrence Estuary

significantly increased their call rates during sparker operations (Di Iorio and Clark 2009). The sparker, used to obtain seismic reflection data, emitted frequencies of 30–450 Hz with a relatively low source level of 193 dB re 1 $\mu\text{Pa}_{\text{pk-pk}}$. If cetaceans exposed to airgun sounds sometimes respond by changing their vocal behavior, this adaptation, along with directional hearing and preadaptation to tolerate some masking by natural sounds (Richardson et al. 1995), would all reduce the importance of masking by seismic pulses.

5. Disturbance by Seismic Surveys

Disturbance includes a variety of effects, including subtle to conspicuous changes in behavior, movement, and displacement. In the terminology of the 1994 amendments to the U.S. Marine Mammal Protection Act (MMPA), seismic noise could cause “Level B” harassment of certain marine mammals. Level B harassment is defined as “...disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering.”

There has been debate regarding how substantial a change in behavior or mammal activity is required before the animal should be deemed to be “taken by Level B harassment”. NMFS has stated that

“...a simple change in a marine mammal’s actions does not always rise to the level of disruption of its behavioral patterns. ... If the only reaction to the [human] activity on the part of the marine mammal is within the normal repertoire of actions that are required to carry out that behavioral pattern, NMFS considers [the human] activity not to have caused a disruption of the behavioral pattern, provided the animal’s reaction is not otherwise significant enough to be considered disruptive due to length or severity. Therefore, for example, a short-term change in breathing rates or a somewhat shortened or lengthened dive sequence that are within the animal’s normal range and that do not have any biological significance (i.e., do not disrupt the animal’s overall behavioral pattern of breathing under the circumstances), do not rise to a level requiring a small take authorization.” (NMFS 2001, p. 9293).

Based on this guidance from NMFS, and on NRC (2005), simple exposure to sound, or brief reactions that do not disrupt behavioral patterns in a potentially significant manner, do not constitute harassment or “taking”. In this analysis, we interpret “potentially significant” to mean in a manner that might have deleterious effects on the well-being of individual marine mammals or their populations.

Even with this guidance, there are difficulties in defining what marine mammals should be counted as “taken by harassment”. Available detailed data on reactions of marine mammals to airgun sounds (and other anthropogenic sounds) are limited to relatively few species and situations (see Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Southall et al. 2007). Behavioral reactions of marine mammals to sound are difficult to predict in the absence of site- and context-specific data. Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, and many other factors (Richardson et al. 1995; Wartzok et al. 2004; Southall et al. 2007; Weilgart 2007). If a marine mammal reacts to an underwater sound by changing its behavior 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., Lusseau and Bejder 2007; Weilgart 2007). Also, various authors have noted that some marine mammals that show no obvious avoidance or behavioral changes may still be adversely affected by noise (Brodie 1981; Richardson et al. 1995:317ff; Romano et al. 2004; Weilgart 2007; Wright et al. 2009). For example, some research suggests that animals in poor condition or in an already stressed state may not react as strongly to human disturbance as would more robust animals (e.g., Beale and Monaghan 2004).

Studies of the effects of seismic surveys have focused almost exclusively on the effects on individual species or related groups of species, with little scientific or regulatory attention being given to broader community-level issues. Parente et al. (2007) suggested that the diversity of cetaceans near the Brazil coast was reduced during years with seismic surveys. However, a preliminary account of a more recent analysis suggests that the trend did not persist when additional years were considered (Britto and Silva Barreto 2009).

Given the many uncertainties in predicting the quantity and types of impacts of sound on marine mammals, it is common practice to estimate how many mammals would be present within a particular distance of human activities and/or exposed to a particular level of anthropogenic sound. In most cases, this approach likely overestimates the numbers of marine mammals that would be affected in some biologically important manner. One of the reasons for this is that the selected distances/isopleths are based on limited studies indicating that some animals exhibited short-term reactions at this distance or sound level, whereas the calculation assumes that all animals exposed to this level would react in a biologically significant manner.

The definitions of “taking” in the U.S. MMPA, and its applicability to various activities, were slightly altered in November 2003 for military and federal scientific research activities. Also, NMFS is proposing to replace current Level A and B harassment criteria with guidelines based on exposure characteristics that are specific to particular groups of mammal species and to particular sound types (NMFS 2005). Recently, a committee of specialists on noise impact issues has proposed new science-based impact criteria (Southall et al. 2007). Thus, for projects subject to U.S. jurisdiction, changes in procedures may be required in the near future.

The sound criteria used to estimate how many marine mammals might be disturbed to some biologically significant degree by seismic survey activities are primarily based on behavioral observations of a few species. Detailed studies have been done on humpback, gray, bowhead, and sperm whales, and on ringed seals. Less detailed data are available for some other species of baleen whales and small toothed whales, but for many species there are no data on responses to marine seismic surveys.

5.1 Baleen Whales

Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable among species, locations, whale activities, oceanographic conditions affecting sound propagation, etc. (reviewed in Richardson et al. 1995; Gordon et al. 2004). Whales are often reported to show no overt reactions to pulses from large arrays of airguns at distances beyond a few kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, baleen whales exposed to strong sound pulses from airguns often react by deviating from their normal migration route and/or interrupting their feeding and moving away. Some of the major studies and reviews on this topic are Malme et al. (1984, 1985, 1988); Richardson et al. (1986, 1995, 1999); Ljungblad et al. (1988); Richardson and Malme (1993); McCauley et al. (1998, 2000a,b); Miller et al. (1999, 2005); Gordon et al. (2004); Moulton and Miller (2005); Stone and Tasker (2006); Johnson et al. (2007); Nowacek et al. (2007) and Weir (2008a). Although baleen whales often show only slight overt responses to operating airgun arrays (Stone and Tasker 2006; Weir 2008a), strong avoidance reactions by several species of mysticetes have been observed at ranges up to 6–8 km and occasionally as far as 20–30 km from the source vessel when large arrays of airguns were used. Experiments with a single airgun showed that bowhead, humpback and gray whales all showed localized avoidance to a single airgun of 20–100 in³ (Malme et al. 1984, 1985, 1986, 1988; Richardson et al. 1986; McCauley et al. 1998, 2000a,b).

Studies of gray, bowhead, and humpback whales have shown that seismic pulses with received levels of 160–170 dB re 1 $\mu\text{Pa}_{\text{rms}}$ seem to cause obvious avoidance behavior in a substantial portion 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 4–15 km from the source. More recent studies have shown that some species of baleen whales (bowheads and humpbacks in particular) at times show strong avoidance at received levels lower than 160–170 dB re 1 $\mu\text{Pa}_{\text{rms}}$. The largest avoidance radii involved migrating bowhead whales, which avoided an operating seismic vessel by 20–30 km (Miller et al. 1999; Richardson et al. 1999). In the cases of migrating bowhead (and gray) whales, the observed changes in behavior 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 (Malme et al. 1984; Malme and Miles 1985; Richardson et al. 1995). Feeding bowhead whales, in contrast to migrating whales, show much smaller avoidance distances (Miller et al. 2005; Harris et al. 2007), presumably because moving away from a food concentration has greater cost to the whales than does a course deviation during migration.

The following subsections provide more details on the documented responses of particular species and groups of baleen whales to marine seismic operations.

Humpback Whales.—Responses of humpback whales to seismic surveys have been studied during migration, on the 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) studied the responses of migrating humpback whales off Western Australia to a full-scale seismic survey with a 16-airgun 2678-in³ array, and to a single 20 in³ airgun with a (horizontal) source level of 227 dB re 1 $\mu\text{Pa} \cdot \text{m}_{\text{p-p}}$. They found that the overall distribution of humpbacks migrating through their study area was unaffected by the full-scale seismic program, although localized displacement varied with pod composition, behavior, and received sound levels. Observations were made from the seismic vessel, from which the maximum viewing distance was listed as 14 km. Avoidance reactions (course and speed changes) began at 4–5 km for traveling pods, with the closest point of approach (CPA) being 3–4 km at an estimated received level of 157–164 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (McCauley et al. 1998, 2000a). A greater stand-off range of 7–12 km was observed for more sensitive resting pods (cow-calf pairs; McCauley et al. 1998, 2000a). The mean received level for initial avoidance of an approaching airgun was 140 dB re 1 $\mu\text{Pa}_{\text{rms}}$ for humpback pods containing females, and at the mean CPA distance the received level was 143 dB re 1 $\mu\text{Pa}_{\text{rms}}$. One startle response was reported at 112 dB re 1 $\mu\text{Pa}_{\text{rms}}$. 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 $\mu\text{Pa}_{\text{rms}}$. The McCauley et al. (1998, 2000a,b) studies show evidence of greater avoidance of seismic airgun sounds by pods with females than by other pods during humpback migration off Western Australia.

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 in³) 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.

Among wintering humpback whales off Angola ($n = 52$ useable groups), there were no significant differences in encounter rates (sightings/hr) when a 24-airgun array (3147 in³ or 5085 in³) was operating vs. silent (Weir 2008a). There was also no significant difference in the mean CPA (closest observed point

of approach) distance of the humpback sightings when airguns were on vs. off (3050 m vs. 2700 m, respectively).

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. 2006), or with direct studies of humpbacks exposed to seismic surveys in other areas and seasons (see above). After allowance for data from subsequent years, there was “no observable direct correlation” between strandings and seismic surveys (IWC 2007, p. 236).

Bowhead Whales.—Responsiveness of bowhead whales to seismic surveys can be quite variable depending on their activity (feeding vs. migrating). Bowhead whales on their summer feeding grounds in the Canadian Beaufort Sea showed no obvious reactions to pulses from seismic vessels at distances of 6–99 km and received sound levels of 107–158 dB on an approximate rms basis (Richardson et al. 1986); their general activities were indistinguishable from those of a control group. However, subtle but statistically significant changes in surfacing–respiration–dive cycles were evident upon statistical analysis. Bowheads usually did show strong avoidance responses when seismic vessels approached within a few kilometers (~3–7 km) and when received levels of airgun sounds were 152–178 dB (Richardson et al. 1986, 1995; Ljungblad et al. 1988; Miller et al. 2005). They also moved away when a single airgun fired nearby (Richardson et al. 1986; Ljungblad et al. 1988). In one case, bowheads engaged in near-bottom feeding began to turn away from a 30-airgun array with a source level of 248 dB re 1 $\mu\text{Pa} \cdot \text{m}$ at a distance of 7.5 km, and swam away when it came within ~2 km; some whales continued feeding until the vessel was 3 km away (Richardson et al. 1986). This work and subsequent summer studies in the same region by Miller et al. (2005) and Harris et al. (2007) showed that many feeding bowhead whales tend to tolerate higher sound levels than migrating bowhead whales (see below) before showing an overt change in behavior. On the summer feeding grounds, bowhead whales are often seen from the operating seismic ship, though average sighting distances tend to be larger when the airguns are operating. Similarly, preliminary analyses of recent data from the Alaskan Beaufort Sea indicate that bowheads feeding there during late summer and autumn also did not display large-scale distributional changes in relation to seismic operations (Christie et al. 2009; Koski et al. 2009). However, some individual bowheads apparently begin to react at distances a few kilometers away, beyond the distance at which observers on the ship can sight bowheads (Richardson et al. 1986; Citta et al. 2007). The feeding whales may be affected by the sounds, but the need to feed may reduce the tendency to move away until the airguns are within a few kilometers.

Migrating bowhead whales in the Alaskan Beaufort Sea seem more responsive to noise pulses from a distant seismic vessel than are summering bowheads. Bowhead whales migrating west across the Alaskan Beaufort Sea in autumn 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 $\mu\text{Pa}_{\text{rms}}$ (Miller et al. 1999; Richardson et al. 1999; see also Manly et al. 2007). Those results came from 1996–98, when a partially-controlled study of the effect of Ocean Bottom Cable (OBC) seismic surveys on westward-migrating bowheads was conducted in late summer and autumn in the Alaskan Beaufort Sea. At times when the airguns were not active, many bowheads moved into the area close to the inactive seismic vessel. Avoidance of the area of seismic operations did not persist beyond 12–24 h after seismic shooting stopped. Preliminary analysis of recent data on traveling bowheads in the Alaskan Beaufort Sea also showed a stronger tendency to avoid operating airguns than was evident for feeding bowheads (Christie et al. 2009; Koski et al. 2009).

Bowhead whale calls detected in the presence and absence of airgun sounds have been studied extensively in the Beaufort Sea. Early work on the summering grounds in the Canadian Beaufort Sea showed that bowheads continue to produce calls of the usual types when exposed to airgun sounds, although numbers of calls detected may be somewhat lower in the presence of airgun pulses (Richardson et al. 1986). Studies during autumn in the Alaskan Beaufort Sea, one in 1996–1998 and another in 2007–2008, have shown that numbers of calls detected are significantly lower in the presence than in the absence of airgun pulses (Greene et al. 1999a,b; Blackwell et al. 2009a,b; Koski et al. 2009; see also Nations et al. 2009). This decrease could have resulted from movement of the whales away from the area of the seismic survey or a reduction in calling behavior, or a combination of the two. However, concurrent aerial surveys showed that there was strong avoidance of the operating airguns during the 1996–98 study, when most of the whales appeared to be migrating (Miller et al. 1999; Richardson et al. 1999). In contrast, aerial surveys during the 2007–08 study showed less consistent avoidance by the bowheads, many of which appeared to be feeding (Christie et al. 2009; Koski et al. 2009). The reduction in call detection rates during periods of airgun operation may have been more dependent on actual avoidance during the 1996–98 study and more dependent on reduced calling behavior during the 2007–08 study, but further analysis of the recent data is ongoing.

There are no data on reactions of bowhead whales to seismic surveys in winter or spring.

Gray Whales.—Malme et al. (1986, 1988) studied the responses of feeding eastern gray whales to pulses from a single 100-in³ 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 μ Pa on an (approximate) rms basis, and that 10% of feeding whales interrupted feeding at received levels of 163 dB re 1 μ Pa_{rms}. Malme et al. (1986) estimated that an average pressure level of 173 dB occurred at a range of 2.6–2.8 km from an airgun array with a source level of 250 dB re 1 μ Pa_{peak} in the northern Bering Sea. These findings were generally consistent with the results of studies conducted on larger numbers of gray whales migrating off California (Malme et al. 1984; Malme and Miles 1985) and western Pacific gray whales feeding off Sakhalin, Russia (Würsig et al. 1999; Gailey et al. 2007; Johnson et al. 2007; Yazvenko et al. 2007a,b), along with a few data on gray whales off British Columbia (Bain and Williams 2006).

Malme and Miles (1985) concluded that, during migration off California, gray whales showed changes in swimming pattern with received levels of ~160 dB re 1 μ Pa and higher, on an approximate rms basis. The 50% probability of avoidance was estimated to occur at a CPA distance of 2.5 km from a 4000-in³ airgun array operating off central California. This would occur at an average received sound level of ~170 dB re 1 μ Pa_{rms}. Some slight behavioral changes were noted when approaching gray whales reached the distances where received sound levels were 140 to 160 dB re 1 μ Pa_{rms}, but these whales generally continued to approach (at a slight angle) until they passed the sound source at distances where received levels averaged ~170 dB re 1 μ Pa_{rms} (Malme et al. 1984; Malme and Miles 1985).

There was no indication that western gray whales exposed to seismic noise were displaced from their overall feeding grounds near Sakhalin Island during seismic programs in 1997 (Würsig et al. 1999) and in 2001 (Johnson et al. 2007; Meier et al. 2007; Yazvenko et al. 2007a). However, there were indications of subtle behavioral effects among whales that remained in the areas exposed to airgun sounds (Würsig et al. 1999; Gailey et al. 2007; Weller et al. 2006a). Also, there was evidence of localized redistribution of some individuals within the nearshore feeding ground so as to avoid close approaches by the seismic vessel (Weller et al. 2002, 2006b; Yazvenko et al. 2007a). Despite the evidence of subtle changes in some quantitative measures of behavior and local redistribution of some individuals, there was no

apparent change in the frequency of feeding, as evident from mud plumes visible at the surface (Yazvenko et al. 2007b). The 2001 seismic program involved an unusually comprehensive combination of real-time monitoring and mitigation measures designed to avoid exposing western gray whales to received levels of sound above about 163 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (Johnson et al. 2007). The lack of strong avoidance or other strong responses was presumably in part a result of the mitigation measures. Effects probably would have been more significant without such intensive mitigation efforts.

Gray whales in British Columbia exposed to seismic survey sound levels up to ~170 dB re 1 μPa did not appear to be strongly disturbed (Bain and Williams 2006). The few whales that were observed moved away from the airguns but toward deeper water where sound levels were said to be higher due to propagation effects (Bain and Williams 2006).

Rorquals.—Blue, sei, fin, and minke whales (all of which are members of the genus *Balaenoptera*) often have been seen in areas ensounded 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 during 110 large-source seismic surveys off the U.K. 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 further (on average) from the airgun array during seismic operations compared with non-seismic periods ($P = 0.0057$; Stone and Tasker 2006). The average CPA distances for baleen whales sighted when large airgun arrays were operating vs. silent were about 1.6 vs. 1.0 km. Baleen whales, as a group, were more often oriented away from the vessel while a large airgun array was shooting compared with periods of no shooting ($P < 0.05$; Stone and Tasker 2006). In addition, fin/sei whales were less likely to remain submerged during periods of seismic shooting (Stone 2003).

In a study off Nova Scotia, Moulton and Miller (2005) found little difference in sighting rates (after accounting for water depth) and initial average sighting distances of balaenopterid whales when airguns were operating (mean = 1324 m) vs. silent (mean = 1303 m). However, there were indications that these whales were more likely to be moving away when seen during airgun operations. Baleen whales at the average sighting distance during airgun operations would have been exposed to sound levels (via direct path) of about 169 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (Moulton and Miller 2005). Similarly, ship-based monitoring studies of blue, fin, sei and minke whales offshore of Newfoundland (Orphan Basin and Laurentian Sub-basin) found no more than small differences in sighting rates and swim directions during seismic vs. non-seismic periods (Moulton et al. 2005, 2006a,b). Analyses of CPA data yielded variable results.⁷ The authors of the Newfoundland reports concluded that, based on observations from the seismic vessel, some mysticetes exhibited localized avoidance of seismic operations (Moulton et al. 2005, 2006a).

Minke whales have occasionally been observed to approach active airgun arrays where received sound levels were estimated to be near 170–180 dB re 1 μPa (McLean and Haley 2004).

⁷ The CPA of baleen whales sighted from the seismic vessels was, on average, significantly closer during non-seismic periods vs. seismic periods in 2004 in the Orphan Basin (means 1526 m vs. 2316 m, respectively; Moulton et al. 2005). In contrast, mean distances without vs. with seismic did not differ significantly in 2005 in either the Orphan Basin (means 973 m vs. 832 m, respectively; Moulton et al. 2006a) or in the Laurentian Sub-basin (means 1928 m vs. 1650 m, respectively; Moulton et al. 2006b). In both 2005 studies, mean distances were greater (though not significantly so) *without* seismic.

Discussion and Conclusions.—Baleen whales generally tend to avoid operating airguns, but avoidance radii are quite variable. Whales are often reported to show no overt reactions to airgun pulses at distances beyond a few kilometers, even though the airgun pulses remain well above ambient noise levels out to much longer distances. However, studies done since the late 1990s of migrating humpback and migrating bowhead whales show reactions, including avoidance, that sometimes extend to greater distances than documented earlier. Avoidance distances often exceed the distances at which boat-based observers can see whales, so observations from the source vessel can be biased. Observations over broader areas may be needed to determine the range of potential effects of some large-source seismic surveys where effects on cetaceans may extend to considerable distances (Richardson et al. 1999; Bain and Williams 2006; Moore and Angliss 2006). Longer-range observations, when required, can sometimes be obtained via systematic aerial surveys or aircraft-based observations of behavior (e.g., Richardson et al. 1986, 1999; Miller et al. 1999, 2005; Yazvenko et al. 2007a,b) or by use of observers on one or more support vessels operating in coordination with the seismic vessel (e.g., Smultea et al. 2004; Johnson et al. 2007). However, the presence of other vessels near the source vessel can, at least at times, reduce sightability of cetaceans from the source vessel (Beland et al. 2009), thus complicating interpretation of sighting data.

Some baleen whales show considerable tolerance of seismic pulses. However, when the pulses are strong enough, avoidance or other behavioral changes become evident. Because the responses become less obvious with diminishing received sound level, it has been difficult to determine the maximum distance (or minimum received sound level) at which reactions to seismic become evident and, hence, how many whales are affected.

Studies of gray, bowhead, and humpback whales have determined that received levels of pulses in the 160–170 dB re 1 $\mu\text{Pa}_{\text{rms}}$ range seem to cause obvious avoidance behavior in a substantial fraction of the animals exposed. In many areas, seismic pulses diminish to these levels at distances ranging from 4 to 15 km from the source. A substantial proportion of the baleen whales within such distances may show avoidance or other strong disturbance reactions to the operating airgun array. However, in other situations, various mysticetes tolerate exposure to full-scale airgun arrays operating at even closer distances, with only localized avoidance and minor changes in activities. At the other extreme, in migrating bowhead whales, avoidance often extends to considerably larger distances (20–30 km) and lower received sound levels (120–130 dB re 1 $\mu\text{Pa}_{\text{rms}}$). Also, even in cases where there is no conspicuous avoidance or change in activity upon exposure to sound pulses from distant seismic operations, there are sometimes subtle changes in behavior (e.g., surfacing–respiration–dive cycles) that are only evident through detailed statistical analysis (e.g., Richardson et al. 1986; Gailey et al. 2007).

Mitigation measures for seismic surveys, especially nighttime seismic surveys, typically assume that many marine mammals (at least baleen whales) tend to avoid approaching airguns, or the seismic vessel itself, before being exposed to levels high enough for there to be any possibility of injury. 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. As noted above, single-airgun experiments with three species of baleen whales show that those species typically do tend to move away when a single airgun starts firing nearby, which simulates the onset of a ramp up. The three species that showed avoidance when exposed to the onset of pulses from a single airgun were *gray whales* (Malme et al. 1984, 1986, 1988); *bowhead whales* (Richardson et al. 1986; Ljungblad et al. 1988); and *humpback whales* (Malme et al. 1985; McCauley et al. 1998, 2000a,b). Since startup of a single airgun is equivalent to the start of a ramp-up (=soft start), this strongly suggests that many baleen whales will begin to move away during the initial stages of a ramp-up.

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 distribution and habitat use in subsequent days or years. However, gray whales have continued to migrate annually along the west coast of North America despite intermittent seismic exploration (and much ship traffic) in that area for decades (Appendix A *in* Malme et al. 1984; Richardson et al. 1995), and there has been a substantial increase in the population over recent decades (Angliss and Outlaw 2008). The western Pacific gray whale population did not seem affected by a seismic survey in its feeding ground during a prior year (Johnson et al. 2007). Similarly, bowhead whales have continued to travel to the eastern Beaufort Sea each summer despite seismic exploration in their summer and autumn range for many years (Richardson et al. 1987), and their numbers have increased notably (Angliss and Outlaw 2008). Bowheads also have been observed over periods of days or weeks in areas ensonified repeatedly by seismic pulses (Richardson et al. 1987; Harris et al. 2007). However, it is generally not known whether the same individual bowheads were involved in these repeated observations (within and between years) in strongly ensonified areas. In any event, in the absence of some unusual circumstances, the history of coexistence between seismic surveys and baleen whales suggests that brief exposures to sound pulses from any single seismic survey are unlikely to result in prolonged effects.

5.2 Toothed Whales

Little systematic information is available about reactions of toothed whales to noise pulses. Few studies similar to the more extensive baleen whale/seismic pulse work summarized above have been reported for toothed whales. However, there are recent systematic data on sperm whales (e.g., Gordon et al. 2006; Madsen et al. 2006; Winsor and Mate 2006; Jochens et al. 2008; 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 2008a; Barkaszi et al. 2009; Richardson et al. 2009).

Delphinids (Dolphins and similar) and Monodontids (Beluga).—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 Osmeck 1998; Stone 2003; Moulton and Miller 2005; Holst et al. 2006; Stone and Tasker 2006; Weir 2008a; Richardson et al. 2009; see also Barkaszi et al. 2009). In most cases, the avoidance radii for delphinids appear to be small, on the order of 1 km or less, and some individuals show no apparent avoidance. Studies that have reported cases of small toothed whales close to the operating airguns include Duncan (1985), Arnold (1996), Stone (2003), and Holst et al. (2006). When a 3959 in³, 18-airgun array was firing off California, toothed whales behaved in a manner similar to that observed when the airguns were silent (Arnold 1996). Some dolphins seem to be attracted to the seismic vessel and floats, and some ride the bow wave of the seismic vessel even when a large array of airguns is 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 2008a).

Weir (2008b) noted that a group of short-finned pilot whales initially showed an avoidance response to ramp up of a large airgun array, but that this response was limited in time and space. Although the ramp-up procedure is a widely-used mitigation measure, it remains uncertain how effective it is at alerting marine mammals (especially odontocetes) and causing them to move away from seismic operations (Weir 2008b).

Goold (1996a,b,c) studied the effects on common dolphins of 2D seismic surveys in the Irish Sea. Passive acoustic surveys were conducted from the “guard ship” that towed a hydrophone. The results indicated that there was a local displacement of dolphins around the seismic operation. However, observations indicated that the animals were tolerant of the sounds at distances outside a 1-km radius from the airguns (Goold 1996a). Initial reports of larger-scale displacement were later shown to represent a normal autumn migration of dolphins through the area, and were not attributable to seismic surveys (Goold 1996a,b,c).

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 in summer found that sighting rates of belugas were significantly lower at distances 10–20 km compared with 20–30 km from an operating airgun array (Miller et al. 2005). The low number of beluga sightings by marine mammal observers on the vessel seemed to confirm there was a strong avoidance response to the 2250 in³ airgun array. More recent seismic monitoring studies in the same area have confirmed that the apparent displacement effect on belugas extended farther than has been shown for other small odontocetes exposed to airgun pulses (e.g., Harris et al. 2007).

Observers stationed on seismic vessels operating off the U.K. from 1997 to 2000 have provided data on the occurrence and behavior of various toothed whales exposed to seismic pulses (Stone 2003; Gordon et al. 2004; Stone and Tasker 2006). Dolphins of various species often showed more evidence of avoidance of operating airgun arrays than has been reported previously for small odontocetes. Sighting rates of white-sided dolphins, white-beaked dolphins, *Lagenorhynchus* spp., and all small odontocetes combined were significantly lower during periods when large-volume⁸ airgun arrays were shooting. Except for the pilot whale and bottlenose dolphin, CPA distances for all of the small odontocete species tested, including killer whales, were significantly farther from large airgun arrays during periods of shooting compared with periods of no shooting. Pilot whales were less responsive than other small odontocetes in the presence of seismic surveys (Stone and Tasker 2006). For small odontocetes as a group, and most individual species, orientations differed between times when large airgun arrays were operating vs. silent, with significantly fewer animals traveling towards and/or more traveling away from the vessel during shooting (Stone and Tasker 2006). Observers’ records suggested that fewer cetaceans were feeding and fewer were interacting with the survey vessel (e.g., bow-riding) during periods with airguns operating, and small odontocetes tended to swim faster during periods of shooting (Stone and Tasker 2006). For most types of small odontocetes sighted by observers on seismic vessels, the median CPA distance was ≥ 0.5 km larger during airgun operations (Stone and Tasker 2006). Killer whales appeared to be more tolerant of seismic shooting in deeper waters.

Data collected during seismic operations in the Gulf of Mexico and off Central America show similar patterns. A summary of vessel-based monitoring data from the Gulf of Mexico during 2003–2008 showed that delphinids were generally seen farther from the vessel during seismic than during non-seismic periods (based on Barkaszi et al. 2009, excluding sperm whales). Similarly, during two NSF-funded L-DEO seismic surveys that used a large 20 airgun array (~7000 in³), sighting rates of delphinids were lower and initial sighting distances were farther away from the vessel during seismic than non-seismic periods (Smultea et al. 2004; Holst et al. 2005a, 2006; Richardson et al. 2009). Monitoring results during a seismic survey in the Southeast Caribbean showed that the mean CPA of delphinids was 991 m during seismic operations vs. 172 m when the airguns were not operational (Smultea et al. 2004).

⁸ Large volume means at least 1300 in³, with most (79%) at least 3000 in³.

Surprisingly, nearly all acoustic detections via a towed passive acoustic monitoring (PAM) array, including both delphinids and sperm whales, were made when the airguns were operating (Smultea et al. 2004). Although the number of sightings during monitoring of a seismic survey off the Yucatán Peninsula, Mexico, was small ($n = 19$), the results showed that the mean CPA distance of delphinids there was 472 m during seismic operations vs. 178 m when the airguns were silent (Holst et al. 2005a). The acoustic detection rates were nearly 5 times higher during non-seismic compared with seismic operations (Holst et al. 2005a).

For two additional NSF-funded L-DEO seismic surveys in the Eastern Tropical Pacific, both using a large 36-airgun array ($\sim 6600 \text{ in}^3$), the results are less easily interpreted (Richardson et al. 2009). During both surveys, the delphinid detection rate was lower during seismic than during non-seismic periods, as found in various other projects, but the mean CPA distance of delphinids was closer (not farther) during seismic periods (Hauser et al. 2008; Holst and Smultea 2008).

During two seismic surveys off Newfoundland and Labrador in 2004–05, dolphin sighting rates were lower during seismic periods than during non-seismic periods after taking temporal factors into account, although the difference was statistically significant only in 2004 (Moulton et al. 2005, 2006a). In 2005, the mean CPA distance of dolphins was significantly farther during seismic periods (807 vs. 652 m); in 2004, the corresponding difference was not significant.

Among Atlantic spotted dolphins off Angola ($n = 16$ useable groups), marked short-term and localized displacement was found in response to seismic operations conducted with a 24-airgun array (3147 in^3 or 5085 in^3) (Weir 2008a). Sample sizes were low, but CPA distances of dolphin groups were significantly larger when airguns were on (mean 1080 m) vs. off (mean 209 m). No Atlantic spotted dolphins were seen within 500 m of the airguns when they were operating, whereas all sightings when airguns were silent occurred within 500 m, including the only recorded “positive approach” behaviors.

Reactions of toothed whales to a single airgun or other small airgun source are not well documented, but tend to be less substantial than reactions to large airgun arrays (e.g., Stone 2003; Stone and Tasker 2006). During 91 site surveys off the U.K. in 1997–2000, sighting rates of all small odontocetes combined were significantly lower during periods the low-volume⁹ airgun sources were operating, and effects on orientation were evident for all species and groups tested (Stone and Tasker 2006). Results from four NSF-funded L-DEO seismic surveys using small arrays (up to 3 GI guns and 315 in^3) were inconclusive. During surveys in the Eastern Tropical Pacific (Holst et al. 2005b) and in the Northwest Atlantic (Haley and Koski 2004), detection rates were slightly lower during seismic compared to non-seismic periods. However, mean CPAs were closer during seismic operations during one cruise (Holst et al. 2005b), and greater during the other cruise (Haley and Koski 2004). Interpretation of the data was confounded by the fact that survey effort and/or number of sightings during non-seismic periods during both surveys was small. Results from another two small-array surveys were even more variable (MacLean and Koski 2005; Smultea and Holst 2008).

Captive bottlenose dolphins and beluga whales exhibited changes in behavior when exposed to strong pulsed sounds similar in duration to those typically used in seismic surveys (Finneran et al. 2000, 2002, 2005). Finneran et al. (2002) exposed a captive bottlenose dolphin and beluga to single impulses from a water gun (80 in^3). As compared with airgun pulses, water gun impulses were expected to contain proportionally more energy at higher frequencies because there is no significant gas-filled bubble, and

⁹ For low volume arrays, maximum volume was 820 in^3 , with most (87%) $\leq 180 \text{ in}^3$.

thus little low-frequency bubble-pulse energy (Hutchinson and Detrick 1984). The captive animals sometimes vocalized after exposure and exhibited reluctance to station at the test site where subsequent exposure to impulses would be implemented (Finneran et al. 2002). Similar behaviors were exhibited by captive bottlenose dolphins and a beluga exposed to single underwater pulses designed to simulate those produced by distant underwater explosions (Finneran et al. 2000). It is uncertain what relevance these observed behaviors in captive, trained marine mammals exposed to single transient sounds may have to free-ranging animals exposed to multiple pulses. In any event, the animals tolerated rather high received levels of sound before exhibiting the aversive behaviors mentioned above.

Odontocete responses (or lack of responses) to noise pulses from underwater explosions (as opposed to airgun pulses) may be indicative of odontocete responses to very strong noise pulses. During the 1950s, small explosive charges were dropped into an Alaskan river in attempts to scare belugas away from salmon. Success was limited (Fish and Vania 1971; Frost et al. 1984). Small explosive charges were “not always effective” in moving bottlenose dolphins away from sites in the Gulf of Mexico where larger demolition blasts were about to occur (Klima et al. 1988). Odontocetes may be attracted to fish killed by explosions, and thus attracted rather than repelled by “scare” charges. Captive false killer whales showed no obvious reaction to single noise pulses from small (10 g) charges; the received level was ~185 dB re 1 μ Pa (Akamatsu et al. 1993). Jefferson and Curry (1994) reviewed several additional studies that found limited or no effects of noise pulses from small explosive charges on killer whales and other odontocetes. Aside from the potential for causing auditory impairment (see below), the tolerance to these charges may indicate a lack of effect, or the failure to move away may simply indicate a stronger desire to feed, regardless of circumstances.

Phocoenids (Porpoises).—Porpoises, like delphinids, show variable reactions to seismic operations, and reactions apparently depend on species. The limited available data suggest that harbor porpoises show stronger avoidance of seismic operations than Dall’s porpoises (Stone 2003; MacLean and Koski 2005; Bain and Williams 2006). In Washington State waters, the harbor porpoise—despite being considered a high-frequency specialist—appeared to be the species affected by the lowest received level of airgun sound (<145 dB re 1 μ Pa_{rms} at a distance >70 km; Bain and Williams 2006). Similarly, during seismic surveys with large airgun arrays off the U.K. in 1997–2000, there were significant differences in directions of travel by harbor porpoises during periods when the airguns were shooting vs. silent (Stone 2003; Stone and Tasker 2006). A captive harbor porpoise exposed to single sound pulses from a small airgun showed aversive behavior upon receipt of a pulse with received level above 174 dB re 1 μ Pa_{pk-pk} or SEL >145 dB re 1 μ Pa²·s (Lucke et al. 2009). In contrast, 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). The apparent tendency for greater responsiveness in the harbor porpoise is consistent with their relative responsiveness to boat traffic and some other acoustic sources (Richardson et al. 1995; Southall et al. 2007).

Beaked Whales.—There are almost no specific data on the behavioral reactions of beaked whales to seismic surveys. 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. 2006b). In any event, it is likely that most beaked whales would also show strong avoidance of an approaching seismic vessel, regardless of whether or not the airguns are operating. However, this has not been documented explicitly. Northern bottlenose whales sometimes are quite tolerant of slow-moving vessels not emitting airgun pulses (Reeves

et al. 1993; Hooker et al. 2001). The few detections (acoustic or visual) of northern bottlenose whales from seismic vessels during recent seismic surveys off Nova Scotia have been during times when the airguns were shut down; no detections were reported when the airguns were operating (Moulton and Miller 2005; Potter et al. 2007). However, other visual and acoustic studies indicated that 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 Cochran 2005; Simard et al. 2005).

There are increasing indications that some beaked whales tend to strand when military exercises involving mid-frequency sonar operation are ongoing nearby (e.g., Simmonds and Lopez-Jurado 1991; Frantzis 1998; NOAA and USN 2001; Jepson et al. 2003; Barlow and Gisiner 2006; see also the “Strandings and Mortality” subsection, later). These strandings are apparently at least in part a disturbance response, although auditory or other injuries or other physiological effects may also be a factor. Whether beaked whales would ever react similarly to seismic surveys is unknown. Seismic survey sounds are quite different from those of the sonars in operation during the above-cited incidents. No conclusive link has been established between seismic surveys and beaked whale strandings. There was a stranding of two Cuvier’s beaked whales in the Gulf of California (Mexico) in September 2002 when the R/V *Maurice Ewing* was conducting a seismic survey in the general area (e.g., Malakoff 2002; Hildebrand 2005). However, NMFS did not establish a cause and effect relationship between this stranding and the seismic survey activities (Hogarth 2002). Cox et al. (2006) noted the “lack of knowledge regarding the temporal and spatial correlation between the [stranding] and the sound source”. Hildebrand (2005) illustrated the approximate temporal-spatial relationships between the stranding and the *Ewing*’s tracks, but the time of the stranding was not known with sufficient precision for accurate determination of the CPA distance of the whales to the *Ewing*. Another stranding of Cuvier’s beaked whales in the Galápagos occurred during a seismic survey in April 2000; however “There is no obvious mechanism that bridges the distance between this source and the stranding site” (Gentry [ed.] 2002).

Sperm Whales.—All three species of sperm whales have been reported to show avoidance reactions to standard vessels not emitting airgun sounds (e.g., Richardson et al. 1995; Würsig et al. 1998; McAlpine 2002; Baird 2005). However, most studies of the sperm whale *Physeter macrocephalus* exposed to airgun sounds indicate that this species shows considerable tolerance of airgun pulses. The whales usually do not show strong avoidance (i.e., they do not leave the area) and they continue to call.

There were some early and limited observations suggesting that sperm whales in the Southern Ocean ceased calling during some (but not all) times when exposed to weak noise pulses from extremely distant (>300 km) seismic exploration. However, other operations in the area could also have been a factor (Bowles et al. 1994). This “quieting” was suspected to represent a disturbance effect, in part because sperm whales exposed to pulsed man-made sounds at higher frequencies often cease calling (Watkins and Schevill 1975; Watkins et al. 1985). Also, there was an early preliminary account of possible long-range avoidance of seismic vessels by sperm whales in the Gulf of Mexico (Mate et al. 1994). However, this has not been substantiated by subsequent more detailed work in that area (Gordon et al. 2006; Winsor and Mate 2006; Jochens et al. 2008; Miller et al. 2009).

Recent and more extensive data from vessel-based monitoring programs in U.K. waters and off Newfoundland and Angola suggest that sperm whales in those areas show little evidence of avoidance or behavioral disruption in the presence of operating seismic vessels (Stone 2003; Stone and Tasker 2006; Moulton et al. 2005, 2006a; Weir 2008a). Among sperm whales off Angola ($n = 96$ useable groups), there were no significant differences in encounter rates (sightings/hr) when a 24-airgun array (3147 in³ or

5085 in³) was operating vs. silent (Weir 2008a). There was also no significant difference in the CPA distances of the sperm whale sightings when airguns were on vs. off (means 3039 m vs. 2594 m, respectively). Encounter rate tended to increase over the 10-month duration of the seismic survey. These types of observations are difficult to interpret because the observers are stationed on or near the seismic vessel, and may underestimate reactions by some of the more responsive animals, which may be beyond visual range. However, these results do seem to show considerable tolerance of seismic surveys by at least some sperm whales. Also, a study off northern Norway indicated that sperm whales continued to call when exposed to pulses from a distant seismic vessel. Received levels of the seismic pulses were up to 146 dB re 1 $\mu\text{Pa}_{\text{p-p}}$ (Madsen et al. 2002).

Similarly, a study conducted off Nova Scotia that analyzed recordings of sperm whale vocalizations at various distances from an active seismic program did not detect any obvious changes in the distribution or behavior of sperm whales (McCall Howard 1999).

Sightings of sperm whales by observers on seismic vessels operating in the Gulf of Mexico during 2003–2008 were at very similar average distances regardless of the airgun operating conditions (Barkaszi et al. 2009). For example, the mean sighting distance was 1839 m when the airgun array was in full operation ($n=612$) vs. 1960 m when all airguns were off ($n=66$).

A controlled study of the reactions of tagged sperm whales to seismic surveys was done recently in the Gulf of Mexico — the Sperm Whale Seismic Study or SWSS (Gordon et al. 2006; Madsen et al. 2006; Winsor and Mate 2006; Jochens et al. 2008; Miller et al. 2009). During SWSS, D-tags (Johnson and Tyack 2003) were used to record the movement and acoustic exposure of eight foraging sperm whales before, during, and after controlled exposures to sound from airgun arrays (Jochens et al. 2008; Miller et al. 2009). Whales were exposed to maximum received sound levels of 111–147 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (131–162 dB re 1 $\mu\text{Pa}_{\text{pk-pk}}$) at ranges of ~1.4–12.8 km from the sound source (Miller et al. 2009). Although the tagged whales showed no discernible horizontal avoidance, some whales showed changes in diving and foraging behavior during full-array exposure, possibly indicative of subtle negative effects on foraging (Jochens et al. 2008; Miller et al. 2009; Tyack 2009). Two indications of foraging that they studied were oscillations in pitch and occurrence of echolocation buzzes, both of which tend to occur when a sperm whale closes-in on prey. "Oscillations in pitch generated by swimming movements during foraging dives were on average 6% lower during exposure than during the immediately following post-exposure period, with all 7 foraging whales exhibiting less pitching ($P = 0.014$). Buzz rates, a proxy for attempts to capture prey, were 19% lower during exposure..." (Miller et al. 2009). Although the latter difference was not statistically significant ($P = 0.141$), the percentage difference in buzz rate during exposure vs. post-exposure conditions appeared to be strongly correlated with airgun-whale distance (Miller et al. 2009; Fig. 5; Tyack 2009).

Discussion and Conclusions.—Dolphins and porpoises are often seen by observers on active seismic vessels, occasionally at close distances (e.g., bow riding). However, some studies near the U.K., Newfoundland and Angola, in the Gulf of Mexico, and off Central America have shown localized avoidance. Also, belugas summering in the Canadian Beaufort Sea showed larger-scale avoidance, tending to avoid waters out to 10–20 km from operating seismic vessels. In contrast, recent studies show little evidence of conspicuous reactions by sperm whales to airgun pulses, contrary to earlier indications.

There are almost no specific data on responses of beaked whales to seismic surveys, but it is likely that most if not all species show strong avoidance. There is increasing evidence that some beaked whales may strand after exposure to strong noise from sonars. Whether they ever do so in response to seismic

survey noise is unknown. Northern bottlenose whales seem to continue to call when exposed to pulses from distant seismic vessels.

Overall, odontocete reactions to large arrays of airguns are variable and, at least for delphinids and some porpoises, seem to be confined to a smaller radius than has been observed for some mysticetes. However, other data suggest that some odontocetes species, including belugas and harbor porpoises, may be more responsive than might be expected given their poor low-frequency hearing. Reactions at longer distances may be particularly likely when sound propagation conditions are conducive to transmission of the higher-frequency components of airgun sound to the animals' location (DeRuiter et al. 2006; Goold and Coates 2006; Tyack et al. 2006a; Potter et al. 2007).

For delphinids, and possibly the Dall's porpoise, the available data suggest that a ≥ 170 dB re $1 \mu\text{Pa}_{\text{rms}}$ disturbance criterion (rather than ≥ 160 dB) would be appropriate. With a medium-to-large airgun array, received levels typically diminish to 170 dB within 1–4 km, whereas levels typically remain above 160 dB out to 4–15 km (e.g., Tolstoy et al. 2009). Reaction distances for delphinids are more consistent with the typical 170 dB re $1 \mu\text{Pa}_{\text{rms}}$ distances. The 160 dB (rms) criterion currently applied by NMFS was developed based primarily on data from gray and bowhead whales. Avoidance distances for delphinids and Dall's porpoises tend to be shorter than for those two mysticete species. For delphinids and Dall's porpoises, there is no indication of strong avoidance or other disruption of behavior at distances beyond those where received levels would be ~ 170 dB re $1 \mu\text{Pa}_{\text{rms}}$.

5.3 Pinnipeds

Few studies of the reactions of pinnipeds to noise from open-water seismic exploration have been published (for review of the early literature, see Richardson et al. 1995). However, pinnipeds have been observed during a number of seismic monitoring studies. Monitoring in the Beaufort Sea during 1996–2002 provided a substantial amount of information on avoidance responses (or lack thereof) and associated behavior. Additional monitoring of that type has been done in the Beaufort and Chukchi Seas in 2006–2009. Pinnipeds exposed to seismic surveys have also been observed during seismic surveys along the U.S. west coast. Some limited data are available on physiological responses of pinnipeds exposed to seismic sound, as studied with the aid of radio telemetry. Also, there are data on the reactions of pinnipeds to various other related types of impulsive sounds.

Early observations provided considerable evidence that pinnipeds are often quite tolerant of strong pulsed sounds. During seismic exploration off Nova Scotia, gray seals exposed to noise from airguns and linear explosive charges reportedly did not react strongly (J. Parsons *in* Greene et al. 1985). An airgun caused an initial startle reaction among South African fur seals but was ineffective in scaring them away from fishing gear (Anonymous 1975). Pinnipeds in both water and air sometimes tolerate strong noise pulses from non-explosive and explosive scaring devices, especially if attracted to the area for feeding or reproduction (Mate and Harvey 1987; Reeves et al. 1996). Thus, pinnipeds are expected to be rather tolerant of, or to habituate to, repeated underwater sounds from distant seismic sources, at least when the animals are strongly attracted to the area.

In the U.K., a radio-telemetry study demonstrated short-term changes in the behavior of harbor (=common) and gray seals exposed to airgun pulses (Thompson et al. 1998). Harbor seals were exposed to seismic pulses from a 90-in³ array (3×30 in³ airguns), and behavioral responses differed among individuals. One harbor seal avoided the array at distances up to 2.5 km from the source and only resumed foraging dives after seismic stopped. Another harbor seal exposed to the same small airgun array showed no detectable behavioral response, even when the array was within 500 m. Gray seals

exposed to a single 10-in³ airgun showed an avoidance reaction: they moved away from the source, increased swim speed and/or dive duration, and switched from foraging dives to predominantly transit dives. These effects appeared to be short-term as gray seals either remained in, or returned at least once to, the foraging area where they had been exposed to seismic pulses. These results suggest that there are interspecific as well as individual differences in seal responses to seismic sounds.

Off California, visual observations from a seismic vessel showed that California sea lions “typically ignored the vessel and array. When [they] displayed behavior modifications, they often appeared to be reacting visually to the sight of the towed array. At times, California sea lions were attracted to the array, even when it was on. At other times, these animals would appear to be actively avoiding the vessel and array” (Arnold 1996). In Puget Sound, sighting distances for harbor seals and California sea lions tended to be larger when airguns were operating; both species tended to orient away whether or not the airguns were firing (Calambokidis and Osmek 1998). Bain and Williams (2006) also stated that their small sample of harbor seals and sea lions tended to orient and/or move away upon exposure to sounds from a large airgun array.

Monitoring work in the Alaskan Beaufort Sea during 1996–2001 provided considerable information regarding the behavior of seals exposed to seismic pulses (Harris et al. 2001; Moulton and Lawson 2002). Those seismic projects usually involved arrays of 6–16 airguns with total volumes 560–1500 in³. Subsequent monitoring work in the Canadian Beaufort Sea in 2001–2002, with a somewhat larger airgun system (24 airguns, 2250 in³), provided similar results (Miller et al. 2005). The combined results suggest that some seals avoid the immediate area around seismic vessels. In most survey years, ringed seal sightings averaged somewhat farther away from the seismic vessel when the airguns were operating than when they were not (Moulton and Lawson 2002). Also, seal sighting rates at the water surface were lower during airgun array operations than during no-airgun periods in each survey year except 1997. However, the avoidance movements were relatively small, on the order of 100 m to (at most) a few hundreds of meters, and many seals remained within 100–200 m of the trackline as the operating airgun array passed by.

The operation of the airgun array had minor and variable effects on the behavior of seals visible at the surface within a few hundred meters of the airguns (Moulton and Lawson 2002). The behavioral data indicated that some seals were more likely to swim away from the source vessel during periods of airgun operations and more likely to swim towards or parallel to the vessel during non-seismic periods. No consistent relationship was observed between exposure to airgun noise and proportions of seals engaged in other recognizable behaviors, e.g., “looked” and “dove”. Such a relationship might have occurred if seals seek to reduce exposure to strong seismic pulses, given the reduced airgun noise levels close to the surface where “looking” occurs (Moulton and Lawson 2002).

Monitoring results from the Canadian Beaufort Sea during 2001–2002 were more variable (Miller et al. 2005). During 2001, sighting rates of seals (mostly ringed seals) were similar during all seismic states, including periods without airgun operations. However, seals tended to be seen closer to the vessel during non-seismic than seismic periods. In contrast, during 2002, sighting rates of seals were higher during non-seismic periods than seismic operations, and seals were seen farther from the vessel during non-seismic compared to seismic activity (a marginally significant result). The combined data for both years showed that sighting rates were higher during non-seismic periods compared to seismic periods, and that sighting distances were similar during both seismic states. Miller et al. (2005) concluded that seals showed very limited avoidance to the operating airgun array.

Vessel-based monitoring also took place in the Alaskan Chukchi and Beaufort seas during 2006–2008 (Reiser et al. 2009). Observers on the seismic vessels saw phocid seals less frequently while airguns were operating than when airguns were silent. Also, during airgun operations, those observers saw seals less frequently than did observers on nearby vessels without airguns. Finally, observers on the latter “no-airgun” vessels saw seals more often when the nearby source vessels’ airguns were operating than when they were silent. All of these observations are indicative of a tendency for phocid seals to exhibit localized avoidance of the seismic source vessel when airguns are firing (Reiser et al. 2009).

In summary, visual monitoring from seismic vessels has shown only slight (if any) avoidance of airguns by pinnipeds, and only slight (if any) changes in behavior. These studies show that many pinnipeds do not avoid the area within a few hundred meters of an operating airgun array. However, based on the studies with large sample size, or observations from a separate monitoring vessel, or radio telemetry, it is apparent that some phocid seals do show localized avoidance of operating airguns. The limited nature of this tendency for avoidance is a concern. It suggests that one cannot rely on pinnipeds to move away, or to move very far away, before received levels of sound from an approaching seismic survey vessel approach those that may cause hearing impairment (see below).

5.4 Sirenians, Sea Otter and Polar Bear

We are not aware of any information on the reactions of sirenians to airgun sounds

Behavior of sea otters along the California coast was monitored by Riedman (1983, 1984) while they were exposed to a single 100 in³ airgun and a 4089 in³ 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. These results suggest that sea otters may be less responsive to marine seismic pulses than some other marine mammals, such as mysticetes and odontocetes (summarized above). Also, sea otters spend a great deal of time at the surface feeding and grooming (Riedman 1983, 1984). While at the surface, the potential noise exposure of sea otters would be much reduced by pressure-release and interference (Lloyd’s mirror) effects at the surface (Greene and Richardson 1988; Richardson et al. 1995).

Airgun effects on polar bears have not been studied. However, polar bears on the ice would be largely unaffected by underwater sound. Sound levels received by polar bears in the water would be attenuated because polar bears generally do not dive much below the surface and received levels of airgun sounds are reduced near the surface because of the aforementioned pressure release and interference effects at the water’s surface.

6. Hearing Impairment and Other Physical Effects of Seismic Surveys

Temporary or permanent hearing impairment is a possibility when marine mammals are exposed to very strong sounds. Temporary threshold shift (TTS) has been demonstrated and studied in certain captive odontocetes and pinnipeds exposed to strong sounds (reviewed in Southall et al. 2007). However, there has been no specific documentation of TTS let alone permanent hearing damage, i.e. permanent threshold shift (PTS), in free-ranging marine mammals exposed to sequences of airgun pulses during realistic field conditions. Current NMFS policy regarding exposure of marine mammals to high-level sounds is that cetaceans and pinnipeds should not be exposed to impulsive sounds ≥ 180 and 190 dB re 1 $\mu\text{Pa}_{\text{rms}}$, respectively (NMFS 2000). Those criteria have been used in establishing the safety (=shut-down) radii planned for numerous seismic surveys conducted under U.S. jurisdiction. However, those criteria were established before there was any information about the minimum received levels of sounds necessary to cause auditory impairment in marine mammals. As discussed below,

- the 180-dB criterion for cetaceans is probably quite precautionary, i.e., lower than necessary to avoid temporary auditory impairment let alone permanent auditory injury, at least for delphinids.
- TTS is not injury and does not constitute “Level A harassment” in U.S. MMPA terminology.
- the minimum sound level necessary to cause permanent hearing impairment (“Level A harassment”) is higher, by a variable and generally unknown 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 recently (Southall et al. 2007). Those recommendations have not, as of late 2009, been formally adopted by NMFS for use in 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. NMFS has indicated that it may issue new noise exposure criteria for marine mammals that account for the now-available scientific data on TTS, the expected offset between the TTS and PTS thresholds, differences in the acoustic frequencies to which different marine mammal groups are sensitive, and other relevant factors. Preliminary information about possible changes in the regulatory and mitigation requirements, and about the possible structure of new criteria, was given by Wieting (2004) and NMFS (2005).

Several aspects of the monitoring and mitigation measures that are now often implemented during seismic survey projects are designed to detect marine mammals occurring near the airgun array, and to avoid exposing them to sound pulses that might, at least in theory, cause hearing impairment. 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. In those cases, the avoidance responses of the animals themselves will reduce or (most likely) avoid the possibility of hearing impairment.

Non-auditory physical effects may also occur in marine mammals exposed to strong underwater pulsed sound. Possible types of non-auditory physiological effects or injuries that might (in theory) occur include stress, neurological effects, bubble formation, and other types of organ or tissue damage. It is possible that some marine mammal species (i.e., beaked whales) may be especially susceptible to injury and/or stranding when exposed to strong pulsed sounds. The following subsections summarize available data on noise-induced hearing impairment and non-auditory physical effects.

6.1 Temporary Threshold Shift (TTS)

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 (especially when mild) is not considered to represent physical damage or “injury” (Southall et al. 2007). 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.

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. In terrestrial mammals, TTS can last from minutes or hours to (in cases of

strong TTS) days. Only a few data have been obtained on sound levels and durations necessary to elicit mild TTS in marine mammals (none in mysticetes), and none of the published data concern TTS elicited by exposure to multiple pulses of sound during operational seismic surveys (Southall et al. 2007).

Toothed Whales.—There are empirical data on the sound exposures that elicit onset of TTS in captive bottlenose dolphins and belugas. The majority of these data concern non-impulse sound, but there are some limited published data concerning TTS onset upon exposure to a single pulse of sound from a watergun (Finneran et al. 2002). A detailed review of all TTS data from marine mammals can be found in Southall et al. (2007). The following summarizes some of the key results from odontocetes.

Recent information corroborates earlier expectations that the effect of exposure to strong transient sounds is closely related to the total amount of acoustic energy that is received. Finneran et al. (2005) examined the effects of tone duration on TTS in bottlenose dolphins. Bottlenose dolphins were exposed to 3 kHz tones (non-impulsive) for periods of 1, 2, 4 or 8 s, with hearing tested at 4.5 kHz. For 1-s exposures, TTS occurred with SELs of 197 dB, and for exposures >1 s, SEL >195 dB resulted in TTS (SEL is equivalent to energy flux, in dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$). At an SEL of 195 dB, the mean TTS (4 min after exposure) was 2.8 dB. Finneran et al. (2005) suggested that an SEL of 195 dB is the likely threshold for the onset of TTS in dolphins and belugas exposed to tones of durations 1–8 s (i.e., TTS onset occurs at a near-constant SEL, independent of exposure duration). That implies that, at least for non-impulsive tones, a doubling of exposure time results in a 3 dB lower TTS threshold.

The assumption that, in marine mammals, the occurrence and magnitude of TTS is a function of cumulative acoustic energy (SEL) is probably an oversimplification. Kastak et al. (2005) reported preliminary evidence from pinnipeds that, for prolonged non-impulse noise, higher SELs were required to elicit a given TTS if exposure duration was short than if it was longer, i.e., the results were not fully consistent with an equal-energy model to predict TTS onset. Mooney et al. (2009a) showed this in a bottlenose dolphin exposed to octave-band non-impulse noise ranging from 4 to 8 kHz at SPLs of 130 to 178 dB re 1 μPa for periods of 1.88 to 30 min. Higher SELs were required to induce a given TTS if exposure duration short than if it was longer. 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 s, SEL must be at least 210–214 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ to induce TTS in the bottlenose dolphin.

On the other hand, the TTS threshold for odontocetes exposed to a single impulse from a watergun (Finneran et al. 2002) appeared to be somewhat lower than for exposure to non-impulse sound. This 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 received energy level of a single seismic pulse that caused the onset of mild TTS in the beluga, as measured without frequency weighting, was ~ 186 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ or 186 dB SEL (Finneran et al. 2002).¹⁰ The rms level of an airgun pulse (in dB re 1 μPa measured over the duration of the pulse) is typically 10–15 dB higher than the SEL for the same pulse when received within a few kilometers of the airguns. Thus, a single airgun pulse might need to have a received level of ~ 196 –201 dB re 1 $\mu\text{Pa}_{\text{rms}}$ in order to produce brief, mild TTS. Exposure to several strong seismic pulses that each has a flat-weighted received level

¹⁰ If the low-frequency components of the watergun sound used in the experiments of Finneran et al. (2002) are downweighted as recommended by Southall et al. (2007) using their M_{mf} -weighting curve, the effective exposure level for onset of mild TTS was 183 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (Southall et al. 2007).

near 190 dB_{rms} (175–180 dB SEL) could result in cumulative exposure of ~186 dB SEL (flat-weighted) or ~183 dB SEL (M_{mf}-weighted), and thus slight TTS in a small odontocete. 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.

The above TTS information for odontocetes is derived from studies on the bottlenose dolphin and beluga. For the one harbor porpoise tested, the received level of airgun sound that elicited onset of TTS was lower. The animal was exposed to single pulses from a small (20 in³) 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 μPa²·s. If these results from a single animal are representative, it is inappropriate to assume that onset of TTS occurs at similar received levels in all odontocetes (*cf.* Southall et al. 2007). Some cetaceans may incur TTS at lower sound exposures than are necessary to elicit TTS in the beluga or bottlenose dolphin.

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. However, as yet there has been little study of the rate of recovery from TTS in marine mammals, and in humans and other terrestrial mammals the available data on recovery are quite variable. 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.

Additional data are needed to determine the received sound levels at which small odontocetes would start to incur TTS upon exposure to repeated, low-frequency pulses of airgun sound with variable received levels. To determine how close an airgun array would need to approach in order to elicit TTS, it is necessary to determine the total energy that a mammal would receive as an airgun array approaches, passes at various CPA distances, and moves away (e.g., Erbe and King 2009). At the present state of knowledge, it is also necessary to assume that the effect is directly related to total received energy even though that energy is received in multiple pulses separated by gaps. The lack of data on the exposure levels necessary to cause TTS in toothed whales when the signal is a series of pulsed sounds, separated by silent periods, remains a data gap, as is the lack of published data on TTS in odontocetes other than the beluga, bottlenose dolphin, and harbor porpoise.

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 modeling 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 are expected given the strong likelihood that baleen whales would avoid the approaching airguns (or vessel) before being exposed to levels high enough for there to be any possibility of TTS (see above for evidence concerning avoidance responses by baleen whales). 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. As discussed earlier, single-airgun experiments with bowhead, gray, and humpback whales show 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. Two California sea lions did not incur TTS when exposed to single brief pulses with received levels of ~178 and 183 dB re 1 $\mu\text{Pa}_{\text{rms}}$ and total energy fluxes of 161 and 163 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (Finneran et al. 2003). However, initial evidence from more prolonged (non-pulse) exposures suggested that some pinnipeds (harbor seals in particular) incur TTS at somewhat lower received levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005; Ketten et al. 2001). Kastak et al. (2005) reported that the amount of threshold shift increased with increasing SEL in a California sea lion and harbor seal. They noted that, for non-impulse sound, doubling the exposure duration from 25 to 50 min (i.e., a +3 dB change in SEL) had a greater effect on TTS than an increase of 15 dB (95 vs. 80 dB) in exposure level. Mean threshold shifts ranged from 2.9–12.2 dB, with full recovery within 24 hr (Kastak et al. 2005). Kastak et al. (2005) suggested that, for non-impulse sound, SELs resulting in TTS onset in three species of pinnipeds may range from 183 to 206 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$, depending on the absolute hearing sensitivity.

As noted above for odontocetes, it is expected that—for impulse as opposed to non-impulse sound—the onset of TTS would occur at a lower cumulative SEL given the assumed greater auditory effect of broadband impulses with rapid rise times. The threshold for onset of mild TTS upon exposure of a harbor seal to impulse sounds has been estimated indirectly as being an SEL of ~171 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ (Southall et al. 2007). That would be approximately equivalent to a single pulse with received level ~181–186 dB re 1 $\mu\text{Pa}_{\text{rms}}$, or a series of pulses for which the highest rms values are a few dB lower.

At least for non-impulse sounds, TTS onset occurs at appreciably higher received levels in California sea lions and northern elephant seals than in harbor seals (Kastak et al. 2005). Thus, the former two species would presumably need to be closer to an airgun array than would a harbor seal before TTS is a possibility. Insofar as we are aware, there are no data to indicate whether the TTS thresholds of other pinniped species are more similar to those of the harbor seal or to those of the two less-sensitive species.

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) even larger arrays of streamers normally must remain farther offshore because of equipment clearance and maneuverability limitations. Exposures of sea otters and sirenians to seismic surveys are more likely to involve smaller seismic sources that can be used in shallow and confined waters. The impacts of these are inherently less than would occur from a larger source of the types often used farther offshore.

Likelihood of Incurring TTS.—Most cetaceans show some degree of avoidance of seismic vessels operating an airgun array (see above). It is unlikely that these cetaceans would be exposed to airgun pulses at a sufficiently high 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.

If some cetaceans did incur mild or moderate TTS through exposure to airgun sounds in this manner, this would very likely be a temporary and reversible phenomenon. However, even a temporary reduction in hearing sensitivity could be deleterious in the event that, during that period of reduced sensitivity, a marine mammal needed its full hearing sensitivity to detect approaching predators, or for some other reason.

Some pinnipeds show avoidance reactions to airguns, but their avoidance reactions are generally not as strong or consistent as those of cetaceans. 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 harbor 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.

NMFS (1995, 2000) concluded that cetaceans should not be exposed to pulsed underwater noise at received levels >180 dB re $1 \mu\text{Pa}_{\text{rms}}$. The corresponding limit for pinnipeds has been set by NMFS at 190 dB, although the HESS Team (HESS 1999) recommended a 180-dB limit for pinnipeds in California. The 180 and 190 dB re $1 \mu\text{Pa}_{\text{rms}}$ levels have not been considered to be the levels above which TTS might occur. Rather, they were the received levels above which, in the view of a panel of bioacoustics specialists convened by NMFS 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. As summarized above, data that are now available imply that TTS is unlikely to occur in various odontocetes (and probably mysticetes as well) unless they are exposed to a sequence of several airgun pulses stronger than 190 dB re $1 \mu\text{Pa}_{\text{rms}}$. On the other hand, for the harbor seal, harbor porpoise, and perhaps some other species, TTS may occur upon exposure to one or more airgun pulses whose received level equals the NMFS “do not exceed” value of 190 dB re $1 \mu\text{Pa}_{\text{rms}}$. That criterion corresponds to a single-pulse SEL of 175–180 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ in typical conditions, whereas TTS is suspected to be possible in harbor seals and harbor porpoises with a cumulative SEL of ~ 171 and ~ 164 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$, respectively.

It has been shown that most large whales and many smaller odontocetes (especially the harbor porpoise) show at least localized avoidance of ships and/or seismic operations (see above). Even when avoidance is limited to the area within a few hundred meters of an airgun array, that should usually be sufficient to avoid TTS based on what is currently known about thresholds for TTS onset in cetaceans. In addition, ramping up airgun arrays, which is standard operational protocol for many seismic operators, should allow cetaceans near the airguns at the time of startup (if the sounds are aversive) to move away from the seismic source and to avoid being exposed to the full acoustic output of the airgun array (see above). Thus, most baleen whales likely will not be exposed to high levels of airgun sounds provided the ramp-up procedure is applied. Likewise, many odontocetes close to the trackline are likely to move away before the sounds from an approaching seismic vessel become sufficiently strong for there to be any potential for TTS or other hearing impairment. Therefore, there is little potential for baleen whales or

odontocetes that show avoidance of ships or airguns to be close enough to an airgun array to experience TTS. In the event that a few individual cetaceans did incur TTS through exposure to strong airgun sounds, this is a temporary and reversible phenomenon unless the exposure exceeds the TTS-onset threshold by a sufficient amount for PTS to be incurred (see below). If TTS but not PTS were incurred, it would most likely be mild, in which case recovery is expected to be quick (probably within minutes).

6.2 Permanent Threshold Shift (PTS)

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). Physical damage to a mammal's hearing apparatus can occur if it is exposed to sound impulses that have very high peak pressures, especially if they have very short rise times. (Rise time is the interval required for sound pressure to increase from the baseline pressure to peak pressure.)

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 might incur at least mild TTS (see above), there has been further speculation about the possibility that some individuals occurring very close to airguns might incur PTS (e.g., Richardson et al. 1995, p. 372ff; Gedamke et al. 2008). Single or occasional occurrences of mild TTS are not indicative of permanent auditory damage, but repeated or (in some cases) single 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). The low-to-moderate levels of TTS that have been induced in captive odontocetes and pinnipeds during controlled studies of TTS have been confirmed to be temporary, with no measurable residual PTS (Kastak et al. 1999; Schlundt et al. 2000; Finneran et al. 2002, 2005; Nachtigall et al. 2003, 2004). However, very prolonged exposure to sound strong enough to elicit TTS, or shorter-term exposure to sound levels well above the TTS threshold, can cause PTS, at least in terrestrial mammals (Kryter 1985). In terrestrial mammals, the received sound level from a single non-impulsive sound exposure must be far above the TTS threshold for any risk of permanent hearing damage (Kryter 1994; Richardson et al. 1995; Southall et al. 2007). However, there is special concern about strong sounds whose pulses have very rapid rise times. In terrestrial mammals, there are situations when pulses with rapid rise times (e.g., from explosions) can result in PTS even though their peak levels are only a few dB higher than the level causing slight TTS. The rise time of airgun pulses is fast, but not as fast as that of an explosion.

Some factors that contribute to onset of PTS, at least in terrestrial mammals, are as follows:

- exposure to single very intense sound,
- fast rise time from baseline to peak pressure,
- repetitive exposure to intense sounds that individually cause TTS but not PTS, and
- recurrent ear infections or (in captive animals) exposure to certain drugs.

Cavanagh (2000) reviewed the thresholds used to define TTS and PTS. Based on this review and SACLANT (1998), it is reasonable to assume that PTS might occur at a received sound level 20 dB or more above that inducing mild TTS. However, for PTS to occur at a received level only 20 dB above the TTS threshold, the animal probably would have to be exposed to a strong sound for an extended period, or to a strong sound with rather rapid rise time.

More recently, Southall et al. (2007) estimated that received levels would need to exceed the TTS threshold by at least 15 dB, on an SEL basis, for there to be risk of PTS. Thus, for cetaceans exposed to a sequence of sound pulses, they estimate that the PTS threshold might be an M-weighted SEL (for the sequence of received pulses) of ~ 198 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ (15 dB higher than the M_{mf} -weighted TTS threshold, in a beluga, for a waterygun impulse). Additional assumptions had to be made to derive a corresponding estimate for pinnipeds, as the only available data on TTS-thresholds in pinnipeds 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 $1 \mu\text{Pa}^2 \cdot \text{s}$ in the case of a harbor seal exposed to impulse sound. The PTS threshold for the California sea lion and northern elephant seal would probably be higher given the higher TTS thresholds in those species. Southall et al. (2007) also note 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 exceeding 230 or 218 dB re $1 \mu\text{Pa}$, respectively. Thus, PTS might be expected upon exposure of cetaceans to either $\text{SEL} \geq 198$ dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ or peak pressure ≥ 230 dB re $1 \mu\text{Pa}$. Corresponding proposed dual criteria for pinnipeds (at least harbor seals) are ≥ 186 dB SEL and ≥ 218 dB peak pressure (Southall et al. 2007). These estimates are all first approximations, given the limited underlying data, assumptions, species differences, and evidence that the “equal energy” model is not be entirely correct.

Sound impulse duration, peak amplitude, rise time, number of pulses, and inter-pulse interval are the main factors thought to determine the onset and extent of PTS. Ketten (1994) has noted that the criteria for differentiating the sound pressure levels that result in PTS (or TTS) are location and species-specific. PTS effects may also be influenced strongly by the health of the receiver’s ear.

As described above for TTS, in estimating the amount of sound energy required to elicit the onset of TTS (and PTS), it is assumed that the auditory effect of a given cumulative SEL from a series of pulses is the same as if that amount of sound energy were received as a single strong sound. There are no data from marine mammals concerning the occurrence or magnitude of a potential partial recovery effect between pulses. In deriving the estimates of PTS (and TTS) thresholds quoted here, Southall et al. (2007) made the precautionary assumption that no recovery would occur between pulses.

The TTS section (above) concludes that exposure to several strong seismic pulses that each have flat-weighted received levels near 190 dB re $1 \mu\text{Pa}_{\text{rms}}$ (175–180 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ SEL) could result in cumulative exposure of ~ 186 dB SEL (flat-weighted) or ~ 183 dB SEL (M_{mf} -weighted), and thus slight TTS in a small odontocete. Allowing for the assumed 15 dB offset between PTS and TTS thresholds, expressed on an SEL basis, exposure to several strong seismic pulses that each have flat-weighted received levels near 205 dB_{rms} (190–195 dB SEL) could result in cumulative exposure of ~ 198 dB SEL (M_{mf} -weighted), and thus slight PTS in a small odontocete. However, the levels of successive pulses that will 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).

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 bowriding 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., harbor seal) as well as the harbor porpoise may be lower (Kastak et al. 2005; Southall et al. 2007; Lucke et al. 2009). If so, TTS and potentially PTS may extend to a somewhat greater distance for those animals. Again, Lloyd's mirror and surface release effects will ameliorate the 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., harbor porpoise and harbor 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 harbor porpoise and harbor seal.

The avoidance reactions of many marine mammals, along with commonly-applied monitoring and mitigation measures (visual and passive acoustic monitoring, ramp ups, and power downs or shut downs when mammals are detected within or approaching the "safety radii"), would reduce the already-low probability of exposure of marine mammals to sounds strong enough to induce PTS.

6.3 Strandings and Mortality

Marine mammals close to underwater detonations of high explosives can be killed or severely injured, and the auditory organs are especially susceptible to injury (Ketten et al. 1993; Ketten 1995). However, explosives are no longer used in marine waters for commercial seismic surveys or (with rare exceptions) for seismic research; they have been replaced by airguns and other non-explosive sources. Airgun pulses are less energetic and have slower rise times, and there is no specific evidence that they can cause serious injury, death, or stranding even in the case of large airgun arrays. However, the association of mass strandings of beaked whales with naval exercises and, in one case, a seismic survey (Malakoff 2002; Cox et al. 2006), has raised the possibility that beaked whales exposed to strong "pulsed" sounds may be especially susceptible to injury and/or behavioral reactions that can lead to stranding (e.g., Hildebrand 2005; Southall et al. 2007). Hildebrand (2005) reviewed the association of cetacean strandings with high-intensity sound events and found that deep-diving odontocetes, primarily beaked whales, were by far the predominant (95%) cetaceans associated with these events, with 2% mysticete whales (minke). However, as summarized below, there is no definitive evidence that airguns can lead to injury, strandings, or mortality even for marine mammals in close proximity to large airgun arrays.

Specific sound-related processes that lead to strandings and mortality are not well documented, but may include (1) swimming in avoidance of a sound into shallow water; (2) a change in behavior (such as a change in diving behavior that might contribute to tissue damage, gas bubble formation, hypoxia, cardiac arrhythmia, hypertensive hemorrhage or other forms of trauma); (3) a physiological change such as a vestibular response leading to a behavioral change or stress-induced hemorrhagic diathesis, leading in turn 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 pathologic mechanism for the strandings and mortality of some deep-diving cetaceans exposed to sonar. The evidence for this remains circumstantial and associated with exposure to naval mid-frequency sonar, not seismic surveys (Cox et al. 2006; Southall et al. 2007).

Seismic 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 impulses with most of the energy below 1 kHz. Typical military mid-frequency sonars emit non-impulse sounds at frequencies of 2–10 kHz, generally with a relatively narrow bandwidth at any one time (though the frequency may change over time). Thus, it is not appropriate to assume that the effects of seismic surveys 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 “pulsed” 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.

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 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 L-DEO seismic vessel R/V *Maurice Ewing* was operating a 20-airgun, 8490-in³ airgun array in the general area. The evidence linking the stranding to the seismic survey was inconclusive and not based on any physical evidence (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 downward-directed beams, 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).

6.4 Non-Auditory Physiological Effects

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, would be mainly associated with chronic noise exposure, which is characteristic of some seismic surveys and exposure situations (McCauley et al. 2000a:62ff; Nieuwkerk et al. 2009) but not of some others.

Available data on potential stress-related impacts of anthropogenic noise on marine mammals are extremely limited, and additional research on this topic is needed. We know of only two specific studies of noise-induced stress in marine mammals. (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 $\mu\text{Pa} \cdot \text{m}_{\text{p-p}}$) 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.

Aside from stress, other types of physiological effects that might, in theory, be involved in beaked whale strandings upon exposure to naval sonar (Cox et al. 2006), such as resonance and gas bubble formation, have not been demonstrated and are not expected upon exposure to airgun pulses (see preceding subsection). If seismic surveys disrupt diving patterns of deep-diving species, this might perhaps result in bubble formation and a form of “the bends”, as speculated to occur in beaked whales exposed to sonar. However, there is no specific evidence that exposure to airgun pulses has this effect.

In summary, very little is known about the potential for seismic survey sounds (or other types of strong underwater sounds) to cause non-auditory physiological effects in marine mammals. Such effects, if they occur at all, would presumably be limited to short distances and to activities that extend over a prolonged period. The available data do not allow identification of a specific exposure level above which non-auditory effects can be expected (Southall et al. 2007), or any meaningful quantitative predictions of the numbers (if any) of marine mammals that might be affected in these ways.

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APPENDIX C: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON FISHES¹¹

Here we review literature about the effects of airgun sounds on fishes during seismic surveys. The potential effect of seismic sounds on fish has been studied with a variety of taxa, including marine, freshwater, and anadromous species (reviewed by Fay and Popper 2000; Ladich and Popper 2004; Hastings and Popper 2005; Popper and Hastings 2009a,b).

It is sometimes difficult to interpret studies on the effects of underwater sound on marine animals because authors often do not provide enough information, including received sound levels, source sound levels, and specific characteristics of the sound. Specific characteristics of the sound include units and references, whether the sound is continuous or impulsive, and its frequency range. Underwater sound pressure levels are typically reported as a number of decibels referenced to a reference level, usually 1 micro-Pascal (μPa). However, the sound pressure dB number can represent multiple types of measurements, including “zero to peak”, “peak to peak”, or averaged (“rms”). Sound exposure levels (SEL) may also be reported as dB. The SEL is the integration of all the acoustic energy contained within a single sound event. Unless precise measurement types are reported, it can be impossible to directly compare results from two or more independent studies.

1. Acoustic Capabilities

Sensory systems – like those that allow for hearing – provide information about an animal’s physical, biological, and social environments, in both air and water. Extensive work has been done to understand the structures, mechanisms, and functions of animal sensory systems in aquatic environments (Atema et al. 1988; Kapoor and Hara 2001; Collin and Marshall 2003). All fish species have hearing and skin-based mechanosensory systems (inner ear and lateral line systems, respectively) that provide information about their surroundings (Fay and Popper 2000). Fay (2009) and some others refer to the ambient sounds to which fishes are exposed as ‘underwater soundscapes’. Anthropogenic sounds can have important negative consequences for fish survival and reproduction if they disrupt an individual’s ability to sense its soundscape, which often tells of predation risk, prey items, or mating opportunities. Potential negative effects include masking of key environmental sounds or social signals, displacement of fish from their habitat, or interference with sensory orientation and navigation.

Fish hearing via the inner ear is typically restricted to low frequencies. As with other vertebrates, fish hearing involves a mechanism whereby the beds of hair cells (Howard et al. 1988; Hudspeth and Markin 1994) located in the inner ear are mechanically affected and cause a neural discharge (Popper and Fay 1999). At least two major pathways for sound transmittance between sound source and the inner ear have been identified for fishes. The most primitive pathway involves direct transmission to the inner ear’s otolith, a calcium carbonate mass enveloped by sensory hairs. The inertial difference between the dense otolith and the less-dense inner ear causes the otolith to stimulate the surrounding sensory hair cells. This motion differential is interpreted by the central nervous system as sound.

The second transmission pathway between sound source and the inner ear of fishes is via the swim bladder, a gas-filled structure that is much less dense than the rest of the fish’s body. The swim bladder, being more compressible and expandable than either water or fish tissue, will differentially contract and

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expand relative to the rest of the fish in a sound field. The pulsating swim bladder transmits this mechanical disturbance directly to the inner ear (discussed below). Such a secondary source of sound detection may be more or less effective at stimulating the inner ear depending on the amplitude and frequency of the pulsation, and the distance and mechanical coupling between the swim bladder and the inner ear (Popper and Fay 1993).

A recent paper by Popper and Fay (2010) discusses the designation of fishes based on sound detection capabilities. They suggest that the designations ‘hearing specialist’ and ‘hearing generalist’ no longer be used for fishes because of their vague and sometimes contradictory definitions, and that there is instead 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.

According to Popper and Fay (2010), one end of this continuum is represented by fishes that only detect particle motion because they lack pressure-sensitive gas bubbles (e.g., swim bladder). These species include elasmobranchs (e.g., sharks) and jawless fishes, and some teleosts including flatfishes. Fishes at this end of the continuum are typically capable of detecting sound frequencies below 1500 Hz.

The other end of the fish hearing continuum is represented by fishes with highly specialized otophysical connections between pressure receptive organs, such as the swim bladder, and the inner ear. These fishes include some squirrelfish, mormyrids, herrings, and otophysan fishes (freshwater fishes with Weberian apparatus, an articulated series of small bones that extend from the swim bladder to the inner ear). Rather than being limited to 1.5 kHz or less in hearing, these fishes can typically hear up to several kHz. One group of fish in the anadromous herring sub-family Alosinae (shads and menhaden) can detect sounds to well over 180 kHz (Mann et al. 1997, 1998, 2001). This may be the widest hearing range of any vertebrate that has been studied to date. While the specific reason for this very high frequency hearing is not totally clear, there is strong evidence that this capability evolved for the detection of the ultrasonic sounds produced by echolocating dolphins to enable the fish to detect, and avoid, predation (Mann et al. 1997; Plachta and Popper 2003).

All other fishes have hearing capabilities that fall somewhere between these two extremes of the continuum. Some have unconnected swim bladders located relatively far from the inner ear (e.g., salmonids, tuna) while others have unconnected swim bladders located relatively close to the inner ear (e.g., Atlantic cod, *Gadus morhua*). There has also been the suggestion that Atlantic cod can detect 38 kHz (Astrup and Møhl 1993). However, the general consensus was that this was not hearing with the ear; probably the fish were responding to exceedingly high pressure signals from the 38-kHz source through some other receptor in the skin, such as touch receptors (Astrup and Møhl 1998).

It is important to recognize that the swim bladder itself is not a sensory end organ, but rather an intermediate part of the sound pathway between sound source and the inner ear of some fishes. The inner ear of fishes is ultimately the organ that translates the particle displacement component into neural signals for the brain to interpret as sound.

A third mechanosensory pathway found in most bony fishes and elasmobranchs (i.e., cartilaginous fishes) involves the lateral line system. It too relies on sensitivity to water particle motion. The basic sensory unit of the lateral line system is the neuromast, a bundle of sensory and supporting cells whose projecting cilia, similar to those in the ears, are encased in a gelatinous cap. Neuromasts detect distorted sound waves in the immediate vicinity of fishes. Generally, fishes use the lateral line system to detect the particle displacement component of low frequency acoustic signals (up to 160 to 200 Hz) over a distance of one to two body lengths. The lateral line is used in conjunction with other sensory systems, including hearing (Sand 1981; Coombs and Montgomery 1999).

2. Potential Effects on Fishes

Review papers on the effects of anthropogenic sources of underwater sound on fishes have been published recently (Popper 2009; Popper and Hastings 2009a,b). These papers consider various sources of anthropogenic sound, including seismic airguns. For the purposes of this review, only the effects of seismic airgun sound are considered.

2.1 Marine Fishes

Evidence for airgun-induced damage to fish ears has come from studies using pink snapper *Pagrus auratus* (McCauley et al. 2000a,b, 2003). In these experiments, fish were caged and exposed to the sound of a single moving seismic airgun every 10 s over a period of 1 h and 41 min. The source SPL at 1 m was about 223 dB re 1 $\mu\text{Pa} \cdot \text{m}_{\text{p-p}}$, and the received SPLs ranged from 165 to 209 dB re 1 $\mu\text{Pa}_{\text{p-p}}$. The sound energy was highest over the 20–70 Hz frequency range. 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 h 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) airgun exposure specifics required to cause the observed damage were not obtained (i.e., a few high SPL signals or the cumulative effect of many low to moderate SPL signals).

The fish exposed to sound from a single airgun in this study also exhibited startle responses to short range start up and high-level airgun signals (i.e., with received SPLs of 182 to 195 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (McCauley et al. 2000a,b). Smaller fish were more likely to display a startle response. Responses were observed above received SPLs of 156 to 161 dB re 1 $\mu\text{Pa}_{\text{rms}}$. The occurrence of both startle response (classic C-turn response) and alarm responses (e.g., darting movements, flash school expansion, fast swimming) decreased over time. Other observations included downward distributional shift that was restricted by the 10 m x 6 m x 3 m cages, increase in swimming speed, and the formation of denser aggregations. Fish behavior appeared to return to pre-exposure state 15–30 min after cessation of seismic firing.

Pearson et al. (1992) investigated the effects of seismic airgun sound on the behavior of captive rockfishes (*Sebastes* sp.) exposed to the sound of a single stationary airgun at a variety of distances. The airgun used in the study had a source SPL at 1 m of 223 dB re 1 $\mu\text{Pa} \cdot \text{m}_{0\text{-p}}$, and measured received SPLs ranged from 137 to 206 dB re 1 $\mu\text{Pa}_{0\text{-p}}$. The authors reported that rockfishes reacted to the airgun sounds by exhibiting varying degrees of startle and alarm responses, depending on the species of rockfish and the received SPL. Startle responses were observed at a minimum received SPL of 200 dB re 1 $\mu\text{Pa}_{0\text{-p}}$, and alarm responses occurred at a minimum received SPL of 177 dB re 1 $\mu\text{Pa}_{0\text{-p}}$. Other observed behavioral changes included the tightening of schools, downward distributional shift, and random movement and orientation. Some fishes ascended in the water column and commenced to mill (i.e., “eddy”) at increased speed, while others descended to the bottom of the enclosure and remained motionless. Pre-exposure behavior was reestablished from 20 to 60 min after cessation of seismic airgun discharge. Pearson et al. (1992) concluded that received SPL thresholds for overt rockfish behavioral response and more subtle rockfish behavioral response are 180 dB re 1 $\mu\text{Pa}_{0\text{-p}}$ and 161 dB re 1 $\mu\text{Pa}_{0\text{-p}}$, respectively.

Using an experimental hook and line fishery approach, Skalski et al. (1992) studied the potential effects of seismic airgun sound on the distribution and catchability of rockfishes. The source SPL of the single airgun used in the study was 223 dB re $1 \mu\text{Pa} \cdot \text{m}_{0-p}$, and the received SPLs at the bases of the rockfish aggregations ranged from 186 to 191 dB re $1 \mu\text{Pa}_{0-p}$. Characteristics of the fish aggregations were assessed using echosounders. During long-term stationary seismic airgun discharge, there was an overall downward shift in fish distribution. The authors also observed a significant decline in total catch of rockfishes during seismic discharge. It should be noted that this experimental approach was quite different from an actual seismic survey, in that duration of exposure was much longer.

In another study, caged European sea bass (*Dicentrarchus labrax*) were exposed to multiple discharges from a moving seismic airgun array with a source SPL of about 256 dB re $1 \mu\text{Pa} \cdot \text{m}_{0-p}$ (unspecified measure type) (Santulli et al. 1999). The airguns were discharged every 25 s during a 2-h period. The minimum distance between fish and seismic source was 180 m. The authors did not indicate any observed pathological injury to the sea bass. Blood was collected from both exposed fish (6 h post-exposure) and control fish (6 h pre-exposure) and subsequently analyzed for cortisol, glucose, and lactate levels. Levels of cortisol, glucose, and lactate were significantly higher in the sera of exposed fish compared to sera of control fish. The elevated levels of all three chemicals returned to pre-exposure levels within 72 h of exposure (Santulli et al. 1999).

Santulli et al. (1999) also used underwater video cameras to monitor fish response to seismic airgun discharge. Resultant video indicated slight startle responses by some of the sea bass when the seismic airgun array discharged as far as 2.5 km from the cage. The proportion of sea bass that exhibited startle response increased as the airgun sound source approached the cage. Once the seismic array was within 180 m of the cage, the sea bass were densely packed at the middle of the enclosure, exhibiting random orientation, and appearing more active than they had been under pre-exposure conditions. Normal behavior resumed about 2 h after airgun discharge nearest the fish (Santulli et al. 1999).

Boeger et al. (2006) reported observations of coral reef fishes in field enclosures before, during and after exposure to seismic airgun sound. This Brazilian study used an array of eight airguns that was presented to the fishes as both a mobile sound source and a static sound source. Minimum distances between the sound source and the fish cage ranged from 0 to 7 m. Received sound levels were not reported by Boeger et al. (2006). Neither mortality nor external damage to the fishes was observed in any of the experimental scenarios. Most of the airgun array discharges resulted in startle responses although these behavioral changes lessened with repeated exposures, suggesting habituation.

Chapman and Hawkins (1969) investigated the reactions of free ranging whiting (silver hake), *Merluccius bilinearis*, to an intermittently discharging stationary airgun with a source SPL of 220 dB re $1 \mu\text{Pa} \cdot \text{m}_{0-p}$. Received SPLs were estimated to be 178 dB re $1 \mu\text{Pa}_{0-p}$. The whiting were monitored with an echosounder. Prior to any airgun discharge, the fish were located at a depth range of 25 to 55 m. In apparent response to the airgun sound, the fish descended, forming a compact layer at depths greater than 55 m. After an hour of exposure to the airgun sound, the fish appeared to have habituated as indicated by their return to the pre-exposure depth range, despite the continuing airgun discharge. Airgun discharge ceased for a time and upon its resumption, the fish again descended to greater depths, indicating only temporary habituation.

Hassel et al. (2003, 2004) studied the potential effects of exposure to airgun sound on the behavior of captive lesser sandeel, *Ammodytes marinus*. Depth of the study enclosure used to hold the sandeel was about 55 m. The moving airgun array had an estimated source SPL of 256 dB re $1 \mu\text{Pa} \cdot \text{m}$ (unspecified measure type). Received SPLs were not measured. Exposures were conducted over a 3-day period in a

10 km × 10 km area with the cage at its center. The distance between airgun array and fish cage ranged from 55 m when the array was overhead to 7.5 km. No mortality attributable to exposure to the airgun sound was noted. Behavior of the fish was monitored using underwater video cameras, echosounders, and commercial fishery data collected close to the study area. The approach of the seismic vessel appeared to cause an increase in tail-beat frequency although the sandeels still appeared to swim calmly. During seismic airgun discharge, many fish exhibited startle responses, followed by flight from the immediate area. The frequency of occurrence of startle response seemed to increase as the operating seismic array moved closer to the fish. The sandeels stopped exhibiting the startle response once the airgun discharge ceased. The sandeel tended to remain higher in the water column during the airgun discharge, and none of them were observed burying themselves in the soft substrate. The commercial fishery catch data were inconclusive with respect to behavioral effects.

Various species of demersal fishes, blue whiting, and some small pelagic fishes were exposed to a moving seismic airgun array with a source SPL of about 250 dB re 1 $\mu\text{Pa} \cdot \text{m}$ (unspecified measure type) (Dalen and Knutsen 1986). Received SPLs estimated using the assumption of spherical spreading ranged from 200 to 210 dB re 1 μPa (unspecified measure type). Seismic sound exposures were conducted every 10 s during a one week period. The authors used echosounders and sonars to assess the pre- and post-exposure fish distributions. The acoustic mapping results indicated a significant decrease in abundance of demersal fish (36%) after airgun discharge but comparative trawl catches did not support this. Non-significant reductions in the abundances of blue whiting and small pelagic fish were also indicated by post-exposure acoustic mapping.

La Bella et al. (1996) studied the effects of exposure to seismic airgun sound on fish distribution using echosounder monitoring and changes in catch rate of hake by trawl, and clupeoids by gill netting. The seismic array used was composed of 16 airguns and had a source SPL of 256 dB re 1 $\mu\text{Pa} \cdot \text{m}_{0-p}$. The shot interval was 25 s, and exposure durations ranged from 4.6 to 12 h. Horizontal distributions did not appear to change as a result of exposure to seismic discharge, but there was some indication of a downward shift in the vertical distribution. The catch rates during experimental fishing did not differ significantly between pre- and post-seismic fishing periods.

Wardle et al. (2001) used video and telemetry to make behavioral observations of marine fishes (primarily juvenile saithe, adult pollock, juvenile cod, and adult mackerel) inhabiting an inshore reef off Scotland before, during, and after exposure to discharges of a stationary airgun. The received SPLs ranged from about 195 to 218 dB re 1 μPa_{0-p} . Pollock did not move away from the reef in response to the seismic airgun sound, and their diurnal rhythm did not appear to be affected. However, there was an indication of a slight effect on the long-term day-to-night movements of the pollock. Video camera observations indicated that fish exhibited startle responses (“C-starts”) to all received levels. There were also indications of behavioral responses to visual stimuli. If the seismic source was visible to the fish, they fled from it. However, if the source was not visible to the fish, they often continued to move toward it.

The potential effects of exposure to seismic sound on fish abundance and distribution were also investigated by Slotte et al. (2004). Twelve days of seismic survey operations spread over a period of 1 month used a seismic airgun array with a source SPL of 222.6 dB re 1 $\mu\text{Pa} \cdot \text{m}_{p-p}$. The SPLs received by the fish were not measured. Acoustic surveys of the local distributions of various kinds of pelagic fish, including herring, blue whiting, and mesopelagic species, were conducted during the seismic surveys. There was no strong evidence of short-term horizontal distributional effects. With respect to vertical distribution, blue whiting and mesopelagics were distributed deeper (20 to 50 m) during the seismic

survey compared to pre-exposure. The average densities of fish aggregations were lower within the seismic survey area, and fish abundances appeared to increase in accordance with increasing distance from the seismic survey area.

Fertilized capelin (*Mallotus villosus*) eggs and monkfish (*Lophius americanus*) larvae were exposed to seismic airgun sound and subsequently examined and monitored for possible effects of the exposure (Payne et al. 2009). The laboratory exposure studies involved a single airgun. Approximate received SPLs measured in the capelin egg and monkfish larvae exposures were 199 to 205 dB re 1 μPa_{p-p} and 205 dB re 1 μPa_{p-p} , respectively. The capelin eggs were exposed to either 10 or 20 airgun discharges, and the monkfish larvae were exposed to either 10 or 30 discharges. No statistical differences in mortality/morbidity between control and exposed subjects were found at 1 to 4 days post-exposure in any of the exposure trials for either the capelin eggs or the monkfish larvae.

In uncontrolled experiments, Kostyvchenko (1973) exposed the eggs of numerous fish species (anchovy, red mullet, crucian carp, blue runner) to various sound sources, including seismic airguns. With the seismic airgun discharge as close as 0.5 m from the eggs, over 75% of them survived the exposure. Egg survival rate increased to over 90% when placed 10 m from the airgun sound source. The range of received SPLs was about 215 to 233 dB re 1 μPa_{0-p} .

Eggs, yolk sac larvae, post-yolk sac larvae, post-larvae, and fry of various commercially important fish species (cod, saithe, herring, turbot, and plaice) were exposed to received SPLs ranging from 220 to 242 dB re 1 μPa (unspecified measure type) (Booman et al. 1996). These received levels corresponded to exposure distances ranging from 0.75 to 6 m. The authors reported some cases of injury and mortality but most of these occurred as a result of exposures at very close range (i.e., <15 m). The rigor of anatomical and pathological assessments was questionable.

Saetre and Ona (1996) applied a “worst-case scenario” mathematical model to investigate the effects of seismic sound on fish eggs and larvae. They concluded that mortality rates caused by exposure to seismic airgun sound are so low compared to the natural mortality that the impact of seismic surveying on recruitment to a fish stock must be regarded as insignificant.

2.2 Freshwater Fishes

Popper et al. (2005) tested the hearing sensitivity of three Mackenzie River fish species after exposure to five discharges from a seismic airgun. The mean received peak SPL was 205 to 209 dB re 1 μPa per discharge, and the approximate mean received SEL was 176 to 180 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ per discharge. While the broad whitefish showed no Temporary Threshold Shift (TTS) as a result of the exposure, adult northern pike and lake chub exhibited TTSs of 10–15 dB, followed by complete recovery within 24 h of exposure. 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.

In another part of the same Mackenzie River project, Jorgenson and Gyselman (2009) investigated the behavioral responses of arctic riverine fishes to seismic airgun sound. They used hydroacoustic survey techniques to determine whether fish behavior upon exposure to airgun sound can either mitigate or enhance the potential impact of the sound. The study indicated that fish behavioral characteristics were generally unchanged by the exposure to airgun sound. The tracked fish did not exhibit herding behavior in front of the mobile airgun array and, therefore, were not exposed to sustained high sound levels.

2.3 Anadromous Fishes

In uncontrolled experiments using a very small sample of different groups of young salmonids, including Arctic cisco, fish were caged and exposed to various types of sound. One sound type was either a single firing or a series of four firings 10 to 15 s apart of a 300-in³ seismic airgun at 2000 to 2200 psi (Falk and Lawrence 1973). Swim bladder damage was reported but no mortality was observed when fish were exposed within 1 to 2 m of an airgun source with source level, as estimated by Turnpenny and Nedwell (1994), of ~230 dB re 1 $\mu\text{Pa}\cdot\text{m}$ (unspecified measure).

Thomsen (2002) exposed rainbow trout and Atlantic salmon held in aquaculture enclosures to the sounds from a small airgun array. Received SPLs were 142 to 186 dB re 1 $\mu\text{Pa}_{\text{p-p}}$. The fish were exposed to 124 pulses over a 3-day period. In addition to monitoring fish behavior with underwater video cameras, the authors also analyzed cod and haddock catch data from a longline fishing vessel operating in the immediate area. Only eight of the 124 shots appeared to evoke behavioral reactions by the salmonids, but overall impacts were minimal. No fish mortality was observed during or immediately after exposure. The author reported no significant effects on cod and haddock catch rates, and the behavioral effects were hard to differentiate from normal behavior.

Weinhold and Weaver (1972, cited in Turnpenny et al. 1994) exposed caged coho salmon smolts to impulses from 330 and 660-in³ airguns at distances ranging from 1 to 10 m, resulting in received levels estimated at ~214 to 216 dB (units not given). No lethal effects were observed.

It should be noted that, in a recent and comprehensive review, Hastings and Popper (2005) take issue with many of the authors cited above for problems with experimental design and execution, measurements, and interpretation. Hastings and Popper (2005) deal primarily with possible effects of pile-driving sounds (which, like airgun sounds, are impulsive and repetitive). However, that review provides an excellent and critical review of the impacts to fish from other underwater anthropogenic sounds.

3. Indirect Effects on Fisheries

The most comprehensive experimentation on the effects of seismic airgun sound on catchability of fishes was conducted in the Barents Sea by Engås et al. (1993, 1996). They investigated the effects of seismic airgun sound on distributions, abundances, and catch rates of cod and haddock using acoustic mapping and experimental fishing with trawls and longlines. The maximum source SPL was about 248 dB re 1 $\mu\text{Pa}\cdot\text{m}_{0\text{-p}}$ based on back-calculations from measurements collected via a hydrophone at depth 80 m. No measurements of the received SPLs were made. Davis et al. (1998) estimated the received SPL at the sea bottom immediately below the array and at 18 km from the array to be 205 dB re 1 $\mu\text{Pa}_{0\text{-p}}$ and 178 dB re 1 $\mu\text{Pa}_{0\text{-p}}$, respectively. Engås et al. (1993, 1996) concluded that there were indications of distributional change during and immediately following the seismic airgun discharge (45 to 64% decrease in acoustic density according to sonar data). The lowest densities were observed within 9.3 km of the seismic discharge area. The authors indicated that trawl catches of both cod and haddock declined after the seismic operations. While longline catches of haddock also showed decline after seismic airgun discharge, those for cod increased.

Løkkeborg (1991), Løkkeborg and Soldal (1993), and Dalen and Knutsen (1986) also examined the effects of seismic airgun sound on demersal fish catches. Løkkeborg (1991) examined the effects on cod catches. The source SPL of the airgun array used in his study was 239 dB re 1 $\mu\text{Pa}\cdot\text{m}$ (unspecified measure type), but received SPLs were not measured. Approximately 43 h of seismic airgun discharge occurred during an 11-day period, with a five-second interval between pulses. Catch rate decreases

ranging from 55 to 80% within the seismic survey area were observed. This apparent effect persisted for at least 24 h within about 10 km of the survey area.

Turnpenny et al. (1994) examined results of these studies as well as the results of other studies on rockfish. They used rough estimations of received SPLs at catch locations and concluded that catchability is reduced when received SPLs exceed 160 to 180 dB re 1 μPa_{0-p} . They also concluded that reaction thresholds of fishes lacking a swim bladder (e.g., flatfish) would likely be about 20 dB higher. Given the considerable variability in sound transmission loss between different geographic locations, the SPLs that were assumed in these studies were likely quite inaccurate.

Turnpenny and Nedwell (1994) also reported on the effects of seismic airgun discharge on inshore bass fisheries in shallow U.K. waters (5 to 30 m deep). The airgun array used had a source level of 250 dB re 1 $\mu\text{Pa} \cdot \text{m}_{0-p}$. Received levels in the fishing areas were estimated to be 163–191 dB re 1 μPa_{0-p} . Using fish tagging and catch record methodologies, they concluded that there was not any distinguishable migration from the ensonified area, nor was there any reduction in bass catches on days when seismic airguns were discharged. The authors concluded that effects on fisheries would be smaller in shallow nearshore waters than in deep water because attenuation of sound is more rapid in shallow water.

Skalski et al. (1992) used a 100-in³ airgun with a source level of 223 dB re 1 $\mu\text{Pa} \cdot \text{m}_{0-p}$ to examine the potential effects of airgun sound on the catchability of rockfishes. The moving airgun was discharged along transects in the study fishing area, after which a fishing vessel deployed a set line, ran three echosounder transects, and then deployed two more set lines. Each fishing experiment lasted 1 h 25 min. Received SPLs at the base of the rockfish aggregations ranged from 186 to 191 dB re 1 μPa_{0-p} . The catch-per-unit-effort (CPUE) for rockfish declined on average by 52.4% when the airguns were operating. Skalski et al. (1992) believed that the reduction in catch resulted from a change in behavior of the fishes. The fish schools descended towards the bottom and their swimming behavior changed during airgun discharge. Although fish dispersal was not observed, the authors hypothesized that it could have occurred at a different location with a different bottom type. Skalski et al. (1992) did not continue fishing after cessation of airgun discharge. They speculated that CPUE would quickly return to normal in the experimental area, because fish behavior appeared to normalize within minutes of cessation of airgun discharge. However, in an area where exposure to airgun sound might have caused the fish to disperse, the authors suggested that a lower CPUE might persist for a longer period.

European sea bass were exposed to sound from seismic airgun arrays with a source SPL of 262 dB re 1 $\mu\text{Pa} \cdot \text{m}_{0-p}$ (Pickett et al. 1994). The seismic survey was conducted over a period of 4 to 5 months. The study was intended to investigate the effects of seismic airgun discharge on inshore bass fisheries. Information was collected through a tag and release program, and from the logbooks of commercial fishermen. Most of the 152 recovered fish from the tagging program were caught within 10 km of the release site, and it was suggested that most of these bass did not leave the area for a prolonged period. With respect to the commercial fishery, no significant changes in catch rate were observed (Pickett et al. 1994).

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APPENDIX D: REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES¹²

This review provides a detailed summary of the limited data and available literature on the observed effects (or lack of effects) of exposure to airgun sound on marine invertebrates. Specific conditions and results of the studies, including sound exposure levels and sound thresholds of responses, are discussed when available.

Sound caused by underwater seismic survey equipment results in energy pulses with very high peak pressures (Richardson et al. 1995). This was especially true when chemical explosives were used for underwater surveys. Virtually all underwater seismic surveying conducted today uses airguns which typically have lower peak pressures and longer rise times than chemical explosives. However, sound levels from underwater airgun discharges might still be high enough to potentially injure or kill animals located close to the source. Also, there is a potential for disturbance to normal behavior upon exposure to airgun sound. The following sections provide an overview of sound production and detection in marine invertebrates, and information on the effects of exposure to sound on marine invertebrates, with an emphasis on seismic survey sound. In addition, Fisheries and Oceans Canada has published two internal documents that provide a literature review of the effects of seismic and other underwater sound on invertebrates (Moriyasu et al. 2004; Payne et al. 2008). The available information as reviewed in those documents and here includes results of studies of varying degrees of scientific rigor as well as anecdotal information.

Sound Production

Much of the available information on acoustic abilities of marine invertebrates pertains to crustaceans, specifically lobsters, crabs and shrimps. Other acoustic-related studies have been conducted on cephalopods. Many invertebrates are capable of producing sound, including barnacles, amphipods, shrimp, crabs, and lobsters (Au and Banks 1998; Tolstoganova 2002). Invertebrates typically produce sound by scraping or rubbing various parts of their bodies, although they also produce sound in other ways. Sounds made by marine invertebrates may be associated with territorial behavior, mating, courtship, and aggression. On the other hand, some of these sounds may be incidental and not have any biological relevance. Sounds known to be produced by marine invertebrates have frequencies ranging from 87 Hz to 200 kHz, depending on the species.

Both male and female American lobsters *Homarus americanus* produce a buzzing vibration with the carapace when grasped (Pye and Watson III 2004; Henninger and Watson III 2005). Larger lobsters vibrate more consistently than smaller lobsters, suggesting that sound production may be involved with mating behavior. Sound production by other species of lobsters has also been studied. Among deep-sea lobsters, sound level was more variable at night than during the day, with the highest levels occurring at the lowest frequencies.

While feeding, king crab *Paralithodes camtschaticus* produce impulsive sounds that appear to stimulate movement by other crabs, including approach behavior (Tolstoganova 2002). King crab also appeared to produce 'discomfort' sounds when environmental conditions were manipulated. These discomfort sounds differ from the feeding sounds in terms of frequency range and pulse duration.

¹² By **John R. Christian**, LGL Ltd., environmental research associates (revised Nov. 2009).

Snapping shrimp *Synalpheus parneomeris* are among the major sources of biological sound in temperate and tropical shallow-water areas (Au and Banks 1998). By rapidly closing one of its frontal chelae (claws), a snapping shrimp generates a forward jet of water and the cavitation of fast moving water produces a sound. Both the sound and the jet of water may function in feeding and territorial behaviors of alpheididae shrimp. Measured source sound pressure levels (SPLs) for snapping shrimp were 183–189 dB re $1 \mu\text{Pa} \cdot \text{m}_{\text{p-p}}$ and extended over a frequency range of 2–200 kHz.

Sound Detection

There is considerable debate about the hearing capabilities of aquatic invertebrates. Whether they are able to hear or not depends on how underwater sound and underwater hearing are defined. In contrast to the situation in fish and marine mammals, no physical structures have been discovered in aquatic invertebrates that are stimulated by the pressure component of sound. However, vibrations (i.e., mechanical disturbances of the water) are also characteristic of sound waves. Rather than being pressure-sensitive, aquatic invertebrates appear to be most sensitive to the vibrational component of sound (Breithaupt 2002). Statocyst organs may provide one means of vibration detection for aquatic invertebrates.

More is known about the acoustic detection capabilities in decapod crustaceans than in any other marine invertebrate group, although cephalopod acoustic capabilities are now becoming a focus of study. Crustaceans appear to be most sensitive to sounds of low frequencies, i.e., <1000 Hz (Budelmann 1992; Popper et al. 2001). A study by Lovell et al. (2005) suggests greater sensitivity of the prawn *Palaemon serratus* to low-frequency sound than previously thought. Lovell et al. (2006) showed that *P. serratus* is capable of detecting a 500 Hz tone regardless of the prawn's body size and the related number and size of statocyst hair cells. Studies of American lobsters suggest that these crustaceans are more sensitive to higher frequency sounds than previously realized (Pye and Watson III 2004).

It is possible that statocyst hair cells of cephalopods are directionally sensitive in a way that is similar to the responses of hair cells of the vertebrate vestibular and lateral line systems (Budelmann and Williamson 1994; Budelmann 1996). 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) and Komak et al. (2005) have tested the sensitivities of various cephalopods to water-borne vibrations, some of which were generated by low-frequency sound. Using the auditory brainstem response (ABR) approach, Hu et al. (2009) showed that auditory evoked potentials can be obtained in the frequency ranges 400 to 1500 Hz for the squid *Sepiotheutis lessoniana* and 400 to 1000 Hz for the octopus *Octopus vulgaris*, higher than frequencies previously observed to be detectable by cephalopods.

In summary, only a few studies have been conducted on the sensitivity of certain invertebrate species to underwater sound. Available data suggest that they are capable of detecting vibrations but they do not appear to be capable of detecting pressure fluctuations.

Potential Seismic Effects

In marine invertebrates, potential effects of exposure to sound can be categorized as pathological, physiological, and behavioral. Pathological effects include lethal and sub-lethal injury to the animals, physiological effects include temporary primary and secondary stress responses, and behavioral effects refer to changes in exhibited behaviors (i.e., disturbance). The three categories should not be considered as independent of one another and are likely interrelated in complex ways.

Pathological Effects.—In water, acute injury or death of organisms as a result of exposure to sound appears to depend on two features of the sound source: (1) the received peak pressure, and (2) the time required for the pressure to rise and decay. Generally, the higher the received pressure and the less time it takes for the pressure to rise and decay, the greater the chance of acute pathological effects. Considering the peak pressure and rise/decay time characteristics of seismic airgun arrays used today, the associated pathological zone for invertebrates would be expected to be small (i.e., within a few meters of the seismic source, at most). Few studies have assessed the potential for pathological effects on invertebrates from exposure to seismic sound.

The pathological impacts of seismic survey sound on marine invertebrates were investigated in a pilot study on snow crabs *Chionoecetes opilio* (Christian et al. 2003, 2004). Under controlled field experimental conditions, captive adult male snow crabs, egg-carrying female snow crabs, and fertilized snow crab eggs were exposed to variable SPLs (191–221 dB re 1 μPa_{0-p}) and sound energy levels (SELs) (<130–187 dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$). Neither acute nor chronic (12 weeks post-exposure) mortality was observed for the adult crabs. However, a significant difference in development rate was noted between the exposed and unexposed fertilized eggs/embryos. The egg mass exposed to seismic energy had a higher proportion of less-developed eggs than did the unexposed mass. It should be noted that both egg masses came from a single female and any measure of natural variability was unattainable (Christian et al. 2003, 2004).

In 2003, a collaborative study was conducted in the southern Gulf of St. Lawrence, Canada, to investigate the effects of exposure to sound from a commercial seismic survey on egg-bearing female snow crabs (DFO 2004). This study had design problems that impacted interpretation of some of the results (Chadwick 2004). Caged animals were placed on the ocean bottom at a location within the survey area and at a location outside of the survey area. The maximum received SPL was ~195 dB re 1 μPa_{0-p} . The crabs were exposed for 132 hr of the survey, equivalent to thousands of seismic shots of varying received SPLs. The animals were retrieved and transferred to laboratories for analyses. Neither acute nor chronic lethal or sub-lethal injury to the female crabs or crab embryos was indicated. DFO (2004) reported that some exposed individuals had short-term soiling of gills, antennules and statocysts, bruising of the hepatopancreas and ovary, and detached outer membranes of oocytes. However, these differences could not be linked conclusively to exposure to seismic survey sound. Boudreau et al. (2009) presented the proceedings of a workshop held to evaluate the results of additional studies conducted to answer some questions arising from the original study discussed in DFO (2004). Proceedings of the workshop did not include any more definitive conclusions regarding the original results.

Payne et al. (2007) recently conducted a pilot study of the effects of exposure to airgun sound on various health endpoints of the American lobster. Adult lobsters were exposed either 20 to 200 times to 202 dB re 1 μPa_{p-p} or 50 times to 227 dB re 1 μPa_{p-p} , and then monitored for changes in survival, food consumption, turnover rate, serum protein level, serum enzyme levels, and serum calcium level. Observations extended over a period of a few days to several months. Results showed no delayed mortality or damage to the mechanosensory systems associated with animal equilibrium and posture (as assessed by turnover rate).

In a field study, Pearson et al. (1994) exposed Stage II larvae of the Dungeness crab *Cancer magister* to single discharges from a seven-airgun array and compared their mortality and development rates with those of unexposed larvae. No statistically significant differences were found in immediate survival, long-term survival, or time to molt between the exposed and unexposed larvae, even those exposed within 1 m of the seismic source.

In 2001 and 2003, there were two incidents of multiple strandings of the giant squid *Architeuthis dux* on the north coast of Spain, and there was speculation that the strandings were caused by exposure to geophysical seismic survey sounds occurring at about the same time in the Bay of Biscay (Guerra et al. 2004). A total of nine giant squid, either stranded or moribund and floating at the surface, were collected at these times. However, Guerra et al. (2004) did not present any evidence that conclusively links the giant squid strandings and floaters to seismic activity in the area. Based on necropsies of seven (six females and one male) specimens, there was evidence of acute tissue damage. The authors speculated that one female with extensive tissue damage was affected by the impact of acoustic waves. However, little is known about the impact of strong airgun signals on cephalopods and the authors did not describe the seismic sources, locations, and durations of the Bay of Biscay surveys. In addition, there were no controls, the observations were circumstantial, and the examined animals had been dead long enough for commencement of tissue degradation.

McCauley et al. (2000a,b) exposed caged cephalopods to noise from a single 20-in³ airgun with maximum SPLs of >200 dB re 1 μPa_{0-p} . Statocysts were removed and preserved, but at the time of publication, results of the statocyst analyses were not available. No squid or cuttlefish mortalities were reported as a result of these exposures.

Physiological Effects.—Biochemical responses by marine invertebrates to acoustic exposure have also been studied to a limited degree. Such studies of stress responses could possibly provide some indication of the physiological consequences of acoustic exposure and perhaps any subsequent chronic detrimental effects. Stress responses could potentially affect animal populations by reducing reproductive capacity and adult abundance.

Stress indicators in the haemolymph of adult male snow crabs were monitored immediately after exposure of the animals to seismic survey sound (Christian et al. 2003, 2004) and at various intervals after exposure. No significant acute or chronic differences were found between exposed and unexposed animals in which various stress indicators (e.g., proteins, enzymes, cell type count) were measured.

Payne et al. (2007), in their study of the effects of exposure of adult American lobsters to airgun sound, noted decreases in the levels of serum protein, particular serum enzymes and serum calcium, in the haemolymph of animals exposed to the sound pulses. Statistically significant differences ($P=0.05$) were noted in serum protein at 12 days post-exposure, serum enzymes at 5 days post-exposure, and serum calcium at 12 days post-exposure. During the histological analysis conducted 4 months post-exposure, Payne et al. (2007) noted more deposits of PAS-stained material, likely glycogen, in the hepatopancreas of some of the exposed lobsters. Accumulation of glycogen could be due to stress or disturbance of cellular processes.

Price (2007) found that blue mussels *Mytilus edulis* responded to a 10 kHz pure tone continuous signal by decreasing respiration. Smaller mussels did not appear to react until exposed for 30 min whereas larger mussels responded after 10 min of exposure. The oxygen uptake rate tended to be reduced to a greater degree in the larger mussels than in the smaller animals.

In general, the limited studies done to date on the effects of acoustic exposure on marine invertebrates have not demonstrated any serious pathological and physiological effects.

Behavioral Effects.—Some recent studies have focused on potential behavioral effects on marine invertebrates.

Christian et al. (2003) investigated the behavioral effects of exposure to airgun sound on snow crabs. Eight animals were equipped with ultrasonic tags, released, and monitored for multiple days prior to exposure and after exposure. Received SPL and SEL were ~ 191 dB re $1 \mu\text{Pa}_{0-p}$ and <130 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$, respectively. The crabs were exposed to 200 discharges over a 33-min period. None of the tagged animals left the immediate area after exposure to the seismic survey sound. Five animals were captured in the snow crab commercial fishery the following year, one at the release location, one 35 km from the release location, and three at intermediate distances from the release location.

Another study approach used by Christian et al. (2003) involved monitoring snow crabs with a remote video camera during their exposure to airgun sound. The caged animals were placed on the ocean bottom at a depth of 50 m. Received SPL and SEL were ~ 202 dB re $1 \mu\text{Pa}_{0-p}$ and 150 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$, respectively. The crabs were exposed to 200 discharges over a 33-min period. They did not exhibit any overt startle response during the exposure period.

Christian et al. (2003) also investigated the pre- and post-exposure catchability of snow crabs during a commercial fishery. Received SPLs and SELs were not measured directly and likely ranged widely considering the area fished. Maximum SPL and SEL were likely similar to those measured during the telemetry study. There were seven pre-exposure and six post-exposure trap sets. Unfortunately, there was considerable variability in set duration because of poor weather. Results indicated that the catch-per-unit-effort did not decrease after the crabs were exposed to seismic survey sound.

Parry and Gason (2006) statistically analyzed data related to rock lobster *Jasus edwardsii* commercial catches and seismic surveying in Australian waters from 1978 to 2004. They did not find any evidence that lobster catch rates were affected by seismic surveys.

Caged female snow crabs exposed to airgun sound associated with a recent commercial seismic survey conducted in the southern Gulf of St. Lawrence, Canada, exhibited a higher rate of ‘righting’ than those crabs not exposed to seismic survey sound (J. Payne, Research Scientist, DFO, St. John’s, Nfld., pers. comm.). ‘Righting’ refers to a crab’s ability to return itself to an upright position after being placed on its back. Christian et al. (2003) made the same observation in their study.

Payne et al. (2007), in their study of the effects of exposure to airgun sound on adult American lobsters, noted a trend for increased food consumption by the animals exposed to seismic sound.

Andriquetto-Filho et al. (2005) attempted to evaluate the impact of seismic survey sound on artisanal shrimp fisheries off Brazil. Bottom trawl yields were measured before and after multiple-day shooting of an airgun array. Water depth in the experimental area ranged between 2 and 15 m. Results of the study did not indicate any significant deleterious impact on shrimp catches. Anecdotal information from Newfoundland, Canada, indicated that catch rates of snow crabs showed a significant reduction immediately following a pass by a seismic survey vessel (G. Chidley, Newfoundland fisherman, pers. comm.). Additional anecdotal information from Newfoundland indicated that a school of shrimp observed via a fishing vessel sonar shifted downwards and away from a nearby seismic airgun sound source (H. Thorne, Newfoundland fisherman, pers. comm.). This observed effect was temporary.

Caged brown shrimp *Crangon crangon* reared under different acoustical conditions exhibited differences in aggressive behavior and feeding rate (Lagardère 1982). Those exposed to a continuous sound source showed more aggression and less feeding behavior. It should be noted that behavioral responses by caged animals may differ from behavioral responses of animals in the wild.

McCauley et al. (2000a,b) provided the first evidence of the behavioral response of southern calamari squid *Sepioteuthis australis* exposed to seismic survey sound. McCauley et al. reported on the

exposure of caged cephalopods (50 squid and two cuttlefish) to noise from a single 20-in³ airgun. The cephalopods were exposed to both stationary and mobile sound sources. The two-run total exposure times during the three trials ranged from 69 to 119 min. at a firing rate of once every 10–15 s. The maximum SPL was >200 dB re 1 μPa_{0-p} . Some of the squid fired their ink sacs apparently in response to the first shot of one of the trials and then moved quickly away from the airgun. In addition to the above-described startle responses, some squid also moved towards the water surface as the airgun approached. McCauley et al. (2000a,b) reported that the startle and avoidance responses occurred at a received SPL of 174 dB re 1 $\mu\text{Pa}_{\text{rms}}$. They also exposed squid to a ramped approach-depart airgun signal whereby the received SPL was gradually increased over time. No strong startle response (i.e., ink discharge) was observed, but alarm responses, including increased swimming speed and movement to the surface, were observed once the received SPL reached a level in the 156–161 dB re 1 $\mu\text{Pa}_{\text{rms}}$ range.

Komak et al. (2005) also reported the results of a study of cephalopod behavioral responses to local water movements. In this case, juvenile cuttlefish *Sepia officinalis* exhibited various behavioral responses to local sinusoidal water movements of different frequencies between 0.01 and 1000 Hz. These responses included body pattern changing, movement, burrowing, reorientation, and swimming. Similarly, the behavioral responses of the octopus *Octopus ocellatus* to non-impulse sound have been investigated by Kaifu et al. (2007). The sound stimuli, reported as having levels 120 dB re 1 $\mu\text{Pa}_{\text{rms}}$, were at various frequencies: 50, 100, 150, 200 and 1000 Hz. The respiratory activity of the octopus changed when exposed to sound in the 50–150 Hz range but not for sound at 200–1,000 Hz. Respiratory suppression by the octopus might have represented a means of escaping detection by a predator.

Low-frequency sound (<200 Hz) has also been used as a means of preventing settling/fouling by aquatic invertebrates such as zebra mussels *Dreissena polymorpha* (Donskoy and Ludyanskiy 1995) and balanoid barnacles *Balanus* sp. (Branscomb and Rittschof 1984). Price (2007) observed that blue mussels *Mytilus edulis* closed their valves upon exposure to 10 kHz pure tone continuous sound.

Although not demonstrated in the invertebrate literature, masking can be considered a potential effect of anthropogenic underwater sound on marine invertebrates. Some invertebrates are known to produce sounds (Au and Banks 1998; Tolstoganova 2002; Latha et al. 2005). The functionality and biological relevance of these sounds are not understood (Jeffs et al. 2003, 2005; Lovell et al. 2005; Radford et al. 2007). If some of the sounds are of biological significance to some invertebrates, then masking of those sounds or of sounds produced by predators, at least the particle displacement component, could potentially have adverse effects on marine invertebrates. However, even if masking does occur in some invertebrates, the intermittent nature of airgun sound is expected to result in less masking effect than would occur with continuous sound.

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