

APPENDIX 1:

CONSULTATION REPORT



MKI Southern Grand Banks Seismic Survey

Stakeholder Engagement Meeting- Environmental Assessment Table

Industry and Government Meetings

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
Environment Canada	Glen Troke	<p>MKI made contact with Environment Canada by phone on December 19, 2013.</p> <p>Follow-up emails were sent on December 20, 2013.</p> <p>Stakeholder indicated a face-to-face meeting was not necessary.</p>		
Fish Food and Allied Workers (FFAW) and One Ocean	<p>Johan Joensen, FFAW</p> <p>Robyn Saunders, FFAW</p> <p>Maureen Murphy, One Ocean</p>	<p>MKI made contact with FFAW by phone on January 3, 2014.</p> <p>Follow-up phone calls were made on January 9, 2014.</p> <p>A face-to-face discussion between MKI and FFAW representatives was conducted on January 22, 2014. A general overview of the project and information package was provided.</p>	<p>Meeting participants requested to identify how close the seismic survey is to the Azores.</p> <p>Meeting participants requested communication and updates on community consultations when they are occurring.</p> <p>Meeting participants requested electronic copies of the Information and information packs.</p>	<p>The Azores are located about 1,600 km west-southwest of the Study Area</p> <p>Information on the list of consulted communities and stakeholder groups was sent on 19 February 2014.</p> <p>The Information was distributed to FFAW on 19 February 2014.</p>
Fisheries and Oceans Canada	<p>Jason Kelly</p> <p>Tanya Warren</p>	<p>MKI made contact with Fisheries and Oceans Canada by phone on December 18, 2013.</p> <p>Follow-up emails were made on December 24, 2013 and January 20, 2014.</p> <p>A face to face discussion between MKI and Fisheries and Oceans Canada representatives were conducted on January 23, 2014. A general overview of the project and information package was provided.</p>	<p>Meeting participants requested that NAFO data be included in the Environmental Assessment.</p> <p>Meeting participants will provide information on plans and results from the post season crab surveys.</p>	NAFO data are discussed in Section 4.3 of the EA.
Nature Newfoundland and Labrador	<p>Len Zedel</p> <p>Allan Stein</p>	<p>MKI made contact with Nature Newfoundland and Labrador by email on January 7, 2014.</p> <p>Follow-up emails were made on January 7, 8, and 9, 2014.</p>	<p>Meeting participants indicated that a map with both survey lines and general shipping traffic may be beneficial for the Environmental Assessment.</p> <p>Meeting participants requested that corals on the shelf break be addressed</p>	<p>Marine transportation is discussed in Section 5.9.2.</p> <p>Corals are discussed in Section 4.2 of the EA.</p>

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		A face to face discussion between MKI and Nature Newfoundland and Labrador representatives were conducted on January 23, 2014. A general overview of the project and information package was provided.	in the Environmental Assessment, as these corals are important biological feature. Meeting participants requested that sea birds be included in the Environmental Assessment	Seabirds are discussed in Section 2.4.4 and 5.8.6 of the EA
Newfoundland and Labrador Department of Fisheries and Aquaculture	David Lewis Tom Duly Wanda Wiseman	MKI made contact with the Newfoundland and Labrador Department of Fisheries and Aquaculture by phone on December 20, 2013. Follow-up emails were made on December 20, 2013 and on January 20, 2014. A face to face discussion between MKI and Newfoundland and Labrador Department of Fisheries and Aquaculture representatives were conducted on January 22, 2014. A general overview of the project and information package was provided.	Meeting participants had no comments, concerns or requests at this time. .	
Association of Seafood Producers	Derek Butler	MKI made contact with the Newfoundland Association of Seafood Producers by phone on December 20, 2013. Follow-up phone calls and emails were made on December 20, 2013 and January 6, 2014. A face to face discussion between MKI and the Newfoundland Association of Seafood Producers representative were conducted on January 21, 2014. A general overview of the project and information package was provided.	Meeting participant had no comments, concerns or requests at this time.	
Ocean Choice International	Rick Ellis Greg Viscount	MKI made contact with Ocean Choice International by phone on January 6, 2014. Follow-up emails were made on January 20, 2014.	Meeting participant had no comments or requests at this time.	

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		A face to face discussion between MKI and Ocean Choice International representatives were conducted on January 22, 2014. A general overview of the project and information package was provided.		
Transport Canada	Captain C.L. Murphy	MKI made contact with Transport Canada by phone on December 18, 2013. Follow-up emails and phone calls were made on January 9 and 10, 2014. Stakeholder indicated a face to face meeting was not necessary.		

Community Organization Meetings

Many communities were contacted and invited to participate in meetings with MKI representatives during January 20, 2014 to January 31, 2014. Not all community representatives were available to meet, as planned, to discuss the proposed project. Meetings with communities that were available to meet are summarized below.

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
Aquaforte				
Aquaforte Town Council	Carol Ann Cose Rhonda Arsenault Donna Keough	Aquaforte Town Council made contact with MKI on January 28, 2014. Follow up phone calls were made on January 29, 2014 and on January 30, 2014. A face to face discussion between MKI and the Aquaforte Town Council representatives were conducted on January 31, 2014. A general overview of the project and information package was provided.	Meeting participants requested an electronic copy of the PowerPoint and information packs. Meeting participants asked about the timeline for this project and how many kilometers of survey lines will be completed throughout the duration of the project. Meeting participants inquired about the project hiring process.	The information was sent to Aquaforte Town Council on 19 February 2014. Information and updates on the specific timing and length of survey will be provided to stakeholders through the project communications systems. The Proponent will provide the stakeholder communities with a list of employment opportunities and inform them of the appropriate recruitment agency.

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
			Meeting participants provided contact information for project updates.	
Argentia				
Argentia Management Authority	Harvey Brenton Loyola (Junior) Pomeroy	MKI made contact with Argentia Management Authority by phone on January 9, 2014. Follow-up phone calls and emails were made on January 14, 2014, January 15, 2014, January 16, 2014, January 17, 2014, and on January 22, 2014. A face to face discussion between MKI and Argentia Management Authority representatives were conducted on January 27, 2014. A general overview of the project and information package was provided.	Meeting participants had no comments, concerns or requests at this time. Meeting participants provided contact information for project updates.	
Bay Bulls				
Bay Bulls Town Council	Christa Luby Keith O'Driscoll	MKI made contact with Bay Bulls Town Council on January 9, 2014. Follow up phone calls and emails were made on January 14, 2014, January 15, 2014, January 27, 2014 and on January 29, 2014. A face to face discussion between MKI and the Bay Bulls Town Council representatives were conducted on January 31, 2014. A general overview of the project and information package was provided.	Meeting participants inquired about the number of full time crew on the <i>Sanco Spirit</i> , what percentage of crew would be from Newfoundland and how the crew will be hired. Meeting participants inquired if seismic sound disrupts marine life. Meeting participants provided contact information for project updates.	The Proponent will provide the stakeholder communities with a list of employment opportunities and then will inform them of the appropriate recruitment agency. The potential effects of seismic sound on marine life are discussed in Sections 5.8.4 to 5.8.7 of the EA.
Burin				
Burin Harbour Authority	Marguerite Drake Morris Fudge	MKI made contact with Burin Harbour Authority on January 7, 2014. Follow up phone calls and emails were made on January 7, 2014, and on January 22, 2014. A face to face discussion between MKI and the Burin Harbour Authority representatives were conducted on	Meeting participants asked if the proposed survey lines will overlap with fishing grounds. Meeting participants requested an electronic copy of the information pack. Meeting participants provided contact information for project updates.	Fisheries are discussed in Section 4.3 of the EA The information was distributed to Burin Harbour Authority on 19 February 2014.

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		January 23, 2014. A general overview of the project and information package was provided.		
Burin Town Council	Leo Hartson	<p>MKI made contact with Burin Town Council on January 7, 2014.</p> <p>Follow up phone calls and emails were made on January 8, 2014, and on January 14, 2014.</p> <p>A face to face discussion between MKI and the Burin Town Council representative were conducted on January 22, 2014. A general overview of the project and information package was provided.</p>	<p>Meeting participant requested an electronic copy of the information pack.</p> <p>Meeting participant provided contact information for project updates.</p>	The information was distributed to Burin Town Council on 19 February 2014.
Wave Energy Research Centre	Michael Graham	<p>MKI made contact with Michael Graham on January 20, 2014. Follow up phone calls were made on January 21, 2014.</p> <p>A face to face discussion between MKI and the Wave Energy Research Centre representative were conducted on January 22, 2014. A general overview of the project and information package was provided.</p>	Meeting participant had no comments, concerns or requests at this time.	
Ferryland				
Ferryland Harbour Authority and Ferryland Town Council	Roddy Paul Dolores Curren William (Billie) Doyle Doris Kavanagh Peter Morey Jim Barnable Peter Kavanagh	<p>MKI made contact with Ferryland Harbour Authority on January 9, 2014. Follow up phone calls were made on January 14, 2014, and on January 29, 2014.</p> <p>MKI made contact with the Ferryland Town Council on January 9, 2014. Follow up phone calls were made on January 14, 2014, and on January 29, 2014.</p> <p>Ferryland Town Council and Harbour Authority decided to hold a joint meeting with MKI.</p> <p>A face to face discussion between MKI and the Ferryland Harbour Authority and Ferryland Town Council</p>	<p>Meeting participants requested information on the hiring process for employment, and to be informed when positions are advertised.</p> <p>Meeting participants requested an electronic copy of the PowerPoint and information pack.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>The Proponent will provide the stakeholder communities with a list of employment opportunities and then will inform them of the appropriate recruitment agency.</p> <p>The Information was distributed to the Ferryland Town Council on 19 February 2014.</p>

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		representatives were conducted on January 30, 2014. A general overview of the project and information package was provided.		
Fortune				
Fortune Harbour Authority	Earl Rose Aubrey Wells Trevor Bungay	MKI made contact with Fortune Harbour Authority on January 7, 2014. Follow up phone calls were made on January 13, 2014, January 20, 2014 and on January 21, 2014. A face to face discussion between MKI and Fortune Harbour Authority representatives were conducted on January 20, 2014. A general overview of the project and information package was provided.	Meeting participants had no comments, concerns or requests at this time. Meeting participants provided contact information for project updates.	
Fortune Town Council	Cory Parsons Dave Holloway Yvonne Harris	MKI made contact with Fortune Town Council on January 7, 2014. Follow up phone calls were made on January 8, 2014 and on January 14, 2014. A face to face discussion between MKI and Fortune Town Council representatives were conducted on January 20, 2014. A general overview of the project and information package was provided.	Meeting participants asked if the sound produced by a seismic survey would stun fish. Meeting participants asked where crew changes would happen and if this could be done in Fortune or locally within the region. Meeting participants provided contact information for project updates.	The potential effects of seismic sound on fishes are discussed in Sections 5.8.4 and 5.8.5 of the EA. It is anticipated that crew changes for the 2 D survey will occur in the Port of St. John's. Other methods may be considered for any 3D survey.
Grand Bank				
Grand Bank Harbour Authority	Arch Evans Lloyd Hines Bruce Burt Hugh Barter George Keeping John Hillier	MKI made contact with Grand Bank Harbour Authority on January 7, 2014. Confirmation email was made on January 7, 2014. A face to face discussion between MKI and Grand Bank Harbour Authority representatives were conducted on January 21, 2014. A general overview of the project and information package was provided.	Meeting participants asked if the generated noise would hurt a person in the water directly next to the sound source. Meeting participants asked if there was any local research on the impacts of seismic sound on fish species. Meeting participants asked how fast sound travels in waters. Meeting participants asked if testing could be conducted immediately before	The underwater sound from an airgun could potentially damage a human's hearing if that human is very close to the discharging airgun. The potential effects of seismic sound on fishes are discussed in Sections 5.8.4 and 5.8.5 of the EA. Underwater sound moves through the water at an approximate speed of 1,450-1,500 m/s. Several scientific studies on the effects of seismic airgun sound on fishes have

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
			<p>and after a seismic survey to better understand how fish are affected by seismic noise.</p> <p>Meeting participants requested information related to the long term effects on fish reproduction from seismic noise.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>been conducted (see Sections 5.8.4 and 5.8.5, and Appendix 2).</p> <p>The potential effects of seismic sound on fish reproduction are discussed in Section 5.8.4 of the EA.</p>
Grand Bank Town Council	<p>Rex Matthews</p> <p>Clayton Welsh</p> <p>Stan Burt</p> <p>Bruce Warren</p> <p>Wayne Bolt</p> <p>Cathy Follett</p>	<p>MKI made contact with the Grand Bank Town Council on January 7, 2014.</p> <p>Follow up phone calls and emails were made on January 7, 2014 and on January 14, 2014.</p> <p>A face to face discussion between MKI and Grand Bank Town Council representatives were conducted on January 21, 2014. A general overview of the project and information package was provided.</p>	<p>Meeting participants requested that information related to employment opportunities be forwarded to them so that they may inform community members of potential opportunities.</p> <p>Meeting participants requested that Clearwater Seafoods be included in stakeholder consultations; and also requested to be informed when this is confirmed.</p> <p>Meeting participants requested to be notified when seismic activities begin, should the project be approved.</p> <p>Meeting participants requested information on the distance that generated sound will travel from the sound source towards the mainland.</p> <p>Meeting participants requested an electronic copy of the PowerPoint and information pack.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>The Proponent will provide the stakeholder communities with a list of employment opportunities and then will inform them of the appropriate recruitment agency.</p> <p>Low levels of the sound will likely reach the mainland.</p> <p>The Information was distributed to the Grand Bank Town Council on 19 February 2014.</p>
Marystown				
Marystown Shipyard	<p>Wayne Butler</p> <p>Bruce</p>	<p>MKI made contact with the Marystown Shipyard on January 8, 2014.</p> <p>Follow up phone calls were made on January 16, 2014, and on January 21, 2014.</p>	<p>Meeting participants requested an electronic copy of the PowerPoint and information pack.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>The Information was distributed to the Marystown Shipyard on 19 February 2014.</p>

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		A face to face discussion between MKI and Marystown Shipyard representatives were conducted on January 23, 2014. A general overview of the project and information package was provided.		
Marystown Town Council	Al Spencer Lisa Slaney Leonard Pittman Dennis Kelly Petrina Power Jody Brushett Jack Brenton	MKI made contact with the Marystown Town Council on January 8, 2014. Follow up phone calls and emails were made on January 13, 2014, January 14, 2014, January 21, 2014, January 22, 2014, and on January 23, 2014. A face to face discussion between MKI and Marystown Town Council representatives were conducted on January 23, 2014. A general overview of the project and information package was provided.	Meeting participants inquired about the distance of the study area from the mainland. Meeting participants requested information on the effects of seismic surveying on the fishery (fish species and fishing grounds). Meeting participants provided contact information for project updates.	The most proximate part of the Project Area is about 100 km from the mainland. The potential effects of seismic sound on fisheries are discussed in Section 5.8.5 of the EA.
Placentia				
Placentia Harbour Authority	Wilfred Hickey Carter Pomeroy Leo Gambin	MKI made contact with the Placentia Harbour Authority on January 9, 2014. Follow up phone calls were made on January 10, 2014, January 13, 2014, January 14, 2014 and on January 23, 2014. A face to face discussion between MKI and Placentia Harbour Authority representatives were conducted on January 27, 2014. A general overview of the project and information package was provided.	Meeting participants requested information on the effects of seismic on plankton, crab, lobster, cod and capelin. Meeting participants requested electronic copies of the PowerPoint and information packs. Meeting participants provided contact information for project updates.	The potential effects of seismic sound on invertebrates and fishes are discussed in Section 5.8.4 of the EA. The Information was distributed to the Placentia Harbour Authority on 19 February 2014.
Placentia Town Council	Wayne Power Debra Gear	MKI made contact with the Placentia Town Council on January 9, 2014. Follow up phone calls and emails were made on January 14, 2014, and on January 15, 2014. A face to face discussion between MKI and Placentia Town Council representatives were conducted on January 27, 2014. A general overview of the project and information package	Meeting participants had no comments, concerns or requests at this time. Meeting participants provided contact information for project updates.	

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was provided.				
Riverhead				
Riverhead Harbour Authority	Matt Corcoran Basil Whelan Billy Squires Wayne Fagan	<p>MKI made contact with the Riverhead Harbour Authority on January 22, 2014. Follow up phone calls were made on January 27, 2014.</p> <p>A face to face discussion between MKI and Riverhead Harbour Authority representatives were conducted on January 28, 2014. A general overview of the project and information package was provided.</p>	<p>Meeting participants requested information about the effects of seismic sound on fish, shellfish and marine mammals.</p> <p>Meeting participants requested information about the species at risk that are present in the study area.</p> <p>Meeting participants requested to be provided the survey lines when they become available.</p> <p>Meeting participants requested information on the width of the towed streamer apparatus.</p> <p>Meeting participants requested information on the long-term effects of seismic surveying on the fishery.</p> <p>Meeting participants requested to be informed when the seismic vessel will be in the area.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>The potential effects of seismic sound on marine life are discussed in Sections 5.8.4 to 5.8.7 of the EA.</p> <p>Species at risk are discussed in Section 4.6 of the EA.</p> <p>Information and updates on the specific timing and length of survey will be provided to stakeholders through the project communications systems.</p> <p>The 2014 2D seismic survey will use only one streamer. Any 3D seismic surveying done during 2015-2018 will be fully described in required annual updates to the EA.</p> <p>The potential effects of seismic sound on fisheries are discussed in Section 5.8.5 of the EA.</p>
St. Bride's				
St. Bride's Community Council	Brian Careen Isabella Conway	<p>MKI made contact with the St. Bride's Town Council on January 9, 2014.</p> <p>Follow up phone calls were made on January 10, 2014, January 13, 2014, January 14, 2014, January 15, 2014, January 17, 2014, January 22, 2014, January 23, 2014, and on January 27, 2014.</p> <p>A face to face discussion between MKI</p>	<p>Meeting participants requested additional information on the effects of seismic sound on crab and shrimp.</p> <p>Meeting participants provided contact information for project updates.</p>	<p>The potential effects of seismic sound on invertebrate marine life are discussed in Section 5.8.4 of the EA.</p>

Stakeholder Group	Stakeholder Participants	Details of Engagement	Comments, Concerns & Requests	Responses & EA Section where Comment/ Concern/ Request Addressed
		and St. Bride's Community Council representatives were conducted on January 28, 2014. A general overview of the project and information package was provided.		
St. John's				
City of St. John's	Ron Ellsworth Dave Lane Bruce Tilley	MKI made contact with the City of St. John's by phone on December 19, 2013. Follow-up phone calls and emails were made on December 19, 2013 and on January 6, 7, 12, and 20, 2014. A face to face discussion between MKI and City of St. John's representatives were conducted on January 21, 2014. A general overview of the project and information package was provided.	Meeting participants requested that MKI continue communication with the City.	
St. John's Port Authority	Jeff McGrath	MKI made contact with the St. John's Port Authority by phone on January 6, 2014. Follow-up emails were made on January 6 and 7, 2014. Stakeholder indicated a face to face meeting was not necessary.		
St. Mary's				
St. Mary's Harbour Authority	Joseph Dillon	MKI made contact with the St. Mary's Harbour Authority on January 22, 2014. Follow up phone calls were made on January 27, 2014, and on January 28, 2014. A face to face discussion between MKI and St. Mary's Harbour Authority representative was conducted on January 28, 2014. A general overview of the project and information package was provided.	Meeting participants requested information on how employment opportunities would be advertised. Meeting participants provided contact information for project updates.	The Propones will provide the stakeholder communities with a list of employment opportunities and then will inform them of the appropriate recruitment agency.

APPENDIX 2:

REVIEW OF POTENTIAL EFFECTS OF AIRGUN SOUNDS ON FISHES¹

The potential effects of seismic airgun sound on fishes has been studied for a variety of taxa that includes 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 [0-p]”, “peak to peak [p-p]”, 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 the duration of a single sound event. Unless precise measurement types are reported, it can be impossible to directly compare results from two or more independent studies. This is what is available at the moment and study methods are continuously developing to address some of the known shortcomings.

This appendix provides an overview of the acoustic capabilities of fishes as well as information on the potential effects of exposure to seismic airgun sound on these animals.

Acoustic Capabilities

Sensory systems, like those that allow for hearing, provide information about an animal’s physical, biological and social environments. 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 potentially 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.

¹ By **John R. Christian and R.C. Bocking**, LGL Ltd., environmental research associates (rev. December 2013)

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 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 (2011) 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 (2011), one end of this continuum is represented by fishes that only detect particle displacement 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 less than 1,500 Hz (e.g., Casper et al. 2003; Casper and Mann 2006, 2007, 2009).

The other end of the fish hearing continuum is represented by fishes with highly specialized otophysic 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, but probably the fish responding to exceedingly high pressure signals of 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 displacement. 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).

There has also been recent study of the auditory sensitivity of settlement-stage fishes. Using the auditory brainstem response (ABR) technique in the laboratory, Wright et al. (2010) concluded that larvae of coral reef species tested had significantly more sensitive hearing than the larvae of pelagic species tested. All reef fish larvae as well as the larvae of one of the pelagic species detected frequencies in the 100-2,000 Hz range. The larvae of the one other pelagic species did not detect frequencies higher than 800 Hz. The larvae of all six species exhibited best hearing at frequencies between 100 and 300 Hz. The results of Wright et al. (2010) suggested that settlement-stage larval reef fishes may be able to detect reef sounds at distances of 100s of metres. Other recent research also indicates that settlement-stage larvae of coral reef fishes may use sound as a cue to locate settlement sites (Tolimieri et al. 2004; Leis et al. 2003; Simpson et al. 2005; Leis and Locket 2005).

Potential Effects

Review papers on the effects of anthropogenic sources of underwater sound on fishes have been published recently (Popper 2009; Popper and Hastings 2009a,b; Fay and Popper 2012). 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. Note that many of the studies were conducted either in a laboratory or in the field using captive fish, and are therefore not representative of the natural scenario of fish being able to move away from the sound source.

There are three categories of potential effects of exposure to air gun sound on marine fishes: pathological, physiological, and behavioural. Pathological effects include lethal and sub-lethal injury to the animals, physiological effects include temporary primary and secondary stress responses, and behavioural effects refer to changes in exhibited behaviours (i.e., disturbance). For the purpose of this review, pathological and physiological effects are grouped as physical effects. The three categories should not be considered as independent of one another and are likely interrelated in complex ways.

Marine Fishes

Physical Effects

Juveniles and Adults

Evidence for airgun-induced damage to fish ears (i.e., pathological effect) has been provided in studies using pink snapper *Pagrus auratus* as subjects (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).

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. Stress can cause the levels of these chemicals to fluctuate. 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).

Eggs and Larvae

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 at a fixed distance. 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. 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.

Behavioural Effects

Studies described in this subsection suggest that effects on fish behaviour due to exposure to airgun sound are temporary in nature, and that response thresholds for various demersal and pelagic species are quite variable.

The fish exposed to sound from a single airgun in the McCauley et al. studies (i.e., pink snapper and trevally *Pseudocaranx dentex*) 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 μPa_{rms} (McCauley et al. 2000a,b; Fewtrell and McCauley 2012). Smaller fish were more likely to display a startle response. Responses were observed above received SPLs of 156 to 161 dB re 1 μPa_{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.

A study by Pearson et al. (1992) also showed that behavioural effects were temporary in nature. They investigated the effects of seismic airgun sound on the behavior of captive rockfishes (*Sebastes* spp.) 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 $\mu\text{Pa} \cdot \text{m}_{0-p}$, and measured received SPLs ranged from 137 to 206 dB re 1 μPa_{0-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 μPa_{0-p} , and alarm responses occurred at a minimum received SPL of 177 dB re 1 μPa_{0-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 μPa_{0-p} and 161 dB re 1 μPa_{0-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 μPa_{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.

Activity levels tend to return to normal within hours of exposure to airgun sound. 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) observed 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, however 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) showed that after an hour of exposure to the airgun sound, the whiting appeared to have habituated as indicated by their return to the pre-exposure depth range, despite the continuing airgun discharge. They 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 μPa_{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. 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*, but their commercial fishery catch data were inconclusive with respect to behavioral effects. 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 \times 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.

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 pulse 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 $\mu\text{Pa} \cdot \text{m}_{\text{p-p}}$. 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.

Peña et al. (2013) studied the real-time behavior of herring schools exposed to a full-scale 3D seismic survey off northern Norway using an omnidirectional fisheries sonar. The feeding herring were observed over a six-hour period as the seismic vessel and active airguns approached them from a distance of 27 km to a point 2 km away. The received SEL increased from about 125 to 155 dB re 1 $\mu\text{Pa}^2 \text{ s}$ during the vessel's approach. The investigators observed a lack of response by the herring and concluded that this observation was likely due to a combination of factors including a strong motivation for feeding, a lack of suddenness of the airgun stimulus, and an increased level of tolerance to the seismic sound.

Indirect Effects on Fisheries

The initial 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 $\mu\text{Pa} \cdot \text{m}_{\text{0-p}}$ 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 $\mu\text{Pa}_{\text{0-p}}$ and 178 dB re 1 $\mu\text{Pa}_{\text{0-p}}$, 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.

Løkkeborg et al. (2012) recently described a 2009 study of the effect of exposure to seismic sound on commercial fishes. Both gillnet and longline vessels fished for Greenland halibut, redfish, saithe and haddock for 12 days before the onset of seismic surveying, 38 days during seismic surveying, and 25 days after cessation of seismic surveying. Acoustic surveying was also conducted during these times. Gillnet catches of Greenland halibut and redfish increased during seismic operations and remained higher after cessation of seismic surveying than they had been before the onset of seismic surveying. Longline catches of Greenland halibut decreased during seismic operations but increased again after the

seismic surveying was completed. Gillnet catches of saithe decreased during seismic operations and remained low during the 25 day period following the seismic surveying. Longline catches of haddock before and during seismic operations were not significantly different although catches did decline as the seismic vessel approached the fishing area. The haddock fishery was conducted in an area with lower sonification compared to the fishery areas of the other three species. Acoustic surveys showed that the saithe had partly left the area, while the distributional changes of the other three species were not observed. Løkkeborg et al. (2012) suggested that an increase in swimming activity as a result of exposure to seismic sound might explain why gillnet catches increased and longline catches decreased.

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) suggested 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.

Turnpenny et al. (1994) examined results of this study 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 sonified 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.

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).

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 μ Pa per discharge, and the approximate mean received SEL was 176 to 180 dB re 1 μ Pa² · 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 to 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.

Popper et al. (2013) recently conducted a study that examined the effects of exposure to seismic airgun sound on caged pallid sturgeon (*Scaphirhynchus albus*) and paddlefish (*Polyodon spathula*). The maximum received peak SPL in this study was 224 dB re 1 μ Pa. Results of the study indicated no mortality, either acute or after seven days post-exposure, and no statistical differences in effects on body tissues between exposed and control fish.

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 pulse or a series of four pulses 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 μ Pa · m (unspecified measure).

Thomsen (2002) exposed rainbow trout and Atlantic salmon held in aquaculture enclosures to recordings of sounds from a small airgun array. Received SPLs were 142 to 186 dB re 1 μ Pa_{p-p}. The fish were exposed to 124 pulses over a 3-day period. Only eight of the 124 pulses 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.

Summary of Potential Effects of Airgun Sound on Fishes

Some studies have shown that various life stages of particular fish species can be physically affected by exposure to airgun sound. In all of these cases, the fish subjects were subjected to exposures that would not likely occur under natural conditions. Studies that demonstrated physical effects on fishes typically involved either captive juvenile/adult subjects that were unable to move away from the sound source or passive ichthyoplankton that were located within a few metres of the sound source. The focus of study related to the potential effects of exposure to airgun sound on fishes has shifted to behavioural effects, particularly those that could result in a decrease in catch rate of the fishes. Fishes will exhibit both subtle and more overt behavioural changes in response to airgun sound and these effects appear to be quite variable both between and within species. Generally, the behavioural effects are localized and temporary, but can result in short-term effect on catch rates.

Recent work in Norway suggests that, in the future, particular acoustic-biological models may be used in the design and planning of seismic surveys in order to minimize disturbance to fishing (Hovem et al. 2012).

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APPENDIX 3: REVIEW OF POTENTIAL EFFECTS OF AIRGUN SOUNDS ON MARINE INVERTEBRATES

The potential effects of exposure to seismic airgun sound on marine invertebrates have been studied for a limited number of species, primarily crustacean and molluscan species.

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 [0-p]”, “peak to peak [p-p]”, 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 the duration of a single sound event. Unless precise measurement types are reported, it can be impossible to directly compare results from two or more independent studies. This is what is available at the moment and study methods are continuously developing to address some of the known shortcomings.

This appendix provides an overview of the known acoustic capabilities of marine invertebrates as well as information on the potential effects of exposure to seismic airgun sound on these animals. Studies of the potential effects of underwater sound on marine invertebrates are limited in number compared to similar studies involving other marine biota. The information includes results of studies of varying degrees of scientific veracity as well as anecdotal information. Fisheries and Oceans Canada has published two internal documents that provide a literature review of the effects of seismic and other underwater sound on marine invertebrates (Moriyasu et al. 2004; Payne et al. 2008).

Acoustic Capabilities

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.

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 fish and aquatic 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 (i.e., particle displacement) (Breithaupt 2002). Statocyst organs may provide one means of vibration detection for aquatic invertebrates. Laser Doppler vibrometer techniques have recently opened the possibility of measuring whole body vibration as a direct stimulus eliciting statocyst response (André et al. 2013).

More is known about the acoustic detection capabilities in decapod crustaceans than in any other marine invertebrate group although cephalopod capability is 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 its body size and the related number and size of statocyst hair cells. Studies involving American lobster 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 displacement with its statocyst. Studies by Packard et al. (1990), Rawizza (1995), Komak et al. (2005) and Mooney et al. (2010) 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 1,500 Hz for the squid *Sepiotheutis lessoniana* and 400 to 1,000 Hz for the octopus *Octopus vulgaris*, higher than frequencies previously observed to be detectable by cephalopods.

Recently, Vermeij et al. (2010) studied the movement of coral larvae in the laboratory and concluded that these larvae are able to detect and respond to underwater sound. This is the first description of an auditory response in the invertebrate phylum Cnidaria. The authors speculate that coral larvae may use reef sound as a cue for orientation. Laboratory and field experiments suggest that underwater sound has a significant effect on settlement rates by the Eastern oyster larvae (*Crassostrea virginica*) (Eggleston et al. 2013).

In summary, only a few studies have been conducted on the sensitivity of 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.

Sound Production

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 together, although they also produce sound in other ways. Sounds made by marine invertebrates may be associated with territorial behaviour, 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. The following paragraphs provide additional context around auditory processes in various invertebrate species that may occur within our Project Area.

Both male and female American lobsters produce a buzzing vibration with their 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 behaviour. Sound production by other species of lobsters has also been studied (Buscaino et al. 2011). 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 produce impulsive sounds that appear to stimulate movement by other crabs, including approach behaviour (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.

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 chela (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 as both offensive and defensive means in feeding and territorial behaviours 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.

Potential Effects

Sound caused by underwater seismic survey equipment results in energy pulses with very high peak pressures (Richardson et al. 1995). Virtually all underwater seismic surveying conducted today uses airguns which typically have lower peak pressures and longer rise times than chemical explosives. Sound levels from underwater airgun discharges might be high enough to potentially injure or kill animals located very close to the sound source. Less overt than physical effects are potential disturbances to normal behaviours that animals may experience when exposed to airgun sound.

There are essentially three types of potential effects of exposure to airgun sound on marine invertebrates; (1) pathological, (2) physiological, and (3) behavioural. Pathological effects include lethal and sub-lethal injury to the animals, physiological effects include temporary primary and secondary stress responses, and behavioural effects refer to changes in exhibited behaviours (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) received peak pressure, and (2) 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 sound produced from 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). Few studies have assessed the potential for pathological effects on invertebrates from exposure to sound produced from seismic airgun arrays, and these are described below.

The pathological impacts of sound from seismic surveys on marine invertebrates were investigated in a pilot study on snow crabs (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 $\mu\text{Pa}_{0-\text{p}}$) 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. There was a significant difference in development rate noted between the exposed and unexposed fertilized eggs/embryos. The egg mass exposed to sound energy had a higher proportion of less-developed eggs than 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).

Another study of the effects of sound from seismic surveys on marine invertebrates had serious design problems that impacted the interpretation of some of the results (Chadwick 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). 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 $\mu\text{Pa}_{0-\text{p}}$. The crabs were exposed for 132 hr of the survey, equivalent to thousands of seismic pulses 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 conclusively linked to exposure to sound from the seismic survey. 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 sound from an airgun source on various health endpoints of the American lobster (*Homarus americanus*). Adult lobsters were exposed either 20 to 200 times to 202 dB re 1 μ Pa_{p-p} or 50 times to 227 dB re 1 μ Pa_{p-p}, and then monitored for changes to survival, food consumption, turnover rate, serum protein level, serum enzyme levels, and serum calcium level. Observations were made over a period of a few days to several months. Results indicated no effects on 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 to single discharges from a seven-airgun array and compared their mortality and development rates with those of unexposed larvae. For immediate and long-term survival and time to molt, this study did not reveal any statistically significant differences between the exposed and unexposed larvae, even those exposed within 1 m of the seismic source.

A recent study involved the exposure of wild New Zealand scallop larvae to recorded seismic pulses. Results indicated significant developmental delays from trocophore to D-veliger larval stage, with 46% of the larvae exhibiting body abnormalities. It was suggested that the malformations could be due to cumulative exposure (de Soto et al. 2013).

In 2001 and 2003, there were two incidents of multiple strandings of the giant squid on the north coast of Spain, and there was speculation that they were caused by exposure to sounds from geophysical seismic surveys 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 surface-floating, 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 suggested that one female with extensive tissue damage was affected by the impact of acoustic waves. However, little is known about the impact of underwater sound 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 presence of seismic activity was entirely circumstantial, and the examined animals had been dead long enough for commencement of tissue degradation.

Caged cephalopods (*Sepioteuthis australis*) were exposed to sound from a single 20-in³ airgun with maximum SPLs of >200 dB re 1 μ Pa_{0-p} (McCauley et al. (2000a,b; Fewtrell and McCauley 2012). Statocysts were removed and preserved, but results of the statocyst analyses were not reported. No squid mortalities were reported as a result of these exposures.

Experiments are planned for 2013-2015 in Australia to study the acute and chronic effects of exposure to airgun sound on scallops and lobsters. Both berried and non-berried lobsters will be used in the experiments (McCauley et al. 2013).

Physiological Effects

Biochemical responses by marine invertebrates to acoustic stress have also been studied. The study of the biochemical parameters influenced by acoustic stress could possibly provide some indication

of the acute extent of the stress and perhaps any subsequent chronic detrimental effects. Stress 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 sound from seismic surveys (Christian et al. 2003, 2004) and at various intervals after exposure. No significant acute or chronic differences between exposed and unexposed animals in terms of the stress indicators (e.g., proteins, enzymes, cell type count) were observed.

Payne et al. (2007), in their study of the effects of exposure to sound from an airgun source on adult American lobsters, noted decreases in the levels of serum protein, particular serum enzymes and serum calcium in the haemolymph of animals exposed. 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 after 30 minutes of exposure whereas larger mussels responded after 10 minutes of exposure. The larger mussels tended to lower the oxygen uptake rate more than the smaller animals.

Behavioural Effects

The limited study of the effects of exposure to sound on marine invertebrates has not indicated any serious pathological and physiological effects. In light of this, some recent studies have focused on the potential behavioural effects on marine invertebrates.

Christian et al. (2003) investigated the behavioural effects of exposure to sound from seismic surveys 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 from a fixed source over a 33-min period. None of the tagged animals left the immediate area after exposure. 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 sound from a seismic source. 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 also 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 to be 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 commercial catches and seismic surveying in Australian waters between 1978 and 2004. They did not find any evidence that lobster catch rates were affected by seismic surveys.

Caged female snow crabs exposed to 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, Newfoundland, personal communication). ‘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 sound from a seismic source on adult American lobsters, noted a trend of increased food consumption by the animals exposed to sound.

Andriguetto-Filho et al. (2005) investigated the impact of sound from seismic surveys on artisanal shrimp fisheries off Brazil. Bottom trawl yields were measured before and after multiple-day activation of an airgun array with a source SPL of 196 dB re 1 $\mu\text{Pa}\cdot\text{m}$. 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, personal communication). More anecdotal information from Newfoundland, Canada, indicated that a school of shrimp observed on a fishing vessel sounder shifted downwards and away from a nearby seismic sound source (H. Thorne, Newfoundland fisherman, personal communication). This observed effect was temporary.

McCauley et al. (2000a,b) provided the first evidence of the behavioural response of southern calamari squid exposed to sound from seismic surveys. McCauley et al. (2000a,b) reported on the exposure of caged cephalopods (50 squid and two cuttlefish) to sound from a single 20-in³ airgun. The cephalopods were exposed to both stationary and mobile sound sources. The two-run total exposure times of the three trials ranged from 69 to 119 min. at an activation interval 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 pulse 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 simulated a soft-start or ramp-up scenario whereby squid were exposed to a received SPL which gradually increased over time. No strong startle response was observed (i.e., ink discharge) but alarm responses were observed once the received SPL reached a level in the 156–161 dB re 1 $\mu\text{Pa}_{\text{rms}}$ range (McCauley et al. 2000a,b; Fewtrell and McCauley 2012).

Although not yet scientifically investigated, 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 functions and biological relevance of these sounds are not understood (Jeffs et al. 2003, 2005; Lovell et al. 2005; Radford et al. 2007). Masking of produced sounds and received sounds (e.g., conspecifics and predators), at least the particle displacement component, could potentially have adverse effects on marine invertebrates.

Summary of Potential Effects of Exposure to Airgun Sound on Marine Invertebrates

While certain studies have suggested that some marine invertebrates are affected physically by exposure to airgun sound, the degree of the suggested effects have been minimal. In addition, the suggested physical effects were observed when constrained marine invertebrates were exposed to airgun sound at very close range, resulting in exposures unrepresentative of those that would occur under natural conditions. Behavioural effects of exposure to airgun sound have also been observed in studies but,

again, the marine invertebrates that exhibited the behavioural changes were constrained and unable to freely move away from the airgun sound source.

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APPENDIX 4:
REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE MAMMALS¹

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TABLE OF CONTENTS

1. REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON MARINE MAMMALS 1

1.1 Categories of Sound Effects..... 1

1.2 Hearing Abilities of Marine Mammals..... 1

1.2.1 Toothed Whales (Odontocetes) 2

1.2.2 Baleen Whales (Mysticetes) 3

1.2.3 Seals and Sea Lions (Pinnipeds)..... 3

1.3 Characteristics of Airgun Sounds 3

1.4 Masking Effects of Airgun Sounds 6

1.5 Disturbance by Seismic Surveys 7

1.5.1 Baleen Whales..... 8

1.5.2 Toothed Whales 14

1.5.3 Pinnipeds 20

1.6. Hearing Impairment and Other Physical Effects of Seismic Surveys 22

1.6.1 Temporary Threshold Shift (TTS) 23

1.6.2 Permanent Threshold Shift (PTS) 28

1.6.3 Strandings and Mortality 30

1.6.4 Non-Auditory Physiological Effects..... 31

1.7 Literature Cited..... 32

1. Review of the Effects of Airgun Sounds on Marine Mammals

The following subsections review relevant information concerning the potential effects of sound from 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.

1.1 *Categories of Sound Effects*

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

1. The sound may be too weak to be heard at the location of the animal, i.e., lower than the prevailing ambient sound level, the hearing threshold of the animal at relevant frequencies, or both;
2. The sound may be audible but not strong enough to elicit any overt behavioural response, i.e., the mammal may tolerate it, either without or with some deleterious effects (e.g., masking, stress);
3. The sound may elicit behavioural reactions of variable conspicuousness and variable relevance to the well being of the animal; these can range from subtle effects on respiration or other behaviours (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 may perceive as a threat;
5. Any man-made sound 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 due to wave action or (at high latitudes) ice movement. Intermittent airgun, sonar or other activities that result in a pulse sound output may result in a strong masking effect for only a small proportion of the time, given the short duration of these pulses relative to the inter-pulse intervals. Mammal calls and other sounds are often audible during the intervals between pulses, but mild to moderate masking may occur during that time because of reverberation.
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.

1.2 *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.
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).

1.2.1 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 auditory evoked potentials (AEP) 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). For a sub-adult Blainville's beaked whale, Pacini et al. (2011) reported the best hearing range to be 40 to 50 kHz.

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).

Beluga whales hear best at frequencies of ~32–100 kHz (e.g., Mooney et al. 2013); the hearing threshold increases progressively (poorer hearing) outside of this range. Beluga whales are capable of hearing seismic and vessel-generated sounds at lower frequencies, but those sounds are not within their best hearing range. Sounds need to be at or above the hearing threshold to be readily detectable. Sounds must also be at or greater than ambient noise levels in order to be detected. There are no specific hearing data for narwhals, but it is assumed that belugas and narwhals have similar hearing abilities because of their taxonomic similarity; the two are the only species in the family Monodontidae.

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 kilometres (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 kilometres.

1.2.2 Baleen Whales (*Mysticetes*)

The hearing abilities of baleen whales (mysticetes) have not been studied directly given the difficulties in working with such large animals. Behavioural 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 signal from a 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 humpback whales, with components up 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 humpback 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 or possibly 25 kHz; baleen whales are said to constitute the “low-frequency” (LF) hearing group (Southall et al. 2007; Scholik-Schlomer 2012). 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 (e.g., MacGillivray et al. 2014). 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 sound from airguns (or other sources) would be detectable and often show no overt reaction to those sounds. Behavioural responses by baleen whales to seismic pulses have been documented, but received levels of pulsed sounds necessary to elicit behavioural reactions are typically well above the minimum levels that the whales are assumed to detect (see below).

1.2.3 Seals and Sea Lions (*Pinnipeds*)

Underwater audiograms have been determined using behavioural study 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 harbour 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). Recent measurements of underwater hearing for spotted seals (*Phoca largha*) show peak sensitivity of ~ 51 dB re 1 μ Pa at 25.6 kHz and good auditory sensitivity extending seven octaves (Sills et al. 2013).

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 (harbour seal).

1.3 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 activation 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 for geophysical purposes (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 μPa_{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 airgun 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-geophysical 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 or comparing quoted source or received levels. In geophysical exploration related literature, sound pressure level (SPL) is often quoted as peak-to-peak (p-p) levels, in bar-metres or (less often) dB re 1 $\mu\text{Pa} \cdot \text{m}$. The zero to peak (0-p) level for the same pulse signal is typically ~6 dB less than the p-p level. In the biological-acoustic 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), depending on the extent of the averaging window used in the rms calculation. A measure that is increasingly used to characterise sound energy is the 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.² Because the level of a given pulse will differ substantially depending on

² 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

which of these measures is being applied, it is important to be aware which measure is in use when interpreting or comparing any quoted sound level. For example, the U.S. National Marine Fisheries Service (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 sediments 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 an airgun 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, which has resulted in a move towards using SEL rather than SPL rms values averaged over pulse duration (Southall et al. 2007) to assess the potential effects (at least hearing impairment) of sound on marine mammals. However, there is also recent evidence that auditory effect in a given animal is not a simple function of received acoustic energy. Frequency, duration of the exposure, and occurrence of gaps within the exposure can also influence the auditory effect (Mooney et al. 2009a; Finneran and Schlundt 2010, 2011; Finneran et al. 2010a,b; Finneran 2012; Finneran and Schlundt 2013; Kastelein et al. 2013a).

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 kilometres 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).

dB re 1 μ Pa² · 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).

1.4 Masking Effects of Airgun Sounds

Masking is the obscuring of sounds of interest by interfering sounds, generally at similar frequencies. 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; Clark et al. 2009). Conversely, 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 biological repercussions of a loss of communication space, to the extent that this occurs, are unknown.

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 would cause strong 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., Gedamke 2011; Guerra et al. 2011, 2013), and this weaker reverberation presumably reduces the detection range of calls and other natural sounds to some degree. Guerra et al. (2013) reported that ambient noise levels between seismic pulses were elevated as a result of reverberation at ranges of 50 km from the seismic source. Based on measurements in deep water of the Southern Ocean, Gedamke (2011) estimated that the slight elevation of background levels during intervals between pulses reduced blue and fin whale communication space by as much as 36 to 51% when a seismic survey was operating 450–2800 km away. Based on preliminary modelling, Wittekind et al. (2013) reported that airgun sounds may reduce the communication range of blue and fin whales 2000 km from the seismic source. Klinck et al. (2012) also found reverberation effects between airgun pulses. Nieukirk et al. (2012) and Blackwell et al. (2013) noted the potential for masking effects from seismic surveys on large whales.

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; Nieukirk et al. 2004, 2012; Smultea et al. 2004; Holst et al. 2005a,b, 2006, 2011; Dunn and Hernandez 2009; Cerchio et al. 2010). However, some of these studies found evidence of reduced calling (or at least reduced call detection rates) in the presence of seismic pulses. One recent report indicates that calling fin whales distributed in a 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 paper whether the whales ceased calling because of masking, or whether this was a behavioural response not directly involving masking. Also, bowhead whales in the Beaufort Sea apparently decrease their calling rates in response to seismic operations, although movement out of the area also contributes to the lower call detection rate (Blackwell et al. 2013). In contrast, Di Iorio and Clark (2010) found that blue whales in the St. Lawrence Estuary *increased* their call rates during operations by a lower-energy seismic source. The sparker used during the study emitted frequencies of 30–450 Hz with a relatively low source level of 193 dB re 1 $\mu\text{Pa}_{\text{pk-pk}}$. There is some evidence that fin whale song notes recorded in the Mediterranean had lower bandwidths during periods with versus without airgun sounds (Castellote et al. 2012).

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, 2011; Jochens et al. 2008). Madsen et al. (2006) noted that airgun sounds would not be expected to cause significant masking of sperm whale calls given the intermittent nature of airgun

pulses. (However, some limited masking would be expected due to reverberation effects, as noted above.) 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, 2011; 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.

Some 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 behaviour in response to increased noise (Dahlheim 1987; Au 1993; reviewed in Richardson et al. 1995:233ff, 364ff; also Lesage et al. 1999; Terhune 1999; Nieukirk et al. 2005; Scheifele et al. 2005; Parks et al. 2007a, 2009, 2011, 2012; Hanser et al. 2009; Holt et al. 2009; Di Iorio and Clark 2010; McKenna 2011; Castellote et al. 2012; Melcón et al. 2012; Risch et al. 2012; Tyack and Janik 2013). It is not known how often these types of responses occur upon exposure to airgun sounds. If cetaceans exposed to airgun sounds sometimes respond by changing their vocal behaviour, 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.

1.5 Disturbance by Seismic Surveys

Disturbance includes a variety of effects, including subtle to conspicuous changes in behaviour, 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 behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering”.

There has been debate regarding how substantial a change in behaviour 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 behavioural 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 behavioural pattern, NMFS considers [the human] activity not to have caused a disruption of the behavioural 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 behavioural 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 behavioural 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). Behavioural 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; Ellison et al. 2012). If a marine mammal reacts to an underwater sound by changing its behaviour or moving a small distance, the impacts of the change are unlikely to be significant to the individual, let alone the stock or population (e.g., New et al. 2013). 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 behavioural changes may still be adversely affected by sound (Brodie 1981; Richardson et al. 1995:317ff; Romano et al. 2004; Weilgart 2007; Wright et al. 2009, 2011). 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. Harwood et al. (2013) emphasized the need for a framework to assess consequences of effects from underwater noise at a population level. 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 (NOAA 2013). Southall et al. (2007) made detailed recommendations for new science-based noise exposure criteria, and NMFS has taken at least some of those into account. The new exposure criteria have not yet been finalized (NOAA 2013); 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 behavioural 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.

1.5.1 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 kilometres, 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); Stone and Tasker (2006); Johnson et al. (2007); Nowacek et al. (2007); Weir (2008a); and Moulton and Holst (2010). 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 $\mu\text{Pa}_{\text{rms}}$ SPL seem to cause obvious avoidance behaviour 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 $\mu\text{Pa}_{\text{rms}}$ SPL. 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 behaviour appeared to be of little or no biological consequence to the animals—they simply avoided the sound source by displacing their migration route to varying degrees, but within the natural boundaries of the migration corridors (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 Whale

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 $\mu\text{Pa} \cdot \text{m}_{\text{p-p}}$ SPL. 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, behaviour, 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 SPL 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 SPL 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 SPL was 143 dB re 1 $\mu\text{Pa}_{\text{rms}}$. One startle response was reported for a SPL of 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 SPL 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. Studies examining the behavioural response of humpback whales off Eastern Australia to airguns are currently underway (Cato et al. 2011, 2012, 2013).

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 SPLs of 150–169 dB re 1 μ Pa. Malme et al. (1985) concluded that there was no clear evidence of avoidance, despite the possibility of subtle effects, at received SPLs up to 172 re 1 μ Pa on an approximate rms basis. However, Moulton and Holst (2010) reported that humpback whales monitored during seismic surveys in the Northwest Atlantic had significantly lower sighting rates and were most often seen swimming away from the vessel during seismic periods compared with periods when airguns were silent.

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). Cerchio et al. (2010) suggested that the breeding display of humpback whales off Angola may be disrupted by seismic sounds, as singing activity declined with increasing received levels.

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 Whale

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, including shorter surfacings, shorter dives, and decreased number of blows per surfacing (Robertson et al. 2013). Bowheads usually did show strong avoidance responses when seismic vessels approached within a few kilometres (~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 was activated 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 μ Pa·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 behaviour. On the summer feeding grounds, bowhead whales are often seen from an 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 kilometres 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 kilometres.

Migrating bowhead whales in the Alaskan Beaufort Sea seem more responsive to sound pulses from a distant seismic vessel compared to 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 at received SPLs of around 120–130 dB re 1 μ Pa_{rms} from a medium-sized airgun source (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 surveying 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 2007–2010, 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. 2013; Koski et al. 2009; see also Nations et al. 2009). Blackwell et al. (2013) reported that calling rates in 2007 declined significantly where received SPLs from airgun sounds were 116–129 dB re 1 μ Pa, and Blackwell et al. (2012) suggested that the cumulative SEL threshold for when bowhead whales cease calling is near 124 dB re 1 μ Pa² · s. This decrease could have resulted from movement of the whales away from the area of the seismic survey or a reduction in calling behaviour, or a combination of the two. 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 2007–2010 showed less consistent avoidance by the bowheads, many of which appeared to be feeding (Christie et al. 2009; Koski et al. 2009, 2011). 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 behaviour during 2007–2010, but further analysis of the recent data is ongoing.

A recent multivariate analysis of factors affecting the distribution of calling bowhead whales during their fall migration in 2009 noted that the southern edge of the distribution of calling whales was significantly closer to shore with increasing levels of airgun sound from a seismic survey a few hundred kilometres to the east of the study area (i.e., behind the westward-migrating whales; McDonald et al. 2010, 2011). It was not known whether this statistical effect represented a stronger tendency for quieting of the whales farther offshore in deeper water upon exposure to airgun sound, or an actual inshore displacement of whales.

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

Gray Whale

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 sound 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 SPL of ~170 dB re 1 μ Pa_{rms}. Some slight behavioural changes were noted when approaching gray whales reached the distances where received sound

pressure levels were 140 to 160 dB re 1 $\mu\text{Pa}_{\text{rms}}$, 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 $\mu\text{Pa}_{\text{rms}}$ (Malme et al. 1984; Malme and Miles 1985).

There was no indication that western gray whales exposed to seismic sound 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 behavioural 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 behaviour 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, as well as a subsequent survey in 2010, involved an unusually comprehensive combination of real-time monitoring and mitigation measures designed to avoid exposing western gray whales to received SPLs of sound above about 163 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (Johnson et al. 2007; Nowacek et al. 2012, 2013). 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. Limited data obtained during a monitoring program in 2010 indicated that an increase in vessel traffic and seismic operations may have displaced gray whales from their preferred feeding area (WWF et al. 2010). However, this study also reports that the number of gray whales in the area increased several days after seismic acquisition ceased.

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 where airgun sources are active (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; Castellote et al. 2012). 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 visibility, sighting rates for mysticetes (mainly fin and sei whales) were similar when large arrays of airguns were active 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 active compared with periods of inactivity ($P < 0.05$; Stone and Tasker 2006). Similarly, Castellote et al. (2012) reported that singing fin whales in the Mediterranean moved away from an operating airgun array and avoided the area for days after airgun activity had ceased. In addition, Stone (2003) noted that fin/sei whales were less likely to remain submerged during periods of seismic surveying.

During seismic surveys in the Northwest Atlantic, baleen whales as a group showed localized avoidance of the operating array (Moulton and Holst 2010). Sighting rates were significantly lower during seismic operations compared with non-seismic periods, baleen whales were seen on average 200 m farther from the vessel during airgun activities vs. non-seismic periods, and these whales more often swam away from the vessel when seismic operations were underway compared with periods when no airguns were operating (Moulton and Holst 2010). Blue whales were seen significantly farther from the vessel during single airgun operations, ramp up, and

all other airgun operations compared with non-seismic periods (Moulton and Holst 2010). Similarly, the mean CPA distance for fin whales was significantly farther during ramp up than during periods without airgun operations; there was also a trend for fin whales to be sighted farther from the vessel during other airgun operations, but the difference was not significant (Moulton and Holst 2010). Minke whales were seen significantly farther from the vessel during periods with than without seismic operations (Moulton and Holst 2010). Minke whales were also more likely to swim away and less likely to approach during seismic operations compared to periods when airguns were not operating (Moulton and Holst 2010). However, MacLean and Haley (2004) reported that minke whales occasionally approached active airgun arrays where received sound levels were estimated to be near 170–180 dB re 1 μ Pa.

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 sound levels from 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 behaviour (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 behavioural changes become evident. Because responsiveness is variable and 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. Responsiveness depends on the situation (Richardson et al. 1995; Ellison et al. 2012).

Studies of gray, bowhead, and humpback whales have determined that received levels of pulses in the 160–170 dB re 1 μ Pa_{rms} range seem to cause obvious avoidance behaviour in a substantial fraction of the animals exposed. In many areas, sound from seismic airgun 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 SPLs (120–130 dB re 1 μ Pa_{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 behaviour (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 is activated 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). In addition, results from Moulton and Holst (2010) showed that, during operations with a single airgun and during ramp up, blue whales were seen significantly farther from the vessel compared with periods without airgun operations. 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. Castellote et al. (2012) reported that fin whales avoided their potential winter ground for an extended period of time (at least 10 days) after seismic operations in the Mediterranean Sea had ceased. 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 (Allen and Angliss 2013). 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 (Allen and Angliss 2013). Bowheads also have been observed over periods of days or weeks in areas ensonified repeatedly by sound from seismic airgun 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 disturbance effects.

1.5.2 Toothed Whales

Historically, little systematic information is available about reactions of toothed whales to sound 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; Moulton and Holst 2010).

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 Osmek 1998; Stone 2003; Moulton and Miller 2005; Holst et al. 2006; Stone and Tasker 2006; Weir 2008a; Richardson et al. 2009; Moulton and Holst 2010; 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; Barry et al. 2010; Moulton and Holst 2010).

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. Moulton and Holst (2010) did not find any indications that long-finned pilot whales, or delphinids as a group, responded to ramp ups by moving away from the seismic vessel during surveys in the Northwest Atlantic. 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). Exposure modeling may be useful to evaluate and optimize ramp-up procedures for intense sound sources (von Benda-Beckmann et al. 2013).

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 whale 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). Preliminary findings of a monitoring study of narwhals in Melville Bay, Greenland (summer and fall 2012) showed no short-term effects of seismic survey activity on narwhal distribution, abundance, migration timing, and feeding habits (Heide-Jørgensen et al. 2013a). In addition, there were no reported effects on narwhal hunting. These findings do not seemingly support a suggestion by Heide-Jørgensen et al. (2013b) that seismic surveys in Baffin Bay may have delayed the migration timing of narwhals, thereby increasing the risk of narwhals to ice entrapment. .

Observers stationed on seismic vessels operating off the U.K. from 1997 to 2000 have provided data on the occurrence and behaviour 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-volume³ airgun arrays were active. 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 airgun activity compared with periods of inactivity. 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 airgun activation (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 airgun activation (Stone and Tasker 2006). For most types of small odontocetes sighted by observers on seismic vessels, the

³ Large volume means at least 1300 in³, with most (79%) at least 3000 in³.

median CPA distance was ≥ 0.5 km larger during airgun operations (Stone and Tasker 2006). Killer whales appeared to be more tolerant of seismic surveying 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 periods when the seismic source was active versus not active (Smultea et al. 2004; Holst et al. 2005a, 2006; Holst 2009; 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). 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 without than with seismic operations (Holst et al. 2005a). During a seismic survey off Taiwan for which the sample size was small ($n = 14$), Holst (2009) noted that the mean CPA distance of delphinids during seismic operations (1698 m) was greater compared with non-seismic periods (888 m).

For two additional NSF-funded L-DEO seismic surveys in the Eastern Tropical Pacific, both using a large 36-airgun array (~ 6600 in³), the results are less easily interpreted (Richardson et al. 2009). During both surveys, the delphinid detection rate was lower during periods when the seismic source was active versus not active, 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 seismic surveys in the Northwest Atlantic, delphinids as a group showed some localized avoidance of the operating array (Moulton and Holst 2010). The mean initial detection distance was significantly farther (by *ca.* 200 m) during seismic operations compared with periods when the seismic source was not active; however, there was no significant difference between sighting rates (Moulton and Holst 2010). The same results were evident when only long-finned pilot whales were considered.

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 in³ or 5085 in³) (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” behaviours.

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-volume⁴ 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 in³) 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 periods when the seismic source was active versus not active. However, mean CPAs were closer during seismic operations during one cruise (Holst et al. 2005b), and greater during another cruise (Haley and

⁴ For low volume arrays, maximum volume was 820 in³, with most (87%) ≤ 180 in³.

Koski 2004). Interpretation of the data was confounded by the fact that survey effort and/or number of sightings during periods when the source was not active during both surveys was small. Results from another two small-array surveys were even more variable (MacLean and Koski 2005; Smultea and Holst 2008; Holst and Robertson 2009).

Captive bottlenose dolphins and beluga whales exhibited changes in behaviour 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 in³). 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 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 behaviours 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 behaviours 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 behaviours mentioned above.

Odontocete responses (or lack of responses) to sound pulses from underwater explosions (as opposed to airgun pulses) may be indicative of odontocete responses to very strong sound pulses. During the 1950s, small explosive charges were dropped into an Alaskan river in attempts to scare beluga whales 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 sound 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 sound 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 harbour porpoises show stronger avoidance of seismic operations than do Dall’s porpoises (Stone 2003; MacLean and Koski 2005; Bain and Williams 2006). In Washington State waters, the harbour porpoise—despite being considered a high-frequency specialist—appeared to be the species affected by the lowest received SPL 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 harbour porpoises during periods when the airguns were active vs. silent (Stone 2003; Stone and Tasker 2006). A captive harbour porpoise exposed to single sound pulses from a small airgun showed aversive behaviour upon receipt of a pulse with received SPL above 174 dB re 1 μ Pa_{pk-pk} or SEL >145 dB re 1 μ Pa² · s (Lucke et al. 2009). Thompson et al. (2013) reported decreased densities and reduced acoustic detections of harbour porpoise in response to a seismic survey in Moray Firth, Scotland, at ranges of 5–10 km (SPLs of 165–172 dB re 1 μ Pa, SELs of 145–151 dB μ Pa² · s); however, animals returned to the area within a few hours. 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 harbour 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 behavioural reactions of beaked whales to seismic surveys. Most beaked whales tend to avoid approaching vessels of other types (e.g., Würsig et al. 1998) and/or change behaviour in response to sound from vessels (e.g., Pirotta et al. 2012). 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. Also, northern bottlenose whales sometimes are quite tolerant of slow-moving vessels not emitting airgun pulses (Reeves et al. 1993; Hooker et al. 2001). Detections (acoustic or visual) of northern bottlenose whales have been made from seismic vessels during recent seismic surveys in the Northwest Atlantic during periods with and without airgun operations (Potter et al. 2007; Moulton and Miller 2005). Similarly, 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 Cochrane 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; D'Amico et al. 2009; Filadelfo et al. 2009; 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 airgun 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 eastern Canada and Angola suggest that sperm whales in those areas show little evidence of avoidance or behavioural disruption in the presence of operating seismic vessels (Stone 2003; Stone and Tasker 2006; Weir 2008a; Moulton and Holst 2010). 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 in^3 or 5085 in^3) 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. Similarly, in the Northwest Atlantic, sighting rates and distances of sperm whales did not differ between periods when airguns were on vs. off (Moulton and Holst 2010). 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 SPLs 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 behaviour 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 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 SPLs of 111–147 dB re $1 \mu\text{Pa}_{\text{rms}}$ ($131\text{--}162 \text{ dB re } 1 \mu\text{Pa}_{\text{pk-pk}}$) at ranges of $\sim 1.4\text{--}12.8$ 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 behaviour 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, beluga whales 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 sound from sonars. Whether they ever do so in response to seismic survey sound 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 beluga whales and harbour 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 SPLs 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 behaviour at distances beyond those where received levels would be ~ 170 dB re $1 \mu\text{Pa}_{\text{rms}}$.

1.5.3 Pinnipeds

Few studies of the reactions of pinnipeds to sound 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 behaviour. 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 sound 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 sound 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 behaviour of harbour (common) and gray seals exposed to airgun pulses (Thompson et al. 1998). Harbour seals were exposed to sound pulses from a 90-in^3 array ($3 \times 30 \text{ in}^3$ airguns), and behavioural responses differed among individuals. One harbour seal avoided the array at distances up to 2.5 km from the source and only resumed foraging dives after the source stopped. Another harbour seal exposed to the same small airgun array showed no detectable behavioural response, even when the array was within 500 m. Gray seals exposed to sound from a single 10-in^3 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 sound

pulses from airguns. 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 behaviour 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 harbour seals and California sea lions tended to be larger when airguns were operating; both species tended to orientate away whether or not the airguns were active (Calambokidis and Osmek 1998). Bain and Williams (2006) also stated that their small sample of harbour seals and sea lions tended to orientate 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 behaviour of seals exposed to sound pulses from seismic airguns (Harris et al. 2001; Moulton and Lawson 2002). Those seismic projects usually involved arrays of 6–16 airguns with total volumes of 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 metres, 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 behaviour of seals visible at the surface within a few hundred metres of the airguns (Moulton and Lawson 2002). The behavioural 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 periods when the source was not active. No consistent relationship was observed between exposure to airgun sound and proportions of seals engaged in other recognizable behaviours, e.g., “looked” and “dove”. Such a relationship might have occurred if seals seek to reduce exposure to strong sound pulses, given the reduced airgun sound 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 independent of source activity, including periods without airgun operations. However, seals tended to be seen closer to the vessel during periods when no source was active vs. active. In contrast, during 2002, sighting rates of seals were higher during, and seals were seen farther from the vessel periods when no source was active vs. active (a marginally significant result). The combined data for both years showed that sighting rates were higher during periods when no source was active vs. active, and that sighting distances were similar independent of source activity. 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 (Funk et al. 2010). These observations indicate a tendency for phocid seals to exhibit localized avoidance of the seismic source vessel when airguns are active (Funk et al. 2010). In the Chukchi Sea, seal sighting rates were greater when no source was active from source vessels at locations with received sound levels (RLs) ≥ 160 and 159–120 dB re 1 $\mu\text{Pa}_{\text{rms}}$. Also, sighting rates were greater from source than monitoring vessels at locations with RLs < 120 dB rms (Haley et al. 2010). In the Beaufort Sea, seal sighting rates in areas with RLs ≥ 160 dB rms were also significantly higher from monitoring than from seismic source vessels, and sighting rates were significantly higher from source vessels in areas exposed to < 120 compared to ≥ 160 dB rms (Savarese et al. 2010). In addition, seals tended to stay farther away and swam away from source vessels more frequently than from monitoring vessels when RLs were ≥ 160 dB rms. Over the three years, seal sighting rates were greater from

monitoring than source vessels at locations with received sound levels ≥ 160 and 159–120 dB rms, whereas seal sighting rates were greater from source than monitoring vessels at locations with RLs < 120 dB rms, suggesting that seals may be reacting to active airguns by moving away from the source vessel.

Walrus near operating seismic surveys tend to swim away from the vessel (Hannay et al. 2011). Walrus calls were monitored during a low-energy shallow-hazards survey in 2009 and a 3-D seismic survey in 2010 (Hannay et al. 2010). During the shallow-hazard survey using a 40 in³ airgun, walrus call detections stopped at SPLs > 130 dB re 1 $\mu\text{Pa}_{\text{rms}}$ and declined at lower SPLs. During the large-array 3-D seismic survey, acoustic detections were negatively correlated with SPL at RLs of 110–140 dB, but no detections were made at SPLs > 140 dB re 1 $\mu\text{Pa}_{\text{rms}}$. Hannay et al. (2011) suggested that walrus likely reduced calling rates upon exposure to higher SPLs without leaving the area.

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 behaviour. These studies show that many pinnipeds do not avoid the area within a few hundred metres 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).

1.6. 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 precautionary for at least some species including bottlenose dolphin and beluga, i.e., lower than necessary to avoid temporary auditory impairment let alone permanent auditory injury.
- the 180-dB criterion may not be precautionary with regard to TTS in some other cetacean species, including the harbour porpoise. Likewise, the 190-dB criterion for pinnipeds may not be precautionary for all pinnipeds, although for pinnipeds the underlying data are indirect and quite variable among species.
- the likelihood of TTS (and probably also PTS) upon exposure to high-level sound may be better correlated with the amount of acoustic energy received by the animal, measured by the cumulative sound exposure level (SEL) in dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$, than it is with maximum received RMS pressure level in dB re 1 $\mu\text{Pa}_{\text{rms}}$. SEL allows for exposure duration and/or number of exposures; the maximum rms level does not. Thus, the current U.S. criteria may not be expressed in the most appropriate acoustic units.
- low and moderate degrees of TTS, up to at least 30 dB of elevation of the threshold, are not considered injury and do not constitute “Level A harassment” in U.S. MMPA terminology. Beyond that level, TTS may grade into PTS (Le Prell 2012).

- 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 sound exposure criteria for marine mammals, frequency-weighting procedures, and related matters were published by Southall et al. (2007). Those recommendations were never formally adopted by NMFS for use in regulatory processes and during mitigation programs associated with seismic surveys, although some aspects of the recommendations have been taken into account in certain EISs and small-take authorizations. NMFS recently proposed new procedures taking at least some of the Southall et al. recommendations into account (NOAA 2013). The new sound exposure criteria for marine mammals will account for the now additional 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.

Nowacek et al. (2013) concluded that current scientific data indicate that seismic airguns have a low probability of directly harming marine life, except at close range. 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 sound-induced hearing impairment and non-auditory physical effects.

1.6.1 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; Le Prell 2012). Rather, the onset of TTS has been considered an indicator that, if the animal is exposed to higher levels of that sound, physical damage is ultimately a possibility. Recent research has shown that sound exposure can cause cochlear neural degeneration, even when threshold shifts and hair cell damage are reversible (Liberman 2013). These findings have raised some doubts as to whether TTS should continue to be considered a non-injurious effect.

The magnitude of TTS depends on the level and duration of sound 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 sound ends. Extensive studies on terrestrial mammal hearing in air show that TTS can last from minutes or hours to (in cases of strong TTS) days. More limited data from odontocetes and pinnipeds show similar patterns (e.g., Mooney et al. 2009a,b; Finneran et al. 2010a). However, 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, belugas, and finless porpoise. 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) and multiple pulses from an airgun (Finneran et al. 2011; Schlundt et al. 2013). 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 (Finneran 2012). Kastak et al. (2005) reported preliminary evidence from pinnipeds that, for prolonged non-impulse sound, 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 sound 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 was 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. Popov et al. (2011) examined the effects of fatiguing noise on the hearing threshold of Yangtze finless porpoises when exposed to frequencies of 32–128 kHz at 140–160 dB re 1 μPa for 1–30 min. They found that an exposure of higher level and shorter duration produced a higher TTS than an exposure of equal SEL but of lower level and longer duration. Kastelein et al. (2012a,b; 2013b) also reported that the equal energy model is not valid for predicting TTS in harbour porpoise or harbour seals, and Supin et al. (2013) reported that SEL may not be a valid metric for examining fatiguing sounds on beluga whales.

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).⁵ 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 kilometres 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 sound pulses from an

⁵ 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).

airgun source that each has a flat-weighted received level 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. However, recent data have shown that the SEL required for TTS onset to occur increases with intermittent exposures, with some auditory recovery during silent periods between signals (Finneran et al. 2010b; Finneran and Schlundt 2011). Schlundt et al. (2013) reported that the potential for seismic surveys using airguns to cause auditory effects on dolphins may be lower than previously thought. Based on behavioural tests, Finneran et al. (2011) and Schlundt et al. (2013) reported no measurable TTS in bottlenose dolphins after exposure to 10 impulses from a seismic airgun with a cumulative SEL of ~195 dB re 1 μPa² · s; results from AEP measurements were more variable (Schlundt et al. 2013).

The conclusion that the TTS threshold is higher for non-impulse sound than for impulse sound is somewhat speculative. The available TTS data for a beluga whale exposed to impulse sound are extremely limited, and the TTS data from the beluga whale and bottlenose dolphin exposed to non-pulse sound pertain to sounds at 3 kHz and above. Follow-on work has shown that the SEL necessary to elicit TTS can depend substantially on frequency, with susceptibility to TTS increasing with increasing frequency above 3 kHz (Finneran and Schlundt 2010, 2011; Finneran 2012). When beluga whales were exposed to fatiguing noise with sound levels of 165 dB re 1 μPa for durations of 1 to 30 min at frequencies of 11.2 to 90 kHz, the highest TTS with the longest recovery time was produced by the lower frequencies (11.2 and 22.5 kHz); TTS effects also gradually increased with prolonged exposure time (Popov et al. 2013a). Popov et al. (2013b) also reported that TTS produced by exposure to a fatiguing noise was larger during the first session (or naïve subject state) with a beluga whale than TTS that resulted from the same sound in subsequent sessions (experienced subject state). Similarly, Nachtigall and Supin (2013) reported that false killer whales are able to change their hearing sensation levels when exposed to loud sounds, such as warning signals or echolocation sounds.

The above TTS information for odontocetes is derived from studies on the bottlenose dolphin and beluga. There have been no studies of narwhal hearing impairment attributable to airgun sounds. For a harbour porpoise, the received level of airgun sound that elicited onset of TTS was lower (Lucke et al. 2009). 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. 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. Tougaard et al. (2013) proposed a TTS criterion of 165 dB re 1 μPa² · s for porpoises based on the data from two studies.

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, one would (as a minimum) need to allow for the sequence of distances at which airgun pulses would occur, and for the dependence of

received SEL on distance in the region of the seismic operation (e.g., Erbe and King 2009; Breitzke and Bohlen 2010; Laws 2012). 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 harbour 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. (2011) suggested that some baleen whales whose closest point of approach to a seismic vessel is 1 km or more could experience TTS.

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 and pulse) exposures suggested that some pinnipeds (harbour seals in particular) incur TTS at somewhat lower received levels than do small odontocetes exposed for similar durations (Kastak et al. 1999, 2005, 2008; Ketten et al. 2001; Kastelein et al. 2013b). Kastak et al. (2005) reported that the amount of threshold shift increased with increasing SEL in a California sea lion and harbour 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. Kastak et al. (2008) exposed a harbour seal to an underwater pure tone at 4.1 kHz for 60 s (SEL of 202 dB re $1 \mu\text{Pa}^2$) and reported an initial threshold shift in excess of 50 dB upon a second exposure to the sound.

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 harbour 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 harbour seals (Kastak et al. 2005). Thus, the former two species would presumably need to be closer to an airgun array than would a harbour seal before TTS is a possibility. Insofar as we are aware, there are no data to indicate whether the TTS thresholds of other pinniped species are more similar to those of the harbour seal or to those of the two less-sensitive species.

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 harbour seal than for odontocetes exposed to impulse sound (see above), it is possible that some pinnipeds close to a large airgun array could incur TTS.

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 harbour seal, harbour 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 harbour seals and harbour 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 harbour 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 metres 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).

1.6.2 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. 2011). In terrestrial animals, exposure to sounds sufficiently strong to elicit a large TTS induces physiological and structural changes in the inner ear, and at some high level of sound exposure, these phenomena become non-recoverable (Le Prell 2012). At this level of sound exposure, TTS grades into PTS. 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 (e.g., Kastak and Reichmuth 2007; Kastak et al. 2008).

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). When a harbour seal was exposed to an underwater pure tone at 4.1 kHz for 60 s (SEL of 202 dB re 1 μPa^2), an initial threshold shift in excess of 50 dB was reported upon the second exposure to the sound; a possible permanent threshold shift of 7–10 dB was still evident two months after the exposure (Kastak et al. 2008). 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. Kastelein et al. (2013b) suggested that for a harbour seal exposed to octave-band white noise centred at 4 kHz for 60 min with mean SPLs of 124–148 re 1 μPa , the onset of PTS would require a level of at least 22 dB above the TTS onset.

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 watergun 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 harbour 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 noted that, regardless of the SEL, there is concern about the possibility of PTS if a cetacean or pinniped received one or more pulses with peak pressure exceeding 230 or 218 dB re 1 μPa , 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 harbour 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, numerous assumptions, and species differences. Also, data have been published subsequent to Southall et al. (2007) indicating that, at least for non-pulse sounds, the “equal energy” model is not be entirely correct—TTS and presumably PTS thresholds may depend somewhat on the duration over which sound energy is accumulated, the frequency of the sound, whether or not there are gaps, and probably other factors (Ketten 1994, 2012). 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 pulses 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., harbour seal) as well as the harbour porpoise may be lower (Kastak et al. 2005; Southall et al. 2007; Lucke et al. 2009; Kastelein et al. 2012a,b, 2013b). 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 sound-induced hearing damage in marine mammals, particularly baleen whales, pinnipeds, and sea otters;
- the seemingly greater susceptibility of certain species (e.g., harbour porpoise and harbour seal) to TTS and presumably also PTS; and
- the lack of knowledge about TTS and PTS thresholds in many species, including various species closely related to the harbour porpoise and harbour seal.

The avoidance reactions of many marine mammals, along with commonly-applied monitoring and mitigation measures (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.

1.6.3 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 behavioural 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 behaviour (such as a change in diving behaviour 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 behavioural 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 behavioural 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; Kvasdshheim et al. 2012).

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. However, Gray and Van Waerebeek (2011) have suggested a cause-effect relationship between a seismic survey off Liberia in 2009 and the erratic movement, postural instability, and akinesia in a pantropical spotted dolphin based on spatially and temporally close association with the airgun array. Additionally, 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 (e.g., Castellote and Llorens 2013). • 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).

1.6.4 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, 2011). 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; Nieuwkirk et al. 2012) 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. (I) 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 μ Pa \cdot m_{p-p}) and

single short-duration pure tones (sound pressure level up to 201 dB re 1 μ Pa) 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. (3) Rolland et al. (2012) suggested that ship noise causes increased stress in right whales; they showed that baseline levels of stress-related faecal hormone metabolites decreased in North Atlantic right whales with a 6 dB decrease in underwater noise from vessels.

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 5:

REVIEW OF THE EFFECTS OF AIRGUN SOUNDS ON SEA TURTLES¹

The following subsections review relevant information concerning the potential effects of airgun sounds on sea turtles. This information is included here as background. Much of this information has been included in varying formats in previous reviews, assessments, and regulatory applications prepared by LGL Limited.

1. Sea Turtle Hearing

Although there have been a limited number of studies on sea turtle hearing (see review by Southwood et al. 2008), the available data are not very comprehensive. However, these data demonstrate that sea turtles appear to be low-frequency specialists (see Table 1).

Sea turtle auditory perception is thought to occur through a combination of both bone and water conduction rather than air conduction (Lenhardt 1982; Lenhardt and Harkins 1983). Detailed descriptions of sea turtle ear anatomy are found in Ridgway et al. (1969), Lenhardt et al. (1985), and Bartol and Musick (2003). Sea turtles do not have external ears, but the middle ear is well adapted as a peripheral component of a bone conduction system. The thick tympanum is disadvantageous as an aerial receptor, but enhances low-frequency bone conduction hearing (Lenhardt et al. 1985; Bartol et al. 1999; Bartol and Musick 2003). A layer of subtympantal fat emerging from the middle ear is fused to the tympanum (Ketten et al. 2006; Bartol 2004, 2008). A cartilaginous disk, the extracolumella, is found under the tympanic membrane and is attached to the columella (Bartol 2004, 2008). The columella is a long rod that expands to form the stapes, and fibrous strands connect the stapes to the sacculle (Bartol 2004, 2008). When the tympanum is depressed, the vibrations are conveyed via the fibrous stapedo-sacular strands to the sacculle (Lenhardt et al. 1985). This arrangement of fat deposits and bone enables sea turtles to hear low-frequency sounds while underwater and makes them relatively insensitive to sound above water. Vibrations can also be conducted through the bones of the carapace to reach the middle ear. Based on studies of semi-aquatic turtles, Christensen-Dalsgaard et al. (2012) speculated that the sea turtle ear may not be specialized for bone conduction, but rather that sound-induced pulsations may drive the tympanic disc if the middle ear cavity is air-filled. Willis et al. (2013) also reported on the importance of the middle ear cavity in underwater sound detection in turtles.

A variety of audiometric methods are available to assess hearing abilities. Electrophysiological measures of hearing (e.g., auditory brainstem response or ABR) provide good information about relative sensitivity to different frequencies. However, this approach may underestimate the frequency range to which the animal is sensitive and may be imprecise at determining absolute hearing thresholds (e.g., Wolski et al. 2003). Nevertheless, when time is critical and only untrained animals are available, this method can provide useful information on sea turtle hearing (e.g., Wolski et al. 2003).

Ridgway et al. (1969) obtained the first direct measurements of sea turtle hearing sensitivity (Table 1). They used an electrophysiological technique (cochlear potentials) to determine the response of

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TABLE 1. Hearing capabilities of sea turtles as measured using behavioural and electro-physiological techniques. ABR: auditory brainstem response; AEP: auditory evoked potential; Beh.: behavioural.

Sea Turtle Species	Hearing		Technique	Source
	Range (Hz)	Highest Sensitivity (Hz)		
Green	60-1000	300-500	Cochlear Potentials ^a	Ridgway et al. 1969
	100-800	600-700 (juveniles) 200-400 (subadults)	ABR ^w	Bartol & Ketten 2006; Ketten & Bartol 2006
	50-1600	50-400	AEP ^{a,w}	Dow Piniak et al. 2012a
Loggerhead	250-1000	250	ABR ^a	Bartol et al. 1999;
	50-1131	100-400	AEP ^w , Beh. ^w	Martin et al. 2012
Kemp's ridley	100-500	100-200	ABR ^w	Bartol & Ketten 2006; Ketten & Bartol 2006
Leatherback	50-1600	100-400	AEP ^{a,w}	Dow Piniak et al. 2012b

^a measured in air; ^w measured underwater. Note that there are no empirical data available for hawksbill, Olive ridley, and flatback sea turtles.

green sea turtles (*Chelonia mydas*) to aerial- and vibrational-stimuli consisting of tones with frequencies 30 to 700 Hz. They found that green turtles exhibit maximum hearing sensitivity between 300 and 500Hz, and speculated that the turtles had a useful hearing range of 60–1000 Hz. (However, there was some response to strong vibrational signals at frequencies down to the lowest one tested — 30 Hz.)

Bartol et al. (1999) tested the in-air hearing of juvenile loggerhead turtles *Caretta caretta* (Table 1). The authors used ABR to determine the response of the sea turtle ear to two types of vibrational stimuli: (1) brief, low-frequency broadband clicks, and (2) brief tone bursts at four frequencies from 250 to 1000 Hz. They demonstrated that loggerhead sea turtles hear well between 250 and 1000 Hz; within that frequency range the turtles were most sensitive at 250 Hz. The authors did not measure hearing sensitivity below 250 Hz or above 1000 Hz. The signals used in this study were very brief — 0.6 ms for the clicks and 0.8–5.5 ms for the tone bursts. In other animals, auditory thresholds decrease with increasing signal duration up to ~100–200 ms. Thus, sea turtles probably could hear weaker signals than demonstrated in the study if the signal duration were longer.

Lavender et al. (2012) used ABR and behavioural audiogram analyses to examine the hearing of sub-adult loggerhead turtles. They found that the turtles responded to sounds with frequencies of 200 to 700 Hz, and that behavioural response time increased near the hearing threshold. Martin et al. (2012) used both behavioural and auditory evoked potential methods to derive an underwater audiogram of an adult loggerhead turtle. Both testing methods confirmed that the loggerhead turtle has low-frequency hearing and that best sensitivity occurred from 100–400 Hz.

Lenhardt (2002) exposed loggerhead turtles while they were near the bottom of holding tanks at a depth of 1 m to tones from 35 to 1000 Hz. The turtles exhibited startle responses (neck contractions) to these tones. The lowest thresholds were in the 400–500 Hz range (106 dB SPL re 1 μ Pa), and thresholds in the 100–200 Hz range were ~124 dB (Lenhardt 2002). Thresholds at 735 and 100 Hz were 117 and 156 dB, respectively (Lenhardt 2002). Diving behaviour occurred at 30 Hz and 164 dB.

ABR techniques have been used to determine the underwater hearing capabilities of six subadult green turtles, two juvenile green turtles, and two juvenile Kemp's ridley (*Lepidochelys kempii*) turtles (Ketten and Bartol 2006; Bartol and Ketten 2006; Table 1). The turtles were physically restrained in a small box tank with their ears below the water surface and the top of the head exposed above the surface. Pure-tone acoustic stimuli were presented to the animals, though the exact frequencies of these tones were not indicated. The six subadult green turtles detected sound at frequencies 100–500 Hz, with the most sensitive hearing at 200–400 Hz. In contrast, the two juvenile green turtles exhibited a slightly expanded overall hearing range of 100–800 Hz, with their most sensitive hearing occurring at 600–700 Hz. The most restricted range of sensitive hearing (100–200 Hz) was found in the two juvenile Kemp's ridley turtles, whose overall frequency range was 100–500 Hz.

Preliminary data from a similar study of a trained, captive green turtle indicate that the animal heard and responded behaviourally to underwater tones ranging in frequency from 100 to 500 Hz. At 200 Hz, the threshold was between 107 and 119 dB, and at 400 Hz the threshold was between 121 and 131 dB [reference units not provided] (Streeter 2003; ONR N.D.).

The hearing sensitivity of leatherback hatchlings was tested in water and in air using auditory evoked potentials (Dow Piniak et al. 2012b). Hatchlings were exposed to 50 ms pulsed tones between 50 and 1600 Hz. The hatchlings responded to sound stimuli between 50 and 1200 Hz in water and 50 and 1600 Hz in air, with best hearing between 100 and 400 Hz in water (84 dB re 1 $\mu\text{Pa}_{\text{rms}}$ at 300 Hz) and 50 to 400 Hz in air (62 dB re 20 $\mu\text{Pa}_{\text{rms}}$ at 300 Hz).

In summary, the limited available data indicate that the frequency range of best hearing sensitivity of sea turtles extends from ~100 to 700 Hz. Sensitivity deteriorates as one moves away from this range to either lower or higher frequencies. However, there is some sensitivity to frequencies as low as 60 Hz, and probably as low as 30 Hz (Ridgway et al. 1969). Thus, there is substantial overlap in the frequencies that sea turtles detect and the dominant frequencies produced by airgun pulses. Given that, plus the high energy levels of airgun pulses, we can conclude that sea turtles hear airgun sounds. However, we are not aware of measurements of the absolute hearing thresholds of any sea turtle to waterborne sounds similar to airgun pulses. Given the high source levels of airgun pulses and the substantial received levels even at distances many km away from the source, it is probable that sea turtles can also hear the sound source output from distant seismic vessels. However, in the absence of relevant absolute threshold data, we cannot estimate how far away an airgun array might be audible to a sea turtle.

2. Effects of Airgun Pulses on Behaviour and Movement

The effects of exposure to airgun pulses on the behaviour and distribution of various marine animals have been studied over the past three decades. Most such studies have concerned marine mammals (e.g., see reviews by Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Southall et al. 2007), but also fish (e.g., reviewed by Thomson et al. 2001; Herata 2007; Payne et al. 2008). There have been far fewer studies on the effects of airgun sound (or indeed any type of sound) on sea turtles, and little is known about the sound levels that will or will not elicit various types of behavioural reactions. There have been four directed studies that focused on short-term behavioural responses of sea turtles in enclosures to single airguns. However, comparisons of results among studies are difficult because experimental designs and reporting procedures have varied greatly, and few studies provided specific information about the levels of the airgun pulses received by the turtles. Although monitoring studies are now providing some information on responses (or lack of responses) of free-ranging sea turtles to seismic surveys, we are not aware of any directed studies on responses of free-ranging sea turtles to seismic sounds or on the long-term effects of seismic or other sounds on sea turtles.

Directed Studies.—The most recent of the studies of caged sea turtles exposed to airgun pulses was a study by McCauley et al. (2000a,b) off Western Australia. The authors exposed caged green and loggerhead sea turtles (one of each) to pulses from an approaching and then receding 20 in³ airgun operating at 1500 psi and a 5-m airgun depth. The single airgun was activated every 10 s. There were two trials separated by two days; the first trial involved ~2 h of airgun exposure and the second ~1 h. The results from the two trials showed that, above a received level of 166 dB re 1 μ Pa (rms)², the turtles noticeably increased their swim speed relative to periods when no airguns were operating. The behaviour of the sea turtles became more erratic when received levels exceeded 175 dB re 1 μ Pa (rms). The authors suggested that the erratic behaviour exhibited by the caged sea turtles would likely, in unrestrained turtles, be expressed as an avoidance response (McCauley et al. 2000a,b).

O’Hara and Wilcox (1990) tested the reactions to airguns by loggerhead sea turtles held in a 300 × 45 m area of a canal in Florida with a bottom depth of 10 m. Nine turtles were tested at different times. The sound source consisted of one 10 in³ airgun plus two 0.8 in³ “poppers” operating at 2000 psi³ and an airgun-depth of 2 m for prolonged periods of 20–36 h. The turtles maintained a standoff range of about 30 m when exposed to airgun pulses every 15 or 7.5 s. Some turtles may have remained on the bottom of the enclosure when exposed to airgun pulses. O’Hara and Wilcox (1990) did not measure the received airgun sound levels. McCauley et al. (2000a,b) estimated that “the level at which O’Hara saw avoidance was around 175–176 dB re 1 μ Pa rms.” The levels received by the turtles in the Florida study probably were actually a few dB less than 175–176 dB because the calculations by McCauley et al. apparently did not allow for the shallow 2-m airgun depth in the Florida study. The effective source level of airguns is less when they are at a depth of 2 m vs. 5 m (Greene et al. 2000).

Moein et al. (1994) investigated the avoidance behaviour and physiological responses of loggerhead turtles exposed to an operating airgun, as well as the effects on their hearing. The turtles were held in a netted enclosure ~18 m by 61 m by 3.6 m deep, with an airgun of unspecified size at each end. Only one airgun was operated at any one time; the firing rate was one pulse every 5–6 s. Ten turtles were tested individually, and seven of these were retested several days later. The airgun was initially discharged when the turtles were near the center of the enclosure and the subsequent movements of the turtles were documented. The turtles exhibited avoidance during the first presentation of airgun sounds at a mean range of 24 m, but the avoidance response waned quickly. Additional trials conducted on the same turtles several days later did not show statistically significant avoidance reactions. However, there was an indication of slight initial avoidance followed by rapid waning of the avoidance response which the authors described as “habituation”. Their auditory study indicated that exposure to the airgun pulses may have resulted in temporary threshold shift (TTS; see later section). Reduced hearing sensitivity may also have contributed to the waning response upon continued exposure. Based on physiological

² rms = root mean square. This measure represents the average received sound pressure over the duration of the pulse, with duration being defined in a specific way (from the time when 5% of the pulse energy has been received to the time when 95% of the energy has been received). The rms received level of a seismic pulse is typically about 10 dB less than its peak level, and about 16 dB less than its peak-to-peak level (Greene et al. 1997, 2000; McCauley et al. 1998, 2000a,b).

³ There was no significant reaction by five turtles during an initial series of tests with the airguns operating at the unusually low pressure of 1000 psi. The source and received levels of airgun sounds would have been substantially lower when the air pressure was only 1000 psi than when it was at the more typical operating pressure of 2000 psi.

measurements, there was some evidence of increased stress in the sea turtles, but this stress could also have resulted from handling of the turtles.

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

Lenhardt (2002) exposed captive loggerhead sea turtles while underwater to seismic airgun (Bolt 600) sounds in a large net enclosure. At received levels of 151–161 dB, turtles were found to increase swimming speeds. Similar to the McCauley et al. studies (2000a,b--see above), near a received level of ~175 dB, an avoidance reaction was common in initial trials, but habituation then appeared to occur. Based on ABRs measured pre- and post-airgun exposures, a TTS of over 15 dB was found in one animal, with recovery two weeks later. Lenhardt (2002) suggested that exposure of sea turtles to airguns at water depths >10 m may result in exposure to more energy in the low frequencies with unknown biological effects.

Despite the problems in comparing these studies, they are consistent in showing that, at some received level, sea turtles show avoidance of an operating airgun. McCauley et al. (2000a,b) found evidence of behavioural responses when the received level from a single small airgun was 166 dB re 1 μ Pa rms and avoidance responses at 175 dB re 1 μ Pa rms. Based on these data, McCauley et al. estimated that, for a typical airgun array (2678 in³, 12-elements) operating in 100–120 m water depth, sea turtles may exhibit behavioural changes at ~2 km and avoidance around 1 km. These estimates are subject to great variation, depending on the seismic source and local propagation conditions.

A further potential complication is that sea turtles on or near the bottom may receive sediment-borne “headwave” signals from the airguns (McCauley et al. 2000a,b). As previously discussed, it is believed that sea turtles use bone conduction to hear. It is unknown how sea turtles might respond to the headwave component of an airgun impulse or to bottom vibrations during seismic surveys in shallow waters.

Related studies involving stimuli other than airguns may also be relevant. (1) Two loggerhead turtles resting on the bottom of shallow tanks responded repeatedly to low-frequency (20–80 Hz) tones by becoming active and swimming to the surface. They remained at the surface or only slightly submerged for the remainder of the 1-min trial (Lenhardt 1994). Although no detailed data on sound levels at the bottom vs. surface were reported, the surfacing response probably reduced the levels of underwater sound to which the turtles were exposed. (2) In a separate study, a loggerhead and a Kemp's ridley sea turtle responded similarly when vibratory stimuli at 250 or 500 Hz were applied to the head for 1 s (Lenhardt et al. 1983). There appeared to be rapid habituation to these vibratory stimuli. (3) Sea turtles in tanks showed agitated behaviour when exposed to simulated boat noise and recordings from the U.S. Navy's Low Frequency Active (LFA) sonar (Samuel 2004; Samuel et al. 2006). The tones and vibratory stimuli used in these studies were quite different from airgun pulses. However, it is possible that resting sea turtles may exhibit a similar “alarm” response, possibly including surfacing or alternatively diving, when exposed to any audible sound, regardless of whether it is a pulsed sound or tone.

Monitoring Results.—Data on sea turtle behaviour near airgun operations have also been collected during marine mammal and sea turtle monitoring and mitigation programs associated with various seismic operations around the world. Although the primary objectives concerned marine mammals, sea turtle sightings have also been documented in some of monitoring projects. Vessel-based observations indicate that avoidance of approaching seismic vessels is small-scale such that sea turtles are often seen from operating seismic vessels. Also, average distances from the airguns to these sea turtles are usually not greatly increased when the airguns are operating as compared with times when airguns are silent.

For example, during six large-source (10–20 airguns; 3050–8760 in³) and small-source (up to six airguns or three GI guns; 75–1350 in³) surveys conducted by L-DEO during 2003–2005, the mean closest point of approach (CPA) for turtles was closer during non-seismic than seismic periods: 139 m vs. 228 m and 120 m vs. 285 m, respectively (Holst et al. 2006). During a large-source L-DEO seismic survey off the Pacific coast of Central America in 2008, the turtle sighting rate during non-seismic periods was seven times greater than that during seismic periods (Holst and Smultea 2008). In addition, distances of turtles seen from the seismic vessel were significantly farther from the airgun array when it was operating (mean 159 m, $n = 77$) than when the airguns were off (mean 118 m, $n = 69$; Mann-Whitney U test, $P < 0.001$) (Holst and Smultea 2008). During another L-DEO survey in the Eastern Tropical Pacific in 2008, the turtle sighting rate during non-seismic periods was 1.5 times greater than that during seismic periods; however, turtles tended to be seen closer to the airgun array when it was operating, but this difference was not statistically significant (Hauser et al. 2008).

Weir (2007) reported on the behaviour of sea turtles near seismic exploration operations off Angola, West Africa. A total of 240 sea turtles were seen during 676 h of vessel-based monitoring, mainly for associated marine mammals mitigation measures. Airgun arrays with total volumes of 5085 and 3147 in³ were used at different times during the seismic program. Sea turtles tended to be seen slightly closer to the seismic source, and at sighting rates twice as high, during non-seismic vs. seismic periods (Weir 2007). However, there was no significant difference in the median distance of turtle sightings from the array during non-seismic vs. seismic periods, with means of 743 m ($n = 112$) and 779 m ($n = 57$). DeRuiter and Doukara (2012) observed that small numbers of basking loggerhead sea turtles ($n = 6$ of 86 turtles of whose behaviour was observed) exhibited an apparent startle response (sudden raising of the head and splashing of flippers, occasionally accompanied by blowing bubbles from the beak and nostrils, followed by a short dive) immediately following an airgun pulse. Diving turtles (49 of 86 individuals) were observed at distances from the center of the airgun array ranging from 50–839 m. The estimated sound level at the median distance of 130 m was 191 dB re 1 μ Pa (peak). These observations were made during ~150 h of vessel-based monitoring from a seismic vessel actively operating an airgun array (13 airgun, 2440 in³) off Algeria—there was no corresponding observation effort during periods when the airgun array was inactive (DeRuiter and Doukara 2012).

Off northeastern Brazil, 46 sea turtles were seen during 2028 h of vessel-based monitoring of seismic exploration using 4–8 GI airguns between June 2002 and August 2003 (Parente et al. 2006). Although slightly more sea turtles were sighted during non-seismic (0.075 turtles per hour) than seismic periods (0.054 turtles per hour), the sighting rates were not statistically significant. Detailed behavioural data during seismic operations were lacking (Parente et al. 2006). Moreira de Gurjão et al. (2005) suggested that sea turtles may have shown some avoidance around a seismic survey off Bahia State, Brazil, during January to May 2002.

Behavioural responses of marine mammals and fish to seismic surveys sometimes vary depending on species, time of year, activity of the animal, and other unknown factors. The same species may show different responses at different times of year or even on different days (e.g., Richardson et al. 1995;

Thomson et al. 2001). Sea turtles of different ages vary in size, behaviour, feeding habits, and preferred water depths. Nothing specific is known about the ways in which these factors may be related to airgun sound effects in sea turtles. However, it is reasonable to expect lesser effects in young turtles concentrated near the surface (where levels of airgun sounds are attenuated) as compared with older turtles that spend more time at depth where airgun sounds are generally stronger.

3. Possible Effects of Airgun Sounds on Distribution

In captive enclosures, sea turtles generally respond to seismic sound by startling, increasing swimming speed, and/or swimming away from the sound source. Animals resting on the bottom often become active and move toward the surface where received sound levels normally will be reduced, although some turtles dive upon exposure. Unfortunately, quantitative data for free-ranging sea turtles exposed to seismic pulses are very limited, and potential long-term behavioural effects of seismic exposure have not been investigated. The paucity of data precludes clear predictions of sea turtle responses to seismic sound. Available evidence suggests that localized behavioural and distributional effects on sea turtles are likely during seismic operations, including responses to the seismic vessel, airguns, and other gear (e.g., McCauley 1994; Pendoley 1997; Weir 2007). Pendoley (1997) summarized potential effects of seismic operations on the behaviour and distribution of sea turtles and identified biological periods and habitats considered most sensitive to potential disturbance. The possible responses of free-ranging sea turtles to seismic pulses could include

- avoiding the entire seismic survey area to the extent that turtles move to less preferred habitat;
- avoiding only the immediate area around the active seismic vessel (i.e., local avoidance of the source vessel but remain in the general area); and
- exhibiting no appreciable avoidance, although short-term behavioural reactions are likely.

Complete avoidance of an area, if it occurred, could exclude sea turtles from their preferred foraging area and could displace them to areas where foraging is sub-optimal. Avoidance of a preferred foraging area may prevent sea turtles from obtaining preferred prey species and hence could impact their nutritional status. The potential alteration of a migration route might also have negative impacts. However, it is not known whether avoidance by sea turtles would ever be on a sufficient geographic scale, or be sufficiently prolonged, to prevent turtles from reaching an important destination.

Available evidence suggests that the zone of avoidance around seismic sources is not likely to exceed a few kilometers (McCauley et al. 2000a,b). Avoidance reactions on that scale could prevent sea turtles from using an important coastal area or bay if there was a prolonged seismic operation in the area, particularly in shallow waters (e.g., Pendoley 1997). If such avoidance were to occur, it is uncertain how long it would last. Sea turtles might be excluded from the area for the duration of the seismic operation, or they might remain but exhibit abnormal behavioural patterns (e.g., lingering longer than normal at the surface where received sound levels are lower). Whether those that were displaced would return quickly after the seismic operation ended is unknown.

It is unclear whether exclusion from a particular nesting beach by seismic operations, if it occurred, would prevent or decrease reproductive success. It is believed that females migrate to the region of their birth and select a nesting beach (Miller 1997). However, the degree of site fidelity varies between species and also intra-seasonally by individuals. If a sea turtle is excluded from a particular beach, it may select a more distant, undisturbed nesting site in the general area (Miller 1997). For instance, Bjorndal et al. (1983) reported a maximal intra-seasonal distance between nesting sites of 290 km, indicating that turtles use multiple nesting sites spaced up to a few hundred kilometers apart. Also, it is uncertain whether a

turtle that failed to go ashore because of seismic survey activity would abandon the area for that full breeding cycle, or would simply delay going ashore until the seismic vessel moved to a different area.

Shallow coastal waters can contain relatively high densities of sea turtles during nesting, hatching, and foraging periods. Thus, seismic operations in these areas could correspondingly impact a relatively higher number of individual turtles during sensitive biological periods. Samuel et al. (2005) noted that anthropogenic noise in vital sea turtle habitats, such as a major coastal foraging area off Long Island, NY, could affect sea turtle behaviour and ecology. There are no specific data that demonstrate the consequences to sea turtles if seismic operations with large or small arrays of airguns occur in important areas at biologically important times of year. However, a number of mitigation measures can, on a case-by-case basis, be considered for application in areas important to sea turtles (e.g., Pendoley 1997).

4. Possible Effects of Airgun Sounds on Hearing

Noise-induced hearing damage can be either temporary or permanent. In general, the received sound must be strong for either to occur, and must be especially strong and/or prolonged for permanent impairment to occur.

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

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

The results from captive, restrained sea turtles exposed repeatedly to seismic sounds in enclosed areas indicate that TTS is possible under these artificial conditions. However, there are no data to indicate whether there are any plausible field situations in which exposure to repeated airgun pulses at close range could cause permanent threshold shift (PTS) or hearing impairment in sea turtles. Hearing impairment (whether temporary or permanent) from seismic sounds is considered unlikely to occur at sea;

turtles are unlikely to be exposed to more than a few strong pulses close to the sound source, as individuals are mobile and the vessel travels relatively quickly compared to the swimming speed of a sea turtle. However, in the absence of specific information on received levels of impulse sound necessary to elicit TTS and PTS in sea turtles, it is uncertain whether there are circumstances where these effects could occur in the field. If sea turtles exhibit little or no behavioural avoidance, or if they acclimate to seismic sound to the extent that avoidance reactions cease, sea turtles might sustain hearing loss if they are close enough to seismic sources. Similarly, in the absence of quantitative data on behavioural responses, it is unclear whether turtles in the area of seismic operations prior to start-up move out of the area when standard ramp-up (=soft-start) procedures are in effect. It has been proposed that sea turtles require a longer ramp-up period because of their relatively slow swimming speeds (Eckert 2000). However, it is unclear at what distance (if any) from a seismic source sea turtles could sustain hearing impairment, and whether there would ever be a possibility of exposure to sufficiently high levels for a sufficiently long period to cause permanent hearing damage.

In theory, a reduction in hearing sensitivity, either temporary or permanent, may be harmful for sea turtles. However, very little is known about the role of sound perception in the sea turtle's normal activities. While it is not possible to estimate how much of a problem it would be for a turtle to have either temporary or permanent hearing impairment, there is some evidence indicating that hearing plays an important role in sea turtle survival. (1) It has been suggested (Eckert et al. 1998; Eckert 2000) that sea turtles may use passive reception of acoustic signals to detect the hunting sonar of killer whales (*Orcinus orca*), a known predator of leatherback sea turtles *Dermochelys coriacea* (Fertl and Fulling 2007). Further investigation is needed before this hypothesis can be accepted. Some communication calls of killer whales include components at frequencies low enough to overlap the frequency range where sea turtles hear. However, the echolocation signals of killer whales are at considerably higher frequencies and based on available evidence, are likely inaudible to sea turtles (e.g., Simon et al. 2007). (2) Hearing impairment, either temporary or permanent, might inhibit a turtle's ability to avoid injury from vessels. A recent study found that green sea turtles often responded behaviourally to close, oncoming small vessels and that the nature of the response was related to vessel speed, with fewer turtles displaying a flee response as vessel speed increased (Hazel et al. 2007). However, Hazel et al. (2007) suggested that a turtles' ability to detect an approaching vessel was vision-dependent. (3) Hearing may play a role in navigation. For example, it has been proposed that sea turtles may identify their breeding beaches by their acoustic signature (Lenhardt et al. 1983). However, available evidence suggests that visual, wave, and magnetic cues are the main navigational cues used by sea turtles, at least in the case of hatchlings and juveniles (Lohmann et al. 1997, 2001; Lohmann and Lohmann 1998).

5. Other Physical Effects

Other potential direct physical effects to sea turtles during seismic operations include entanglement with seismic gear (e.g., cables, buoys, streamers, etc.) and ship strikes (Pendoley 1997; Ketos Ecology 2007; Weir 2007; Hazel et al. 2007). Entanglement of sea turtles with marine debris, fishing gear, and other equipment has been documented; turtles can become entangled in cables, lines, nets, or other objects suspended in the water column and can become injured or fatally wounded, drowned, or suffocated (e.g., Lutcavage et al. 1997). Seismic-survey personnel have reported that sea turtles (number unspecified) became fatally entrapped between gaps in tail-buoys associated with industrial seismic vessel gear deployed off West Africa in 2003 (Weir 2007). However, no incidents of entanglement of sea turtles have been documented during NSF-funded seismic surveys, which since 2003 have included dedicated ship-based monitoring by trained biological observers, in some cases in areas with many sea turtles (e.g.,

Holst et al. 2005a,b; Holst and Smultea 2008; Hauser et al. 2008). Turtle guards installed on tail buoys are thought to minimize the risk of entanglement (Ketos Ecology 2007).

6. Conclusions

Based on available data concerning sea turtles and other marine animals, it is likely that some sea turtles exhibit behavioural changes and/or avoidance within an area of unknown size near an operating seismic survey vessel. There is also the possibility of temporary hearing impairment or perhaps even permanent hearing damage to turtles close to the airguns. However, there are very few data on temporary hearing loss and no data on permanent hearing loss in sea turtles exposed to airgun pulses. Although some information is available about effects of exposure to sounds from a single airgun on captive sea turtles, the long term acoustic effects (if any) of a full-scale marine seismic operation on free-ranging sea turtles are unknown. Entanglement of turtles in seismic gear and vessel strikes during seismic survey operations are also possible but do not seem to be common. The greatest effects are likely to occur if seismic operations occur in or near areas where turtles concentrate, and at seasons when turtles are concentrated there. However, there are no specific data that demonstrate the consequences of such seismic operations to sea turtles. Until more data become available, it would be prudent to avoid seismic operations near important nesting beaches or in areas of known concentrated feeding during times of year when those areas are in use by many sea turtles.

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