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A Preliminary Evaluation of Potential Effects of Vibroseis on Marine Organisms and Recommended Experimental Approach for Effect Studies on Selected Commercial Marine Invertebrate Species in Nova Scotia

Report Prepared

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By

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Summary

The purpose of this report was to suggest an experimental approach for investigating the potential effects of marine vibroseis on invertebrates and fish, mainly those that could be of importance for management and fisheries interests in Atlantic Canada. Special attention was given to an approach that would include potential use of DRDC-Atlantic's Acoustic Calibration Barge.

Upon providing some background material on sound in water, the first major step was to gather information on the effects of sound from various sources, including air guns, sonar, explosives, pile driving and ship traffic. Such information was identified to be important since it would provide an important perspective on risks associated with different sources of sound as well as an appreciation of effects which might be relevant to consider in experimental trials with the marine vibrator.

For instance, if more powerful sound sources such as from pile driving and air guns are indicated to have limited biological effects, lesser effects might be expected with vibroseis. Also, if only explosives have been shown to have effects on invertebrate mortality at close range or for instance the rupture of fish swim bladders, these effects would not be important to evaluate from the perspective of marine vibroseis.

Effects related to mortality, histopathological and physiological changes as well as behaviour modification were assessed in relation to each sound source. Special attention was given to including detailed information on metrics in the appended tables in addition to observed effects. The review considered scientific journal articles, technical reports, industry reports, workshop proceedings and other web material as well as contacts regarding some on-going seismic work at DFO – understanding that a review of this nature cannot be considered exhaustive.

The review found that there were a limited number of investigations on the effects of sound on invertebrates and studies which have mainly focused on the effects of explosives or air gun exposures. There have been more studies on effects of high intensity sounds on fish than on invertebrates. Only one published study was found specifically dealing with the effects of vibroseis [on a freshwater fish species].

The review of effects associated with different sources of sound resulted in statements for effects on invertebrates and fish. Other than short-term behavioural effects (e.g., temporary hearing loss, startle reactions, stress responses, etc), evidence from field studies indicate that damaging effects on fish and invertebrates might only be expected to occur, if at all, within the immediate area (probably in meters to tens of meters range) of other sound sources, with protracted pile driving probably indicating the most risk. Accordingly it can be speculated that vibroseis would present even lesser risk.

Also considered was the possible relevance, in an approximate sense, of some provisional sound exposure criteria which could provide perspective for vibroseis.

Taking all background material into account, an experimental assay approach using the DRDC Acoustic Calibration Barge located in the Bedford Basin, Halifax Harbour is described in this report. The DRDC barge offers a stable platform in a near-shore marine environment to carry out controlled mesocosm experiments. Initial studies with the vibrator would be exploratory in nature with the results forming a basis as to the need or kind of any further studies. The scope of the suggested experimental design includes

the evaluation of potential acute, chronic and behavioural effects of marine vibroseis on selected fish and invertebrate species of commercial importance in Nova Scotia namely, lobster and snow crab (crustaceans), sea scallop (bivalve) and Atlantic cod (fish).

1.0 Introduction

DRDC Atlantic under a funding agreement with the Offshore Energy Environmental Research Association contracted with Hurley Environment Ltd. and Oceans Ltd. to investigate if the potential impacts on commercial marine invertebrates during seismic exploration for offshore oil and gas could be reduced by replacing the air gun with a marine vibroseis source with lower peak intensity than the air gun, but longer pulse length. [Note: While the study was intended to focus on marine invertebrates, it was decided to widen the scope to include a review of effects of sound on fish].

1.1 Study Objectives

The three (3) objectives of the study were:

(1) Carry out a scientific literature review on the acute and chronic effects of sound on marine organisms, particularly bottom-dwelling species;

(2) Determine the relevance of the studies for assessing the potential effects of vibroseis;

(3) Design experiments for assessing the potential effects of vibroseis on key commercial marine invertebrate species in Nova Scotia with particular focus on snow crab.

1.2 Scope of Work

The scope of work includes the following four (4) tasks (relevant sections of this report are in brackets alongside each task) :

(1) Assemble information on the particular frequencies, sound levels (and metrics) of various sounds (Section 2).

(2) Carry out a scientific literature review on the acute and chronic effects of sound on marine organisms, particularly bottom dwelling species, from various sound sources such as air gun, vibroseis, pile driving, oil and gas production, sonar, underwater explosions, shipping noise and other vibration type studies if existing (Section 3).

(3) Determine to the extent feasible the relevance of the cited studies for assessing the potential effects of vibroseis, keeping in mind that a marine vibroseis source would involve lower sound levels but longer pulse length than an air gun (Sections 4.1, 4.2).

(4) Recommend experimental design/approaches for carrying out effect studies on key commercial marine invertebrate species in Nova Scotia with focus on crustacean species, such as snow crab and lobster, and possibly a bivalve species like sea scallop (Sections 4.3).

2.0 Background on Underwater Sound

2.1 Sound Measurement

2.1.1 Sound Pressure and Volume

Sound is caused by subtle, rapid variations in air pressure that spread out from the sound source, so that the air pressure at a particular point oscillates above and below ambient levels. Atmospheric pressure varies, but is usually around 101 kilo-Pascals (kPa) (or 14.6 psi, or 1.01 bar). The changes in pressure caused by sound are much lower: humans can hear sounds when the pressure fluctuation is 1/5,000,000,000 atmospheres.

Because of the large numbers involved, sounds are usually expressed on a logarithmic scale. The volume of sound in decibels is calculated by

$$\text{SPL}\,(dB) = 20 \times \log_{10}(P/P_O).$$

SPL is the sound pressure level. P_O is a reference pressure, which for airborne sounds is taken to be the lower limit of human hearing, 20 μPa. This means the quietest sound that can be heard has a volume of 0 dB. Sounds of 120 dB are painfully loud; that corresponds to a pressure change of 20 Pa, or 1/5,000 atmospheres.

Sound also travels through water (or indeed through any material at all). When speaking of underwater sound, a different reference P_O is used for the decibel scale, P_O = 1 μPa. This means that for sounds of equal pressure, the sound level in water is 26 dB higher than the sound level in air. When reporting a decibel level, to be entirely clear, the reference P_O needs to be specified, so one would describe a sound as having a volume of 72 dB re 20 μPa in air, or 98 dB re 1 μPa in water.

However, when comparing sounds in air or water, pressure is not the best comparison. Because of differences in the physical properties of air and water, the energy transmitted by sound waves gives a more meaningful comparison. When the energy transmitted is the same, the sound level in water is 62 dB higher than the sound level in air, including the change in reference level[1]. Thus a sound in water that is 122 dB re 1 μPa transmits the same energy as a sound in air that is 60 dB re 20 μPa.

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[1] Acoustic intensity I depends on pressure P and impedance Z as $I = P^2/Z$.

For sea water, Z=1.58 MPa-s/m, and for air Z=413 Pa-s/m at 20°C. Therefore for equal I,

$P_{water} = P_{air} \times \sqrt{Z_{water}/Z_{air}} = 62P_{air}$. The difference in sound level is given by

$$\Delta SPL = 20 \times \log_{10}(P_{water}/P_{O,water}) - 20 \times \log_{10}(P_{air}/P_{O,air}) = 62 \text{ dB}.$$

2.1.2 Peak, Peak-to-peak, and RMS Measurements

In some situations, there may be ambiguity in how pressure is measured, and therefore how the corresponding decibel level is determined. Most sounds of interest persist for an appreciable time, so that the pressure level oscillates many times with essentially the same strength. For such sounds, one reports a modified average, known as the root-mean-square (RMS) pressure. In principle, RMS values are found by squaring the pressure at each instant, averaging the squared values over some time interval, and then taking the square root of the result. In most applications when sound pressure levels or decibel levels are reported, they are RMS values.

However when the sound is very brief, there may be very few oscillations of the pressure, which makes the RMS value inconvenient or even useless. In such situations, it is more common to report the maximum pressure (the peak value) or the difference between the maximum and minimum (the peak-to-peak value). Figure 1 shows the three techniques.

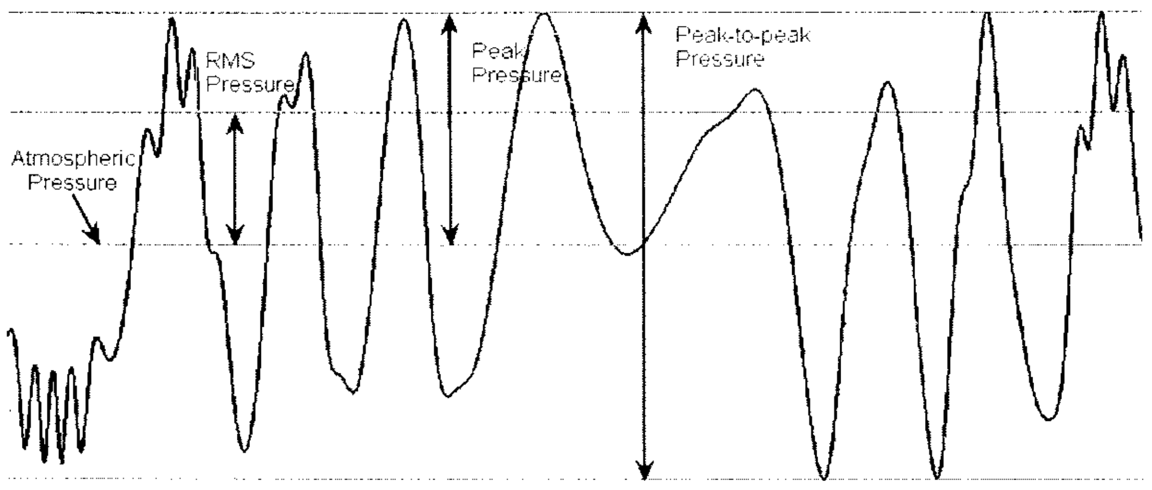

Figure 1 - RMS pressure, Peak pressure, and Peak-to-peak pressure for a sample sound wave.

2.1.3 Sound Frequency, Speed, and Wavelength

Since sound causes a fluctuation between high and low pressure, we are usually interested in how rapid this fluctuation is. Period is the time elapsed between one maximum pressure peak and the next. Frequency is the number of pressure maximums that occur in a period of time, which is also one divided by the period. Frequency is usually reported in Hertz (Hz), which is the number of oscillations per second. Humans can hear sounds with frequencies from about 16 Hz up to about 20,000 Hz. A standard piano can produce notes between 32.70 Hz and 4186 Hz.

The speed at which sound travels away from the source depends upon the medium through which it is traveling. Sound speed in air is about 340 m/s, but depends significantly on temperature, air pressure, and humidity. Sound travels much faster through water, with a speed of around 1522 m/s in the ocean. In solids such as rock or steel, sound speeds are even faster.

The wavelength of sound is the distance between two adjacent locations where the sound pressure is at a maximum. This is also equal to the speed of sound divided by the frequency of the sound. For typical speech, with a frequency of 400 Hz, this corresponds to a wavelength of 85 cm. The same sound in water would have a wavelength of 3.8 m, because it is traveling so much faster.

2.1.4 Sound Frequency Spectrums

The simplest sound is a pure tone, which is a sinusoidal pressure oscillation with a given frequency. By combining several tones, a more complicated sound wave can be built up (see Figure 2). Alternatively, one can take a sound wave and mathematically determine the individual tones that compose it, and their relative strengths. This is the frequency spectrum of the sound. It is analogous to shining light through a prism and getting a rainbow, where each colour band is light of one specific frequency.

If the frequency spectrum of a sound does not overlap the frequency sensitivity of a listener, then the listener will not be able to hear the sound, regardless of how loud it is. The sound frequency spectrum of a dog whistle is entirely outside the audible range of human beings, so we cannot hear the sound.

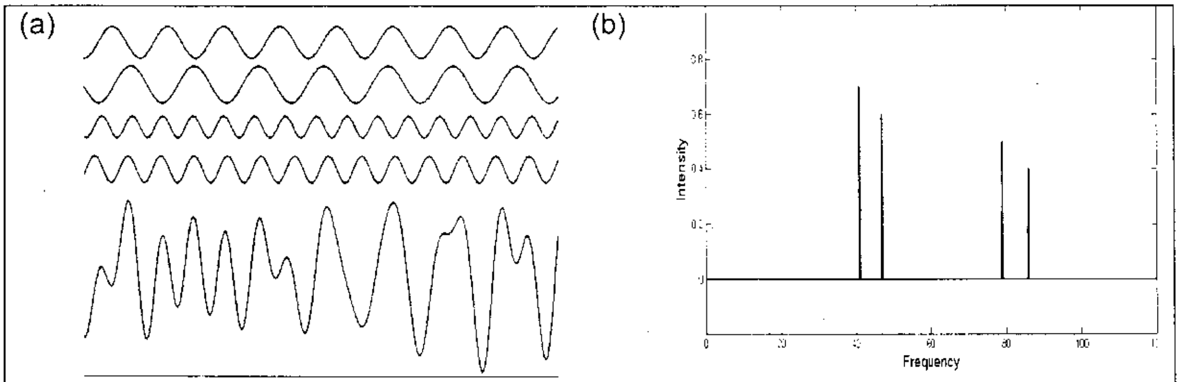

Figure 2 - (a) Four tones (top) combine to form a more complicated sound wave (bottom). (b) Frequency spectrum of the combined wave from (a). There is a spike in the spectrum for each tone composing the sound.

2.1.5 Particle Velocity

The pressure fluctuations of sound exert a force upon the molecules in the air, causing them to vibrate back and forth a small distance. Particle displacement refers to the distance that the molecules move away from equilibrium. Particle velocity refers to the speed they move. Both particle displacement and velocity can be measured as RMS, peak, or peak-to-peak values, as explained above.

For an arbitrary sound wave, the relation between pressure and velocity is complicated, but for a pure tone, far from the source, velocity v is given by $v = P/Z$, where P is the pressure of the wave and Z is the acoustical impedance of the medium. (For sea water, Z = 1.58 MPa-s/m, and for air Z = 413 Pa-s/m at 20°C.) The particle displacement x is $x = v/(2\pi f) = P/(2\pi f Z)$. This means air molecules move much more than water molecules because of sound.

For speech, with a frequency of 400 Hz and volume of 60 dB re 20 μPa, the particle velocity is approximately 50 μm/s (20,000 times slower than walking speed), and the displacement is approximately 20 nm (about 1000 times smaller than a cell). For a loud underwater sound (such as a seismic air gun), with a frequency of 25 Hz and a volume of 230 dB re 1 μPa, the particle displacement is over a millimeter.

In enclosed containers, standing sound waves can be established. With a standing wave, there are locations where the pressure is always zero, and other locations where the particle velocity is always zero. By testing animals in standing waves, biologists have learned that some animals hear the pressure of sound, but others hear the particle velocity.

2.1.6 Elaboration on the Relation Between Pressure and Particle Velocity

Although fish and mammals hear the pressure component of sound, decapod crustaceans such as lobsters hear the particle velocity component (Popper et al., 2001). Therefore assessing the effects of sound on such animals requires a better understanding of how particle velocity is related to pressure.

In general, particle velocity v depends upon pressure P by

$$v = -\frac{1}{\rho}\int \nabla P dt$$

which essentially is a rewriting of $F=ma$ as applied to a volume element. An arbitrary sound wave can take any form consistent with the wave equation

$$\nabla^2 P = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}P,$$

subject to boundary conditions. Note that the wave equation is linear, so that two sound waves can simply be added together to form a new sound wave.

The wave equation is satisfied by any equation of the form

$$P(\vec{r},t) = P(\omega t - \frac{\omega}{c}x)$$

known as a plane wave. It follows that for any such wave,

$$v = \frac{1}{Z}P$$

so that for a plane wave, particle velocity is proportional to pressure, in phase with pressure, and has no frequency dependency. At a sufficient distance from the sound source, any traveling sound wave behaves like a plane wave.

The wave equation is also satisfied by standing waves, of the form

$$P(x,t) = P(\omega)\cos(\omega t)\sin(\frac{\omega}{c}x)$$

which leads to

$$v(x,t) = \frac{1}{Z} P(\omega)\sin(\omega t)\cos(\frac{\omega}{c}x).$$

This means

$$\|v\| = \frac{1}{Z}\|P\|,$$

but there is a phase difference in both time and space. With a standing wave, pressure maxima occur at particular discrete locations, and particle velocity maxima occur at a different set of discrete locations, and at different times (see Figure 3).

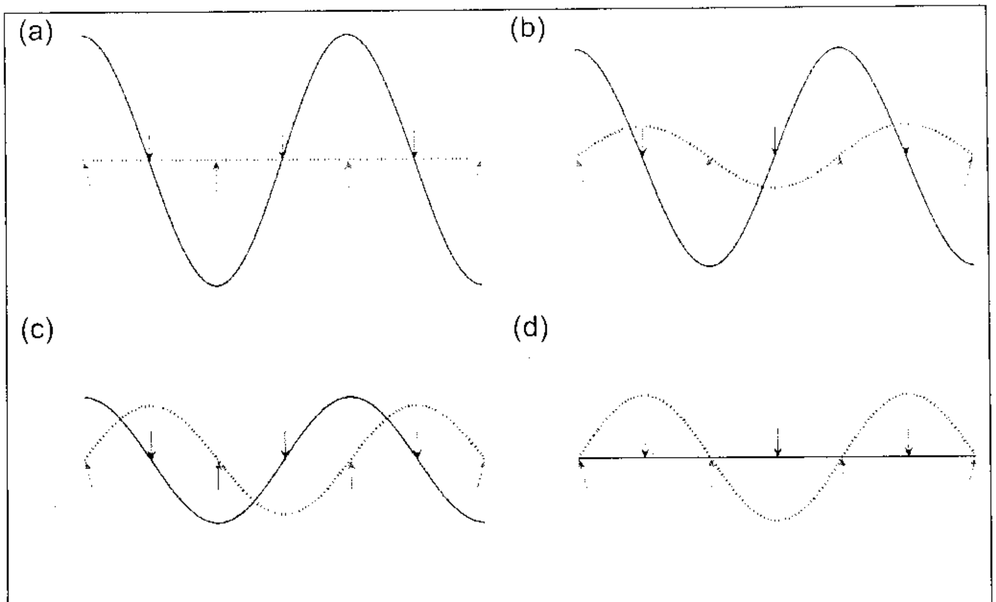

Figure 3 - A standing sound wave over time. Pressure is shown solid, and particle velocity dashed. Particle velocity is always zero at the red arrows, and reaches peaks at the blue arrows. Pressure is the opposite.

Another solution to the wave equation is the radial sound wave

$$P(\vec{r},t) = P_0 \frac{r_0}{r}\cos(\omega t - \frac{\omega}{c} r)$$

which leads to a more complicated expression for *v*:

$$v = \frac{1}{Z} P_0 \frac{r_0}{r}\left[\cos(\omega t - \frac{\omega}{c} r) + \frac{c}{r\omega}\sin(\omega t - \frac{\omega}{c} r)\right].$$

The first term is the same as in the plane wave case. However the second term is a phase-shifted term with a dependence upon both *r* and *ω*. Therefore at long ranges, the radial wave behaves like a plane wave, as expected. But where $\frac{c}{r\omega}$ is non-negligible, the behaviour of the radial wave is significantly different. We are interested in knowing when $\frac{c}{r\omega} \ll 1$, or when $r \gg \frac{\lambda}{2\pi}$. For low frequency sounds of around 25 Hz in seawater, such as would be used in seismic exploration, $\frac{\lambda}{2\pi} \approx 10\,\text{m}$. Therefore unless the range is significantly greater than 10 m, using $v = \frac{1}{Z}P$ will significantly underestimate the particle velocity. For a range of 1 m, the particle velocity is 10 times greater than would be expected for a plane wave, and even at 25 m, the particle velocity is 7% higher.

2.1.7 Use of Different Sound Metrics

In underwater acoustics, a variety of units are used to define signals. Sound can be measured as sound pressure level (SPL) or sound exposure levels (SEL). SPLs are typically reported as dB re 1 µPa at a distance of 1 m. However, the dB number can differ with the type of measurement carried out such as "peak" or "zero to peak (p or 0–p)," "peak to peak (p–p)," or averaged on a root mean square basis (RMS). SEL, expressed in dB re 1 $\mu Pa^2 \cdot s$, is a measure of the received energy in the pulse and represents the SPL that would be measured if the pulse energy was spread evenly across a 1-s period.

Unless measurement types are provided, it is difficult to provide direct comparisons between studies. It is essential to be aware of all units, references, ranges, what is being measured and how. With transient sounds, the time over which a measurement's data are collected becomes important (Madsen, 2005). Treatments in Richardson et al. (1995) are helpful.

2.2 Sound Propagation

2.2.1 Plane Waves

Sound waves consist of pressure fluctuations spreading outwards from a sound source. Far from the source, where all the sound is traveling in the same direction, this is a plane wave, as shown in Figure 4 (a). The intensity of a sound wave can be plotted as a function of time. For a plane wave, this same plot also shows the intensity of the sound in space. The wave simply moves through space at a constant speed without alteration.

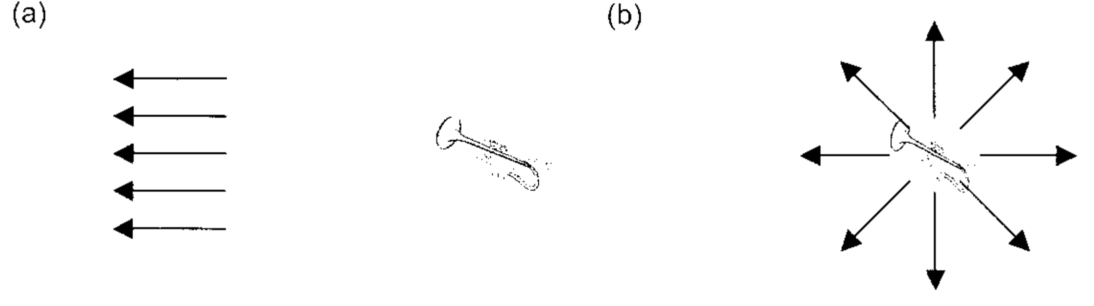

Figure 4 - (a) Plane wave sound propagation. (b) Radial sound propagation.

2.2.2 Simple Spreading

Figure 4(b) shows sound spreading radially from a source. The total sound power at any distance from the source is always the same, but at farther distances it is distributed over a greater area. In the figure, this is indicated by the arrows spreading farther apart. The total sound power reaching any receiver therefore diminishes over distance.

If the sound expands spherically through a uniform medium without reaching any barriers, then the intensity of the sound wave decreases proportional to the square of the distance from the source. This means that the sound pressure level decreases by 6 dB every time the distance doubles. The shape of the sound wave (or the way it sounds) does not change, but it gets fainter.

In some situations sound may be free to expand in a cylinder. For example, sound spreading through a large body of shallow water can expand horizontally but not vertically. Even within deeper water, sound may expand cylindrically, for reasons explained below. With cylindrical expansion, the intensity of the sound decreases linearly with distance from the source. Therefore the sound pressure level decreases by 3 dB for every doubling of distance.

Because the volume of sound depends upon the distance from the source of the sound, sources are usually described as though the listener is one metre away. Thus if a source is producing an 85 dB sound, then a listener one metre away would hear a sound volume of 85 dB. A listener only 25 cm away would hear a much louder sound: 97 dB following our rules for spherical spreading.

If a source is generating a sound with level L_S (as measured one metre away), then a receiver a distance r away (measured in metres) will hear a sound level L_R given by:

$$L_R = L_S - 20 \times \log_{10} r$$

when spherical spreading applies

or $$L_r = L_S - 10 \times \log_{10} D - 10 \times \log_{10} r$$

when cylindrical spreading applies. The distance D indicates the depth of the cylinder in which the sound is constrained. Observe that in the spherical case the logarithm is multiplied by 20, but in the cylindrical case only by 10.

Simple spreading rules provide easy approximations, but they can be surprisingly inaccurate. Since loud sounds can be safety hazards, one should avoid using these simple rules for determining where sound levels will reach particular levels. Computer models (see below) can provide more accurate predictions.

2.2.3 Point Sources, Near Sources, and Far Sources

Some sounds are produced within a very small space. For example, when we speak, most of the sound emanates from our mouths. In contrast the sound of the ocean on the beach is generated along the entire length of the beach.

If sound measurements of an extended source are taken from within (or very close to) the source, the measured levels will depend considerably upon the precise location. Instead, a single measurement is commonly made far from the source, and then the source level is back-calculated assuming spherical spreading. Thus if the sound is 80 dB when measured 32 meters from the source, the source is attributed a source level of 110 dB at one meter. (32 meters represents five doublings in distance, each of which accounts for 6 dB according to spherical spreading). For an extended source, there may be no actual location where the sound level is that high, but the total production of the entire source is equivalent to one point source with that volume.

The far field zone is usually any location where the distance from the source is greater than the largest dimension of the source. Anywhere that is not in the far field zone is in the near field zone.

Another complicating factor is the possibility of dipole sound sources. A monopole source is one in which the sound is produced by an object expanding and contracting equally in all directions. With a dipole source the object moves back and forth. Dipole waves behave somewhat differently than monopole waves while close to the source. In particular, some of the sound propagates circularly around the source, rather than just radially away from the source. When the distance from the source is at least several wavelengths, the dipole behaves similarly to a monopole, although fainter in some directions. However, for low-frequency sound in water, a wavelength can be 100 meters or more, meaning dipole contributions can be relevant for substantial distances.

2.2.4 Directionality

Omnidirectional sound spreads out from the source equally in all directions. The physical arrangement of most manmade sources causes them to be not omnidirectional. For example, you are more likely to hear someone speak if you are in front of them. Some sounds are projected in a narrow beam, which is what a person attempts when cupping their hands around their mouth to yell.

Most natural sound sources are omnidirectional. However the echolocation clicks of whales are focused into a narrow beam. Shipping noises and construction noises are omnidirectional. The sounds produced by seismic air gun arrays are directed primarily downwards, although horizontally directed sounds are still significant. Depending on the configuration of any air gun array, the sound volumes beside the array will be different than those in front of or behind the array.

Strictly speaking, ambient sounds are those which come from all directions at once. However the term is more commonly used to mean those sounds which are always present, or even the total sound from all sources not currently of interest.

2.2.5 Reflections and Refractions

When a wave strikes a boundary between two mediums, some of the wave is reflected back and some may be transmitted through (see Figure 5). If there is a significant difference in the acoustic properties of the materials, then almost the entire wave is reflected. When sound travels from air to water, 99.9% of the sound intensity is reflected, due to differences in the acoustical impedance of air and water (NDT, 2010). Although the transmitted intensity is tiny, the transmitted pressure is double the initial pressure. On the other hand, when sound travels from water to air, the transmitted pressure is 0.05% of the original.

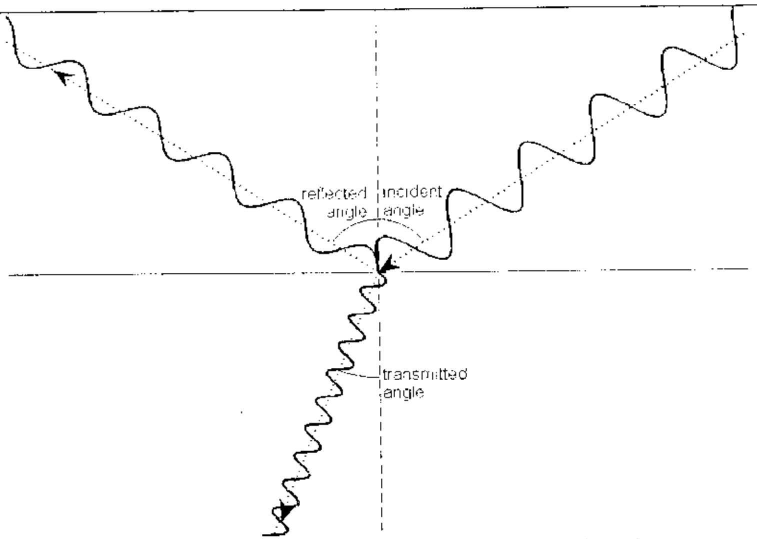

Figure 5 - When a sound wave strikes a boundary, part is reflected and part transmitted. In this case the top medium has higher sound speed than the bottom medium. The wave in the medium with slower speed has shorter wavelength and is closer to the perpendicular.

Notice that the transmitted sound proceeds in a different direction than the original. This is the property of refraction, and is also observed when objects appear to bend when placed in water. Snell's law tells us that the incident angle θ_I and the transmitted angle θ_T are related by

$$\frac{\sin(\theta_I)}{\sin(\theta_T)} = \frac{c_I}{c_T}$$

where c_I and c_T are the sound speeds in the two mediums. If the incident angle is large, then the above formula would give a transmitted angle exceeding 90°. In this case no sound at all is transmitted. A listener underwater will only hear an airborne sound source if the source is almost directly overhead, regardless of how loud the source is.

The frequency of the initial, reflected, and transmitted sounds will all be the same. Since the sound speed will be different in the mediums, the wavelength will change.

In the ocean, the temperature, pressure and salinity of the water change with depth, and therefore the speed of sound also does. This means that sound in water is continually undergoing significant refraction. At a certain depth, the speed of sound reaches a minimum, so that sound is refracted towards this layer. Once any sound gets into this so-called SOFAR axis, it can efficiently travel long distances, similar to a signal in a fiber-optic cable. The depth of the SOFAR axis depends upon latitude, as deep as 1200 m equatorially and rising to the surface in arctic waters (Johnson and Norris, 1968).

Closer to the surface, sound propagation depends upon the season. In the summer, sound speed rises continually right to the surface, so that any sound near the surface is refracted into deeper water. This means that shallow water is quieter than deep water in the summer, and that shallow-water sound sources will be more clearly audible deeper down. In the winter, changes in ocean temperature cause a sound speed maximum at a particular depth. Sound above this layer is refracted up, so that in winter the surface layer becomes a good sound conductor.

2.2.6 Scattering and Absorption

When sound passes through obstacles, some of the sound wave bounces in all directions, scattering it. Some of the sound energy is converted into heat or other forms, absorbing it. Due to the combined effects of scattering and absorption, sound waves lose energy as they travel (Figure 7). This effect is much greater for high frequencies than for low frequencies. Very high frequencies are filtered out rapidly, but low frequencies can travel a very long distance. Indeed, the Heard Island Feasibility Test was a global weather experiment to determine average ocean temperatures by broadcasting sound from Heard Island in the southern Indian Ocean, and listening for it as far away as Nova Scotia and California (Munk et al., 1994).

Table 1 lists some attenuation rates. Sound with a frequency of 10 Hz can travel around the world and lose less than a decibel due to attenuation (although it will diminish due to spreading), but 100 kHz sound loses a decibel every 25 metres it travels. Francois and Garrison (1982) give a detailed general formula for accurate calculation of attenuation in sea water.

Frequency	**Sound Loss**
10 Hz	10^{-5} dB / km
100 Hz	0.001 dB / km
1000 Hz	0.07 dB / km
10 kHz	1 dB / km
100 kHz	40 dB / km

Table 1 - Attenuation rates for a few frequencies (Rogers and Cox, 1988).

2.2.7 Solids, Liquids, and Gasses

Within fluids (air and water), sound exists as compressional waves. The air molecules vibrate back and forth in the same direction that the sound is traveling. In solids, sound can also travel as shear waves, where the atoms vibrate perpendicularly to the motion of the sound. These two modes have different speeds, so there are two speeds of sound in solids.

Attenuation is lower in water than in air, and lower still in hard solids such as rock. Therefore sound is audible over much longer distances in water than in air.

When sound is generated in the ocean, it reflects very efficiently off the surface, although it undergoes a phase change during this reflection. At the sea bottom, sound is readily transmitted into the substrate (rock, sand, or mud). It can travel through the ground and re-emerge into the water at a distant location before the water-borne sound wave has arrived, since sound speeds are faster in rock. Any animals sitting on or burrowing into the sediment may be able to perceive the sound wave directly from the ground. In fact, crab "ears" are located in their legs for this reason (Aicher et al., 1983).

In air, wind speeds can be within an order of magnitude of sound speeds, so that wind will have an effect on the transmission of sound. Sounds will be more audible downwind than upwind, causing asymmetric situations where person A can hear person B yelling, but person B cannot hear person A yelling back. In water, sound speed is much higher and current speed is much lower, so current has negligible effects on sound. All sound transmission in water is therefore symmetric.

2.2.8 Frequency Dependence and Wave Distortion

As sound travels, there will be slight variations to the path the sound takes, so that some will take longer to reach the listener than the rest. Also, high-frequency sounds attenuate more as they travel. Because of these effects, the shape of a sound wave changes substantially the farther the listener is from the source. Sharp pulses become broadened out, and high pitches become quieter. This means that what may sound like a "crack" at close range may become a "thump" or even a "rumble" farther away.

Variations in the properties of a sound medium may lead to sound channels, which are portions of the medium where sound can propagate more effectively. Sound can only use a channel if the width of the channel is approximately at least as large as the wavelength of the sound. Therefore high frequency (short wavelength) sound will find more such channels to use, and so can propagate with much less attenuation than would be expected.

2.2.9 Computer Models

All the characteristics of sound propagation – diffraction, absorption, interference, and so on – are physically well understood. Computer programs exist which can evaluate the physics, and tell us how any given sound source will propagate in any given situation. They can provide very accurate results over large regions (Fan et al., 2007; Tashmukhambetov et al., 2008).

However, as propagation depends upon temperature gradients, bottom contours, sediment makeup and other factors, all these must be well known before the situation can be described to the computer. Using predictions based on insufficient data, or even using predictions for a different time of year, can give misleading results (McQuinn and Carrier, 2005). In a recent review of sound propagation modeling, Lawson (2009) noted that model predictions are useful for planning and preparing environmental impact statements, but advised of the importance of obtaining empirical data.

2.2.10 Summary

For quick, rough estimation of sound levels at a given distance from the source, one can use a mixture of spherical and cylindrical spreading rules. Sound spreads spherically until it is constrained between the bottom and surface of the sea, after which it spreads cylindrically. Every time the distance from the source doubles, the received sound level drops by 6 dB if the spreading is spherical, or 3 dB if cylindrical.

Long distances discourage high frequencies. Sounds with a frequency above 10 kHz rapidly become inaudible as the distance from the source exceeds about a kilometre. Sounds below 10 Hz travel efficiently for vast distances.

Ocean depth influences sound audibility. During the summer, it is much quieter near the surface of the ocean, but this effect disappears in the winter. At a particular depth, known as the SOFAR axis, sound travels particularly well, and very distant sounds can be easily heard.

Detailed predictions of sound levels can be made using advanced computer programs. The models require that the particular situation be carefully described, as changes in temperatures and bottom profiles will change the received sound levels.

2.3 High Intensity Low Frequency Underwater Sound Sources

2.3.1 Air guns

Seismic air gun is the source most often used in marine oil and gas seismic exploration. An air gun produces sound by suddenly discharging compressed air into the water. The largest air guns hold over 30 liters of air at up to 13.8 MPa (137 atmospheres or 2000 psi) (Richardson et al., 1995). Formation of the initial air bubble causes a sharp pressure wave. The bubble then collapses and oscillates, producing additional, lesser pressure waves. From a seismic perspective, these bubble pulses are undesirable. Figure 6 shows how multiple air guns can be combined into an array, so that the initial pressure waves add together, but the trailing bubble pulses cancel each other out.

The peak source level generated by an air gun array is in the range of 235-259 dB re 1 μPa-m (Richardson et al., 1995). (See section 3 for an explanation of sound measurements). The main pressure pulse lasts for about 25 ms, and has a 5-10 ms initial rise time (Caldwell, 2000). However, air gun arrays are far from point sources. Some arrays have as many as 64 individual air guns spread over 2500 m^2. The highest pressure experienced within the array will be much lower, usually comparable to that produced by the nearest individual gun, which is less than 235 dB.

The pressure wave from an individual gun expands in all directions. The upward wave reflects off the surface, causing the negative pressure trough following the positive peak of the main pulse. Air gun arrays are usually operated 6 m below the surface of the ocean to yield a half wavelength virtual dipole source at ~120 Hz, which gives a downward directed beam pattern of an optimal shape.

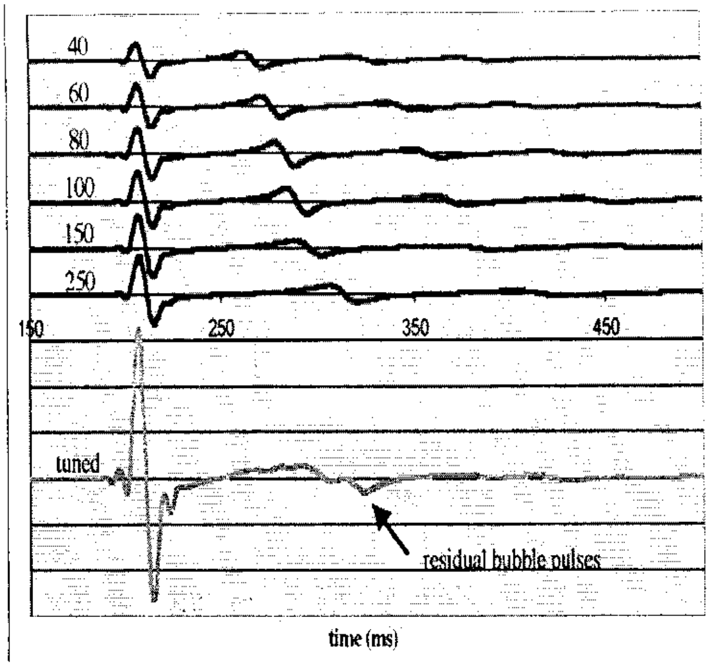

Figure 6 (Taken from Dragoset, 2000) – Sound waves produced by air guns. Blue waves show pulses from different air guns, with bubble pulses at different times. The red wave shows the signal from the combined array.

2.3.2 Marine Vibrators

Instead of a single pressure pulse, vibrators produce a tone of gradually ascending frequency (Figure 7). Proper mathematical processing of the results allows seismic explorers to translate the data into a form equivalent to what an impulsive source would have generated. The initial low frequency is around 25 Hz, and rises to around 200 Hz. Vibrators, currently in development, seek to lower this to a range of 5 – 100 Hz as such signals are more useful for generating seismic data, especially of deep rock formations. Each signal sweep lasts for 10 – 20 seconds.

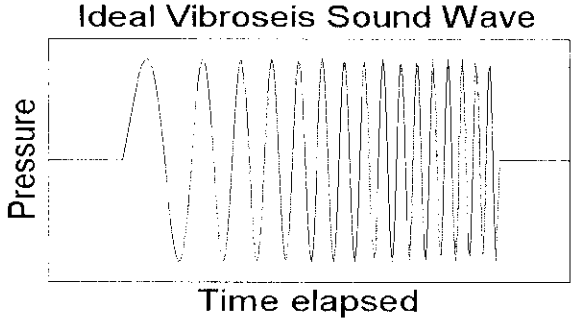

Figure 7 - The sound wave produced by a seismic vibrator.

The sound wave generated by marine vibrators is much lower pressure than that from air gun arrays, but because the vibrator has a much longer duration signal, the two sources produce comparable acoustic energy, and consequently comparable seismic data quality. Roughly speaking, a vibrator produces the same energy as an air gun that is 26 dB louder[2]. Since deepwater air gun arrays operate at up to 259 dB, vibrators would need to produce 233 dB to achieve similar results, which is beyond current capabilities.

The rise time of the pressure wave from a vibrator is only about 2 ms, somewhat shorter than for air guns. In comparison, explosive sources such as dynamite are characterized by very short rise times, which are why they are particularly damaging to animals, especially fish. The rise time for the shock wave from a chemical explosion is around 1 μs (Watson et al., 2006).

For an ideal vibrator, the signal strength at all frequencies within the sweep range is constant, and there is no sound generated at any other frequencies. The 10 – 100 Hz range of a vibrator is below the audible range of most fish and mammals, but harmonics of the generator cause there to be some higher frequency content, which might be significant to marine animals. A new vibrator under development is expected to have harmonics at least 30 dB weaker than the primary signal (PGS, 2005). With land Vibroseis systems, the output above 120 Hz is more than 60 dB below the main signal strength (Driml et al., 2004). Unfortunately, no data is available for the actual sound pressure levels generated by marine vibrators at frequencies above 500 Hz, making it impossible to assess how much a vibrator disturbs fish.

Use of marine vibrators is currently limited due to various practical considerations. The signal produced is not as constant in amplitude as desired, nor is the frequency as low. Maintenance requirements and reliability do not compare favorably with air guns. However they can be used in shallower water than air guns – they can even be placed on the sea bottom in water not deep enough to cover them. Still, the vast majority of seismic exploration is performed with air gun arrays.

2.3.3 Low Frequency High Intensity Sonar

Military low frequency sonar pulses are in some cases similar to seismic vibrator signals. Much attention recently has focused on the US Navy's Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA), which also generates a swept-frequency pulse, although at a higher frequency and stronger pressure than vibrators. As both sonar and seismic vibrators are non-impulsive sources, studies on sonar may be more applicable in predicting the impacts of vibrators than air guns studies would be. The peak pressure from sonar is comparable to a large individual air gun, but well above current vibrator levels. The rise time of LFA is slightly faster than vibrators.

In the context of sonar, low frequency is taken to mean any system using frequencies below 1000 Hz. SURTASS LFA used by the US Navy uses the band 100 – 500 Hz. Sound source levels are 235 dB re 1 μPa-m RMS. A single signal lasts for between 6 and 100 seconds, but typically 60 seconds. The system is capable of a 20% duty cycle, but in practice achieves 7.5% operation time (NAVY, 2007). It operates primarily in littoral waters.

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[2] The approximate difference in sound level is given by

$$\Delta(SPL) = 10 \times \log_{10}\left(\frac{vibrator\_duration}{airgun\_duration}\right).$$

2.3.4 Pile Driving

Pile driving is undertaken for harbour works, bridge construction, oil and gas platform installations, and the construction of offshore wind farm foundations. Most recent published work has concerned the last activity. Some pile driving can be performed with a vibrating weight on top of the column, which drives the column to most of the desired depth into the ocean floor. However pile driving must generally be completed with weight-drop impacts, which produces intense sounds. Overall the sound generated by pile driving is quite similar to that of air guns, with a sound level ranging from 191 – 262 dB re 1 µPa-m (Nedwell et al., 2006). The frequency spectrum ranges from less than 20Hz to more than 20 kHz with most energy around 100-200 Hz (for an extended overview see Nedwell et al., 2003; Nedwell and Howell, 2004; Thomsen et al., 2006). Some techniques exist to limit the spread of sound, such as using perforated air hoses to generate bubble curtains, which act as acoustic barriers.

2.3.5 Explosion

Explosions are used in construction and occasionally in the removal of unwanted subsea structures. Underwater explosions are one of the strongest point sources of anthropogenic sound in the seas. Source levels vary with the type and amount of explosives used and can range from 272 to 287 dB at 1 m distance. Frequencies are rather low (range 2 to 1,000 Hz with main energy between 6 to 21 Hz) and duration less than 1 ms.

2.3.6 Other Man-made Sounds

Shipping noise is a major contributor to ambient background sound in the ocean at low frequencies (Hildebrandt, 2004). Shipping noise includes white noise from water flow past the hull and cavitations sounds produced by the propeller. It also includes tones from engine noise and propeller blades. Most noise for large ships is in the 5 – 500 Hz band and may be 198 dB re 1 µPa for a single large supertanker (OSPAR, 2009). Shipping noise is obviously more prevalent in busy shipping lanes and near ports. Also, although large ships may produce relatively high source levels of sounds, all boats contribute to ocean noise (e.g. Wysocki and Ladich, 2005 and references therein).

Underwater excavation sometimes makes use of explosives to clear rocky bottoms. The effects of explosive shock waves on fish are well known, and rigorous procedures exist for protecting marine or river animals from undue exposure. Often many small charges must be used to minimize the radius of effect.

Continuous industry such as wind farms can generate some noise. Offshore wind turbines generate low frequency sounds continuously. However the sound intensity of an operational wind farm is low, so that they are inaudible 100 meters away (Vella et al., 2001). The foundations and even tower of operational wind turbines are observed to serve as colonization sites (or artificial reefs) for a variety of marine fauna and flora.

Drilling associated with petroleum exploration and development can also be a significant localized source of noise for the ocean (e.g. Richardson et al., 1995). Dredging, carried out to extract resources such as sand and gravel, or to create navigable waterways is also a common sources of ocean noise.

Military exercises occasionally involve detonating powerful explosions underwater, for purposes of training, testing, or disposal. In ship shock trials, the explosive force needed to rupture new hull designs is tested. Such explosions are very powerful, but fortunately rare. In fact, Hildebrandt (2004) points out that although underwater nuclear tests have not been performed since 1996, the sound energy produced by them was greater than that from all other sources combined in all the time since then.

2.3.7 Natural Sounds

At very low frequencies, wave and current motions are always audible as a low rumbling sound. Because sound travels so well at low frequency, waves from the entire ocean contribute, so that local surface conditions do not particularly influence local sound levels.

At moderate frequencies, wind, waves, and rain all contribute towards making the ocean a naturally noisy environment. From about 100 Hz up to about 30 kHz – spanning the audible range of most species – wind noise is the dominant effect. Wind is generally louder at low frequencies, although it is strongest below 1000 Hz. Depending upon the strength of the wind, sound levels may be anywhere from 45-90 dB re 1 μPa. Precipitation produces noise above 100 Hz, at levels up to 80 dB (Richardson et al., 1995).

Currents add to the sound, especially when they can interact with noisy bottom conditions, such as gravel. Near shore, the sound of waves on the beach is audible. Sea ice contributes groaning and cracking sounds. However, ice covered waters are generally much quieter than open sea. The uneven bottom surface of broken sea ice greatly inhibits sound propagation.

At very high frequencies, thermal molecular motion takes over, providing an upper limit for any underwater sensors or communication. Above approximately 1 MHz, it is the only audible sound (Richardson et al., 1995).

Biological sounds may be transient or continuous. In some parts of the world, snapping shrimp are a dominant sound in the 2 – 40 kHz range. By clicking their claw, they can generate a shock wave capable of stunning their prey. Other invertebrates also produce sounds, but the intensity is too low to be audible except at short range. Many invertebrates communicate through ground-transmitted sound waves (Aicher et al., 1983).

Many fish produce sounds either by swim bladder vibration or through rubbing body parts. Often entire schools participate in fish choruses lasting for many hours (Locascio and Mann, 2005). Such sounds are typically in the 100 – 1000 Hz range and may exceed a sound pressure level of 120 dB. Whales and other cetaceans vocalize, communicating at frequencies from 12 Hz (blue whales) up to 5 kHz (seals). Toothed whales such as dolphins use echolocation clicks spanning 20 – 130 kHz. The loudest echolocation clicks are as much as 230 dB at the source (McCauley, 1994) but communications remain under 190 dB.

2.4 Sound Reception/Detection in Invertebrates and Fish

2.4.1 Invertebrates

Among invertebrates only a few insects, arachnids, and centipedes are known to have organs specialized for sound perception (Brusca and Brusca, 2003). More generally, sensitivity to sound or vibrations is achieved incidentally through proprioceptors and statocysts.

Animals use proprioceptors to determine the position and movement of their limbs. These are organs in joints or muscles which react to being stretched or compressed. Some also react to changes in force or pressure without any necessary motion. When an animal is exposed to vibrations, its joints will often vibrate in response, which can be detected by the proprioceptors.

Statocysts are a hollow chamber containing a free solid pellet called a statolith. The chamber is lined with sensory hair cells, capable of detecting where the statolith is resting, which tells the animal which direction is down. Motion of the statolith can provide information on the acceleration of the statocyst, and therefore of the animal. Invertebrate statocysts are rather sensitive to the particle motion component of sound than to the pressure (Kaifu et al., 2008).

Among the invertebrate groups, decapod crustaceans are the most studied marine species in relation to their acoustic detection capabilities. They appear to be most sensitive to sounds of frequencies lower than 1,000 Hz (e.g. Popper et al., 2001). However, prawn has been shown to be sensitive to frequencies up to 3,000 Hz or more (Lovell et al., 2005) and sexually mature lobster up to 5,000 Hz (Pye and Watson, 2004).

2.4.2 Fish

Fish have two sensory systems for detection of sounds: the lateral line system and the inner ear. The lateral line, which is found along both sides of the body, detects low frequency sounds generally less than 200 Hz and is considered as a detector of water motion.

The inner ear, situated in the cranial cavity of the head, contains sensory hair cells which are stimulated by sound induced vibrations of small crystalline structures known as otoliths. Most species of fish are able to detect sounds from 50 Hz to upward of 500-1,500 Hz (e.g. Popper, 2003) which are within the range of many sources of underwater noise(s).

There is a wide variability in fish hearing capabilities in relation to the diversity of anatomical structures involved in sound detection (Popper and Fay, 2010). This ranges from hearing specialist species, which have morphological specializations linking the ear to their swim bladder (a gas-filled cavity) directly or through a series of bones, to non-hearing specialist species without swim bladder. Hearing specialists, such as herrings, which are able to detect the pressure component of sound, have an enhanced hearing sensitivity and a broad range of detectable frequencies (up to several kHz) whereas hearing non-specialists without swim bladder, such as flatfish, which are only able to detect particle motion, are less sensitive to sound with a relatively narrow bandwidth (up to 300 Hz). All the other species have hearing capabilities that fall somewhere between these two extreme categories. For example, cod which has a swim bladder not connected to the inner ear but quite close to it, exhibits an intermediate sensitivity with a wide bandwidth.

3.0 Review on Effects of Underwater Noise on Invertebrates and Fish

The question can be asked as to the reason for carrying out a review on the effects of different types of sound sources when the topic in question is vibroseis. Vibrators are being considered as a possible safer alternative to air guns for certain types of seismic surveys.

Thus, it was important to gather information on the effects of sound from various sources in order to provide an appreciation of effects which might be relevant to consider in any experimental trials with a marine vibrator, taking into consideration the local need and species of possible interest.

It is noted that any assessment of the effects of sound cannot entertain the question of the potential for subtle neuro-endocrine responses of a chronic nature which might be occurring in the environment when fish are subjected to low sound levels in association with for instance 2-4 week surveys. However, the question of the importance of low levels of sound can also be asked in relation to boat and ship noise in general.

It is commonly recognized that fish and invertebrates use sound for a variety of functions, including feeding, predation, avoidance and mating. Thus it is important to have some appreciation of sound levels which harm fish via various physiological and histopathological changes or major behavioural modification as well as direct mortality.

The following sections provide a review of available information on various effects of high intensity low frequency sounds on invertebrates and fish. Special attention was given to including detailed information on metrics in the tables in addition to observed effects. The review considered scientific journal articles, technical reports, industry reports, workshop and conference proceedings and web material as well as contacts regarding some on-going seismic work at DFO. However, the review cannot be considered to be exhaustive.

3.1 Effects of Low Frequency High Intensity Sounds on Invertebrates

There are a limited number of investigations on the effects of sound on invertebrates and studies have mainly focused on the effects of explosives or air gun exposures. Recent literature reviews of seismic impacts on invertebrates have been published (Moriyasu et al., 2004; Payne, 2004; Payne et al., 2008).

3.1.1 Effects of Air Guns on Invertebrates

Impacts of air guns on invertebrates are summarised by life stage of organism (adults, larvae and eggs) in relation to types of effects.

- **Effects on Adult Invertebrates**

Mortality and Visible Injuries

Most available literature indicates that there is no evidence of immediate mortality in various groups of invertebrates upon air gun exposure, even at very close proximity (within 2 m) (Table 1 Appendix). Recent studies have also showed no delayed mortality (up to 5 to 8 months post exposure) for commercial crustaceans. These included field exposure of caged snow crab to a single or an array of air guns with received levels of 197 to 237 dB re 1 μ Pa (Christian et al., 2004) or under the conditions of a seismic program in deep waters off Cape Breton with received levels of 170 to 192 p-p dB re 1 μ Pa (DFO, 2004; Courtenay et al., 2009). Laboratory and field exposure of lobster to multiple shots of a single air gun with received levels of ~202 (laboratory) to ~227 (field) dB re 1 μ Pa p-p also resulted in no differences in mortality in animals maintained in the laboratory for several months (Payne et al., 2007). Similar observations were also made on female snow crab maintained in the laboratory several months post exposure (DFO, 2004 and 2009).

Concerning visible injuries, 2 studies reported some physical impacts. Matishov (1992) observed shell splitting in 1 of 3 scallops tested and a 15% ablation of spines in sea urchins exposed in laboratory at very close range (2m) to estimated received levels of 214-220 dB. Guerra et al. (2004) suggested that seismic surveys may have caused or contributed to the massive organ damage observed in giant squid stranded in waters off Northern Spain but the observed effects could also be interpreted to be due to post-mortem changes.

Histopathological and Physiological Effects

A few studies have examined the effects of seismic air guns on the histopathology and physiology of adult invertebrates (Table 2 Appendix). No significant structural changes to various organs/tissues were detected between control and exposed animals of a number of species immediately or several months post exposure. The organs observed included gills and gonads of shrimp and red lobster (GIA, 2002), hepatopancreas, heart, eye, statocysts, heart, and gonads of snow crab (Christian et al., 2003; 2004; DFO, 2004) or hepatopancreas and gonads of lobster (Payne et al., 2007; Oceans Ltd., 2010). However, although no overt damage per se was observed in the hepatopancreas, some differences were observed in exposed animals such as decrease in lipid concentration in one type of hepatopancreatic cells (R-cells) in shrimp and red lobster in an experimental field trial (GIA, 2002). Some minor changes noted in exposed snow crab from the Cape Breton study included a slight increase in carbohydrate deposits and change in nuclear shape in hepatopancreatic tissues (DFO, 2004; Courtenay et al., 2009). Overall, the exposed crabs had fewer "abnormalities" than control crabs, so the differences observed may simply be due to natural variability. Payne et al. (2007) noted an increase in deposits of carbohydrates in hepatopancreatic tubules of lobster exposed in the laboratory. They also observed a slight increase in food consumption in a number of exposures.

Regarding biochemical responses, Christian et al. (2003), in their pilot study, did not find significant effects in haemolymph solute, serum proteins or haemocyte counts between control and exposed crabs sampled immediately and 2 weeks after exposure with received levels ranging from 197 to 227 dB. No major effects as assessed by the semiquantitative API enzyme technique, was also found for selected enzymes. Payne et al. (2007) also did not observe elevated levels of aspartate aminotransferase and creatine kinase enzymes in the serum of exposed lobsters indicating no major organ damage. However, there was evidence for a decrease of these enzymes along with a decrease in protein and calcium in the serum of exposed lobsters which lasted up to 33 days post exposure. This could suggest the possibility of haemodilution with potential for osmoregulatory disturbance.

Behavoural Responses

Of 4 studies investigating behavioural responses in adult invertebrates exposed to air guns (Table 3 Appendix), 3 reported no observation of readily visible movement upon and after firing. This included a laboratory study with lobster exposed to levels of 202 to 227 dB p-p (Payne et al., 2007), and a caging study in Conception Bay (NL) with snow crab exposed at 50 m from an air gun array with received levels ranging from 197 to 237 dB o-p (Christian et al., 2003). A study carried out on an inshore reef also reported no obvious movement of free crustaceans, echinoderms and mollusks receiving levels ranging from 195 to 218 dB o-p depending on the distance from the source (Wardle et al., 2001).

As commonly observed in fish, McCauley et al. (2000 a and b) observed alarm responses in caged squid at received levels starting at 156-161 dB RMS with a strong startle response involving ink ejection and rapid swimming at received levels of 174 dB RMS. They suggested thresholds for affecting squid behaviour being 161-166 dB RMS.

Effects on Catch Success

Most available studies on effects of air gun detonations on fishing success for invertebrates did not indicate any apparent short-term (days) changes between pre- and post-exposure catch rates (Table 4 Appendix). This included studies on snow crab (Christian et al., 2003), various shrimp species (La Bella et al., 1996; Webb and Kempf, 1998; Andriguetta Filho et al., 2005), 2 lobster species (La Bella et al., 1996; Parry and Gason, 2006), one squid and 2 bivalve species (La Bella et al., 1996). Also, snow crab catches carried out before and after the Cape Breton seismic survey were similar (Courtenay et al., 2009). La Bella et al. (1996) reported differences between pre and post catches for Murex, a species of gastropod, when gill nets were used, but no differences when hydraulic dredges were used.

Parry and Gason (2006) carried out an investigation on the potential for long-term effects of seismic surveys on rock lobster. Results of the statistical analysis of catch rates in Western Victoria, Australia, between 1978 and 2004 did not find evidence that catch rates were affected by seismic surveys in the weeks or years following the surveys. However, it is noted that although no short- or long- term changes in catch rates were detected in the areas subjected to intense seismic surveying, a change in catch rates in the order of 50% would have been required in order to discriminate the effects of surveying.

- **Effects of Air Gun Exposure on Embryos and Larvae of Invertebrates**

Data on the effect of air gun sound on developing eggs and larvae of invertebrates are extremely limited (Table 5 Appendix). Pearson et al. (1994) did not find any significant effects of very high levels of exposure (234 dB re 1µPa) at very close range from the source (1 to 10 m) on immediate and long-term survival of different larval stages of Dungeness crab. A preliminary study by Christian et al. (2003) on a pool of approximately 4,000 fertilized eggs from a snow crab suggested that exposure to very high levels of received sound at very close range (221 dB re 1µPa RMS at 2 m) retarded the development of exposed versus unexposed eggs. However, a DFO study (2004) where egg-bearing female snow crab were exposed to an authentic seismic survey (174 dB re 1µPa RMS at m) in Cape Breton waters did not demonstrate any effects on the development and viability of embryos or locomotion after hatch. DFO (personal communication, J. Payne) also carried out a study in which female snow crab bearing eggs at an early stage of development (orange) were exposed to a number of shots at a relatively high level of sound. No effect was observed after several months holding in the laboratory with eggs uniformly reaching the brown stage of development after ~ 5 months post exposure. There was also no evidence of impact on swimming ability of decapods and copepod zooplankton exposed at a range of 0 to 200 m from the air gun source (GIA, 2002).

3.1.2 Effects of Explosives on Invertebrates

Some information is available on effects of explosives on invertebrates and most of the studies examined immediate mortality and gross pathology (e.g. Moriyasu et al. 2004). Observations were variable depending on the species studied and experimental conditions (Table 6 Appendix).

No mortality was observed in white shrimp (Gowanloch and McDougall, 1944 and 1945; Kemp, 1956) or oyster (Gowanloch and McDougall, 1944; Sieling, 1951 and 1953) when charges were placed on or below the ocean floor. Similarly, no mortality was observed in spiny lobster (Aplin, 1947) with a suspended charge, or in blue crab (Kemp, 1956) or Dungeness crab (Anonymous, 1962) when charges were placed below the ocean floor.

Mortality was reported for white shrimp 46-60 m from suspended charges (Linton et al., 1985), and for oyster at 46 m (Linton et al., 1985) or 60 m (Anonymous, 1948; Kemp, 1956) from charges suspended or placed beneath the ocean floor. Mortality was also found in association with suspended discharges for abalones at 15 m (Aplin, 1947), as well as for blue crab at 46 m (Anonymous, 1948; Linton et al., 1985).

No study was found on behavioural changes. One study (Sieling, 1951) examined potential biochemical/physiological effects of explosives on oyster by measuring glycogen. The analyses did not show any consistent trend among the various experimental conditions.

Overall, mortality of invertebrates was less than 10 % when they were exposed to powerful high explosives discharged more than 50 m away.

3.2 Effects of Low Frequency High Intensity Sounds on Fish

There have been more studies on effects of high intensity sounds on fish than on invertebrates. Sounds include those from air guns, pile driving, explosives and sonar.

When relevant, effects of some other sound sources, such as pure tones, white noise, aquaculture and boating, were also examined.

3.2.1 Effects of Air Guns on Fish

There have been substantially more studies on effects of seismic devices than other high intensity sound sources. Recent literature reviews of seismic impacts on fish have been published (Worcester, 2006; Payne et al., 2008; Popper and Hastings, 2009). Impacts of air-gun use are summarised here by life stage of organism (adult or larval/egg forms) and types of effects.

- **Effects of Air Gun Exposure on Adult Fish**

Mortality

There is very little evidence of immediate mortality of adult fish exposed to air guns, even at very close proximity (within 5 m) (Table 7 Appendix). No significant mortality has been observed in laboratory studies carried out at DFO with codfish, salmon, cunners and smolt (Andrews et al., 2007 and DFO unpublished), and experimental caging studies or caging studies in conjunction with an authentic seismic survey (Hassel et al., 2003; CEF Consultants, 2006). Hastings (1990) earlier reported a lethal threshold for sound beginning at 229 dB and stunning effect at 192-198 dB.

Effects on Non auditory Tissues

Some studies have examined the effects of exposure to air guns on non-auditory tissues of fish (Table 8 Appendix). Swim bladder injuries were reported in 2 of 14 young coregonid fish exposed to 1 shot of a single air gun within 0.6-1.5 m range (estimated received levels of 222 to 234 dB re 1μPa) (Falk and Lawrence, 1973). However it is noted that in the same study, no damages were observed in fish exposed to 4 shots at the same range or in fish exposed to 1 shot at 1.5 to 3.4 m range. Holliday et al. (1987) also reported swim bladder damage in Northern anchovy exposed to multiple discharges of 4 air guns at 1.5 to 3 m range (received levels between 215 and 134 dB re 1μPa). Internal bleeding was observed in young and mature cod exposed to a single or an array of air guns at 0.5m range (estimated received level: 226 dB), but no effects were noted at or beyond 1m (Koshleva, 1992).

No visible damage to external or internal organs/tissues was attributable to air gun exposure in other studies. These included (a) laboratory exposure of juvenile cod to multiple shots of a single air gun at 2.5 m range (SPL ~ 202 dB) (Andrews et al. 2007), (b) caged sea bass exposed for about 2h to a 16 air gun array of a seismic survey as close as 180m (estimated received level: 210dB) (Santulli et al., 1999), (c) whitefish, lake chub and Northern pike exposed to 5 or 20 shots of a 8 air gun array at 13-17 m range (received level: 205-210 dB mean peak) (Popper et al., 2005), (d) a variety of freshwater fish from the Mackenzie River exposed to an air gun array at distance from 2 to 3000 m to the source (received level: 169-224 dB peak; 159-204 dB RMS) (IMG-Golder Corp, 2002), and (e) juvenile cod caged in conjunction with a seismic survey in Sydney Bight (received level of 204 dB p-p) (CEF Consultant, 2006). Also, Boeger et al.

(2006) did not record any visible external damage in coral reef fish exposed to air guns (196 dB at 1m) as close as 0.5 m range from the source.

A few studies have examined the effects of air gun exposure on tissue histopathology (Table 9 Appendix). No histopathological abnormalities attributable to exposure were detected in various organs of juvenile cod caged in conjunction with a seismic survey in Sydney Bight (CEF Consultant, 2006), various freshwater species from the Mackenzie River (IMG-Golder Corp., 2002) and red snapper and Brazilian mojarra exposed to a 4 air gun array moving at a distance of 0 to 200 m (estimated source level of 196 dB) (GIA, 2002). However, Koshleva (1992) observed bubble formation in nuclei of blood cells but only within 0.5 m with an estimated exposure level of 226 dB.

Effects on Auditory Tissues

Before discussing the effects of exposure to air guns on auditory tissues, notation is given to studies that have demonstrated some damage to sensory hair cells in the ears of fish upon exposure to pure tones in the laboratory. However, these studies often involved fairly high sound pressure levels and long exposure times. Enger (1981) exposed cod (*Gadus morhua*) to 180 dB re 1μPa sounds for 1-5 h while Hastings et al. (1996) exposed oscar (*Astronotus ocellatus*) to 180 dB re 1μPa for hours. Hastings (a.k.a. Cox et al., 1986 a and b; 1987) in an earlier study reported limited damage to sensory cells in goldfish (*Carassius auratus*) exposed for 2 hours to quite high pressure levels of 204 and 197 dB re 1μPa. As to hair cell repair, Smith et al. (2006) noted that goldfish had significant capacity to regenerate hair cells in goldfish exposed for 48 h to 170 dB re 1μPa RMS. (Note an RMS value of 170 dB corresponds to a o-peak value of 180, using the formula of adding 10-12 dB to an RMS value to obtain an approximate o-peak value).

The effect of air gun exposure on fish auditory tissues has been examined to some extent (Table 10 Appendix). McCauley et al. (2003) noticed some damage to the sensory hair cells of the ear of pink snapper exposed to hundred of shots from a single seismic air gun (received SEL exceeding 180 dB re 1μPa^2.s for several of the shots). Damage was reported to occur in small regions of the saccule and it increased (but did not constitute a major proportion of sensory cells) for up to at least 58 days post exposure. However, no damage to the sensory hair cells of the ear was reported for juvenile cod caged as close as 55 m (received levels at the cage of 204 p-p) from a seismic survey (CEF consultants, 2006). Likewise Song et al. (2008) did not find any damage to sensory hair cells of the ear of 3 species of fish (1 hearing specialist, 1 hearing generalist and 1 intermediate) exposed to 5 or 20 shots from a small seismic air gun array (average mean peak SPL 207dB; mean RMS sound level 197dB; mean SEL 177 dB; Popper et al., 2005).

Temporary Hearing Loss

Exposure to relatively high levels of sounds (or energy) can result in a temporary hearing shift whereby an increase in sound pressure level is required to maintain adequate hearing. There is some information available with respect to air guns in this area (Table 11 Appendix). Popper et al. (2005) exposed 3 fish species, 2 non-specialists and 1 specialist, to 5 or 20 shots of a small seismic air gun array, with each shot having a received peak sound level of about 205-210 dB (see above). No temporary hearing loss was found for 1 hearing generalist but a 10-25 dB shift was observed for the 2 other species. Noticeably, hearing recovered within 24 h after exposure. A recent study by Hastings and Miksis-Olds (2010) did not find any temporary hearing shift for 4 tropical fish species exposed to 2 passes of an air gun array in a seismic survey, even when cumulative sound exposure levels reached 190 dB re $1\mu Pa^2.s$.

Physiological Effects

A few studies on the physiological effects of air gun exposures in fish have been reported (Table 12 Appendix). Santulli et al. (1999) observed significant changes in cortisol, lactate, glucose and adenylates, which are characteristic parameters of stress response, in European sea bass exposed to an air gun source at a distance of 180 to 6,500 m (estimated received levels: 199-210 dB) as compared to controls. Most of these parameters returned to pre-exposure levels in the 72 hours following exposure. McCauley et al. (2000 a and b) reported no significant changes in cortisol, glucose and white blood cell counts in fish exposed to air gun exposure (146-195 dB RMS). It is noted that responses like elevation of cortisol, lactate or glucose can be commonly expected in many fish species upon frightening.

Behavioural Effects

Behavioural reactions of fish to air gun operations are commonly reported and can range from very subtle changes to strong avoidance reactions that can lead to horizontal or vertical migration away from the source as well as to impacts on catch rates.

Subtle Responses

Subtle responses have been observed in a number of studies with different fish species exposed to air guns, including for example sea bass (Santulli et al., 1999), rockfish (Pearson et al., 1992), pink snapper (McCauley, 2000), sandeel (Hassel et al., 2003; 2004), pollock (Wardle et al., 2001), coral reef fish (Boeger et al., 2006), and cod (CEF consultants, 2006). However, no changes in behavioural characteristics were reported with trout (Thomsen, 2002) and other freshwater fish (Popper et al., 2005; Jorgenson and Gyselman, 2009) exposed to air gun shots (Table 13 Appendix).

Subtle responses may be short-term in nature and vary between species in relation to sound properties. The ecological significance of on-going exposure of fish to sound levels sufficient to evoke subtle responses is unknown.

Effects on fish distribution

Changes in vertical distribution of fish have been reported upon exposure to air-guns in a number of studies (Table 14 Appendix). Many of them indicated a downward movement of fish, including for example whiting (Chapman and Hawkins, 1969; Dalen and Knutsen, 1987), black rockfish (Pearson et al., 1992; Skalski et al., 1992), and various pelagic species (La Bella et al., 1996; Slotte et al., 2004). However, fish such as sandeel appeared to move higher (Hassel et al., 2004) whereas vermillion and olive rockfish either rose in the water column or moved to the bottom (Pearson et al., 1992). It is uncertain how far from a seismic survey changes in vertical distribution might occur and for how long, though most authors speculated that these types of responses would be temporary and generally confined to the period of sound exposure (e.g. Worcester, 2006).

Change in horizontal distribution of fish has also been reported in some studies (Table 15 Appendix). Cod, haddock, herring and blue whiting migrated away from the sound source area (Engas et al., 1996; Slotte et al.,2004; Dalen and Knutsen, 1987). However, no effect on horizontal distribution was detected in other studies with pollock, sandeel, sea bass and freshwater fish (Pickett et al., 1994; Wardle et al., 2001; Hassel et al., 2003). The interpretation of the results is difficult due to the lack of information on received intensity of sounds in some cases, the variety of species studied and their different biological characteristics (sedentary or migratory), and various experimental conditions.

Effects on Catch Rates

Changes in the behaviour of fish populations, as measured by catch rates, has also been observed in fish exposed to seismic surveys (Table 16 Appendix). Catch rates of groundfish and rockfish were reduced in the immediate vicinity of a survey area and probably out to a few km range (Skalski et al., 1992; Engas et al., 1996; Lokkeborg, 1991; Lokkeborg and Soldal, 1993; Lokkeborg et al., 2010) or substantially increased (Dalen and Knutsen, 1987; Engas et al., 1996; Skalski et al., 1992; Lokkeborg and Soldal, 1993; Lokkeborg et al., 2010). However, no changes in catch rates have also been reported in other studies (La Bella et al., 1996; Engas et al., 1996; Lokkeborg and Soldal, 1993; Pickett et al., 1994; Thomsen, 2002). Changes in behaviour and catch rates may sometimes be related to the presence of a swim bladder.

The differences in effects on catches observed in these studies are not surprising given that different species were studied in different areas at different phases of their annual cycles, with the use of different gear types.

Hirst and Rodhouse (2000) in their review suggested that the lowest sound pressure levels of air gun in the open sea shown to elicit a behavioural response which resulted in altered fish catch were estimated at less than ~ 160 dB.

Behavioural responses of fish to air gun discharges are likely to be highly variable and site, device and species specific.

- **Effects of Air Gun Exposure on Early Stages of Fish**

The effects of seismic impacts on early stages of fish eggs and larvae have been reviewed to some extent (Payne, 2004; Payne et al., 2008) and are summarized in Table 17 (Appendix).

Kostyuchenko (1973) exposed fish eggs of various species (anchovy, red mullet, crucian carp, blue runner) to a single air gun (estimated exposure level of 210 to 236 dB) at 0.5 to 10 m range and reported a survival rate of 75% at 0.5 m and 90% at 10 m from the source compared to 93% survival for controls. Pathological effects were observed in a small percentage and at a distance less than 10 m from the gun.

Holliday et al. (1987) exposed eggs, yolk sac and early swim bladder larvae of Northern anchovy to multiple discharges of an air gun array at 1.5 to 3 m range. There was a decrease in survival of the eggs (9%) and 4-day yolk sac larvae (~35%). No survival differences were observed for swim bladder larvae. Growth rate was reduced for 2- and

4- day yolk sac larvae as well as 22- day swim bladder larvae. Except for yolk sac larvae, there was no indication of histological damages.

Koshleva (1992) reported high mortality of eggs and larvae of plaice exposed to an air gun (estimated 214 to 220 dB) at 1 m but no mortality at 2 m.

Booman et al. (1996) exposed eggs, larvae and fry of various commercially important fish species (cod, saithe, herring, turbot and plaice) to an air gun array at a distance of 0.75 to 6 m corresponding to received levels ranging from 242 to 220 dB. They reported some cases of mortality and injury but most of these occurred within 5 m. Damage to brain cells was observed in yolk sac larvae of turbot at a distance of 1.6 m or less.

Matishov (1992) exposed 5 day old cod larvae to a series of air gun shots at 1 to 4 m range (estimated exposure levels of 214 to 220 dB). Except for the observation of damage to retinal tissue at a distance of 1 m, no other histological alterations were detected in various tissues at any distances.

Payne et al. (2009) observed no differences in mortality/morbidity between control and exposed capelin eggs and monkfish larvae exposed to 10 or 30 shots of a single air gun at a distance of 1.5 to 2.5 m (received levels of 199 to 205 dB p-p).

Dalen and Knutsen (1987) did not observe any difference in mortality, feeding success or behaviour for any stages examined (eggs, larvae and fry) of cod exposed to one shot of a single air gun having a source level of 220 to 231 dB. However, they reported a transient effect on buoyancy in older fry.

3.2.2 Effects of Pile Driving on Fish

There is some information on the effects of pile driving on fish (e.g. Hasting and Popper, 2005; OSPAR 2009; Popper and Hastings, 2009; OSPAR, 2009). A summary of more recent investigations is provided in Table 18 (Appendix). One study reported mortality and some injury in several free swimming fish, including salmon, anchovy and surfperch that were within 50m of a very high sound source (Caltrans, 2001). Additionally, it was suggested, based on the numbers of fish that came to the surface dead after pile driving, there was less (or no) mortality at greater distances from the source. Experimental caging studies with surfperch and steelhead (Caltrans, 2001; 2004), black fish (Abbott and Bing-Sawyer 2002), brown trout (Nedwell et al., 2003; 2006), and coho salmon (Ruggerone et al., 2008; Oestman and Earle, 2010) have also suggested that fish experienced little or no mortality and/or non-auditory tissue damage beyond the near vicinity of pile driving. Popper et al. (2006) proposed that interim noise exposure criteria values for the onset of direct physical injury in fish exposed to the impact sound associated with pile driving be set at an SEL level of 187 dB re 1μPa^2.s and a peak sound pressure of 208 dB re 1μPa (p) in any single strike.

Mueller-Blenke et al. (2010) observed a significant movement response at relatively low received sound pressure levels (~ 140-161 dB p, particle motion between 6.51) in a behavioural study on cod and sole exposed to pile driving playbacks. On the other hand, Nedwell et al. (2006) did not note any increase in activity or startle response when brown trout were exposed as close as 50m to vibro-piling equipment (with a source level of 194 dB at 1m). The later study also examined the effects of pile driving on fish hearing.

They did not find any evidence of trauma in the inner ear of brown trout, however, it was noted that this species is recognized to be a poor hearing generalist.

In a recent outdoor exposure study, Ruggerone et al. (2008) subjected juvenile coho salmon (*Oncorhynchus kisutch*) to a total of 1627 pile-driving pulses over a period of 4.3 hours. The peak noise level was 208 dB and the SEL 179 dB, corresponding to an accumulative SEL value of up to 207 dB. Neither mortalities nor external or internal injuries which could be traced back to pile-driving were observed. Also, only a low level of behavioural responses was noted (Ruggerone et al., 2008).

3.2.3 Effects of Sonar on Fish

A few studies have been carried out on the effects of sonar (Table 19 Appendix). Data obtained to date showed no evidence of fish mortality and no damage to auditory and non-auditory tissues upon exposure of adult fish, including rainbow trout *(Oncorhynchus mykiss),* channel catfish (*Ictalurus punctatus*) and sunfish *(Lepomis sp.)*, to emissions from SURTASS Low Frequency Active sonar with received sounds as high as 193 dB re 1µPa RMS (Halvorsen et al., 2006; Popper et al., 2007) or up to 210 dB re 1µPa RMS (Kane et al., 2010). However, some temporary hearing loss was observed.

The effects of pure tones (1.5, 4 and 6.5 kHz) with received sound levels varying from 150 to 189 dB were also studied on larval and juvenile fish of several species (Jorgensen et al., 2005). The results of the study showed no significant effect on behavior or tissue damage. Some mortality in juvenile herring was reported with the highest sound levels.

3.2.4 Effects of Explosives on Fish

Effects on fish associated with underwater explosions have been widely documented and selected studies are summarized in Table 20 (Appendix). Explosives can cause mortality and tearing or rupturing of the swim bladder of some (but not all) fish species (e.g. Aplin, 1947; Coker and Hollis, 1950; Gaspin et al., 1976; Yelverton et al., 1975; Govoni et al., 2003). Other internal damages most commonly observed in adults included haemorrhages (e.g. Aplin, 1947; Coker and Hollis, 1950; Linton et al., 1985; Govoni et al., 2003, 2008), as well as liver, spleen and kidney injury (e.g. Coker and Hollis, 1950; Yelverton et al., 1975; Govoni et al., 2003, 2008).

Some studies have suggested that there is more damage to fish with swim bladders (e.g. Coker and Hollis, 1950; Gaspin, 1975) while the work of Yelverton et al. (1975) showed no difference in damage between fish with ducted and non ducted swim bladders. The latter authors also found a direct correlation between body mass and the acoustic impulse which caused 50% mortality. It has also been shown that the effects on fish decline rapidly with increasing distance from explosion source (e.g. Nedwell et al., 2004; Govoni et al., 2008) as the peak overpressure and impulse decreases. From the effects of exposure to submarine detonations on juvenile pinfish, Govani et al. (2003) concluded that the total energy in the sound wave, regardless of pressure polarity, was responsible for the observed effects.

Sverdrop et al. (1994) reported no mortality but damage to vascular endothelium and suppressed stress response, with recovery within a week, in Atlantic salmon exposed to explosives (246 db re 1μPa) within a range of several meters.

The few studies that have examined the effects of explosions on fish larvae/embryos have shown that they can have harmful effects on certain early life stages (e.g. Godard et al., 2008) with sub-lethal effects (gross pathology and tissue histopathology) being observed for instantaneous pressure changes as low as 69 kPa (Godard et al., 2008). As with adult fishes, the presence of a swim bladder is believed to contribute to internal damage in larval and juvenile fishes (Settle et al., 2002).

It is clear that there is considerable variability in the effects of explosive blasts on fish, and that the variables include received sound energy, presence or absence of a swim bladder and fish mass.

3.2.5 Effects of Aquaculture Sounds on Fish

Results of studies on the potential effects of aquaculture sounds on fish are of interest since they involve long term exposure. Survival, growth, hearing and disease resistance was reported not to be affected in rainbow trout (*Onchorhynchus mykiss*) exposed to intensive aquaculture production noise (115, 130 and 150 dB re 1μPa RMS) (Wysocki et al., 2007). Similar results were reported by Davidson et al. (2009) in rainbow trout exposed for 5 months to 149 dB re 1μPa RMS.

3.2.6 Effects of Boat Noise on Fish

An appreciation of the effects of boat noise on fish is of interest since it would be expected to be the predominant source of man made noise in the ocean (e.g. OSPAR, 2009; Slabbekoorn et al., 2010).

Studies have shown various types of effects on fish in relation to shipping noise or equivalent noise (i.e. noise with a frequency band within the hearing range of fish as well as within the range produced by vessel traffic) such as white noise and pure tones.

Temporary hearing loss (or temporary threshold shift) has been reported for fathead minnow after 2 hours exposure to horse boat engine noise (Scholik and Yann, 2001; 2002) and for toadfish exposed to ferry-boat noise with a maximum SPL of 130.8 dB at 20 m (Vasconcelos et al., 2007). The later study also showed a potential masking effect since the ability of females to detect nesting males was fairly restricted under ship noise conditions. Hearing loss has also been observed in the case of exposure of goldfish to white noise (170 dB re 1μPa SPL) within 10 minutes of noise onset (Smith et al., 2004a). The hearing recovery time varied with the frequency of the sound and the duration of exposure (Smith et al., 2004 a and b; 2006).

Physiological effects have also been recorded in freshwater species, including increased levels of cortisol in fish exposed to ship noise (153 dB re 1μPa RMS) for 30 min (Wysocki et al., 2006) as well as increased in heart rate and decrease in stroke volume in fish exposed to various recreational boating activities (e.g. canoe paddling, trolling, outboard motor noise) for 60 s (Graham and Coke, 2008). Recently, Buscaino et al. (2010) reported a significant increase in motility as well as an increase in blood glucose, lactate and haematocrit levels in European sea bass and gillhead sea bream exposed to a 0.1-1 kz linear sweep (150 dB re 1µPa RMS). However, these types of effects (e.g. enhanced heart rate, increase in haematocrit or elevated serum cortisol and glucose) would not be unexpected in frightened fish.

As to behavioural effects on fish, vessel avoidance reactions have been reported both in acoustic and stock assessment trawl surveys for species including capelin (Jorgensen et al., 2004), cod (Handegard et al., 2003), herring (Vabo et al., 2002), and various other species (Mitson, 1995; Mitson and Knudsen, 2003). Sara et al (2007) also showed alteration of schooling behaviour of bluefin tuna when exposed to sound generated by hydrofoil passenger ferries, small boats and large car ferries. The determination of behavioural startle responses thresholds of 8 North Sea fish species exposed to pure tones in the frequency range 0.1 to 64 kHz, showed that responses varied per frequency within and between species (Kastelein et al., 2008).

3.3 Effects of Seismic Vibrators on Fish

A marine vibrator is essentially a marine loudspeaker. The reason for calling this sound source a marine vibrator is the similarity with the equivalent source used for land seismic surveys.

Since marine vibrators have been rarely used to date there are, to our knowledge, no investigations that have investigated their potential effects on marine organisms. However, the effects of vibroseis on fish were studied on frozen lakes in Alaska where fish were exposed to 1 or 5 vibrators (Morris and Winters, 2005).

The study was carried out with caged Arctic char (*Salvelinus alpinus*) exposed to 5 vibrators at 106 Hz for 6 seconds. Relying on earlier work, it was assumed that the pressure at the fish cages immediately below the vibrator rigs was approximately 201 dB re 1µPa. The results indicated no increased mortality between control and exposed as well as no swim bladder damage. Damage to muscles, eyes, and mouths were found in some exposed fish, but this was attributed to attempts by the fish to escape the sound, as video footage showed fish trying to escape the cages during the exposure. The authors concluded that the pressure waves from the vibroseis were not directly responsible for any fish injury. This seems quite reasonable given that the fish were contained in small cages having a steel wire mesh.

The second part of the study investigated the behaviour of wild broad whitefish (*Coregonus nasus*) exposed to a vibrator. Cameras were installed in a whitefish wintering area, and their reactions were recorded while a vibroseis truck operated above them. As the initial cameras were installed underwater, the fish appeared sedentary, but continued human activity aroused them. When the vibroseis was initiated, the fish moved from the area, but swimming speeds quickly slowed, and within two minutes fish had returned to their initial locations and behaviour. Repeated application of the vibrator resulted in a reduced response each time, with more rapid resumption of pre-disturbance behaviour. Thus the behaviour response with vibroseis was not unlike a commonly observed startle response found in many species of fish exposed to sound.

3.4 Metrics Associated with Various Sources of Sound

Table 8 provides a comparison of metrics associated with various sources of sound, understanding that the comparisons are not meant to provide absolute but relative values.

Table 8 Some Reported Metrics Associated with Various Sources of Noises

Source	Bandwidth (Hz)	Dominant Frequency (Hz)	Signal Duration (ms or s)	Source Level (dB re 1 μPa-m)	Prevalence
Explosives	2 – 1000 Hz	6 – 21	~ 1 – 10 ms	272 – 287 peak	Localized, infrequent
Air guns	10 – 100,000	10 – 120	30 – 60 ms	200 – 262 p-p	Approx. 90 crews worldwide
Pile Driving	20 – 20,000	100 – 500	30 – 70 ms	243 – 257 p-p	Localized, infrequent
Shipping Large vessels	6 – 30,000	> 200	Continuous	150 – 190 RMS	Ubiquitous
Low Frequency Active Sonar	100 – 500		0.6 - 1 s	235 RMS	No more than 4 crews
Mid Frequency Sonar	2800 – 8200	3500	0.5 – 2 s	223 – 235 p	Several hundred in use
Marine Vibrators (current)	15 - ?	25 – 200	10 – 20 s	200	Almost non-existent
Marine Vibrators (next generation)	5 - ?	5 – 120	10 – 20 s	235	

Adapted from OSPAR (2009)

Since marine vibrators may become a substitute for air gun arrays under certain conditions, such as for surveys in shallow waters, differences in air gun and vibrator metrics are briefly noted. Firstly, as noted by Bird (2003), the concept of using swept signal sources as a more environmentally friendly alternative to impulse sources, such as from air guns, has been around for some time. For instance, amplitude is widely recognized to be important in producing certain types of biological damage and this can be reduced through use of marine vibrators. Use of much lower sound levels at source would result in much lower sound at some distance in the environment and thus less potential for biologic effects.

Bird (2003) further discusses the value of using vibrators in shallow waters when there may be concern about the impact of pressure waves on bottom living organisms. To be effective an impulsive source must be at a depth of several meters to minimize surface loss of energy. Marine vibrators are able to produce full output in as little as 1 m of water and according to Bird (2003), a marine vibrator in 5 m of water, producing 0.4 bar will generate a bottom pressure 40 times smaller than a typical shallow water air gun array.

3.5 Comparison of Sound Transmission Losses Between Air Guns and Vibrators

Table 9 provides a comparison of hypothetical transmission losses from typical air gun arrays and an array of 4 marine vibrators. The significant loss of sound at points distant through use of marine vibrators versus air gun arrays is noted.

Table 9 **Hypothetical Vertical Transmission Losses by Spherical Spreading from Typical Air Gun Arrays and an Array of 4 Marine Vibrators**

Distance from the Source (m)	Peak Pressure (dB re 1μPa)	
	Array of Air Guns	Array of 4 Marine Vibrators
1	250 260	220 230
10	230 240	200 210
100	210 220	180 190
1,000	190 200	160 170

Assumes spherical spreading and the peak pressure of a marine vibrator being about 30 dB lower than the corresponding peak pressure of an impulsive source (Bird, 2003; Weilgart, 2010). Assumption of cylindrical spreading such as in shallow water would involve a reduction of 10 dB rather than 20 dB for a 10 fold increase in distance. Note, Bird (2003) assumes an output of 220 dB for an array of 4 marine vibrators but an output of 230 dB is also included for interest.

3.6 Noise Exposure Criteria Proposed for Mammals and Fish

Information on noise exposure criteria is presented for general interest with the understanding that it is difficult to make cross comparisons in relation to SPL, RMS, SEL etc.. for different sources of sound and effects on different species. Further, although approximate conversions are sometimes carried out for a particular source such as converting o-p pressure or p-p pressure to RMS, or for instance SPL to SEL, such calculations are often prefaced with caution.

Recently, Southall et al. (2007) proposed sound exposure criteria for whales and seals (Table 10). It is noted that all criteria are provisional as they are based on extrapolations from limited sets of data.

Table 10 **Noise Threshold Levels Protective of Injury for Marine Mammals**

Organisms	**Peak Level dB re 1μPa**	**Sound Exposure level (SEL) dB re 1μPa^2.s**
Cetaceans (whales) Single or multiple exposure over 24h	230	198
Pinnipeds (seals) Single or multiple exposure over 24h	218	186

Southall et al. 2007

If we assume a pressure level at source for a marine vibrator to be 230 dB (following the approximation that the source pressure level for a vibrator could be 30 dB less than an impulsive source such as an air gun array of 260 dB), 230 dB is noted as the criteria for causing auditory damage to cetaceans by air gun arrays. In other words, the potential injury zone for cetaceans would only be in the immediate vicinity of the vibrator, if at all, not for instance even some tens of meters away. Could this small injury zone be also transposed to an approximate extent to fish exposed to vibroseis?

Carlson et al. (2007) similarly proposed interim criteria for fish exposed to pile driving (Table 11).

Table 11 Pile Driving Interim Exposure Criteria For Fish

Reference	Effect	Sound Type	Fish Characteristics	Received Sound Pressure Level
Popper et al. 2006	Injury	Pile driving single pulse	All fish	208 dB re 1μPa peak
				187 dB re 1μPa².s SEL
Carlson et al. 2007	Temporary Threshold Shift	Single pulse	Hearing specialist	205 dB re 1μPa peak
			Hearing generalist	207 dB re 1μPa peak
		Multiple pulses	Hearing specialist	183 dB re 1μPa².s SEL
			Hearing generalist	185 dB re 1μPa².s SEL
Carlson et al. 2007	Auditory Tissue Damage (Hair Cells)	Single pulse	Hearing specialist	> 205 dB re 1μPa peak
			Hearing generalist	> 207 dB re 1μPa peak
		Multiple pulses	Hearing specialist	>185 dB re 1μPa².s SEL
			Hearing generalist	>189 dB re 1μPa².s SEL

From ICES 2010

In reference to the criteria for fish, injury or auditory damage to hair cells which may be produced by a single pile driving pulse is given as 208 dB re 1μPa, > 205 dB re 1μPa and > 207 dB re 1μPa peak.

Assuming a peak level of 230 dB for a marine vibrator array, a peak level of 210 dB would only be found within a depth of 10 m or so (see Table). Temporary threshold shifts (TTS), which are also provided, do not represent injury as such but are reversible physiological effects, or temporary fatigue (Ward, 1997). However, it is noted that the peak values for TTS are also relatively high, 205 and 207 dB re 1μPa for hearing specialists and generalists respectively. Again, could these small injury zones indicated for fish exposed to pile driving be transposed to some extent to fish exposed to vibroseis?

Since pile driving is from a fixed point, it commonly exposes any nearby animals to hundreds or thousands of strikes. Thus, cumulative noise or SEL values are often estimated, with cumulative SEL being given as the SEL of a single strike + 10 log of the number of strikes. This means that the SEL will increase by 10 dB with every tenfold increase of the number of strikes. An estimation of the distance from the source at which these criteria are reached, or potential impact zone, for single and multiple strikes (n=500) of a pile driving (broadband source sound pressure = 216 dB re 1μPa².s SEL; TL = 15 log) is provided in Table 12.

A ship carrying a vibrator array and moving 6 knots (similar to a ship using air guns) would not be comparable to a situation such as pile driving whereby nearby organisms would receive hundreds to thousands of high intensity exposures from a fixed source over a few or number of days.

Table 12 Suggested Impact Zones for Fish exposed to Pile Driving

Effect	Group	Cumulative SEL	Single Strike Impact Zone (m)	Multiple Strikes Impact Zone (m)
Non-Auditory Tissue Damage	Mass of fish < 0.5 g	183	158	7,973
	Mass of fish > 200 g	> 213	< 1.58	< 79
Auditory Tissue damage	Hearing generalist	> 213	< 1.58	< 79
	Hearing generalist	> 189	< 63	< 3,162
	Hearing specialist	> 185	< 115	< 6,309
Temporary threshold Shift	Hearing generalist	185	115	6,309
	Hearing specialist	183	158	7,943

From Carlson et al. (2007)
Broadband source sound pressure = 216 dB re 1μPa^2.s SEL; TL = 15 log; multiple strikes = 500

It is noted that in the case of marine vibrators which may replace air guns for some types of surveys, the pulse duration would be higher with vibrators. This can lead to speculation about the potential for short term masking effects. However, speculation about potential for masking can also be invoked for ships.

Recommendations for interim criteria for continuous broadband sounds, such as those associated with vibratory pile driving were also recently proposed by Hastings (2010). They consist of 2 metrics, RMS sound pressure level and cumulative SEL (Table 13). This table is given for general interest.

Table 13 Interim Criteria for Vibratory Pile Driving

Effect	Application	Peak Level RMS dB re 1μPa	Cumulative SEL dB re 1μPa^2.s	Notes
Non-auditory tissue damage	Mass < 0.6 g	Not relevant	191	
	Mass > 102 g	Not relevant	234	
Auditory Tissue damage	Hearing generalist	>170	>234	If RMS exceeded then SEL should be reduced by the same number of dB
	Hearing specialist	170	222	
TTS	Hearing generalist	80 dB above lowest hearing threshold	234	
	Hearing specialist	55 dB above lowest hearing threshold	185	

4.0 Discussion

4.1 Overview on Effects of Underwater Sounds on Invertebrates and Fish

4.1.1 Effects on Invertebrates

Based upon currently available information, there is little evidence of immediate mortality or physical injuries to adult and larval stages of invertebrates when they are at a distance of more than 5 m from air guns and 50 m from powerful explosive shots.

Also, there is no evidence of delayed mortality and physical injuries in snow crab and lobster kept in laboratory for several months after exposure to air guns under the conditions of a seismic program (DFO, 2004) or in experimental conditions with high intensity received levels (Christian et al., 2003; Payne et al., 2007). Guerra et al. (2004) suggested that seismic surveys may have caused or contributed to the organ damage observed in giant squid stranded in waters of Northern Spain on 2 occasions. However, the observed effects could also be interpreted as being due to post-mortem changes in stranded animals.

Histopathological effects have been investigated in a few studies with air gun exposure. No significant structural changes were detected in various organs/tissues between control and exposed adults of a number of crustaceans species, immediately or several months after exposure. This has included laboratory studies (Payne et al., 2007; Oceans Ltd., 2010), experimental field trials (GIA, 2002; Christian et al., 2003) as well as a seismic survey off Cape Breton (DFO, 2004; Courtenay et al., 2009). Some slight histological differences were noted in the hepatopancreas of control and exposed snow crab from the seismic survey, with the most "abnormalities" noted in the control group. Such differences could be linked to natural variability.

With regard to biochemical/physiological responses to high intensity sounds, some stress responses were reported in lobster exposed to air guns whereas no obvious effects were reported for glycogen in oyster exposed to explosives or in various serum parameters of snow crab exposed to air guns (Sieling, 1951; La Bella, 1996, Christian et al., 2003; Payne et al., 2007). A small increase in food consumption was observed in lobster exposed to several air gun shots and this was observed for weeks to months after exposure (Payne et al., 2007). Lagardere (1982) and Lagardere and Regnault (1980) demonstrated decreases in both growth and reproductive rates as well as physiological changes in shrimp exposed to aquaculture sound at 30 dB above ambient noise, but this involved a 3 month exposure.

With respect to effects of air guns on early life stages of invertebrates, except for signs of delayed development of snow crab eggs exposed to a very high level of sound at 2-4 meter range, no significant effects were detected in the development of various stages of Dungeness crab larvae exposed at very close range or in various embryonic stages of snow crab exposed under the conditions of a seismic program (Pearson et al., 1994; Christian et al., 2003; DFO, 2004). Also, DFO noted no effect on egg development in snow crab exposed to a number of air gun shots at a relatively high level of exposure during their orange-egg stage of development with eggs progressing through to the brown stage upon holding of animals for approximately 5 months.

Concerning behavioural responses, no readily visible reactions of caged lobster and snow crab or various free invertebrates were observed upon and after air gun exposure (Wardle et al., 2001; Christian et al., 2003; Payne et al., 2007). Also, experiments carried out in the laboratory by DFO (personal communication, J. Payne) found no evidence for scaring of scallop (*Placopecten magellanicus*) exposed to air gun discharges. Condition indices were also unaltered in animals retained in the laboratory 5 months post exposure. As commonly observed for fish, McCauley et al. (2000 a and b), noted startle/alarm responses in caged squid and suggested thresholds for affecting squid behaviour at 161-166 dB re 1µPa RMS. In another study, Wilson et al. (2007) did not observe any apparent effects of playback of intense ultrasonic echolocation clicks of killer whales on squids. Also, from the studies found on effects of air gun exposure on plankton, there was no evidence of impact on swimming ability or distribution of the organisms (GIA, 2002; Lokkeborg et al., 2010).

Most available studies on effects of air gun detonations on fishing success did not indicate any apparent short-term (days) changes between pre- and post-exposure catch rates for various invertebrate species (Christian et al., 2003; La Bella et al., 1996; Webb and Kempf, 1998; Andriguetta Filho et al., 2005; Parry and Gason, 2006; Courtenay et al., 2009). Differences between pre and post catches were reported for one species of gastropod and only in the case of a specific fishing gear (La Bella et al., 1996).

The only investigation on potential long-term effects of seismic surveys on fishery success is the study of Parry and Gason (2006) which showed that catch rates of rock lobsters appeared to be unaffected in the weeks or years following intense seismic surveying. However, it was noted that a change in catch rates in the order of 50% would have been required to be detected.

Summary Statement for Effects on Invertebrates

Given available information on the effects of sound on invertebrates, although explosives may present risk to nearby animals, it is unlikely that air gun based arrays pose a significant risk to marine organisms. However, an appreciation of dose-response relationships for some histopathological and physiological indices would provide a better foundation for assessing risk. There are concerns in Atlantic Canada about the possibility for animal movement and attendant catch problems of commercially important species such as lobster and snow crab. Studies in the laboratory with lobster and snow crab found no evidence for animal movement, including during exposure to high sound levels. Also, snow crab catch rates carried out before and after the Cape Breton seismic survey were similar. However, given concerns, it could be useful to carry out confirmation studies in the field.

4.1.2 Effects on Fish

There have been more studies on effects of high intensity sounds on fish than on invertebrates. These sounds include those from air gun, pile driving, explosives, sonar.

When appropriate (relevant), effects of some other sound sources, such as pure tones, white noise and boating, were also examined.

Mortality and Physical Injuries in Fish

Immediate mortality and visible external or internal injuries (including haemorrhagee and swim bladder damages), when observed, have been reported in fish exposed at close range (within 50 m) to very high intensity sounds (>230 db p) such as explosives and pile driving, and particularly from driving of large piles (Aplin, 1947; Coker and Hollis, 1950; Gaspin et al., 1976; Yelverton et al., 1975; Caltrans, 2001; Govoni et al., 2003). However, there is no or very little evidence of mortality of fish, adult and early life stages, exposed to other sound sources such as air gun and sonar, even at very close proximity (within 5 m).

To our knowledge, there are no studies available on delayed mortality and physical injuries of fish exposed to high intensity low frequency sounds.

Histopathological Effects

From the few studies that have investigated the potential for histopathological effects of high intensity sounds on fish, there was no evidence of histopathological changes in various tissues in adult or early life stages of a number of species exposed to sources at distances more than 5 m, including air gun (Koshleva, 1992; GIA, 2002; IMG-Golder Corp, 2002), pile driving (Oestman and Earle, 2010), and sonar exposures (Jorgensen et al., 2005; Popper et al., 2007; Kane et al., 2010). It is noted that no histopathological studies on the effects of explosives on fish were found.

Effects on the Auditory System

Damage to the Inner ear

There are a number of studies demonstrating damage (often slight) to auditory hair cells upon prolonged exposure to pure tones. McCauley et al. (2003) observed a small amount of hair damage in fish exposed to air guns (180 dB re 1µPa) in the field. However, no ear damage was observed in fish exposed to air guns with a received mean peak sound level of 205-210 dB re 1µPa (Song et al., 2008) or 204 dB re 1µPa peak to peak (CEF Consultants, 2006), low frequency sonar sounds with received peak signal level of 193 dB re 1µPa RMS (Popper et al., 2007; Kane et al., 2010) or pile driving with a 193 db re 1µPa source level (Nedwell et al., 2006). It has been shown in at least one study that a small amount of hair cell damage had no effect on hearing (Smith et al., 2006).

Temporary Hearing Loss

There have been very few studies on the effects of high intensity sounds on the hearing capacity of fish. Results varied with the species and source examined. The hearing of some generalist and specialist species was not affected by air gun (Popper et al., 2005; Hastings and Miksis-Olds, 2010) whereas a temporary loss of hearing was observed for other species, including generalist and specialist, exposed to an air gun array (Popper et al., 2005) and low frequency sonar (Popper et al., 2007).

There are also a few studies carried out on the potential effects of longer duration exposure to relatively lower intensity sounds (e,g, below 170-180 received levels) on the hearing of fish. They generally indicated little or no effects on hearing generalists exposed to white noise (e.g Scholik and Yan, 2002a; Amoser and Ladich, 2003; Smith et al., 2004 a) and increased background sounds (Wysocki et al., 2007), with the exception of the study of Vasconcelos et al. (2007) which showed hearing loss of a generalist exposed to ferry-boat noise. On the other hand, temporary hearing loss was generally observed for hearing specialists exposed to continuous broadband white noise (Scholik and Yan, 2001; Smith et al., 2004a and b; 2006; Wysocki and Ladich, 2005), and boat engine (Scholik and Yan, 2002b). Generally, the amount of hearing loss appears to relate to how loud the noise is compared to the threshold of hearing at that frequency and the recovery time (from hours to weeks) varies with the frequency of the sound, the duration of exposure and the species considered (OSPAR, 2009). It is of note that the recent study carried out in Australia in association with a seismic survey found no evidence of temporary hearing loss in fish even at very high SEL levels (Hastings and Miksis-Olds, 2010).

Physiological effects

A few investigations have been carried out on physiological effects of exposure to high intensity low frequency noise on fish. Stress responses have been reported after exposure to underwater explosions with a sound pressure of 246 dB (Sverdrup et al., 1994) and air gun blasts with an estimated pressure level of 199-210 dB re 1µPa (Santulli et al., 1999), whereas no stress effects were observed after exposure to an air gun with a pressure level of 146-195 dB re 1µPa RMS (McCauley et al., 2000 a and b).

Some studies have also examined physiological responses of exposure to lower levels of sound (e,g, below 170-180 dB re 1µPa received levels) for a relatively long period of time. No changes were found in corticosteroid levels after exposure to white noise with a pressure level of 170 dB re 1µPa RMS (Smith et al., 2004a) or in stress response after a few months of exposure to intensive aquaculture noise at a pressure level of 150 dB re 1µPa RMS (Wysocki et al., 2007) and 149 dB re 1µPa RMS (Davidson et al., 2009). On the other hand, increased stress response was reported after exposure to ship noise at a pressure level of 153 dB re 1µPa RMS for 30 min (Wysocki et al., 2006) and pure tones linear sweep at a pressure level of 150 dB re 1µPa RMS (Buscaino et al., 2010). Furthermore, Graham and Cooke (2008) demonstrated cardio-vascular disturbances in response to noise propagated from recreational boating activities.

It is of interest to note that stress response such as elevation in blood cortisol and glucose, enhanced heart rate or stroke volume, or increase in haematocrit are not unexpected in frightened fish whatever the sound source. Also, chronic stress mediated by sound from any source could in theory affect a variety of biological functions.

Behavioural Effects

Behavioural reactions of fish to noise are commonly reported and can range from very subtle changes to strong avoidance reactions that can lead to horizontal or vertical migration away from the source.

A number of studies noted that various fish species display alarm/startle responses to various noises including air gun, pile driving, boats and vibroseis operated above frozen lakes.

Both increases and decreases in catch rates of commercially exploited species have been documented, but changes do not occur consistently. Although some species may move to a sufficient extent to cause decreases in catch rates at a particular time, there has been no noted loss to the fishing industry.

Behavioural responses are likely highly variable and site, device and species specific and expected to be short-term (DFO, 2004.002).

Summary Statement for Effects on Fish

Considering endpoints of mortality, overt physical damage and non-auditory organ histopathology, it is unlikely that air gun based arrays or low frequency sonar pose a significant risk to fish. Equally pile driving, which can involve protracted exposures for days to very high levels of sound, has been demonstrated in field studies not to pose significant risk to fish, except for animals exposed in the immediate vicinity of piles.

Damage (often limited) to auditory hair cells has been observed in the laboratory upon prolonged exposure of fish to pure tones (sometimes at relatively high exposure levels). Prolonged exposures to relatively high sound levels would not be expected under field conditions (except probably in relation to pile driving, but not in relation to moving seismic survey ships) but a small amount of hair cell damage was observed in fish in one air gun based field exposure. A few other field surveys did not find evidence for hair cell damage nor did a field experiment with sonar. It has been demonstrated in laboratory studies that hair cells can regenerate, moreover there is some evidence that a small amount of damage may not affect hearing.

A number of studies have demonstrated temporary hearing loss in fish exposed to sound. Temporary hearing loss is not injurious as such and has been described as temporary physiological fatigue. However, in theory temporary hearing loss of a short nature might for instance alter communication and prevent fish from avoiding a predator.

Regarding fish behaviour, there is considerable literature dealing with the effects of recreational boating, vessel traffic, air gun surveys and pile driving. Startle or slight movements are common, but extended movement can occur in some situations with some species of fish.

A study dealing with the effects of vibroseis on freshwater fish found no evidence for mortality or damaging effects which could be attributed to the exposure to 5 vibrators.

Stress responses such as elevation in blood cortisol and glucose, enhanced heart rate or stroke volume, or increase in haematocrit (blood cells) would not be unexpected to occur in frightened fish whatever the sound source.

4.2 Relevance of Overview in Relation to Marine Vibrator Devices

Given present information, it is understood that the marine vibrator is a transient non-impulsive source producing high intensity sounds at low frequencies. It can generate a sweep over a frequency range from 10 to 200 (or less in the new generation) Hz and the tone will last several seconds. The levels of noise generated by the marine vibrator are relatively less intense (suggested to be around 30 dB) than those generated by air gun sources (commonly 250-260 dB for air gun arrays) or other high intensity sources including explosives (>270 dB), pile driving (from 240 to 262 p-p), and low frequency sonar (235 RMS).

Effects on invertebrates and fish that have been studied in association with high intensity sound from explosives, pile driving, air guns and low frequency sonar were reviewed in this report. Also covered was information related to vessel and aquaculture noise. Effects reviewed included mortality and gross pathology as well as histopathological, physiological and behavioural changes.

Other than obvious effects of explosives, evidence from field studies indicate that damaging effects on fish and invertebrates might only be expected to occur, if at all, within the immediate area (probably in meters to tens of meters range) of other sound sources, with protracted pile driving probably indicating the most risk. Accordingly it can be speculated that vibroseis would present even lesser risk. It is also understood that a ship traveling at 5 to 6 knots with an array of vibrators would only result in a transient exposure to any nearby animals.

One effect which is common to all sources of sound extending from recreational boating to explosives is effect on fish behaviour. However, this would appear not to be the case for invertebrates such as lobster, crab and scallop as demonstrated in exploratory studies in the laboratory.

Noise exposure criteria are presently being sought for fish as well as marine mammals. Caution is warranted in making inter comparisons between different sources of sound in relation to effects on the same or dissimilar species. However, peak pressure levels are of interest whatever the source, and it is noted that 230 dB is the criteria for auditory injury to marine mammals. If we assume a source level for a marine vibrator to be 230 dB (following the approximation that the source pressure level for a vibrator to be ~30 dB less than an impulsive source such as an air gun array of 260 dB), the potential injury zone for cetaceans would only be in the immediate vicinity of the vibrator. Thus the question can be asked, could this potential small injury zone also be transposed to an approximate extent to fish exposed to vibroseis? A similar question can be asked in relation to some sound exposure criteria and sound exposure levels which take energy into account.

It is also of interest to note that the sound characterization of a marine vibrator is similar to that of low frequency sonar and 2 studies to date have shown transient hearing loss but no evidence of damage to auditory tissues.

In terms of effects associated to sound intensity, a marine vibrator would be expected to have a much reduced impact zone in comparison with air gun arrays. If we consider a seismic air gun array with a source level of 250 dB, according to spherical spreading, this would present a received sound level of 210 dB at 100 m. In the meantime, a vibrator source with a source level of 220 dB, would produce a sound pressure level of 180 dB at 100 m.

While the vibrator generates a less intense sound, the total acoustic energy transmitted by the device could be equivalent to that of air guns due to the extended duration of the vibrator signal. It is not known to what extent different types of effects, which could be produced by sound, are linked to peak pressure or cumulative energy, or a combination of same. In the event that injury to animals is a function of total exposed energy, then vibrators could be no less harmful than air guns in the impact zone. But as noted above, the vibrator could still have the advantage of exhibiting a reduced impact zone.

The marine vibrator is also characterized by a narrower frequency wideband than air guns which, although producing most of their sound energy at low frequencies, have also high frequency content that are clearly audible in all bands. Since most organisms can only detect and therefore affected by a limited range of frequencies, the vibrator will likely cause less damage than air guns.

Another aspect to take in account with underwater noises are signal duration and duty cycle (ratio of time during which sound is produced to the time during which no sound is produced). In general, it is expected that fish could be less sensitive to intermittent sounds than to continuous sounds of the same intensity. Since the marine vibrator has longer duration and increased duty cycle than air guns, this could potentially result in masking effects thereby altering fish communication.

However, given the low frequency range for vessels which "overlaps" with the frequency range of vibrators (and air guns), it is also of interest that chronic vessel noise in general could have considerable potential for producing masking effects whereby communication by fish could be altered to some degree. Thus, any potential masking effects associated with the transient use of marine vibrator could be trivial in comparison with the vast potential for noise from ship traffic in coastal and ocean waters to produce masking effects.

Further, given the noted potential in rivers for noise from fast moving waters to produce masking effects, masking could for instance be a common occurrence along shoreline during storm conditions.

Although not specifically related to vibroseis, the review has indicated that an appreciation of some dose-response relationships for subtle endpoints such as changes in some histopathological and physiological parameters would be helpful to provide a better overall foundation for assessing risks to marine fish and invertebrates.

4.3 Experimental Approach

It is envisaged that the initial studies with the vibrator would be exploratory or "range-finding" in nature with the initial results forming a basis as to the need or kind of any further studies. The scope of the suggested experimental design includes the evaluation of potential acute, chronic and behavioural effects of marine vibroseis on selected species of commercial importance in Nova Scotia.

Experimental Setup

An approach similar to that used by Popper et al. (2007) in a study on the effects of low frequency sonar on fish is recommended for use on the DRDC Atlantic Acoustic Calibration Barge (see attached brochure) with a marine vibrator. The DRDC barge, located in the Bedford Basin, Halifax Harbour, offers a stable platform in a near-shore marine environment to carry out controlled mesocosm experiments.

Animals would be placed in a ~1m^3 soft net cage lowered in the water column with the cage having a number of attached hydrophones and a particle velocity meter as well as a camera when investigating animal movement. Sound metrics would include peak pressure, RMS, SEL and particle velocity.

A first step would involve exposing a set of 25 test animals suspended 10 to 20 m directly below the vibrator to a single "normal sweep" (e.g. of 20 s or 30 s duration depending on the type of vibrator). A set of 25 control animals would be handled in the same manner as the experimental set except for the sound exposure.

This will be followed by a "worst case" exposure ten times longer than the first sweep on another set of 25 animals. A set of 25 control animals would be handled in the same manner as the experimental set except for the sound exposure.

The results of these initial exploratory studies would be used to determine if an experiment(s) involving a shorter sweep time and/or a reduction in amplitude might be warranted.

Species under consideration

The focus would be on selected marine species of commercial importance in Atlantic Canada, namely lobster and snow crab (crustaceans) , sea scallop (bivalve) and Atlantic cod (fish), with the understanding that the results would also be of some generic value. Further, although the initial findings could indicate little or negligible risks, especially when translated to the size of any impact zones in the marine environment, this information in itself would be valuable for assurance.

The characteristics of the animals would be as follows:

- Lobster and scallop would be of commercial size and same sex.
- Snow crab would be mature females.
- Cod would be immature (~100g). This size would be appropriate for studies on fish hearing as well as a practical size for fish histopathology. Fish of this size will also only require a small holding tank on the barge.

Also, larvae of lobster, crab and cod are considered since early life stages are commonly held to be sensitive. Exposures would be carried out in triplicate in plastic "bottles" (~1L) containing ~ 50 larvae per bottle.

Endpoints

As to choice of endpoints, it is noted that the focus is on those which might be of practical importance at this time for management and fisheries interests. Depending on the species considered, the endpoints could include mortality, behaviour (scaring, valve closure), turnover rate, feeding, tissue histopathology, serum chemistry, and/or hearing threshold shift (Table 14). A brief rationale is also given in the table.

Table 14 Endpoints and Rationale

Species	End Point	Why?
Lobster and/or crab, and/or cod larvae	• Mortality Exposure in commonly available plastic sound translucent bottles	• Larvae often considered to be sensitive
Cod	• Shift in hearing threshold using the auditory brain stem response (ABR method). If a significant shift in hearing, assess recovery time. • Scaring (with attention to major startle responses rather than transient C-starts which would not be unexpected) • Tissues fixed and archived for further analysis if necessary. (Opportunistic sampling with little added effort).	• Hearing is an important sensory function • Concern about fish behaviour • Should there be a need to address concerns about tissue damage
Lobster	• Scaring • Feeding • Turnover rate • Histopathology, serum chemistry and haematology	• Concern about animal movement • Important function • Indicator for potential damage to geo-orientation and equilibrium functions • Commonly used indicators for crustacean health
Snow crab	• Scaring • Tissues fixed and archived for further analysis if necessary. (Opportunistic sampling with little added effort).	• Concern about animal movement • Should there be a need to address concerns about tissue damage
Snow crab could be substituted for lobster for detailed studies, but given snow crab is fished at considerable depth, lobster which is a more shallow water species would be a suitable proxy – at least for the initial trials. There can also be greater aquarium holding considerations in experiments with snow crabs.		
Scallop	• Scaring • Valve closure • Serum chemistry • Tissue histopathology	• Concern about animal movement • Commonly used indicators for mollusk health
Although an important commercial species, there is a lack of studies on scallops		

As noted, the experiments are geared toward practical interest. However, it is understood that more fundamental studies such as those dealing with the vast area of mechanisms of potential immunological, neurological, electro-physiological, cardiac and endocrine responses to ocean sound in general are important topics for basic research.

For instance, lobsters can sense sound as measured electro-physiologically but does transient electrophysiological responses result in more commonly accepted deleterious endpoints such as scaring or organ damage which is the focus here?

Time Frame

An approximate time frame for initial experimental trials is provided in Table 15.

Table 15 Approximate Time Frame for Initial Experimental Trials

Endpoint	Time Frame
Larval mortality	Approximately 96 hours holding (post exposure) with regular observations carried out on the barge.
Movement of cod, lobster, snow crab and scallop	Video observations on the cage a few hours or so before, during and after exposure for each species.
Lobster turn over	On the barge within a few hours after exposure.
Lobster feeding	Assessment after 3 weeks holding in an aquarium system onshore. Lobster fed weighed quantity of shucked mussels at the end of the period. Amount remaining in tank after 24 hours reweighed.
Lobster serum chemistry and haematology *	Assessed after 3 weeks holding in an aquarium. Since these parameters may also be affected somewhat by animal handling in the experiment, one is really assessing if parameters are being affected beyond that which might be due to handling.
Lobster and snow crab histopathology *	Tissues fixed after 3 weeks of animal holding in an aquarium.
Scallops Endpoints *	Tissues fixed and serum and haemocytes taken after 3 weeks of animal holding in the aquarium.
Assessment of alteration of hearing threshold in codfish	Approximately a week through work on the barge. This would require arranging a suitable test chamber on the barge and using special equipment.

* Although a 3 week holding period post exposure is recommended for lobster, scallop and snow crab endpoints to account for the possibility of delayed effects, sampling of animals immediately after exposure could also be an option. This would then forego need for an aquarium holding facility except for lobster feeding.

Aquarium Facilities

Suitable aquarium facilities may only be found onshore.

Lobster, snow crab and scallops would be transferred to the aquarium facility after the exposures. Two aquaria in the 400-600 gal range (1.5-2 m in diameter) would be required for each exposure involving 50 animals (25 control; 25 experimental) for each species. Since two sweep conditions are being suggested (one of short duration and one 10 times longer), this would require 4 aquaria per species.

It is important to note that the trials would involve exploration for acute effects under short term exposure conditions such as animals might be subjected to at very close range. Questions can be asked about the potential for effects when animals might be chronically subjected to much lower levels of sound over a more broad scale geographical area such as during a survey lasting for a few weeks. However, this is not a unique question for vibroseis, since the same question can be asked in relation to survey studies using air guns. Further, in the case of lower sound levels at distance, the relative importance of seismic surveys versus noise from ship traffic would have to be considered from a management perspective.

APPENDICES

Table A1. Effects of Air Guns on Mortality and Visible Injuries in Adult Invertebrates

Organism	Study Description	Sample C control E exposed	Source Level (dB re 1 μ Pa) at 1 m	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Scallop	24 air gun array			19	230	No increase in mortality over 17 days.	Parry et al. 2002
Iceland Scallop *Chlamys islandicus*	Laboratory Single air gun	3 E 0 C	233 assumed	2	214-220 E	-No mortality. -Shell split in 1 of 3 tested.	Matishov 1992
Sea Urchin	Laboratory Single air gun	not available	233 assumed	2	217 E	-No mortality. -15 percent of spines fell off.	
Giant squid *Architeuthis dux*	Bay of Biscay where seismic surveys were performed	not available	not available	not available	not available	-Stranded animals with acute & extensive tissue damage appearing to be linked spatially and temporally to the seismic surveys performed in the Bay.	Guerra et al. 2004
Cephalopods -squid *Sepioteuthis australis*	Caging 1 air gun	14 Pre E 14 post E	not available	900-1500 2100-5000	156-161 dB RMS 174 RMS	-No mortality.	McCauley et al. 2000 a and b
Mussel *Mytilus edulis*	Laboratory A single 60-180 in^3 air gun	not available	223 assumed	0.5, 1 and 2	229 E	-No mortality or detectable effect within 30 days.	Kosheleva 1992 *Estimation by Turnpenny and Nedwell 1994*
Periwinkle *Littorina obstusata and littorea*	Laboratory A single 60-180 in^3 air gun	not available	223 assumed	0.5, 1 and 2	229 E	-No mortality or detectable effect within 30 days.	
Crustacean *Gammarus locusta*	Laboratory A single 60-180 in^3 air gun	not available	223 assumed	0.5, 1 and 2	229 E	-No detectable effect within 30 days.	
Brown Shrimp *Crangon crangon*	Field in salt mashes in the Wadden Sea. Array of air guns in 2 m water depth	not available	230 to 250	< 2	190	-No mortality.	Webb and Kempf 1998
3 shrimp species *Litopenaeus schmitti* *Farfantepenaeus subtilis* *Xyphopenaeus kroierii*	Caging in shallow waters (~5m) of Camamu-Almanda region, Brazil Boat with a 4 air gun array sailing from 0 to 200 m from the cages	180 E 60 C	196	0, 10, 20 and 200	not available	-No mortality immediately or 48 hours after exposure.	GIA 2002 Andriguetta Filho et al. 2005
Lobster *Homarus americanus*	Various trials of exposure to 20 to 50 shots of stationary (a) 10 in^3 air gun in laboratory or (b) 40 in^3 air gun in the field at 2 m depth	117 E (total) 118 C (total)	not available	2 or 4	(a) ~ 202 pp 144 to 169 dB Pa^2/Hz (b) ~ 227 pp 175 to 187 dB Pa^2/Hz	-No immediate mortality and gross pathology. -No delayed mortality within 9 months. -No effects on mechano-balancing systems (righting ability test). -No differences in loss of appendages.	Payne et al. 2007
2 species of red lobster *Panulirus laevicauda* *Panulirus argus*	Caging in shallow waters (~5m) of Camamu-Almanda region, Brazil Boat with a 4 air gun array moving from 0 to 200 m from the cages	not available	196	0, 10, 20 and 200	not available	-No mortality immediately, 6 and 48 hours after exposure.	GIA 2002
Snow crab *Chionoecetes opilio*	Caging in Conception Bay, NL 200 shots on 33 min of (a) one 40 in^3 single air gun or (b) a 200 in^3 air gun array	92 C 92 E		(a) 2, 10, 15 or (b) 4, 50, 85, 170	(a) 201-227 dB or 183-187 1μPa^{2}Hz (b) 197-237 dB or max 175 1μPa^{2}Hz	-No immediate increased mortality or visible injuries in both studies. -No delayed (within 3 months) increased mortality or visible injuries in both studies.	Christian et al. 2003, 2004
Snow crab *Chionoecetes opilio*	Caging under the conditions of a seismic program off Cap Breton 4 sub-arrays of 2 guns + 2 single guns deployed at 6m. 27 seismic lines of 506 km	90 E 90 C (short-term) 90 E 94 C (long-term)		E = 0.1 max to 12.4 km C = 23 to 37 Km	E 170 to 192 pp at distances < 1.5 km 156 to 177 dB Pa^2/Hz C ~ 125 to 132 pp 112 to 118 dB Pa^2/Hz	- No evidence of acute or delayed mortality within 5 months. - Soiling of gills, antennules and statocysts at the exposure site but cleared after 5 months.	DFO 2004 Courtenay et al. 2009
Lobster (female) *Homarus americanus*	3 exposures (low, high and very high intensity level) with a stationary air gun in laboratory	16 to 20 E / exposure 16 to 20 C / exposure	not available	1.6	204 to 211 p-p; 174 to 178 RMS; Particle velocity of 137 to 142 dB re 1μPa^2/sec	-No immediate or delayed (7 months) mortality. -No immediate effects on mechano-balancing systems (righting ability test).	Oceans Ltd. 2010

Table A2. Effects of Air Guns on Histopathological and Physiological Endpoints in Adult Invertebrates

Organism	Study Description	Sample C control E exposed	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Snow crab *Chionoecetes opilio*	Caging in Conception Bay, NL 200 shots on 33 min of (a) one 40 in^3 single air gun or (b) a 200 in^3 7 air gun array	92 C 92 E	not available	(a) 2, 10, 15 or (b) 4, 50, 85, 170	(a) 201-227 dB or 183-187 1$\mu Pa^2 Hz$ (b) 197-237 dB or max 175 1$\mu Pa^2 Hz$ (M)	-No histological effects on hepatopancreas, heart and statocysts immediately after exposure. -No significant differences in haemolymph solute, serum proteins and enzymes or haemocyte counts between control and exposed crabs sampled immediately and 2 weeks after exposure.	Christian et al. 2003, 2004
Snow crab *Chionoecetes opilio*	Caging under the conditions of a seismic program off Cape Breton 4 sub-arrays of 2 guns + 2 single guns deployed at 6m. 27 seismic lines of 506 km for a 23-day duration	90 E 90 C for short-term 90 E 94 C for long-term		Exposed = 138 m max Control = 23 km	Exposed = 178 RMS 162 dB Pa^2/Hz (M) Control = ~ 125 to 132 pp (M) ~118 dB Pa^2/Hz	-Slight histological differences that can be attributed to environmental differences between the test and control sites.	DFO 2004 Courtenay et al. 2009
3 shrimp species *Litopenaeus schmitti* *Farfantepenaeus subtilis* *Xyphopenaeus kroierii*	Caging in shallow waters (~5m) of Camamu-Almanda region, Brazil Boat with a 4 air gun array sailing from 0 to 200 m from the cages	180 E 60 C	196	0, 10, 20 and 200	not available	-No histological effects associated with air gun discharges in gills and gonads. -A decrease in lipid concentration in R-cells was observed in the hepatopancreas of shrimps exposed up to 20m.	GIA 2002 Andriguetta Filho et al. 2005
2 species of red lobster *Panulirus laevicauda* *Panulirus argus*	Caging in shallow waters (~5m) of Camamu-Almanda region, Brazil Boat with a 4 air gun array moving from 0 to 200 m from the cages	not available	196	0, 10, 20 and 200	not available	-No histological effects associated with air gun discharges in gills and gonads -A decrease in lipid concentration in R-cells was observed in the hepatopancreas of lobsters exposed up to 200m.	GIA 2002
Golden carpet shell *Paphia aurea*		14 exp + 14 con	210 estimated	15	<147 dB	-Significant difference in hydrocortisone, glucose and lactate in hepatopancreas and muscle between testing and control sites.	La Bella et al. 1996 Estimation by Hirst and Rodhouse 2000
Lobster (female) *Homarus americanus*	3 exposures (low, high and very high intensity level) with a stationary air gun in laboratory	16 to 20 E / exposure 16 to 20 C / exposure	not available	1.6	204 to 211 p-p 174 to 178 RMS (M) Particle velocity of 137 to 142 dB re 1$\mu Pa^2/sec$	-No delayed (7 months) histopathological changes in ovary and hepatopancreas.	Oceans Ltd. 2010
Lobster *Homarus americanus*	Various trials of exposure to 20 to 50 shots of stationary (a) 10 in^3 air gun in laboratory or (b) 40 in^3 air gun in the field at 2 m depth	117 E (total) 118 C(total)	not available	2 (a) or 4 (b)	(a) ~ 202 pp (M) 144 to 169 dB Pa^2/Hz (b) ~ 227 pp 175 to 187 dB Pa^2/Hz	-No histopathological changes in gonads -Increase in food consumption and elevated deposits of carbohydrates in hepatopancreas of exposed lobsters.	Payne et al. 2007

Table A3. Effects of Air Guns on Behaviour in Adult Invertebrates

Organism	Study Description	Sample C control E exposed	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Snow crab *Chionoecetes opilio*	Caging in Conception Bay, NL After 1 or 2 sets of 200 shots on 33 min of a 200 in^3 air gun array	92 E 94 C	not available	4, 50, 85, 170	Received levels 197 to 237 o-p (M) Max 175 dB Pa^2/Hz within the 17 to 19 Hz frequency range	-No readily visible startle reactions of caged crabs (video camera) to the array being fired 50 m above the cage. -All of the 6 free tagged crabs were still within 200 m radius after 48 hours post shooting.	Christian et al. 2003
Cephalopods -squid *Sepioteuthis australis*	Caging 1 air gun Between 22 and 61 min for each continual set of shots	31 total on 3 trials		5 to 450	139-184 RMS (M)	Behavioural responses observed: -Alarm response (increased swimming behaviour) at received levels of 155-161 dB RMS. -Strong startle responses at 174 dB RMS. -Firing ink was not evident if the array was ramped up.	McCauley et al. 2000 a and b
Lobster *Homarus americanus*	Various trials of exposure to 20 to 50 shots of stationary (a) 10 in^3 air gun in laboratory or (b) 40 in^3 air gun in the field at 2 m depth	117 E (total) 118 C(total)	not available	2 (a) or 4 (b)	(a) ~ 202 pp (M) 144 to 169 dB Pa^2/Hz (b) ~ 227 pp 175 to 187 dB Pa^2/Hz	-No behavioural responses.	Payne et al. 2007
Various invertebrates including crustaceans, echinoderm and molluscs	Field study on a bank in sheltered and shallow waters (10 to 20 m depth) ~ 300 shots of a stationary 3 air gun array over a 4 day period at various distances	not available	not available	(a) 5.3, (b) 16 (c) 109	218 (a), 210 (b) and 195 (c) o-p (M)	-No movement of the invertebrates away from the gun during the various firing.	Wardle et al. 2001

Table A4 . **Effects of Air Guns on Catch Rates of Adult Invertebrates**

Organism	Study Description	Number of Hauls Before and After	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Various shrimp species	Shallow waters (2 to 15 m) of Camamu Bay, Brazil Boat with a 4 air gun array sailing from 0 to 200 m from the cages	46 trawl hauls before and 46 after	196	Hauls at 148, 496 and 680	na	-No significant decrease in density and catch of artisanal shrimp fisheries 12 to 36 h after air gun use.	Andriguetta Filho et al. 2005
Snow crab *Chionoecetes opilio*	Caging in Conception Bay, NL. 1 or 2 sets of 200 shots on 33 min of a 200 in^3 air gun array		not available	4, 50, 85, 170	Received levels 197 to 220 o-p Max 175 dB dB Pa^2/Hz within the 17 to 19 Hz frequency range	-Post seismic catches of commercial fishery traps were higher than pre seismic catches but this was likely due to physical, biological or behavioural factors unrelated to the seismic source.	Christian et al. 2003
Snow crab *Chionoecetes opilio*	Caging under the conditions of a seismic program off Cape Breton	not available				-No significant difference in catch rates in the general area.	Courtenay et al. 2009
Norway lobster *Nephrops norvegicus*	Pre and post seismic air gun survey catch rates comparisons in Central Adriatic Sea I air gun array with 2 sub arrays of 8 air guns each	8 trawl stations before and 8 after	210 at 1m	not available	~ 149 estimated	-No difference in size frequency distributions and catch rate of lobster by bottom trawl.	La Bella et al. 1996 Estimation by Hirst and Rodhouse 2000
Squid *Illex coindetti*						-No difference in catch rate of squid by bottom trawl.	
Shrimp *Squilla mantis*		2 sets of 3,200 m gillnets before and 2 sets after				-No difference in catch rate of shrimp by gill net.	
Golden carpet shell *Paphia aurea*		14 stations for clam dredge before and 14 after as well as 2 sets of 3,200 m gillnets both before and after				-No difference in catch rate by clam dredge.	
Inaequivalvis ark shell *Anadara inaequivalvis*						-No difference in catch rate by clam dredge.	
Purple die murex *Bolinus brandaris*						-No difference in catch rate by clam dredge. -Difference observed in catch rate by gill net.	
Rock lobster	Statistical analysis of catch rates in Western Victoria, Australia between 1978 and 2004 in regions subject to seismic surveys	not available	not available	not available	not available	-No evidence that catch rates were affected by seismic deep water surveys in weeks or years following the surveys. -However, it is noted that a change in catch rates in the order of 50% would have been required to be detected.	Parry and Gason. 2006
Brown Shrimp *Crangon crangon*	Field in salt mashes in the Wadden Sea Array of 15 air guns in 2 m water depth	not available	230-250	From 65 to 4500	190	-No evidence of reduced catch rate.	Webb and Kempf 1998

Table A5. Effects of Air Guns on Eggs, Embryos and Larvae of Macro-Invertebrates as well as Plankton

Life stage/ Organism	Study Description	Sample C control **E exposed**	Source Level	Distance from Source (m)	Exposure Level (dB re 1 µ Pa) E (estimated) M (measured)	Observations	Reference
Fertilised eggs Snow crab *Chionoecetes opilio*	Caging in Conception Bay, NL 200 shots on 33 min of a 40 in^3 air gun	1 pool of 2,000 eggs for both C and E	221	2	216 (M)	Indication of higher mortality and slower development in exposed fertilized eggs when sampled 12 weeks after exposure.	Christian et al. 2004
Embryos Snow crab *Chionoecetes opilio*	Caging under the conditions of a seismic program off Cap Breton 4 sub-arrays of 2 guns + 2 single guns deployed at 6m depth				SPL received : 174 (exposed) 118 (control) (M)	No effect on the survival of embryos carried by females and on the locomotion of larvae after hatch.	DFO 2004
Macro zooplankton (larvae of decapods and copepods)	Caging in shallow waters (~5m) of Camamu-Almanda region, Brazil Boat with a 4 air gun array moving from 0 to 200 m from the cages	3 trials at different dates with 1 sub sample of a trawl for control and each condition per trial	196	0, 10, 20 and 200	not available	No evidence of air gun impact on swimming ability.	GIA 2002
Plankton	Field survey prior (12 days), during (38 days) and after (up to 25 days) seismic activities in the area	not available	not available	not available	not available	No distribution changes.	Lokkeborg et al. 2010
Various stages of larvae Dungeness crab *Cancer majister*	Controlled field experiments Single discharge of a 7 air gun array	not available	240	1, 3 and 10	Up to 231 (M)	No significant effects in immediate and long-term survival, development and behaviour.	Pearson et al. 1994

Table A6. Effects of Explosives on Invertebrates

Modified from Moriyasu et al. 2004 and Parry and Gason 2006

Organism	Conditions	Exposure Distance from Shot (m)	Explosive charge Characteristics	Observed Response	Reference
Oyster *Crassostrea virginica* Blue crab *Callinectes sapidus*		Between 8 and 293	From 30 to 300 pounds of suspended charges of TNT	-Within 60 m, ~ 2% of immediate mortality of oysters exposed to charges of both 30 and 300 pounds. -5.4 % delayed mortality (compared to 0 % for controls) 2 weeks post exposure. Lethal damage for crab was in a radius ≤ 45 m.	Anonymous 1948
Dungeness crab *Cancer magister*	Various experimental conditions were set in relation to crab sizes, charge sizes, cage depth and carapace condition		5-lbs (0.6 m beneath the surface) or 25-lbs (1.2 m beneath the surface) of nitro-cabonitrate	No significant differences in mortality or physical damage in any experimental conditions.	Anonymous 1962
Abalone *Haliotis corrugta and H. fulgens* Spiny lobster *Panulirus interruptus*	No controls were used in this study	~ 15	9.1 kg of 60 % Petrogel placed at 1.2 m under the surface	-All abalones died within a few hours following the explosion. The shell of one abalone was broken. -No mortality or signs of damage (after dissection) for lobsters.	Aplin 1947
White shrimp *Penaeus seliferus* Oyster *Crassostrea virginica*	Cages placed midway between surface and bottom or on the bottom.	15, 30, 45, 60 and 90	200-800 pounds of 60% gelatin dynamite placed on the ocean floor at 6 m depth	-Shrimps were uninjured regardless of the amount of explosive used. -For oysters, no mortality when cages were placed on the bottom.	Gowanloch and McDougal 1946
White shrimp *Penaeus setiferus* Oyster *Crassostrea virginica* Blue crab *Callinectes sapidus*	3 trials with cages set up on the bottom at different depth ~ 3, 7 and 13 feet	0, 8, 15, 45, 90 from the shot hole	40 pound of Nitramon at the depth of 6 m below the ocean bottom	-No effects on shrimp and crabs. -Some mortality for oysters as far as 60 m with damage more severe within a 8 m radius of the blast.	Kemp 1956
White shrimp *Penaeus seliferus* Oyster *Crassostrea virginica* Blue crab *Callinectes sapidus*	Cages were set at the surface or bottom for crustaceans and on the bottom for oysters	1, 11, 23 and 46 Control at 136	33 m of 100 g/33 Primacord detonation cord	-Mortality of shrimps (10 to 35%) at distances less than 46 m with no well-defined pattern in relation to distance. -Mortality of crabs (40% at 1m to 10% at 46m) and oysters (15% at 1 m to 1% at 46m) related to the distance from the site of detonation.	Linton et al. 1985
Oyster *Crassostrea virginica*	Two experiments: Oysters suspended or placed on the bottom. In both cases, exposition to 2 different charges.	6, 18, 40 and 76 from the shot point	50 pounds of Nitramon placed at 21 m and 20 pounds placed at 9 m below the ocean bottom	-No immediate or long term (4 to 8 months) increased mortality in any experimental conditions up to 6 m. -Glycogen analyses did not show any consistent trend in any experimental conditions.	Sieling 1951 and 1953

Table A7. Effects of Air Guns on Fish Mortality

Organism	Exposure Conditions	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Various marine species Cod, salmon, cunner and smolt	Laboratory 200 shots of a single gun		1.5 to 2.5	~ 202 (M)	-No mortality immediately or within 2-month post exposure.	Andrews et al. 2007 DFO unpublished
Cod (juvenile) *Gadus morhua*	Authentic seismic survey in Sydney Bight (120 m depth)	259 p-p	55, 138, 340, 860 and 1360	204 p-p at cages (M)	-No increased mortality immediately and after 5 days.	CEF consultants 2006
Demersal fish, blue whiting and some pelagic fish	Wild fish along the path of a seismic survey which lasted ~ 1 week	222 to 250	Within 150 to 300	200 to 210 (E)	-No mortality observed upon exposure.	Dalen and Knutsen 1987
Coregonids including *Coregonus autrumnalis*	One or 4 impulses of 1 air gun in Mackenzie River Delta (3-6 m depth)	230 (E)	0.6, 1.5, 3 or 3.4	234 at 0.6 m (E) 219 at 3.4 m (E)	-No mortality of caged fish or wild fish in the River within 16 km.	Falk and Lawrence 1973
Red snapper *Lutjanus synagris* Mojara *Haemulon aurolineatum*	Boat with a 4 air gun array moving from 0 to 200 m from cages in ~5m depth waters	196	0, 10, 20, and 200	not available	-No mortality at any distances.	GIA 2002 Boeger et al 2006
Sandeel *Ammodytes marinus*	Cages on bottom along a 3-day seismic survey (28 air gun array) in Southern North Sea	256	55 to 7,500	221 (E) at 54 m (water depth)	-No differences in mortality between control and experimental groups.	Hassel et al. 2003
Northern anchovy *Engraulis mordax*	Multiple (7 to 71) shots with increase and decrease of amplitude to simulate a seismic survey	Up to 2,000 psi	1.5-3	215 to 234 (M)	-No mortality reported.	Holliday et al. 1987
Various freshwater species Chub, longnose sucker, northern pike, pearl dace	Mackenzie River (3-5 m depth) 2 stationary air gun array with ramp up followed by 1 min at full volume	230 o-p	2 to 3,000	224 at 2 m, 193 (178 RMS) at 85 m, and 169 (159 RMS) at 446 m (M)	-No mortality attributable to the seismic program within a 48h holding time.	IMG-Golder Corp 2002
Cod (young and mature) *Gadus morhua*	I array of air guns	220 to 240 (E)	0.5 to 2	226 at 0.5m, 220 at 1 m and 214 at 2 m (E)	-No mortality at any distances.	Koshleva 1992
Twelve species	Nine trials in Jervoise Bay (Australia) with 1 air gun towed repeatedly	223 p-p	5 to 800	p-p 146 to 195 RMS (M)	-No immediate mortality. No delayed mortality (up to 58 days) for 1 species.	McCauley et al. 2000 a and b
Broad whitefish *Coregonus nasus*, lake chub *Couesius plumbeus*, Northern pike *Esox pucius*	Cages in Mackenzie River Delta (1.9 m depth) 5 or 20 shots of a 8 air gun array		13-17	Average mean peak of 207 (M) Mean RMS of 197 (M) Mean SEL 177 (re 1 $\mu Pa^2.s$) (M)	-No mortality of fish from the 3 species held for 24 h after exposure.	Popper et al. 2005
Sea bass (juveniles) *Dicentrarchus labrax*	Experimental seismic survey off coast of Italy (15 m depth) with 2 sub-arrays of 8 air guns each for 2h	256 o-p	180 to 6,500	210 at 180 m (E) 204 at 800 m (E) 199 at 2500 m (E)	-No mortality up to 72 h post exposure.	Santulli et al. 1999
Rainbow trout (*Salmo gairdneri*) Salmon smolt (*Salmo salar*)	124 pulses of a 4 small air gun array over 3 days	229	150-6,700	142 p-p at the cages (4km) (M) 186 p-p at 150 m from guns (M)	-No mortality during or immediately after exposure.	Thomsen 2002
Juvenile saith and cod Adult pollock and mackerel	Free fish in a reef Cluster of 3 guns fired over 4 days (~300 shots)	na	> 5.3	218 o-p at 5 m (M) 210 o-p at 16 m (M) 195 o-p at 109 m (M)	-No indication of mortality.	Wardle et al. 2001
Coho salmon (smolt) *Onchorhynchus kisutch*	One shot of a single air gun or an 8 air gun array in a 13 m depth Lake	234 to 241	1 to 10	208 to 241 (M)	-Mortality of 1 to 10 fish at 1m and no mortality at other distances within 72 h after exposure.	Weinhold and Weaver, 1972

Table A8. Effects of Air Guns on Non-Auditory Tissues in Fish 1 - Gross Pathology (Visible External and Internal Damage)

Organism	Exposure Conditions	Source Level E (estimated) M (measured)	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Cod *Gadus morhua*	Laboratory 200 shots of a single gun		2	~ 202 (M)	-No gross pathology observed immediately or 2 month post-exposure.	Andrews et al. 2007
Cod (juvenile) *Gadus morhua*	Authentic seismic survey in Sydney Bight (120 m depth)	259 p-p	55, 138, 340, 860 and 1360	204 p-p at cages (M)	-No gross pathology.	CEF consultants 2006
Coregonids including *Coregonus autrumnalis*	One or 4 impulses of 1 air gun in Mackenzie River Delta (3-6 m depth)	230 (E)	0.6, 1.5, 3 or 3.4	234 at 0.6 m (E) 219 at 3.4 m (E)	-Some cases of swim bladder damage for fish at 0.6 and 1.5 m from the gun.	Falk and Lawrence 1973
Northern anchovy *Engraulis mordax*	Multiple (7 to 71) shots with increase and decrease of amplitude to simulate a seismic survey	Up to 2,000 psi	1.5-3	215 to 234 (M)	-Higher prevalence of swim bladder damage at the highest exposure.	Holliday et al. 1987
Various freshwater species Chub, longnose sucker, northern pike, pearl dace	Mackenzie River (3-5 m depth) 2 stationary air gun array with ramp up followed by 1 min at full volume	230 o-p	2 to 3,000	224 at 2 m, 193 (178 RMS) at 85 m, and 169 (159 RMS) at 446 m (M)	-Some fish at very close range were temporarily stunned but recovered within 30 min.	IMG-Golder Corp 2002
Cod (young and mature) *Gadus morhua*	One array of air guns	220 to 240 (E)	0.5 to 2	226 at 0.5 m, 220 at 1 m and 214 at 2 m (E)	-Internal damage such as bleeding as well as eye injuries were observed only at 0.5 m.	Koshleva 1992
Broad whitefish *Coregonus nasus*, lake chub *Couesius plumbeus*, Northern pike *Esox pucius*	Cages in Mackenzie River Delta (1.9 m depth) 5 or 20 shots of a 8 air gun array	not available	13-17	Average mean peak SPL of 207.3 (M) Mean RMS of 197.4 (M) Mean SEL 177.7 (re 1 $\mu Pa^2.s$) (M)	-No gross pathology observed on swim bladder, eyes, gills or internal organs.	Popper et al. 2005
Sea bass (juveniles) *Dicentrarchus labrax*	Experimental seismic survey off coast of Italy (15 m depth) with 2 sub-arrays of 8 air guns each for 2h	256 o-p	180 to 6,500	210 at 180 m (E) 204 at 800 m (E) 199 at 2500 m (E)	-No modification of spinal chord or alteration of fin rays.	Santulli et al. 1999
Juvenile saith and cod Adult pollock and mackerel	Free fish in a reef Cluster of 3 guns fired over 4 days (~300 shots)	not available	> 5.3	218 o-p at 5 m (M) 210 o-p at 16 m (M) 195 o-p at 109 m (M)	-No observation of external damage.	Wardle et al. 2001
Coho salmon (smolt) *Onchorhynchus kisutch*	One shot of a single air gun or an 8 air gun array in a 13 m depth Lake	234 to 241	1 to 10	208 to 241 (M)	-No gross pathology attributable to air gun.	Weinhold and Weaver, 1972

Table A9. Effects of Air Guns on Non-Auditory Tissues in Fish 2 - Histopathology (Microscopical analysis)

Organism	Exposure Conditions	Source Level E (estimated) M (measured)	Distance from Source (m)	Exposure Level (dB re 1 µ Pa) E (estimated) M (measured)	Observations	Reference
Cod (juvenile) *Gadus morhua*	Authentic seismic survey in Sydney Bight (120 m depth)	259 p-p (M)	55, 138, 340, 860 and 1360	SEL 204 p-p at cages (M)	-No morphological changes in the 16 fish sent for histopathology.	CEF consultants 2006
Red snapper *Lutjanus synagris* Mojara *Haemulon aurolineatum*	Boat with a 4 air gun array moving from 0 to 200 m from cages in ~5m depth waters	196 (M)	0, 10, 20, and 200	na	-No changes in gills, liver, kidney and gonads attributable to exposure.	GIA 2002 Boeger et al. 2006
Various freshwater species Chub, longnose sucker, northern pike, pearl dace	Mackenzie River (3-5 m depth) 2 stationary air gun array with ramp up followed by 1 min at full volume	230 o-p (M)	2 to 3,000	224 at 2 m, 193 (178 RMS) at 85 m, and 169 (159 RMS) at 446 m (M)	-None of the 18 fish sent for histopathology had abnormalities attributable to air gun exposure.	IMG-Golder Corp 2002
Cod (young and mature) *Gadus morhua*	One array of air guns	220 to 240 (E)	0.5 to 2	226 at 0.5 m, 220 at 1 m and 214 at 2 m (E)	-Injury to blood cells such as bubble formation observed in cell nuclei at 0.5 m.	Koshleva 1992

Table A10. Effects of Air Guns on Auditory Tissues in Fish

Organism	Exposure Conditions	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Cod (juvenile) *Gadus morhua*	Authentic seismic survey in Sydney Bight (120 m depth)	259 p-p	55, 138, 340, 860 and 1360	204 p-p (M) at cages 138 m from the vessel	-No abnormalities seen in the inner ear of the 11 fish sent for scanning electron microscopy.	CEF consultants 2006
Pink snapper *Chrysophrys auratus*	Hundred of shots of 1 air gun towed repeatedly at distances of 5 to 800 m from cages	223 p-p	5 to 800	146 to 195 RMS (M) < 212 p-p at 5 m	-Some damage to the hair cells of the saccula observed as early as 18 hours post-exposure. -Damage more extensive 58 days post exposure.	McCauley et al. 2003
Broad whitefish *Coregonus nasus*, lake chub *Couesius plumbeus*, Northern pike *Esox pucius*	Cages in Mackenzie River Delta (1.9 m depth) 5 or 20 shots of a 8 air gun array	na	13 to 17	Average mean peak SPL of 207.3 (M) Mean RMS of 197.4 (M) Mean SEL 177.7 (re 1 μPa^2.s) (M)	-No damage observed in the sensory cells of the inner ear, despite the fact that 2 of the species had shown a temporary threshold shift.	Song et al. 2008

Table A11. Effects of Air Guns on Hearing Capacity of Fish

Organism	Exposure Conditions	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Tropical species *Chromis viridis*, *Lutjanus kasmira*, *Myripristis murdjan* and *Sargocentron spiniferum*	Cages along an authentic seismic survey Thresholds determined before and after 1 or 2 passes of an air gun array	na	45 to 2,743	Up to 190 dB re 1 μPa^2.s (M) cumulative SEL	-No threshold shift in any species.	Hastings and Miksis-Olds 2010
Broad whitefish *Coregonus nasus*, lake chub *Couesius plumbeus*, Northern pike *Esox pucius*	Cages in Mackenzie River Delta (1.9 m depth) 5 or 20 shots of a 8 air gun array	202	13 to 17	Average mean peak of 207 (M) Mean RMS of 197 (M) Mean SEL 177 (re 1 μPa^2.s) (M)	-Temporary hearing threshold shifts in the hearing specialist (chub) and intermediate (pike) species with recovery within 24h of exposure. -No shift was observed for the generalist whitefish. -Concerning pike, a shift was observed only in adults and not in juveniles.	Popper et al. 2005

Table A12. Physiological Effects of Air Guns on Fish

Organism	Exposure Conditions	Source Level	Distance from Source (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Pink snapper *Chrysophrys auratus*	Hundred of shots of 1 air gun towed repeatedly at distances of 5 to 800 m from cages	223 p-p	5 to 800	146 to 195 RMS (M) < 212 p-p at 5 m	-No changes in blood cortisol and glucose levels and in blood smear cell counts for air gun exposure of 146-195 dB RMS	McCauley et al. 2000 a and b
Sea bass (juveniles) *Dicentrarchus labrax*	Experimental seismic survey off coast of Italy (15 m depth) with 2 sub-arrays of 8 air guns each for 2h	256 o-p	180 to 6,500	210 dB at 180 m (E) 204 dB at 800 m (E) 199 dB at 2500 m (E)	-Variations of cortisol, glucose, lactate, AMP, ADP and cAMP in different tissues indicate a typical primary and secondary stress response after air gun detonations. -Parameters returned to normal within 72h.	Santulli et al. 1999

Table A13. Subtle Responses of Fish to Air Guns

Organism	Experimental Conditions	Source Level	Distance (m)	Exposure Level (dB re 1 μ Pa) E (estimated) M (measured)	Observations	Reference
Coral reef fishes: *Lutjanus apodus, Lutjanus synargris and Chaetodipterus faber*	Cages at different distances of a moving 8 air gun array	196	0.5 to 7		-Startle response (increased speed, directional shift) showing habituation after repeated exposure.	Boeger et al. 2006
Cod (juvenile) *Gadus morhua*	Authentic seismic survey in Sydney Bight (120 m depth)	259 p-p	55, 138, 340, 860 and 1360	204 p-p (M) at cages 138 m from the vessel	-Slight behavioural responses at the closest exposure (55m).	CEF consultants 2006
Sandeel *Ammodytes marinus*	Cages on bottom along a 3-day seismic survey (28 air gun array) in Southern North Sea	256	55 to 7,500	221 (E) at 54 m (water depth)	-C-start reactions observed at distances up to 5 km.	Hassel et al. 2003, 2004
Various wild freshwater species	Mackenzie River Delta 5 or 20 shots of a 8 air gun array	202	13-17	Average mean peak of 207 (M) Mean RMS of 197 (M) Mean SEL 177 (re 1 $\mu Pa^2.s$) (M)	-No changes in fish behavioral characteristics due to air gun noise.	Jorgenson and Gyselman 2009
Pink snapper *Chrysophrys auratus*	Hundred of shots of 1 air gun towed repeatedly at distances of 5 to 800 m from cages	223 p-p	5 to 800	146 to 195 RMS (M) < 212 p-p at 5 m	-Alarm responses at 156 to 161 dB RMS. -Startle response at 182-195 dB RMS from 200 to 800 m. -Occurrence of responses decreased over time. -Downward distribution shift. -Return to pre-exposure state 15 to 30 min after cessation of seismic firing.	McCauley et al. 2000 a and b
Rockfish *Various species*	Field enclosures exposed to 2-6 times of 10 min discharges of a stationary air gun	223 o-p	11 to 5,800	137 to 206 o-p (M)	-Varying degrees of startle and alarm responses depending on the species. -General threshold found around 180 dB for alarm and 161 dB for startle responses.	Pearson et al. 1992
Broad whitefish *Coregonus nasus*, lake chub *Couesius plumbeus*, Northern pike *Esox pucius*	Cages in Mackenzie River Delta (1.9 m depth) 5 or 20 shots of a 8 air gun array	202	13-17	Average mean peak of 207 (M) Mean RMS of 197 (M) Mean SEL 177 (re 1 $\mu Pa^2.s$) (M)	-Normal swimming behaviour upon exposure.	Popper et al. 2005
Sea bass (juveniles) *Dicentrarchus labrax*	Experimental seismic survey off coast of Italy (15 m depth) with 2 sub-arrays of 8 air guns each for 2h	256 o-p	180 to 6,500	210 at 180 m (E) 204 at 800 m (E) 199 at 2500 m (E)	-Startle response evident for some fish at distances up to 2,500m, -General startle response at 800m, and fish bunched in the central part of the cage with increased activity at 180m. -Recovery when the vessel was ~ 1.5 km away.	Santulli et al. 1999
Rainbow trout (*Salmo gairdneri*) Salmon smolt (*Salmo salar*)	124 pulses of a 4 small air gun array over 3 days	229	150-6,700	142 p-p at the cages (4km) (M) 186 p-p at 150 m from guns (M)	-Calm and consumed normal amount of food throughout the experiment.	Thomsen 2002
Juvenile saith and cod Adult pollock and mackerel	Free fish in a reef Cluster of 3 guns fired over 4 days (~300 shots)	na	> 5.3	218 o-p at 5 m (M) 210 o-p at 16 m (M) 195 o-p at 109 m (M)	-C-start reaction but no substantial or permanent changes in behaviour throughout the course of the study.	Wardle et al. 2001

Table A14. **Effects of Air Guns on Vertical Distribution of Fish**

Organism	Experimental Conditions	Source Level	Distance (m)	Exposure Level (dB re 1 µ Pa) E (estimated) M (measured)	Observations	Reference
Whiting *Merlangius merlangus*	One air gun fired during 1 hour in Scottish waters (91 m deep)	~ 220 (E)	0 to 91	192 at 25 m to 185 at 55 m (E)	-Fish descended forming a compact layer at greater depth. -Habituation after 1h of shooting.	Chapman and Hawkins 1969
Demersal fish, blue whiting and some pelagic fish	Wild fish along the path of a seismic survey which lasted ~ 1 week in North Sea	222 to 250	Within 150 to 300	200 to 210 (E)	-Demersal fish appeared to move towards the ocean bottom.	Dalen and Knutsen 1987
Sandeel *Ammodytes marinus*	Cages on bottom along a 3-day seismic survey (28 air gun array) in Southern North Sea	256	55 to 7,500	221 (E) at 54 m (water depth)	-Fish tended to remain higher in the water during discharges.	Hassel et al. 2003, 2004
Various freshwater species: Chub, longnose sucker, northern pike, pearl dace	Two stationary air gun array with ramp up followed by 1 min at full volume in Mackenzie River (3-5 m depth)	230 o-p	Not provided	not measured	-No herding or vertical shift.	IMG-Golder Corp 2002
Pelagic fish , primarily Hake *(Merluccius merluccius)* and clupeoids	Experimental study with firing a 16 air gun array for ~ 5 – 12h off coast of Italy	256 o-p	variable	not measured	-A lower proportion of the total pelagic assemblage migrated to the surface layer.	La Bella et al. 1996
Rockfish *Various species*	Field enclosures exposed to 2-6 times of 10 min discharges of a stationary air gun in water off California coast	223 o-p	11 to 5,800	137 to 206 o-p (M)	-Tightening of schools and downward distributional shift. -Pre-exposure behaviour re-established from 20 to 60 min post exposure.	Pearson et al. 1992
Rockfish *Sebastes sp.*	A single air gun discharging during 1h 25 in a fishing area off California coast	223 o-p	82 to 183	186-191 (M) at base of rockfish aggregation	-Overall downward shift in fish distribution during exposure.	Skalski et al. 1992
Pelalgic fish including herring (Clupea harengus) and blue whiting (*Micromesistius poutassou)* and mesopelagic species	Wild fish exposed to 2 seismic arrays of 20 air guns each 12 days of operation spread over a month in Norwegian Sea	222.6 p-p	< 50,000	197 at 20 m (E) 189 at 50 m (E)	-Downward shifts were observed for blue whiting and mesopelagic fish.	Slotte et al. 2004

Table A15. **Effects of Air Guns on Horizontal Distribution of Fish**

Organism	Experimental Conditions	Source Level	Distance (m)	Exposure Level (dB re 1 µ Pa) E (estimated) M (measured)	Observations	Reference
Demersal fish, blue whiting and some pelagic fish	Wild fish along the path of a seismic survey which lasted ~ 1 week in North Sea	222 to 250	Within 150 to 300	200 to 210 (E)	-Non-significant reduction in abundances of blue whiting and small pelagic fish post exposure with trend to migrate out the seismic area.	Dalen and Knutsen 1987
Cod *Gadus morhua* Haddock *Melanogrammus aeglefinus*	Continuous active seismic survey over 5 days using 3 arrays of 6 air guns in the Barrents Sea (water depth 250-280 m)	248 to 253	Up to 37,000	205 o-p at seafloor (E) 178 o-p at 18 km (E)	-Acoustic density of fish decreased by 45% during exposure in the seismic survey area. -After exposure, fish density decreased by a further 19%. -Large fish more affected than small fish.	Engas et al. 1993, 1996
Halibut Redfish Haddock Saithe	Vesteralen waters, Norway				-During seismic shooting, no changes in the horizontal distribution of halibut, haddock and redfish were observed. -However, a lower concentration of saithe was measured in the survey area, indicating a migration away from area.	Lokkeborg et al. 2010
Sea bass *Dicentrarchus labrax*	Seismic survey with 2 arrays of 8 air guns, over a period of 4 to 5 months	250 (E)	Up to 10,000	163 to 191 (E)	-Most of the 152 fish tagged were caught within 10 km of the release site, suggesting no large scale migration away from the seismic operation.	Pickett et al. 1994
Pelagic fish including herring (Clupea harengus) and blue whiting (*Micromesistius poutassou*) and mesopelagic species	Wild fish exposed to 2 seismic arrays of 20 air guns each 12 days of operation spread over a month in Norwegian Sea	222.6 p-p	< 50,000	197 at 20 m (E) 189 at 50 m (E)	-Lower density of fish in seismic survey area.	Slotte et al. 2004
Juvenile saith and cod Adult pollock and mackerel	Free fish in a reef Cluster of 3 guns fired over 4 days (~300 shots)	na	> 5.3	218 o-p at 5 m (M) 210 o-p at 16 m (M) 195 o-p at 109 m (M)	-No animals appeared to leave the reef.	Wardle et al. 2001

Table A16. Effects of Air Guns on Fish Catch Rates

Organism	Experimental Conditions	Source Level	Distance (m)	Exposure Level (dB re 1 µ Pa) E (estimated) M (measured)	Observations	Reference
Demersal fish, blue whiting and some pelagic fish	Wild fish along the path of a seismic survey which lasted ~ 1 week in North Sea	222 to 250	Within 150 to 300	200 to 210 (E)	-Catch of demersal fish increased by 34% to 290% after exposure to air guns.	Dalen and Knutsen 1987
Cod *Gadus morhua* Haddock *Melanogrammus aeglefinus*	Continuous active seismic survey over 5 days using 3 arrays of 6 air guns in the Barrents Sea (water depth 250-280 m)	248 to 253		205 o-p at seafloor (E) 178 o-p at 18 km (E)	-Trawl catch rates greatly reduced (between 45 and 70%) for both species within an area of 33 km out from the shooting area and continued at least 5 days after shooting. -Longline catches of haddock decreased whereas those for cod increased.	Engas et al. 1993, 1996
Sandeel *Ammodytes marinus*	Cages on bottom along a 3-day seismic survey (28 air gun array) in North Sea	256	55 to 7,500	221 (E) at 54 m (water depth)	-Temporary drop in the amount of landed fish up to 14 days after the experiments.	Hassel et al. 2003, 2004
Various species including Hake, sole, gunard and Clupeids	Experimental study with firing a 16 air gun array for ~ 12h off coast of Italy	256 o-p	variable	not measured	-No apparent changes in (1) trawl or gill net catches or (2) size frequency distribution of finfish before and after (1 day) seismic operation.	La Bella et al. 1996
Cod *Gadus morhua*	Seismic survey in Norwegian waters with 4 air guns fired during 43 hours over 11 days	239	Within ~ 15,000	~ 161 at 5 km (E)	-Longline catches within the seismic area declined by 55 to 85% compared to those set 1-8 nautical miles away. Effects occurring up to ~ 9 km for at least 24h.	Lokkeborg 1991
Cod *Gadus morhua*	Study along 2 long seismic surveys (3 to 6 days) with 20 to 40 air guns and 1 short survey (12 hours) with 1 air gun array	239 to 250 (E)	Within 9,300	160 to 171 (E)	-Significant cod by-catch reductions (79 to 83%) within 9.3 km for the 2 seismic survey areas, with by-catches returning to pre-shooting levels about one day after the end of shooting. -Three times increase for cod by-catch during short periods of air gun exposures (less than 9h), returning to pre-exposure levels within 12h.	Lokkeborg and Soldal 1993
Halibut Redfish Haddock Saithe	Vesteralen waters, Norway				-Gillnet catches of halibut and redfish increased during and after seismic activity whereas. Those of saithe decreased both during and after seismic activity, although not statistically significant. -Longline catches of halibut decreased during the seismic campaign, but increased again within the 25 day period post seismic. -Longline catch of haddock decreased as the seismic vessel approached.	Lokkeborg et al. 2010
Sea bass *Dicentrarchus labrax*	Seismic survey with 2 arrays of 8 air guns, over a period of 4 to 5 months	250 (E)	Up to 10,000	163 to 191 (E)	-No discernable effects on local catch rates.	Pickett et al. 1994
Rockfish *Sebastes sp.*	A single air gun discharging during 1h 25 in a fishing area off California coast	223 o-p	82 to 183	186-191 (M) at base of rockfish aggregation	-Catch-per-unit-effort declined by ~ 52% during seismic discharges.	Skalski et al. 1992
Cod (*Gadus morhua*) Haddock	124 pulses of a 4 small air gun array over 3 days	229	Within 7,000	142 p-p at 4 km (M) 186 p-p at 150 m (M)	-No negative effects on cod and haddock catch rates by 1 long line vessel during and after shooting in the nearby area.	Thomsen 2002

Table A17. Effects of Air Guns on Early Stages of Fish

Organism	Life Stage	Conditions	Exposure Level (dB re 1 µ Pa)	Exposure Distance from Air Sleeve (m)	Observed Response	Reference
Various commercial species including: Cod Saithe Herring Turbot	Eggs and yolk sac larvae	Air-gun cluster	220 to 242	0.75 to 6	-Effects varied, with the highest mortality rates and pathology in the 1.6 m range and low or no mortality rates and infrequent pathology in the 5 m range. -Pathological effects in turbot larvae included strong vacuolation of the brain, nerve tissues and eyes as well as ablation of sensory cilia of neuromasts at 0.75 m.	Booman et al. 1996
Cod *Gadus morhua*	Eggs, larvae and fry	One discharge of a small or large stationary air gun	220 to 231	1 to 10	-No mortality and no differences in feeding success for any stages studied at any distance. -No behaviour changes in all stages, except for the older fry which exhibited brief balance problems after exposure at 1 m, but recovered in a few minutes.	Dalen and Knutsen 1987
Northern anchovy *Engraulis mordax*	Eggs, yolk sac (YS) and early swim bladder (SB) larvae	4 x 4.9L air guns Multiple discharges of increasing and decreasing pressure	223 to 235 p	1.5 to 3	-Egg survival decreased slightly (9%) at lower peak level and energy but no differences at higher levels. -4-day YS larvae survival decreased (~35%). -No survival differences for SB stages. -Growth rate reduced for 2 and 4-day YS and 22-day SB. -No indication of histological damages in eggs and SB, but ~ 6% decrease in general condition in YS.	Holliday et al. 1987
Plaice *Pleuronectes platessa*	Eggs and larvae		214 and 220	1 and 2	-High mortality (unspecified) at 1 m and no mortality at 2 m.	Kosheleva 1992
Red mullet Anchovy Blue runner Crucian carp Other commercial fish	Eggs	Air gun with a 200 in (5L) and a chamber pressure of 140 atm	Estimated exposure level 210 to 236	0.5, 5 and 10	-Survival (combined species) one day post exposure: 75.4% at 0.5 m, 87.7% at 5 m, 90.2% at 10 m compared to 92.3% in controls. -Pathological effects (embryo curling, membrane perturbation and yolk displacement) observed in small percentage in anchovy and blue runner eggs at 5 m and crucian carp at 0.5 m. No effects noted in mullet eggs. -It is reasonable to assume a cause effect relationship at 5 m since effects were recorded at this distance for 2 species but absent at 10m.	Kostyuchenko 1973
Cod *Gadus morhua*	5-day larvae	Series of shots from grouped Bolt air guns	Estimated 214-220	1, 2, 3 and 4	-No histological changes detected in gills, liver, kidney, and intestine. Rupturing of nerve and epithelial layers in the retinal tissues was found in larvae exposed at 1m.	Matishov 1992
Monkfish (*Lophius americanus*) Capelin	larvae fertilized eggs	10 or 30 shots of a single air gun	199 to 205 p-p	1.5 to 2.5	-No differences between controls and exposed for hatched larvae of monkfish or capelin eggs in relation to survival (24h-72h post exposure).	Payne et al. 2009

Table A18. Effects of Pile Driving on Fish

Organism	Conditions	Distance from source (m)	Exposure Level (dB re 1 µ Pa)	Observed Response	Reference
Shiner perch *Cymatogaster aggregata* Chinook salmon Northern anchovy	4 min of pile driving or ~ 200 impulses	~ 10		-No difference in mortality between controls and exposed. -No behavioral differences post exposure (but no assessment during exposure). -No pathological differences.	Abbot 2004 Marty 2004
Black fish *Orthodon microlepidotus*	Cages	From 45 to 850	Not measured	-No mortality and no behavioral effects (as observations for 5 hours post exposure). Suggestion of no damages below 183 dB p (but no measured sound levels at the cages) and more damage to fish closer to the source.	Abbot and Bing-Sawyer 2002
Various wild species including salmon, anchovy and Surfperch *Cymatogaster aggregata* held in cages	San Francisco Bay Field Cages	100 to 200	160 to 196 RMS estimated	-Mortality of several different species in the field at a distance within a range of 50m: with zone of direct mortality about 10-12 m from source and zone of delayed mortality assumed to extend out at least to 150 to 1,000 m. -A variety of external and internal injuries, including reddening of the liver, rupture of the swim bladder or internal bleedings were observed. -Increased damage rates with extended exposure times and when closer to the source.	Caltrans 2001
Steelhead *Oncorhynchus mykiss* Shiner surfperch *Cymatogaster aggregata*	Multiple pile driving strikes in San Francisco Bay For 1 to 20 min	From 23 to 314	158 to 182 dB re 1 µPa^2 s^{-1} at distances of 23 to 314 m from the pile	-No statistically significant mortality following exposure or 48h post exposure. Gross pathology similar in controls and exposed. -Suggestion of less trauma in animals exposed to pile driving in the presence of an air bubble curtain, but not sample size insufficient for statistical analysis.	Caltrans 2004
Cod Sole	Pile driving play-backs in mesocosms	Relatively large distance from a pile driving	Received sound pressure 144-156 p, cod: 140-161 p Particle motion between 6.51x10^{-3} and 8.62x10^{-4} m/s^2 p	-Significant movement response to the pile driving at relatively low received sound pressure levels (sole: 144-156 dB p, cod: 140-161 dB p) particle motion between 6.51x10^{3} and 8.62x10^{4} m/s^2 p). -Indications of directional movements away from the sound source in both species. -However, high inter individual variability and decrease of response with multiple exposures.	Mueller-Blenke et al. 2010
Brown trout *Salmo trutta*	Caged in harbour of Southsampton	From 25 to 400	Source level 193 at 1 m pp 134 p estimated at 400m	-No evidence that trout reacted to impact piling at 400m, nor to vibropiling as close as 25 m. -Gross pathology (eye hemorrhage and rupture of swim bladder) was only monitored for fish at 400 m and no injuries were reported.	Nedwell et al. 2003
Brown trout *Salmo trutta*	Caged in harbour of Southsampton, UK		Source level 193 at 1 m pp	-No mortality or evidence of trauma (inner ear microscopy, gross pathology including swim bladder rupture, eye haemorhage or embolism). -No increase in activity or startle response.	Nedwell et al 2006
Coho salmon *Oncorhynchus kisutch*	Caged	15	SPL 208 dB SEL 179 µPa^2-s or 207 over the 4.3h exposure period	-No mortality and no gross pathology in fish sampled at 10 and 19 days post exposure. -No significant changes in behaviour.	Ruggerone et al. 2008
Steelhead *Oncorhynchus mykiss*	Caged	35 to 150 Control at 350	SPL 163-188 p SEL 178-194	-No mortality and no significant differences in pathology and histopathology (head, gill, liver, swim bladder, kidney, spinal chord and vertebrae).	Oestman and Earle 2010

Table A19. Effects of Low Frequency Sonar on Fish

Organism	Life Stage	Conditions	Exposure Distance from Air Sleeve (m)	Exposure Level (dB re 1 µ Pa)	Observed Response	Reference
Herring *Clupea harengus* Cod *Gadus morhua* Saithe *Pollachius virens* Spotted wollfish *Anarhichas minor*	Larvae and juvenile	The exposure was given as 1s pure tone pulses that varied in frequency (1.5, 4 and 6.5 Kz), sound pressure (150 to 190 dB) and in the number of pulses (4 to 100).	3	150 to 190	-No direct mortality among the fish larvae or juveniles exposed, except for 2 experiments (of a total of 42) repeated on juvenile herring where significant mortality (20 to 30%) was observed for a 189 dB SPL.. -No differences in delayed mortality or growth related parameters (up to 4 weeks). -Some behavioral responses (panic, confused and irregular swimming) were observed during and after sound exposure (particularly in herring juveniles for 1.5 Kz. -No obvious differences in histology of various tissues and SEM of neuromast organs for selected herring experiments.	Jorgensen et al. 2005
Rainbow trout *Oncorhynchus mykiss* Channel catfish *Ictalurus punctatus* Sunfish *Lepomis sp.*	Adult	Caging in Seneka Lake Exposure to high intensity sonar: low frequency sounds for 324 or 628 s or mid- frequency sounds for 15 s.	16.6	Received peak signal of 193 RMS for low frequency	Examination of effects immediately after exposure: -No exposure-related mortality. -No effects on inner ear tissues using SEM. -No gross pathology or histological effects in various tissues and organs (gill, skin, eye, liver, spleen and kidney). -No differences in haematocrit.	Kane et al. 2010
Rainbow trout *Oncorhynchus mykiss* Channel catfish *Ictalurus punctatus*	Adult	Fish were placed in test tank and exposed to low frequency high intensity SURTASS LFA sonar for 324 or 648 s		Max received RMS 193 dB µPa^2 for either 324 or 648 s	-No mortality -No ultra structural differences on the sensory hair cells, but a 10-20 dB auditory threshold shift at 400 Hz immediately after exposure. -Recovery took 24 h for catfish and 48 h for trout. -No histopathological effects on non-auditory tissues (brain, swim bladder, heart, liver, gonads and blood). No change in behavior of fish before and after exposure.	Popper et al. 2007 Halvorsen et al. 2006 Popper 2008

Table A20. Selected Studies on Effects of Explosives on Fish

Organism	Conditions	Exposure Distance from Blast (m)	Peak Pressure	Observed Response	Reference
Various species including anchovies, sardine, kingfish, perch, barracuda, croaker, shad, white sea bass, smelt	Depth of water 11 to 28 m		4.5 to 18 kg of 60 % Petrogel placed from 0.9 to 6.1 m under the surface	-Mortality -Swim bladder ,ruptured or damaged. Ruptured blood vessels -Fish without swim bladders were apparently unhurt, when suspended in cages at set distances from shots.	Aplin 1947
Larvae and adults of various species including menhaden, croaker, trout, rock striped bass, alewife, shad, perch, spot, hake, half beak, harvestfish and gizzard shad	Depth of water 41 m		114 to 545 kg of hexahydro-1, 3, 5 Trinitro-8-Triazine (HBX) placed from 15 to 41 m under the surface	-Mortality. -Swim bladder ruptured or damaged and haemorhage of its vascular system. -Rupture of the vascular system of the abdominal cavity and in liver and spleen. -Distended abdomens (croaker, trout, hake and small rock. -Severe body trauma (menhaden).	Coker and Hollis 1950
12 species but the majority were spot *(Leiostomus xanthurus)* and white perch (*Morone Americana*)			.45 to 32 kg of charges at depths from 1.5 to 21 m	-Swim bladder ruptured or damaged.	Gaspin et al. 1976
Rainbow trout *Oncorhynchus mykiss* 3 life stages examined: Eggs, sac fry and juveniles	Depth of water 4 m Cages suspended at 2 m	1.5 and 6	Charges from 0 to 280 kPa burried 1 to 3 m into sediment	-Changes in both the area and circumference of the cranial region of eyed eggs, as well as damages in swim bladder, eye and kidney of juveniles. -Haemorrhages also observed in juveniles with extent increasing with pressure level. -No tissue disruption in eyed eggs and sac fry. Impacts to eye structures, swim bladder integrity, and kidney tissue were observed in fish exposed to pressures that were ≥69 kPa.	Godard et al. 2008
Pinfish (juveniles) *Lagodon rhomboids* Spot (juveniles) *Leiostomus xanthurus*			12-grain Primadet PDT 1403 detonators 637 kPa at 3.6 m 231 kPa at 7.5 m 110 kPa at 17 m 236 p dB re 1 μPa	-Internal hemorrhaging. -Swim bladder damaged. -Coagulative necrosis in liver. -Damage to kidney tubules. -Total energy in the sound wave, regardless of pressure polarity, is responsible for effects.	Govoni et al. 2003
Spot (larvae) *Leiostomus xanthurus* (larvae) *Brevoortia tyrannus*				-Internal haemorrhaging. -Swim bladder damaged. -Correlation of injury with distance from the explosion and impulse metric.	Govoni et al. 2008
Black drum *Pogonias cromis*		1 to 136	33 m of 100 g/33 Primacord detonation	-Fish for both species survived at distances more than 1 m but could have many internal injuries.	Linton et al. 1985

Organism	Conditions	Exposure Distance from Blast (m)	Peak Pressure	Observed Response	Reference
Red drum *Sciaenops ocellatus*			cord lying on the bottom in water 2.4 m deep	-Most frequently damaged organs were swim bladder, kidney and peritoneum. -Fish caged at the surface were less damaged than fish caged on the bottom of the ocean.	
				Fish kills occurred at a distance of 400 m from an explosive source but did not occur where the estimated received peak level was only 134 dB. However, no other distances were assessed.	Nedwell et al. 2004
Late stage larval and recently metamorphosed fish Spot *Leiostomus xanthurus* Pinfish *Lagodon rhomboids*	12-grain Primadet PDT detonators	3.6 7.5 17	639.4 kPa 231.3 kPa 110.6 kPa	-Within 24h of blast: evisceration; haemorrhaging dorsal to the swim bladder and ventral to the kidney; death. -Following 24h period: damage to kidney tubules; hemorrhage within coelom, swimbladder and liver; ruptured pancreas; death.	Settle et al. 2002
Atlantic salmon	Ten underwater explosions over 70 min, each of ~ 2MPa in pressure amplitude, in a laboratory tank.			-No mortality immediately or during the subsequent 7 days of observation. The response to each detonation was cessation of swimming for a few minutes and failure to express a flight reaction. -The vascular endothelium revealed temporary injuries within the first 30 min which disappeared after 1 week. -The cholinergic and adrenergic vasoconstrictor responses were markedly reduced during the 1st day after the shock. -Adrenaline and cortisol revealed different patterns of delayed increases.	Sverdrup et al. 1994
Poecilia reticulate (G) *Lepomis* (G) *Machrochirus* (G) *Oncorhynchus mykiss* (G) *Micropterus salmoides* (G) *Carassius auratus* (S) *I. punctatus* (S) *Gambusia affinis* (S) *Cyprinus carpio* (S)			Bare spheres of pentolite, fired by electric blasting caps Peak pressure: 530-9025 kPa Impulse 4.1-428 kPa/msec	-Injuries included swim bladder rupture, kidney and liver damage. -Direct correlation between body mass and the received sound impulse which caused 50% mortality with sound energy more indicative than peak pressure for damage thresholds. -Fish with ducted swim bladders were found to be just as vulnerable to blast injury and death as those without ducts.	Yelverton et al. 1975

(G) = hearing generalist
(S) = hearing generalist

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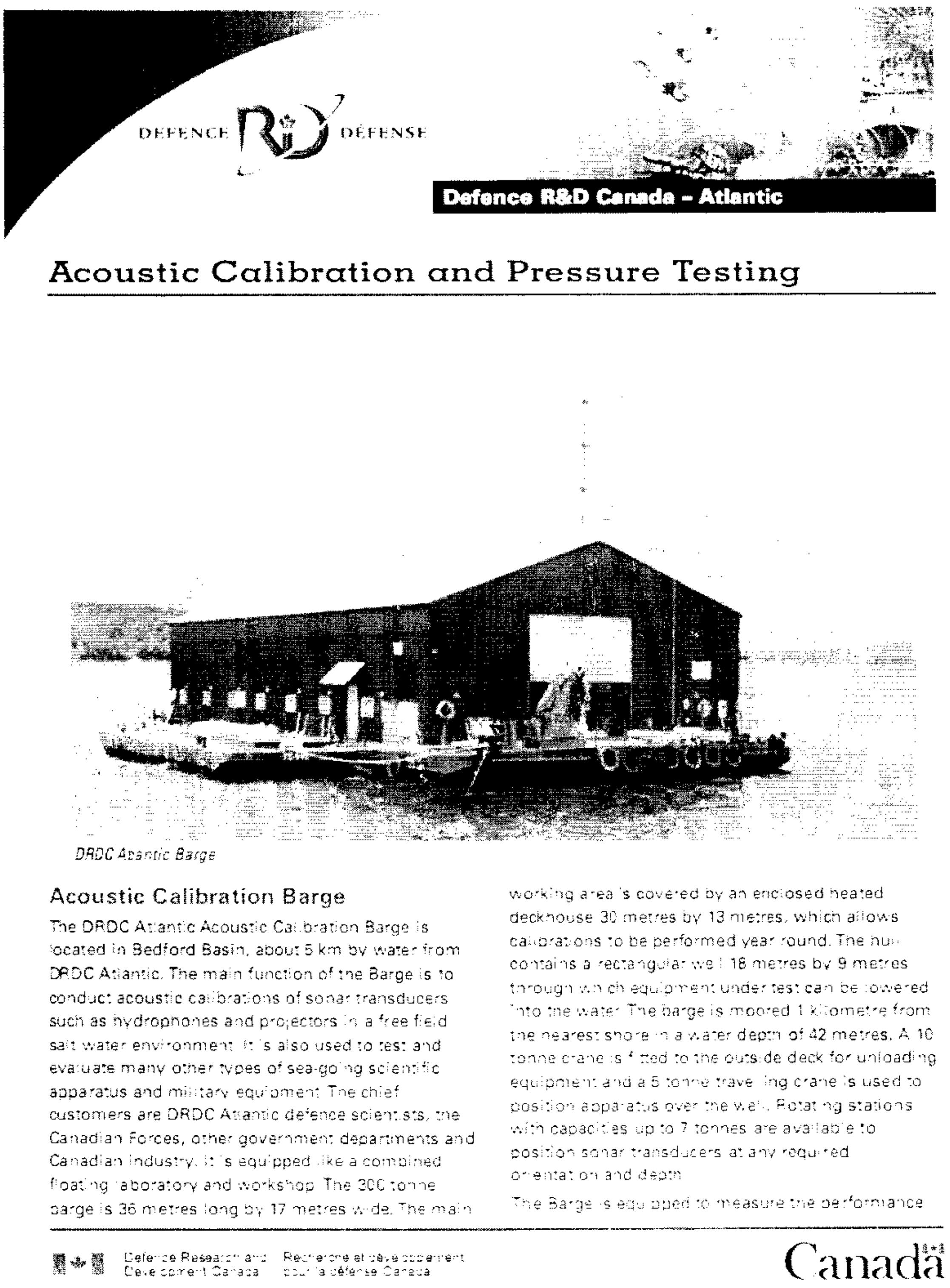
DRDC Atlantic Acoustic Calibration Barge Brochure



DEFENCE R&D DÉFENSE

Defence R&D Canada - Atlantic

Acoustic Calibration and Pressure Testing

DRDC Atlantic Barge

Acoustic Calibration Barge

The DRDC Atlantic Acoustic Calibration Barge is located in Bedford Basin, about 5 km by water from DRDC Atlantic. The main function of the Barge is to conduct acoustic calibrations of sonar transducers such as hydrophones and projectors in a free field salt water environment. It is also used to test and evaluate many other types of sea-going scientific apparatus and military equipment. The chief customers are DRDC Atlantic defence scientists, the Canadian Forces, other government departments and Canadian industry. It is equipped like a combined floating laboratory and workshop. The 300 tonne barge is 36 metres long by 17 metres wide. The main working area is covered by an enclosed heated deckhouse 30 metres by 13 metres, which allows calibrations to be performed year round. The hull contains a rectangular well 18 metres by 9 metres through which equipment under test can be lowered into the water. The barge is moored 1 kilometre from the nearest shore in a water depth of 42 metres. A 10 tonne crane is fitted to the outside deck for unloading equipment and a 5 tonne travelling crane is used to position apparatus over the well. Rotating stations with capacities up to 7 tonnes are available to position sonar transducers at any required orientation and depth.

The Barge is equipped to measure the performance

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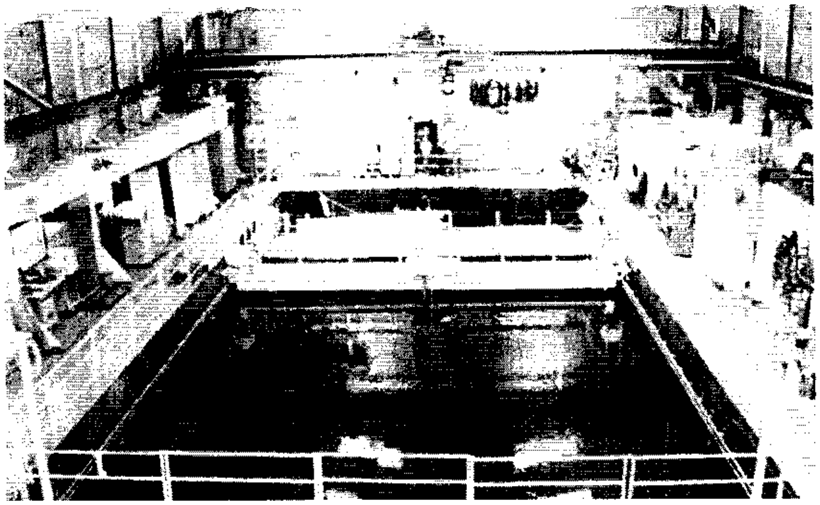
Acoustic Calibration and Pressure Testing



Interior of the DRDC Atlantic Barge.

of sonar transducers over the range 100 Hz to 100 kHz. A 16 kilowatt power amplifier is available for power testing of sonar projectors, although the relatively shallow water depth places a cavitation limit on the radiated power levels that can be achieved.

Acoustic Calibration Tank

The Acoustic Calibration Tank Facility, located at the main DRDC Atlantic site, is primarily used for calibration of hydrophones and other underwater acoustic transducers, whose size and frequency range are compatible with the tank's dimensions. The freshwater tank is circular in cross section, 7.3 metres in diameter and 4.5 metres deep. It is build of redwood and lined with insulkrete and rubber to reduce reverberation. The dimensions are such that the tank's operating frequency range is typically greater than 1 kHz, as limited by the computerized data collection and analysis system. Sonar transducers operating below 1 kHz are usually calibrated at the Acoustic Barge. The tank has a 0.5 tonne hoist for positioning heavier equipment and precision rotating stations that are used to measure transducer beam patterns. The tank is also used to test and evaluate other types of sea-going scientific apparatus and military equipment.

High Pressure Test Facility

DRDC Atlantic operates two pressure vessels for testing underwater sensor systems or components, such as transducers, cables and connectors, under hydrostatic loading that simulates great depths in the ocean. This is an important part of the evaluation of equipment that is designed for use in the undersea environment. The smaller pressure vessel is 12 cm in diameter and 45 cm in length with a maximum pressure rating of 34 MPa, equivalent to an ocean depth of 4 kilometres. The larger vessel is 90 cm in diameter and 2.4 metres in length and is rated for 58 MPa, equivalent to a depth of 6.8 kilometres.

Customers include DRDC Atlantic defence scientists, the Canadian Forces, other government departments and Canadian industry. Bookings for all of the facilities should be made well in advance. Customers are charged either an hourly or daily rate for use of the facilities.

For more information

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