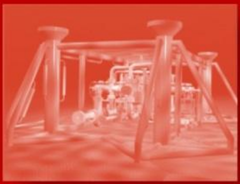




DEPARTMENT OF ENERGY & CLIMATE CHANGE

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GLOSSARY

Amplitude: Magnitude of change in the oscillating variable (such as pressure) with each oscillation

Ambient marine noise: Sound from natural and man-made sources that contribute to background levels

DeciBel (dB): The logarithmic measure of sound intensity / pressure. The deciBel value for sound pressure is 20 log 10 (P/P0) with P=actual pressure and P0= reference pressure

EU Task Group 11: Specialist group set up to provide advice on the Marine Strategy Framework Noise Descriptor and provide indicators to work towards measurement of Good Environmental Status

Hearing Threshold: The average sound pressure level that is just audible to a subject under quiet conditions

Hertz (Hz): The unit of frequency with 1 Hz is 1 cycle per second

Intensity: Measure of the energy flux averaged over the period of the wave

Period: Duration of once cycle in a repeating event

Permanent Threshold Shift (PTS): A permanent elevation of the hearing threshold due to physical damage in the auditory system

Pressure: is the force per unit area applied in a direction perpendicular to the surface of an object

Site survey: Geophysical site investigation survey to determine shallow seabed sediments, usually applying small airgun volumes ~160 cubic inches

Sound is a mechanical wave that is an oscillation of pressure transmitted through a solid, liquid, or gas, composed of frequencies within the range of hearing and of a level sufficiently strong to be heard

Sound Exposure Level: or (SEL) is the time integral of the square pressure over a fixed time window, long enough to include the entire pulse

Sound Pressure Level (SPL) / Sound level: logarithmic expression of the sound pressure in deciBels (dB)

Sound source: Instrument that generates sound signal / origin of a sound signal (eg seismic airgun)

Source Level: Acoustic pressure at a standard reference distance of 1m. Units in dB re1µPa at 1m

Source volume: Geophysical terminology used to describe acoustic volume of an airgun array (cubic inches)

Speed (waveform): Rate of travel of a wave through an elastic medium

Temporary Threshold Shift (TTS): Temporal and reversible elevation of the auditory threshold

Zero–Peak (or 0-peak) Sound Pressure Level (SPL) is a sound signals maximum rise in pressure from an ambient pressure

ACRONYMS

dB	deciBel
dBHT	deciBel values above hearing threshold
BHP	Break Horse Power
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment Food and Regulatory Affairs
EC	European Commission
EIA	Environmental Impact Assessment
GES	Good Environmental Status
HP	Horse Power
Hz	Hertz
JNCC	Joint Nature Conservation Committee
k	Kilo (one thousand)
kg	kilogram
kHz	kilo hertz
Km	kilometre
m	Metre
ms	millisecond
MMO	Marine Mammal Observer
MSFD	Marine Strategy Framework Directive
NMFS	National Marine Fisheries Service
OBC	Ocean Bottom Cabling
OGP	International Association of Oil & Gas Producers
OSPAR	Oslo Paris Commission
PON	Petroleum Operators Notice
PTS	Permanent Threshold Shift
rms	Root Mean Squared
s	Second
SEL	Sound Exposure Level
TTS	Temporary Threshold Shift
Pa	Pascal (Pressure)
psi	Pounds Per Square Inch
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UKDEAL	United Kingdom Digital Energy Atlas
VSP	Vertical Seismic profile

EXECUTIVE SUMMARY

Underwater sound and the potential impacts on marine life has received increased attention in recent years, with measures to assess underwater sound having been included within the European Marine Strategy Framework Directive (MSFD). As part of the proposed requirements of this Directive Member States may have to report on the occurrence and distribution of activities within their jurisdictions that generate loud, low and mid frequency impulsive sounds that exceed levels capable of causing significant impact to marine animals. However, current EC guidance does not provide any specific levels of sound that are deemed capable of causing a 'significant impact' to marine animals, so there remains considerable flexibility in how this can be interpreted by Member States.

This report examines information on underwater sound generated by the offshore oil and gas industry, and reviews the main activities, these being: geophysical surveys, use of explosives, construction of oil and gas infrastructure, impact piling, production, vessel and drilling noise.

The Department of Energy and Climate Change (DECC) is responsible for regulating the activities of the UK oil and gas industry and ensuring compliance with applicable legislation and European Directives. In order to provide DECC with an indication of what oil and gas activities could be considered as requiring reporting under new the Marine Strategy Framework Directive, a number of recognised sound exposure thresholds and pressure level indicators proposed by Southall et al (2007) and a specialist EU Task Group were compared against the sound levels generated by oil and gas activities.

In the absence of any clear guidance as to the peak sound and exposure levels that are considered capable of causing significant impact to marine life, it was decided by the authors of this report that oil and gas activities that produced sound in excess of the levels deemed capable of inducing a Temporary Threshold Shift (TTS) in hearing of cetaceans using the Southall impact exposure criteria, were likely to qualify for reporting requirements.

This assessment identified the following activities as being most likely for reporting: **high powered sparker systems**, **high powered boomers**, **single airguns in excess of 100 cubic inches**, **airgun arrays**, **pile driving activities** and **use of explosives**.

The noise descriptor as specified in the MSFD is for low and mid frequency impulsive sounds within the frequency range of 10 Hz – 10 kHz. A number of oil and gas activities, whose sound levels were documented in this review, do not qualify under this criteria because they either produce continuous sounds (shipping and dredging) or generate high frequency sounds in excess of the upper limit of the noise descriptor (multibeam and side scan sonar).

A difficulty faced when compiling information on underwater sound measurements is that much of the information presented in technical reports have not been subject to the rigours of the scientific review process. The accuracy of the data in many of the reports reviewed was difficult to ascertain due to lack of detail provided as to how measurements were recorded and the calibration methods applied to the recording equipment.

This report provides a comprehensive review of sound pressure levels that are available for oil and gas activities and details the processes used by DECC to record information on activities most likely to be reported. This report will enable DECC to determine if any changes are required to the reporting of oil and gas activities and, should further guidance be provided on the sound levels that need to be reported, this will enable them to revaluate the oil and gas activities that have been preliminary identified within this report.

1. INTRODUCTION

There is an increasing body of scientific evidence that exposure to high levels of underwater sound, or sustained exposure, has the potential to adversely affect the health and wellbeing of marine animals. There is also heightened awareness both politically and socially of the issues associated with anthropogenic sound. Concern has arisen that man made sounds can impact marine life including; marine mammals, fishes, diving seabirds and invertebrates (Popper, et al. 2001, NRC 2005, Richardson, et al. 1995, Nowacek, et al. 2007). The oil and gas industry activities, particularly those that emit underwater sound, have been receiving increased public scrutiny as the potential impacts of introducing underwater noise has received greater attention in the last few years. Specifically, it is primarily the widespread use of airguns for hydrocarbon exploration, and the associated underwater noise produced, that has raised concern on the effects sound has on marine life (Richardson, et al. 1995; Gordon, et al. 2004). The production of underwater sound is not, however, limited to the exploration phase of oil and gas, as every type of activity undertaken offshore produces sound, albeit the characteristics and source levels differ significantly from one another.

There are a number of distinct phases of oil and gas activities, from initial exploration to drilling and production through to decommissioning, and the underwater sounds associated with each phase are dependent upon the nature and scale of activities being undertaken. Geophysical surveys associated with the exploration and management of reserves is a notable noise source. Drilling for hydrocarbon reserves requires the use of mobile drilling units and fixed platforms and the type of installation and the propulsion mechanisms of mobile drilling units influence the levels of sound being generated. Construction activities such as underwater hammer piling used for infrastructure installation, and explosives, sometimes used in the decommissioning of subsea equipment, are other notable activities that can generate high levels of underwater sound. A review of sounds generated by the oil and gas industry activities is provided in Section 3.

The investigation of sound generated by oil and gas activities has been the focus of many academic, regulatory and industry investigations. Several significant reviews on oil and gas noise have been undertaken, notably in 1995 by Richardson et al. and more recently in 2007 by a study funded by the Oil and Gas Producers (OGP), (reported in Wyatt (2008)). A difficulty faced in this review when compiling information on the sound produced by oil and gas activities was that much of the material is in technical reports (grey literature) and has not necessarily gone through the scientific peer-review process. While some of this grey literature has significant scientific and methodological problems, it is critical to include it in this review since it makes up a considerable proportion of the available information, this is especially the case where the report provides information on a particular type of activity not addressed elsewhere. The results presented in this report are based on evaluation of these grey literature reports as well as on peer-reviewed articles. It is also important to note that the approach and analysis in each study reviewed may differ considerably, and so comparisons between studies, and especially those done in different locations or by different groups of investigators may not be valid, and any extrapolations of the original data may also introduce error.

1.1 DOCUMENT SCOPE

The purpose of this study is to provide DECC with an evidence based catalogue of underwater sound levels produced by the oil and gas industry. The scope of the report was to focus on one of the low and mid-frequency impulsive sounds between the frequency range 10 Hz – 10 kHz. The report documented sounds generated during the exploration, construction, production and decommissioning phases of oil and gas activities.

The sound levels documented in the review were compared to exposure thresholds and pressure thresholds proposed by Southall et al. (2007) and a specialist EC task group in order to identify the type of oil and gas activities that potentially could cause 'significant impacts' to marine animals, and hence might need to be reported under the EU Marine Strategy Framework Directive (MSFD) (2008/56/EC) (discussed in Section 1.2). DECC, as regulators of the UK oil and gas industry, are responsible for ensuring the industry's activities are managed in line with current UK legislation and European Directives. This report identified the activities that DECC specifically regulates which may require to be reported as part of the MSFD, and for the activities that are most likely to be reported (geophysical surveys, piling and explosive use) the current mechanisms for recording and managing information about these activities will be detailed.

Underwater sound is a complex issue requiring an understanding of standard units of measurement and how they have been applied in the recording of underwater levels. Where possible sound pressure levels will be reported and referenced to the appropriate units. An introductory chapter on underwater acoustics is provided to help guide the reader through the terminology used, units of measurement, and also the standard calculations applied in underwater sound measurements (Appendix A).

1.2 Marine Strategy Framework Directive and Noise

The Marine Strategy Framework Directive (2008/56/EC) requires member states to determine Good Environmental Status (GES) for their marine waters, and design and implement programmes of measures aimed at achieving it by 2020, using an ecosystem approach to marine management. Each member state must put in place a marine strategy which requires an initial assessment of the current environmental status of that Member State's waters using a series of 11 descriptors, for which the Commission, Member States and the European Parliament had to agree initial criteria by 15th July 2010, this was also the date the Directive was transposed into UK law. As part of the work towards achieving GES an initial assessment stage is required (UK target date July 2011), once this phase is completed, specific monitoring programmes will be set up to measure progress towards, and then achievement of, GES.

Of the eleven descriptors which have been put forward to work towards the achievement of GES, underwater noise is captured in descriptor 11, this specifies that the '*introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*'(Full details of the noise descriptor is provided in Appendix B). As part of this descriptor two indicators were proposed (European Commission 2010):

1. Distribution in time and place of loud, low and mid frequency impulsive sounds

Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1µPa^2.s) or as peak sound pressure level (in dB re 1µPa peak) at one metre, measured over the frequency band 10 Hz to 10 kHz.

2. Continuous low frequency sound

Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1µPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate.

Prior to the European Commission's publication on the standards and guidance on good environmental status for marine waters several specialist EU task groups were set up to establish guidance and recommendations for suitable criteria to measure for the 11 descriptors.

1.2.1 Background information on the development of the noise descriptor in the MSFD

An EU Task group (Task Group 11) was convened to establish guidance and recommended suitable for the noise descriptor. They produced a report detailing a number of preliminary noise indicators that could be used in the initial assessment of Good Environmental Status for the noise descriptor. Indicators were proposed for the following types of sounds (Tasker, *et al*. 2010):

- low and mid frequency impulsive sounds
- high frequency impulsive sounds (*subsequently not included in the MSFD noise descriptor*)
- continuous low frequency sounds (*not the focus of this report*)

The indicator for low and mid-frequency impulsive sound is the only one which will be discussed in detail as the high frequency impulsive sound indicator was not included in the European Commission noise descriptor and 'continuous low frequency sounds' are not the focus of this report.

The choice of frequency bandwidth for the low and mid frequency impulsive sound indicator (10Hz to 10kHz) was selected on the basis that higher frequency sounds do not travel as far as sounds within this frequency band. Although it was recognised that higher frequency sounds may affect the marine environment, they do so over shorter distances than low frequency sounds. Another reason for the selection of this frequency band was that this excluded most depth-finding and fishery sonars (Tasker, *et al*. 2010).

The initial approach put forward by the EU Task Group for the noise indictor for 'low and mid-frequency impulsive sounds' was to specify relatively high noise threshold levels, with all activities that exceeded these values potentially subject to a reporting requirement (Tasker, *et al*. 2010). The EU Task Group 11 recommended that sound pressure levels that were in excess of 224 dB (0-peak)[1] and 183 dB[2] sound exposure levels should be reported. The rationale behind these levels was based on best available scientific information at the time (Southall, *et al*. 2007). The noise indicator had a spatial element (as specific areas were defined), and also a temporal element, (in terms of the proportion of days within a year in a given area that the sound thresholds were exceeded).

The intention was for Member States to collect information on the proportion of days and spatial extent of sounds of a 'high level' and this was why sound levels that were attributed with causing a biological effect were chosen as the threshold levels for reporting. Once collected individual Member States could then, if deemed necessary, regulate either the proportion of days or the spatial extent of activities that generated the highest levels of underwater sound.

Germany, supported by others, advocated lower threshold values than those proposed by the Task Group. These levels were sound pressure levels 180 dB (0-peak) and Sound Exposure Levels of 159 dB.

Consequently, due to the conflicting thresholds for the indicator for impulsive sounds Member States could not reach unilateral agreement as to what sound levels should be detailed in the criteria and methodological standards on good environmental status of marine waters. An alternative approach was then put forward by the European Commission which required the reporting of loud, low and mid frequency impulsive sounds which; '*exceed levels that are likely to entail significant impact on marine animals'* (European Commission 2010).

The EC guidance does not specify what *significant impacts* on marine animals are, or make reference to any accepted impact criteria for marine animals (European Commission 2010). Therefore, there remains

[1] Zero–Peak (or 0-peak) Sound Pressure Level (SPL) is a sound signals maximum rise in pressure from an ambient pressure
[2] Sound Exposure Level (SEL) is the sum of acoustic energy over the measurement period.

considerable flexibility in how significant impacts on marine animals may be interpreted across Member States jurisdictions. This may be further resolved through the establishment of a further EU specialist group.

Our understanding of marine noise and the potential negative impacts this has on marine receptors is incomplete, but as our knowledge in this area increases through time there is likely to be substantial modification and development of the indicators and methodologies to assess Good Environmental Status. For the noise descriptor, it is widely accepted, and mentioned in the EC guidance, that additional scientific and technical progress is still required to support the further development of criteria related to this descriptor, including in relation to the impacts introduction of sound energy has on marine life.

1.3 Importance of Sound for Marine Life

Sound is an important sensory modality for many marine organisms, especially since other senses such as vision, touch and chemical cues can be limited in range and speed of signal transmission. Marine life, including marine mammals, fish and certain species of invertebrates have developed a range of complex mechanisms both for emitting and detecting sound signals (Richardson, *et al*. 1995).

The auditory and sensory mechanism of many animals are capable of receiving and processing sounds from the surrounding environment, however it is important to appreciate that the sounds effectively 'heard' by the animal are likely to differ considerably from the actual sounds emitted from the source. This has to do with the fact that hearing systems of animals are not equally sensitive to all frequencies. Unsurprisingly, given the diversity of marine life, there is considerable variability between the frequency ranges that marine fauna can hear and emit.

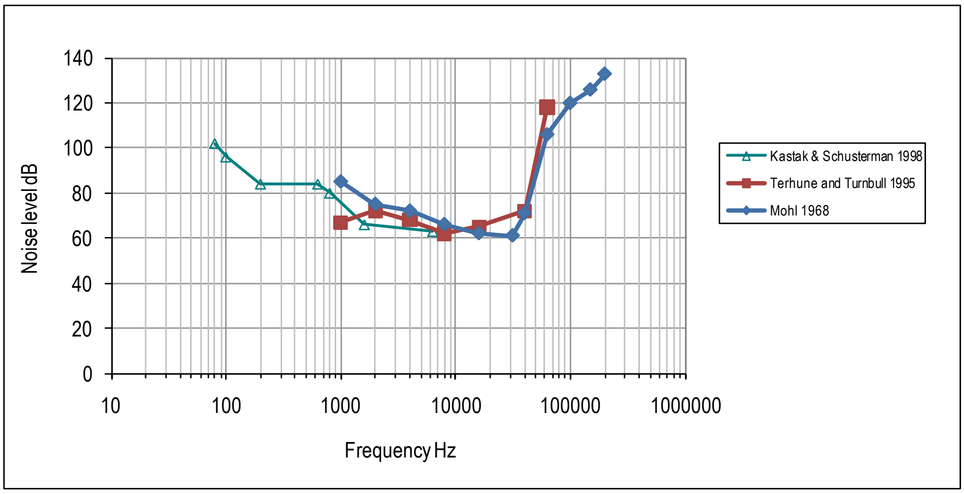
The hearing ranges of mammalian ears is extensive and as humans judge the relative loudness of sounds by the ratio of different values of sound pressure, which is essentially a logarithmic type of sound processing, it is common to describe physical attributes of sounds with logarithmic units called sound levels. The use of a logarithmic scale compresses the range of numerical values that must be used and is appropriate when describing underwater sounds that have an extensive range. The most frequently applied scale for describing sounds is the deciBel scale (dB). When a numeric value is expressed in deciBels it is important to state the value of the units and reference level used; sound levels are meaningless without the correct application of metrics. Unfortunately, researchers often don't state what dB value they have used, which makes comparisons between studies difficult (see discussion by Richardson *et al*. 1995).

Through exposing animals to sounds across a range of frequencies and noting their behavioural or physiological responses, this allows for an audiogram to be produced that illustrates the hearing threshold over a range of frequencies. The hearing threshold is the average sound pressure level that is just audible to a subject under quiet conditions.

As a result of the difficulties of testing on marine mammals, and also various ethical and legal considerations, this has limited intrusive methods of collecting audiogram data on marine mammals. Only a limited number of audiograms are available mostly for smaller cetaceans, and baleen whales are notably absent from the record. For illustrative purposes, three audiograms are presented that have been derived for the common seal from behavioural tests, although there are general similarities between the audiograms there are notable differences at specific frequency bands, for example 1 kHz (Figure - 1). Inevitably, marine animals will have varying hearing capabilities between individuals. Part of this variation will result from natural variability in hearing ability, and it is possible that certain individuals may have suffered hearing damage as a result of age, disease processes, or as a result of damage caused by exposure to sound (Nedwell, Needham, *et al*. 2001). Consequently, the number of individuals tested in any given audiogram measurement has to be sufficient to establish reasonable confidence in the quality of the measurement and this is often not the case for marine mammal audiogram data.

Collecting information on fish audiograms is less troublesome than marine mammals and an extensive number of audiograms have been collected and often sufficient individuals have been tested to have statistical confidence in the results (Nedwell, *et al*. 2004). Although given the diversity of fish species and their anatomical and physiological differences a considerable amount of research is still required to gain a better understanding of hearing capabilities of fish.

Figure - 1 Audiogram Data for the Common Seal from Behavioural Responses
(Audiogram data taken from (Møhl 1968; Terhune and Turnbull 1995 and Kastak and Schusterman 1998)



Marine mammals use sound for a variety of purposes including in communication, orientation, predator avoidance and foraging. The range of sounds used by marine mammals is broad, and ranges from the low frequency calls <10 Hz of the blue whales to the ultrasonic clicks of 145 kHz in harbour porpoise (Villadsgaard, *et al*. 2007). The hearing of marine mammals spans an equally wide range of frequencies as the emitted sounds, and can range from <1 kHz – 180 kHz (Richardson, *et al*. 1995; Southall, *et al*. 2007).

Many species of marine fish produce sounds for communication, these are typically emitted at frequencies below 1 kHz, and it is also suggested that fish use acoustic cues for orientation (Montgomery, *et al*. 2006). Fish display a number of hearing mechanisms, some species are probably only sensitive to a sound's particle motion (which is the kinetic component of a propagating sound wave) through to species that hear in the lower frequencies below 1 kHz and fish, such as herring species, that are able to perceive frequencies above 3 kHz (Popper, Fay, *et al*. 2003). Given the diversity of fish species relatively few have been investigated, and the knowledge of fish hearing capabilities and how they respond to acoustic signals is still very limited.

Although scientific research to date has tended to focus on marine mammals and fish, other marine life sensitive to underwater sound include invertebrates such as decapod crustaceans, that are sensitive to sounds <3 kHz, and cephalopods that are known to be sensitive to very low frequencies <20 Hz, and sea turtles with hearing capabilities in the lower frequency bands (NRC 2005; O' Hara and Wilcox 1990; Popper, Salomon and Kenneth 2001).

1.4 IMPACT OF SOUND ON MARINE LIFE

Assessing the impact of anthropogenic sound sources on marine life can be a highly complex process requiring detailed knowledge of sound sources and the receiving environment. Determining the potential significance of an exposure to a sound source upon a receiver, such as a marine mammal, can be a scientifically contentious area in environmental impact assessments (EIA). It is worth noting that it has not been possible to conclusively determine the significance and potential impacts that exposure to airborne sound can have on many terrestrial animal groups that are much more amenable to research than marine species, and for which there is considerably more data available.

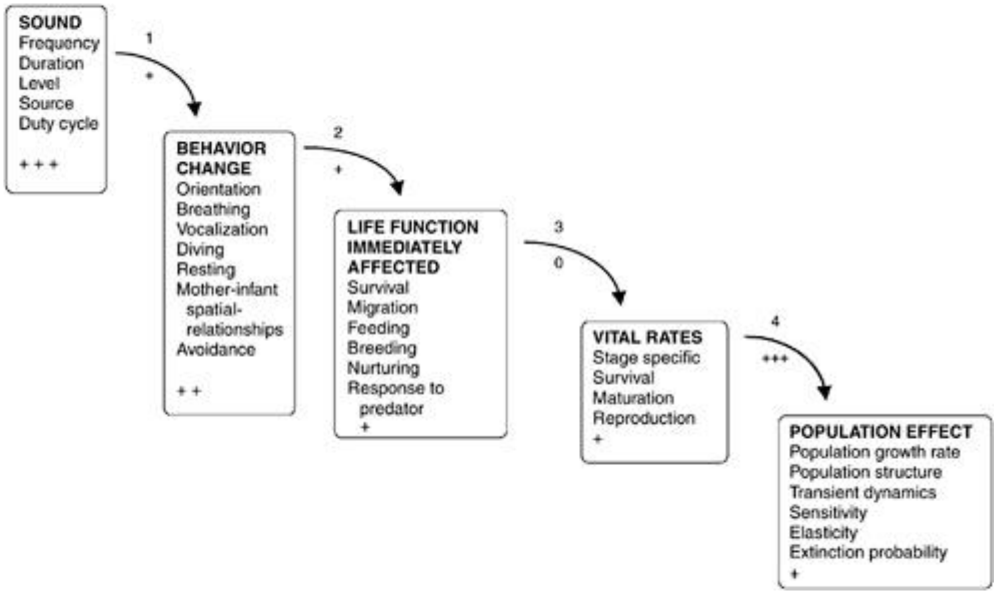
However, it is generally accepted that exposure to anthropogenic sound can induce a range of adverse effects on marine life. These range from insignificant impacts to significant behavioural changes and also include non-injurious type effects including masking of biologically relevant sound signals, such as communication signals. Activities that generate very high sound pressure levels can cause auditory injuries and other types of physical injury and, in some circumstances, lead to the death of the receiver (Richardson, *et al*. 1995, Southall, *et al*. 2007). Organisms that are exposed to sound can be adversely affected over a short time scale (acute effect) or a long time-scale (chronic effect). When evaluating the effects of underwater sound sources the properties of the waveform that are important are peak pressure, received energy, signal duration, spectral type, frequency range, duty cycle, kurtosis, rise time and directionality.

One of the main difficulties faced in assessing the impacts of sound on marine life stems from our incomplete understanding in determining how behavioural or physiological changes ultimately affect an animal's ability to survive grow or reproduce (NRC 2005).

In order to illustrate the current scientific understanding of the consequences that exposure to underwater sounds has on a marine mammal population, the conceptual Population Consequences of Acoustic Disturbance model (PCAD) is shown in Figure - 2 (NRC 2005). The model describes several stages required to relate acoustic disturbance to effects on a marine population and highlights how easily we can measure the relationship between the transfer functions and their effect on the population

In this model five groups of variables are of interest, and 'transfer functions' specify the relationships between the variables listed (shown by the arrows). Each box lists variables with observable features (sound, behaviour change, life function affected, vital rates, and population effect). In most cases, the causal mechanisms of responses are not known. The causal steps between reception of sound and death are by no means known or agreed on. The "+" signs at the bottoms of the boxes indicate how well the variables can be measured. The indicators between boxes show how well the black box nature of the transfer functions is understood; these indicators scale from "+++" (well known and easily observed) to "0" (unknown). It can be seen that sounds sources themselves are well understood and measurable, but we know progressively less about the relationships between how sound signals cause behavioural changes and how this affects the life functions and vital rates and leads to population effects. It is worth highlighting that no studies to date have conclusively demonstrated a link between exposure to sound and detrimental effects upon a marine mammal population (NRC 2005).

Figure - 2 The Population Consequences of Acoustic Disturbance model (reproduced from NRC 2005).

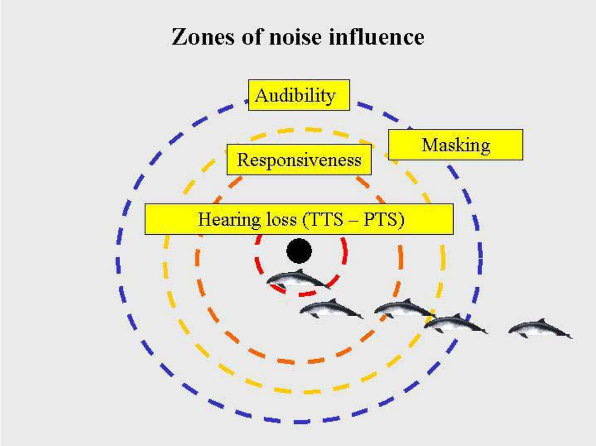


The problems of investigation and study of marine animals is compounded given the inherent difficulties of observing them in their natural environment. Given the above constraints, it is unlikely that the effects of sound on marine animals, particular at the population level, will ever be fully understood or be distinguishable from other influences.

Sound can cause a number of distinct auditory effects on marine receptors, these include either inducing a temporary reduction in hearing sensitivity (termed Temporary Threshold Shift, TTS) which is recoverable with time, or cause a permanent reduction in hearing sensitivity (termed Permanent Threshold Shift, PTS), this is a non-recoverable auditory impact. A number of the impact criteria put forward for marine mammals specify thresholds capable of causing both TTS and PTS. The basic concept in deriving these values is to measure the faintest sound an animal can hear, then expose the animal to a noise stimulus and retest hearing. Measuring the noise just loud enough to cause a temporary reduction in hearing sensitivity gives a conservative estimate of the exposure that could pose a risk of injury if sustained or increased.

Richardson *et al*. (1995) proposed four zones of noise influences that are caused with increasing distance from a sound source, and these are shown in Figure - 3. The zone of audibility is the extent to which the animal can detect the sound signal. The zone of responsiveness is the area which the animal would exhibit either a type of behavioural (such as swimming away) or physiological response. The zone of masking can be variable and is somewhere in-between the zone of audibility and responsiveness and is caused by the sound signal masking or distorting relevant biological sounds (such as communication calls). Closest to the sound source is the area where hearing loss (PTS or TTS) could be possible.

Figure - 3 Zones of Noise Influence from a Point Source (Reproduced from Richardson, *et al*. 1995)



Sound can also potentially induce a range of non-auditory effects, such as damaging body tissues, especially air filled cavities including swim bladder and muscle tissues (reviews in Richardson, *et al*. 1995). However, research and understanding of non-auditory effects of sound on marine receptors is still in its infancy (OSPAR 2009).

A number of oil and gas activities, such as seismic surveys and piling can continue over a considerable duration and be associated with hundreds or sometimes tens of thousands of individual impulses. It has been proposed that it is appropriate to assess cumulative issues relating to the total noise dosage of an activity, rather than only assessing criteria that would be specific to a single impulse (for example, sound pressure level and sound exposure level). Because sound exposure level is a measure of the total energy it is possible to assess cumulative impacts of an ongoing activity (e.g. multiple pulses) by summing individual sound exposure levels to establish a total noise dosage that an animal could receive (Southall, *et al*. 2007). A number of approaches have been put forward for summing total energy, however, there a number of uncertainties regarding cumulative impacts of multiple pulses. One of the principles difficulties is determining the amount of hearing recovery that would be expected to occur in-between individual pulses, as current methods tend to be precautionary and assume no recovery in hearing between exposures (Southall, *et al*. 2007).

This report provides a summary review of the available scientific impact criteria for marine animals and will focus on those criteria that appear to be the most widely accepted or recognised within the scientific community. It is outside the scope of this report to discuss in detail the appropriateness of different impact assessment thresholds, there are already several detailed reviews on this subject, (reviews in Southall *et al* 2007). The approach taken in this report is to compare a number of thresholds, which may be considered within the scientific community as being precautionary. A number of the impact criteria reviewed have different sound threshold levels for 'impact' to marine mammals and the adoption of such metrics could influence the type of oil and gas activities identified as being of potential risk to marine animals.

1.4.1 Marine Mammal Impact Criteria

This section of the report describes briefly the criteria proposed by various authors to assess the impact of underwater sound upon marine species. These criteria are typically used to estimate impact zones around a particular sound source and are often used in combination with the results from underwater sound propagation modelling. Many acoustic metrics (for example, Root Mean Square, Sound Exposure Level (SEL), 0-Peak Sound Pressure Level (0-peak SPL)) could be considered in relation to assessing noise impacts on animals (these metrics are described in detail in Appendix A). There is no 'best' metric associated with the likelihood of causing injury or significant behavioural disturbances across all taxa because of species differences and the fact that real world sound exposures contain many widely differing temporal patterns and pressure signatures.

Impulsive sounds can have very high peak sound pressure levels but carry very little energy (Price and Wansack 1989). Therefore, it is not appropriate to use only one type of metric to establish thresholds at which physical injury is achieved (Masden 2005), as physical damage and impairment of the auditory system is caused not only by the high peak pressure but also the total energy of the sound wave (Finneran, Carder and Ridgway 2002). Consequently, any safety limits or impact thresholds for sound exposure should include both a maximum received energy level, along with a maximum received peak pressure level (Madsen, 2005). This approach would address concerns for physical damage due to short high pressure pulses as well as the effects of longer high energy transients with lower peak pressures. Following a wide scientific review Southall (2007) proposed initial impact thresholds based on a dual metric approach.

The use of Sound Exposure Level (SEL) is based on the assumption that sounds of equivalent energy will have generally similar effects on the auditory systems of exposed subjects, even if they differ in SPL, duration, and / or temporal exposure pattern. However, numerous authors have questioned the predictive power of using a simplistic total energy approach in all conditions, as it fails to account for varying levels and temporal patterns of exposure and recovery amongst other factors, and will likely overestimate the TTS resulting from a complex noise exposure (Hamernik, Qui and Davis 2002; Strasser, Irle and Legler 2003).

A number of marine mammal impact criteria have been developed since the mid 90's. However, these have all been derived from controlled tests with a few captive animals and, as a consequence of not being based on very compelling evidence, are often discussed critically within the scientific community (OSPAR 2009). Also captive enclosure sound exposure experimentation may produce results on individuals that may not be representative of natural open water conditions. Furthermore, it is difficult to establish the variability in responses to noise stimuli and hearing abilities that exists between similar species and individuals. One of the marine mammal impact thresholds discussed below are those put forward by Lucke *et al*. (2009). These were collected from a solitary captive animal which may not be representative of responses from free-ranging harbour porpoises.

In the UK, for oil and gas activities, there is no recommended impact threshold to use in underwater noise impact assessments although a number of different thresholds are used between the industry and accepted by DECC. Recently the JNCC has recommended the use of the Southall *et al*. (2007) criteria when assessing the risk of causing disturbance and injury to European protected species[3] from sound (JNCC 2010 draft).

The UK approach to underwater noise impact assessment is different to other areas of the world, such as marine waters of the United States. In this case noise assessments must be related against specific levels, such as those initially proposed by the National Marine Fisheries Service (NMFS 1995). The level of detail and scope of underwater noise assessment required from the oil and gas industry in other jurisdictions is highly variable, often no mandatory underwater noise assessments are required.

A summary of underwater noise impact criteria is shown below. In cases where the impact threshold has been superseded and amended by an updated impact threshold level then the original threshold has been omitted from this review. An example of this is the Southall *et al*. (2007) criteria which builds upon the impact criteria originally proposed by the National Oceanic and Atmospheric Administration in 2006 which in turn revised the National Marine Fisheries Service (NMFS) impact criteria first proposed in 1995.

1.4.1.1 Southall et al. 2007

Southall and his co-workers produced a comprehensive review of the evidence for impacts of underwater noise on marine mammals, and proposed criteria for preventing injury to individuals based on both peak sound levels and Sound Exposure Level (SEL) and also thresholds for pulsed and non-pulsed sounds (Table 1).

[3] European Protected Species include all cetaceans

As there are always two choices of impact criterion that can be used (Peak or SEL) for any situation, when applying these criteria, Southall recommends to use the more conservative exposure criteria (i.e. whichever criteria is exceeded first).

For whales and dolphins, the criteria set a maximum 0-peak sound pressure level of 230 dB re 1 µPa and a SEL of 198 dB for pulsed sounds, and a maximum SEL of 215 dB for non-pulsed sounds. Data from seals suggest that their auditory system may be affected by lower levels of sound; criteria for them are a maximum of 0-peak pressure level of 218 dB and a maximum SEL of 186 dB for non-pulsed sounds.

In assessing the effects of noise on humans, either A or C weighting curve is applied to correct the sound level measurement for the frequency-dependent hearing function of humans. Southall, *et al*. (2007) took account of the wide frequency dependence in the auditory response of marine species, and proposed M-Weighting frequency functions for low, mid and high frequency hearing cetaceans and pinnipeds. Otherwise extremely low and high frequency sounds that are detected poorly, if at all, might be subject to unrealistic criteria, for example a reduction of 10 deciBels would be applied for a mid-frequency cetacean on exposure to a sound of 100Hz. M-weighting is essentially a simple way of applying a frequency dependant weighting to the hearing threshold of an animal, a more complex approach the 'dBht' is discussed in Section 1.4.1.3.

Figure - 4 M –Weighting Criteria Proposed for Low, Mid and High Frequency Cetaceans and Pinnipeds

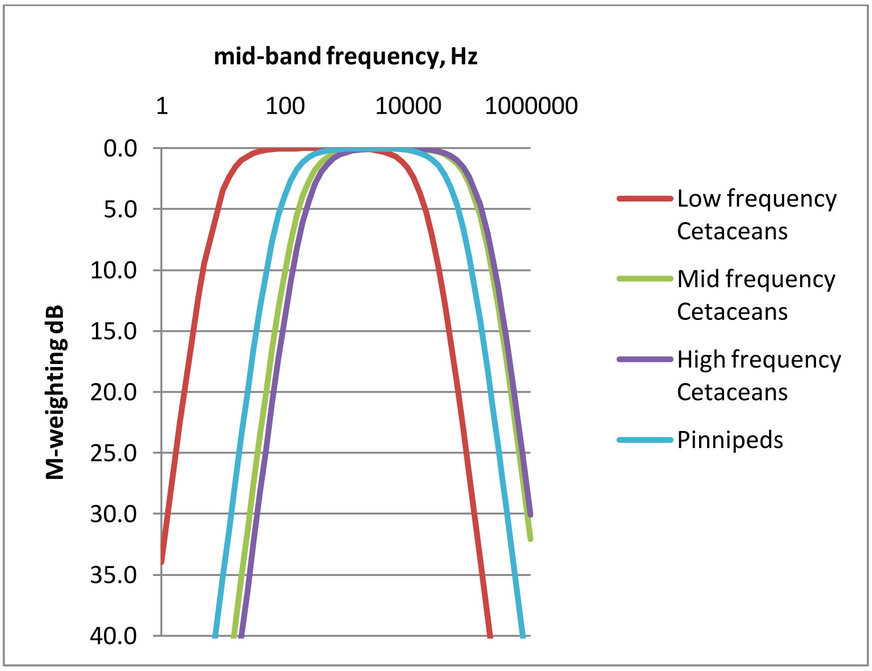


Table 1 Southall *et al.* (2007) proposed injury (PTS) or TTS criteria for functional hearing groups of marine mammals exposed to discrete noise events (either single or multiple exposures within a 24-h period).

Marine Mammal Functional Hearing Group	Sound Type		
	Single pulses (e.g. explosive use)	Multiple pulses (e.g. piling)	Non-pulses (e.g. shipping noise)
Low-frequency Cetaceans			
Sound pressure level	230 dB re: 1 µPa (0-peak)	230 dB re: 1 µPa (0-peak)	230 dB re: 1 µPa (0-peak)
Sound exposure level	198 dB re: 1 μPa^2-s (Mlf)	198 dB re: 1 μPa^2-s (Mlf)	215 dB re: 1 μPa^2-s (Mlf)
Mid-frequency Cetaceans			
Sound pressure level	230 dB re: 1 µPa (0-peak) (flat)	230 dB re: 1 µPa (0-peak)	230 dB re: 1 µPa (0-peak)
Sound exposure level	198 dB re: 1 μPa^2-s (Mmf)	198 dB re: 1 μPa^2-s (Mmf)	215 dB re: 1 μPa^2-s (Mmf)
High-frequency Cetaceans			
Sound pressure level	230 dB re: 1 µPa (0-peak) (flat)	230 dB re: 1 µPa (0-peak)	230 dB re: 1 µPa (0-peak)
Sound exposure level	198 dB re: 1 μPa^2-s (Mhf)	198 dB re: 1 μPa^2-s (Mhf)	215 dB re: 1 μPa^2-s (Mhf)
Pinnipeds (in water)			
Sound pressure level	218 dB re: 1 µPa (0-peak)	218 dB re: 1 µPa (0-peak)	218 dB re: 1 µPa (0-peak)
Sound exposure level	186 dB re: 1 μPa^2-s (Mpw)	186 dB re: 1 μPa^2-s (Mpw)	203 dB re: 1 μPa^2-s (Mpw)

All criteria in the Sound Pressure level are based on the peak pressure known or assumed to elicit TTS - onset plus 6 dB. Criteria in the Sound Exposure level are based on the SEL eliciting TTS-onset plus 1) 15 dB for any type of marine mammal exposed to single or multiple pulses or 2) 20 dB for cetaceans or pinnipeds in water exposed to non-pulses.

1.4.1.2 Lucke et al. 2009 Report

In a series of controlled exposure experiments, Lucke *et al*. (2009) exposed a harbour porpoise to seismic airgun sounds. It was found that TTS was exceeded at a received level of 193.7 dB(0-peak) re 1 µPa and an SEL of 164.3 dB re. 1 μPa^2.s. Aversive behavioural reactions (eg moving away from source) were consistently recorded above 168 dB (0-peak) re 1 µPa and an SEL of 145 dB re. 1 μPa^2.s. It is noted that this work represents the only available data on TTS in harbour porpoises and that the levels proposed by Lucke *et al*. are 24 dB lower than those put forward by Southall *et al*. (2007) for other high-frequency hearing mammals.

The EU Task Group 11 considered the Lucke *et al*. (2009) data but as their results differed considerably from other records the TTS levels for the harbour porpoise were not used in the development of the threshold levels for the noise indicator for loud, low and mid frequency impulsive sounds.

The Lucke *et al*. (2009) thresholds will not be considered further in this review.

1.4.1.3 Nedwell dBht

Nedwell *et al*. (2005) proposed to use the audiogram as a surrogate weighting function for marine species exposed to underwater sound and suggested threshold values for mild and strong behavioural reactions in fish and marine mammals as 'deciBel values above hearing threshold' (termed dBht). Their values indicate received levels above hearing threshold of the receiver and are thus identical to sensation levels (dBA). Yet the absolute audiogram threshold function (audiogram), which their values are reliant on, has not been tested empirically and as such has received very little support within the marine scientific community. However, this is the approach that is essentially applied in human noise impacts and in that respect is strongly validated.

The dBht metric will not be considered further in this review.

1.4.2 Noise Impact Criteria for Other Marine Fauna

There has been considerable research aimed at investing the potential impact of underwater sound to other marine fauna, especially some commercially fished species. However, with the exception of fish with air bladders there are currently no other underwater noise impact criteria for injury.

Popper *et al*. (2006) provided an interim dual noise criterion for injury to fish with air bladders from pile driving noise. A single pulse criterion based on a Sound Exposure Level of 187 dB re 1 $\mu Pa^2.s$ and a peak sound pressure of 208 dB re 1 µPa was proposed by Popper as capable of causing impact to fish (both of these metrics being measured 10 m from the sound source).

Fish species are thought to be more sensitive to particle motion rather than sound pressure, and many of them lack swim bladders which is a primary air filled cavity that can be damaged with pressure fluctuations. As threshold levels for injury from both particle motion and sound pressure have yet to be determined there is a substantial body of work that is needed to further develop impact criteria for fish species and other marine fauna.

In the absence of impact criteria for other types of marine fauna this report will only be able to compare sound levels generated by oil and gas activities in relation to impact criteria that, although potentially appropriate to assess noise risks in other marine taxa, were specifically developed for marine mammals.

2. REVIEW OF OIL AND GAS NOISE SOURCES

The following section details the studies that have measured underwater noise from oil and gas activities. The review separated the activities into those associated with exploration, construction, production and decommissioning. Notable activities that were reviewed in detail were geophysical surveys, with particular emphasis on seismic using airguns, piling of offshore structures during construction and the removal of structures using explosives.

Many studies describing sound pressure levels and subsequent investigations describing potential impacts have been published in non-refereed sources, these are often difficult to evaluate and verify. Often incomplete descriptions are provided as to the methods they followed and there is a tendency to present their results without appropriate metrics and reference units, and details of calibration methods of equipment. Further information on the lack of standardisation in reporting on underwater noise values and the inherent errors associated with underwater noise measurements are discussed in detail in Richardson, *et al*. (1995) and NRC (2005). Consequently a great deal of caution needs to be applied in quoting specific numerical levels.

2.1 EXPLORATION AND GEOPHYSICAL SURVEYING

Geophysical surveys principally use sound to make measurements of the seabed and the sub-seabed. Sound generated from a source travels through the water column and reflects from the seabed, or depending upon how powerful it is, penetrates into the seabed before being reflected back to a receiver. The sound sources can be produced from a variety of different means including; electromagnetic (echosounders, side-scan sonar, pingers boomers and chirp sonar), electrical discharges (sparker) and pressurised airguns (seismic survey).

The principal objective of geophysical surveys performed by the oil and gas industry is the identification of potential hydrocarbon reserves, principally through seismic surveys. Additional types of geophysical survey are performed to map the extent of the discovery and develop the best engineering methods to extract the reserves and identify any potential drilling hazards.

The two fundamental characteristics of the acoustic waves used in geophysical surveys are amplitude and frequency. The properties of the waveform and its power determine how much penetration, and hence information about the seabed layers the waveform will transmit back to the receiver. High frequency low amplitude signals provide high resolution information, but tend to have limited ranges, whereas a low frequency high amplitude signal will travel further into the seabed, but have a lower resolution.

The UKCS is a harsh operating environment to work in with changeable weather patterns and has very variable oceanographic conditions that include shallow coastal waters and deeper waters of the continental slope area. Water depth is one of the main oceanographic parameter that influences the types and configurations of geophysical surveys, and their operational effectiveness.

The terminology used to describe geophysical surveying equipment can vary, but the equipment can be separated broadly into two categories dependent upon the dominant frequency of sound they generate (low or high frequency) (Table 2).

Table 2 Types of Geophysical Equipment and Dominant Operating Frequencies

Geophysical Equipment	Examples	Frequency
Seabed Measuring Sensors	Echosounder Multibeam Echosounder Side Scan Sonar	High
Sub-bottom Profiling Equipment	Pingers Boomers, Chirp Sparkers	High
Exploration Seismic	Airguns	Low

Independent measurements of the noise produced by geophysical surveys measured in the far field are scarce for all sources, with the exception of airguns. The power output level of geophysical surveying equipment is normally specified by giving its source level in dB re1µPa at a distance of 1 metre from the source.

2.1.1 Echosounders and Multibeam Echosounders

Echosounders and multibeam echosounders provide a water depth estimate by emitting pulses of sound that reflect from the seabed. The difference between a multibeam echosounder is that rather than emitting a single beam it produces a fan of beams. Multibeam echosounders can produce high resolution depth profile maps of the seafloor. The typical frequency range of echosounders is from 10-200 kHz. These emit very short (0.2 – 20 millisecond) pulses with a repetition rate that ranges from 4-8 seconds in deeper water to 10 pulses a second for shallower water. Pressure levels are greatest in the 'on axis' direction, which is immediately below the echosounder, or 'along track' for a multibeam echosounder. Pressure levels fall rapidly as beam width increases, with the level being ~20 dB down at twice the beam width (Kongsberg 2005). Various high source levels have been reported ranging from 225-245 dB re 1µPa@1m (SCAR 2005, Kongsberg 2005, Hildebrand 2009), although in each case it was not clear how these had been derived and no measurements were provided in units other than root mean squared (Table 3).

The frequency range of echosounders and multibeam sounders is in excess of the upper limit of the indicator for loud, low and mid-frequency impulsive sounds. There are currently no proposed reporting requirements under the Marine Strategy Framework Directive for these systems that generate high frequency sound.

Table 3 Sound Characteristics of Multibeam Systems

Source Type	Notes	Source Level	Bandwidth kHz	Characteristic	Reference
Multibeam Kongsberg EM 122 (deep water)	Manufacturers specifications	245 dB(rms) re 1µPa @1m	10.5 -13	Pulsed 0.01 ms	(Kongsberg 2005) (Same units also quoted in Hildebrand 2009)
Multibeam Kongsberg (shallow water)	Manufacturers specifications	232 dB(rms) re 1µPa@1m	70-100	Pulsed 0.002 ms	(Kongsberg 2005) (Same units also quoted in Hildebrand 2009)
Multibeam Kongsberg EM 1002	Manufacturers specifications	225 dB(rms) re 1µPa@1m	95	Pulsed 0.2, 0.7, 2 ms	(Kongsberg 2005)

2.1.2 Side-scan Sonar

Side scan sonar system are used in the mapping of upper layers of the seabed. The oil and gas industry uses side scan sonar to map areas of interest to assist in the optimal positioning of infrastructure and to detect and potential seabed hazards. The sound pulses are usually centred at frequencies between 100-500 kHz, the higher frequencies provides a greater resolution but reduces seabed penetration.

The frequency range of side-scan sonar is in excess of the upper limit of the indicator for loud, low and mid-frequency impulsive sounds. There are currently no proposed reporting requirements under the Marine Strategy Framework Directive for these systems that generate high frequency sound.

Table 4 Sound Characteristics of Side Scan Sonar Systems

Source Type	Notes	Measurement Provided	Bandwidth kHz	Characteristic	Reference
Kongsberg Side scan sonar 196D	Manufacturers specifications	220-226 dB (rms)re 1µPa@1m Source level	114 / 455	Pulsed 300-600 µsec	(Kongsberg 2009)

2.1.3 Pingers

In the oil and gas industry pingers and boomers have largely been replaced by more modern forms of survey equipment. Pingers periodically emit a high frequency 'ping' and typically operate on a range of single frequencies between 3.5 - 7 kHz. These devices share a common terminology with acoustic mitigation devices used for the purposes of moving marine mammals away from certain areas, although they both emit a very short duration high frequency ping, they are completely different equipment. Geophysical pingers are used to achieve information from the seabed immediately below the surface layers. Pingers offer a very high resolution but limited penetration dependent upon the seabed sediments a few tens of metres in mud, much less in sand or rock (Philip, Brooks and Hill 2002). It was not possible to obtain any reliable information on measured source characteristics for geophysical pingers.

2.1.4 Boomers

Boomers consist of two plates separated by a coil across which a high voltage impulse is created, the induced magnetic field causes one plate to vibrate and radiate acoustic energy into the surrounding water. Boomers have a broadband acoustic source ranging between 500 Hz - 5 kHz and are used to map the seabed layers between 30 - 100 m depth. There was a considerable variation in the source levels of boomer devices these ranged from 204-227 dB (rms) re 1µPa@1m (Table 5). No information was available as to how the source levels were calculated.

Table 5 Sound Characteristics of Boomer Systems

Source Type	Notes	Measurement Provided	Measurement Bandwidth kHz	Characteristic	Reference
Boomer 350 Joules	Not available	204 dB (rms*) re 1µPa@1m	Not available	Pulse	(NRC 2005)
Boomer plate model 5813B 280 Joules	Manufacturers specifications	227 dB (rms*) re 1µPa@1m	Not available	Pulse 0.2 ms	(Geoacoustic Ltd 2000)
AA301 Boomer	Manufacturers specifications and modelling	209 dB (rms) re 1µPa@1m	0.5-300	Pulse 150-400 ms	(Federal Register 2008) (Applied Acoustics 2010)

*rms values were presumed no units were supplied

2.1.5 Chirp Systems

Chirp systems were designed to replace pingers and boomers, and are now frequently used in oil and gas site surveys in place of the older systems. Chirp systems operate around a central frequency which is swept across a range of frequencies between 3 - 40 kHz. The information available for Chirp systems was derived from technical specifications provided by the manufacturers of such devices. For illustrative purposes, a high resolution deep penetration Geoacoustics sub-bottom profiler specifications are shown in Table 6.

Table 6 Sound Characteristics of Chirp Systems

Source Type	Notes	Measurement provided	Measurement bandwidth kHz	Characteristic	Reference
GeoChirp II Sub-bottom profiler	Manufacturers specification	202-208 dB (rms)re1µPa@1m	1.5-13	Pulse 32 ms	(Geoacoustics Ltd 2008)

2.1.6 Sparkers

Sparkers, in a similar way to boomers use an electrical discharge to generate sound. A high voltage impulse generates a spark across a pair of electrodes forming a gas bubble whose oscillations generate the sound. Sparkers are powerful devices and can be used to penetrate seabed layers upto 1 km. Sparker systems were used frequently in the past for geophysical investigations, but their use today is infrequent, especially for North Sea oil and gas surveys. Only one study conducted by Nedwell (1994) measured the peak pressure from a sparker under laboratory conditions, no additional field or laboratory studies were identified. Manufacturers specifications were provided for two commercially available sparkers (Squid 500 and Squid 2000) no details were provided as to how these source levels were calculated (Table 7).

Table 7 Sound Characteristics of Sparker Systems

Source Type	Notes	Measurement provided	Peak level	Peak to Peak level	Measurement bandwidth	Characteristic	Reference
Sparker 8kV	Laboratory tank used	0.4 x 10^5Pa@0.25m (peak)	180 dB re1µPa@1m	Unknown	0-300 kHz	Pulsed source	(Nedwell 1994)
Sparker Squid 500	Manufacturers specifications	216 dB (rms**) re1µPa@1m (source level)	Not available	224*	Not available	Pulsed source	(Applied acoustics 2010; Wyatt, 2008)
Sparker squid 2000	Manufacturers specifications	222 dB (rms**) re1µPa@1m (source level)	Not available	Not available	Not available	Pulsed source	(Applied acoustics 2010)

*Extrapolated peak-peak level provided in Wyatt (2008)
**rms values were presumed no units were supplied

2.1.7 Airguns

All recent marine seismic surveys carried out by oil and gas industry have used airguns as their sound source. An airgun consists of two chambers, the first chamber is fed air at pressure typically between 2000 - 2500 psi from an air compressor onboard the seismic vessel. An electrical signal triggers the opening of a valve within the airgun which causes the release of the pressurised air within the chamber to the sea. The bubble formed by the release of air oscillates according to the operating pressure, the depth of the airgun, water temperature and the volume of air released into the water.

In exploration surveys for the oil and gas industry individual airguns are arranged within an airgun array consisting of multiple guns. Airgun volume is measured in cubic inches and typical volumes of guns used in exploration vary from 20 - 800 cubic inches, whereas the total volume of the array can typically be between 2000 - 9000 cubic inches. Total energy source volumes vary from survey to survey and are designed to provide sufficient seismic energy to meet the geophysical objectives of the survey. Guns are often arranged into clusters, this causes the individual guns to act together and behave as a larger gun, and also helps to improve the characteristics of the signal (Caldwell and Dragoset 2000).

Airguns are designed to emit a vertical beam of sound towards the seabed, it is not the intention to radiate sound out from other angles. It is important to realise that most of the measurements of underwater noise have been obtained at some distance away from the source, thus not directly measuring the main beam of the airgun array but the side lobes and reflections of the main beam from the seabed and the sea surface which may be larger than the direct arrival in the horizontal axis (Wyatt 2008). Patterson (2007) measured received levels of seismic noise at different locations in relation to the source positioning and found little aspect dependence on the received levels of sound when measured using a bottom mounted hydrophone. Peak levels were found to be greatest when the hydrophone was located in front of the survey vessel 266.4 dB (0-peak) re 1µPa@1m in comparison to stern 249.8 dB (0-peak) re 1µPa@1m or broadside 253.5 dB (0-peak) re 1µPa@1m measurements.

There are two main types of seismic surveying with each type having several variants, these are 2 dimensional (2-D) and 3 dimensional (3-D) surveys. In 2-D surveys a single streamer and airgun array is towed behind a vessel, this effectively produces a two dimensional image of the subsurface. A 3-D survey uses two airgun arrays to produce a three dimensional image of the subsurface, these surveys are considerably more expensive than 2-D surveys and are conducted after a 2-D survey has identified a prospect of geological interest (IAGC, 2002). Another type of survey is 4-D, this is essentially a repeat of a 3-D survey but with time as the only variable, a 4-D survey allows for the investigation of how a reservoir has changed upon development and allows for accurate reservoir management.

Rather than tow hydrophones behind a survey vessel, in Ocean Bottom Cabling (OBC) the hydrophones are laid on the seafloor and the airgun array is towed above these in either a 2-D or 3-D configuration. This is becoming increasingly common practice to accurately monitor reservoir depletion.

Prior to the drilling of a well in the UKCS, there is both a legal and operational need to obtain detailed information about the seabed in the area immediately surrounding the well location and the geological layers immediately below the subsurface. The resolution from other forms of seismic survey is not sufficient enough to be able to identify potential hazards, such as shallow gas, so high resolution 2-D 'site surveys' are performed. The source volumes used are relatively small and are typically in the region of 160 cubic inches and consist of a four gun cluster. Occasionally smaller airguns are used in site surveys such as the 'mini-airgun' which has a very small volume 10 cubic inches and is fired individually.

Upon drilling a well, in order to complete a Vertical Seismic Profile (VSP) geophones are lowered into the well and a seismic source is either lowered over the well (from a drilling rig or platform) termed zero-offset VSP, or from a source vessel which travels away from the well, known as offset VSP. Source volumes are generally smaller (~500 cubic inches) than conventional surveys, but larger than site surveys. The duration of these surveys is typically short with data acquisition taking approximately 1-2 days.

The pressure signature of an individual airgun consists of a sharp rise and then fall in pressure, the downward directed pressure pulse lasts only 10-20 ms with only one strong negative and one strong positive peak pressure created (Caldwell and Dragoset 2000). Airguns generate high levels of low frequency sound, the oscillating bubble generated by airguns produces 90 per cent of its energy in the frequency band 70 - 140 Hz (Van de Sman 1998). Airguns are oriented towards the seafloor so that the low frequency sound waves can travel through the subsurface layers. The emitted sound pressure amplitude is proportional to the cube roots of the individual airgun volumes, increases with air pressure at firing and is proportional to the number of guns in an array (Caldwell and Dragoset 2000).

The levels of noise measured around the airguns is dependent upon the airgun array configuration and the local ocean conditions (DeRuiter, *et al*. 2006). The sound propagation is also dependent upon the oceanographic conditions and will vary between areas with differing conditions, therefore in order to have accurate modelling it is important to have a detailed knowledge of the geographic and oceanographic parameters.

Measurements were provided of single airguns with volumes of 40 cubic inches to 18 gun arrays with volumes of 3955 cubic inches. Sound pressure levels recorded increased with gun volume and these ranged from 186-271 dB (peak-peak) re 1µPa@1m (Table 8).

2.1.7.1 Frequency Spectrum of Airgun Sounds

Only a few studies have been published which have described the spectral properties of received airgun signals up to several kilohertz frequency (Goold and Fish 1998, Tolstoy, *et al*. 2004, DeRuiter, *et al*. 2006, Madsen, *et al*. 2006, Breitzke, *et al*. 2008). These studies have suggested that under certain environmental conditions high frequency components emitted from the airguns may propagate horizontally with sound pressure levels and spectral density levels that cannot be explained by simple geometric spreading laws.

Such environmental conditions were probably present in the shallow coastal environments of the Irish Sea where Goold and Fish (1998) found that airguns produce energy above background noise up to frequencies in excess of 22 kHz at range of 2 km and frequencies in excess of 8 kHz at ranges of 8 km. In a deep water locality in the Gulf of Mexico during a controlled exposure experiment a high speed shallow surface duct in the water column was found to permit the propagation of high frequency elements with relatively little transmission loss (Madsen, *et al*. 2006) and the high frequency elements were found to be absent when the surface duct was not present.

The observation that certain environmental conditions may favour propagation of high frequency elements is of particular importance to consider when assessing potential impacts of airgun signals on marine fauna sensitive to such frequencies.

Other environmental factors which influence the frequency spectrum generated by the airguns will be dependent upon the depth at which they are deployed. To provide an optimal frequency spectrum for mapping of seabed layers, whilst minimising acoustic impedance caused by the air water interface, the arrays depth is usually set to between 5-7 m.

Gun design and configuration also influence the frequency spectra with smaller guns emit higher frequencies and larger guns emit lower frequencies (Jones 1999).

The majority of energy produced by the airguns is contained in the low frequency component, these frequencies have been found to travel considerable distances with seismic surveys conducted offshore Brazil being detectable in the mid Atlantic Ocean 3000 km away.

2.2 OGP Sound and Marine Life Programme

The Exploration and Production Sound and Marine Life Programme aims to conduct a research programme to fill gaps in the knowledge about the effects of sound generated by exploration and production activities on marine fauna. A number of current research projects are applicable to this study including 3D seismic source characterisation study and single/airgun measurements and source modelling. Despite these studies having been carried out several years ago the results are not yet published (John Campbell, OGP, pers. comm.).

Table 8 Single Airgun and Airgun Array Sound Pressure Level and Sound Exposure Measurements.

Source Type	Volume Cubic inches	Pressure psi	Water depth m	Measurements Provided: Rms dB re 1µPa@1m (unless stated)	Peak- Peak level dB re 1µPa@1m (unless stated)	0 Peak dB re 1µPa@1m (unless stated)	SEL dB re $1\mu Pa^2$@1m	Measurement bandwidth kHz	Reference
Airgun single	40	Not available	15	129dB re 1µPa@5km	186*	Not available	Not available	0.020- 20	(Greene and Richardson 1988)
Airgun Bolt gun	40	1500	'Shallow'	191	200*	Not available	Not available	Not available	(Nedwell and Edwards 2004)
		2000		193	202*	Not available	Not available	Not available	
Gas Injector Airgun Non –GI mode	103	2755	263	216	229	224	202	0.005-80	(Breitzke, *et al*. 2008)
Array 4 guns	280 (4 x 70 inch guns)	Not available	48	Not available	249	242.7	Not available	0.005-20	(Patterson, *et al*. 2007)
Array	330	Not available	34	167 dB re 1µPa@ 3km	226*	Not available	Not available	0.005-20	(Greene and Richardson, 1988)
Array GI Guns Non-GI mode	452	2755	263	224	236	231	210	0.005-80	(Breitzke, *et al*. 2008)
Array GI Guns True GI mode	452	2755	263	225	241	238	211	0.005-80	(Breitzke, *et al*. 2008)
Airgun Single	518	2030	263	221	237	234	207	0.005-80	(Breitzke, *et al*. 2008)
Array 8 guns	1049	2000	42	260.4	266*	Not available	Not available	0.005-20	(Patterson, *et al*. 2007)
Array 3 Sercel G-guns	1150	1950	3860	225	Not available	235.7	Not available	0.072 (peak Hz) 0.005-100	(Roth and Schmidt 2010)
Array 8 VLF Prakla seismos guns	1464.5	1740	263	228	243	240	214	0.005-80	(Breitzke, *et al*. 2008)
Array 3 G-Guns	1562	2030	263	227	241	237	213	0.005-80	(Breitzke, *et al*. 2008)
Array 12 Guns	1709	Not available	20	179	233*	Not available	Not available	0.020- 20	(Greene and Richardson 1988)
Airgun single	2000.5	1885	263	230	242	239	216	0.005-80	(Breitzke, *et al*. 2008)
Array 24 Guns	3147	2000	42	266.4	272*	Not available	Not available	0.005-20	(Patterson, *et al*. 2007)
Array 18 guns	3955	Not available	100	262.9	271*	Not available	Not available	Not available	(Nedwell,2004)

*Conversion from measurement value to peak-peak performed by Wyatt (2008)

2.3 Explosives

Upon cessation of production oil and gas structures should be removed, where possible, from the seabed according to OSPAR recommendations and DECC licence conditions. The majority of oil and gas infrastructure that needs to be removed are cylindrical metal structures that protrude from the seabed, such as wellheads and platform legs. Explosives provide a quick and reliable way to detach structures that are firmly anchored or difficult to access using cutting methods. Historically, explosives were frequently used in the deeper waters of the central North Sea and northern North Sea to remove oil and gas infrastructure, although their use today has decreased with the rise of alternative cutting techniques such as tungsten-carbide blade cutters, diamond wire and hydraulic sheer cutters. As the offshore oil and gas industry further matures and the scale of decommissioning increases then it is possible that explosive use will also increase. Even if explosives are not the preferred tool their use is often included within decommissioning plans as a contingency measure in case the mechanical cutting is unsuccessful.

Other explosives used by the oil and gas industry 'downhole' that are not expected to generate levels of underwater noise that would be any cause for concern, such as well casing perforation explosives (used within the well reservoir) have not been considered in the review.

2.3.1 Types of Explosive Charge

There are three main groups of explosive charges used to remove oil and gas equipment, these are: bulk charges, configured bulk charges and cutting charges.

Bulk charges, examples being Comp-B and C-4, are the most commonly used technique for explosive cutting. These types of explosives are readily mouldable and have high velocity on detonation and high shattering power.

Configured bulk charges, such as ring charges and focussing charges are designed to collide or focus the detonation front to concentrate more energy along the fracture line, and thus reduce the size of the explosive charge required.

Cutting charges include linear shaped charges and cutting tape. Linear-shaped charges use high velocity explosive energy to accelerate a v-shaped band of cutting material usually copper, in a high velocity jet that penetrates through the material. It can be effective in cutting through steel. Explosive cutting tape is a flexible version of the linear shaped charge.

2.3.2 Sound Characteristics of Explosive Charges

Explosive sources produce broadband frequencies with very high peak source levels and rapid rise times. Due to the interest from military applications a substantial amount of research effort has been given to the study of sound characteristics generated by chemical explosives.

For unconfined (open water) TNT charges in deep water the values of peak pressure and impulse have been determined by systematic experiments and can be derived using the explosive scaling laws (reproduced from Barrett (1996)).

Peak pressure (Pmax) $= 5 \times 10^{7}\, W^{0.27}\, R^{-1.13}$ (Units Pascal)

Impulse (I) $= 6 \times 10^{3}\, W^{0.63}\, R^{-0.89}$ (Units Pascal/Second)

Where W is the charge weight in kilograms and R is the range from the explosive source in metres. As these calculations were derived from military experiments involving deep water applications they are not necessarily applicable to shallow water areas where a considerable proportion of the oil and gas industry in the UKCS is located.

For decommissioning purposes explosive charges will not be freely suspended in the water column. Depending upon the type of decommissioning taking place, explosives will be either contained within, or resting on the structure to be detonated and often positioned below the seabed level. Positioning charges within the seabed will greatly change the pressure wave, specifically the pressure level generated is lower and the higher frequency components are lost. Nedwell and Edwards (2004) have provided formulae for calculating peak pressure and impulse based on their measurements of confined charges where:

Confined charges:

Peak pressure (Pmax) $= 2.5 \times 10^{6}\ W^{0.27}\ R^{-1.13}$ (Units Pascal)

Impulse (I) $= 1.8 \times 10^{3}\ W^{0.63}\ R^{-0.89}$ (Units Pascal/Second)

The source level and frequency components of chemical explosives can be predicted if certain parameters are known, these being charge weight (w) and depth of detonation. The zero-peak (0-peak) source pressure level of the initial shock wave, the largest amplitude component in the decay time series, is given by the formulae:

Source Level (0-peak) dB re 1µPa@1m = 271 dB + 7.533log(w) (Urick 1975)

Where w is the weight of the explosive charge. The source levels from explosive detonations are the largest sounds generated by anthropogenic activities and can have sound pressure levels typically from 272-287 dB (0-peak) re1µPa@1m or greater. Shock waves created by different high explosives can have slightly different pressure/time/distance/depth relationships and caution should be applied when applying generic formulae to estimate potential safe ranges at which impacts to marine animals will be avoided.

The underwater transmission of explosive sounds is complex, upon initiation of a detonation there is the shock pulse, followed by a succession of oscillating bubble pulses. Depending upon the energy of the detonation these oscillating bubbles will contribute additional energy to the overall source level. Bubble pulses occur as a result of the hot gases associated with an underwater explosion forcing back the surrounding mass of water, the momentum of this force causes a bubble to be formed that exerts force on the surrounding water pressure, this causes a series of expansions and collapses and results in a series of secondary pressure waves (Nedwell and Edwards 2004). During the decommissioning of a hydrocarbon production platform in the Gulf of Mexico it was found that all the bottom severance detonations produced a direct shock wave pulse and a pulse from the bubble oscillations, the peak overpressure of the direct shock wave was between 2-10 times greater than the bubble pulse (Connor 1990).

The initial wave front contains much of the high frequency energy of the blast wave, and consequently has a much higher acoustic pressure, the secondary pulses produce a longer duration waveform with significant low frequency energy components. Explosions generate low frequencies 2-1000 Hz with the main energy between 6-21 Hz and have very rapid durations <1ms-10ms (Richardson, *et al*. 1995; NRC 2005).

2.3.3 Wellhead Decommissioning

The decommissioning of wellheads in the North Sea has provided an opportunity to collect information on the acoustic signatures of explosive and the results of a decommissioning campaign have been reported in Nedwell (2001). Measurements of sound pressure were taken at two locations from the explosive operation, these being the *CSO Seawell*, when it moved to its standoff position (which ranged from 600-800 m from the wellhead), and from an underwater seabed mounted hydrophone (termed a ‘slave station’). The variability in the sound pressure levels recorded for similar size charges at comparable ranges are typical of the variability that exists when recording measurements of underwater explosions. The highest sound pressure level recorded for a 45 kg charge detonation recorded by the slave station was 232 dB (0-peak) re1µPa and was recorded at a distance of 300 m (Table 9 & 10). The results below are interesting in that the peak pressure of the charges were similar to the values predicted for unconfined (open water) detonations and this implied that the pipe work surrounding the charge and the sediment below which the charge detonated, did not act as an effective confinement for the charge. Nedwell and Edwards (2004) suggested that the explosive energy will couple effectively into the sediment adjacent to the pipe, due to it being of comparable density, and hence energy will be able to couple as well into the water for explosives detonated within wellheads as it would when fired in an open water setting.

Table 9 Sound Pressure Levels (0-Peak) recorded from the detonation of 45 kg explosive charges measured from a seabed mounted hydrophone at varying water depths (84-116 m) and ranges from explosion (75-400 m), reproduced from Nedwell, *et al*. (2001).

Range m	Charge Size kg	Depth of hydrophone (slave station)	Received level (0-Peak) dB re1µPa@range
75	45	116	227 dB re1µPa @75
125	45	87	226 dB re1µPa @125
200	45	110	225 dB re1µPa @200
300	45	91	232 dB re1µPa @300
300	45	84	230 dB re1µPa @300
400	45	108	223 dB re1µPa @400

Table 10 Sound Pressure Levels (0-Peak) recorded from the detonation of explosive charges (36-81 kg) measured from the CSO Seawell at varying water depths (25-40 m) and ranges from explosion (575-800 m) adapted from Nedwell, *et al*. (2001).

Range m	Charge size kg	Depth of hydrophone	Received level (0-peak) dB re1µPa @range
650	36	30	221 dB re1µPa@650m
650	36	25	222 dB re1µPa@650m
800	36	30	221 dB re1µPa@800m
575	45	30	211 dB re1µPa@575m
575	45	25	211 dB re1µPa@575m
600	45	40	213 dB re1µPa@600m
600	45	35	214 dB re1µPa@600m
600	45	30	214 dB re1µPa@600m
600	45	25	214 dB re1µPa@600m
650	45	40	216 dB re1µPa@650m
650	45	35	218 dB re1µPa@650m
650	45	40	218 dB re1µPa@650m
650	45	35	217 dB re1µPa@650m
650	45	40	221 dB re1µPa@650m
650	45	35	217 dB re1µPa@650m
650	45	40	221 dB re1µPa@650m
650	45	35	221 dB re1µPa@650m
650	45	30	218 dB re1µPa@650m
650	45	25	217 dB re1µPa@650m
600	73	30	220 dB re1µPa@600m
650	73	25	226 dB re1µPa@650m
600	81	30	220 dB re1µPa@600m
600	81	25	226 dB re1µPa@600m

2.4 Drilling and Production

A number of studies have measured the noise generated from drilling and production activities from mobile drill rigs and platforms. The majority of these studies only record measurements in the near field and have not been able to calculate source levels. As the noise generated from drilling and production noise is a continuous type sound, the units of measurement typically recorded have been root mean squared.

Offshore exploration rigs that operate in the UKCS include drill ships, semi-submersibles and jack-up drilling rigs. The most common type of mobile drilling vessel is the jackup with 363 vessels operating worldwide, there are fewer semi-submersibles and drill ships in operation, totalling 169 and 50 respectively (Rigzone 2010).

Underwater sound is generated from drilling and production platforms through the transmission of the vibrations of the machinery and drilling equipment such as pumps, compressors and generators that are operating on the platform. Drill ships and some types of semi-submersible maintain position using dynamically positioned thrusters. Where the drilling rig or production platform is reliant upon support and supply from other standby and supply vessels these are often equipped with dynamically positioned thrusters and powerful engines and therefore contribute towards the overall noise level of drilling and production activities.

Conventional fixed production platforms are numerous in the UKCS with many of the larger platforms also having a drilling capability. There are currently 289 oil and gas platforms in the UKCS, of which 149 are manned and 140 normally unmanned (DECC 2010). Fixed drilling platforms are either steel or concrete structures and their size is dependent upon the field properties and amount of machinery required to process production fluids. Underwater noise produced from platforms standing on metal legs would be expected to be relatively low given the small surface area for sound transmission and given all the machinery is located above the waterline.

Sound levels from a drillship are typically higher than those produced from a drilling platform, as all the machinery is contained within the hull and it has a large surface area with which to radiate out into the water column and as drillships use dynamic positioning. Drillships have been reported to produce higher sound levels than semi-submersible drilling rigs, with maximum sound pressure levels of 195 dB (rms) re 1µPa@1m having been reported. With the exception of drill ships the sound levels produced by other forms of offshore drilling are relatively low levels and are predominantly low frequency (refer to Table 11)

One of the most extensive studies of sound from production and drilling platforms was made by Gales (1982) who took measurements from 11 types of platform in operation off California. It was observed that during production operations all the tonal sounds detected were of low frequency typically 5 - 38 Hz, with the highest frequency tones recorded being 100 - 500 Hz.

During periods of drilling other types of equipment, such as the turntable, will be in operation, in addition to the standard machinery such as generators and pumps which would operate at a higher power than non-drilling periods. The operation of additional equipment at higher energy levels changes the level of noise and tonal frequencies transmitted into the water column during drilling periods. A review of the sounds produced from the three main types of mobile drilling unit is provided below.

2.4.1 Semi-Submersibles

Semi-submersibles are rig types most commonly used in the deep waters of the North Sea. Semi-submersibles are a floating platform type drilling rig which uses pontoons that are partially submerged in the water. Although no studies were found that reported noise measurements from semi-submersibles in UK waters, the sound from a SEDCO 708 drilling in water 114 m deep in the Bering Sea was measured by Greene (1986). At a distance of 1 km away from the drilling location the broadband noise did not exceed ambient noise, although some weak tones were detected to a distance of 18 km away. The drilling source level was estimated to be 154 dB re1µPa@1m in the broadband frequency levels of 10 - 500 Hz and 80 - 400 Hz.

McCauley (1998) measured noise from the *Ocean General* in the Timor Sea during periods when the rig was drilling and not drilling. During non-drilling periods the typical broadband level encountered was ~113 dB (rms) re 1µPa@125m with various tones from the machinery observable in the noise spectra. There was significant variation in the broadband noise during non-drilling periods this was attributed to the operation of specific types of machinery. During drilling periods the broadband noise level increased to the order of 117 dB (rms) re1µPa@125m which was an approximate 4 dB increase compared to the non-drilling recorded levels.

Measurements of a semi-submersible drilling rig *Jack Bates* in deep water northwest of the Shetland were made when the rig was drilling and on location (reported in Nedwell and Edwards 2004). During both drilling and non-drilling periods there was a peak noise level at about 10 Hz with other low frequency tonal signals being detected in the range 10 - 600 Hz. It was found that the use of dynamic positioned thrusters, and the associated cavitation noise, caused a significant elevation of the low frequency sounds from 3 - 30 Hz. It would be reasonable to predict that the sound levels produced from semi-submersibles that use dynamic positioning would be greater than those that are only positioned by anchors and chains. However, the anchor handling vessels would contribute to the sound levels associated with drilling activities.

2.4.2 Jackup Drill Rigs

Jack up drill rigs do not use any form of anchor and are positioned using large spud cans which are 'jacked up' into the seabed. Jackup drilling rigs are used in shallower waters in the UKCS, typically in water depths of less than 100 m. A jackup rig generally consists of three steel legs attached to a platform deck containing the drilling equipment, machinery and accommodation units. The platform deck is buoyant and floats on the sea surface when the legs are raised, this allows it to be towed by tugs to the drill location. There is no propulsion on jackup rigs. To position the jackup on the seabed the three legs are lowered until the spud cans establish a firm contact, at the same time the platform rises from the sea surface. No studies were available that measured the sound levels from jackup drilling rigs, although it is expected that sound levels generated would be similar to those arising from steel production platforms.

2.4.3 Drill Ships

In the UK, drill ships are most likely to operate in deeper waters found on the western side of the continental shelf. The drillship contains the rig generators, drilling machinery, and the rig itself. The hull is in constant contact with the water surface and provides good acoustic coupling to the water this allows the transfer of sound energy easily.

Measurements were taken from the drill ship *West Navion*, during normal operations and during drilling in deepwater west of the Hebrides (Nedwell and Edwards, 2004). A series of measurements were taken at a range of water depths and distances from the drill ship. However, the authors did not indicate what equipment was in operation during the measurement or distinguished recordings made during periods of drilling and normal operations. The predominant frequencies were broadband and in the range 100-400 Hz and the source level was 195 dB (rms) re 1mPa @ 1m. Beyond a distance of 5 km the noise from the *West Navion* had fallen below background noise levels.

Table 11 Sound Levels Measured from Different Types of Drilling Platform during Periods when Drilling and not Drilling

Source type	Activity	Depth of hydrophones m	Measurement provided	Measurement bandwidth kHz	Characteristic	Reference
Drill Ship – converted freighter	Logging	17	125 dB (rms) re 1µPa@170m	0.02-1	Continuous tones up to 1850 Hz	(Greene 1987)
	Drilling	27	134 dB (rms) re 1µPa@200m	0.02-1	Continuous strong tones at 277 Hz	
Drill Ship '*West Navion*' 250m long	Drilling	50, 100 & 200	195 dB (rms) re 1µPa@1m	0.001-139	Continuous low frequency 100-400 Hz band	(Nedwell and Edwards 2004)
Semi-Submersible	Active not drilling	110	117 dB (rms) re 1µPa@125m	0.01-10	Continuous low frequency	(McCauley 1998)
	Drilling	110	115 dB (rms) re 1µPa@405	0.01-10	Tones produced from drill string in low frequency bands <70 Hz	
Platform	Drilling, production and water injection		162 dB (rms) re 1µPa@1m	0.01-10	Broadband noise	(Hannay, *et al*. 2004)

2.5 Construction Activities

Construction activities involve the placing of some form of equipment or structure onto the seabed and the installation of topside equipment, such as platforms. There are a variety of different types activities that are associated with construction by the oil and gas industry, the main types being: piling of structures, dredging, trenching and rock placement. Invariably offshore construction involves a variety of different types of vessels including heavy lift, barges, pipelay, anchor handling and support vessels. For many types of oil and gas construction activities the principal noise sources will be those associated with the vessels themselves and not the specific activity. The noise from vessels involved with marine construction activities of the oil and gas industry are reviewed in Section 2.7.

2.5.1 Piling

Piling is required to fix subsea structures into the seabed such as manifolds and platform legs. The size of piles required are dependent upon a number of factors including the size of the structure to be installed and seabed conditions.

Piling involves the repetitive striking of metal piles by a hammer to drive them into the seabed, these are usually hollow metal structures but can also be sheet or solid pins. Piling noise is characterised by a waterborne impulse which has a rapid rise time. Depending upon the type of pile driver used there may be other pathways for the sound to propagate from including the sediments and airborne noise, especially if the pile driver is located above the waterline.

Different types of pile diameter, driven in by different techniques into variable seabed conditions have been found to give rise to a wide range of sound levels. Consistent with other forms of underwater measurements, there appears to be a considerable variability in the measurements received from comparable sized piles (Table 12). Sound pressure levels in impact pile driving are dependent on the length and diameter of the pile and impact energy (Nedwell, *et al*. 2003). The diameter of the pile installed is one of the key variables in terms of determining the levels of underwater sound that will be generated.

A number of different formulae have been put forward to estimate the source level if the diameter of a pile is known:

Sound Pressure Level (peak-peak) = 230.25 *$D^{0.0774}$ (Wyatt 2008)

Sound Pressure Level (peak-peak) = 24.3D + 179 (Nedwell, *et al*. 2005)

Where D is the diameter of the pile in metres and the units are dB re 1µPa@1 metre. Neither of these equations have been validated and are based on relatively few measurements of pile driving and are therefore only able to provide indicative predictions of potential sound levels. The formulae put forward by Nedwell overestimates sound pressure levels for larger diameter piles, for example a 5 m pile would produce a sound pressure level of 300.5 dB (peak-peak) re 1µPa @1m (the author is aware of the limitations of the formulae for larger diameter piles).

The majority of recent measurements of underwater sound produced by pile driving has been the result of research carried out by the renewable energy industry (Nedwell *et al*. 2007). As the diameter of the piles driven to install wind turbines overlap with some of the larger sizes of pile used for certain oil and gas applications, it is a useful source of information to review for comparative purposes.

Pile driving generates predominantly low frequency sound within the range of 100-400 Hz, although there are also tones above 1 kHz produced (ITAP 2005 presented in Thomsen, *et al*. 2006). The duration of the pulse is relatively rapid showing both a peak positive pressure and negative pressure. The duration of the pressure pulse associated with a hammer strike has been shown to increase with range from the pile (Blackwell, *et al*. 2004).

Sound measurements are available for piles with diameters ranging from 0.75- 4.7 m. The largest measurement recorded (not modelled) was 205 dB (0-peak) re 1µPa @30m for a 1.5 m diameter pile. For many of the pile driving measurement the authors did not calculate source levels, for those measurements available the source levels ranged from 210 dB (0-peak) re 1µPa @1m (for a 0.75 m pile) to 257 dB (0-peak) re 1µPa @1m (for a 4.2 m pile). The largest diameter pile did not have the highest source level, a number of factors could be attributed to this including, but not limited to, strike energy of the pile driver, seabed conditions and oceanographic factors. The sound measurements that are available for a number of hammer piling activities are shown in Table 12 and are arranged in relation to increasing pile diameter.

Table 12 Sound Characteristics of Impact Pile Driving

Piling location and type of pile driving	Pile diameter m	Water depth m	Measurements recorded - dB re1µPa @ range	Peak Spectral Level Hz	Sound Exposure Level dBre1µPa^2@range	Measurement Range kHz	Source Level dBre1µPa@m	Reference
Oil and gas construction 'hot-tap' operation	0.75 (100m long)	95	153 dB rms @0.535m 168 dB (0-peak) @ 0.535m	~200 Hz	Not available	Upto 120 kHz	210 dB (0-peak) re 1µPa@1m	(McHugh, McLaren and Hayes 2005)
Port Construction, 2005	0.9	11	188 dB (0-peak) re 1µPa @340m	Not available	162 dB re 1µPa^2@340m	Not available	Not available	(ITAP 2007)
Port Construction, 2005	1.0	11	190 dB (0-peak) re 1µPa @340m	Not available	164 dB re 1µPa^2@340m	Not available	Not available	(ITAP Unpublished, 2008) (results presented in ITAP 2007)
FINO research platform Germany Pile installation, 2003	1.5	~30	179.5 dB (0-peak) re 1µPa @400m (broadband)	125 Hz	162 dB re 1µPa^2@400m (1/3rd Octave Bands)	0.03-20	228 dB (0-peak) re 1µPa@1m	(ITAP 2005 presented in Thomsen, *et al*. 2006)
Beatrice Windfarm, Moray Firth Scotland	1.8 m (x4 piles for steel jacket)	>42	205 dB (peak-peak) re 1µPa @100m (broadband)	Not available	166 dB re 1µPa^2@400m (M-weighted SEL)	1Hz- 170kHz	250 dB (peak-peak) re 1µPa@1m	(Bailey, *et al*. 2010)
Alpha Ventus, 2008, windturbine	2.7	28	197 dB (0-peak) re 1µPa @1100m	Not available	199 dB re 1µPa^2@1100m	Not available	Not available	(Betke and Matuschek 2008)
Sky 2000, wind turbine 2002	3	21	196 dB (0-peak) re 1µPa @260m	Not available	170 dB re 1µPa^2@260m	Not available	Not available	(ITAP 2004)

Utgrunden, Sweden wind turbine, 2000	3	10	205 dB (0-peak) re 1µPa @30m (broadband)	250 Hz	140 and >180 dB re1µPa^2 @30m (1/3rd Octave Bands) (Varied between values)	0.04-16	Not available	(McKenzie-Maxon 2000)
FINO II research platform Germany, 2006	3.3	24	190 dB (0-peak) re 1µPa @530m	Not available	170 dB re 1µPa^2@530m	Not available	Not available	(ITAP 2007)
Amrumbank West, wind turbine, 2005	3.5	23	196 dB (0-peak) re 1µPa@ 850m	Not available	174 dB re 1µPa^2@850m	Not available	Not available	(ITAP 2007)
Horns Rev II, 2008	3.9	12	195 dB (0-peak) re 1µPa @720m	Not available	172 dB re 1µPa^2@720m	Not available	Not available	(ITAP 2008)
North Hoyle wind turbine, 2003	4	10 - 15	198 (p-p) dB re 1µPa @955m	Not available	Not available	Not available	249 (p-p) 243 (0-peak)*	(Nedwell, Parvin, *et al.* 2007)
Scroby Sands wind turbine	4.2	3 - 30	Not available	Not available	Not available	Not available	257 (p-p) 251 (0-peak)*	(Nedwell, Parvin, *et al.* 2007)
Kentish Flats wind turbine	4.3	5 - 8	Not available	Not available	Not available	Not available	243 (p-p) 237 (0-peak)*	(Nedwell, Parvin, et al. 2007)
Barrow wind turbine	4.7	10 - 20	204 (p-p) dB re 1µPa @500m	Not available	Not available	Not available	252 (p-p) 246 (0-peak)*	(Nedwell, Parvin, *et al.* 2007)
Burbo Bank wind turbine	4.7	7 - 24	Not available	Not available	Not available	Not available	249 (p-p) 243 (0-peak)*	(Nedwell, Parvin, *et al.* 2007)

*Source level (Zero-peak) calculated by subtracting 6 dB from peak-peak value

2.5.2 Dredging

Dredging is required to remove or alter areas of the seabed that are not optimal for infrastructure installation, for example, it may be necessary to remove large sand waves and flatten the seabed prior to pipelay activities. A comprehensive review of dredging noise profiles associated with commercial aggregate dredging operations has recently been carried out by (Thomsen, McCully, *et al*. 2009).

There have been very few studies describing noise from dredging, the studies that are available have tended to focus on either the cutter suction dredger or the trailing suction hopper dredger.

Four of the more common types of dredger are cutter suction dredger, bucket ladder dredger, grab dredger and trailing section hopper dredger and the descriptions below are adapted from (Thomsen, McCully, *et al*. 2009).

2.5.2.1 Cutter Suction Dredger

Cutter suction dredgers are used in the removal of hard substrates. A cutting head is lowered from the dredger and moved in an arc, with suction used to bring the removed material to the surface. This type of dredger is typically towed to location using tugs and does not have any propulsion mechanisms.

2.5.2.2 Bucket Ladder Dredger

A bucket ladder dredger uses a set of buckets on a rotating wheel which are scraped across the seafloor and then deposited inside the dredger. The bucket ladder dredger is moored using anchors. Bucket ladder dredgers can remove most substrates with the exception of rock. No studies were available that measured sound from these type of dredgers.

2.5.2.3 Grab Dredger

Grab dredgers use a grab device which is lowered from the seafloor in a bucket and bites into the seabed, with the material being deposited on the dredger or an awaiting barge.

2.5.2.4 Trailing Suction Hopper Dredger

Trailing suction hopper dredger tows a drag head across the seafloor that sucks up material which is then deposited onto the dredger. These types of dredgers can remove sand and shingle sediments but are less effective at the removal of harder substrates.

2.5.3 Noise Characteristics of Dredging

Although the noise from a dredger can be categorised as continuous, there are of course a number of discrete events that would produce and contribute to the underwater noise generated. These include method of collection, pumping noise and deposition noises, as well as the noise associated with the vessel itself such as propulsion and other ship machinery. The noise emitted by a dredger will be influenced by local environmental conditions, one of the predominant influences would be the sediment type being removed.

Certain types of dredging operation can also generate impulsive type sounds in addition to those sounds produced from the dredging vessel. An example would be the dropping of a dredge bucket onto the seafloor, which is essentially an impulsive type sound with short duration. The level of noise and frequency spectrum produced by different types of dredger varies as a consequence of the different processes by which the material is collected from the seafloor.

CEFAS measured the noise from a trailing suction hopper dredger operating at two different locations in the Southern North Sea. The results were presented in the form of noise spectra at various distances from the dredger. The noise was predominantly low frequency <500 Hz, with peak spectral levels approximately 122 dB re1µPa at a range of 56 m and at a frequency of 320 Hz (Defra 2003). Parvin (2008) measured the source levels of a trailing suction hopper dredger operating on the Hastings shingle and calculated the broadband source level to be 186 dB re 1µPa@1m, it was estimated that the dredging noise would not be audible beyond a range of 6 km. Of the studies available, dredging noise characteristics are typically of low frequency below 1 kHz and the sound source levels typically range from 168-186 dB (rms) re 1µPa@1m.

A summary of noise measurements available for dredging is provided in Table 13.

Table 13 Summary of Published Results for Dredging Noise, table adapted from Thomsen, McCully, *et al*. (2009)

Dredger Type and Name of Vessel	Dredger Size Indicator	Measurements Recorded - Received Levels dB (rms)re1µPa @ Range	Peak Spectral Level	1/3rd Octave Received Levels dB(rms)re1µPa@range	Source Level (rms)	Reference
CSD *Beaver Mackenzie*	Transfer rate: 100,000m^3 day	133 dB re 1µPa@190m	122 dB @190m (120 Hz)	128 dB @200m (80Hz)	168 dB re 1µPa@1m 1/3rd Octave Bands at 80Hz	(Greene 1987)
CSD *Aquarius*	Transfer rate: 100,000m^3 day	140 dB re 1µPa@200m	122 dB @200m (120 Hz)	134 dB @160m (80Hz)	178 dB re 1µPa@1m 1/3rd Octave Bands at 125Hz	(Greene 1987)
TSHD *Cornelis Zanen*	Capacity: 8,500m^3	142 dB re 1µPa@930m	125 dB @200m (175 Hz)	Not available	Not available	(Greene 1987)
TSHD *Geopotes X*	Capacity: 9,000m^3	139 dB re 1µPa@430m	125 dB @430m (100 Hz)	147 dB @500m (80Hz)	Not available	(Greene 1987)
TSHD *W.D. Gateway*	Capacity: 6,000m^3	131 dB re 1µPa@1500m	131 dB @1500m (350 Hz)	Not available	Not available	(Greene 1987)
Grab *Viking*	10m^3 bucket	124 dB re 1µPa@150m	123 dB @1100m (108 Hz)	Not available	Not available	(Clarke, *et al*. 2002)
CSD *James B*	10,000hp and 24" cutter	Not available	112 dB @<500m (105 Hz)	Not available	Not available	(Clarke, *et al*. 2002)
TSHD *Stuyvesant*	Capacity: 8,500m^3	Not available	142 dB @>40m (105 Hz)	Not available	Not available	(Clarke, *et al*. 2002)
TSHD *Acro Adur*	Capacity: 2,890m^3	Not available	122 dB @50m (320 Hz)	Not available	Not available	(Defra 2003)
TSHD *The City of Westminster*	Capacity: 2,700m^3	144 dB re 1µPa@150m	125 dB @251m (80 Hz)	126 dB @514m (31.5Hz & 100Hz)	186 dB re 1µPa@1m	(Parvin *et al*. 2008)

CSD – Cutter Suction Dredger; TSHD – Trailing Suction Hopper Dredger

2.6 PIPELINE INSTALLATION

Pipelay vessels refer to all types of vessels involved in the installation of subsea pipelines, and includes: barges, reel lay vessels, modified bulk carriers and semi-submersible lay vessels. Pipelay vessels can either be self propelled, such as certain types of deeper water reel lay vessels, or require tugs or anchor handling vessels to tow them onto location, or position their anchors and replenish supplies. Figures 5 to 10 illustrate the broadband source level measurements for pipeline installation vessels that were measured and modelled as part of the Sakhalin Energy Acoustic Monitoring programme (Hannay, MacGillivary, *et al*. 2004). In each case, the frequency spectrum was predominantly low 10-1000 Hz with peak levels typically below 500 Hz. Pipeline installation vessels that were fixed by anchors generated lower sound levels than their support vessels and associated anchor handling vessels, which generated higher sound levels due to the use of thrusters and engines for propulsion. Nedwell and Edwards (2004) presented the frequency spectrum of a pipelay vessel *Solitaire* whilst operating in Yell Sound in the Shetland Islands and reported that the vessel noise peaked at 200 Hz.

Pipelines can either be laid directly on the seabed or trenched and buried. There was no information available on the sound levels generated by a seabed plough or other trenching methods. However, it is expected that the noise levels will be dominated by the vessel noise associated with the pipeline installation. It would seem justifiable to predict that the noise generated by pipeline installation, including trenching and backfilling activities, is likely to generate comparable noise levels to dredging activities, with cutter trailing dredgers and trailing suction hopper dredgers potentially being suitable types of dredgers to compare.

Figure - 5 Source Level measured in 1/3[rd] Octave Bands of a semi-submersible Semac pipelay barge performing anchor winch out and held on station with an anchor spread, broadband source level 179.3 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).

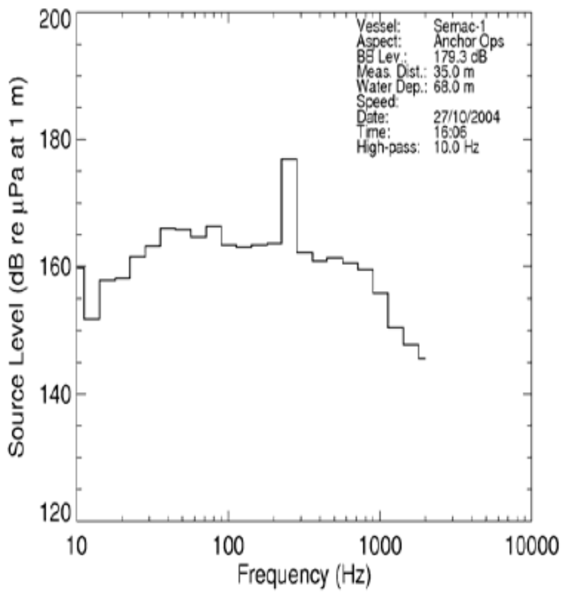


Figure - 6 Source Level measured in 1/3[rd] Octave Bands of an anchor handling vessel *Katun* while performing anchor pull, broadband source level 184.4 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).

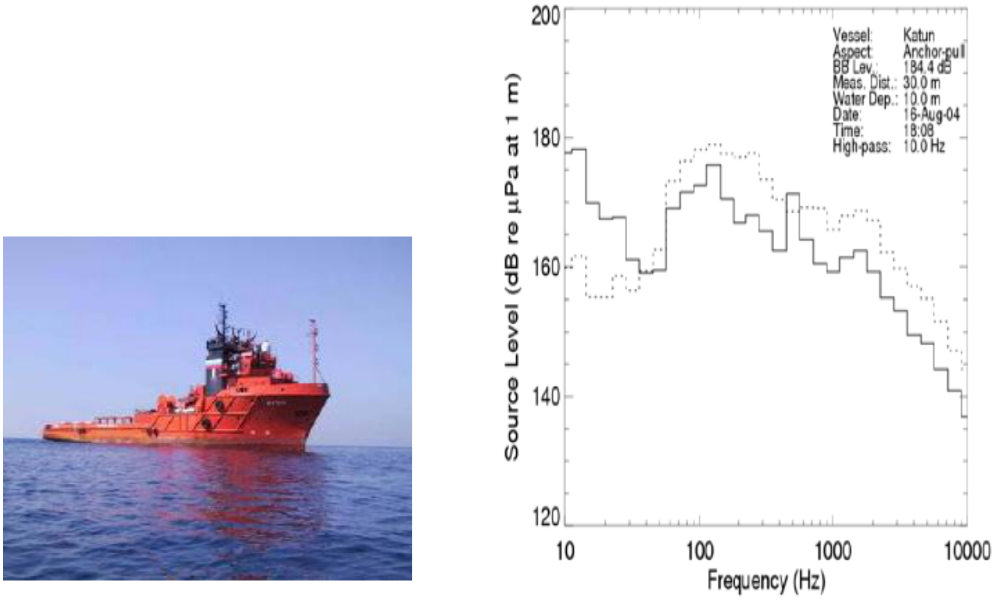


Figure - 7 Source Level measured in 1/3[rd] Octave Bands of an anchor handling vessel *Katun* while transiting, broadband source level 190.3 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).

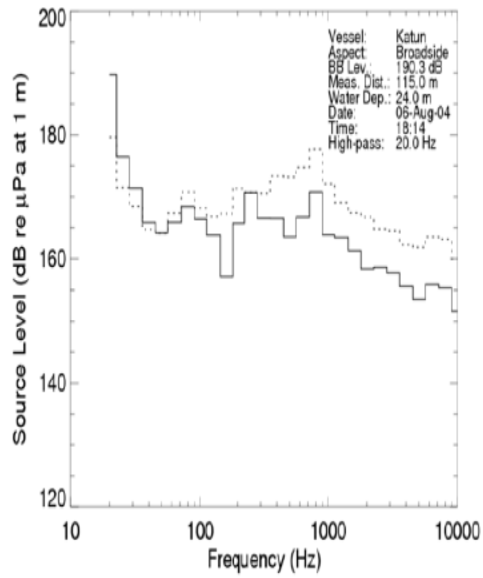


Figure - 8 Source Level measured in 1/3rd Octave Bands of a Mono-hull pipelay barge held on station by an anchor spread during anchor line winch operations, broadband source level 166.6 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).

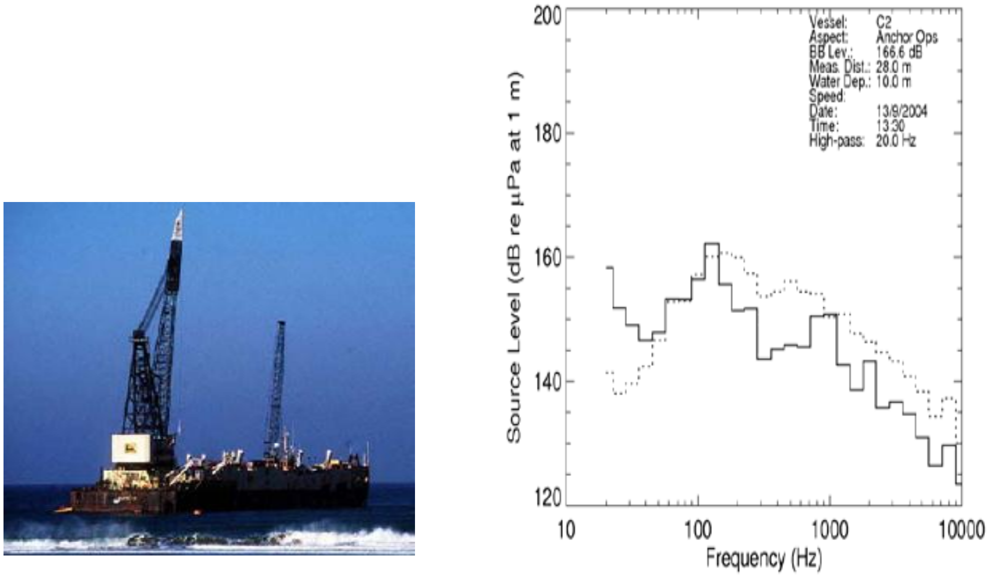


Figure - 9 Source Level measured in 1/3rd Octave Bands of a support vessel *Pompei* while discharging spoil, source level measured abeam of the vessel, , broadband source level 184 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).

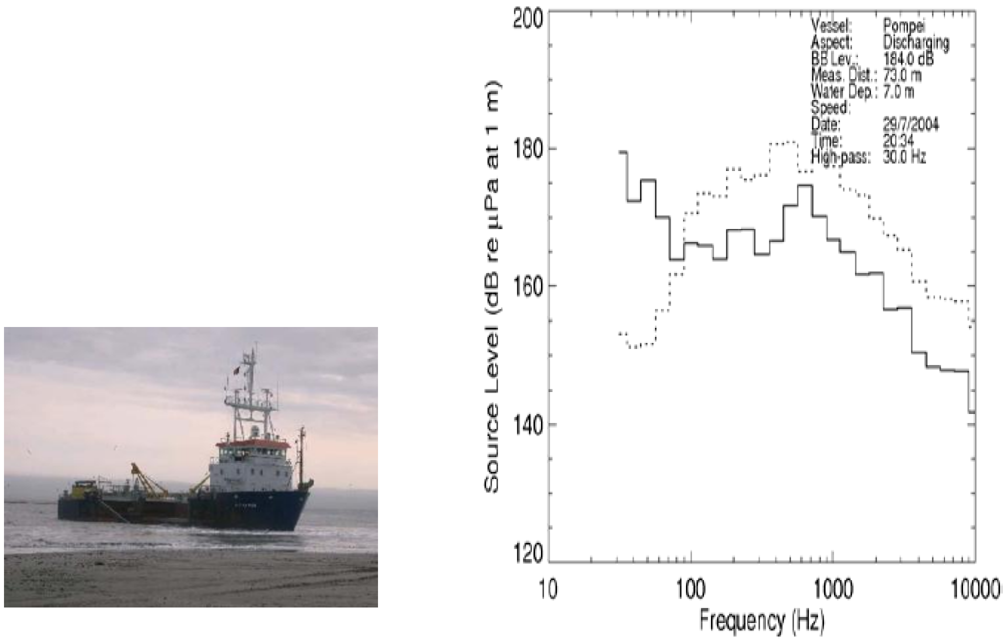
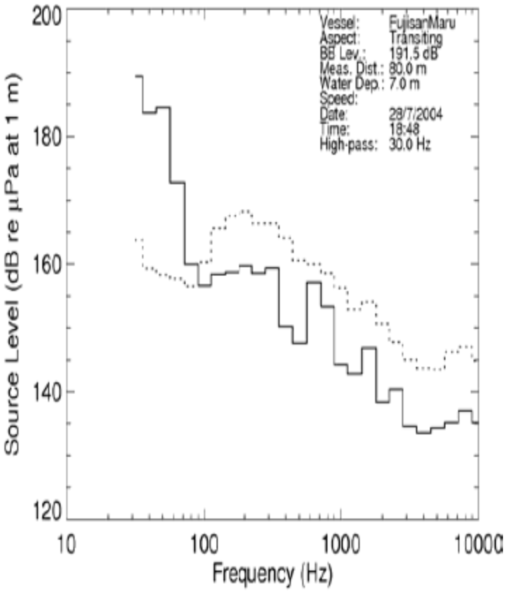


Figure - 10 Source Level measured in 1/3rd Octave Bands of an Tug Fujisan Maru support vessel, source measured abeam of the tug while transiting, broadband source level 191.5 dB re 1µPa@1m (Reproduced from Hannay *et al*. (2004).



2.6.1 Pipeline Protection

Once a pipeline has been laid on the seabed in order to achieve the required burial depth it may be required to deposit rock or concrete mattresses on top of the pipeline. Nedwell and Edwards (2004) measured the sound from a fall pipe vessel *Rollingstone*, this vessel has a specialised underwater chute that can accurately position rock on the seabed. The vessel used dynamic positioning and was powered by two main pitch propellers, two bow thrusters and two azimuth thrusters. When comparing normal operations and during rock placement activities there was no noticeable rise in the level of underwater noise, and this indicated the sound levels were dominated by the vessel noise and not the rock dumping activities (Nedwell and Edwards 2004).

2.7 SHIPPING NOISE

Shipping noise is the largest contributor to low frequency noise in the oceans. Since the 1950s there has been an apparent 3 dB increase in ambient levels of ocean noise per decade, although this rise has not occurred uniformly across all areas, and this rise has been attributed to noise generated from propeller driven vessels (McDonald, *et al* 2006). As the oil and gas industry, accounts for nearly 50%[4] of the gross tonnage of vessels in the world's commercial fleet it is responsible for a considerable proportion of the low frequency marine noise (McDonald, *et al* 2006).

Thrusters, a form of rotatable propeller, can be mounted on the bow of the ship, or in the case of azimuth thrusters at the stern. Thrusters are used to maintain position and permit moving of the vessel and are widely used in offshore support vessels. Ships that use computer controlled dynamic positioning control the operation of the propellers and thrusters to enable precise movements to be made.

Shipping noise is typically within the 50-300 Hz band and is the dominant noise source in deeper water between 20- 500 Hz (Ulrick 1983). Analysis of the noise from ships has revealed that their propulsion systems, specifically the propellers are a dominant source of radiated underwater nose at frequencies <200 Hz (Ross

[4] This figure includes all types of vessels involved in the oil and gas industry, including oil tankers. The movement of shipping is not regulated by the Department of Energy and Climate Change

1976). Propellers on vessels all have the potential to produce cavitation noise. This sound is caused by vacuum bubbles that were generated by the collapse of bubbles created by the spinning of the propellers. It has been estimated that 85% of vessel noise results from propeller cavitations, this sound represents wasted energy to propel ships (Barlow and Gentry 2004). Cavitation noise includes both broadband noise due to bubble collapse, and tonal components that are related to blade passage frequency (Hildebrand 2009).

The size of the vessel has an influence on the type of sounds generated, in general, larger vessels require larger propulsion mechanisms and there is a greater area of hull in contact with the water surface. Hydrodynamic flow over the ship's hull is an important broadband noise generating mechanism, especially with increased speed (Hildebrand 2009). The general trend is that larger vessels typically produce sound levels at lower frequencies than smaller high powered propeller driven craft, which often exceed larger vessel noise in the frequencies above 1 kHz (Kipple 2002).

Acoustic broadband source levels typically increase with increasing vessel size, with smaller vessels (<50 m) having source levels 160-175 dB (re 1µPa), medium size vessel (50-100 m) 165-180 dB (re1µPa) and large vessels (>100 m) 180-190 dB (re 1µPa) (OSPAR 2009, Richardson, *et al*. 1995). Large vessels, predominantly the type of vessels used by the oil and gas industry, have powerful engines and large slow turning propellers and these vessels produce high sound levels mainly at low frequencies.

Every vessel has a unique noise signature and for each vessel this can change in response to a number of factors, including; ship speed, operational status, vessel load, the condition of the vessel and even the properties of the water that the vessel is operating in (Ross 1976). A summary of published noise sources for vessels associated with oil and gas activities is provided in Table 14.

Table 14 Summary of Published Results for Shipping Noise

Vessel	Tonnage	Length m	Propulsion	Activity	Measurement	Measurement Bandwidth	Reference
Cargo vessel	25515	173	Diesel	Transiting 16 knots, 140 rpm	192 dB (rms) re 1 µPa@1m	Not available	(Averson and Vendittis 2000)
Cargo vessel	Not available	Not available	Diesel	In dock unloading	133.5 dB (rms) re 1 µPa@1m	0.01 - 20	(Blackwell and Greene 2002)
Barge Semi-Submersible Pipelay Barge	Not available	Not available	Anchor	Stationary	1/3 Octave broadband source levels 179.3 dB re1µPa	0.10 - 10	(Hannay, MacGillivary, *et al*. 2004)
Barge – Mono-hull Pipelay Barge	Not available	Not available	Anchors	Anchor winch	1/3 Octave broadband source levels 166.6 dB re1µPa	0.10 - 10	(Hannay, MacGillivary, *et al*. 2004)
Anchor Handling Vessel *Katun*	Not available	Not available	Diesel	Anchor pull	1/3 Octave broadband source levels 184.4 dB re1µPa	0.10 - 10	(Hannay, MacGillivary, *et al*. 2004)
				Transiting	1/3 Octave broadband source levels 190.3 dB re1µPa		
Offshore Support Vessel (Rig Tender)	2600	64	4 Diesel engines 2000 HP	Transiting 11 knots	136 dB (rms) re 1 µPa@1m	0.01 - 20	(McCauley 1998)
Seismic Survey Vessel	3779	84.9	5 Diesel electric engines 10123 BHP	Shooting Seismic	125-132 dB (rms) re 1 µPa@500m	0.01 - 20	(Patterson, *et al*. 2007)
Tug and Offshore Support Vessel	1894 tonnage	67	4 Diesel engines 2 *600 HP thrusters 1*800 HP thrusters	Transiting	187.76 dB (rms) re 1 µPa@1m	0.10 - 10	(Austin and MacGilliviary 2005)
Tug	783	47	4 Caterpillar V6 D399 Diesel Engines total 7200 BHP	Transiting	122 dB (rms) re 1 µPa@500 160.8 dB (rms) re 1 µPa@1m	0.01 - 20	(Patterson, *et al*. 2007)
Support Vessel *Pompei*	Not available	Not available	Diesel and Dynamic Positioning	Discharging Spoil	1/3 Octave broadband source levels 184 dB re1µPa	Not available	(Hannay, MacGillivary, *et al*. 2004)
Tug – Support Vessel *Fujisan Maru*	Not available	Not available	Not available	Transiting	1/3 Octave broadband source level 191.5 dB re 1 µPa*	0.10 - 10	(Hannay, MacGillivary, *et al*. 2004)

*1/3 Octave Broadband Source Levels for these vessels are presented in Figures 5 - 10

3. ASSESSMENT OF OIL AND GAS SOUNDS MOST LIKELY TO BE REPORTED AS PART OF THE MSFD

This section of the report reviews the available evidence from the sound generated by oil and gas activities documented in Section 2 and considers which of these are most likely to be required to be reported.

The principal difficulty faced in this assessment is the interpretation that might be placed on the wording of the noise indicator for loud, low and mid-frequency sounds. Further clarification is required from the European Commission to define what significant impacts to marine animals actually are, or the sound levels that should be reported. It would be unrealistic to expect that there will be agreement over the levels of sound which cause significant impacts to marine life, given the current level of knowledge and considerable political and scientific debate this topic generates. Without an agreed definition of the sound levels capable of causing significant impact, or clarity as to the definition of significant impact, the task of identifying the types of activities that could potentially qualify for reporting is challenging.

The basic goal of conservation is the prevention of harm to animal populations, and the population concept is important because establishing acceptable population effects is essentially a management question. An example of a management strategy that has been applied to marine mammals sets the number of animals that can be removed from the population without endangering the population's viability (Taylor, *et al*. 2000). In the absence of supporting guidance provided for the Marine Strategy Framework Directive indicator for loud, low and mid-frequency sounds it is not clear if significant impacts are to be interpreted from a population perspective, or the individual or both. This is an important distinction as it would invariably have an effect on the sound levels, and hence activities, that could be identified as causing significant impacts.

It is beyond the scope of this report, and also not possible given the current level of understanding as to the biological effects that underwater sound has on marine life, to be able to identify conclusively the oil and gas activities that are capable of causing significant impact to marine life. Rather the approach taken here is to compare and categorise the sound levels documented for oil and gas activities against the exposure thresholds proposed by: Southall *et al* (2007); pressure thresholds put forward by the EU task Group; and the lower threshold values proposed by the EU (Table 15).

Given the current wording of the noise indicator it is likely that the EU will provide further clarification to Member States on how significant impacts are to be interpreted. The approach taken in this report will provide DECC with an indication of the oil and gas activities that could be subject to reporting requirements. Should significant impacts be better defined then the preliminary assessment of oil and gas activities that are likely to be subject to reporting requirements can be revisited.

This report has chosen to use the EU Task Group pressure levels as the benchmark for activities that could be subject to reporting, with all activities that generated sound levels below these values considered unlikely to be reported. The Task Group's sound levels were based on the Southall exposure criteria and hence attributed with a biological effect (TTS in cetacean hearing). The noise indicator that was proposed by the EU, following the advice of Germany and supported by others which specified lower levels for reporting, did not correspond with any known exposure levels for biological effects. In fact, there is no consistent science available to set levels lower than the Task Group's draft noise indicator (Southall threshold levels). With the European Commission ultimately rejecting the idea of specifying noise levels to be reported, or clarifying the levels of sound capable to causing significant impacts to marine animals, then this has merely delayed the problem of reaching agreement on appropriate threshold levels.

A number of oil and gas activities, specifically the use of geophysical survey equipment such as echosounders and sidescan sonar produce high frequency sounds in excess of the upper limit specified by the noise indicator for low and mid frequency impulsive sounds (> 10 kHz). There is a new EC task group that is being set up to address ‘underwater noise and other forms of energy’ and it may provide further guidance on appropriate indicators and guidance for high frequency sounds (Mark Tasker pers. comm.). A number of oil and gas activities do not generate impulsive sounds and instead generate continuous sounds such as shipping and dredging and are consequently not captured in reporting requirements for the noise descriptor.

Data transformations had to be applied to a number of sound levels so that they could be compared to criteria of the same reference unit (0-peak and rms). It is recognised that the transformations between measurement units discussed in Appendix A are only applicable to sine waves and not necessarily applicable, or accurate when applied to other waveforms. However it was deemed necessary to apply these transformations to allow comparisons to be made. Where data transformations have been performed these are marked by an asterisk symbol on Table 15.

Table 15 Comparison of Oil and Gas Sounds against Southall Exposure Criteria and Pressure Indicators from the Task Group and EU

✓Denotes that the sound is in excess of the threshold

X Denotes that the sound is below the threshold level

*** Denotes that a data transformation on original sound measurement was performed (rms – peak to peak etc)**

	Activity	**Southall Exposure Criteria (2007)** Injury PTS cetaceans	Injury PTS pinnipeds	TTS Cetaceans	TTS pinnipeds	**Task Group indicator thresholds**	**EU lower threshold levels (proposed by Germany)**
Geophysical (High frequency) Equipment	Echosounders & Multibeam (50-200 kHz)	✓*	✓*	✓*	✓*	*Outwith frequency range of indicator*	*Outwith frequency of indicator*
	Side-scan sonar (100-500) kHz	X*	✓*	✓*	✓*	*Outwith frequency of indicator*	*Outwith frequency of indicator*
	Chirp Systems (3-40 kHz)	X*	X*	X*	X*	X*	✓*
	Boomers (500 Hz – 4 kHz)	✓*	✓*	✓*	✓*	✓*	✓*
	Sparker (200-800 Hz)	X*	✓*	✓*	✓*	✓*	✓*
Airguns (Single shot)	Single airgun 40 cubic inches	X*	X*	X*	X*	X*	X*
	Single airgun 100 cubic inches	X	✓	✓	✓	✓	✓
	Array 280 cubic inches and above	✓	✓	✓	✓	✓	✓
Explosives	Wellhead removal 45 kg	✓	✓	✓	✓	✓	✓
Drilling and Production	Semi-Submersibles	X*	X*	X*	X*	X*	X*
	Platforms	X*	X*	X*	X*	X*	X*
	Drillships	X*	X*	X*	X*	X*	✓
Construction	Piling <1.5 m piles	X	✓	✓	✓	✓	✓
	Piling >1.5 m piles	✓*	✓*	✓*	✓*	✓*	✓*
	Dredging Cutter Suction	X*	X*	X*	X*	*Dredging continuous sound not covered by TG noise indicator*	*Dredging continuous sound*
	Dredging Trailing Hopper	X*	X*	X*	X*		
Shipping	Cargo vessel 25515 tonnes (transiting)	X*	X*	X*	X*	*Shipping continuous sound not covered by TG noise indicator*	*Shipping continuous sound*
	Tug (transiting)	X*	X*	X*	X*		
	Barge (pipelay)	X*	X*	X*	X*		
	Anchor handling vessel	X*	X*	X*	X*		

3.1.1 Echosounders and Multibeam Systems

Echosounders and multibeam systems are high frequency devices and do not generate sounds within the frequency range of the indicator for loud, low and mid-frequency impulsive sounds (multibeam systems operate at frequencies in excess of 10 kHz) and as such there will be no requirement to report on the use of such devices .

Multibeam systems that operate in mid-range and deep ocean depths typically run at lower frequencies and higher power than shallow water multibeam systems. As a consequence of the overlap in the operating frequencies of these devices with the likely hearing range of marine mammals, and the high source levels documented for deeper water multibeams, there remains the potential of such devices causing physical injury or short term disturbance to animals at very close proximity.

For echosounders on small vessels the frequencies used are typically between 50 and 200 kHz. As marine mammals use frequencies up to about 180 kHz for communication there is a potential overlap in frequency usage and they may therefore be audible to some marine animals.

Multibeam systems operating in shallow waters, which captures the majority of oil and gas activities in the UKCS, tend to operate at a lower power and utilise a higher frequency range >100 kHz than echosounders. The frequency range they operate in falls outside of the hearing range of most marine mammals and fish, and also the higher frequencies attenuate rapidly so the risk of causing physical injuries to marine animals is very low. However, there is a distinct lack of peer reviewed studies that have measured the sound outputs of such multibeam systems, and further research is required to be able to verify the manufacturer's specifications and source level documented in this review.

Multibeam and echosounder systems produce frequencies out with the frequency range of the indicator for loud, low and mid-frequency sounds and therefore will not require to be reported under this indicator.

3.1.2 Sidescan Sonar

Side scan sonar systems operate in excess of the upper frequency range of the noise indicator for loud, low and mid-frequency impulsive sounds and therefore do not qualify for reporting requirements.

Side scan sonar operates at high frequencies (typically around 100-500 kHz) the higher frequencies (>180 kHz) are outside the hearing thresholds of cetaceans, even of harbour porpoises (1.4- 2.5 kHz for communication and sonar-clicks at 110- 140 kHz), and well above the hearing level of other marine mammals and fish. Although sound output levels are relatively high 220-226 dB (rms) re 1µPa@1m, because these high frequencies attenuate more quickly than lower frequencies, the levels of sound will fall off rapidly away from the source. There was only one side scan sonar measurement available for review and its pressure level at source exceeded all of the Southall exposure thresholds with the exception of the PTS to cetaceans.

The intermittent nature of side scan sonar signals also results in lower noise doses than would occur for continuous signals. Upon considering the potential impact of side-scan sonar systems upon cetaceans it is the view of JNCC that they will have a negligible risk of causing an injury to cetaceans (under normal operating conditions) (JNCC 2010 draft).

Side scan sonar systems produce frequencies out with the frequency range of the indicator for loud, low and mid-frequency sounds and therefore will not require to be reported under this indicator.

3.1.3 Pingers

There was insufficient information available on pingers to provide any meaningful assessment. The frequencies emitted by these devices overlap with hearing ranges of marine mammals, and dependent upon the peak sound pressure levels of these devices they may pose a risk to animals, but it is not possible to assess to what extent.

Unknown if pingers would qualify for reporting requirements.

3.1.4 Boomers

There was considerable variation in the sound pressure levels reported for commercially available boomer systems this possibly reflects the differences in operating power between systems. If the boomer with the highest source level is used in the assessment (source level of 227 dB (rms) re 1µPa@1m) by applying a simplistic conversion to peak levels by adding 3 dB, then this source level may potentially exceed the Southall exposure levels for PTS to cetaceans. Whereas, if other boomers are used, such as the AA301. which had a considerably lower source level of 209 dB(rms) re 1µPa@1m, then the results would differ as this device is below the levels considered capable of inducing TTS in cetaceans. It should be noted that only rms values were provided for the source levels and it was not clear how these reported values were derived. Further information is required on the sound pressure levels generated by these devices for a complete assessment to be made.

There appears to be considerable variability in the sound measurements provided for boomer systems. Certain types of high powered boomer systems could potentially qualify for reporting requirements.

3.1.5 Sparkers

There was a range of source levels 216-222 dB (rms) re 1µPa@1m provided for commercially available sparker systems. All source levels were taken from manufacturers specifications, and it was unclear how these had been derived. Taking a worst case assessment of these systems and applying the highest source level provided, there is the potential for sparker systems to exceed all of the exposure and pressure thresholds with the exception of Southall criteria for injury to cetaceans.

Certain high powered sparker systems could potentially qualify for reporting requirements.

3.1.6 Chirp systems

Sound measurements were available for one sub-bottom profiler chirp system, with the information being taken from the manufacturers specifications. This device may not be representative of other chirp systems used by the oil and gas industry, or cover a similar frequency range. Chirp systems emit frequencies that extend into high frequency ranges beyond 10 kHz but also produce mid-frequency signals that are within the frequency range of the noise indicator. Further information is required on the sound pressure levels generated by these devices for a complete assessment to be made.

Based on the limited data for chirp systems it seems unlikely they would qualify for any reporting requirements.

3.1.7 Airguns

The assessment considered single airguns of 40 and 100 cubic inches and multi-gun airgun arrays. By comparing the sound pressure levels recorded for airguns it is only the individual 40 cubic inch guns that fall below the threshold levels for inducing TTS in cetaceans, with individual airguns of 100 cubic inches and airgun arrays being in excess of these threshold levels.

For physical injury in cetaceans to occur a peak pressure of 230 dB (0-peak) re 1 µPa is considered to be required when applying the Southall criteria (2007). This sound pressure level would only be found within a few meters of the largest airguns used in most airgun arrays (Caldwell and Dragoset 2000).

Airgun arrays produce short duration multiple pulse sounds with high peak source levels (242-265 dB (0-peak) re: 1µPa). These sound levels are actually an overestimate of the true output since they are not based on actual empirical near field measurements but are reliant upon modelling. Modelling assumes that the array is a point source, but as the airguns within an array are separated from each other, an array is really a multi-source device, and at close distances the sound received would be dominated by that arriving from individual guns and not all guns simultaneously. Given the potential inaccuracies with source levels reported from airgun arrays, for reporting requirements, the size of individual airguns could be a useful parameter to consider.

Single airguns of 40 cubic inches, or less, would potentially not qualify for reporting requirements. Larger single airguns that are 100 cubic inches or more are likely to qualify for reporting. Airgun arrays that consist of multiple large guns will qualify for reporting requirements.

3.2 Explosives

The source levels from explosive detonations are some of the largest sounds generated by anthropogenic activities and can produce source levels of 272-287 dB re1µPa@1m (0-peak), or greater. Underwater explosions have the potential to cause injury or even death to marine animals, the potential to cause physical injuries arises not only from the high peak pressures but also the initial shock wave that is emitted. Explosive activities have sometimes been attributed to fish kills during the decommissioning of oil and gas platforms, and have been associated with causing physical injuries to other types of wildlife, such as marine turtles. The low frequency energy has the potential to travel considerable distance and also cause injury at long range (Parvin, *et al*. 2007). The results presented in this study for wellhead decommissioning support the available literature on explosive detonations and indicate that the peak sound pressure levels could be in excess of levels likely to cause injury (PTS) to cetaceans out to a distance of at least 300 m and injury (PTS) in pinnipeds out to 800 m (applying the Southall 2007 criteria).

It was not possible to obtain any measurements of underwater explosives used by the oil and gas industry other than those used to sever wellheads from the seafloor.

All types of oil and gas decommissioning activities involving explosives are likely to be subject to reporting requirements.

3.3 Drilling and Production Sound Levels from Mobile Drilling Units and Production Platforms

Underwater sound levels increase during periods of drilling in comparison to non-drilling periods, although the sound levels during these periods and normal production activities are still relatively low.

Sound levels from all types of mobile and drilling platforms were all below the threshold levels for TTS in cetaceans and pinnipeds according to the Southall criteria (2007). From the limited information on noise measurements drillships are considered to produce the highest sound levels in comparison to semi-submersibles and fixed platforms. Sound generated from production and drilling activities is generally continuous sound and is not applicable to the noise indicator which is for impulsive sounds. That is not to say there is no likelihood for any impact, rather that it would not be captured by the indicator for impulsive sounds.

Unlikely that noise associated with platform production or fixed / mobile drilling vessels will be subject to reporting requirements. Drilling and production sounds are continuous and are not applicable to indicator for impulsive sounds.

3.4 CONSTRUCTION

3.4.1 Piling

Pile driving can generate high levels of low frequency sound. One of the principal influences on the sound levels generated during pile driving is the diameter of the pile, although there are many other factors that have an influence including oceanographic conditions choice of pile driver and the energy used to install the pile. Although pile diameter to be installed has been selected as a way of categorising activities which could qualify for reporting, the selection of this parameter is a reflection of this information being more readily available in noise studies in comparison to detailed information on the type of hydraulic pile driver being used or if measurements were recorded at full power.

The majority of pile driving undertaken in the North Sea for oil and gas purposes will involve relatively small diameter piles <1.5 m. The sound levels of piles 1.5 m or less, and greater than 1.5 m were compared. owing to a small number of studies that have recorded measurements on smaller diameter piles it was considered inappropriate to sub-divide the pile diameters into a larger number of size categories. Four studies provided sound measurements of small diameter piles <1.5 m. Two studies extrapolated measured values to estimate source levels, with the other two studies providing sound pressure measurements at 340 m. The source level of a 1.5 m pile was calculated to be 228 (0-peak) dB re µPa@1m, which is in excess of the TTS criteria for cetaceans (Southall, *et al*. 2007). However, the smallest pile (0.75m) was calculated to have a source level 210 (0-peak) dB re µPa@1m which is below the exposure criteria for TTS in marine mammals. Larger diameter piles, 1.5 m and above, were found to generate sound pressure levels in excess of the PTS criteria for cetaceans.

Piles <1.5m diameter are likely to qualify for reporting requirements, although some smaller diameter piles <0.75 m diameter may be excluded from this requirement. As the sound pressure level increases with increasing pile diameter, piles greater than 1.5 m diameter are highly likely to qualify for reporting requirements.

3.4.2 Dredging

Sound levels produced by dredging is dominated by the vessel noise and as vessel noise is a continuous type sound it is not applicable to be reported under the noise indicator for loud, low and mid-frequency sound.

All the reported noise measurements provided for dredging indicate that the predominantly low frequency sound is below the threshold levels for causing TTS in cetaceans (Southall criteria). Comparing the relatively sparse noise studies of dredging activities that are available, the evidence indicates that dredging source levels will be in the range 168-186 dB (rms) re1µPa@1m. On comparison to other types of oil and gas activity it is considerably less noisy than the impulsive sounds generated by piling and seismic, drilling and shipping.

Dredging noise is continuous and is not captured within the indicator for loud, low and mid-frequency impulsive sounds and will not be required to be reported.

3.4.3 Other Forms of Construction Activities

Evidence from measurements of rock dumping activities suggests that the noise is dominated by shipping noise and it is likely that most forms of oil and gas construction activities including trenching of pipelines (with the exception of pile driving) will generate noise levels that are dwarfed by those of the construction vessels.

Construction noise is typically dominated by vessel noise which is continuous and is not captured within the indicator for loud, low and mid-frequency impulsive sounds and will not be required to be reported.

3.5 Shipping Noise

Vessel noise is continuous and is not captured within the indicator for loud, low and mid-frequency impulsive sounds and will not be required to be reported.

Oil and gas shipping represents a considerable proportion of the gross vessel tonnage and is a significant contributor to ocean noise. The increase in ambient levels has been identified as being of concern to marine animals as it might result in the masking of biological relevant signals, for example, communication calls in marine mammals and fish) considerably reducing the range over which individuals are able to exchange information (Clark and Ellison 2004; Nowacek, *et al* 2007). It is also known that marine mammals alter their communication signals in noisy environments which might have adverse consequences (McDonald, *et al* 2006; Parks and Clark 2005). Prolonged exposure to increased ambient noise may lead to physiological and behavioural stress. Thus chronic exposure to noise can permanently impair important biological functions and may lead to consequences that are as severe as those induced by acute exposure from impulsive type sounds.

However, for the purposes of this assessment the issues associated with potential cumulative impacts upon marine animals associated with shipping are not considered further, and it is only the potential one-off exposure to the sound from various types of shipping noise that is being reviewed.

In terms of direct physical injuries to hearing structures in marine mammals, it appears from the available data that loud and/or sustained exposures are required to cause even temporary changes in hearing sensitivity. Consequently, the likelihood that an isolated exposure of shipping noise would be sufficient to permanently damage the hearing of a marine mammal appears to be remote. However, our understanding of potential impacts to marine from shipping noise, and ability to assess impacts from multiple and ongoing exposures from shipping noise is still in its infancy and in need of further research.

Vessel noise is continuous and is not captured within the indicator for loud, low and mid-frequency impulsive sounds and will not be required to be reported.

3.6 Current Recording of Information by DECC for Oil and Gas Activities Most Likely to Qualify for Reporting Requirements

3.6.1 Geophysical Surveys (Airguns, Sparkers and Boomers)

Anyone who wishes to undertake a geophysical survey for an oil or gas activity must submit details of the proposed activity to DECC within a Petroleum Operation notice (PON14a) application form[5]. Applicants are required to supply precise details about the proposed survey (survey area, type of survey, location, vessels used and survey equipment), the only flexibility is regarding the time period that the survey will occur providing it adheres within the range stipulated on the form.

There may be temporal restrictions on seismic applications for certain areas, for example those based on fish spawning periods and these would be detailed within the licence conditions.

Seismic applications can, subject to DECC's discretion, be required to have a supporting environmental impact assessment (EIA) which can be reported within the PON application (as an additional document) or be reported in an Environmental Statement, and both types of application are subject to statutory consultation and review. As offshore surveys are heavily reliant upon favourable weather conditions, offshore operator's

1. [5] The PON14a application is available from DECC', guidance notes for Geophysical surveys are currently being amended by DECC *www.og.decc.gov.uk/regulation/pons/pon14a.doc*

with DECC's agreement, can allow themselves a degree of flexibility in the time period that their survey is proposed to occur within, (this is providing there are no other permit constraints stipulated by DECC which prohibit data collection during specific times or areas). For example the flexibility afforded to the time period of the consent is typically related to the size of the survey, a large regional seismic survey which could involve multiple months of data collection may specify a time period that could include the whole year, whereas a small site survey may have a survey permit timeframe of only a couple of weeks. There is a trade-off here between providing sufficient flexibility to allow for foreseeable project delays, whilst also avoiding the need for the oil and gas industry and DECC to have to submit and process numerous survey application variations which would be required given the weather conditions in the North Sea.

Once the survey has been completed a 'close out' form[6] is submitted within 4 weeks after the survey has finished. This is a highly detailed report that describes the actual data acquisition that took place (survey area, shot point interval, area acquired etc). The seismic data returns are held both by DECC and other data repositories, an example being the UK Digital Energy Atlas (UKDEAL). DECC sequentially produces reports on the occurrence and distribution of seismic surveys carried out in the UKCS as part of the UK's ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas) commitments.

3.6.2 Piling

Piling activities are invariably associated with construction activities. For larger projects the proposals and impacts would therefore be captured within the EIA process and for projects that are below the threshold to qualify for an Environmental Statement would be detailed in a PON15 application. The proposed duration and scale of piling activities would be supplied within the accompanying Environmental Statement (ES) for the development. If the ES is granted approval the consent will specify the time period which the ES is valid to, any variations that are outwith the project timings will be subject to amendment applications. The ES would detail with a high degree of accuracy the locations of all piling activities and the PON15 requirements would be similar.

Once piling has been completed there is no formal requirement to report back on the specifics of the activity (for example, duration of piling, strike rate etc). All the specifics relating to the piling operation would have been detailed in the ES and there may, depending upon any other environmental considerations, have been a large timeframe in which piling activity could have occurred. It would be relatively straightforward for DECC to establish procedures where more precise information is supplied by the operator as to the duration of actual piling activities should this be necessary.

3.6.3 Explosive Activities

DECC regulates oil and gas activities that use explosives for decommissioning purposes. If explosives are expected to be used within a decommissioning programme they will be subject to an Environmental Impact Assessment (EIA) that is presented in a decommissioning plan, that has to be approved by DECC prior to any decommissioning operations commencing. If individual wellheads are to be removed that are not necessarily included within a decommissioning plan, the Petroleum Operations Notice 5 (PON5) application to abandon or temporary abandon a well is used as the mechanism by DECC to regulate explosive use for wellhead removal.

Prior to any explosive use in the UKCS for oil and gas decommissioning purposes DECC is notified by the operator wishing to use explosives and the project detail is supplied in either the PON5 or decommissioning plan. The project details would include the location of the activity, scale of explosive use and projected timeframe for the activity. The approval of the decommissioning plan and PON5 may be dependent upon a number of project specific permit conditions relating to the use of explosives.

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1. [6]Close out form available from DECC's website: *https://www.og.decc.gov.uk/regulation/pons/pon14_closeout.doc*

Explosives are often included as a contingency method that would be used after an unsuccessful mechanical cutting attempt of infrastructure, although they may also be proposed as a primary means of removal. Once the activity is carried out there is no requirement for operators to detail the specifics of the activity and it is possible that improvements could be made in terms of recording any explosive use that occurred, as an unrealistic picture of explosive use in the UKCS could be presented if all the proposed explosive activities were assumed to have actually occurred. There is no equivalent of a 'close out' form for explosive operations and DECC is not necessarily notified if explosives operations were carried out.

As of August 2011 there is no specific permit for explosive use that is separate from a PON5 or decommissioning plan. The introduction of the Marine and Coastal Act 2009 and the Marine Scotland Act 2010 have specified that along with introducing changes to the existing planning system, the use of any explosive substance offshore will become a licensable activity. Where the Act applies, DECC will be the licensing authority for oil and gas with certain exemptions related to the devolved settlements. Improvements and coordination to the way explosive use is consented and managed across the UKCS are expected once the new system is in place. DECC is currently reviewing the procedures in place relating to the use of explosives for oil and gas activities.

3.7 Summary of the Control Procedures and Information Submitted to DECC for Oil and Gas Activities Most Likely to Qualify for Reporting Requirements

The oil and gas industry is highly regulated by DECC, the main activities that are most likely to be subject to any reporting requirements, these being; explosive use, piling and geophysical surveys (sparkers, boomers and airguns) are all subject to EIA and are controlled through permits and project consent approvals. There is generally highly detailed information provided by operators' about planned activities, with precise information given to the location and scale of activity this is necessary to ensure that they are operating within their correct licence area. The timeframe for proposed activities is an area where the information provided becomes of lower precision and the details provided can be variable and is generally very project specific (Table 16). DECC can specify the timeframe in which activities have to be completed by and this is project specific and detailed on the permit consent.

In the case of geophysical seismic operations, operators are required to report on the exact specifics of any seismic acquisition via the close out form. There is no formal reporting route once piling or explosive operations have been carried out.

The review of any Marine Mammal Observer (MMO) reports for piling or explosive use, if submitted, is one option to allow DECC to determine if any project specific consent conditions relating to mitigation measures were carried out, but as these do not necessarily provide precise details as to specifics of the activity (areas surveyed, duration, etc) or are reported in a standard or consistent format, they are not as reliable as the close out forms used for reporting completed seismic surveys. DECC can acquire project details relating to the use of piling or offshore explosives, if necessary, by contacting the operator directly.

In the current system with an absence of any formal reporting system for piling or explosive use there could be potential difficulties in DECC determining exactly where piling activities have taken place, where new activities are planned and the duration of these, this has implications for reporting of noise emissions, assessing cumulative effects and marine spatial planning. The provision of detailed information relating to the exact use of explosives or piling would be a relatively simple process providing suitable guidance is supplied for operators to complete at the application stage, and also once the project has been completed. These changes could improve the records of the duration and extent of loud underwater activities, this may be important especially if DECC has to report on the duration and extent of these activities.

Table 16 Summary Information relating to Impact Assessment requirements and the Precision of Information provided for Explosive use, Piling and Seismic Surveys

		Precision of information supplied		
Activity	**Subject to EIA**	**Location of activity**	**Timing of activity**	**Close out information submitted after development activity completed**
Explosives Decommissioning (not wellheads)	Yes, included in decommissioning plan	High. Precise information available on location infrastructure to be removed.	Moderate (project specific). Within a period specified in the application.	Low. No requirement to submit details of explosive use.
Explosives Wellheads	Yes, included in PON 5. Explosives will be subject to new licensing requirements in 2011.	High. Precise information available on wellhead positions that will be removed.	Moderate (project specific). Within a period specified in the application.	Low. No requirement to submit details of explosive use,
Piling	Yes, included in Environmental Statements for larger projects. Smaller projects below ES threshold subject to EIA in the PON 15 application.	High. Precise information provided about location of infrastructure to be installed.	Low – Moderate (project specific). Within a period specified in the ES, developmental periods can be large and piling could occur at any time once consent is granted.	Low. No requirement to submit details of piling use.
Geophysical Surveys	At DECC's discretion. Certain surveys subject to EIA and ES. Otherwise PON 14a application (circulated to statutory consultees for review).	High. Exact survey coordinates and area of operations specified in PON 14	Moderate (project specific). Within a period specified in the PON14a – Generally within a year of submission of application.	High. Precise details given of seismic acquisition that took place.

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A. APPENDIX A UNDERWATER ACOUSTICS

A.1 INTRODUCTION

Sound is produced when an elastic medium, such as water, is set into motion, often by a vibrating object within the medium, such as a ships propeller. As the object vibrates its motion is transmitted to adjacent particles in the medium and the motion of these particles is then transmitted to the next adjacent particles, and so on. The result is a mechanical disturbance, hence the sound wave, that moves away from the source of the sound at a speed dependent upon the properties of the medium (in the case of underwater sounds, the medium is seawater and seabed). As the sound wave travels through the medium, the individual particles of the medium oscillate about their static positions but do not travel with the sound wave. It is the oscillations within the medium which creates fluctuations in the medium, one of them being pressure.

The physical attributes of a sound are normally quantified by measuring fluctuations in the pressure of the medium that accompany the passage of a sound wave. The two main physical attributes of a sound wave are its frequency and amplitude. Frequency is related to the speed at which the medium particles oscillate about their static positions. Frequency is the number of times that the medium pressure varies from its static pressure through a complete cycle in unit time, the unit of frequency is hertz (Hz). Amplitude is related to how loud any sound is and is the degree that the medium particles vary in relation to their static positions.

Water is an excellent conductor of sound due to the tightly packed arrangement of water molecules. In seawater, that is free from air bubbles or suspended sediment, sound travels at approximately 1560 m/s, which is approximately 5 times faster when compared to air. The speed of sound in seawater depends, amongst other factors, upon pressure (hence depth), temperature and salinity (Wong 1995).

Sound waves produced from a source, such as a seismic airgun, are pressure fluctuations in the medium through which the sound propagates. Only compressional waves can travel through water, and are therefore the only type of wave that needs to be considered in terms of potential impact upon marine life. Sound waves are characterised by the generic properties of waves which are frequency, wavelength, period, amplitude, intensity, speed and direction.

Sounds can be broadly categorised as being either continuous or impulsive sounds. Although there is no standard definition for continuous and impulsive sounds, in the context of oil and gas activities, continuous sounds are those with a fixed level and frequency range such as sounds attributed to vessel movements and drilling. Impulsive sounds are those that either involve a rapid release of energy for example, seismic surveying and explosive use or are generated from a mechanical impact for example, hydraulic pile driving.

In order to detect an underwater sound a receiver must be able to detect either the intensity of the sound, or more commonly its pressure. In underwater acoustics a receiver used to measure pressure differences is a hydrophone. Underwater sounds are audible to marine life that is able to detect either the change in pressure and or the particle motion.

The most frequently applied scale for describing sounds is the deciBel scale (dB), this is a logarithmic scale that compresses the range of numerical values that must be used and is appropriate when describing underwater sounds that have an extensive range.

A.2 SOUND PRESSURE

Sound pressure is the incremental variation in a medium’s static pressure as a sound wave travels through it. The unit of sound pressure is the Pascal (Pa) (1 Pa = 10µbar = 1.45 10^{-4} psi).

For a regularly oscillating sinusoidal waveform, with pressure as the y axis and time as the x axis, amplitude can be represented by the vertical distance between the extremities of the curve (Figure- 11). In underwater acoustics there are a number of ways in which sound pressure can be reported and this is often dependent upon the properties of the waveform being recorded.

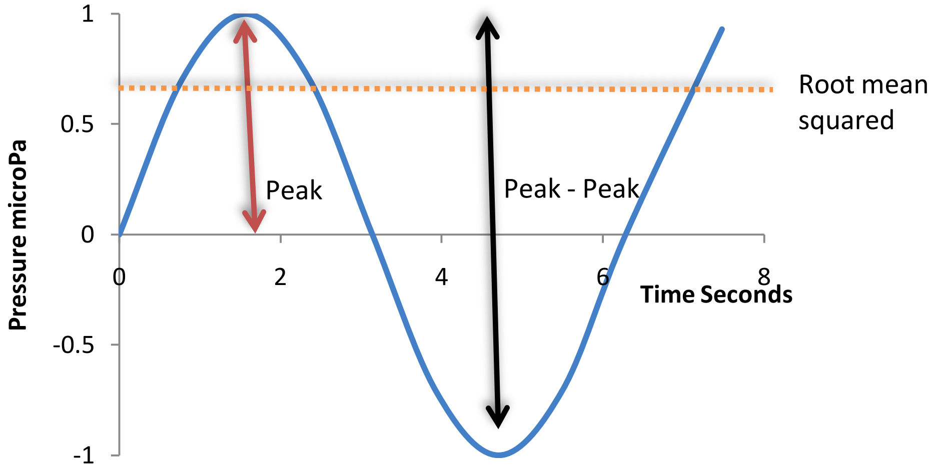
A.2.1 Peak Sound Pressure

Peak sound pressure (0-peak) is the maximum rise in pressure from an ambient pressure and can be an appropriate metric to use for noises that have a clear pressure peak, such as certain types of impulsive sounds such as explosions that have an asymmetric waveform (Figure- 11).

A.2.2 Peak to Peak Sound Pressure Level

Peak to peak sound pressure value is taken as the measurement between the maximum and minimum pressure values, and for waveforms that are symmetrical the peak to peak level will be double the peak level, and hence 6 dB higher.

Figure- 11 Sinusoidal wave with pressure (µPa) on the y axis and time (seconds) on the x axis illustrating the measurement parameters for Peak pressure, Peak to Peak pressure and Root Mean Squared



A.2.3 Root-Mean-Square (rms) Sound Pressure Level

Root mean square (rms) sound pressure level measures the total sound intensity, then divides it by the duration of the signal. It is also useful biologically, because our perception of a sound's intensity takes place over time, not instantaneously. Root mean squared is an appropriate metric to use for certain types of continuous sounds such as drilling noise, shipping or background noise and less so for impulsive sounds. As root mean squared uses time of the signal, in practice it is not easy to precisely identify when a sound starts and stops, especially at some distance from the source, where individual sound impulses are indistinct from other background noise sources. This problem can tend to cause researchers to over-estimate the length of the sound, thereby under-measuring the rms value, where the noise is continuous the time period over which the measurements are taken is not relevant as the measurement will give the same results independent of the period over which the measurements are averaged. Such time averaging is well defined in the context of continuous type sounds, but this is not so for transient sounds, such as airgun pulses. For such signals the period over which the time averaging should be performed is a matter of convention and can significantly affect the rms value obtained (Leighton 2007). The formulae for rms Sound Pressure Level is given by:

Sound pressure level (rms) = 20 x $\log_{10}$ Pressure (rms) / Pressure (reference)

Historically all of the research on marine mammals in response to anthropogenic sounds has quantified the sound levels in terms of rms, something which is entirely appropriate for many acoustic signals such as shipping noise, however, as mentioned previously, this is less appropriate for many oil and gas impulsive type sounds such as seismic surveys or explosions. The units of rms are dB re 1µPa.

Note that for a sine wave the following transformations can be performed between rms, peak to peak and 0-peak units. These transformations were applied to certain noise measurements to provide alternative units for comparison purposes.

Peak to Peak = 2 * *Amplitude*
rms = Amplitude / 2
*Peak to Peak = rms** (2)*2
Peak to Peak (*dB*) = *rms* (*dB*)+9 *dB*
Zero to Peak (dB) = Peak to Peak – 6dB

The above transformations are not necessarily accurate for other wave forms and impulsive sounds. Where the above transformations have been applied the error may, in some cases, be significant.

A.3 Source Level

In order to compare sound levels generated from different types of operation source levels can be used. A source level is the apparent strength of a sound source at a reference distance. In underwater acoustics is it is common practice to use 1 m as the reference distance in which source levels are expressed. In practice, for both underwater and in-air sounds, it is very difficult to accurately measure the source levels of sounds, so modelling is normally used.

A.3.1 Calculating source level

The source level is usually inferred by back-calculating the sound from a number of far field measurements. To do this a number of hydrophones are placed at a distance from the sound source (for example an airgun) and the received levels of pressure are recorded at these distances. As sound energy travels away from the source the fluctuating acoustic pressure falls as the inverse of range (Section A.4). Thus pressure levels detected by the hydrophones when multiplied by the range forms a characteristic constant source output and when converted to a deciBel scale this becomes the source output. It should be borne in mind that this type of conversion is only applicable to sounds that spread spherically, or where the transmission loss is known, and is also only accurate for far field measurements as it tends to result in the overestimation of source levels.

A.4 Propagation of Sound and Transmission Loss

The process of a sound travelling through a medium is termed propagation. Transmission loss refers to the loss in acoustic power with distance travelled, and the rate of this decrease is influenced by a number of factors the most important being the frequency of the sound. High frequency sounds attenuate rapidly with distance, whereas low frequency sounds, which suffer lower levels of absorption loss can travel great distances.

A.5 Metrics Used to Describe Sound

Authors reporting on oil and gas sounds have used a variety of different metrics to describe the levels of sounds received at their measurement positions. These measurements are often described and presented with different units so that comparison between studies and reported value cannot readily be made. In this report sound levels are presented where possible as sound pressure Levels (0-peak, peak-peak and root mean squared) other metrics for sound exposure have been used including, sound exposure levels and impulse.

Where data has been the subject to transformations that were not done in this study the authors have been identified. The errors associated with converting the units and transforming the data, in some cases, may have introduced significant error, it is not possible to know the magnitude of any of these type of data manipulation errors.

A.5.1 Sound Pressure Level

Sound Pressure Level is commonly used to describe a level of sound. Sound Pressure Level (SPL) of a sound of pressure P is given in deciBels (dB) by:

$$\textit{Sound Pressure Level} = 20 \log_{10} (P/ P_0)$$

Where P is the measured pressure level and P_0 is the reference pressure. In underwater acoustics sound levels are typically referenced to a pressure of 1µPa. As this is a logarithmic scale caution should be applied when comparing sounds that are only a few dB apart using this reference system. For example, doubling the pressure of a sound leads to a 6dB increase in sound pressure level. Sounds measured in air using the dB scale are not directly comparable to measurements of underwater sounds unless they have been appropriately converted this is due to a different reference pressure 20 µPa being applied to air measurements.

A.5.2 Impulse

Impulse can best be considered as the average pressure of a wave multiplied by its duration and has been applied in the study of structural mechanics and in characterising the likely impacts of impulsive sounds on marine mammals (Yelverton, et al. 1975; Hamernik and Hsueh 1991). Acoustic impulse is defined by:

$$Impulse = \int_0^T P(T) \infty \, \mathrm{t}$$

Where I is the acoustic impulse in Pascal–seconds (Pa.s), P(t) is the acoustic pressure in Pa of the sound wave at time (t) and T is the effective duration of the waveform. The importance of acoustic impulse is that it takes into account the time, for example a wave acting for a given period of time will have the same effect as a wave of twice the pressure acting for half the time.

A.5.3 Sound Exposure Level

Sound Exposure Level or (SEL) is the time integral of the square pressure over a fixed time window, long enough to include the entire pulse and is therefore the sum of the acoustic energy over a measurement period. In order to calculate SEL Sound Exposure is first calculated by the formula below:

$$SE = 10log_{10} \int_0^T p^2 dt$$

Where P is the acoustic pressure in Pascals, T is the duration of the sound in seconds and t is time. The sound exposure is a measure of the acoustic energy and therefore has units of Pascal squared seconds (Pa^2-s).

To express the sound exposure as a logarithmic deciBel, it is compared with a reference acoustic energy level of 1 µPa.s. The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10log_{10} \int_0^T \frac{p^2 (t)dt}{Po^2}$$

A.6 Frequency Spectrum and Bandwidth

Oil and gas sounds, like most sounds, can be composed of many different frequencies. Spectral displays are a useful means of describing and presenting the frequency content of a sound. A common way of presenting the frequency content of a sound pressure density spectrum is in 1/3-Octave bands because in humans the effective filter bandwidth of the hearing system is roughly 1/3-Octave bands, bandwidth describes the frequency range of a sound.

A.7 Ambient Noise

Ambient noise, or background noise, are the overall sound levels that exist that are a result of both the anthropogenic sources (e.g. shipping intensity) and natural sources including wind, rain and biological sources for example, animal vocalisations. Ambient noise characteristics differ at different frequencies and under varying conditions. It is highly variable in shallow water where the primary sources of noise (such as meteorological, hydrodynamic or anthropogenic sources change and the dominant source, at that particular time, would dominate the frequency spectrum and associated source level.

B. APPENDIX B MARINE STRATEGY FRAMEWORK DIRECTIVE DESCRIPTOR 11:

The EU's Marine Strategy Framework Directive requires the setting of objectives for various descriptors, underwater noise is dealt with in Descriptor 11, the goal is to ensure that the *"Introduction of Energy, including underwater noise, is at levels that do not adversely affect the marine environment"*

A Task Group was set up to define possible indicators that could be used by Member States to define potential objectives. The task group focussed on sounds that reflect broad areas of the marine environment and suggested three possible indicators of underwater sound. Only the indicator for low, impulsive sounds will be discussed here, other indicators for high frequency impulsive sounds and low frequency continuous sounds were recommended. Following the recommendation by the Task Group the final European version of the indicator, which differed from the original Task Group recommendation is shown below.

Distribution in time and place of loud, low and mid frequency impulsive sounds

> *Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1µPa$^{2\cdot}$s) or as peak sound pressure level (in dB re 1µPa$_{peak}$) at one metre, measured over the frequency band 10 Hz to 10 kHz (11.1.1)*

Together with underwater noise, which is highlighted throughout Directive 2008/56/EC, other forms of energy input have the potential to impact on components of marine ecosystems, such as thermal energy, electromagnetic fields and light. It is recognised that additional scientific and technical progress is still required to support the further development of criteria related to this descriptor, including in relation to impacts of introduction of energy on marine life, relevant noise and frequency levels (which may need to be adapted, where appropriate, subject to the requirement of regional cooperation). At the current stage, the main orientations for the measurement of underwater noise have been identified as a first priority in relation to assessment and monitoring, subject to further development, including in relation to mapping. Anthropogenic sounds may be of short duration (e.g. impulsive such as from seismic surveys and piling for wind farms and platforms, as well as explosions) or be long lasting (e.g. continuous such as dredging, shipping and energy installations) and these sounds will affect organisms in different ways. Most commercial activities entailing high level noise levels affecting relatively broad areas are executed under regulated conditions subject to a license, for example oil and gas activities. This creates the opportunity for coordinating coherent requirements for measuring such loud impulsive sounds.