Underwater Noise Study Supporting Scottish Executive Strategic Environmental Assessment for Marine Renewables

S D Richards, E J Harland and S A S Jones

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QinetiQ Ltd
Cody Technology Park
Farnborough
Hampshire
GU14 0LX

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Authors	
S D Richards QinetiQ, Winfrith Technology Centre, Dorchester, Dorset. DT2 8XJ	01305 212327 sdrichards@QinetiQ.com
E J Harland QinetiQ, Winfrith Technology Centre, Dorchester, Dorset. DT2 8XJ	01305 212522 ejharland@taz.QinetiQ.com
S A S Jones QinetiQ, Winfrith Technology Centre, Dorchester, Dorset. DT2 8XJ	01305 212680 sajones@QinetiQ.com

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Abstract

A desktop study of underwater noise has been carried out in support of the Scottish Executive's strategic environmental assessment for marine renewables. Sources of ambient noise in the study area have been identified and characterised in terms of their: frequency content; relative level; and spatial and temporal variability. The mechanisms of noise generation in marine renewable devices have been identified and the sources of noise in a range of device types have been assessed. Illustrative noise spectrum levels for two examples of marine renewable devices (a tidal device and a wave device) have been used to assess the potential impact of device noise on receptors in the marine environment. The noise from these devices has also been compared with expected levels of ambient noise. Based on the limited information available to this study noise from these devices is not expected to result in significant impacts. Finally, the information shortfalls in this study have been identified.

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1 Introduction

1.1 Background

Scotland's geography and climate provide significant potential for the exploitation of renewable energy, including wind, hydro and marine. This places Scotland in a good position to contribute to the UK's overall renewable energy targets. The promotion of renewable energy is devolved and the Scottish Executive has assigned its own development targets for renewable energy to reach 18% of electricity generation by 2010 and 40% by 2020. A market-based mechanism has been put in place for the promotion of renewables in Scotland, the Renewable Obligation (Scotland). This places a legal obligation on electricity suppliers to provide a specified proportion of electricity generated using renewable energy sources. Marine renewables (wave and tide) are recognised and promoted by the Scottish Executive as offering a pivotal role in fulfilling its renewable energy targets.

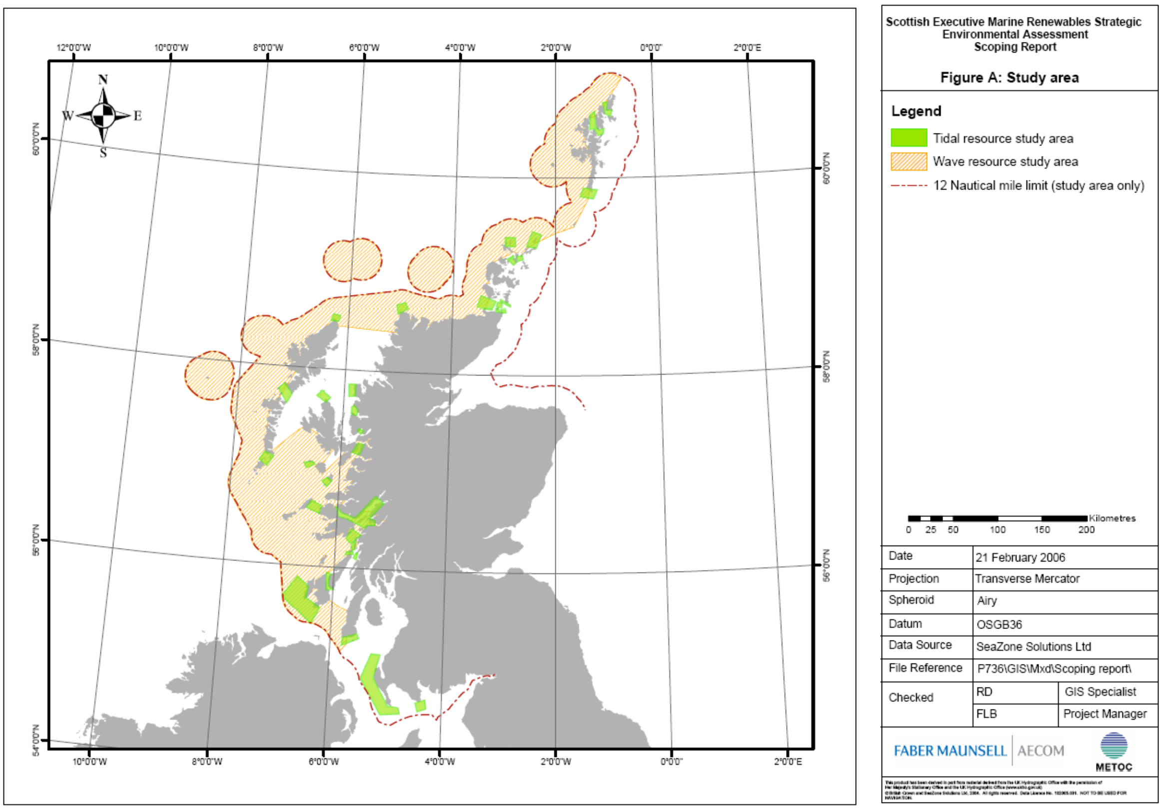

Figure 1-1: The SEA study area [1]

In 2005, the Scottish Executive commissioned a Strategic Environmental Assessment (SEA) prior to the development of marine renewable energy devices (wave and tidal) off the coast of Scotland. The study area considered in this SEA is shown in Figure 1-1. The SEA is a legal requirement of EU Directive 2001/42/EC enacted as the Environmental Assessment of Plans and Programmes (Scotland) Regulations 2004. Under this legislation, all spatial plans and programmes should be subjected to an SEA. Under the criteria set out in the Directive, the development of marine renewables is prescribed as requiring an SEA. The Environmental Assessment

(Scotland) Bill 2005 commits the Scottish Executive to go further than required by the SEA Directive, but does not apply retrospectively to the marine renewables programme.

The SEA for marine renewables is being conducted on behalf of the Scottish Executive by Faber Maunsell and Metoc Plc. The SEA is a transparent process and consultation is guided by a steering group that represents a broad range of stakeholders. All interested parties are given every opportunity to participate in the assessment or to examine the findings

The Scottish Executive requires some additional desk studies to be undertaken to support the SEA and address some of the gaps in information and understanding that have already been identified in a scoping report [1]. This report presents the findings of one of those studies, namely, underwater ambient noise, underwater noise from the operation of marine renewable devices and the potential impact of this noise.

1.2 This report

Section 2 of this report presents a general introduction to underwater ambient noise and the underlying mechanisms that generate sound.

Section 3 then identifies a number of sources of underwater acoustic noise, describes the characteristics of the noise including frequency content, levels and variability, and also identifies the current state of knowledge on each source. In all cases the sources are considered in the context of the SEA study area. Mechanisms that can modify the ambient sound levels are described in Section 4 and the dominant noise sources in the SEA area are identified in Section 5. It should be noted that the comments on noise sources are appropriate for the waters of the SEA area and may not be appropriate for other areas.

The noise from marine renewable devices is considered in Section 6, beginning with an introduction to the sources of noises in generators and how the sound may couple to the water column. Brief descriptions of some representative marine renewable devices are given and the likely dominant noise components from these devices are assessed qualitatively.

Section 7 discusses some pertinent measurements of underwater noise, including measurements of noise around a tidal current turbine in the Bristol Channel, the only known measurements of underwater noise emitted by a marine renewable device. Also discussed are some limited measurements of ambient noise previously conducted by QinetiQ in the SEA study area.

The noise field around marine renewable devices is considered in Section 8. Ambient noise modelling has been conducted to predict the background noise spectrum level in the study area. Projections of device noise levels from tidal current turbines are based on the measurements of noise from the turbine presented in Section 7. Estimates of the noise from a wave generator device have been carried out based on the engineering details and comparison with radiated noise from other similar marine systems. Section 8 also presents an analysis of the likely noise from arrays of marine renewable energy generators, and the effect of the number and spatial arrangement of devices in the array.

Section 9 presents a methodology for assessing the impact of noise from marine renewable devices on biological receptors in the marine environment. The potential impacts of single, commercial-scale devices and device arrays are considered, and the noise levels from devices are compared with predicted background levels at different ranges from the devices.

Information relating to noise from marine renewable devices is very scarce, and even the ambient noise levels are not well characterised. Section 10 therefore discusses the information shortfalls identified in this study.

Finally, the conclusions and recommendations of this study are presented in Sections 11 and 12.

1.3 Previous work

QinetiQ has a wealth of experience in underwater acoustics, primarily through its work in relation to military sonar. In addition the authors have previously carried out underwater noise studies for the Department of Trade and Industry's Strategic Environmental Assessment programme in SEA areas 6 and 7, which partly overlap with the present study area. This report draws upon those earlier studies.

2 Underwater ambient noise

2.1 What is ambient noise

Ambient noise is that sound received by an omni-directional sensor which is not from the sensor itself or the manner in which it is mounted. Noise from the sensor or its mounting is termed self-noise. Ambient noise is made up of contributions from many sources, both natural and anthropogenic. These sounds combine to give the continuum of noise against which all acoustic receivers have to detect the signals they are looking for.

Some researchers define ambient noise as the residual when identifiable sources, such as passing shipping, are removed. For this document the definition used is all contributions of noise, both local and distant, since this is the level that impacts bioacoustic receivers.

Ambient noise is generally made up of three constituent types – wideband continuous noise, tonals and impulsive noise. Impulsive noise is transient in nature and is generally of wide bandwidth and short duration. It is best characterised by quoting the peak amplitude and repetition rate. Continuous wideband noise is normally characterised as a spectrum level, which is the level in a 1 Hz bandwidth. This level is usually given as intensity in decibels (dB) relative to a reference level of 1 micropascal (μPa). Tonals are very narrowband signals and are usually characterised by their amplitude in dB re. 1 μPa, and their frequency. Ambient noise covers the whole acoustic spectrum from below 1 Hz, to well over 100 kHz. Above this frequency the ambient noise level drops below the thermal noise level due to the thermal motion of the molecules of the sea water.

In deep water the levels of ambient noise are now well defined and the contributions from various sources well understood. Urick [2] summarised this in the curve shown in Figure 2-1. In regions I and II the sound originates from turbulence and hydrostatic sources (e.g. tides). In region III the sound is more variable and is due to distant shipping. Region IV is dominated by sea surface noise originating close to the point of measurement while region V is dominated by thermal noise. In the context of this report, regions III and IV are the most important in the comparatively shallow Scottish coastal waters while all regions will apply in the deep water off the continental shelf, outside of the SEA study area. This difference between the deep water and shallow water regimes is primarily due to the fact the shallow water does not support the long range propagation of low frequency sound. This may best be understood in terms of normal mode theory. Normal modes are complicated functions representing waves travelling outwards from a source with an amplitude that is a function of the source and receiver depths. Figure 2-2 shows the sound pressure as a function of depth for the first four normal modes in a shallow water environment with a pressure-release surface[1] and a rigid (hard) seabed. The first mode occurs when the water depth is equal to one quarter of the acoustic wavelength. The frequency corresponding to this wavelength is termed the cut-off frequency, below which long range propagation is not supported. As an example, for a water depth of 25 m the wavelength at which the first mode is excited is 100 m, and the cut-off frequency is about 15 Hz. The cut-off frequency increases as the water depth reduces.

[1] A pressure-release surface has a pressure-amplitude reflection coefficient of -1, and a rigid boundary has a pressure-amplitude reflection coefficient of +1.

Wenz [3] summarised the noise levels in this part of the spectrum as shown in Figure 2-3. These are known as Knudsen spectra from the pioneering work carried by Knudsen to measure the levels of ambient noise [4]. The ambient noise spectrum will normally lie between the two thick black lines and is made up from a number of contributing sources. At the lower frequencies shipping noise will dominate, while at the higher frequencies noise from waves and precipitation will dominate. The frequency at which the change occurs is a complex function of local bathymetry, propagation conditions, shipping levels and weather.

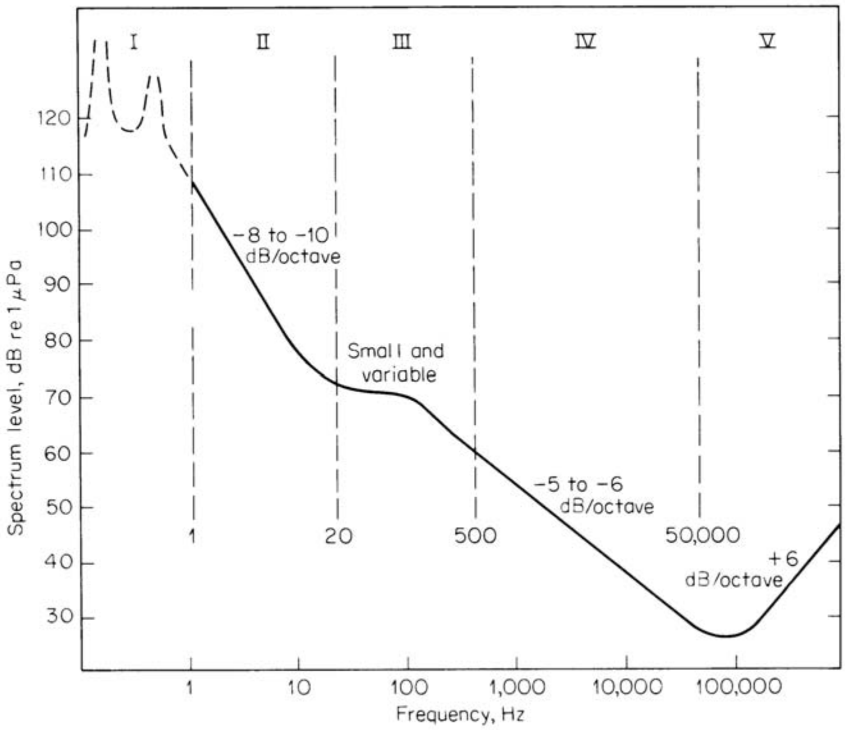

Figure 2-1: Deep water ambient noise (adapted from [2])

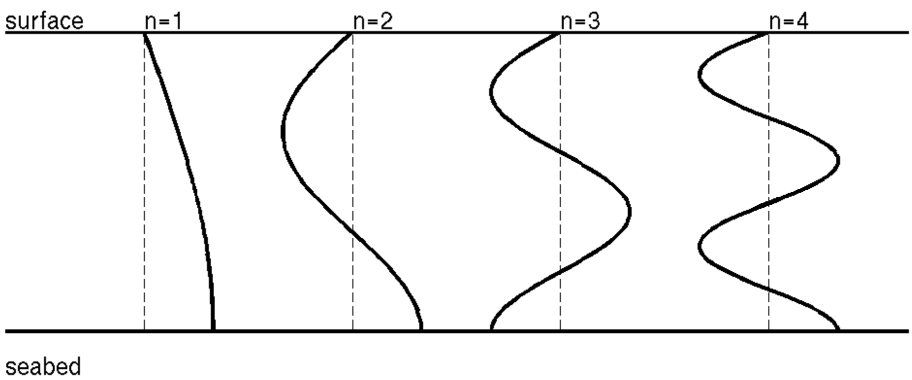

Figure 2-2: Sound pressure versus depth for the first four normal modes, for a pressure-release surface and a rigid bottom (adapted from [2])

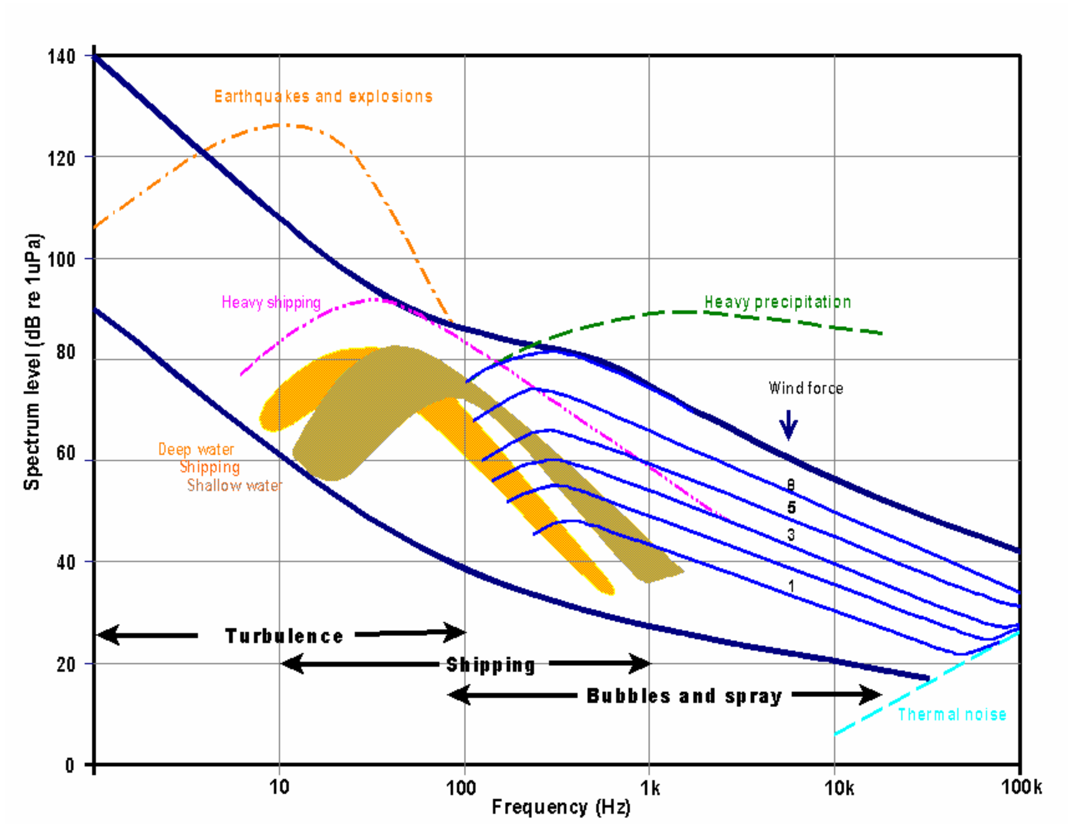

Figure 2-3: Composite of ambient noise spectra. (Adapted from [3])

In the deep waters to the west of the SEA area the curves in Figures 2-1 and 2-3 will be a good approximation to the levels found. At low frequencies shipping noise will dominate, particularly in the south of the area near the shipping lanes. At high frequencies (>10 kHz) increasing absorption prevents sound propagating over great distances so the ambient noise is dominated by local sound sources. Values for absorption are typically around 1 dB/km at 10 kHz rising to around 30 dB/km at 100 kHz. At 100 kHz, only very local sources contribute to ambient noise and above this frequency thermal noise takes over as the dominant source of noise.

In the shallower coastal waters around Scotland, the water is too shallow to support long range propagation of very low frequencies, owing to the cut-off effect described above, so the ambient noise at these frequencies will generally be lower than these curves suggest. Above about 100 Hz, depending on water depth, the Knudsen spectra will again provide a good approximation away from the coasts.

Close to the coasts, and particularly amongst the Scottish islands, the ambient noise levels are likely to be modified by shielding effect of the islands and the contribution from very local noise sources, such as surf noise.

2.2 Noise generation processes

Underwater noise can be generated by a number of processes:

2.2.1 Impact noise

Impact noise occurs when water strikes water, e.g. breaking waves; water strikes solid, e.g. waves hitting a rock; solid strikes water, e.g. hail hitting the water surface;

or solid strikes solid underwater, e.g. sediment noise ("saltation"). It is usually a broadband, transient noise, possibly with resonant peaks if solids are involved.

2.2.2 Bubble noise

Bubbles in sea water may be classified as either active or passive. Passive bubbles are quiescent and do not generate noise. Active bubbles are formed during an energetic process such as breaking waves or rain striking the surface. These bubbles oscillate and generate comparatively narrowband signals centred on the resonant frequency of the bubble, typically in the range 15 to 300 kHz. Collective oscillations of bubble clouds, particularly under breaking waves, can have resonant frequencies which are much lower than this.

2.2.3 Turbulence

Turbulence associated with surface disturbance or turbulent tidal flow around an obstruction generates low frequency continuous noise.

2.2.4 Seismic

Movement of the seabed can be coupled into the water column and generate very low frequency noise.

2.2.5 Anthropogenic

Anthropogenic noise can be generated by all of the above processes. As an example, a ship moving through the water will generate impact noise by wave slap, bubble noise from entrained bubbles due to the propulsion and passage through the water and turbulence noise due to the disturbed water. In addition a number of additional generation processes may be encountered:

a. Cavitation - propellers and other fast moving objects in the water can cause cavitation noise when the pressure in the flow around the moving object drops sufficiently below the ambient pressure. This causes cavitation bubbles which very quickly collapse, causing a loud transient sound. The resulting spectrum is wideband but generally has a peak between 100 Hz and 1 kHz;

b. Machinery noise - machinery generally produces a broadband continuous spectrum with tonals superimposed resulting from the rotation rates of the various parts of the machinery and their harmonics. There may also be impulsive sounds;

c. Tonals - some systems either deliberately, or as a by-product, generate high levels of tonal signals e.g. sonar systems, seal scarers; and

d. Air guns - these are used in seismic surveying, and generate high levels of low frequency, broadband sound.

3 Sources of ambient noise

3.1 Wind-sea noise

A number of early observations of ambient noise suggested that between 500 Hz and 25 kHz the ambient noise levels were dependent on wind speed. Based on these observations the Knudsen spectra were defined [4], relating noise level to wind speed, or sea state, as shown in Figure 2-2. Later observations showed that that the noise level was dependent on wind speed in the vicinity of the receiver.

The dominant mechanism for the generation of wind-sea noise at the ocean surface is breaking waves, although this mechanism is still not fully understood. Laboratory measurements reported by Medwin *et al*. [5,6] demonstrated that the characteristic 5 dB/octave slope of the Knudsen wind-sea noise spectra results from the incoherent sum of the noise from individual resonant bubbles. At higher sea states, with vigorous breaking waves, large amounts of air are entrained and bubble oscillations may be coupled, leading to collective oscillation of bubbles in a plume [7]. Melville *et al*. [8] found that the sound radiated by breaking waves increases with sea state and is related to the volume of air entrained as a result of waves breaking.

The dependence on wind speed holds even below the speeds that produce breaking waves and this may be due to flow noise as the wind passes over the sea surface and/or by bubbles induced from capillary waves produced at the sea surface by the wind.

To determine wind-sea related ambient noise levels in a particular area a knowledge of the wind statistics is needed and from this an assessment of the contribution of wind-sea noise can be made. The contribution is made up of locally-generated noise at all frequencies plus a contribution from more distant sources at lower frequencies. Because of interaction with the seabed and sea surface, particularly in areas on the continental shelf, a knowledge of acoustic propagation conditions is also needed to determine the overall contribution from wind-sea interactions.

There is likely to be a diurnal and annual cycle in the contribution of wind noise to ambient noise levels due to seasonal and diurnal changes in the meteorological conditions and water column properties. In those areas with a significant tidal flow there will also be tidal and lunar cycles.

3.2 Precipitation noise

Precipitation in the form of rain or hail can cause significant elevation of ambient noise levels in the 1 to 100 kHz region. The noise is generated by a number of mechanisms, including impact noise as the rain or hail impacts the surface of the water and oscillation of the bubble entrained by the raindrop. Large raindrops can cause a more complex acoustic signature through multiple impacts and entrainment of more than one bubble. At low wind speeds bubble oscillation is the dominant noise source in UK waters, with impact noise dominating at higher wind speeds.

In the SEA area, particularly during the winter months, precipitation is likely to be a significant contributor to ambient noise. To estimate the contribution of precipitation noise to ambient noise, knowledge of the statistics of precipitation for the area of interest is needed. The annual cycle may then be integrated to calculate the relative contribution of precipitation to ambient noise levels. There will be an annual cycle in the variation of the contribution of precipitation noise to ambient noise.

3.3 Shore and surf noise

The shoreline around the SEA study area is predominantly rocky and exposed to extreme wave action. The few beaches are predominantly sandy.

Because of the exposure to waves coming in off the Atlantic, it is likely that shore and surf noise will be a major contributor to ambient noise in coastal waters in the SEA area. The noise will mostly be impact noise as the wave hits the rocks, spray noise as the water falls back onto the sea, bubble oscillation noise and some limited sediment transport noise, including surfseisms[2] and saltation[3]. Figure 3-1 shows the regions of the spectrum in which each of these mechanisms is important.

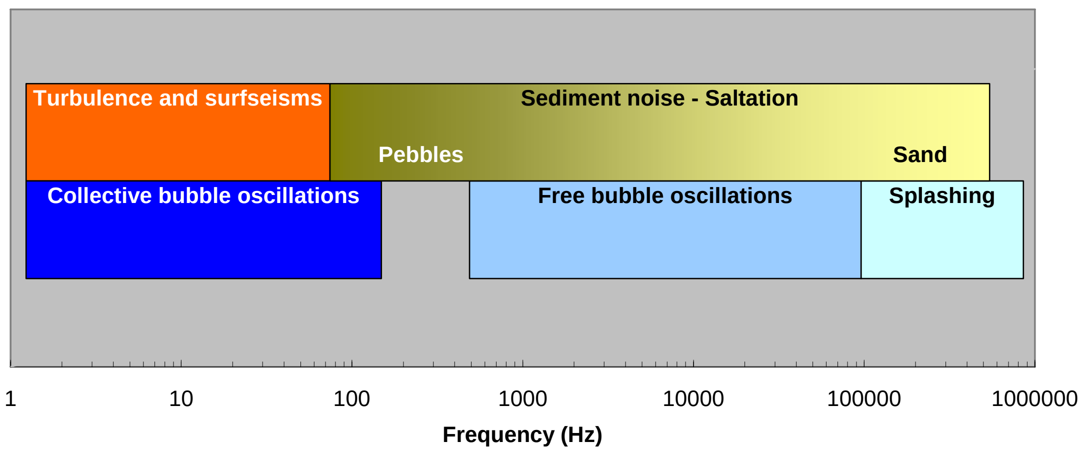

Figure 3-1: Contributions to the surf noise spectrum

It should be remembered that apart from the Scottish coastal waters, there are the offshore island groups, e.g. the St Kilda group and the Flannan Isles. Because of the extreme wave action they are likely to contribute high levels of noise into their immediate environment.

There will be an annual cycle associated with the contribution of shore and surf noise to overall ambient noise.

3.4 Sediment transport noise

Under some circumstances it is possible for the surficial sediment on the seabed to become highly mobile. The surf zone is perhaps the obvious example, but sediment transport can also occur away from the shoreline. Sediment transport predominantly occurs where the water is shallow (<10 m) and there is a current running and/or there is significant wave height to disturb the seabed. This occurs most readily with light

[2] Surfseisms are elastic waves generated in the seabed by pounding surf.
[3] Saltation refers to the bouncing motion of particles which are dislodged from the bed, are suspended for a short distance and then fall back to the bed, dislodging more particles on impact.

sediments such as clays or fine sand. The sediment particles collide with each other and obstacles on the seabed and this generates high frequency noise. The noise is mostly above 10 kHz with peak frequencies at a few tens of kHz. The actual spectrum depends on particle size and material. The effect has been observed in the English Channel [9] (and pers obs[4]), the North Sea [10], and the Bristol Channel (pers obs[5]). The effect can last for periods of less than a minute up to periods greater than an hour, depending on the tidal conditions.

Measuring sediment transport noise is very difficult. Deploying a hydrophone can result in measurements of noise levels which are elevated by up to 40 dB above the background level during major events, but most of this noise is caused by the particles hitting the hydrophone and its surrounds and it is then questionable whether one is measuring ambient noise or self noise. In terms of impact on a biological receptor, the impact noise is likely to be less because of the nature of flesh compared with metalwork or hard epoxy encapsulant. It is also likely that the receptor would choose to move out of the main sediment flow for a number of reasons. Within the SEA area there will be some sediment transport noise associated with surf, and there will be some movement associated with the very strong tides around some of the Scottish islands.

The sediment transport noise contribution to ambient noise will vary with the tidal cycle, the lunar cycle and the annual cycle.

3.5 Aggregate extraction

The dredging of deep deposits of gravel is inherently a noisy operation. The resulting noise is a mixture of mechanical noise from operation of the dredge and a noise similar to sediment transport noise resulting from the disturbance of the gravel.

No published information on noise levels from aggregate extraction in the SEA area has been identified in the course of this study. There is some published information on aggregate extraction in the English Channel [11] and dredging activity associated with oil field development [12] but this is likely to have been carried out in different water depths, over different sediment types and with different types of dredgers. It is believed that a number of other acoustic measurements have been made of aggregate extraction activity but the information is in company reports and could not be obtained during this short study.

Although aggregate extraction is not taking place in the SEA study area there may be areas where shipping channels in the vicinity of ports are dredged.

3.6 Commercial shipping

Shipping noise is the dominant contribution to ambient noise in shallow water areas close to shipping lanes and in deeper waters. Shipping noise is most evident in the 50-300 Hz frequency range. At longer ranges the sounds of individual ships merge into a background continuum. At higher frequencies the dominant noise source is likely to be wind generated noise. Shallow water acts as a high pass filter, with the cut-off frequency increasing as the water gets shallower, as discussed in Section 2.1. In very shallow coastal waters distant shipping noise makes little or no contribution

[4] A hydrophone 1.5 metres above the mixed sand and broken shell seabed in Durlston Bay in Dorset detected noise levels raised by 40 dB at 15-20 kHz during easterly gales and mid-tide.
[5] A hydrophone deployed mid-water in the tidal rip off Bull Point in Devon detected noise levels raised by ~20 dB at 15-20 kHz for 30 minutes during the flood tide.

to ambient noise. In the context of this paragraph, shallow water is defined as being too shallow to support the long range propagation of shipping noise, i.e. typically tens of metres.

Close to ships under way the noise spectrum splits into a number of regions. At low frequencies below 1 kHz there is a continuous wideband spectrum of noise with a number of tonals originating from rotating machinery superimposed. Above 1 kHz the machinery noise diminishes and water displacement noise becomes dominant. This drops below other sources of noise above 20 kHz. Additional noise may be caused by propeller cavitation and faulty machinery. Strong tonals can be generated by a singing propeller[6], a faulty gearbox or by electrical generation machinery. As an example a recent set of measurements for an 11 m workboat revealed a tonal at 800 Hz that was 40 dB above the other noise sources on the boat. This was traced to a faulty gearbox [14].

Different types of ships have different contributions from the different noise sources. For a fast ferry, the major noise sources are from displaced water in the 5-20 kHz region plus strong tonals in the region of a few hundred Hertz from the machinery, while for a small coaster virtually all of the noise is from the propulsion machinery below 200 Hz.

The SEA area carries a significant amount of commercial shipping. This mostly originates from traffic to and from the major ports of Liverpool, Dublin and Belfast moving into and out of the North Channel. In addition, shipping passing around the north of Scotland and out into the Atlantic will also make a significant contribution. There are few major ports within the SEA area and although there are still ports operating in the Clyde area the number of port movements has reduced greatly since the mid-twentieth century. However, within the coastal waters of Scotland, inter-island ferries will make a significant contribution to shipping noise and there are a number of oil and gas supply vessels operating in the study area.

Away from the main shipping lanes a major contribution is likely to come from fishing boats. There is a variety of fishing activity in and around the SEA area, ranging from inshore potting to offshore deep-water trawling. As the fishing boats move around the area they are likely to provide a significant contribution to shipping noise. See Section 3.13 for information on noise arising from fishing activities.

Shipping noise will vary on a diurnal cycle (ferry and coastal traffic) and an annual cycle (seasonal activity). In the vicinity of ports having a tidal dependency, the shipping noise may also vary over the tidal cycle.

3.7 Leisure craft

Over a number of years there has been a steady increase in the numbers and types of leisure craft in use around the UK. There has also been a steady increase in the engine power available to such craft. This has resulted in a considerable increase in underwater noise levels produced by this class of sound source and in holiday areas this can be the dominant sound source through the summer months. A number of workers have attempted to gather statistics on leisure craft traffic, particularly with regard to environmental impact [15, 16].

Leisure craft can generally be grouped into a number of classes:

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[6] Propellers can oscillate strongly when the blade resonance is excited by vortex shedding from the blade tips. The tonal is usually in the 100-1000 Hz region. See [13] for a more detailed explanation of the effect.

a. sailing craft;

b. slow motorboats;

c. high speed motorboats; and

d. personal watercraft.

Sailing craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise. Racing yachts produce higher noise levels because of their increased speed, but are still much quieter than motorboats travelling at the same speed.

Slow motorboats generally produce low frequency noise from propulsion machinery containing broadband and tonal components, plus higher frequency broadband noise due to water impact and disturbance.

High speed motorboats use one or more high-powered engines to achieve planing speeds and generally cause considerable disturbance to the water surface. As well as the low frequency sounds, often with loud tonal components from the machinery, the high frequency sounds are enhanced by the disturbed water thrown up by the passage of the boat impacting the surface of the water and generating broadband noise. This noise typically dominates the signature in the region 5-25 kHz.

Personal watercraft, such as jet skis, are generally very small craft capable of carrying just one person, but fitted with a high power engine. The propeller is normally ducted and this reduces the noise output. The engines and impellers usually operate at high speeds so the predominant noise output is higher in frequency than other leisure craft.

Leisure craft activity is highest around their home ports where they are used for day running. Other common activities include racing and port to port cruising. Because they generally use smaller ports or purpose built marinas the main leisure craft routes are generally separated from the commercial shipping routes and are usually closer inshore.

Variations in leisure craft noise occur on a number of cycles. The diurnal cycle is generally bimodal with a morning peak as craft leave harbour and move out to whatever activity they are undertaking plus a second peak in the late afternoon as the craft return to harbour. These two peaks are superimposed on a broader day/night cycle with much reduced activity through the night. On a weekly basis there is a broad peak in noise corresponding to weekend activity. There is also an annual cycle with much increased activity through the summer months and very little activity through the winter months.

Within the SEA area, leisure boating is mostly confined to the Scottish coastal waters, but during the summer months there can be a high level of activity.

There is generally a good understanding of the noise levels produced by the different vessel classes but there appears to be little information on the numbers and distribution of such craft through the year. It is also not clear how the very different noise contributions from the different types of craft combine to contribute to the ambient noise levels and spectra.

3.8 Industrial noise – offshore

Offshore industrial noise includes the noise generated by the operation of offshore wind turbines, tidal and wave energy generators, oil and gas rigs and offshore construction noise.

Oil and gas rigs generate underwater noise by conduction of the noise from machinery on the platform into the water column. This is likely to comprise low frequency tonal noise from the rotating machinery (<1 kHz) and a wideband noise level made up of many individual contributions from all the noises sources on a typical rig. A literature search of peer-reviewed journals did not find any information on the noise fields around oil and gas rigs.

Wind farm operational noise is likely to originate from machinery noise coupling via the tower into the water column and/or substrate and also from the rotating blades coupling via air movement into the water surface. A likely third source will be noise from the power cables to the shore. When cables carry high alternating currents the magnetic field around each core causes alternate attraction and repulsion and this can result in physical movement and hence a signal in the water. Again, a literature search failed to find any papers on the noise from wind farms in the peer-reviewed journals and only a very small number in the grey literature [e.g. 17-20].

The construction of offshore and near-shore facilities such as wind farms, marine renewable devices or harbours may involve pile driving and this is inherently a noisy operation. Nedwell claims source levels as high as 262 dB re. 1µPa at 1 m, inferred from measuring the noise of piling associated with the construction of the North Hoyle and Scroby Sands wind farms [19]. Sounds from harbour construction pile driving have been heard 50 miles away (pers obs[7]). Attempts have been made to reduce the radiated noise by using bubble curtains around piling sites [21] with limited success.

Within the SEA study area there are no operational oil or gas platforms and no offshore wind farms. Seismic surveying activities for hydrocarbon exploration are considered in Section 3.11.

Noise from the operation of marine renewable devices is considered later in this report.

3.9 Industrial noise – onshore

Industrial activity onshore adjacent to the coastline can produce underwater noise by coupling through the substrate. Noise levels are only significant if the noise is intense e.g. quarry blasting[8], or if there are a number of noise sources e.g. an area of heavy industry.

Transport systems close to the coastline e.g. motorways or railway lines can also couple noise into the underwater environment via the substrate.

The coupling through the substrate will generally only occur at very low frequencies (<100 Hz).

A literature search found no information on levels or spectra from this type of source.

In the SEA area this is not a major contributor to ambient noise. Although a few quarries are operating adjacent to the coasts, their contribution to ambient noise levels will be insignificant.

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[7] During a research cruise in the Tyrrhenian Sea, pile driving in Monaco harbour was clearly heard off the north coast of Sardinia.

[8] Quarry blasting in the Purbecks, Dorset, can be clearly heard on a hydrophone 400 metres offshore and 3 miles from the quarry.

There may be significant levels of road noise coupling through the substrate to the water column from the Inner Clyde area.

3.10 Military noise

The military can generate underwater noise by the use of ships, aircraft, explosives and active sonar transmissions. Active sonar use within the SEA area is described in the next section.

Military ships are generally very quiet and make only a small contribution to overall shipping noise. The sounds generated by explosives are very impulsive close to the event, but long-distance propagation smears the energy in time and frequency to give sounds above ambient for many seconds. There are a number of areas where military exercises and trials may take place:

a. Benbecula ranges;

b. Clyde noise ranges (Loch Goil, Loch Fyne) and the Clyde exercise areas;

c. Raasay BUTEC range; and

d. Cape Wrath bombing range.

In addition, the whole area, particularly out to 12 degrees west, is widely used by the Royal Navy for research trials, exercises and live firings. Although explosives are used across the whole area, the only area where this is likely to be significant is the Cape Wrath bombing range. No statistics were available on usage of the range so it is not possible to identify the contribution to ambient noise.

3.11 Sonar

Sonar is widely used by leisure, fishing and commercial vessels and there is also military usage within the SEA area. Typical sonars currently in use are:

a. echosounders;

b. fish-finding sonars;

c. fishing net control sonars;

d. research sonars;

e. acoustic modems;

f. air guns for seismic surveys and reservoir monitoring; and

g. military sonar.

By far the most prevalent of these is the ubiquitous echosounder. Most vessels from small leisure craft up to the largest commercial ships have at least one echosounder. These work at frequencies from 26 kHz to 300 kHz with source levels up to 220 dB re. 1 µPa at 1 m. These sonars direct their energy downwards into the seabed but there is significant energy travelling horizontally either from the sidelobes of the transducer or by scatter off the seabed. The higher frequencies are attenuated over short distances by absorption, but the contribution to ambient noise is significant due to the high numbers of such units.

Commercial fishing sonars can also make a major contribution to ambient noise because of their lower frequencies, higher power and greater power directed horizontally. The contribution is mostly limited to the grounds favoured for fishing, but it should be noted that this is also the most sensitive region, with the highest density of fish and cetaceans.

Research sonars are used to map the seabed and to study oceanographic conditions. The SEA area has been visited by research ships on many occasions over the years to either map the area in some detail, or to test new equipment.

Acoustic modems are used to carry data from seabed installations to the surface and typically work in the range 2 to 20 kHz, depending on data rate and range required. They are generally omnidirectional and can generate high power levels. It is not known how many are in use in the SEA area but it is likely that they will be in use by scientific equipment deployed throughout the area.

Air guns are used to generate very high level impulses of low frequency sound directed downwards into the seabed for geological survey work. Source levels may be as high as 250 dB re. 1 µPa at 1 m, with a centre frequency between 50 and 100 Hz. These system have been widely used in the area and on a number of occasions the authors have observed ambient noise levels raised by >50 dB for many hours due to operation of multiple profilers along the shelf-edge and deeper waters to the west of the SEA area. In more recent years there has been a downturn in exploration activity but there is still activity around the SEA area. In the summers of 2004 and 2005 weak signals could be heard from exploration activity well outside the SEA study area.

Military sonars use high power transmitters to generate tonal signals in the range 1 to 300 kHz and with pulse lengths between 0.1 and 4 seconds, depending on mode of operation. High frequencies above 80 kHz are used by mine hunters and the high acoustic absorption coefficient of seawater at such frequencies means that any impact is limited to a very small area around the ship, typically less than 3 km. Lower frequencies (<3 kHz) are used in the deeper waters but can fill a whole ocean basin with sound. In the shelf region to the west of the Hebrides medium frequencies are most likely to be used (3 to 10 kHz).

No published information has been identified in this study on the statistics of sonar usage. It is not clear how many civilian and military sonars are operating in the SEA area at any one time so it is not possible to judge their contribution to ambient noise levels.

3.12 Aircraft noise

Aircraft noise can couple through the sea surface when an aircraft flies low over the sea [22]. This can happen when fixed wing aircraft approach a runway located on the coast, or a helicopter operates low over the sea.

Helicopter noise originates from the disturbance of the sea surface by the down wash from the blades and by coupling of blade noise directly into the sea. The down wash noise is very similar to wind noise in frequency characteristics and is greatest in the 2 to 20 kHz region. Blade noise contains a number of components originating from the rotation of the blades and the machinery that drives the blades. There are a number of strong tonals in the 10 to 100 Hz region associated with rotor operation and a strong tonal component at the turbine blade rate which is typically around 10 kHz[9].

[9] Most information on helicopter noise is classified by the military. This information was derived from an opportunistic measurement of the Portland Coastguard search & rescue Sea King helicopter.

Aircraft noise is not expected to be a significant contributor to ambient noise in the majority of the SEA area, except perhaps in the vicinity of some of the offshore island airports (e.g. Benbecula). Noise caused by helicopters servicing lighthouses and oil/gas rigs is significant during the event, but these events happen so infrequently that there is unlikely to be any major impact on the environment.

Desharnais and Chapman [23] showed that sonic booms from aircraft can also penetrate into the water column, producing a low frequency pressure pulse. The only current source of such booms in the SEA area is likely to be military aircraft and such booms happen so infrequently that their contribution to ambient noise levels is negligible.

3.13 Fishing activity

Commercial fishing can make a contribution to ambient noise in a number of ways. Apart from the contribution of the vessel noise and the use of sonar to find fish and monitor nets, the most significant contribution is trawl noise, particularly from bottom trawls. The sound of chains and rollers being dragged across the seabed can often be heard several miles from the activity.

The overall noise field from the fishing gear consists of low frequency noise from the rollers, mid and high frequency noise from the general disturbance of the seabed and high frequency noise from the chains. No published information on absolute levels or typical spectra has been found.

Personal observation suggests that the major area for trawling is along the shelf-edge to the west of the Hebrides, where trawling noise has been tracked on military sonars at ranges in excess of 8 km.

Fishing noise is likely to vary on a diurnal cycle, a lunar cycle and an annual cycle.

3.14 Biological noise

Many fish can produce sound, particularly as part of the mating process. Although the UK does not have the highly vocal species to be found in tropical seas, many UK fish can produce some sound.

The most vocal of marine species are the cetaceans, and species to be found in the SEA area can produce sounds over the range 15 Hz to 200 kHz. In the deep waters off the shelf fin whales (*Balaenoptera physalus*) and sperm whales (*Phyceter macrocephalus*) can be major contributors to ambient noise levels. In the inshore waters there are many of the smaller species, particularly Atlantic white-beaked dolphins (*Lagenorhyncus albirostris*), Atlantic white-sided dolphins (*Lagenorhyncus acutus*) and harbour porpoises (*Phocoena phocoena*). These also contribute to the ambient noise levels.

Cetacean sounds are either tonal whistles in the range 2 to 25 kHz, or wideband echolocation clicks with maximum energy in the 40 to 140 kHz region. Source levels for the tonals sounds are around 170 to 180 dB re. 1 µPa at 1 m, while echolocation clicks range from a source level of 175 dB re. 1 µPa at 1 m for the harbour porpoise up to 226 dB re. 1 µPa at 1 m for the bottlenose dolphin (*Tursiops truncatus*).

Seals are also very common in the waters around the Hebrides and northern islands, and, although not as vocal as the cetaceans, can make a significant contribution to ambient noise at certain times of the year, particularly during the breeding season (July to August) when the male harbour seals emit a broadband roar.

Biological noise has been observed to vary on a diurnal cycle, a tidal cycle and an annual cycle.

3.15 Thermal noise

In the absence of all other sources of ambient and self noise, the underlying noise level is determined by thermal motion of the molecules. This noise rises proportionally with frequency and typically is only important above about 100 kHz. Ambient noise generally falls with increasing frequency until thermal noise dominates when the slope changes to a 6 dB per octave rise with increasing frequency. The noise spectrum level from thermal noise is given by

$$N_{\text{thermal}} = -15 + 20\log_{10}(f) \quad \text{dB re. 1 μPa,} \qquad (3\text{-}1)$$

where f is the frequency in kHz.

3.16 Typical source levels

Table 3.1 summarises the typical source levels and frequency bands for a number of discrete sources of underwater noise. Note these figures are indicative only and should not be taken as absolute values for specific sources.

Source	**Typical source level (dB re. 1 µPa at 1 m)**	**Typical frequency range (kHz)**
piling noise	262 (see [19])	0.1 – 5
airgun array	250	0.05 – 0.1
sperm whale echolocation	237	2 – 40
medium frequency sonar	235	3 – 7
multibeam echosounder	up to 235	10 – 300
bottlenose dolphin echolocation	226	80 – 120
supertanker	200	0 – 0.3
cetacean tonals	170 - 190	2 – 25
harbour porpoise echolocation	175	130
fishing vessel	150	0.01 – 1

Table 3-1: Typical source levels and frequency bands for sources of underwater noise (for indication only)

4 Ambient noise field modifiers

4.1 Introduction

Section 3 set out the variety of sources of ambient noise in the SEA area. The sound field at any one site is a composite of many of these sources. In addition to the complicated sum of components there are additional effects which will modify the level and spectral content of the ambient sound field. This section will describe these effects and the sound field modification that may be observed.

4.2 Acoustic propagation

Sound produced by the various ambient noise sources propagates to a receiver through the very complex underwater environment. Because of variations in the sound speed profile, caused by variations in temperature, salinity and pressure, the path followed by the sound waves can deviate markedly from a straight line. The structuring is most marked in the vertical plane, causing sound to be refracted upwards or downwards, depending on the sound speed gradient, but horizontal structuring can also be encountered. As sound is refracted up or down it may interact with the surface and the sea bed by reflection and scattering. The level of signal arriving at a distant point is a complex sum of many paths that may or may not have interacted with the seabed and sea surface.

Variations in salinity are generally very small, except perhaps at the mouth of major rivers, and pressure variations are due almost entirely to depth so temperature variations have the major effect on sound propagation in shallow water.

Under some conditions, a mixed isothermal layer forms close to the sea surface as a result of mixing initiated by waves and turbulence. The existence of a mixed layer, and its thickness (typically 25 m to 200 m) depend upon atmospheric factors such as the wind stress at the surface and the heat flux across the surface, and fresh water exchange. The mixed layer acts as a surface duct which may trap the acoustic signals, because the sound speed profile within the duct tends to refract sound upwards and the surface acts as a reflector. A source and receiver located within this surface duct experience significantly less propagation loss than when there is no surface duct. During the day the sea surface can heat up and introduce a temperature gradient close to the sea surface that causes downwards refraction and hence increased propagation loss for a receiver in the surface layer.

Because the sound can interact strongly with the seabed, the sediment types and sea bed roughness can affect propagation loss. Similarly, waves on the surface can also affect propagation loss by scattering the sound interacting with the surface rather than just reflecting it.

Suspended sediments or bubbles can cause additional propagation loss.

Propagation loss varies on a diurnal basis, particularly during the early summer, and on an annual cycle, as the air temperature variations through the year warm and cool the water. A period of sustained strong wind can also disrupt the temperature structuring.

4.3 Multi-path effects

Because of the surface and sea bed reflections sound can travel between a source and receiver by a multitude of paths. This has the effect of dispersing the arrived signal in time. This effect is particularly important for wideband impulsive sounds such as explosions, pile driving or seismic exploration air guns. If any of the propagation effects are frequency sensitive then frequency dispersion will also occur. A common example of this is the sound of air guns operating at distances of 30 to 50 km from a receiver in which the low frequencies travel more slowly than the high frequencies so the single impulse at the source turns into a pronounced frequency sweep at the receiver. The effect of time dispersion is to reduce the peak energy in the received signal. The integrated level is unchanged by time dispersion, but the peak levels can be significantly reduced. When considering the contribution to ambient noise levels this can be an important factor. For narrowband signals, the effects of multi-path propagation can cause large fluctuations in the received signal level.

4.4 Source and receiver depth

The vertical sound speed structure described above can lead to significant variations in the propagation loss between a sound source and the receiver as the depth of the source and/or the receiver is varied. The most extreme example is the surface duct where a shadow zone may form under the duct. Within the shadow zone levels from a distant sound source in the duct are much reduced compared with the level from the same source within the duct.

4.5 Tides

In the deep waters to be found to the west of the SEA area, the variations in depth due to tides are insignificant. However, in inshore waters the effect is much more pronounced and can significantly alter ambient noise fields through the tidal cycle.

Sand banks that dry at low water can also break acoustic paths so a receiver hearing a loud noise source across a sand bank at high tide may not receive it at low tide.

5 The composite noise field

Section 3 listed the possible contributors to ambient noise within the SEA area and Section 4 showed how this sound can be modified by a number of environmental factors. In this section the most likely dominant noise sources across the area are mapped. This information is based on the information gleaned during this study, from the experience of the authors when working in the SEA area and from a much wider experience of studying the various sources of ambient noise over many years of sonar research trials.

Figure 5-1 is a map of the SEA area and surrounding regions, showing the authors' assessment of the dominant noise sources across the area. Note that this map represents the situation at low wind speeds and with no precipitation noise. When the weather deteriorates it is likely that wind and rain noise will dominate over large areas and that the region within which shore and surf noise dominates will extend further offshore. It should also be noted that the areas affected by different noise contributions will vary through the year as acoustic propagation loss varies through the seasons.

From Figure 5-1, it can be seen that shipping noise is likely to dominate across large parts of the SEA area. The coastline is likely to be dominated by surf noise and shore noise. The map shows the areas in which local shipping activity is likely to dominate the ambient noise level. These areas include the shipping lanes which pass through the region and also the shelf edge, which is where fishing activities are likely to be most prevalent. In addition there are a number of ferry routes operating between the Hebrides and the mainland which will also contribute to the local shipping noise. Also plotted are the location of the Foinaven offshore oil production facility at 60° 19' N, 4° 17' W, the Schiehallion production facility at 60° 20' N, 4° 02' W and the Beatrice oil field in the Moray Firth area. Although these installations are not within the SEA area it is possible that, under the right conditions (e.g. the presence of a strong surface duct with a calm, flat surface), sound could propagate into the SEA study area. It is also worth noting that a wind farm demonstration project is under construction at Beatrice.

Some of the sheltered sea lochs will have very low levels of ambient noise when there is little or no wind or precipitation, and the dominant contributions here are likely to be natural background noises, including biological sounds.

It should be noted that just because a particular noise source is dominant in a given area it does not necessarily mean that other sources may be neglected in that area: the total noise level from all sources may be significantly higher than the level due to the dominant source alone; different sources may dominate in different parts of the spectrum; and bio-receptors may be more sensitive to a less dominant noise source in a different frequency range.

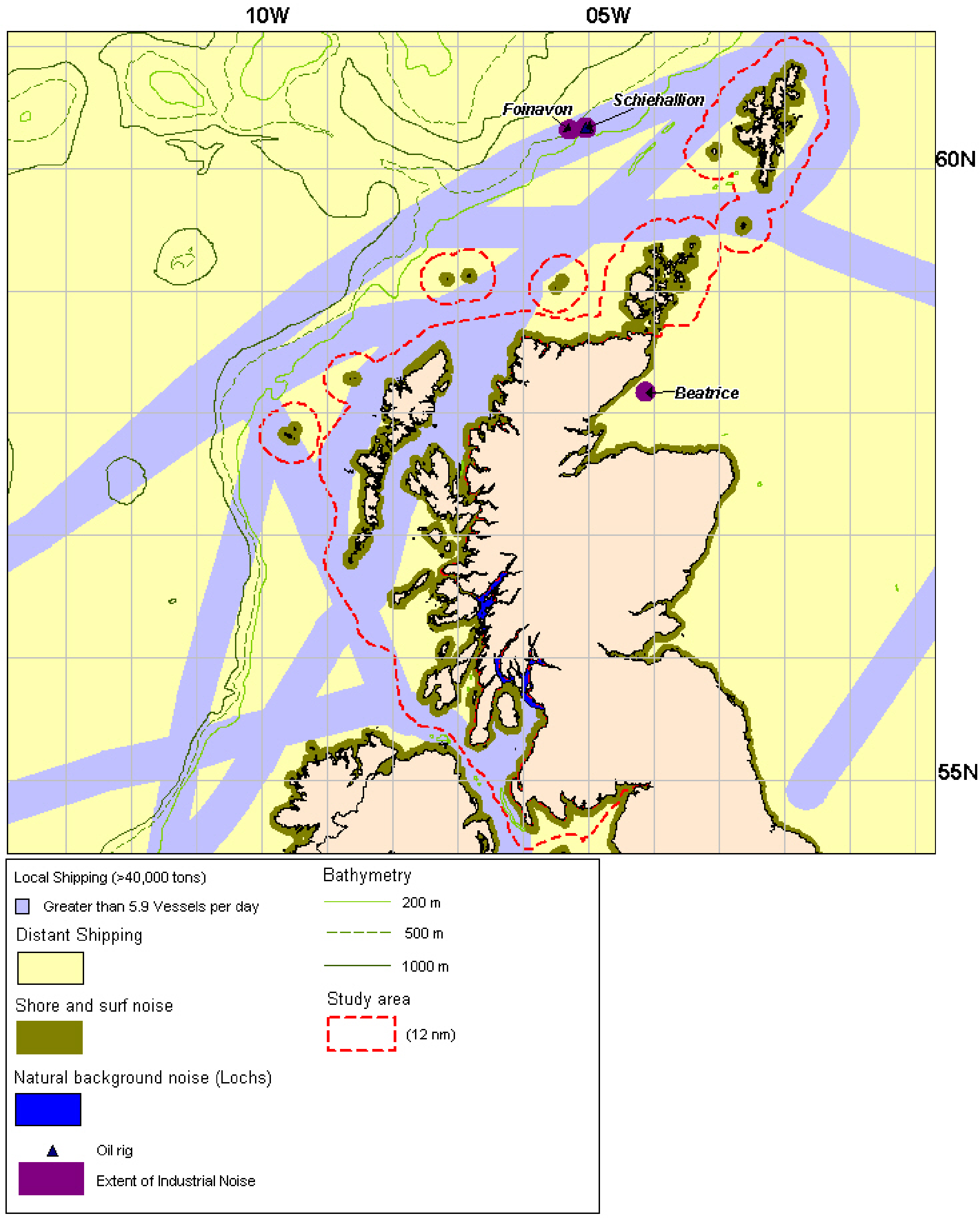

Figure 5-1: Dominant noise sources in the SEA study area when there is little or no wind and precipitation. When weather conditions deteriorate wind and precipitation noise will dominate over most of the area and the region in which shore and surf noise dominates will extend further offshore.

6 Noise from marine renewable devices

This section describes the generic sources of noise in typical machinery and how that noise can be coupled into the marine environment. It then looks at each of the types of tide and wave generators and attempts to identify potential sources of noise.

In this short study it has only been possible to consider a subset of the variety of proposed tidal and wave energy devices. Due to the paucity of information most of the devices considered here have been assessed qualitatively. However one illustrative tidal device and one wave device will be considered in more detail in later sections of this report. This approach is considered appropriate for the purposes of this SEA, but more information would be required to inform individual environmental impact assessments (EIAs).

6.1 Sources of noise in generators

6.1.1 Rotating machinery

Rotating machinery generates a broadband noise associated with frictional losses and tonal noises related to the rotation rate. The broadband noise will be modified by transmission paths which may include resonant structures introducing peaks and troughs in the spectrum. The tonal noise will be related to the fundamental rotation rate and to multiples of this rate. Multiples can be introduced if the rotating parts are multi-segmented, e.g. rotor or turbine blades. Additional related tonals can be introduced if a gearbox is used, although these are unlikely to be direct multiples of the rotational rate. Broadband impulses can also be generated at a rate related to the rotational rate by mechanical impact, e.g. commutator noise.

Many systems use hydraulics to couple energy from the primary circuit to the secondary or tertiary generation circuit. Hydraulic motors and rams can generate significant tonal and flow noise.

6.1.2 Flexing joints

Flexing joints can introduce both broadband and tonal noise. The broadband noise is derived from frictional losses while the tonal noise will generally occur at particular parts of the flexing cycle as parts rub together. There may also be squeaking from rubber seals during the flexing motion.

6.1.3 Structural noise

As structures move, particularly in surface interacting units, the structure may well resonate and generate tonal or narrowband noise sounds. These will generally be at a very low frequency (<20 Hz). The resonance may be excited by the mechanical systems used to generate electricity or by the transfer of energy from the waves.

6.1.4 Moving air

Some devices use water movement to move air through turbines. Apart from the rotational machinery noise as described in Section 6.1.1, additional noise can be generated by the movement of air under pressure. This will generally be broadband in nature, but may contain tonals due to ‘organ piping’ effects. These tonals would be expected to occur at frequencies of the order hundreds of Hertz, for structures with dimensions of the order metres.

6.1.5 Moving water

All devices rely on moving water to provide the energy needed to generate electricity. Apart from the mechanical effects described in Subsections 6.1.1 and 6.1.2, additional noise may be generated by the water splashing or gurgling. There may also be cavitation noise under extreme conditions.

All devices with a surface presence will cause wave noise as they interact with the surface waves.

6.1.6 Moorings

Some devices need flexible moorings and these can generate a significant amount of noise. The noise can arise from a number of sources which include rattling chains, strumming ropes, and squeaking rubber. The more solid fixing of tidal generators can also result in noise from vortex shedding (i.e. turbulent eddies) from the structure and sediment transport noise at the seabed fixing triggered by flow around the structure.

Deep water moorings usually rely on a heavy flexible section on the seabed connected to the moored unit by a lighter more flexible section. The heavy seabed section is typically heavy chain, while the lightweight section will be steel or synthetic rope. In rough seas parts of the heavy section are progressively lifted off the seabed to provide the compliance needed in such moorings. A badly constructed mooring system can generate noise from the lifting and falling of chains, the mechanical impact of components in loose couplings and cable strum in a strong tide.

The chain noise has a very characteristic sound. Each chain link has a mechanical resonance and as the chain is lifted off the seabed and then dropped back the mechanical impact excites this resonance. Each link has a similar, but not identical, resonant frequency resulting in a series of decaying tonals in the frequency range 500 Hz to 10 kHz, depending on the link size.

Cable strum results in a loud tonal at very low frequencies. The frequency is determined by the physical characteristics of the cable and the tension in the cable. The sound can be very loud. For fixed moorings the problem can be alleviated by using fairings on the cable.

6.1.7 Electrical noise

Many electrical generation systems use electronic switching units to convert the raw generator output to the controlled voltage and frequency needed for a grid connection. These units use inductors as part of the switching system and these can generate a high level of acoustic noise. It is typically a tonal of a few kHz which may be frequency modulated by variations in the load power and the final output frequency.

The power is brought ashore by a long cable and there is potential for the cable itself to generate noise due to the physical movement resulting from varying magnetic forces at the power frequency.

All of the wave and tidal systems listed below can suffer from one or both of the electrical noise problems. Without knowing the detailed design of each unit it is not possible to comment on the levels likely to be seen. In the authors' experience it is a common problem on ships, and the one set of measurements of a tidal generator show a strong line at 5 kHz which is almost certainly due to the switching frequency in the power conversion unit (see Section 7.1).

6.1.8 Instrumentation noise

Although designers will try and minimise incidental noise in the power generation process, many of the systems, particularly at this early stage of development, will include instrumentation systems that deliberately introduce noise into the water. These may include:

a. echosounders;

b. Doppler current meters; and

c. acoustic modems.

These systems can produce very high levels of sound over a limited frequency range. As an example, echosounder source levels can be as high as 220 dB re. 1 µPa at 1 m, and with a bandwidth of around 10% centred in the low hundreds of kHz region.

6.2 Coupling of noise into the sea

The noise generated by the various mechanisms described above can be coupled into the sea by a variety of paths. These include:

6.2.1 Direct coupling

This results when the noise generator is in direct contact with the sea, e.g. the flexing joints of a wave generator or the rotating blades of a tidal current turbine. This mechanism is generally the most efficient coupling mechanism.

6.2.2 Mechanical coupling

This mechanism requires a mechanical path between the noise source and the sea. An example would be the rotational noise of an air-driven turbine being coupled via the turbine mounts into a metal shell which is then in direct contact with the sea. The path will generally modify the spectral content of the sound.

6.2.3 Seabed coupling

For units firmly secured to the seabed, noise may be coupled through the structure into the substrate and thence into the water column.

6.2.4 Air coupling

Sound can also be generated from the in-air part of a generation system and coupled through the air-water interface into the water column. This is generally a very inefficient coupling system because of the acoustic impedance mismatch between air and water.

6.3 Tidal devices

6.3.1 Horizontal axis turbines

These use one or more large rotor blade systems mounted with the axis horizontal to extract energy from the tidal flow. They generally resemble large propellers. The noise sources associated with these devices are likely to be:

a. rotating machinery noise;

b. moving water noise;

c. structural noise; and

d. mooring noise (only for those examples not piled into the seabed).

6.3.2 Vertical rotor turbines

These use an alternative rotor blade system with a vertical axis, but still make use of the horizontal tidal flow. Noise sources are as for the horizontal axis turbine.

6.3.3 Venturi units

These devices use a large, shaped duct with a constriction to speed up the flow of water. This results in a pressure drop which draws air or water from a secondary circuit into the flow. The fluid drawn in is used to turn a turbine and generate electricity. Most devices draw in air rather than water such that moving parts are above the waterline. It is also possible to multiplex a number of individual primary collectors to drive a remote turbine. The main sources of noise will be:

a. moving water noise;

b. moving air noise; and

c. structural noise.

6.3.4 Oscillating hydrovanes

These units use hydrovanes mounted on seabed structures in a strong tidal flow. The hydrovane oscillates up and down in the tidal flow and this motion is used to generate electricity. Main sources of noise are likely to be:

a. flexing joints;

b. rotating machinery; and

c. structural noise.

6.4 Wave devices

6.4.1 Oscillating water column devices

These extract energy from the vertical movement of the water surface. They generally have a chamber in which the water moves vertically forcing air through a bi-directional turbine system to generate electricity. The design will generally minimise vertical movement of the floating unit to maximise relative motion of the water. All of the rotating machinery is housed above the waterline so coupling of noise to the water will generally be low. The noise associated with these devices is likely to be:

a. moving water noise;

b. moving air noise; and

c. structure noise.

The shoreline versions of these devices are considered to be within the envelope of this summary. Although there is likely to be a high level of wave impact noise, this will probably be comparable to the noise of waves impacting the shoreline in the absence of the device. Noise from one example of a shoreline device, the WaveGen Limpet, has been reported [24] but underwater noise has yet to be assessed.

6.4.2 Overtopping devices

These units capture water from the wave peaks and return this to the sea via turbines. Wave height may be amplified by suitable associated structures. The turbines are located underwater in these units. The main sources of noise are likely to to be:

a. rotating machinery noise;

b. moving water noise;

c. mooring noise; and

d. structural noise.

Although designers will try and minimise vertical movement of the main device, and hence stress on the mooring system, any wave amplification structure may well be on a less substantial mooring and more prone to mooring noise. One variant places the device on the shoreline and this would eliminate mooring noise.

6.4.3 Point absorber/attenuator

Point absorbers and attenuators use the vertical movement associated with waves. This movement is converted into a mechanical movement which in turn is converted into electrical energy. This conversion may rely on flexing of joints as a wave passes or inertial effects as a surface buoy lifts and falls. All of these devices rely on vertical movement so require a compliant mooring system. This places a lot of stress on the mooring system. The main sources of noise will be:

a. mooring noise;

b. flexing joints;

c. structural noise; and in some examples

d. rotating machinery noise.

Although the design of the moorings will be optimised for the particular site and system, it will never be possible to remove all sources of noise.

An alternative system uses a paddle mounted on a seabed structure in shallow water so the paddle is moved by the wave passing over it. Although there will be no mooring noise associated with this type of structure, the flexing joint and structural noise will be significant.

6.4.4 Wave rotor

This uses the rotary motion within a wave. It appears to have been tried some years ago then no further information has been published. From the limited information available it would appear to have similar noise characteristics to the vertical rotor tidal turbines.

6.5 Fault conditions

System designers will generally seek to minimise radiated noise, but because wave and tide energy devices are deployed in a very hostile environment it is inevitable that they will develop faults at some stage. Under these conditions the noise output can rise significantly and this section will discuss what may happen under these conditions.

6.5.1 Rotating machinery noise

A faulty bearing can produce very strong tonal signals during the period leading up to disintegration of the bearing. It can also produce elevated levels of wideband noise. Worn gearboxes can become progressively noisier. Anti-vibration mounts become worn and less efficient.

6.5.2 Flexing joints

Bearings can become faulty and produce tonals at different stages of the flexing cycle. Frictional losses can increase. Joints can partially or fully seize resulting in a change in the way the unit interacts with the waves and thereby increasing wave noise. Rubber seals can become worn and start squeaking.

6.5.3 Mooring noise

As moving parts wear they will generally become noisier. This is likely to result in an increase in mechanical impact noise from the joints.

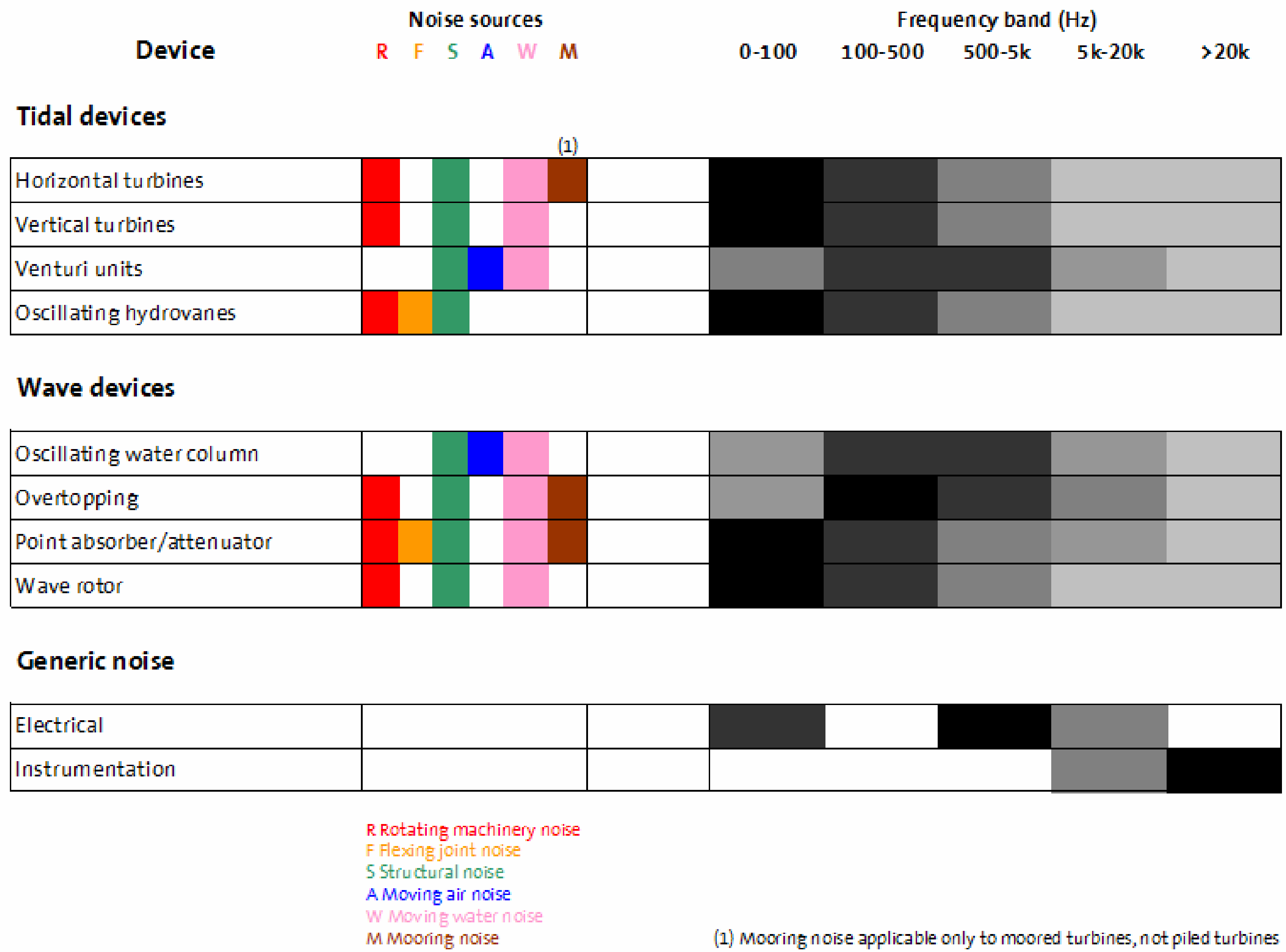

Table 6-1: Summary of the main noise sources associated with different device types. The greyscale indicates the relative noise level in each part of the spectrum, with black indicating the highest level and white indicating no or negligible noise.

7 Review of available noise measurements

7.1 Measurements at Lynmouth

The only known underwater measurements in the vicinity of an operating wave or tide energy device were carried out at the site of the Marine Current Turbines (MCT) tidal current generator near Lynmouth in the Bristol Channel [25]. These data have been kindly supplied by Subacoustech Ltd. On behalf of MCT to provide an indication of the noise generated by tidal energy devices.

Figure 7-1 shows the position of the turbine and the positions of the noise measurements (some additional measurement points lie beyond the eastern border of the chart). Some of the measurements were taken when the turbine was not running to get a baseline estimate of the local ambient noise field. All of the measurements were taken within a period of about four hours on 9th March 2005, so the key timescales for the variability of ambient noise have not been captured.

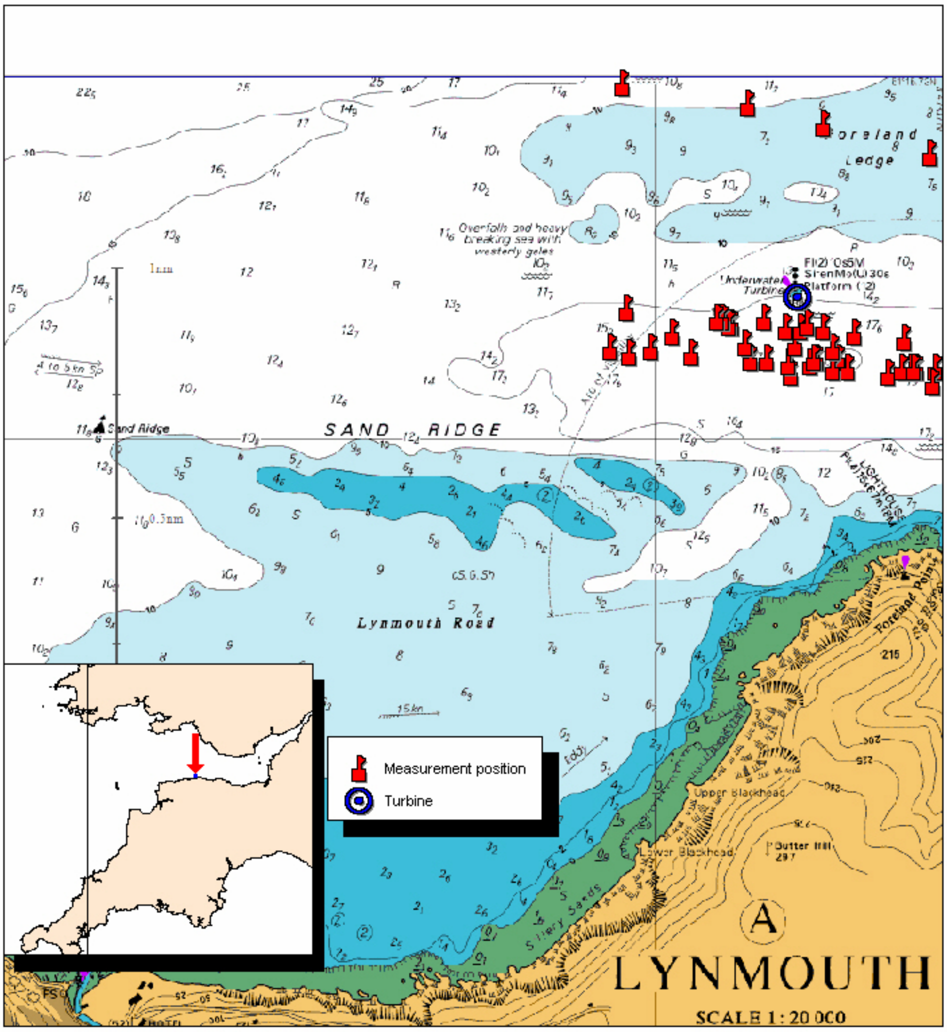

Figure 7-1: Chart showing the positions of the MCT tidal current turbine in the Bristol Channel, and the positions of the underwater noise measurements on 9th March 2005 (source material: UK Hydrographic Office)

Figure 7-2 shows the sound pressure level measured at each point as a function of its range from the turbine. The levels plotted here have been computed from time-series data provided by Subacoustech as WAVE files sampled at 192 kHz. The data have been filtered with a 4^{th}-order Butterworth high pass filter, with a filter frequency of 5 Hz, in order to remove low frequency, large amplitude ripples due to hydrostatic pressure fluctuation. The ranges from the turbine have been calculated from the GPS coordinates, assuming spherical geometry.

It may be seen from this figure that there is a large degree of variability in the sound pressure level at similar ranges, and that in some cases, especially at larger ranges from the turbine, the ambient noise level is higher than the noise level from the turbine. Listening to the recordings indicates that the ambient noise at the site contains a large amount of shore and surf noise, which is to be expected given the proximity of the site to the cliffs of the Exmoor coastline. The recordings also reveal audible local shipping noise, probably from large merchant ships transiting up and down the Bristol Channel. The line plotted on this graph is 166-13.7log(R), which was derived by Subacoustech to be the best fit to the measurement points. This implies an **effective** source level of 166 dB re. 1 μPa at 1 m, although great care must be exercised in the interpretation of this effective source level, since interference effects will result in large fluctuations in sound pressure level at short distances from the source.

Figure 7-3 shows the spectrum of the noise from the turbine, measured at a range of approximately 250 m, together with the spectrum of the ambient noise measured at the site. These spectra were computed by Subacoustech and are presented as $1/27^{th}$ octave band levels. It is clear that the spectrum level of the noise from the turbine is significantly higher than that of the ambient noise over most of the spectrum at this range. The measurement of the turbine noise includes the ambient noise that was present at the time of the measurement.

These $1/27^{th}$ octave bands are sufficient for describing the broadband noise from the device, but they hide some of the details of the full spectra. For example, examination of the individual spectra of the data reveal a very narrow tonal at about 5 kHz, which is smeared over a broader range of frequencies in the $1/27^{th}$ octave analysis. Discussions with the developer of the device suggested that this tone was due to a switching frequency in the power conversion system within the generator. Closer examination of this part of the spectrum revealed sidebands consistent with the modulation of a 5 kHz switching frequency to produce fixed-frequency alternating current suitable for transmission to shore. This is therefore consistent with this tonal being produced in the power conversion module. The developers also stated that there was a faulty bearing in the device at the time of the measurements, which they believe to be responsible for the large peak in the spectrum below 100 Hz. The developer has subsequently replaced the bearing and reports that noise emissions are perceptibly reduced, although the underwater noise measurements have not been repeated. This may have an effect on the assessment of some of the low frequency impacts discussed in this report.

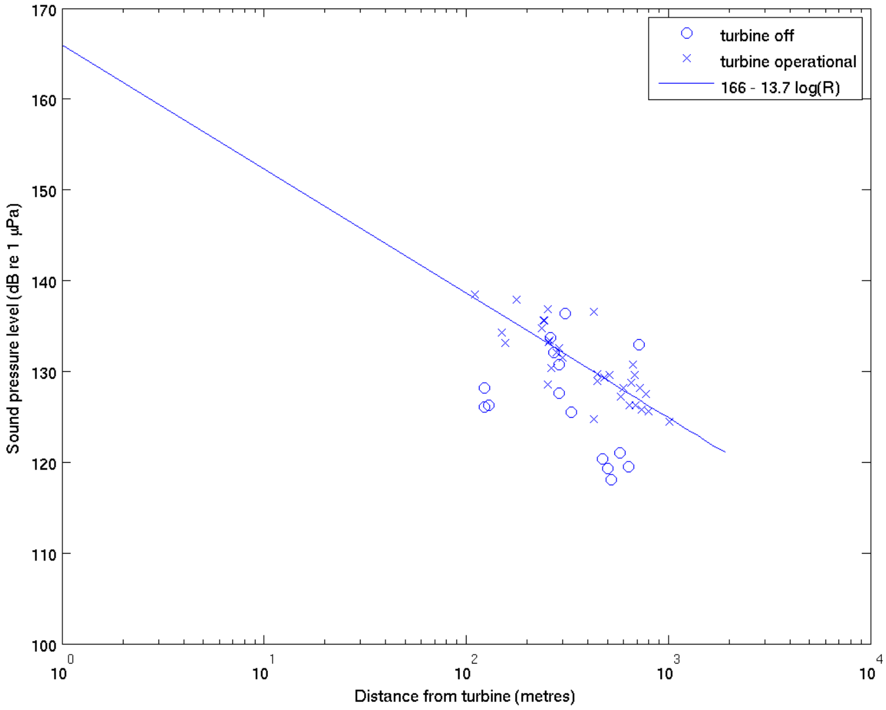

Figure 7-2: Sound pressure levels measured within a four hour period at various ranges from the turbine (data courtesy of MCT and Subacoustech Ltd).

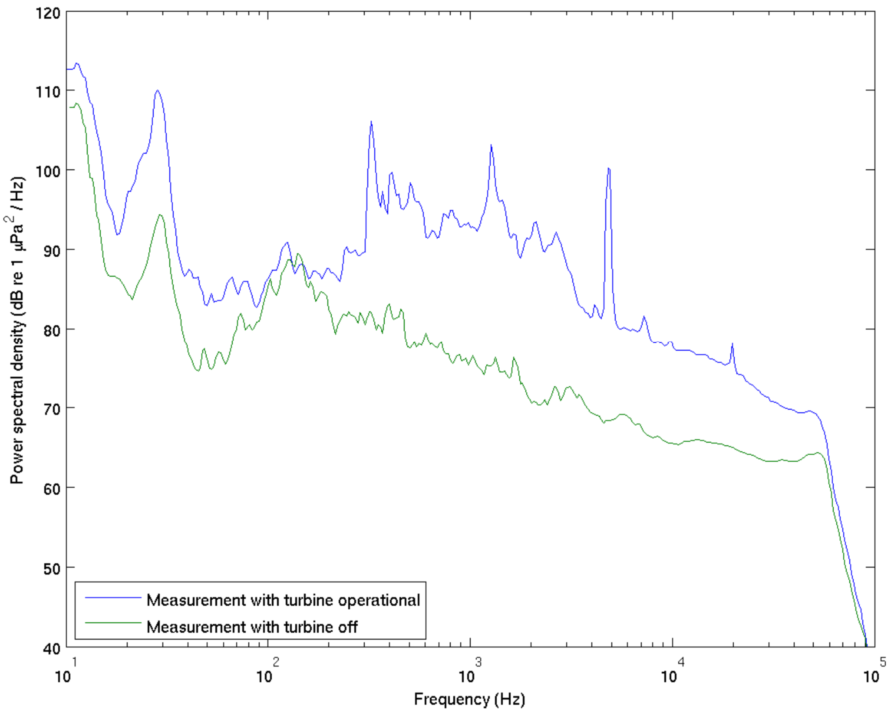

Figure 7-3: 1/27th octave spectra of ambient noise and turbine noise at the Lynmouth site (data courtesy of MCT and Subacoustech Ltd)

7.2 Measurements off Barra Head

In June 2004 QinetiQ deployed a number of autonomous recording units (ARUs) in the North West Approaches to the UK to record underwater sounds continuously over a period of around two weeks. Most of these units were deployed in the deep waters to the west of the continental shelf break, but some were deployed on the shelf and one sensor was deployed within the SEA study area. It is therefore useful to include some data from that sensor in this study, given the general scarcity of such data.

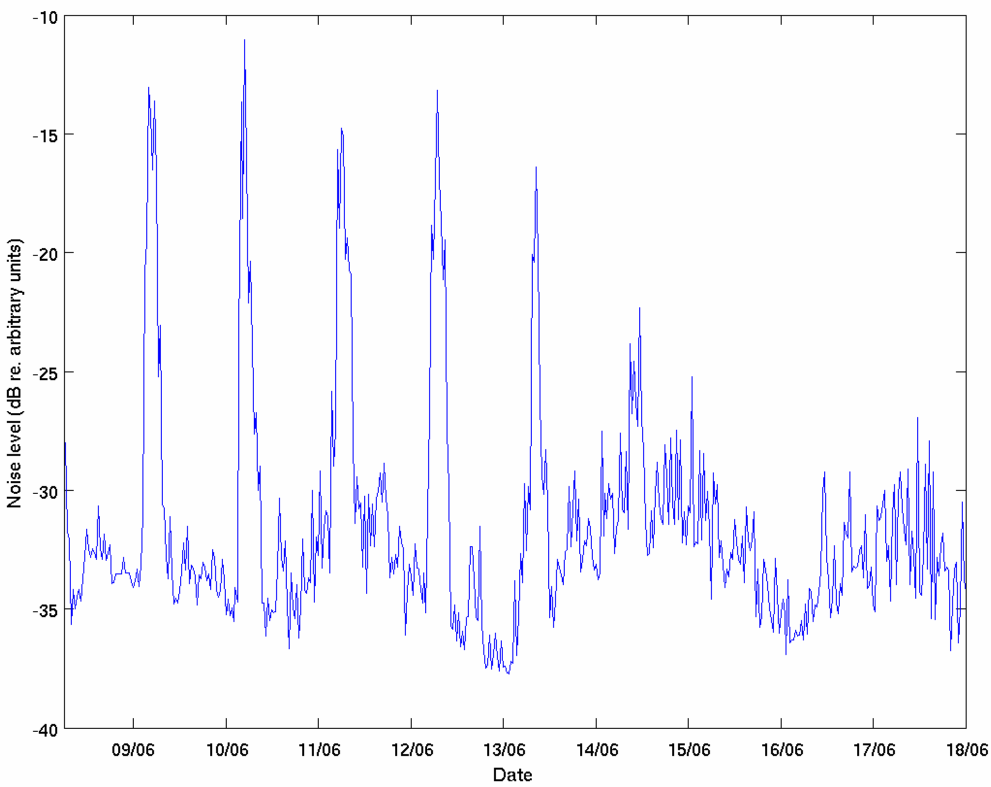

Figure 7-4: Time history of noise level measured off Bara Head in June 2004 (arbitrary reference level)

The relevant ARU was deployed on the seabed in about 40 metres of water, some 10 km to the west of Barra Head, at 56°47.1' N, 7° 48.3' W. Figure 7-4 shows the time history of the noise level measured by this ARU throughout its deployment. The ARUs sampled continuously at a sampling rate of 20 kHz throughout their deployment, amassing a large quantity of data. The data in the figure have been reduced by computing the mean of the signal squared (to give a measure of power) over a 10 second extract of the data every 30 minutes. This processing might miss short-duration events and short-period variability, but is sufficient to show the general level of temporal variability in the noise level. Calibration data for the ARUs are not available, so absolute level cannot be determined and the data are therefore plotted in dB relative to some arbitrary reference. However, this figure does serve to demonstrate the temporal variability in noise level at a single location over the period of the deployment (approximately 10 days).

The most notable features in this time series are the large amplitude peaks. These occur with a period of about 25 hours, strongly suggesting that they are tidal in origin. Figure 7-5 shows that they are indeed correlated with the tide data from a tide gauge located in Stornoway. The tide data show that there is asymmetry in the semi-diurnal tides, and the acoustic events are correlated with the larger of the two, indicating that at these times the tidal currents in the location of the sensor exceed the threshold for some noise-generating mechanism around the sensor, such as turbulence, cable strumming or sediment impact noise. These events may therefore be classified as self-noise as opposed to ambient noise.

It may be seen that the underlying variability in the noise level is some 10 dB over the deployment period. This is largely attributable to changes in the windspeed.

Figure 7-6 shows the spectrum of the noise measured in the quiet periods between the tide-generated events.

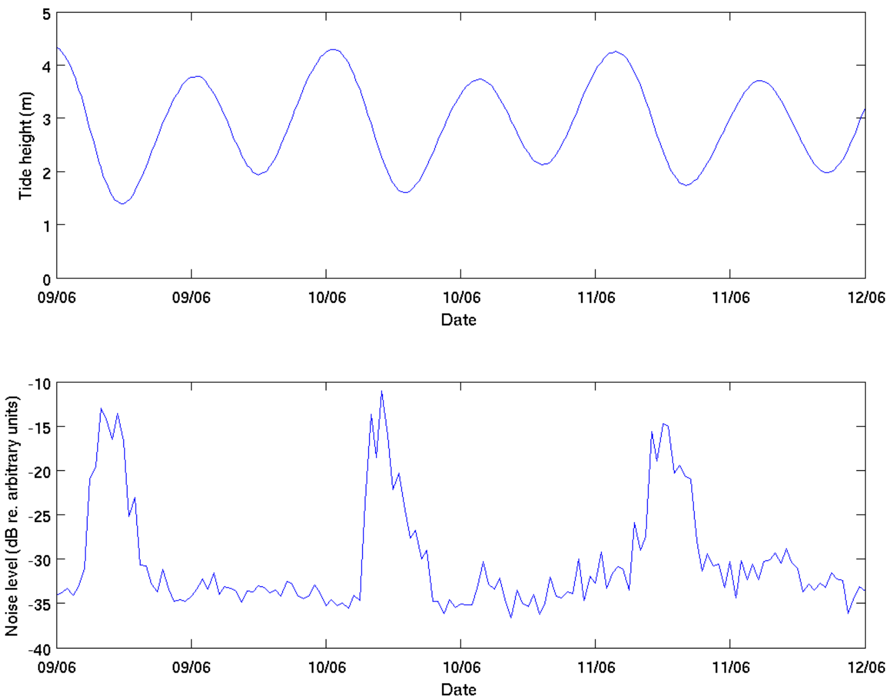

Figure 7-5: Tidal data from Stornoway tide gauge (top) and variations in noise level measured by ARU off Barra Head (bottom)

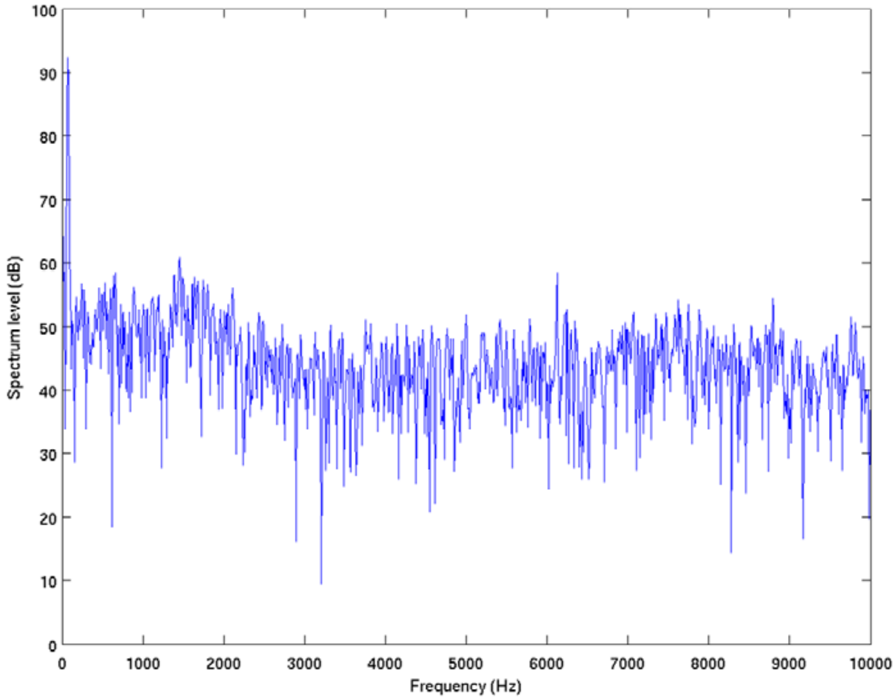

Figure 7-6: An example of the spectrum of ambient noise measured off Barra Head (arbitrary dB reference level)

8 Noise field around devices

8.1 Introduction

The noise field around a renewable device will be a combination of the radiated noise from the device and the ambient noise present at the site. In this section the results of ambient noise modelling for the SEA study area are presented and projections of radiated noise from devices are discussed.

8.2 Ambient noise model

The modelling of ambient noise in the SEA study area has been carried out using a numerical model called SANE (Synthetic Ambient Noise Environment). SANE was developed by QinetiQ in conjunction with SEA Ltd to provide rapid estimation of the ambient noise field directionality and level. The model uses ray theory and has been validated against real data.

SANE models the noise generated by the wind at the surface of the ocean by a distribution of dipole sources and can produce synthetic signals with appropriate statistics. The received intensity at a specified frequency, receive angle and depth can be obtained from the model and converted to an isotropic sound pressure level by integrating over all angles at the desired location. The model does not include shipping noise or shore and surf noise.

The sea surface reflection loss data used are based on the Bechman-Spizzichino formula [26] and are related to wind speed. The surface noise level and surface noise spectrum data are based on [27] and are also dependant on wind speed.

Acoustic absorption in sea water absorption is modelled within SANE using the Francois-Garrison formula [28, 29] and sea bed reflection loss is produced from geoacoustic parameters using LARES (Langer Approximation for Reflection from the Seabed) [30, 31].

8.3 Model results

Model predictions have been carried out for a number of environments representing the SEA study area, including different water depths, sound speed profiles, seabed types, and receiver depths (i.e. the depth at which the ambient noise spectrum level is calculated).

The combinations of parameters used for the modelling study are summarised in Table 8-1. For each combination the ambient noise spectrum levels were modelled for receivers at the surface, at the seabed and at mid-water.

For the shallow water case (20 m) it was assumed that the water column would be well mixed. This will certainly be the case at the sites of interest for tidal generators, and will generally also be the case at the wave sites, except perhaps on calm, sunny days when the surface heating could lead to the development of a surface layer of warmer water. Under such conditions a wave generator is unlikely be producing much noise anyway. It was therefore considered reasonable to assume an isothermal sound speed profile for all of the shallow water runs. For the deeper water cases (200 m) an isothermal profile has also been used to represent winter conditions, when storm conditions will cause deeper mixing of the water column. A representative sound speed profile for the SEA area in summer has been taken from a climatology database to represent the deep water environment in summer. These generic assumptions are appropriate for this strategic study, but *in-situ* measurements of the sound speed profile should be used to inform individual EIAs.

In analysing the results of all of these model runs it was found that the only parameter in these environments which significantly affected the results was the wind speed. The results of this modelling study can therefore be summarised by the two curves shown in Figure 8-1. These curves show the isotropic noise spectra due to surface-generated noise at the two limiting wind speeds plus the thermal noise which has been added to the model results using Equation (3.1). Note that these results do not include the noise due to shipping, which will dominate at low frequencies, or the shore and surf noise. When device noise is compared with the ambient noise at low wind speeds, the effect of neglecting the shipping noise in particular will be more precautionary at low frequencies than an assessment which included these terms.

Water depth (m)	SSP	Wind speed (knots)	Bottom type
20	isothermal	3	soft
			hard
		30	soft
			hard
200		3	soft
			hard
		30	soft
			hard
	summer	3	soft
			hard
		30	soft
			hard

Table 8-1: Combinations of parameters used in the modelling of surface-generated ambient noise

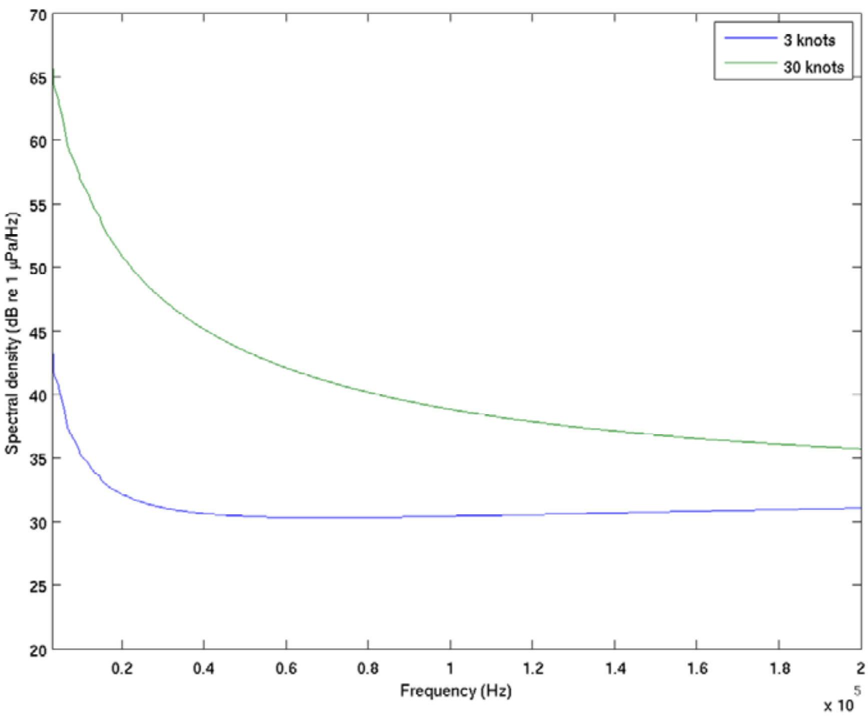

Figure 8-1: Predicted ambient noise levels in the SEA study owing to surface-generated noise and thermal noise, for wind speeds of 3 knots and 30 knots.

8.4 Comparisons between modelling and measurements

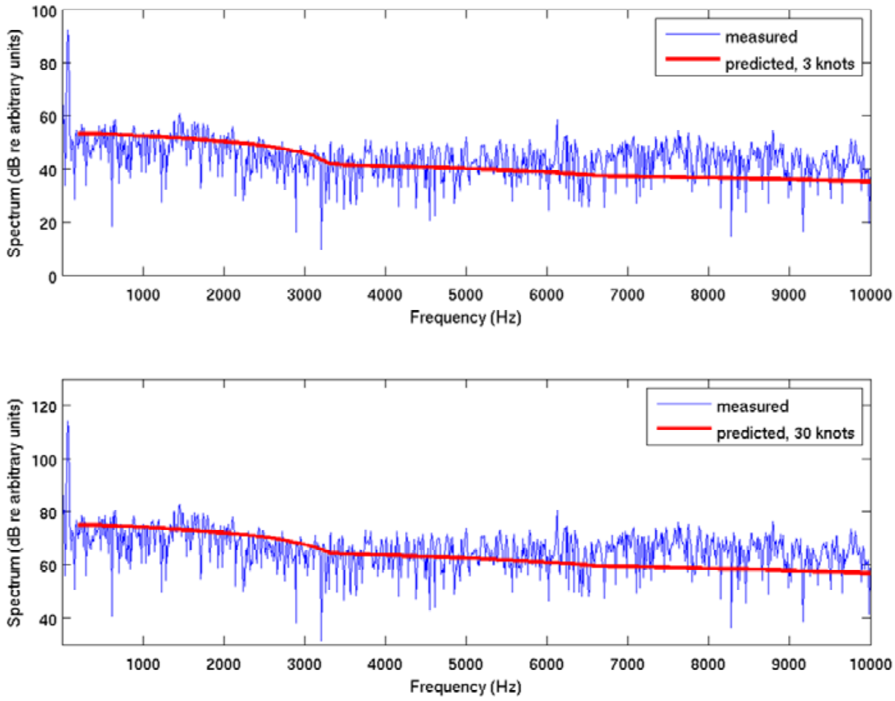

Figure 8-2: Comparison of ambient noise predictions, for two different wind speeds, with measurements of the ambient noise spectrum off Barra Head in June 2004.

Figure 8-2 shows model predictions compared with the measurements of noise made off Barra Head in June 2004, as shown in Figure 7-6. The data acquisition units in the ARUs had a sampling frequency of 20 kHz, so the spectrum of the measured data is limited to 10 kHz. No calibration data are available for the ARUs, so it is not possible to compare the absolute measured level with the predicted level. However, the relative spectral levels may be compared, and in Figure 8-2 the measured spectrum has been shifted on the vertical axis to allow comparison with the predicted spectra. In this part of the spectrum the two model results are very similar in shape, although different in level (note the different vertical axes on the two plots) so each plot shows a very similar level of agreement with the measured spectra. This indicates that the model is giving a realistic prediction of the spectral shape of the surface-generated ambient noise in the SEA study area.

8.5 Vertical directionality

It should be noted that ambient noise typically has vertical directionality, as shown by Figure 8-3, which is a SANE prediction of the vertical directionality with a mud bottom type, and Figure 8-4, which shows the result for an olivine[10] bottom type [32]. In both cases the water depth was 100 m and the receiver depth was 50 m The upper and lower hemispheres are the very similar over the highly reflective olivine bottom, but the lower hemisphere shows lower noise levels over the absorbing mud

[10] The mineral olivine is a magnesium iron silicate.

sediment. The relevance of these figures to the current study is simply to demonstrate that ambient noise has vertical anisotropy.

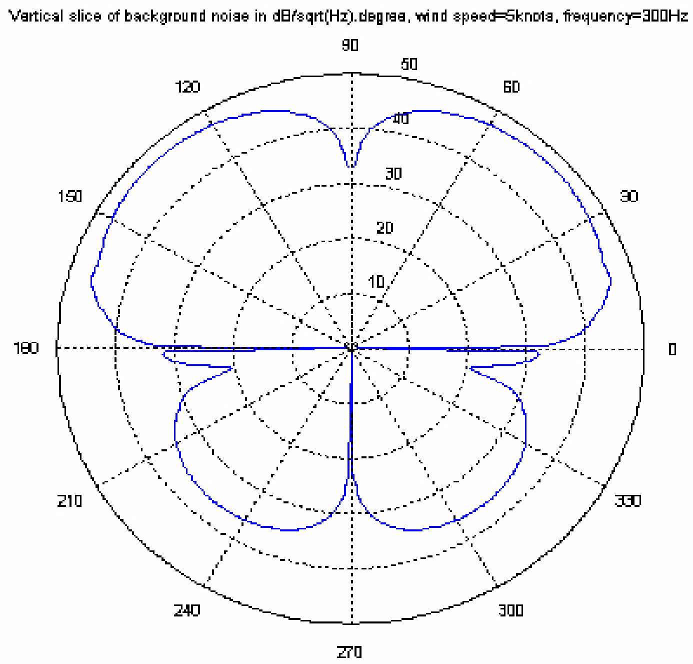

Figure 8-3: Vertical directionality (level v angle) of ambient noise for a mud bottom

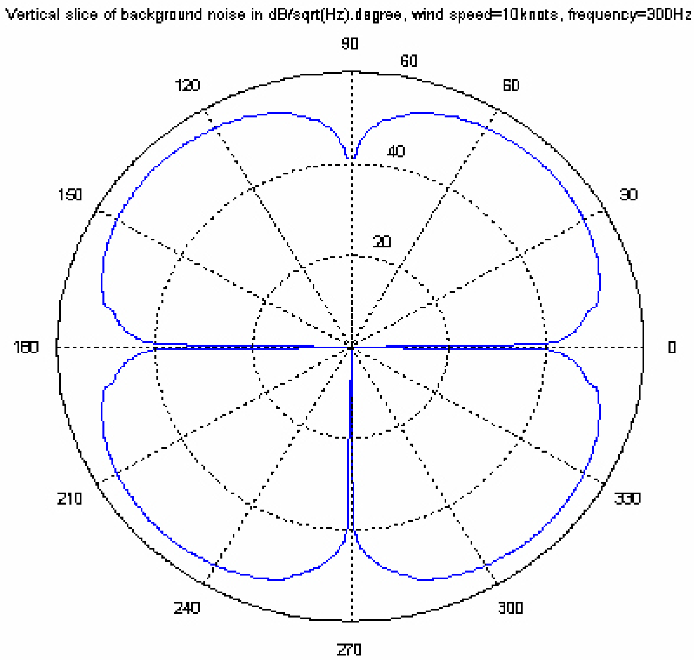

Figure 8-4: Vertical directionality (level v angle) of ambient noise for an olivine bottom

8.6 Projections of device noise levels

In order to assess the noise field around devices quantitatively it is necessary to know the radiated noise spectrum level. For most of the devices considered in Section 6 this information is not available. Some of the devices have not yet been developed to the stage of a working prototype, and underwater noise measurements only exist for one device: the MCT tidal current turbine. These measurements were described in Section 7.1, and will be used here as the primary source of device noise data for the example impact assessment described in Section 9.

The next subsection provides a projection of the noise characteristics for the Pelamis wave device, for which underwater noise measurements are currently unavailable. This will serve as an example of the potential underwater noise emissions from a wave device

8.6.1 Pelamis

As it was not possible to measure the radiated noise from Pelamis within the timescale of this study, experts from QinetiQ's Noise and Vibration Assessment team in the Maritime Structures and Survivability business group at QinetiQ Rosyth have carried out an assessment of the likely underwater radiated noise from Pelamis. This assessment is based on engineering information from OPD [33], a pre-installation noise review [34] supplied by OPD, and experience in measuring the radiated noise from similar types of marine mechanical systems. Figure 8-5 shows an internal view of one of the power conversion modules.

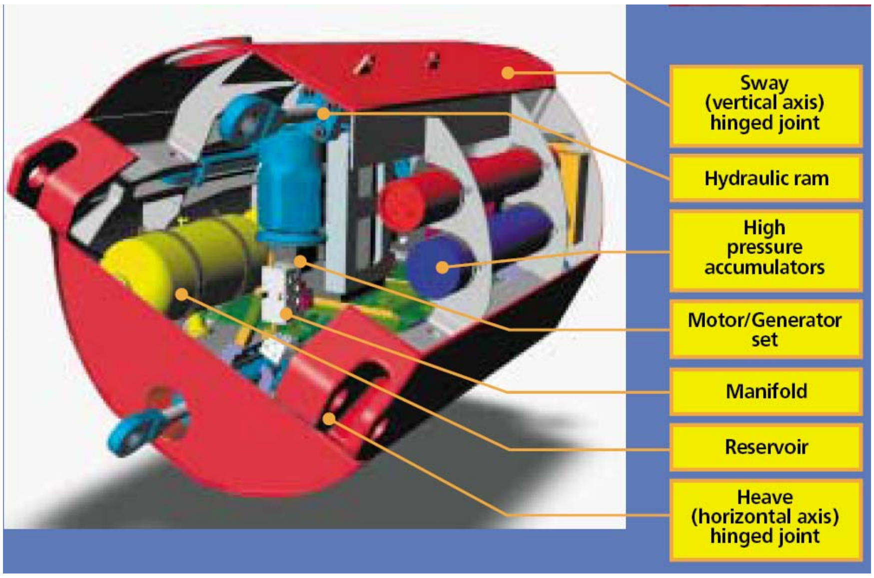

Figure 8-5: Internal view of a Pelamis power conversion module (source: OPD)

The results in [34] were not considered representative of the likely noise radiated by Pelamis in normal operation. During the pre-installation noise review two hydraulic power packs were used to provide the motor-generators with hydraulic flow in order to run them close to operating conditions. It was stated in that reference that the noise emanating from the hydraulic power pack masked that generated by the noise sources of interest. The hydraulic power pack will not be present during operation at sea. For this reason and due to the lack of other technical information it is not possible to make any assessment of the likely underwater radiated noise based upon these measurements. The following paragraphs describe the noise sources that are expected to be the largest contributors to the underwater radiated noise based upon the technical information made available to this study. Some very tentative estimates of the expected radiated noise levels in normal operation are given. These estimates have been prepared by QinetiQ for the purposes of the present study.

Hydraulic motor generator packs

The most significant noise sources within this unit are likely to be the hydraulic motor. In addition to these it is possible that any cooling fans associated with the electrical generators may make a tonal contribution at shaft speeds and blade passing frequencies, and a small broad band contribution at higher frequencies. The level and frequencies of noise and vibration generated will depend largely upon the type of hydraulic motor and gearbox. The hydraulic motor is likely to produce discrete tones at multiples of the motor shaft speed. A swash plate type hydraulic motor may be expected to produce tones at multiples of the number of cylinders multiplied by the shaft speed. As an example, a seven cylinder[11] motor running at 1500 rpm would be expected to produce tones at multiples of 175 Hz. Generally the higher multiples of this frequency would be expected to have lower amplitudes.

Hydraulic rams and associated pipe work

Hydraulic rams are normally associated with two types of underwater radiated noise. There is usually some 'hydraulic hiss' due to the flow of fluid through restrictions in the hydraulic circuit. This is contributes to the broad band spectrum at high frequencies. In the case of the Pelamis system the radiated power from this noise source may be a much smaller proportion of the rated power of the machine than would be the case in typical marine hydraulic systems, such as a ship’s steering gear or stabiliser. This is because the hydraulic hiss is normally generated by restrictions in the circuit such as spool valves. Such flow restrictions are likely to have been designed out of the Pelamis as far as practical in the interests of maximising efficiency. This is supposition and would have to be confirmed by further investigation. Another noise source associated with hydraulic rams is 'rub' which results from friction on sliding parts of the ram and stick-slip motion interacting with a structural resonance of the ram or attached structure. The occurrence of a rub would not be considered to be within normal operating conditions of a piece of hydraulic equipment but, as a general observation, this phenomenon is a common fault and is sometimes left un-remedied as it generally does not impact the efficacy of such equipment in the short term.

Wave noise

The breaking of waves on the Pelamis in operation will generate some underwater radiated noise. In heavy seas this may include wave slam noise and some resultant tonal noise from the structural resonances that are excited. At more benign sea states the noise will probably resemble broadband surface-generated wind-sea noise. Wind-sea noise is typically the dominant source of ambient oceanic noise in the 1 kHz to 100 kHz range, as discussed in Section 2, depending upon wind speed.

Transmission paths

All of the sources discussed above have the potential to generate significant radiated underwater noise. The transmission paths connecting the noise sources and the sea water may be air-borne, structure-borne or hydraulic-structural. The air-borne paths

[11] In commenting on a draft of this report OPD stated that the Pelamis hydraulic motor has 9 cylinders. This would be expected to produce tones at multiples of 225 Hz at 1500 rpm.

are from the source in question into the air volume within the Pelamis module followed by transmission through the hull of the module into the sea water. The structure-borne paths result from structure-borne vibration transmitted from the source equipment through the supporting steel-work to the hull and then to the water. The hydraulic-structural path is through pressure pulsations in the hydraulic oil and vibration of the pipe work into the sea water oil coolers. The hydraulic-structural path is potentially a very direct means of transmission of noise into the water and may result in high radiated noise levels.

Estimating the underwater radiated machinery noise

In order to predict underwater radiated noise with any degree of confidence more technical information and certain measured data would be required. In one approach the structural, airborne and fluid sound power of each source is measured in operation under load and combined with noise transmission models and measurements to determine the radiated underwater noise. Another approach is to seal the module and measure the hull vibration levels in air with all (or each in turn) of the noise sources operating under load. From these hull measurements, and an allowance for the differences in acoustic impedance of water and air, the underwater radiated noise may be estimated. As these data are not available neither of these approaches is possible here.

A very approximate indication of the expected radiated underwater noise can be made using measured far-field data for machinery of a similar type. Ship steering gear systems typically use electrically-powered hydraulic pumps which drive rams that operate the rudder(s). These contain hydraulic pumps with a similar design to the motors used in Pelamis. The power conversion is in the opposite direction but this is not expected to affect the radiated noise for a given size of machine. Some scaling of the data is required because the hydraulic power of a steering system is not as high as that of the 250 kW Pelamis units.

Far-field radiated underwater noise from a steel hulled vessel was used as source data for the estimate. The vessel type was chosen because its was considered to be the closest to Pelamis in terms of its size, construction and certain transmission paths between the hydraulic pumps and the sea water. Also the hydraulic pumps are, as far as can be ascertained, of a similar design to the hydraulic motors used by Pelamis. The rated power of the steering pump in question was smaller than the 125 kW individual hydraulic motors used in the Pelamis power packs. Some published literature [35] suggests that is reasonable to expect the radiated sound power to scale linearly with the rated power of the machine. This extrapolation will introduce some error but it will hopefully be minimal as the machines are still within an order of magnitude in power rating terms. Underwater radiated noise measurements were taken from a number of nominally identical vessels when the steering pumps were operating under load. The power-compensated values which are expected to be representative of tones generated by the Pelamis hydraulic power packs and are shown in Table 8-2.

Frequency (Hz)	**Level (dB re. 1 μPa at 1 m)**
175 (assuming 7 cylinder motor at 1500 rpm)	129 to 140
350 (assuming 7 cylinder motor at 1500 rpm)	127 to 141

Table 8-2: Estimated underwater radiated tonal noise levels due to Pelamis hydraulic motors

The levels shown in Table 8-2 show the minimum and maximum power-compensated levels derived from a number of vessels. The expected port, starboard, stern, bow and keel aspect noise levels of the two tones fall within the ranges shown in the table. The tonal frequencies assume 7 cylinder hydraulic motors operating at 1500 rpm.

Estimating the underwater radiated wave noise

Without a substantial program of experimental and/or theoretical work it would not be possible to predict accurately the additional wave noise generated by the operation of a wave device such as Pelamis. It is possible to produce a very approximate indicator of the likely levels of broad band wave noise by comparison with the underwater radiated noise of a surface vessel underway. Results were chosen from a vessel operating with propulsion shaft power levels higher than, but within an order of magnitude of 250 kW, the rated output of the Pelamis modules. The vessel was below its propeller cavitation inception speed. It is expected that a significant proportion of this energy will be converted into surface wave energy. In the 1 kHz third octave band the measured level is approximately 140 dB re. 1 µPa at 1 m. The third octave band levels drop by approximately 10 dB per decade as the frequency increases such that the 10 kHz band level is approximately 130 dB re. 1 µPa at 1 m. Relating these levels to the a wave energy device such as Pelamis requires a number of sweeping assumptions. For this reason these levels can only be regarded as a tentative indicator of the possible high frequency broadband wave noise one might expect to be generated by a wave energy device in operation close to its rated load. This approach is considered appropriate for present purposes but a more detailed assessment would be required for individual devices.

Discussion

The estimated values given in this subsection are merely presented as the best indication available in the absence of any measured data. They do not take into account certain details of the construction of the device, for example the use of adhesives to fix internal bulkheads which may reduce the structure-borne noise transmission and therefore the radiated noise levels. On the other hand the transmission of noise and vibration into the water by the hydraulic/seawater cooling pipes could provide a very direct transmission path which is not available in the steering pump data. If this were the case it could result in a device such as Pelamis generating considerably greater tonal levels of underwater radiated noise. Another factor which may introduce errors into the levels quoted in Table 8-2 is the actual power levels in operation of the steering pump. This is a system with a certain redundancy built into is and the rated power may not be a good indication of the actual power consumed under load. This effect would also suggest that the actual radiated noise levels generated by Pelamis at full rated capacity would be higher than those given in Table 8-2.

It has not been possible in this study to estimate the noise levels due to structural resonances in Pelamis.

8.7 Effects of array geometry

Commercial scale development of marine renewable sites will see devices installed in arrays of varying size and configuration. It is therefore necessary to consider the effect of array geometry on the underwater noise levels. The number of devices that is likely to be incorporated into commercial arrays depends on the device types and the development site characteristics. Due to the current developing state of the industry the majority of device developers have not fully addressed the design issues associated with large arrays of devices.

In order to assess the underwater noise field from an array of devices, it would be necessary to know the details of the array, i.e. the shape of the array and the spacing between the devices. It would also be necessary to know the acoustic environment (i.e. water depth, sound speed profile and seabed type) in order to compute the sound propagation between devices in the array, and from the array to long range. The data required for this approach are not available, nor would it be appropriate to investigate specific geometries in that level of detail in this strategic study.

It is likely that many arrays will be rectangular, or approximately rectangular, and it was therefore considered pragmatic to consider the two limiting cases: a linear array; and a square array. In such arrays the highest noise levels would be expected in the vicinity of the device which is located closest to the centre of the array. The dominant contribution would be from that device itself, the nearest neighbours might also contribute a significant amount of sound energy, depending on the element separation, with more distant devices contributing progressively lower levels as the distance increases, as a result of geometric spreading and absorption.

The following figures show estimates of the additional noise level at the central device of the array, due to the rest of the devices in the array. These levels have been computed assuming spherical spreading over the relatively short distances between elements. This is a reasonable assumption for nearest neighbours, which contribute the most to the additional noise level. Although this may slightly underestimate the noise level from the more distant devices, their overall contribution is relatively weak.

Figure 8-6 shows the increase in noise level at the central device of a linear array, due to the rest of the devices in the array, as a function of the separation between devices. Results are shown for arrays containing 3, 9 and 51 devices. This figure shows the noise level raised by up to 5 dB relative to the noise level of a single device, for a 51-device array with 10 m separation, and 3 dB for a 9-device array. In practice device separations are likely to be greater than 10 m, and noise levels will therefore be lower. For separations greater than 20 m the maximum noise level at the centre device will be less than 3 dB above that of a single device for arrays containing up to 51 devices.

Figure 8-7 shows the maximum noise level relative to the noise of a single device, at the centre device of a line array, as a function of the number of devices in the array, for separation of 10 m, 20 m, and 100 m. It can be seen that for separations of 20 m or greater the maximum noise level is less than 3 dB above the noise of a single device for arrays of up to 50 devices. For greater separations the maximum noise level is lower.

Figure 8-8 shows the maximum noise level relative to the noise of a single device, at the centre device of a square array, as a function of the orthogonal separation between devices, for arrays containing 9, 25 and 49 devices. The levels are generally higher than for a linear array owing to the larger number of devices within a given range, for a given separation. The maximum levels are less than 3 dB above that of a single device for separations greater than about 50 m, for arrays containing up to 49 devices.

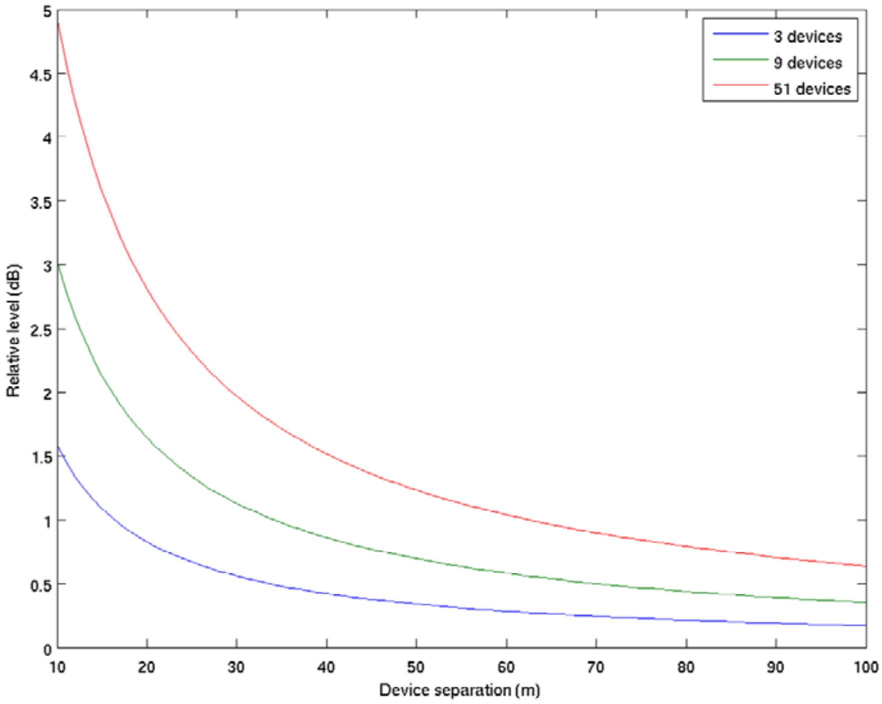

Figure 8-6: Noise level relative to the noise of a single device, at the centre device of a linear array, as a function of the separation between devices

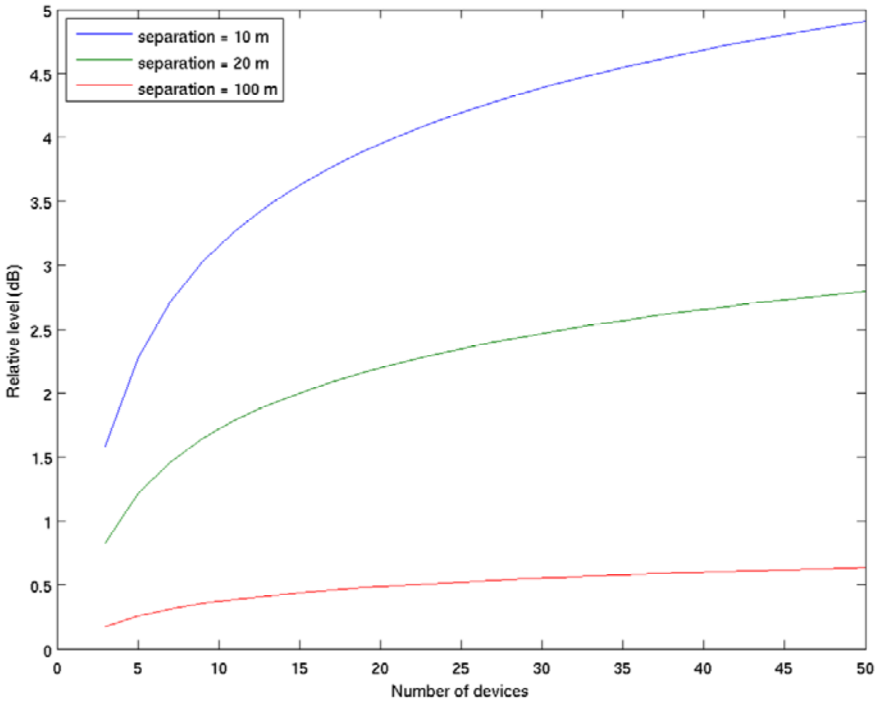

Figure 8-7: Noise level relative to the noise of a single device, at the centre device of a linear array, as a function of the number of devices in the array

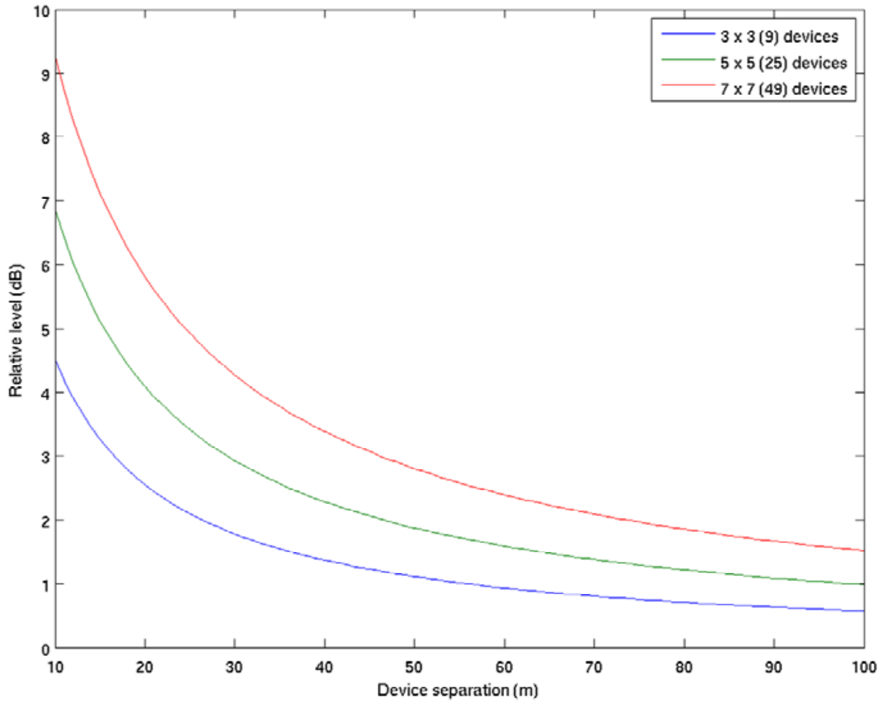

Figure 8-8: Noise level relative to the noise of a single device, at the centre device of a square array, as a function of the separation between devices

All of the above estimates are for the noise level at the centre device in the array, as that is expected to be the noisiest position and therefore the one with the maximum potential physiological impact on receptors. However it must be remembered that marine mammals may exhibit behavioural responses at much lower levels than those which may result in physiological impact. In particular they may exhibit avoidance reactions at relatively low levels [36], and an array of sources may therefore appear to them as an impenetrable barrier, even though there may be plenty of space to pass between devices without encountering damaging sound levels. Whilst there appears to be little reference to this effect in the peer-reviewed literature, it does receive attention in the grey literature. For example the question of a potential barrier effect of tidal arrays is raised in [37]. Furthermore, it is well known from many acoustic drive fisheries targeting small cetaceans that boat operators can use sound produced by various means to provide an acoustic barrier that can be used to drive animals to shore until a mass stranding results ([38] citing [39]). The combination of herding with small vessels and acoustic deterrents has been successful in preventing several milling events from becoming mass strandings of Atlantic white-sided dolphins (*Lagenorhynchus acutus*) in the Cape Cod region of Massachusetts ([38] citing [40]). Although these examples refer to the deliberate use of a moving barrier to herd cetaceans, they do support the conjectured acoustic barrier effect.

At large distances from an array of devices (i.e. at ranges much greater than the device separation) each device will contribute approximately equally to the total noise level. However, the overall level at these ranges will be small compared to the noise levels within the array.

Table 8-3 summarises the key results of this assessment of the effects of array geometry. This analysis suggests that for device separations greater than about 50 m the maximum noise level will be within 3 dB of the noise level from a single device.

Device separation (m)	Noise level relative to a single device (dB)					
	Linear array			Square array		
	3 devices	9 devices	51 devices	9 devices	25 devices	49 devices
10	1.6	3.0	4.9	4.5	6.9	9.3
20	0.8	1.6	2.8	2.6	4.1	5.8
50	0.3	0.7	1.2	1.1	1.8	2.8
100	0.2	0.4	0.6	0.6	1.0	1.5

Table 8-3: Noise level relative to that of a single device, at the centre device of an array, for various array configurations

9 Impact assessment

9.1 Assessment methodology

9.1.1 Introduction

In order to assess the impact of sound on the receptors likely to be encountered in the marine environment, it has been necessary to define thresholds, corresponding to various levels of severity of impact. Thresholds for acoustic impact in fish, marine mammals and human beings have been developed by QinetiQ [41]. Investigation of the effect of sound energy on human beings, marine mammals and fish reveals that consideration of the frequency, intensity and duration is required. It has been determined that these three aspects can be brought together in terms of the concept of 'dosage' and thus damage risk criteria (DRC) can be developed.

9.1.2 Effects of duration of exposure, intensity and frequency of underwater sound

Research on damage to human hearing in air has resulted in DRC being established by a number of authorities in different countries, including the UK Health and Safety Executive (HSE)[12]. Calculation of the dosage, as defined by HSE [42], involves integrating the acoustic energy received by an individual human being over a 24 hour period, with the dosage being dependent on:

a. the ratio (dB difference) between the received level and the threshold of hearing;

b. the total duration of exposure; and

c. the frequency content of the sound.

Owing to the paucity of data for aquatic animals, human DRC modelling is considered, at present, to be the only viable means of linking frequency, intensity and duration. The scientific grounds that support the application of human DRC modelling techniques to marine mammals and fish [43] are based upon the anatomical similarities in the inner ear and the basic audiometric responses that are found to be similar across all species. Because of this, it is possible to develop impact criteria for fish and marine mammals based on the concept of sound exposure dosage. Daily sound exposure dosage is defined as the total sound energy (i.e. the product of integrated sound intensity and duration) that is experienced by a receptor over any 24 hr period. While this approach is not perfect, it has been accepted as a reasonable method by the research community [41].

QinetiQ has shown that human in-air DRC could be applied to other species, such as marine mammals and fish, by utilising the threshold of hearing for each species in the appropriate medium (water), at the relevant frequency and that the findings agreed with experimental data [41].

[12] The UK DRC was based on, amongst others, an action level of 85 dB(A). European Noise at Work Regulations, implemented in December 2005, resulted in this action level being reduced by 5 dB to 80 dB(A).

9.1.3 Exposure of fish, marine mammals and human beings to underwater sound.

The onset of permanent or temporary hearing damage in fish, marine mammals and humans in the marine environment is dependent on the intensity of the sound to which an organism is exposed, its hearing response and the duration of exposure. Two levels of damage are considered in this document:

a. permanent threshold shift (PTS). PTS constitutes irreversible physiological damage caused by rupture of the hair cells of the inner ear, resulting in a non-recoverable partial loss of hearing sensitivity; and

b. temporary threshold shift (TTS). TTS constitutes a temporary loss in the efficiency of the mechanical–chemical–electrical transfer function in the inner ear, resulting in a temporary and partial loss of hearing sensitivity.

Investigation of published data [41] indicates that the onset of PTS in fish, marine mammals or submerged human beings is possible at sound pressure levels (SPLs) greater than 95 dB above the threshold of hearing of the animal in question, for an exposure duration of 8 hours or more in any period of 24 hours. Similarly, the onset of TTS has been found to be possible for SPLs of 75 dB above the threshold of hearing, for the same exposure duration. The SPLs at which onset of PTS and TTS might occur increases as the duration of exposure decreases. These SPLs are, respectively, 10 dB below and 10 dB above an extrapolation of the UK Noise at Work Regulations (NAWR) DRC to the marine environment, for total durations of exposure between 10 s and 8 hours.

In order to assist in the determination of the distance from the source of noise at which a fish, marine mammal or human diver is likely to be subjected to any given impact criterion, a frequency-dependent generic threshold curve (Figure 9.1) has been produced, bounding the available audiograms and corresponding to the threshold of hearing of the most sensitive creature at any frequency. It may be seen that the lowest threshold (i.e. highest sensitivity) occurs at a sound pressure level of about 30 dB re 1 μPa between 10 and 11 kHz.

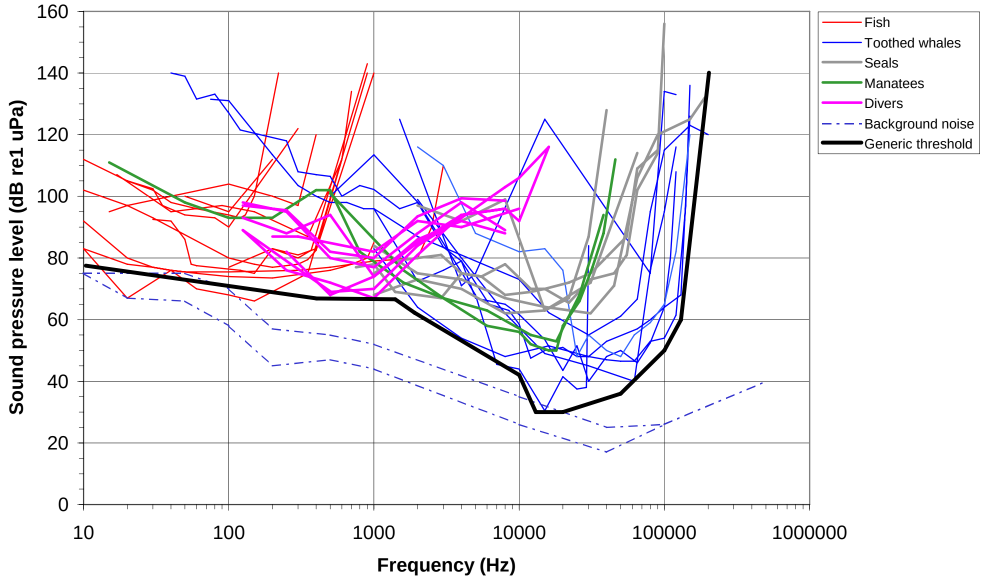

Figure 9-1: In-water threshold of hearing for fish, man, and marine mammals. Also shown are typical ambient noise levels and the generic threshold curve.

9.1.4 Application of dosage limits

Determining dosages likely to be experienced by environmental receptors is problematic in that they are generally moving, resulting in variable sound intensity at the receptor over a period of time. All the sound thus received contributes to the total dosage and therefore application of a simple stand-off range (SOR) requires careful consideration.

For generic cases, the equivalent daily dosage (D) for an individual (animal or human being) is given by:

$$D = 10\log_{10}\left[\frac{1}{28800}\int_{0}^{24\,\text{hours}} 10^{\frac{SPL-GTV}{10}}\,\mathrm{d}t\right], \tag{9.1}$$

where SPL - GTV is the difference between the sound pressure level, SPL (dB re. 1 µPa) in the water and the frequency-dependent threshold of hearing ($GTV \equiv$ generic threshold value (dB re. 1 µPa)). The figure 28800 represents an 8 hour period, expressed in seconds and is a normalisation constant in the NAWR DRC.

The GTV could be generic to all species (see Figure 9-1) or generic to families or sub-families. It can be seen, from Figure 9-1, that generic curves could be generated for such families groups where audiograms are similar. In this study the GTV for all species has been used, i.e. the black curve in Figure 9-1. This is a precautionary approach.

9.1.5 Acoustic impact thresholds

The sound dosage depends on how the sound exposure experienced by an animal accumulates during any 24 hour period. When considering SOR from sensitive sites, (e.g. known fixed sensitive sites such as seal haul out sites or Special Areas of Conservation, the precautionary principle dictates that the threshold should be based upon the total duration of sound radiated during any 24 hour period. The threshold of hearing of the most sensitive species that is identified for protection at the site should be taken into account, hence the adoption of a GTV.

The generic threshold of hearing curves, discussed above, have been used in conjunction with a TTS dosage threshold of 75 dB and a PTS dosage threshold of 95 dB above the threshold of hearing in order to estimate ranges of influence. The PTS threshold and TTS threshold relevant to any total daily exposure duration (T) are given by Equations 9.2 and 9.3 respectively:

$$PTS = GTV + 95 - 10\log_{10}\frac{T}{28800} \tag{9.2}$$

and

$$TTS = GTV + 75 - 10\log_{10}\frac{T}{28800}, \tag{9.3}$$

where GTV is the frequency dependent, generic threshold of hearing appropriate for the identified area, T is the total duration of exposure (in seconds) experienced by a receptor within a 24 hour period, as given by Equation 9.4:

$$T = \sum_{i=1}^{n} \Delta t_i \,, \tag{9.4}$$

where Δt_i (s) is the duration of the i^{th} period of radiated noise in any 24 hour period, n is the number of periods of noise radiation in the 24 hour period, if the source of noise is not continuous. If $T > 28800$, i.e. if the noise source is continuous, T should be set to 28800 in Equations 9.2 and 9.3.

9.2 Potential impacts on sensitive species / zones of influence

The assessment methodology described in Section 9.1 has been applied here to calculate PTS and TTS ranges for illustrative wave and tidal energy devices. The only devices for which sufficient data are available to carry out a quantitative analysis of this nature are the MCT tidal current turbine and the OPD Pelamis. The analysis for the tidal current turbine is based on the measurements described in Section 7.1, and the analysis for the Pelamis is based on the indicative estimates provided in Section 8.6.

9.2.1 Tidal device

Table 9-1 shows the results of the PTS analysis for the broadband noise spectrum of the tidal current turbine, for an exposure duration of 30 minutes. The analysis was performed for a duration of 30 minutes as this is deemed to be representative of the dive time of many of the shallow water species, but other periods could also have been chosen. The spectrum has been divided into third octave bands and the calculations performed at the centre frequency of each band. The source levels have been scaled up to the estimated source levels for a 1 MW[13] generator based on the assumption that the acoustic power scales linearly with the generator power [35]. This assumption is a potential source of error in the analysis, but this is likely to be the worst case and it is therefore a precautionary assumption. As an aid to interpreting this table consider the following example. In the third octave band centred on 19953 Hz (highlighted in yellow) the source level is 157.6 dB and the generic hearing threshold is 30 dB. The threshold for this GTV and exposure duration is calculated to be 137 dB, so the source level exceeds the threshold by 20.6 dB. Assuming propagation loss of 20 log R and 17 log R yields impact ranges of 11 and 16 m respectively. It will be noted that in many of the third octave bands the source level is lower than the PTS threshold, resulting in a negative threshold excess. In these cases there is no PTS impact and therefore no indicative range of influence. The cells highlighted in red show those frequencies at which there is a positive threshold excess, and therefore a potential PTS impact. However, it will be noted that the indicative ranges are very short, with the maximum being 16 metres at about 20 kHz (highlighted in yellow). This means that if the most sensitive receptor were to spend 30 minutes within 16 metres of the device it may suffer permanent hearing damage. It is unlikely that an animal would choose to remain in such close proximity to the source of a loud noise. It should be noted that the source levels above about 50 kHz will be underestimates, as the response of the hydrophone used for the measurements can be seen to begin rolling off in this frequency range (see Figure 7-3).

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[13] This analysis is for a generic turbine with a single, 1 MW rotor. It is noted that MCT's 1 MW device consists of two 500 kW rotors separated by around 30 m.

Note that two values are given for the indicative range, based on two different geometric spreading regimes. The 20 log R regime assumes spherical spreading and is most appropriate at short ranges and/or in deeper water or where the seabed is very lossy (e.g. mud), whilst the 17 log R regime is appropriate for somewhat longer ranges and/or in shallower water or where the seabed is more reflective (e.g. sand or rock). It is not possible to give absolute values for these ranges and depths, rather it is the ratio of water depth to propagation range which is important. The 20 log R regime is typical where the range is comparable with, or less than the water depth and the 17 log R regime is more appropriate for propagation over ranges equal to several water depths. These are fairly crude simplifications, but are considered appropriate for this strategic assessment. To achieve greater finesse numerical propagation models would be needed, requiring detailed knowledge of the environment and the scenarios under investigation.

Table 9-2 shows the results of similar calculations for the TTS threshold, assuming an exposure duration of 8 hours. A note of explanation is perhaps required here regarding the significance of the 8 hour period. The body of scientific evidence concerning hearing damage has been gathered by study of the hearing of humans in air. These data have been used to formulate guidance, regulations and law concerning noise exposure for humans in the workplace. Hearing may be harmed by high intensity sound of short duration or by lower intensity sound but over a longer duration. Also, the ear (in humans, fish and sea mammals) does not recover immediately but sound at a later time may add to the impact of a previous noise. In order to take these various effects into consideration the total integrated A-weighted energy per day is taken. Where the total duration of sound is greater than 8 hours, then the energy within an 8 hour period is taken. This may seem somewhat arbitrary although it should be noted that it corresponds to measured effects and is based on a typical human being's working life. As no better data are available, these figures have been applied to mammals in the marine environment. What data are available indicate that such an approach is realistic. Few data are available regarding whether the effect of duration of exposure declines after a composite 8 hours of exposure. It will be noted that the output of a tidal turbine is related to tidal stream flow and continuous operation for an 8 hour period will not occur. Generally, full-rated generation periods during spring cycles are expected to be of the order of 4 hours. With two semi-diurnal tides per day the cumulative exposure time within each 24 hour period will be approximately 8 hours, consistent with the use of the 8 hour exposure duration considered in this analysis. In neap cycles the turbine may not reach rated power and the noise emissions will be lower.

Taking an example as before, consider the third octave band centred at 15849 Hz (highlighted in yellow). The source level in this band is 157.2 dB and the GTV threshold is 30 dB. The TTS threshold is calculated to be 105.0 dB so the threshold excess is 52.2 dB and the impact ranges assuming 20 log and 17 log R are found to be 378 m and 934 m respectively.

As a result of the lower TTS threshold and longer duration, there is a positive threshold excess over much more of the spectrum than was the case for PTS, and the indicative ranges are much greater, up to 934 m at about 16 kHz (highlighted in yellow). This means that the most sensitive receptor may experience a temporary and recoverable threshold shift as a result of spending 8 hours within about 1 km of the device.

It is perhaps worth noting the difference between the methodology used in this study and the impact assessment presented in [25]. Here we consider the cumulative effects of noise exposure, which have been shown to be important in studies of hearing damage in humans. A simple consideration of threshold exceedance without considering the cumulative effects, as used in [25], would tend to predict lower impacts.

9.2.2 Wave device

The PTS and TTS calculations based on the estimated noise levels from Pelamis are given in Table 9-3. The tonals due to the hydraulic power packs have been scaled up to a 1 MW generator, again assuming that acoustic power scales linearly with generator power. However, the third octave levels representing the broadband wave noise spectrum have not been scaled up. Although it may be expected that a physically larger device might generate somewhat higher levels of wave noise, this is not expected to scale linearly with generator power. It may be seen from this table that the estimated noise spectrum does not exceed the 30 minute PTS threshold at any frequency. Therefore, based on the limited data available, it is not expected that a wave energy device of this type would present any potential for causing PTS. The maximum predicted TTS range for an exposure of 8 hours is only 6 metres, so the risk of an animal experiencing TTS from a single 1 MW device of this type is insignificant. Note that this analysis does not include structural noise, which is unknown and may be significant.

9.2.3 Arrays

The analysis presented in Section 8.7 indicates that for commercial-scale arrays the maximum noise level is likely to be within 3 dB of the noise level for a single device. Therefore the zones of influence for arrays of 1 MW devices have been estimated by increasing the source levels of a single 1 MW device by 3 dB. The maximum indicative ranges for the 30 minute PTS threshold for the tidal turbine, and the 8 hour TTS threshold for both devices, are shown in Table 9-4. There is no PTS impact from the wave attenuator array. The maximum PTS range for the tidal turbine array is just 24 m.

These results indicate that there is unlikely to be a significant PTS impact for commercial arrays of wave devices like Pelamis, and only a very small (less than 25 m) PTS zone around individual devices within a typical array of tidal current turbines.

Biological receptors may exhibit avoidance reactions to underwater noise at levels much lower than the PTS and TTS thresholds. It should therefore be noted that arrays of devices may appear as impenetrable barriers to an animal, perhaps separating them from feeding grounds, even though there may be plenty of room between devices for the animal to pass without experiencing damaging noise levels. The available evidence for this was discussed in Section 8.7.

9.3 Potential behavioural effects

The potential effects of anthopogenic underwater noise on the behaviour of marine mammals and fish are more difficult to determine than for physiological effects; they are context dependent, and must be statistically based. In particular, the contribution to long-term disturbance is, with present knowledge, not quantifiable.

Although researchers have reported the behavioural disturbance of marine mammals as a result of anthropogenic activity or human presence, very few data are available on specific corresponding sound levels. Richardson et al. [43] state that:

"almost all data on disturbance reactions, whether observational or experimental, have concerned short-term behavioural reactions".

Behavioural responses of marine mammals to wide variety of sources of underwater noise are documented in [43]. A marine animal may avoid an area immediately surrounding the source if the sound is sufficiently disturbing. This (potentially short-term) disturbance to normal activities may result in disruption of feeding, breeding, social interaction and changes to diving cycles and other behaviour. Any such short-term behavioural responses may or may not be significant to the long-term wellbeing of individuals and populations. Equally, brief and/or extended interruptions to normal behaviour can also occur as a result of natural as well as other anthropogenic causes and the effect of noise emissions must be viewed in this context. Variations in responsiveness depend on the individual within the context of the environment and the animal's activities, thus making it impossible to define a single criterion of responsiveness.

It is possible that fish might be displaced during the process of spawning, but there is no evidence that disaggregation is associated with such displacement. It is therefore likely that displaced fish will later continue to spawn. Non-lethal disturbance outside the spawning season may alter the distribution of fish. Little is known of the effect, if any, of acoustic energy on fish eggs and larvae in the water column during the spawning season.

In those cases where a response by marine mammals to acoustic disturbance has been detected, it usually involves a change in behaviour and movement away from the source. In most cases this will probably have little or no long-term consequence. Infrequent and minor changes in movement directions may be completely benign, while more frequent or recurrent incidents of interrupted feeding and rapid swimming, especially if they are of prolonged duration, could have negative effects on individuals or populations. In a number of studies [44-47] the study subjects, variously humpback, gray, bowhead, blue and fin whales, showed a range of reactions following exposure to sonar and seismic sound sources. The reactions varied from apparently completely ignoring the sounds through to changing migration paths to avoid the sound source and altering the length and structure of the vocalisations. A further study [48, 49] discovered that humpbacks sang longer songs following exposure to transmissions of the US Navy SURTASS (Surveillance Towed Array Sensor System) low frequency active sonar. In addition, songs that ended within a few minutes of sonar transmissions were found to be longer than songs recorded during periods of non-transmission. The whale's response represents a localised, short-duration adaptation to compensate for interference from the sonar transmissions. There is no evidence of any longer-term alteration of singing behaviour. Although the present study is not concerned with the deliberate transmission of sound into the underwater environment, these sonar and seismic references are included here as documented examples of the effects of anthropogenic noise on the behaviour of marine receptors.

There now appears to be fairly strong circumstantial evidence linking the use of active sonar with some marine mammal stranding events [50]. At a meeting convened by the US Office of Naval Research and the US National Marine Fisheries Service Office of Protected Resources [51], it was accepted that mid-range tactical sonar was responsible for the mass stranding of cetaceans in the Bahamas.

Other recent mass strandings appear to be coincident with tactical mid-frequency sonar operations. This includes the stranding of twelve animals in the Kyparissiakos Gulf, Greece, in May 1996, the stranding of five Cuvier's beaked whale in Puerto Rico, 1998, the stranding of four Cuvier's beaked whale on Madeira in 2000, and the stranding of nine Cuvier's beaked whale and three Blainville's beaked whale in the Bahamas, March 2000 and in September 2002, the stranding of beaked whales in the Canary Islands which has been linked to the military exercise Neo Tapon 2002 [52]. The report on the technical meeting that followed the Bahamas stranding [51] recommended that:

"until more accurate guidance can be provided, the 'precautionary principle' that applies in Environmental Impact Assessment should ensure that beaked whales are not exposed to received SPLs in excess of 160 dB re 1 μPa".

In a further development surrounding beached whales, Jepson et al. [53] reported damage to the internal organs of a number of whales that had died following strandings. It is suggested the whales had suffered acute decompression sickness as indicated by extensive damage to the animals' internal organs, especially the liver. Two possible causative mechanisms were mooted. The first is that the damage was initiated by the acoustic excitation of nitrogen in the bloodstream, causing dissolved gas to expand rapidly while the second was that the sonar disturbed the whale so much that the animal surfaced rapidly and the resulting sudden change in pressure led to decompression sickness. These research findings are controversial and contradict the findings reported in [51]. A recent paper [54] suggests an alternative mechanism for damage to the animals' internal organs i.e. overheating or hyperthermia caused by modified behaviour of an animal trying to avoid a source of high intensity sound.

Animals that can tolerate anthropogenic noise and disturbance may, after repeated exposure, eventually appear to be less affected by the acoustic source. In some cases, this may be attributed to habituation – the potential for an animal, over time, to become less sensitive to certain types of noise and disturbance to which they are repeatedly exposed and which they perceive as non-threatening. However, the presence of marine mammals in an area which is subject to anthropogenic noise does not prove that the population or individual therein is unaffected by the noise, as they may stay in the area despite the presence of noise disturbance if there are no alternative areas that meet their requirements, particularly if prey species are present in the area and are unaffected by the noise. It is not known whether marine mammals that tolerate chronic noise exposure are stressed or otherwise deleteriously affected.

Marine renewable devices are stationary noise sources, and stationary offshore activities often seem to have less effect on cetacean behaviour than do moving sound sources. Responsiveness varies significantly, however reactions have only been found when received noise levels were well above ambient levels [43].

There are no cetacean migration routes within the shallow waters of the current SEA study area and therefore the development of renewable energy projects within the study area is not expected to have any effect on migration.

9.4 Comparison with ambient noise levels

It is instructive to compare the noise levels from the devices with the background noise levels, because levels which fall below the background noise level will not generally be perceived by receptors.

The spectrum levels for a 1 MW tidal current turbine and a 1 MW Pelamis-like device (see Tables 9-2 to 9-4) have been used here for comparison with the background noise levels. The ambient noise levels used are the model predictions presented in Figure 8.1, for limiting wind speeds of 3 knots and 30 knots. To compute the attenuation of the device noise with range a spreading law of 17 log R has been used. This is typically applicable for much of the coastal waters of the UK continental shelf except at very short ranges, where 20 log R is more appropriate. The effect of using 20 log R in this analysis would be to reduce the ranges over which the device noise exceeds the ambient noise. Therefore the approach taken here is precautionary.

Since the radiated noise spectra extend up to 100 kHz and ranges of several kilometres are being considered, it is necessary to include the frequency-dependent absorption coefficient in the attenuation calculation (see e.g. [2]).

The ambient noise predictions only include the surface-generated noise and thermal noise contributions to the total noise field. In this short study it has not been possible to estimate absolute levels of other contributions to the ambient noise. The effect of additional noise contributions will be to reduce the ranges at which the device noise exceeds the background. This analysis should therefore be considered precautionary.

Table 9-6 summarises the results of this analysis. The noise excess figures indicate the ratio of the device noise at the stated ranges and at each frequency, to the ambient noise at that frequency, quoted in dB. For example, for the 1 MW tidal current turbine, in the third octave band centred on 1259 Hz, the device noise at a range of 5000 m from the device is 2 dB above the ambient noise at a wind speed of 3 knots. At a range of 10000 m the device noise in that band has fallen to 3 dB below the ambient noise at that wind speed.

The results for the tidal current turbine show that at low wind speeds the device noise at 1 km exceeds the background noise across much of the spectrum, and even at 10 km there is still a region of the spectrum between 3 kHz and 16 kHz where the background noise is exceeded. At the higher wind speed the ambient noise is greater and at 100 m from the source the noise is below the background up to about 4 kHz, and at 1300 m the entire spectrum falls below ambient. It has not been possible to estimate the absolute spectrum levels due to shipping noise and shore and surf noise, but where these sources are significant the overall ambient noise level will increase and the ranges over which the device noise exceeds the background noise will be reduced. Furthermore, tidal devices will necessarily be sited in locations with strong tidal flows, and the ambient noise associated with these currents (e.g. sediment transport noise) could be significant, reducing the impact of the device noise.

Based on the limited information available it would appear that the wave energy device of the type considered is likely to be quieter than the tidal current turbine, and the ranges of influence are therefore shorter. However it must be noted that the estimated noise levels do not include structural noise, which may be significant at frequencies below 100 Hz. At the lower wind speed the noise from the device at 100 m exceeds the ambient noise at all frequencies, but at 1 km only the 10 kHz band noise exceeds the background. At 3000 m from the source the entire spectrum is below the background noise at this wind speed. At the higher wind speed it is only the 100 kHz noise band which exceeds the background noise at 10 m and 100 m, and even this band falls below the background at 165 m from the device.

Frequency (Hz)	Source Level (dB re. 1 µPa at 1 m)	Hearing threshold GTV (dB)	Threshold (dB re. 1 µPa)	Threshold excess (dB)	Indicative range (m)	
					20log R	17log R
10	158.5	77.5	184.5	-26.2		
13	161.1	77.5	184.5	-23.4		
16	151.2	77.5	184.5	-33.4		
20	148.2	77.5	184.5	-36.3		
25	157.9	75.6	182.6	-24.8		
32	160.0	75.6	182.6	-22.7		
40	142.6	75.6	182.6	-40.0		
50	140.3	73.6	180.6	-40.3		
63	142.3	72.4	179.5	-37.2		
79	142.9	72.4	179.5	-36.5		
100	145.4	70.9	178.0	-32.6		
126	149.4	70.4	177.5	-28.1		
158	148.4	70.0	177.0	-28.6		
200	149.1	69.2	176.3	-27.2		
251	152.4	68.4	175.4	-23.0		
316	165.0	67.8	174.8	-9.8		
398	162.6	67.1	174.1	-11.5		
501	162.5	66.9	173.9	-11.4		
631	159.7	66.8	173.9	-14.1		
794	162.2	66.8	173.8	-11.6		
1000	162.0	66.7	173.7	-11.7		
1259	168.8	66.6	173.7	-4.9		
1585	163.9	65.1	172.2	-8.3		
1995	164.1	61.9	168.9	-4.8		
2512	164.0	58.9	165.9	-1.9		
3162	160.7	56.1	163.1	-2.5		
3981	157.2	53.3	160.4	-3.2		
5012	170.4	50.5	157.5	12.9	4	6
6310	157.1	47.7	154.7	2.4	1	1
7943	157.5	44.9	152.0	5.5	2	2
10000	156.8	42.1	149.1	7.7	2	3
12589	157.1	31.8	138.8	18.3	8	12
15849	157.2	30.0	137.0	20.2	10	15
19953	157.6	30.0	137.0	20.6	11	16
25119	155.9	31.5	138.5	17.4	7	10
31623	154.9	33.0	140.0	14.9	6	7
39811	154.8	34.5	141.6	13.2	5	6
50119	155.2	36.0	143.0	12.1	4	5
63096	149.1	40.7	147.7	1.4	1	1
79433	137.3	45.2	152.3	-15.0		
100000	124.9	50.0	157.0	-32.1		

Table 9-1: Results of permanent threshold shift calculations for 30 minute exposure to third octave noise levels for a 1 MW tidal current turbine. The red cells indicate a positive threshold excess and the yellow line shows the frequency band with the maximum projected impact. The grey cells indicate that the threshold has not been exceeded and therefore there is no impact range

Frequency (Hz)	Source Level (dB re. 1 µPa at 1 m)	Hearing threshold GTV (dB)	Threshold (dB re. 1 µPa)	Threshold excess (dB)	Indicative range (m)	
					20log R	17log R
10	158.5	77.5	152.5	6.0	2	2
13	161.1	77.5	152.5	8.6	3	3
16	151.2	77.5	152.5	-1.3		
20	148.2	77.5	152.5	-4.3		
25	157.9	75.6	150.6	7.3	2	3
32	160.0	75.6	150.6	9.4	3	4
40	142.6	75.6	150.6	-8.0		
50	140.3	73.6	148.6	-8.3		
63	142.3	72.4	147.4	-5.2		
79	142.9	72.4	147.4	-4.5		
100	145.4	70.9	145.9	-0.6		
126	149.4	70.4	145.4	4.0	2	2
158	148.4	70.0	145.0	3.4	1	2
200	149.1	69.2	144.2	4.8	2	2
251	152.4	68.4	143.4	9.0	3	3
316	165.0	67.8	142.8	22.3	13	20
398	162.6	67.1	142.1	20.5	11	16
501	162.5	66.9	141.9	20.7	11	16
631	159.7	66.8	141.8	17.9	8	11
794	162.2	66.8	141.8	20.5	11	16
1000	162.0	66.7	141.7	20.3	10	16
1259	168.8	66.6	141.6	27.2	23	40
1585	163.9	65.1	140.1	23.8	15	25
1995	164.1	61.9	136.9	27.2	23	40
2512	164.0	58.9	133.9	30.2	32	59
3162	160.7	56.1	131.1	29.6	30	55
3981	157.2	53.3	128.3	28.9	28	50
5012	170.4	50.5	125.5	45.0	176	437
6310	157.1	47.7	122.7	34.5	53	106
7943	157.5	44.9	119.9	37.6	75	160
10000	156.8	42.1	117.1	39.8	96	213
12589	157.1	31.8	106.8	50.3	314	800
15849	157.2	30.0	105.0	52.2	378	934
19953	157.6	30.0	105.0	52.6	377	881
25119	155.9	31.5	106.5	49.4	259	570
31623	154.9	33.0	108.0	46.9	191	398
39811	154.8	34.5	109.5	45.2	153	302
50119	155.2	36.0	111.0	44.2	130	243
63096	149.1	40.7	115.7	33.5	42	75
79433	137.3	45.	120.2	17.0	7	10
100000	124.9	50.0	125.0	-0.1		

Table 9-2: Results of temporary threshold shift calculations for 8 hour exposure to third octave noise levels for a 1 MW tidal current turbine. The red cells indicate a positive threshold excess and the yellow line shows the frequency band with the maximum projected impact. The grey cells indicate the threshold has not been exceeded and therefore there is no impact range

Frequency (Hz)	Source Level (dB re. 1 µPa at 1 m)	Hearing threshold GTV (dB)	Threshold (dB re. 1 µPa)	Threshold excess (dB)	Indicative range (m)	
					20log R	17log R
PTS, 30 minute exposure						
175	146.0	69.6	176.6	-30.6		
350	147.0	67.4	174.4	-27.4		
1000	140.0	66.7	173.7	-33.7		
10000	130.0	42.1	149.1	-19.1		
100000	120.0	50.0	157.0	-37.0		
TTS, 8 hour exposure						
175	146.0	69.6	144.6	1.4	1	1
350	147.0	67.4	142.4	4.6	2	2
1000	140.0	66.7	141.7	-1.7		
10000	130.0	42.1	117.1	12.9	4	6
100000	120.0	50.0	125.0	-5.0		

Table 9-3: Results of PTS and TTS calculations for a 1 MW attenuator type wave energy device. The red cells indicate a positive threshold excess and the yellow line shows the frequency band with the maximum projected impact. The grey cells indicate that the threshold has not been exceeded and therefore there is no impact range

Frequency (Hz)	Source Level (dB re. 1 µPa at 1 m)	Hearing threshold GTV (dB)	Threshold (dB re. 1 µPa)	Threshold excess (dB)	Indicative range (m)	
					20log R	17log R
N x 1 MW Tidal turbine array, PTS, 30 minute exposure						
19953	160.6	30.0	137.1	23.6	15	24
N x 1 MW Tidal turbine array, TTS, 8 hour exposure						
15849	160.2	30.0	105.0	55.2	517	1284
N x 1 MW Pelamis array, TTS, 8 hour exposure						
10000	133.0	42.1	117.1	15.9	6	9

Table 9-4: Maximum indicative ranges for arrays of 1 MW devices

	Frequency (Hz)	Noise excess (dB)					
Wind speed (kts)		3 knots			30 knots		
		1 MW tidal current turbine					
Range (m)		1000	5000	10000	10	100	1300
	200	-9	-21	-26	-18	-35	-54
	251	-6	-17	-23	-15	-32	-51
	316	7	-5	-10	-2	-19	-38
	398	5	-7	-12	-4	-21	-40
	501	6	-6	-11	-3	-20	-39
	631	3	-9	-14	-6	-23	-42
	794	5	-7	-12	-4	-21	-40
	1000	6	-6	-11	-3	-20	-39
	1259	14	2	-3	4	-13	-32
	1585	10	-2	-7	1	-16	-35
	1995	12	0	-5	3	-14	-33
	2512	16	4	-1	3	-14	-33
	3162	20	7	2	10	-7	-26
	3981	23	11	5	12	-5	-24
	5012	39	27	21	28	11	-8
	6310	29	16	9	19	2	-17
	7943	33	19	12	23	6	-13
	10000	36	21	12	26	9	-11
	12589	38	21	10	30	13	-7
	15849	41	22	8	34	17	-4
	19953	43	19	0	40	22	0
	25119	41	12	-16	42	24	0
	31623	40	1	-39	45	27	0
	39811	39	-14	-71	49	31	-1
	50119	34	-37	-117	53	35	-2
	63096	23	-72	-182	50	31	-13
	79433	3	-120	-265	41	21	-31
	100000	-19	-173	-356	32	11	-50
		1MW Pelamis					
Range (m)		100	1000	3000	10	100	165
	175	5	-12	-20	-21	-38	-42
	350	6	-11	-19	-20	-37	-41

Table 9-5: Generator noise excess over background noise levels (surface-generated and thermal) for different ranges and wind speeds

10 Identified information shortfalls

10.1 Device noise

10.1.1 Levels and spectra

The major area of information shortfall in this study is the radiated noise from the wide variety of marine renewable devices under consideration. At the time of writing underwater noise measurements were only available for one single device (the tidal current turbine at Lynmouth) at one location, on one day. These measurements have therefore been used as the prime source of radiated noise information for analysis in this report. It must however be recognised that other types of device may have very different noise signatures.

Those devices having all of their major mechanical and electrical components submerged are likely to cause the highest overall levels of underwater noise, especially devices such as tidal current turbines having submerged rotors, gearboxes, generators and power conversion modules. Therefore, although noise data for other devices are not available, it is expected that their total contributions to the underwater noise field will be lower for a given generator power. However, depending on the details of the device they may contribute higher levels of sound in certain parts of the spectrum. For example, devices operating on the surface may contribute high levels of wave and splashing noise at frequencies up to around 100 kHz.

10.1.2 Transients

No information has been identified on the likely levels of transient sounds from marine renewable devices.

10.1.3 Directionality

No information on the directionality of the radiated noise from marine renewable devices has been identified in the course of this study. Therefore all assessments have been based on the assumption that the devices radiate omnidirectionally. If there is any anisotropy in the radiation pattern this would lead to higher levels in some directions than those assumed in this report, and lower levels in other directions. Although the measurements of the tidal current turbine at Lynmouth were made at a number of positions around the device it would not be possible to decouple any azimuthal variability from other sources of spatial and temporal variability in this dataset.

10.2 Natural sounds

10.2.1 Wind, waves and precipitation

Although there is still some doubt about the exact mechanisms by which noise is generated from these processes, there are a number of theoretical models available which give good agreement with measured levels and which can therefore be used to predict the level of contribution to ambient noise based on weather statistics.

A quick search for weather statistics for the SEA study area failed to find data with the level of detail needed to model the contribution of these sources.

10.2.2 Surf noise

The mechanics of noise generation in the surf zone are still not fully understood, but again there are a number of empirical models that give good agreement with measured levels and which can be used to predict sound levels. These models need weather statistics, sea and shore contour, and sediment information as input. There is also a need for a better understanding of the noise levels from rocky shorelines.

Sediment transport noise

No published information on the contribution of sediment transport noise to the total ambient noise in the SEA area has been found in the course of this study.

Biological noise

No detailed maps of biological noise sources exist. Whilst the authors have a good understanding of the distribution of cetaceans in the area, much less is known about the presence of sound-producing fish species. Work is therefore required to identify and map these species. This should allow temporal and spatial distribution maps to be produced so that the level of contribution to ambient noise can be assessed. Since the sound-producing species are also likely to be the species most affected by increases in ambient noise levels this information will also assist later environmental impact studies.

10.3 Anthropogenic sounds

10.3.1 Aggregate extraction

No information on noise levels associated with this activity in the SEA area was indentified during the course of this short study.

10.3.2 Shipping noise

This has been well studied over the years and shipping statistics for the SEA area ports combined with acoustic propagation models will give a good assessment of noise fields within the study area. The major shipping lanes and shipping density were identified in Section 5, but information on the tracks and numbers of ships using the smaller ports is needed to characterise shipping noise fully.

10.3.3 Leisure craft

No statistics exist for levels of leisure craft activity within the SEA area. It may be possible to extrapolate the data gathered elsewhere by scaling for port size, but ideally a more controlled data gathering exercise is needed.

10.3.4 Industrial noise

There has been no coordinated effort to characterise Industrial noise. Some aspects have been well documented, driven by specific environmental impact requirements, while others have not been documented at all. No oil and gas installations have been identified in the SEA study area, although the Foinaven, Schiehallion and Beatrice fields may contribute to ambient noise levels in study under the right propagation conditions. No operational offshore wind farms have been identified in the SEA area, although there is a development project located close to Beatrice. Power cables have been identified in the area, but no data have been found on the likely noise levels associated with these cables. Areas of high onshore industrial activity should be identified and measurements made of the noise coupled into the sea.

10.3.5 Military noise

There are a number of submarine exercise areas around the Scottish coastline in the SEA study area, and a number of trials locations including BUTEC, Benbecula, the Clyde ranges, and Cape Wrath. It is unlikely that it will be possible to obtain detailed information on military activities in the area. Acoustic data collection in the main exercise areas will give a good guide to the level of any contribution by such activities to ambient noise levels.

10.3.6 Sonar

No statistics on sonar usage are available for the SEA study area at the current time. This may well be a major contributor to ambient noise levels in some areas so a data gathering exercise could prove useful.

10.3.7 Aircraft noise

It has not been possible to identify aircraft movement statistics during this short study, but it is believed that fixed wing aircraft make a very small contribution to underwater ambient noise levels. However, the use of helicopters to service marine facilities is increasing and it would be useful to gather data on this activity in order to assess the level of the contribution this activity makes to ambient noise. The noise signatures of the aircraft commonly in use also need to be established.

10.3.8 Fishing activity

No information on trawl noise could be found during this study and it would be useful to make measurements of a range of trawls typical of those in use in the SEA area. Detailed fishing statistics combined with information on sound levels would enable the contribution to ambient noise levels to be judged.

It is not possible to rank the above noise sources in terms of their contribution to the overall ambient noise spectrum because of the lack of information on the sources and also because their relative effects depend on many factors including water depth, weather conditions, seabed type, geographic location, etc.

11 Summary and conclusions

This report has presented the results of a desktop underwater noise study in support of the Scottish Executive strategic environmental assessment (SEA) for marine renewables.

Potential sources of ambient noise in the study area have been identified and their characteristics have been described, including spectral characteristics. The spatial (depth and location) and temporal (tidal, diurnal, lunar, seasonal) variability in these sources have also been discussed. An assessment of the likely composite ambient noise field in the study area has been made, and this information has been presented as a geographical information system (GIS) map.

Modelling has been carried out to predict the ambient noise levels in the study area and the results have been compared, as far as possible, with the available measured data. This study considered a range of water depths, seabed types, oceanographic conditions, and wind speeds appropriate to the study are and it was found that the only significant variability was due to wind speed. This was therefore the only source of environmental variability considered in subsequent analysis.

The likely sources of radiated noise from the operation of marine renewable devices have been described, together with their likely spectral characteristics and relative levels.

A limited set of measurements of underwater noise from a tidal current turbine in the Bristol Channel have been presented and analysed for illustrative purposes. These are the only known underwater noise measurements of the radiated noise from an operating marine renewable device, and therefore form the primary dataset for analysing the potential impact of underwater noise from such devices. Measurements of ambient noise previously carried out by QinetiQ in the study area are also presented. Estimates of the likely radiated noise spectrum from a wave energy device have been carried out based on the known engineering details of the device and QinetiQ's experience with the radiated noise signatures of similar marine systems.

An assessment has been made of the noise levels due to commercial-scale arrays of devices, including an analysis of how the number and arrangement of devices could affect the noise emissions, compared to those from single devices. This has shown that the noise level from a commercial-scale array is likely to be within 3 dB of the noise from a single device.

Impact assessments have been carried out to determine the potential zones of influence within which devices and device arrays may cause permanent or temporary physiological impacts to receptors in the marine environment. Based on the data available and the necessary assumptions made, it is concluded that there is very little risk of the devices or devices arrays causing any permanent hearing damage to marine animals, but it must be stressed that detailed impact assessments should be carried out on a case by case basis for each specific project development.

The radiated noise from renewable devices has also been compared with the ambient noise predictions, and propagation loss calculations have been used to determine the ranges at which the likely noise from the devices falls below the background noise level for different wind speeds. This analysis included only wind-generated surface noise and is therefore considered precautionary. Where the ambient noise levels are higher due to additional sources, e.g. local ferries or sediment transport due to high tidal currents at tidal generator sites, the relative impact of the devices will be smaller.

There is a general paucity of information regarding the underwater noise from marine renewable devices, and these information shortfalls have been discussed in this report. Furthermore, ambient noise levels are not generally sufficiently well characterised to inform project-specific environmental impact assessments. Therefore this study has involved a large number of necessary assumptions and simplifications. However, it is considered that the level of information in this report is sufficient and appropriate for the purposes of the current strategic study.

In addition to the detailed supporting descriptions and analyses presented in this report there are a number of key outputs which inform the SEA process:

a. a GIS map of the ambient noise distribution in the study area (Figure 5-1) and supporting GIS data files;

b. a summary of the main noise sources associated with the different device types (Table 6-1);

c. a summary of the effects of array size and configuration on the noise levels (Table 8-3);

d. a summary of the potential impact ranges of devices and arrays (Tables 9-3 to 9-5); and

e. a comparison of the device noise levels with ambient noise levels at various ranges (Table 9-6).

12 Recommendations

The assessment of the impacts of marine renewable devices presented in this study has been conducted at a strategic level, as appropriate for contributing to the strategic environmental assessment for marine renewables. Although specific devices have been used to inform this assessment and illustrate potential impacts, the analysis has been generic and it has been necessary to make many assumptions. It is therefore recommended that specific detailed underwater noise studies be carried out for each individual project development. Such studies should include the following components:

a. a detailed baseline assessment of the ambient noise field at the development site, including variations over the tidal, diurnal, lunar, and annual cycles, and under a range of meteorological conditions;

b. a detailed estimate of the radiated noise spectrum level for a single device, ideally based on underwater noise measurements. If that is not possible then estimates should be made based on appropriate and representative measurements of noise and vibration levels in air, from which in-water effects could be estimated;

c. an assessment of the noise field in and around the development site based on underwater acoustic propagation models, utilising the proposed array geometry, and oceanographic and geoacoustic parameters of the development site; and

d. where the proposed development is expected to lead to underwater noise levels in excess of the local ambient noise levels, an assessment of the impact of the underwater noise on marine receptors. This should be based on the audiogram data for the most sensitive receptor likely to be present in the area or, to be precautionary, the generic threshold curve presented in this report.

It is also recommended that continuous or routine *in-situ* underwater noise measurements be carried out at development sites, to monitor for increases in noise level due to the development of fault conditions in the deployed device(s). This would enable the early detection of potentially harmful levels of underwater sound as well as facilitating timely repair of mechanical faults. Mitigation measures should be in place, for example the facility to shut down the device(s) on detection of noise levels above some threshold.

Finally, it has only been possible in this study to estimate the likely broadband continuous noise from a wave energy device, based on known engineering details and experience with similar maritime systems. This required a number of assumptions to be made, and neglected the potentially important structural noise. It is therefore strongly recommended that underwater measurements of noise from an operating wave energy device are conducted at the earliest opportunity.

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Abbreviations

ARU	autonomous recording unit
DRC	damage risk criteria
EMEC	European Marine Energy Centre
EU	European Union
GIS	geographical information system
GPS	global positioning system
HSE	Health and Safety Executive
LARES	Langer approximation for reflection from the seabed
MCT	Marine Current Turbines
NAWR	noise at work regulations
OPD	Ocean Power Delivery
PTS	permanent threshold shift
SANE	synthetic ambient noise environment
SEA	strategic environmental assessment
SOR	stand-off range
SPL	sound pressure level
SSP	sound speed profile
TTS	temporary threshold shift

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Abstract

A desktop study of underwater noise has been carried out in support of the Scottish Executive's strategic environmental assessment for marine renewables. Sources of ambient noise in the study area have been identified and characterised in terms of their: frequency content; relative level; and spatial and temporal variability. The mechanisms of noise generation in marine renewable devices have been identified and the sources of noise in a range of device types have been assessed. Illustrative noise spectrum levels for two examples of marine renewable devices (a tidal device and a wave device) have been used to assess the potential impact of device noise on receptors in the marine environment. The noise from these devices has also been compared with expected levels of ambient noise. Based on the limited information available to this study noise from these devices is not expected to result in significant impacts. Finally, the information shortfalls in this study have been identified.

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