REPORT

NOA Krafla, Noise assessments on fish farms and marine wildlife

CLIENT

Aker Solutions AS

SUBJECT

Noise assessment on fish farms and marine wildlife

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REPORT

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SUMMARY

This document comprises results from noise simulation in connection with blasting of sea cable trenches at the Landfalls in Årskog and Ospeviki. Results are evaluated with regards to environmentally important assets. Specifically, Fish farms Nygård (13020) and Matløyso (21915) are considered, together with spawning grounds Fitjarvika near Årskog and Samnanger – Tysse, and Flesjane – Notaholmane, Klubben and Gjerde near Ospeviki. Land based fish tanks is also considered with regards to the planned blasting works at Årskog.

Årskog

• Matløyso fish farm. Unit charge sizes below 50 kg, placed in stemmed holes together with the use of a bubble curtain will cause noise levels low enough to avoid TTS completely. However, some reaction may be expected from the fish in the farm. It would be even more conservative to use 15 kg charges placed in stemmed holes and using a bubble curtain. This would ensure very mild fish reactions, boarding to the "no-reaction"-limit.

• Fitjarvika spawning ground. Blasting with a charge of 15 kg will induce noise levels that may cause temporary damage (TTS) to fish within roughly half the spawning ground. The use of a bubble curtain can reduce this range to 700 meters away from the blasting site. Behavioural changes in fish are expected in the whole spawning ground. It is recommended that blasting at Årskog takes place outside the spawning period (February – April).

• For land-based aquaculture facility at Årskog, a vibration limit of 13 mm/s is recommended, in addition to camera monitoring of the fish in the tanks. If behavioural changes are registered on fish, blasting must be limited to one charge per day.

Ospeviki

• Nygård fish farm. The sound level pressures from 50 kg unit charges without bubble curtain is close to being unacceptable in terms of TTS. We propose to use either bubble curtain or decrease the charge unit weight to 15 kg to avoid TTS in fish. By using 15 kg charges, further reduction with the use of a bubble curtain, to avoid strong responses of fish, is not deemed necessary because the fish farm is topographically shielded from the blasts.

• Samnanger – Tysse, and Flesjane – Notaholmane spawning grounds. Roughly a third of the spawning ground Samnanger – Tysse is exposed to levels above temporary effects (TTS), when a charge of 15 kg is used. The use of a bubble curtain can reduce this area to approximately 700 meters from the blasting site. Behavioural changes are expected in the whole spawning ground, even for smaller charges. Blasting at Ospeviki should take place well outside the spawning period (February – April).

General

Effects on populations residing in the areas outside the spawning period is largely unknown and mitigating measures should be applied to reduce possible negative effects. i.e., blasting with smaller cartridges is preferred over larger ones.

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1 Introduction

1.1 Background

Underwater noise pollution is expected in the context of the establishment of trenches for sea cables for NOA Krafla at the Landfalls in Årskog in the Fitjar fjord and Ospeviki in the Samnanger fjord.

1.2 Objective

This report comprises assessment of noise levels for fish in nearby fish farms and spawning grounds, together with effect descriptions and suggestions for charge sizes and noise mitigating measures.

1.3 Scope of work

Table 4. shows the details of the associated sound propagation simulations, including coordinates for explosions, charge sizes, possible mitigations, and the metrics used for assessment of hazards to fish and other marine life in the considered areas. Figure 1 shows an overview of the area, and the planned blasting locations. Blasting induced vibration effects for land-based fish farms are also included.

Table 1. Overview of blasting locations used in the analysis of underwater blasting and sound exposure. Coordinates are given in UTM32. It is assumed that charges comprise several detonations with a time delay of between 10 and 50 milliseconds.

Activity / place	Coordinates		Blast sizes [kg]	Considered mitigations	Noise quantity
Blasting / Ospeviki	X: 318950	Y: 6697093	15 and 50	Bubble curtain	SPL, Particle velocity
Blasting / Årskog	X: 294792	Y: 6650265	15 and 50	Bubble curtain	SPL, Particle velocity

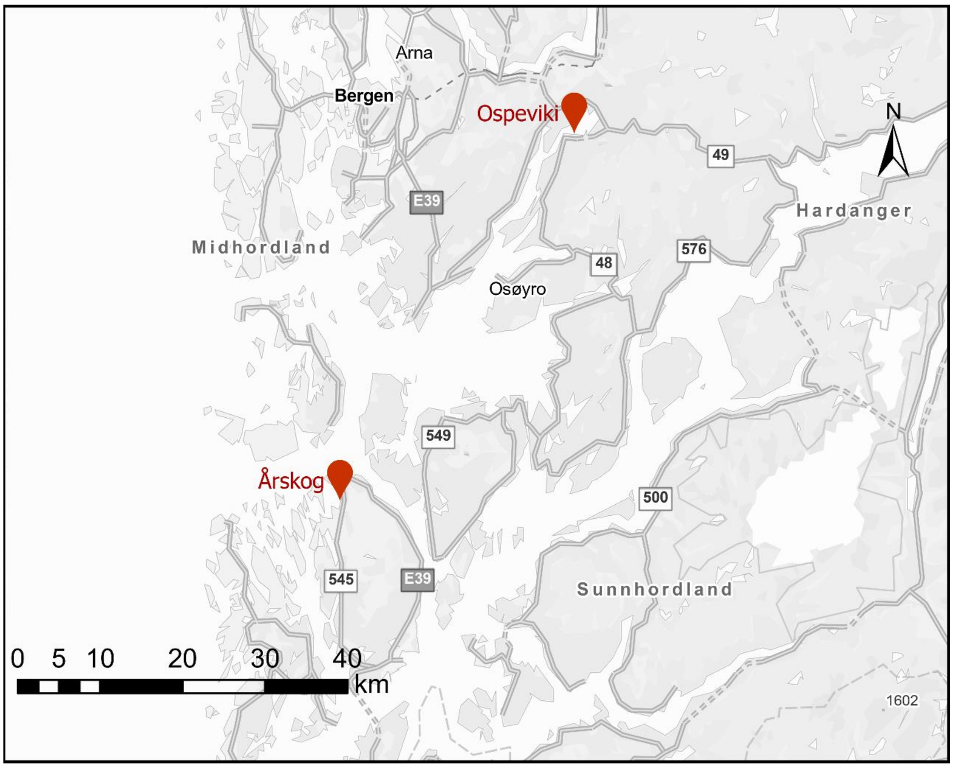

Figure 1. Overview of the area with the two planned landfall locations / blasting sites.

1.4 Revision history

Rev	Changes from previous version
01	First issue
02	Updated after comments from the client, clarifying some aspects of action.

2 Noise and shock propagation due to subsea blasting

Multiconsult has developed tools for cost effective and conservative estimates of sound level exposure from underwater and coastal activities. This method is described in full detail in this document (Appendix 1 - 5).

Blasting of bedrock near Årskog and Ospeviki has been assessed in terms of sound level exposure with respect to injury of fish and altered behaviour in the respective areas.

2.1 Considerations for blasting at Ospeviki and Årskog

The left panel in Figure 2 shows the location of the planned blasting site at Ospeviki, which is located about 2.2 km from the fish farm 13020 Nygård. Following the fjord, the distance is roughly 2.9 km. The blasting site Ospeviki is inside the Samnanger – Tysse spawning ground for cod, and only 700 meters from the Flesjane – Notaholmane spawning ground. In the north part of the Samnanger fjord two other spawning areas are identified, Klubben and Gjerde, 2.7 and 3.5 km away from the blasting site, respectively (not shown in the map).

There is a fish farm (21915 Matløyso) roughly 2.8 km from the planned blasting site at Årskog, which is also situated inside the Fitjarvika spawning ground for cod (right panel, Figure 2).

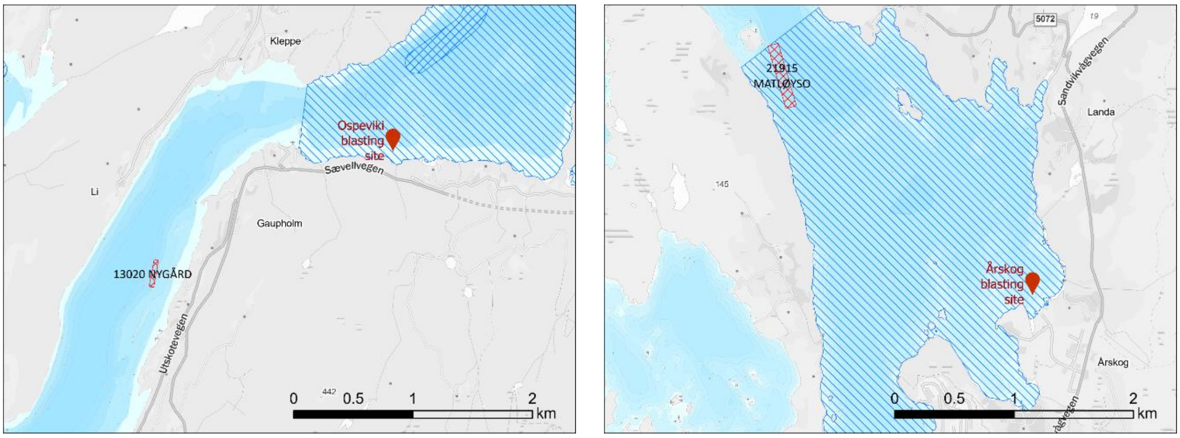

Figure 2. Left panel: Overview of the area where bedrock blasting at Årskog is planned. Blue back-hashed area indicates the Fitjarvika spawning ground for cod and red area indicates the Matløyso fish farm. Right panel: Overview of the blasting area at Ospeviki. Back-hashed area indicates the Samnanger Tysse spawning ground for cod, and the forward-hashed area shows the spawning ground Flesjane – Notaholmane (Fiskeridirektoratet, 1988), and the red hashed area indicates the Nygård fish farm.

2.2 Blasting at Ospeviki

2.2.1 *Blasting at Ospeviki, affecting spawning grounds*

The sound pressure waves created from blasting may propagate uninterrupted towards the northeast of the inner part of the Samnanger fjord and will therefore reach the spawning grounds with a high amplitude. Using a bubble curtain would reduce the SPL by approximately 10 dB re 1 µPa, which is the equivalent to a 90 % reduction in terms of pressure.

Using a unit charge of 50 kg without a bubble curtain would produce a pressure wave which would reach the closest part of the Flesjane – Notaholmane spawning field at over 200 dB re 1 µPa. With the use of a bubble curtain, the sound pressure level is reduced to 190 dB re 1 µPa at the same location (Figure 3, upper panels). A unit charge of 15 kg produces considerably less noise. The SPL level is less than 200 dB re 1 µPa without the bubble curtain and less than 190 with it, at the same location (the edge of the Flesjane – Notaholmane spawning field).

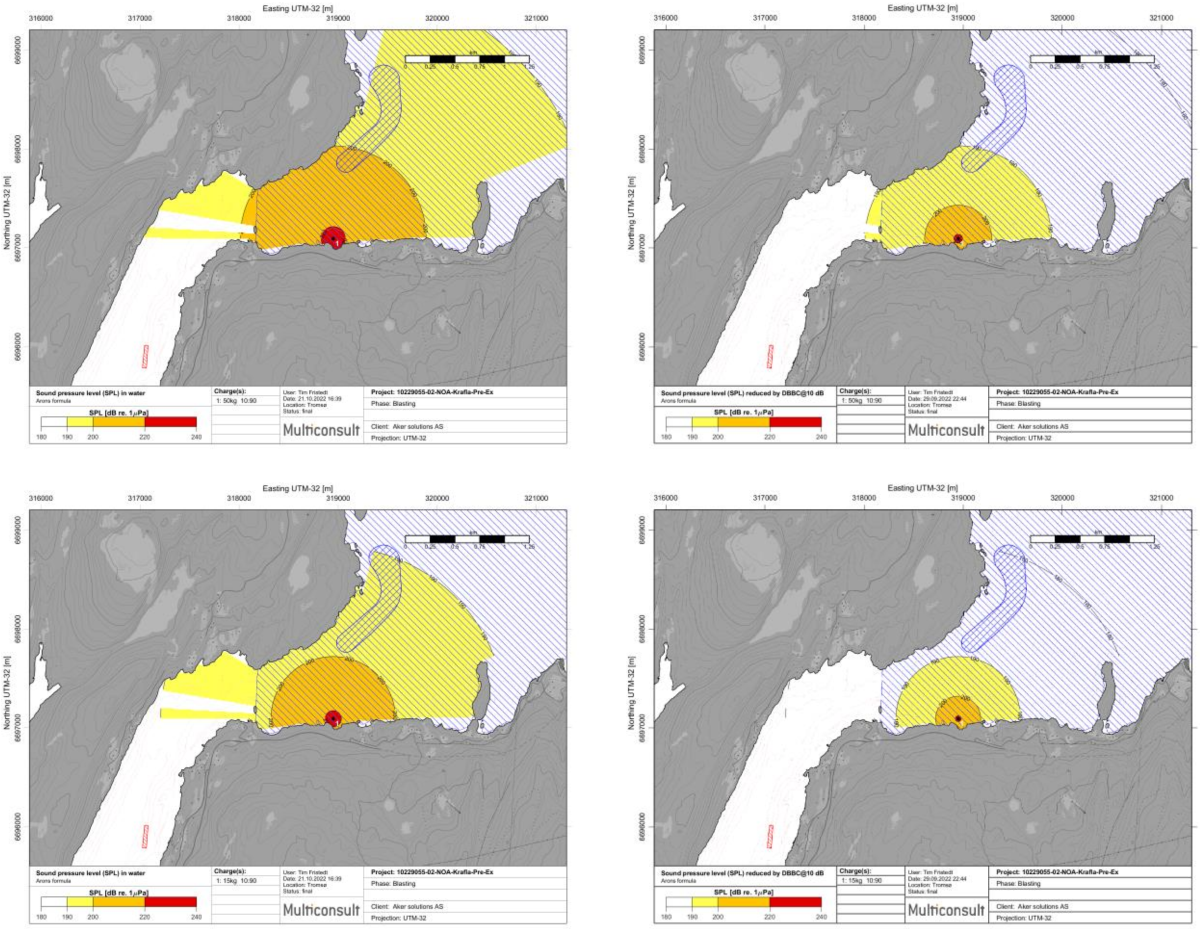

Figure 3. Blasting at Ospeviki with 50 and 15 kg unit charge sizes. Left panels shows the sound pressure level (SPL re 1 µPa) without bubble curtain and the right panels show the exposure from blasting with a double bubble curtain. Upper panels show the resulting SPL from 50 kg unit charges and the bottom panel shows 15 kg results.

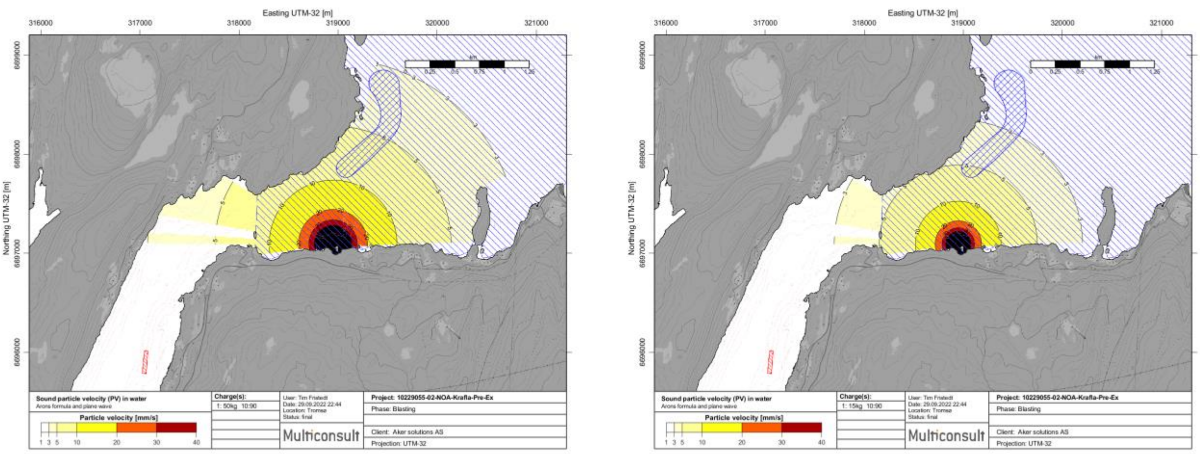

Figure 4. Particle speeds resulting from blasting. Panels show blasting with 50 (left) and 15 (right) kg unit charge sizes.

The particle speeds resulting from blasting at Ospeviki, using 50/15 kg unit charges are roughly 10/5 mm/s at the edge of the Flesjane – Notaholmane spawning field. The threshold for injury to fish is around 6 mm/s, which gives roughly the same conclusion as for the SPL. Hence, the particle velocities resulting from a 50 kg blast, may cause injury to fish in the Flesjane – Notaholmane spawning field. The same location will not receive harmful levels with a 15 kg unit charge.

Since the Ospeviki blasting site is inside the spawning field Samnanger - Tysse, it is not feasible to reduce unit charges so that no part of the spawning ground is exposed to damaging sound pressure levels. By visual inspection of the sound propagation charts, the areas exposed to sound pressure levels higher than the limit for TTS (190 dB re 1 µPa) are seen in Table 2.

Table 2. Area of the fjord / spawning ground that is exposed to sound pressure levels higher than 190 dB re 1 µPa (the limit for TTS). "Relative area" indicates the ratio of area with SPL>190 dB re 1 µPa over the total spawning ground area.

Unit charge weight (kg)	Bubble curtain	Relative area
15	No	1/3
15	Yes	1/8
50	No	3/4
50	Yes	1/6

2.2.2 *Blasting at Ospeviki, affecting the Nygård fish farm*

Further south, and closer to the Nygård fish Farm, the signal is hindered by land, making the estimation of sound exposure more challenging. Two approaches are possible for this estimate.

No screening: The easiest and most conservative method is to let the pressure wave propagate through the land barrier without further damping than the radial spreading. This method, here called *no screening*, can be used as an upper bound for estimation of the sound pressure at the Nygård fish farm. Using this method for a unit charge of 50 kg, the SPL reaches 190 – 200 dB re 1 µPa without a bubble curtain, and 180 – 190 dB with a bubble curtain (Figure 5, upper panels). For a 15 kg unit charge, the SPL is lower. Figure 5 (lower panels) show SPL for a unit charge of 15 kg, without and with bubble curtain. The SPL at Nygård is 180 – 190 dB re 1 µPa without the curtain and 170 – 180 dB re 1 µPa with the curtain.

Channel propagation*:* The second method is to let the pressure wave propagate through the fjord channel. In this case, there is considerable attenuation because the sound wave loses energy along its path through the strait. A fraction of the sound wave energy is lost each time the wave reflects on the seafloor. The surface may also damp or disperse sound energy, but to keep the estimates conservative we treat the surface as a perfect reflector). A method for estimating the reaming sound pressure wave energy at a certain distance away from a source is described in section 0. Figure 6 shows the remaining pressure resulting from this method together with the signal attenuated through radial spreading only. The sound pressure level at the Nygård fish farm is 150 and 155 dB re 1 µPa for 15 and 50 kg unit charges respectively, using the *channel propagation* method.

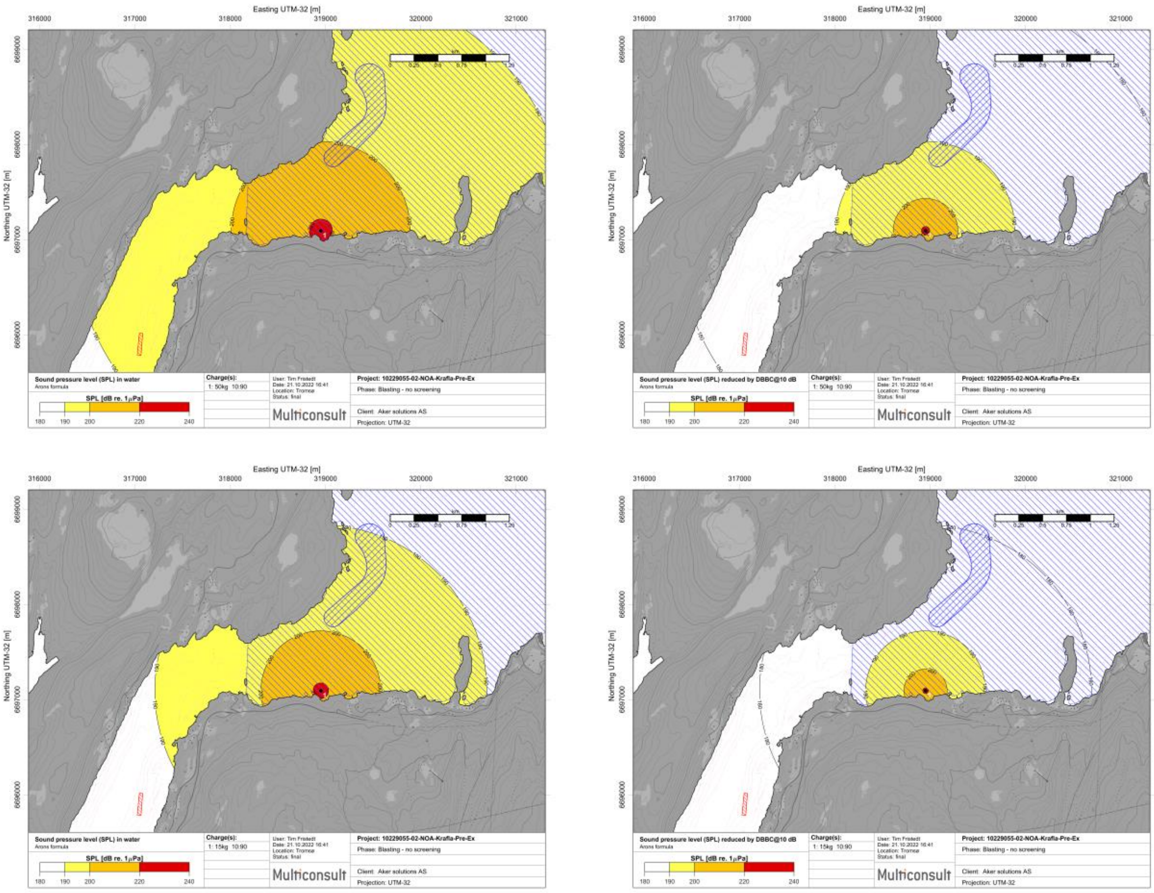

Figure 5. Blasting with "no screening" at Ospeviki. Left panels shows the sound pressure level without bubble curtain and the right figures show the exposure from blasting with a double bubble curtain. Top and bottom panels show results from 50 and 15 kg unit charges respectively.

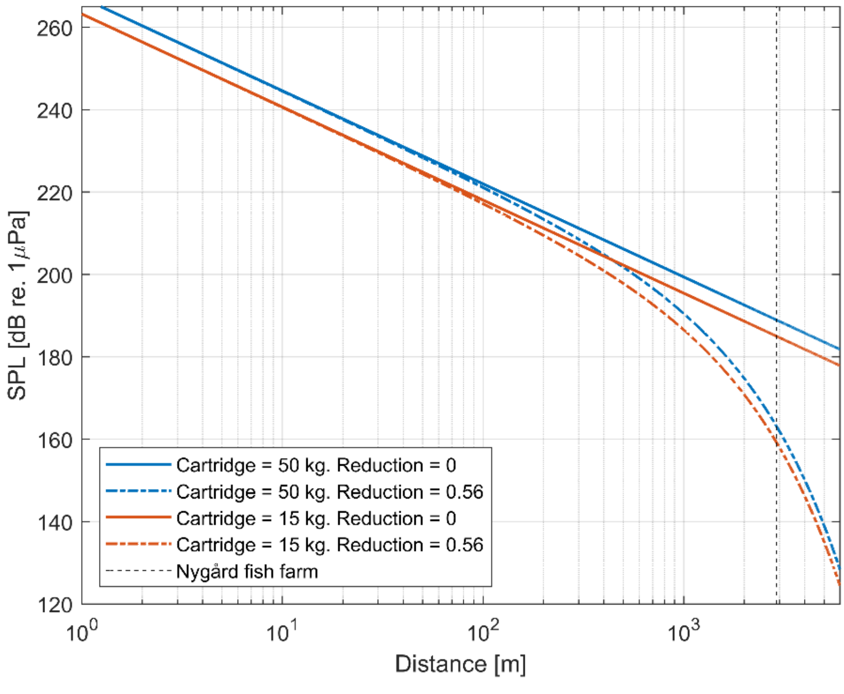

Figure 6. Attenuation of sound waves propagating through a channel. Solid lines show radial spreading only, while dashed lines show the sound pressure level (SPL) of the signal, attenuated through several reflections on the seafloor and surface. Colours indicate the unit charge weight (blue = 50 kg, red = 15 kg).

In summary, SPL levels at the Nygård fish farm is within tolerable noise levels when a 15 kg unit charge is used, also without a bubble curtain. 150 dB re 1 µPa is below the response threshold for salmon.

2.3 Blasting at Årskog

2.3.1 *Blasting at Årskog, affecting the Fitjarvika spawning ground*

The Årskog blasting site is inside the Fitjarvika spawning field and so blasting should be restricted to periods outside the spawning period (February – April).

In Fitjarvika, the sound pressure waves can propagate unimpeded towards the northwest, and the bulk part of the fjord can be exposed to high amplitude pressure waves (high SPL). A unit charge of 50 kg without a bubble curtain would produce a pressure wave which would expose almost the entire fjord to levels above the threshold for TTS (SPL>190 dB re 1 µPa). With the use of a bubble curtain, the area is reduced to approximately one sixth of the fjord area (Figure 7, upper panels). A unit charge of 15 kg produces considerably less noise, and a bubble curtain would reduce the area of high SPL to less than 20% of the fjord. Table 3 shows a rough estimate of the areas which will be exposed to high SPL as a result of blasting with different unit charge sizes and use of bubble curtains.

Table 3. Area of the fjord / spawning ground that is exposed to sound pressure levels higher than 190 dB re 1 µPa (the limit for TTS). "Relative area" indicates the ratio of the area with SPL>190 dB re 1 µPa over the total spawning ground area. Ratios are estimated by visual inspection of the sound propagation maps.

Unit charge weight (kg)	Bubble curtain	Relative area
15	No	1/2
15	Yes	1/10
50	No	4/5
50	Yes	1/6

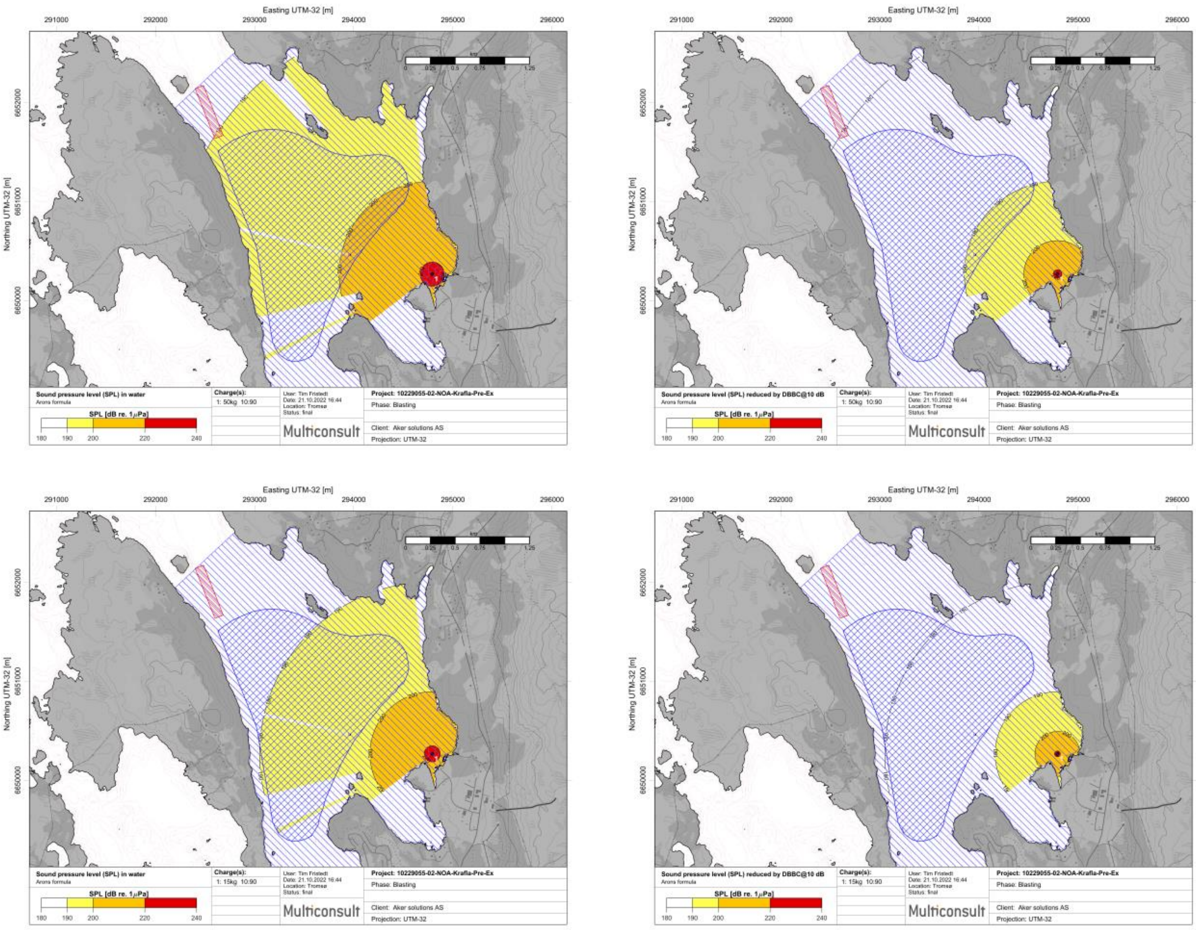

Figure 7. Blasting at Årskog with 50 and 15 kg unit charge sizes. Left panels shows the sound pressure level (SPL re 1 µPa) without bubble curtain and the right panels show the exposure from blasting with a bubble curtain. Upper panels show SPL re 1 µPa resulting from 50 kg unit charges and the bottom panels show 15 kg results. Blue hashed area indicates the spawning field Fitjarvika, and red hashed area is the Matløyso fish farm.

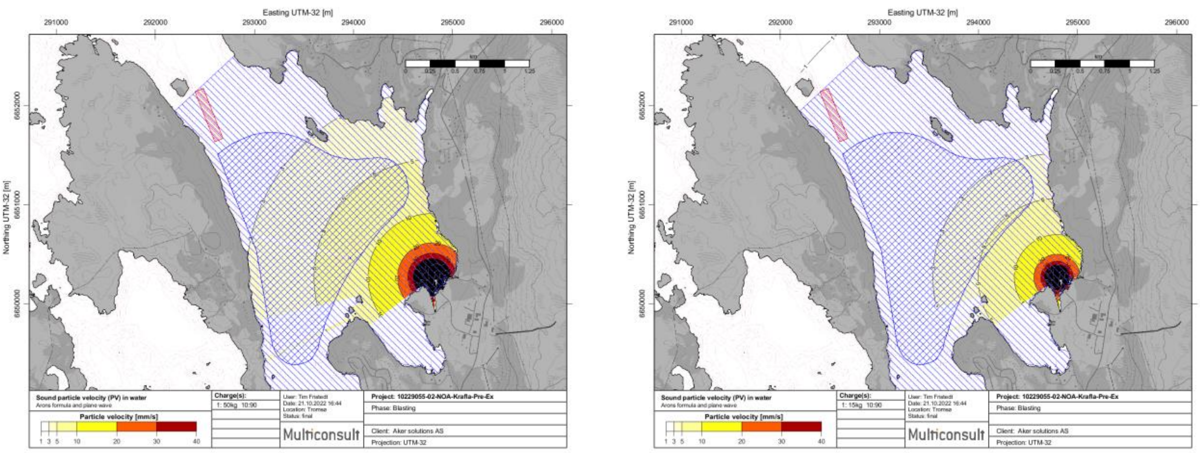

Figure 8. Particle speed maps for 50 kg unit charge (left) and 15 kg unit charge (right). The particle speed is indicated by colour. Blue hashed area indicates the spawning field Fitjarvika, and red hashed area is the Matløyso fish farm.

2.3.2 *Blasting at Årskog, affecting the Matløyso fish farm*

The planned blasting activities at Årskog will produce sound pressure waves, introducing moderate risk of injury to fish in the Matløyso fish farm.

At the Matløyso fish farm, SPL is just above 190 dB re 1 µPa when a 50 kg unit charge is used without a bubble curtain (Figure 7, top left panel). A way to mitigate the exposure is to use a bubble curtain, which can reduce the levels by -10 dB. Consequently, the level is 180 dB re 1 µPa when a bubble curtain is in use while blasting with a 50 kg charge (Figure 7, top right panel). This level is above the response limit but below the limit for injury (PTS or TTS).

Using a 15 kg unit charge, SPL reaches around 185 dB re 1 µPa at the fish farm, and as low as 175 dB re 1 µPa with a bubble curtain (lower panels in Figure 7). This noise level (175 dB re 1 µPa) is above the response threshold for salmonoids (150 dB re 1 µPa), but well below the TTS threshold. Research suggests that one can attribute reactions of fish to noise exceedance of hearing thresholds (dB_{ht}). Reactions to different dB_{ht} intervals are described in the Subacoustech Report No. 534R1231 [1][1]. Assuming that the hearing threshold of salmon is 110 dB re 1 µPa, the conservatively calculated 175 dB re 1 µPa sound pressure wave represents 65 dB_{ht}, and so the response is in the low end of the "stronger response" scale[1]. We translate this to a mild response that will decrease with repeated exposures due to habituation. Mild reactions in fish due to subsea blasting has been observed while measuring 168 dB re 1 µPa. In the observed case, the fish swam slowly downwards at the time of explosion, only to return to the surface about 10 seconds later [2].

2.4 Blasting at Årskog, affecting fish in land-based tank

The planned blasting at Årskog will be executed approximately 250 m from an existing fish tank on land. Mortality and injuries on fish due to blasting is most commonly caused by rapid pressure changes. Pressure waves from blasting is most prominent from detonation of unconfined explosives (open or unstemmed). When explosives are confined in bore holes (stemmed holes), the resulting pressure wave is generally only around 10 % of the pressure wave produced from an unconfined bore hole, see Appendix 3.

The pressure wave from the planned, confined detonation will propagate through several medias. This, together with the significant distance of 250 m, is expected to reduce the pressure wave to a level not harmful for fish in the tank.

The blasting will produce vibrations and noise. Vibrations and noise are known to cause damages to incubating eggs and sublethal effects to fish, such as changes in behaviour.

"Guidelines for the Use of Explosives In or Near Canadian Fisheries Waters" [3] defines guidelines for overpressure and vibrations near fish habitat and spawning areas. It is recommended that these guidelines are implemented for the land-based fish tank. These guidelines are as follows:

- Overpressure must be lower than 100 kPa
- Vibrations must be lower than 13 mm/s

Unit charges can be calculated based on Norwegian Standard NS8141:2001. However, the distance from the detonation to the fish tanks implies that these calculations will allow for quite high unit charges. Instead of these calculations, it is recommended that test blasting and registered vibrations

[1] Responses reported in [1]: 0 – 50 dB_{ht} elicits a mild reaction in a minority of individuals, probably not sustained;
50 – 90 dB elicits a stronger reaction by the majority of individuals, but habituation may limit effect;
90 dB and above elicits a strong avoidance reaction by virtually all individuals;
above 110 dB is the tolerance limit of sound, – unbearably loud".

are used for calculating unit charges. A unit charge of 50 kg, as defined in chapter 2.3, will most likely produce vibrations that are well under the limits stated by the guidelines.

It is recommended that fishes in the fish tank are monitored during blasting, to register potential changes in behaviour. Fishes in the fish tank are enclosed in caged and have no possibilities to escape when exposed to stress. Repeated blasting can therefore lead to chronic stress. Based on this, it is recommended that more than one blast per day is avoided if vibrations on the fish tank is registered.

2.5 Effects on populations

Long term effects on populations from subsea blasting is difficult to assess in detail. Larvae and eggs are more resistant to sound and vibrations than adult fish and have a naturally high mortality rate. This could mean that the additional noise exposure may not play a significant role for their mortality rate. On the other hand, juvenile fish are physiologically more sensitive than adult fish, and are more habitat dependent.

There is little information in public databases regarding natural values, other than the spawning areas in Samnanger Tysse and Fitjarvika. Unidentified juvenile fish were observed during the ROV-survey conducted in September 2021 [4].

It cannot be ruled out that populations in the vicinity of the blasting areas may be negatively affected by sound exposure from the planned activities. Therefore, activities should be executed with a general care to avoid unnecessary sound exposure.

3 Conclusion

3.1 Implication for fish farms

- Nygård: The sound level pressures introduced to the fish farm from detonating 50 kg unit charges without bubble curtain is close to be unacceptable in terms of TTS. We propose to use either bubble curtain or decrease the charge unit weight to 15 kg to avoid TTS in fish. Further reduction with the use of a bubble curtain in order to avoid strong responses of fish is not deemed necessary, since the farm is partly shielded from the blast.
- Matløyso: Unit charge sizes should be below 50 kg, and use of bubble curtain is necessary to avoid risk of TTS in fish. The use of 15 kg unit charges together with a bubble curtain would reduce levels enough to cause very mild reactions of fish in the farm. Charges are assumed to be paced in stemmed holes.
- Land-based fish tanks: Unit charges of 50 kg will most likely not produce vibrations that are above stated guidelines, and it is recommended that fish in the tanks are initially monitored during blasting. Furthermore, it is recommended maximum one blast per day if any effects are registered.

3.2 Implication for spawning grounds

- Fitjarvika: The blast location is inside the spawning field and blasting activities should therefore be planned outside the spawning season (February – April). To limit damage to populations in the area outside the spawning period, one could use 50 kg unit charges and a bubble curtain to reduce the TTS risk zone to one sixth of the fjord area.
- Ospeviki: The blasting site is inside the Samnanger-Tysse spawning ground, and only 700 meters from Flesjane – Notaholmane. Klubben and Gjerde spawning grounds are both in the north end of the Samnanger fjord. Blasting activities should be executed outside the spawning period. Limiting risks to populations in the area outside the spawning period may be achieved by using 15 kg unit charges, which cause exposure to levels above TTS in one third of the fjord.

3.3 Effects on populations

It is largely unknown how populations of fish, birds and marine mammals react to exposures from noise pollution over time. In the fjord system Selbørnsfjorden, Børnafjorden, Fusafjorden, and Samnangerfjorden, including Fitjarvika commercial fishing is ongoing the whole year. Therefore, care should be taken to avoid unnecessary sound exposure that could potentially harm the marine wildlife.

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Appendix 1: Definitions

Table 4. Overview of definitions used in connection with sound waves and underwater acoustics.

Term/abbreviation/expression	Explanation	Description
Sound pressure level (SPL)	Peak pressure	Short-term sound pulse measured in dB. Often used in conjunction with blasting.
SEL (Sound exposure level)	Sound exposure	Prolonged sound exposure. This is used in connection with the exposure of sound over time and is indicated in dB integrated over time. It is thought that sound is produced at a time of day, such as 12 hours and that sound occurs a certain percentage of the time.
SEL_{24}	Daily weighted Sound exposure	Mean value of SEL over a day. Aimed at judging long-lasting effects, from activities repeated over a long period of time.
Duty cycle	Fraction of time a source produces sound	Fraction of the time when an active sound source actually makes sound. For example, a piling machine makes noise up to 15% of the time.
Work hours	Working hours per day	The average time per day that the sound source is active. For example, the number of hours a piling machine is in use throughout a day. Depends on how long the working day is.
Hearing threshold		Threshold value for when a species can perceive sound (peak pressure).
Response		Some fish show changes in behaviour, such as changes in swimming patterns, orientation and scare reactions.
Response threshold		Loudness (dB) required to observe response in fish
S_0	Source strength Source level	The source is characterized by a source strength in [dB re. 1µPa @ 1m], defined 1 m from the source.
Interval	Time interval within which one unit charge ignites.	Blasts are most often performed with several smaller charges that are detonated within short time intervals (teeth interval) for example 15-30 milliseconds.
Unit charge	Amount of explosive that detonates at the same time.	Total weight of explosive charges detonated within an interval.
TTS	Temporary threshold shift	Temporary hearing damage / impaired hearing
PTS	Permanent threshold shift	Chronic hearing damage - irreparable impairment of hearing

Appendix 2: Sound in water / Hydroacoustics

Sound in water can be described by analogy with sound in air, but the differences are large since water is significantly denser than air. This is one of the reasons why one cannot directly compare sound pressure in air with sound pressure in water. Sound propagation in water is generally more complicated than in air, as there are frequent interactions between sound fields and the interfaces (surface /bottom) in addition to modulation, refraction, and dispersion in the medium itself. Wave propagation is about 5 times faster in water than in air, in addition to the distribution of temperature and salt can provide significant refraction and refraction of the sound field.

Hydroacoustic levels (dB) are given with a reference pressure of 1µPa, implying that the sound pressure values in water are different to those in air, where a 20µPa reference level is regularly used.

The interaction of sound with the bottom depends largely on the type of bottom. If it is hard (rock, stones) much of the energy is reflected back into the water and if it is soft (sediment, clay, sand), a large portion of the acoustic energy can be broken down at the bottom and thus absorbed more efficiently.

Description of sound as pressure

Normally, sound is described as a pressure oscillation and this is, in the vast majority of cases, an adequate approach. Due to the fact that pressure is measured in Pascal [Pa] and most often range over orders of magnitude, it is appropriate to report and visualize noise levels in the logarithmic scale dB relative to a reference pressure:

$$p_{dB} = 20 \cdot \log_{10}(p/p_{ref}) \tag{1}$$

where p is the pressure and p_{ref} is a reference pressure (1 µPa). Here it should be noted that for air acoustics the reference pressure is often set to 20 µPa, which represents the hearing threshold for humans. This means that the dB levels in air are lower than the corresponding dB level in water, even though the source has the same energy/intensity level. The source is characterized by a source strength [dB re 1µPa @ 1m], which means that the pressure field is defined 1 m from the source and is a characteristic property of the source itself, regardless of the propagation from source to receiver.

Source strength

There is a large range of source strengths for various machines and equipment that produce underwater noise. Multiconsult has extensive experience from a wide range of equipment that generates sound in air, and this library can be used to calculate relevant source strengths in water, S_0. To compare air acoustics with underwater acoustics, one can investigate the intensity of sound in different medium. The instantaneous intensity *I* of a sound wave is:

$$I = \frac{p^2}{Z} = \frac{p^2}{c\,\rho} \tag{2}$$

, where *Z* is the acoustic impedance, p is the pressure, c and ρ are the sound speed and density of the medium. Requiring that intensities are the same in water and air gives that the pressures (expressed in decibel, dB) in air p_{dBa} and water p_{dBw} relate according to:

$$p_{dBa} \approx p_{dBw} - 62\ dB \tag{3}$$

This equation can be relied upon to estimate a realistic hydroacoustic source strengths based on our overall experience of noise sources from a wide range of air acoustic noise calculations and noise zone maps. This allows us to estimate with high confidence source strengths of equipment commonly used by contractors in and around Norway. It should be emphasized that the calculated source strengths S_0 are compared and calibrated with the information contained in the literature, further increasing confidence that the sources are relevant to the analysis.

Peak pressure and exposure

There are several metrics that characterize sound pressure. The most common and intuitive is SPL_{peak} which is the maximum deviation t from the normal ambient pressure (mean pressure) during a defined time. Sometimes the peak-to-peak value $SPL_{peak\text{-}peak}$ or SPL_{pp} *is used.* In this report, only the peak pressure SPL_{peak} is used as this is suitable for describing impulsive processes, such as blasting, piling and spunting. In the entire report, therefore, "peak" is dropped and only *SPL* is used as a term for the target pressure to simplify the discussion and highlight the content of the report.

For processes with longer duration and less impulsive character, such as dumping, drilling, and shipping, other metrics can be defined: for example, root-mean-square values: SPL_{rms}. In several cases, it has been shown that relatively low sound pressure over longer time periods can cause permanent damage to fish, marine mammals, and birds [5, 6]. It is therefore appropriate to define Sound Exposure Level (*SEL*) being the integral of the square of the sound pressure over a specified time interval or event (for example, an acoustic pulse). Sound exposure levels are expressed in dB re 1 $\mu Pa^2 s$. Sound exposure is a measure of the energy in the acoustic field where the unit for SEL is $Pa^2 s$ or Jm-2, i.e., energy per unit area.

$$\mathrm{SEL_{dB}} = 10\log_{10}\left(\int \frac{p(t)^2}{p_{ref}^2}\,dt\right) \tag{4}$$

As with SPL, there are many variations on acoustic exposure, for example the definition of a single strike of a pile hammer (Single-strike-SEL). Cumulative effects are sometimes used to characterize repetitive impulsive sources, *CSEL* (Cumulative SEL). In this report, the term SEL is used for describing sound exposure in a simplified manner, based on the "duty cycle" of equipment causing sound. This enables us to evaluate aggregate effects from several different places and activities in an area over time.

Frequency content and noise

The pressure oscillations can be described as waves, and like all other waves, have a specific frequency content. A pure tone is described as a single frequency and a combination of tones gives a spectrum. Normally, every natural sound is a combination of many different tones since sound propagation in nature is more or less stochastic. The frequencies of the tones are combined (often nonlinearly) and distribute their energy over a spectrum. This is called frequency expansion and forms a sound blanket. If a sound source is to be perceived from a distance, the sound from it must penetrate such a background sound blanket. The sound level that makes up the lowest tone in a spectrum is called noise level and can come from many different sound sources. Underwater noise can be described as a chorus, where sounds of different nature and origin are mixed together:

• Natural noise or geophony is the noise of cracks in the earth, movement of marine sediments, weather and wind, breaking waves, precipitation, etc.

• Biological or biophonic noise is of biological origin produced by marine fauna.

Anthropogenic or anthropophonics noise is man-made noise created by maritime activities, such as shipping, vibrations from cars, trains, and railways, etc.

These sounds blend with each other and form the sound context of an area of study. All sound sources contribute to ambient noise at a variable weight, depending on frequency, environmental conditions, human activities, and local conditions. For a fish to be able to hear a specific sound, it must exceed the acoustic background level.

Particle motion

Sound waves are pressure waves causing material motion, which is called *particle motion,* its derivative is called *particle acceleration*. The velocity of particle motion, *u* can be associated with the pressure *p* through the acoustic impedance $Z= c\ \rho$ in the medium, where *c* is the speed of sound and ρ is the density.

$$u = \frac{p}{Z} = \frac{p}{c\ \rho} \tag{5}$$

It has been shown that several marine species are sensitive to the physical effects of particle movement. This movement is difficult to measure and is therefore, in studies on acoustic noise in water, often neglected, or not sufficiently investigated. Particle movements are often very small [7, 5] and weak (often < mm/s) but can be much larger near a detonation or close to an interface. Moreover, the movement is vectorial, which further complicates the measurement process. Although the significance of particle motion for the hearing of fish is well known, it is only in recent years that evidence has been presented as to how much fish and marine animals make use of this property of the acoustic field. It contains information about distance, direction, and other state of food, threats, or potential partners [8].

Appendix 3: Method description

Modelling noise propagation

Multiconsult has developed a methodology for calculating, assessing, and visualising noise levels under water, with the aim of assessing the risk of damage to selected marine animal species in the vicinity of action areas. Sound energy, which is primarily a pressure wave, propagates in all directions, and the acoustic energy is dissipated, absorbed, broken, and reflected. This causes the sound wave to change its signature. For example, a sound pulse which is short and intense at its source can be modified by the physical environment and perceived more prolonged and less intense some distance away from its source.

In order to carry out a risk assessment, a simplified methodology based on the prediction of horizontal scattering of sound waves has been used. The core of acoustic modelling is primarily the geometric dispersion of the pressure energy. For deep conditions without interaction with surface or bottom, propagation is spherical and sound intensity decreases quadratically with distance ($1/d^2$) or expressed as dB scale: 20 $\log_{10}(d)$. In shallower conditions, the energy is dissipated cylindrically, and the pressure falls with the distance as 1/d, or 10 $\log_{10}(d)$.

It has been shown that cylindrical dispersion is an overly conservative model with too slow energy loss. In coastal contexts one often measures a dispersion factor between 14 and 17 $\log_{10}(d)$, which can be explained by the fact that the energy loss, compared to cylindrical dispersion (10 $\log_{10}(d)$), increases due to losses at the seafloor and surface, as well as in volume [5].

A realistic sound propagation model in coastal areas is thus something in between cylindrical and spherical scattering, and we have chosen 14 $\log_{10}(d)$ as the loss coefficient for the sound propagation / exposure model. This ensures a realistic but conservative method for estimating sound propagation and exposure to sound/noise energy, a so-called realistic worst-case scenario.

These assumptions allow that sound propagation calculations can be carried out cost-effectively and provide clients and contractors with valuable information. For example, which maximum unit charge can be used for blasting, what effect or active working hours can be used when piling and spunting, to minimize injury to fish from both an impulsive and an exposure perspective.

Exposure to sound is divided into two methods:

- In transient impulsive sound, a peak pressure, sound pressure level, *SPL* is calculated. This method is used for blasting, for example.
- For sound over time, sound exposure level, *SEL* is calculated. This is used for work that takes place over time, such as piling, drilling, excavating, dumping of rocks, or other activities in the sea or around the shoreline.

Transient impulsive sound

When blasting of subsea bedrock is carried out, the blast-energy is partitioned into a fraction that crushes rock, and a fraction that produces shock waves in the water. The literature describes mostly freely hanging charges in water and to a lesser extent blasting of charges detonated below the seafloor. When the charge is drilled into the rock, the pressure is concentrated to blast rock and a smaller part of the energy forms the pressure wave. This is also the reason why several studies recommend sealing boreholes (stemming) with crushed stone and delaying ignition (each borehole is detonated separately with a delay of 20 – 50 ms). The hazards to marine life caused by blasting can be classified in three zones:

1. Near field zone/mortality zone - The peak pressure rises in a short period of time to several hundred MPa (>240 dB), but the peak value will decay quickly to half of its original pressure within a millisecond.

2. Transition zone/Injury zone - The probability of instantaneous mortality is small. Fish on the surface or near the bottom may die. The peak pressure in this zone is below 1 MPa (<240 dB).

3. Far zone - the sound will consist of many reflections and the pulse pressure will be significantly reduced.

Equation (6) can be used to calculate the peak pressure (*SPL*) from the weight of an explosive charge with weight *Q [kg]*:

$$p = A\left(\frac{d}{\sqrt[3]{Q}}\right)^{-b} \tag{6}$$

, where *A* is a material constant, characteristic of the explosive agent, and *b* is a reduction exponent representative of the exponential spread of the pressure wave. Equation (6) is widely called Aarons' formula and describes the maximum overpressure as a function of the distance *d* [m] to the detonation. *A* is typically in the range 50 – 60 MPa, and *b* ranges from 1.13 to 1.19 for a wide variety of explosives and conditions. It can be mentioned that for cylindrical dissipation of energy b = 1, and for spherical dissipation b = 2. A conservative yet realistic estimate is achieved by setting $b = 1.13$, and $A = 52.4 \cdot 10^6$ Pa, which are typical values for slurry charges [9]. Here, p is the pressure signature of freely hanging charge.

For a charge placed in a stemmed borehole, one assumes that a fraction of the blast pressure energy crushes rock and the remaining fraction produces a sound pressure wave. The stemming coefficient λ is thus defined as:

$$p_m = (1 - \lambda)p \tag{7}$$

, where p_m is the energy that comprises the sound wave. A common value for the stemming coefficient λ is 90 %, which means that 10 % of the blast energy translates to the sound pressure wave, in agreement with previous experience from blasting projects [10] , [9].

Deepening of waterways is by large done by blasting charges of 30 – 50 kg drilled into boreholes at intervals of 1 – 2 blasts per day, depending on natural conditions (type of seafloor, depth, waves, winds, and currents), personnel and equipment.

For tunnelling, a strict sequence is followed (pre-injection, drilling, charging, blasting, cleaning, and securing). Approximately 5 m long boreholes are charged with multiple blast intervals with weights of 60 – 100 kg. For larger tunnelling projects, the goal is to reach approx. 20 m per week, which gives approximately 1/2 charge per day. Smaller road tunnel projects can detonate up to 2 charges per day.

Sound exposure over time

Sound exposure level, *SEL*, as a result of long-term sound source is defined as the pressure squared integral over a specific time *t*:

$$\mathrm{SEL} = \int_0^t p(t)^2 dt \, . \tag{8}$$

Most often, it is most appropriate to express SEL in dB relative a reference pressure, in hydroacoustics, usually p_{ref} = 1 µPa²s;

$$\mathrm{SEL_{dB}} = 10 \log_{10}\left(\int_0^t \frac{p(t)^2}{p_{ref}^2} dt\right). \tag{9}$$

There are other ways to define the exposure. For example, SEL_{1s} where the integral in (9) is evaluated continuously for each point in time:

$$\mathrm{SEL}_{1s}(t, 1s) = 10 \log_{10}\left(\int_t^{t+1s} \frac{p(t)^2}{p_{ref}^2} dt\right). \tag{10}$$

By defining (S_0) as the effective broadband source strength [Pa] 1 meter away from the source and estimating cylindrical dispersion of the acoustic energy, the pressure is inversely proportional to the distance from the source. One can estimate $\mathrm{SEL_{dB}}$ at the distance from the source d [m].

$$\mathrm{SEL_{dB}} = 10 \log_{10}\left(\int \frac{S_0(t)^2}{d \;\, p_{ref}^2} dt\right) \tag{11}$$

If the time variation of the source is known in terms $work\_hours$ and $duty\_cycle$ (see Table 4. for definitions) the integral can be calculated explicitly. This provides the integrated sound exposure $\mathrm{SEL_{dB}}$ [dB re 1 µPa²s] relevant to fauna in the area:

$$\mathrm{SEL_{dB}}(d) = 10 \log_{10}\left(\frac{3600 \cdot (work\_hours) \cdot (duty\_cycle)}{d} \frac{{S_0}^2}{p_{ref}^2}\right) \tag{12}$$

Here, $work\_hours$ [h] is the length of the working day, $duty\_cycle$ [%] is the fraction of the time that the utilized equipment emits sound, and S_0 [Pa] is the source strength 1 meter from the source.

Another way to characterize sound exposure over time is to average $\mathrm{SEL_{dB}}$ over 24 hours:

$$\mathrm{SEL_{dB24}} = 10 \log_{10}\left(\frac{3600 \cdot (work\_hours) \cdot (duty\_cycle)}{(24 \cdot 3600)\, d} \frac{{S_0}^2}{p_{ref}^2}\right) \tag{13}$$

This provides a measure of the sound exposure to which marine wildlife is exposed, on average per day. This metric may be more relevant to compare with threshold values in cases with prolonged intermittent exposure when wildlife can recover from harmful sound effects between sound bursts.

Formulas (12) and (13) assume that the sound pressure is constant and equal S_0 as the equipment is active. For sources with pressure variation within the active time, e.g., piling, it is better to calculate the single-strike sound exposure, SEL_{ss}. Because the sound exposure is defined as the integral of the pressure squared (8), and that the pressure comprises many frequencies (is broad banded), one can assume that the pressure squared integral is equal to the integral of the amplitude of the pressure. Figure 9 shows an example of sound pressure from a piling machine where the pressure amplitude decreases rapidly after each pile stroke. The pressure amplitude is assumed to decrease exponentially with time immediately after the sound pulse and can be drawn:

$$A(t) = P_{max} e^{-kt} \, , \tag{14}$$

Where *k* is a damping coefficient, which can be adjusted so that the amplitude matches the measured pressure. P_{max} is the highest absolute value of the pressure. In this example, the amplitude matches well then *k*=34. This allows the single-strike sound exposure to be written:

$$\mathrm{SEL_{ss}} = \int_0^{\Delta t_s} \left(P_{max} e^{-kt}\right)^2 , \tag{15}$$

where Δt_s the time interval between the sound pulses from each pile stroke.

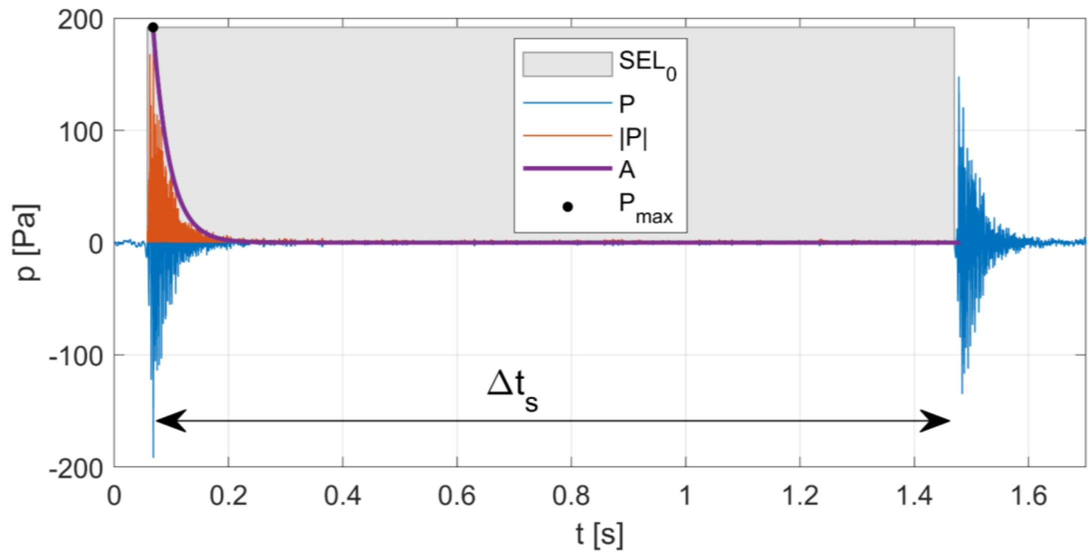

Figure 9. Example of broadband sound pressure from piling. Blue indicates instantaneous sound pressure, red shows the absolute value of the pressure and purple shows the amplitude. Δt_s is the interval between pile strikes and P_{max} is the maximum pressure. Gray area is sound exposure in case of constant sound pressure. The example is from measurements in Hammerfest harbour in connection with piling.

In cases when source strength and attenuation are known from measurements, it is useful to define the fraction α:

$$\alpha = \frac{SEL_{ss}}{SEL_0}, \tag{16}$$

where SEL_0 is the sound exposure from a sound source of constant strength (grey field in Figure 9).

If one knows the source strength S_0 and the attenuation coefficient *k*, it is possible to calculate the sound exposure based on the time interval between the sound pulses, for example from piling strikes. Figure 10. shows how α depends on the strike interval Δt_s.

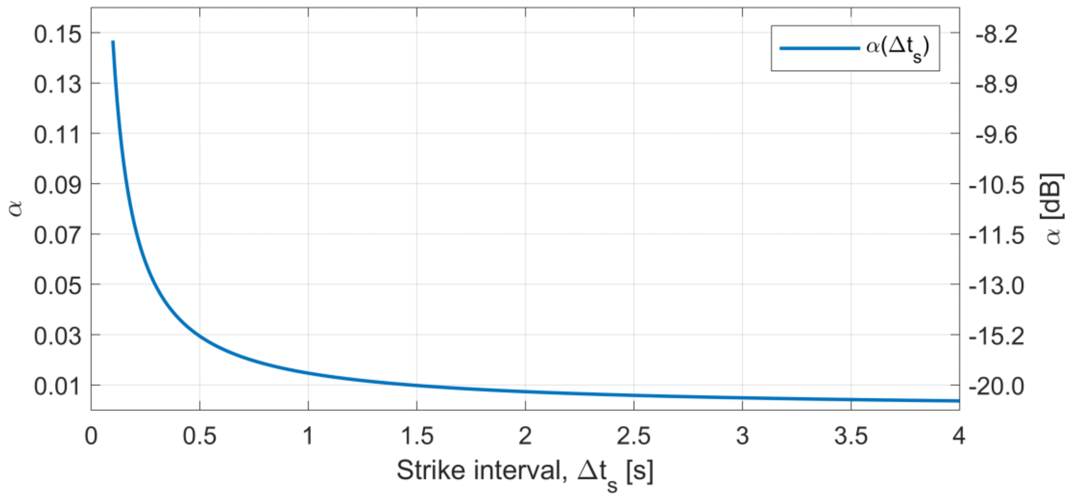

Figure 10. Dependence of α on the strike interval.

Sound exposure from intermittent sound sources should therefore, if one takes the sound exposure from a constant source as a reference, be reduced according to:

$$SEL = SEL_0 \cdot \alpha \,, \tag{17}$$

or simpler:

$$SEL_{dB} = SEL_{0dB} + \ \alpha_{dB} \,, \tag{18}$$

where $\alpha_{dB} = 10 \cdot \log_{10}(\alpha)$. In the example from Hammerfest harbour, in connection with piling with a stroke rate of 1.5 seconds, sound exposure calculated this way is reduced by about 20 dB re 1 µPa^{2}s compared to SEL_{0dB}.

Reflection and transmission

When sound passes through the interface between media with different acoustic impedances, a partition of the acoustic energy takes place. Part of the energy reflects, and the rest is transmitted. For a pressure wave, the reflection coefficient R^2 and transmission coefficient T^2 partition the energy as follows:

$$R^2 = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2}$$
$$T^2 = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} \tag{19}$$

where Z_1 is the acoustic impedance of the original medium with incident and reflected sound field and Z_2 is the impedance of the medium with the transmitted field. According to typical values for sound speed and density (Table 5.), roughly 70% of the energy is reflected and about 30% propagates (is transmitted) from rock to water.

Table 5. Values that form the basis for calculating reflection and transmission through a media transition between mountains (medium 1) to water (medium 2).

	Medium 1 Rock/Crushed rock		**Medium 2 Water**	
Parameter	c_1	ρ_1	c_2	ρ_2
Typical values	6000 m/s	2300-2800 kg/m3	1500 m/s	1000-1030 kg/m3

Damping of sound waves from reflections on the seafloor

A simple way to describe damping of the acoustic wave energy is to evaluate the number of times the wave reflects on the seafloor while propagating away from its source. It is sufficient to evaluate the 45° "sound rays" which propagates between the bottom and surface interfaces. If one considers the surface a perfect reflector, only the reflections on the seafloor will cause reduction. In a fjord with mean depth H the distance *L* between each reflection is:

$$L = 2\sqrt{2}h \tag{20}$$

Since L is linearly dependent on the depth *h*, it is sufficient to consider the mean fjord depth *H* along the path of the sound wave. This means that for each distance *L* the sound wave only retains *R* % of its energy (*R* is thus the reflection coefficient). The number of reflections $N_r(d) = d/L$, is a function of the distance to the source and the remaining energy can therefore be described continuously, avoiding stepwise damping. The fraction of energy remaining at some distance away from the source can be written:

$$\lambda(d) = R^{N_r(d)} = R^{d/L} \tag{21}$$

Equations (6), (7) and (21) gives a convenient expression for the pressure at some distance, *d* from a charge detonation of weight *Q*, a stemming coefficient γ and $\lambda(d)$:

$$p = (1 - \gamma) \cdot \lambda(d) \cdot A \left(\frac{d}{\sqrt[3]{Q}} \right)^{-b} \tag{22}$$

Appendix 4: Hazards for marine wildlife

When managing risk, particularly two parameters are used. *SPL* (Maximum Sound Pressure Level) and *SEL* (Sound Exposure Level). The specific expressions are explained in Appendix A and are detailed in Appendix B. In addition to this, the Norwegian Environment Agency has published Norwegian translations for some of the expressions used in the report. [11].

Detection thresholds

Fish have a wide range of sound detection abilities and are very sensitive to pressure changes. Because the ocean is often dark and murky, fish typically rely on hearing as their primary sense, and generally have good perception of both pressure and particle movement. Most fish species have a pressure-sensitive lateral line organ, most likely used for hunting, flight and school coordination [12].

The common species relevant for Norwegian conditions, salmonoids (*Salmonidae*), codfish (*Gadidae*) and herring fishes (*Clupeidae*) have somewhat different hearing thresholds and perceive somewhat different frequency ranges, see Table 5, Appendix E. Adult Salmonoids have an open swim bladder connected via a pneumatic duct to the gut, thus through water, and have a hearing threshold of just above 100 dB re 1uPa. Cod fish perceive sound better, with a threshold approximately 20 – 30 dB lower. This is because codfish have a closed swim bladder that acts as a resonant chamber, which is also close to the hearing organs. Herring perceives sound even better and display a hearing threshold 10 dB lower than codfish. Herring are able to perceive a wider frequency spectrum, and many herring species have gas-filled organs close to the hearing organs, making them more sensitive to sound (Table 6.) [5].

These thresholds should be set in relation to the ambient noise blanket found in the water with different amplitude and character around the clock. Noise blankets vary from very quiet areas with no anthropogenic impact, where only wind, rain, waves and wind make up the noise background (approximately 60 – 80 dB re 1 µPa) to very noisy areas close to infrastructure such as ports, harbours, or heavy industry, where the noise blanket can be up to between 120 and 140 dB re 1 µPa [13, 14].

To describe the risk of detection, the term «Probable reaction» is used, based on the threshold levels for detection (Table 6., Appendix 5).

Permanent and Temporary Damage

The type of injuries that do not lead to death are divided into two subgroups: Permanent (chronic) or Temporary (temporary) injuries. Both types are, in principle, mild barometric traumas that occur with lower pressure exposure.

It is indicated that both temporary and permanent threshold shifts (*PTS* and *TTS*) can be inflicted on fish exposed to peak pressure close to threshold values for «probable harm» (SPL > 200 dB re 1 µPa).

For longer-term sound exposure, temporary damage can occur to SEL > 180 dB re 1 μPa^2s, and more serious (but recoverable) injuries can occur above about 200 re 1 μPa^2s. [15]

For this type of injury, the range is much greater than for direct barometric trauma, as these effects can cause secondary damage, e.g., water is sucked into the swim bladder (especially species with an open swim bladder such as salmon). This can stress the fish and cause them to change their behaviour. Long-term sound exposure may make the fish unable to adapt to causes and a so-called tertiary stress response can lead to greater mortality as a result of the extra stress it causes. This is strongly linked to repeated exposure, which means that an apparent low pressure exposure over a long period of time can accumulate significant damage in fish. Overstimulation of the ear's hair cells, or nerves can cause temporary impairment of hearing, but naturally, this type of damage is difficult to study in experiments and observations [16].

Death/Barometric Trauma

Death or permanent injury, so called barometric trauma, happens almost exclusively in the "Near Field Zone/Mortality Zone", and to some extent in the "Transition Zone/Injury Zone". The boundaries of these zones depend on species, size, age, fitness, distance from charge as well as orientation and location in the water column. Primarily internal organs such as liver, kidneys or gonads are damaged in relation with barometric trauma. Air- and gas-filled organs, such as swim bladders and lungs (mammals) are particularly vulnerable since trauma occurs when gas pockets expand with the sudden decompression (pressure drop) that follows the initial compression. This causes stress on tissues and muscles, and can cause ruptures, bleeding, or other injuries. The decompression can release gas, forming bubbles in the heart, gills, gonads, kidneys, eyes, or brain, which can inhibit important functions and lead to death. The reflection of a sound wave on a smooth surface can cause local extreme compression/ decompression, and therefore severely harm fish or mammals near the sea surface.

To judge the risk of severe barometric trauma, it is appropriate to use the wider scale: "probable harm" for SPL > 200 dB re 1µPa (10 kPa) and "very likely injury" SPL > 220 dB re 1µPa (100 kPa). There are more finely defined threshold values given in [17, 18] which are used when higher precision is desired.

Pressures above 229 – 234 dB re 1 µPa entail a high risk of instantaneous death.

It should be emphasized that uncertainties are numerous in terms of the sensitivity of fish and the sound exposure calculation results depend on the quality of the underlying data. For this reason, while doing an initial risk assessment, the use of the courser risk scale is sufficient.

Masking, fear, and stress

Changes in behaviour are easier to capture in experiments. It should be emphasised that behavioural changes are specific to species, background noise and the situation of the fish. In general, it can be said that for pressure pulses below approx. 200 dB re 1 µPa, no damage to fish can be detected from observations, but behavioural changes are observed down to just over 150 dB re 1 µPa. Most experiments observe that the fish hear the sound and make changes in direction or depth, – a reflex response. Both salmon and cod tend to swim towards the seafloor when exposed to sound. After a few repetitions, fish sometimes get used to the sound and cease their behaviour change. Fish enclosed in fish farms, do not have the opportunity to swim away from the noise, which can lead to increased stress and altered behaviour so that a secondary injury is induced.

Other aspects of sound revolve around masking communication or other behaviour where the fish make use of sound. Cod grunts when spawning as the males assert themselves and show an aggressive behaviour. These grunts are relatively low-frequency and have a source strength around SPL = 120 – 133 dB re 1 µPa [19, 20]. It is likely that the effects of this type of sound disturbance, if persistent over a long time period, may impact the spawning itself and consequently effect the evolution of the population. It may be that if the drivers are strong enough, the fish could change their habitat.

Particle motion

The least known way for fish to detect sound is the one that most fish species use. Particle movement and acceleration have only been identified in the last 10-15 years as perhaps the most important parts of the hearing sense of fish. In general, particle motion and acceleration comprise lower frequencies than the direct pressure signal (Table 6., Appendix 5). Here it is seen that for common species in Norwegian waters, salmonoids, codfish and herring, the properties for particle movements follow the same as for pressure detection. Herring hear/feel best, followed by cod, and salmon.

Directly translated from the dB scale the particle speed is around 0.01 - 1 mm/s and the accelerations is about 1 - 50 mm/s^2 (Table 6., Appendix 5). There is little empirical data on what levels are harmful to fish. Recalculating the threshold value for «probable harm» SPL > 200 dB 1µPa (10 kPa) gives particle speeds of about 6 mm/s and accelerations around 40 mm/s^2. Most probably the more sensitive species have a lower threshold for injury.

It is worth noting that for particle motion the scaling is based on a plane wave, which may not be applicable in all cases. In the middle of the water column, this approximation is often adequate, but near the seafloor an underestimation of the particle movement associated with acoustic sound propagation is expected by up to 10 dB re 1 mm/s [21]. The same author also shows that specific sources such as piling and spunting have a wave propagation similar to planar waves. Thus, the exposure in terms of particle motion can be described using the planar wave approximation.

Effects on Population

The consequences of noise pollution for fish populations are very unclear. The ocean is open to migration between different habitats, which makes it difficult to prove that migration or behavioural changes are related to the soundscape. Mortality of eggs and larvae even without anthropogenic influence is usually high, therefore many researchers argue that transient periods of loud noise or strong sound exposure do not significantly impact populations. There are many places on Earth with extremely high acoustic noise levels where animals still come to eat or spawn, despite struggling with both communication and temporary damage. [5, 22]

Appendix 5: Threshold values

Table 6. Detection threshold values and frequency range for some common Norwegian species given for pressure and particle velocities [5, 23].

Type of species	Swim bladder	Pressure dB re 1 µPa	Particle motion dB re 1 µm $^{s-1}$	Particle acceleration dB re 1 µm $^{s-2}$
Flatfish (Pleuronectiformes), Sharks and Skates (Chondrichthyes)	-	90 - 130 dB 100 - 1000 Hz	30 - 70 dB (approx. 1 mm/s) 0.1Hz – 200 Hz	30 - 100 dB (30 mm/s^2- 100 m/s^2) 0.1-200 Hz
Salmon (Salmonidae)	Open (adults)	95 - 130 dB 30Hz - 400Hz	30 - 70 dB (approx. 1 mm/s) 30 - 300Hz	50 - 100 dB (0.3 - 100 mm/s^2) 30Hz - 300Hz
Horse mackerel (Carangidae)	Closed	90-110 dB[2] 300Hz-2000Hz		
Cod (Gadidae)	Closed	75 - 100 dB 30Hz - 500Hz	10 - 40 dB (approx. 0.01 mm/s) 0.1Hz - 400Hz	10 – 75 dB (0.003 - 5 mm/s^2) 0.1Hz – 400Hz
Sill (Clupeidae)	Open with additionally gas-filled organ at the ears.	70 - 75 dB 30Hz - 5kHz	10 - 20 dB (approx. 0.01 mm/s) 30Hz - 5 kHz	30 – 65 dB (0.03 - 2 mm/s^2) 30Hz - 5 kHz

Table 7. Threshold values for short- and long-term sound exposure. Table based on studies by blasting and piling. The peak pressure, SPL is indicated in [dB re 1 µPa], and sound exposure, SEL is indicated in [dB re 1 µPa^{2}s] [5, 15, 23, 6].

	Response or changed behaviour		TTS - Temporary Threshold Shift		PTS – Permanent threshold shift		Death		Harmful particle movement
Type of species	SPL	SEL	SPL	SEL	SPL	SEL	SPL	SEL	mm/s
Without swim bladder	153[3]/192[4]	-	206	186	213	216	229-234	219	~6 [5]
Fish with swim bladder not part of hearing organ	153/192	-	206	186	207	203	229-234	210	6
Fish with swim bladder as part of the hearing organ	153/189	160	206	173	207	203	229-234	207	6
Fish larvae / eggs	-	-	-	-	-	-	217-242	-	13[6]
Thresholds used in Multiconsults reports	150	160	190	180	210	200	220	210	6

[2] No data available for Hestmakrill. Data relates to its smaller relative, *Trachurus japonicus*.
[3] Ref: [23] Converted from 150 dB_{Rms} re 1 µPa
[4] Ref: [6]
[5] Based on TTS 200 dB re 1 µPa
[6] Ref: [24].