NPL REPORT AC 22

CHARACTERISATION OF ACOUSTIC FIELDS GENERATED BY UXO REMOVAL
PHASE 5 QUARRY TRIALS OF BUBBLE CURTAIN MITIGATION

(BEIS OFFSHORE ENERGY SEA SUB-CONTRACT OESEA-22-142)

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MAY 2023

Department for
Business, Energy
& Industrial Strategy

FUNDED BY BEIS

Characterisation of acoustic fields generated by UXO removal
Phase 5B quarry trials of bubble curtain mitigation

(BEIS Offshore Energy SEA Sub-Contract OESEA-22-142)

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SUMMARY

This report describes part 1 of the work undertaken in the project *Characterisation of acoustic fields generated by UXO removal - Phase 5*. The aim was to investigate the effectiveness of small bubble curtains used as a barrier mitigation for the acoustic output from UXO during low-order disposal by conducting controlled experimental trials in a quarry facility. This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the Offshore Energy Strategic Environmental Assessment programme (OESEA), Sub-Contract OESEA-22-142.

A total of nine explosive tests were undertaken during a two-day trial at the Limehillock Quary test facility in order to assess the attenuation of bubble curtain on the acoustic signal generated by underwater explosions. Three charge sizes were used of 45 g, 250 g and 465 g respectively, these being typical values in the range of charge sizes used on low-order techniques such as deflagration. Three air flow rates were used to generate a two-layer bubble curtain, with results presented for flows of 4.2 m^3/min, 2.1 m^3/min and no flow (no bubble curtain).

The results demonstrate that, under the conditions of the experimental trial, the bubble curtains can achieve a reduction in peak sound pressure level of between 13 dB and 17 dB, and in Sound Exposure Level of between 7 dB and 8 dB. The results show promise for use of a small bubble curtain to provide additional mitigation during low-order deflagration disposals, and suggest that further work may be justified to optimise the technique.

ISSN 1754-2936

DOI: https://doi.org/10.47120/npl.AC22

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This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the Offshore Energy Strategic Environmental Assessment programme, Sub-Contract OESEA-22-142.

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1 INTRODUCTION

1.1 BACKGROUND

The location and spatial size of many offshore wind farm developments and cable connector projects means there is a high potential to encounter unexploded ordnance (UXO) during construction. This is particularly so in the southern North Sea and Irish Sea due to overlap with World War I and World War II conflict areas, military training areas and munitions disposal sites, but it is relevant also in Scottish waters [Davies, 1996; Detloff *et al*., 2012; Eitner and Tröster, 2018]. As part of development planning, detailed surveys are undertaken to identify possible UXO and confirm what action is needed to reduce health and safety risks to a tolerable level. When UXO cannot be avoided or safely removed, detonation on site may be necessary (subject to obtaining required licences).

A common method used for the disposal of UXO is the deliberate detonation initiated by a small donor charge placed on the munition to initiate an explosion of the main charge (Cooper, 1996; Sayle *et al*., 2009; Albright, 2012; Aker *et al*., 2012; Cheong *et al*., 2020). This can be achieved in a number of ways, and recent work has shown that the use of deflagration (internal combustion initiated using small-shaped charges) can reduce the severity of the detonation and offer the possibility of lower source levels. High-order underwater detonations of explosives can produce some of the highest sound pressures of all anthropogenic sound sources with the potential to cause fatal injury to marine mammals and other marine fauna in close proximity to the blast, but also auditory damage and behavioural responses at much longer ranges. (Sertlek *et al*., 2019; Merchant *et al*., 2020, Yelverton *et al*., 1973; Ketten *et al*., 1993; Dahl *et al*., 2020; Todd *et al*., 1996; Finneran *et al*., 2000; Danil and St. Leger, 2011; Sundermeyer *et al*., 2012; von Benda- Beckmann *et al*., 2015; Parsons *et al*., 2000; Salomons *et al*., 2021, Siebert *et al*., 2022; Robinson *et al*, 2022; Jenkins *et al*, 2022 ; Smith *et al* 2022).

Impulsive sounds of very high amplitude also present challenges for effective mitigation, with potentially large exceedance areas for commonly-used exposure thresholds (Finneran and Jenkins, 2012; Popper *et al*., 2014; NMFS, 2018; Southall *et al*., 2019). Common mitigation strategies involve the use of spatial and temporal restrictions on the activity, visual and passive acoustic monitoring, and the introduction of additional noise of lower amplitude to create an aversive reaction by use of Acoustic Deterrent Devices (ADDs), and by use of small “scare” charges (JNCC, 2010; Merchant and Robinson, 2020, Robinson *et al*, 2022). Noise abatement technologies have also been employed including the use of bubble curtains to attenuate the radiated sound (Loye and Arndt, 1948; Domenico, 1982; Schmidtke, 2010; Schmidtke, 2012; Croci *et al*., 2014; Bohne *et al*, 2019). In recent years, there has been a focus on alternative methods of disposing of UXO (Koschinski, 2011; Koschinski and Kock, 2009; Koschinski and Kock, 2015) including the use of low-order techniques such as deflagration, a method that until recently has been more commonly used for military EOD operations where a small, shaped charge creates a plasma jet which penetrates the UXO casing and initiates a low-order combustion (Merchant and Robinson, 2020; ESTCP, 2002). Deflagration has been shown to produce substantially reduced levels of radiated sound in controlled experiments compared to high-order detonations (Robinson *et al*., 2020), but as yet such low-order techniques have been infrequently used offshore.

The JNCC guidelines (2010) focus on minimising the risk of physical trauma and permanent auditory injury (PTS). The distance at which detonations could cause physical injury must be established as part of a noise risk assessment to inform the licensing process and estimate the effectiveness of mitigation measures. The NMFS thresholds (NMFS 2018) and those of Southall *et al* 2019 incorporate the latest research results and provide an update of the 2007 Southall *et al.* thresholds referred to in the guidelines, and have been adopted by Statutory Nature Conservation Bodies (SNCBs). Estimates of PTS injury zones to NMFS thresholds have resulted in much larger impact ranges than were previously estimated, extending in the most extreme cases well beyond any effective mitigation zone (e.g. up to 15 km from detonation for a UXO charge of >700 kg). Such results raise grave concerns for the protection of the marine environment and for industry, as the consequence of a risk assessment concluding that an UXO detonation is likely to result in a large PTS injury zone is onerous.

Underwater explosions as sources of sound have been the subject of considerable scientific study since the 1940s, both theoretically and experimentally (Cole, 1948; Arons, 1954 and 1970; Weston, 1960). The models developed in the above papers for deep water have been shown to agree reasonably well with experimental characterisation of explosive sources in shallow water environments (Gaspin and Shuler, 1972; Gaspin *et al*., 1979; Chapman 1985 and 1988; Hannay and Chapman, 1999; Soloway and Dahl, 2014; Wiggins et al., 2019), but there are limited experimental data available to describe shallow-water propagation over considerable distances for these sources, and few estimates of the acoustic output from explosive sources positioned on or below the seabed (NOAA, 2016; Salomons *et al*., 2021; Robinson *et al* 2022). It is acknowledged that source level estimates are highly uncertain, due to technical challenges and gaps in knowledge. Sound produced by the detonation of explosives is affected by various factors e.g. age, state of corrosion, design, composition, position, sediment type, degree of burial, orientation, and multiple device aggregation (Salomons *et al*., 2021, Robinson *et al*, 2022). This leads to a high degree of uncertainty about the source noise level. Explosions are inherently a nonlinear source but most often a linear source is assumed. The transition to the region where the sound field may be considered to propagate linearly is not fully understood. The detonations generate acoustic waves which propagate on and through the seabed and a full understanding of this aspect of the propagation is currently lacking. In addition, measurement is ideally required of acoustic particle velocity to assess potential exposure of fish and invertebrates to the sound fields generated by explosions. Some of these issues are highly challenging and may take time to resolve fully.

1.2 INITIAL PROJECT PHASES

A series of projects have been undertaken with the overall aim to provide information to underpin more realistic exposure assessments at strategic and project levels, the identification of appropriate mitigation and guide EPS licence applications/decisions. The project series is titled *Characterisation of acoustic fields generated by UXO removal*. As with this current Phase 5 project, the work undertaken was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the Offshore Energy Strategic Environmental Assessment programme (OESEA).

Phase 1 (OESEA-19-104) reviewed the scientific research in the field and the current operational procedures for UXO disposal, and provided initial guidance for offshore developers to gather acoustic data during UXO clearance operations.

Phase 2 (OESEA-19-107) included an experimental study to understand the acoustic 'near-field' of known explosive sources in the controlled environment of a flooded quarry and to characterise the effectiveness of deflagration as a sound attenuation mitigation method.

Phase 3 (OESEA-20-110) analysed a range of existing data (raw and interpreted) from offshore UXO clearance operations to evaluate the range and variability of measured and calculated acoustic metrics both from UXO detonations and those of donor charges, and scare charges (used as mitigation measures).

Phase 4 (OESEA-21-127) work measured the radiated noise levels from UXO disposal of a number of WW2 sea mines in the Baltic Sea undertaken by the Danish Navy using both high-order and deflagration techniques.

In addition, the partners liaised with UK Regulators and advisory bodies at periodic meetings to promote good practice in acoustic measurement of UXO clearance and to discuss the potential for use of alternative explosive ordnance disposal (EOD) techniques to minimise the environmental impact. Outputs of the project so far include:

- a guidance protocol was published for those undertaking measurements of UXO clearance in the ocean (including consultation with stakeholders) (Cheong *et al* 2020)

- a report for BEIS was published reviewing the scientific work in the field and describing all work undertaken in both Phase 1 and Phase 2 (Cheong *et al*, June 2020)
- a journal paper was published (https://doi.org/10.1016/j.marpolbul.2020.111646) in Marine Pollution Bulletin describing a controlled experiment in a flooded quarry to measure the acoustic output during deflagration, with the results also presented at a stakeholder meeting at The Royal Society (Robinson *et al* 2020)
- a journal paper was published (https://doi.org/10.1016/j.marpolbul.2022.114178) in Marine Pollution Bulletin describing the acoustic characteristic of UXO disposal in the North Sea (Robinson *et al* 2022),
- the research findings for high and low-order disposal were presented at a number of international conferences such as Effect of Noise on Aquatic Life (Berlin, 2022), the International Conference on Underwater Acoustics (Southampton, 2022), and Oceanoise 2023 (Villanova, 2023).
- offshore measurements of deflagration during a sea-trial in coordination with collaborators and Danish Navy with measurement strategies building on the initial phases of the project (journal paper to be submitted).
- presentations made at a number of online meetings and fora (UK Underwater Sound Forum 2021, BEIS OESEA Research Seminar 2022) and to UK and US regulators and stakeholders.

For the Phase 5 work reported here, an Offshore Wind Innovation Exchange (OWiX) technology challenge (through the ORE Catapult) has led to four potential low order/low noise technologies being proposed for UXO clearance. Of the four systems only two were considered ready for field deployment and testing. The aim of the Phase 5 project is to test the efficacy and acoustic outputs of these two technologies in the flooded quarry test facility used in Phase 2.

1.3 SCOPE OF WORK

1.3.1 Introduction

In Phase 5, a controlled quarry trial was conducted to test currently available noise abatement technologies. The aim is to investigate the acoustic characteristics and other environmental effects generated when disposing of UXO using these methods. The five-day trial undertaken at the Limehillock Quarry facility was supervised by Thornton Tomassetti Ltd who supplied the explosives/surrogate munitions. The mitigation technologies were provided by the two client companies, the results of the experiments are reported separately.

1.3.2 Overall Scope

The technology reported here is produced and operated by EODEX Group Ltd. It is based on a small-scale bubble curtain applied as a noise abatement barrier for explosive charges, including shaped charges commonly used in low-order EOD methods. A bubble curtain is a technique commonly used in underwater construction to mitigate activities that produce a significant amount of underwater noise, such as pile driving. The system tested here has been miniaturised and is designed to be mobile in order to focus on a single UXO target.

The project determined the attenuation (acoustic output reduction) when using bubble curtains compared to unmitigated charges. The activities included:

- Short-range underwater pressure monitoring using low sensitivity underwater pressure gauges

- Far field acoustic monitoring of the low order and high order detonation with and without the bubble curtain.
- Spatial underwater noise measurement to determine received levels as a function of position
- Ambient underwater noise monitoring using an underwater recorder.
- Sound speed measurement using temperature sensor.

The acoustic data available for analysis includes:

- Received levels of all measurements made using the acoustic instrumentation including time waveforms and spectral content for measurements of sound pressure
- Determination of the source spectrum of the detonation and calculation of transmission loss as a function of acoustic frequency and distance from source

The trial took place at Limehillock Quarry facility at week commencing 14th November 2022, with the bubble curtain testing undertaken between 16th to 18th November 2022.

2 EXPERIMENTAL METHODOLOGY

2.1 TEST FACILITY

The test facility is operated by Thornton Tomasetti Defence Ltd, a multidisciplinary firm who specialises in structural shock testing using explosives and seismic airgun technology. Their main facility at Limehillock Quarry (near Keith in the northeast of Scotland) is the only UK inland underwater testing facility licensed for a wide range of test targets with access suitable for testing of naval structures to UK and NATO standards. Thornton Tomasetti operates a number of Shock Test Vehicles (STV) for use in underwater shock testing and their shock barge has an available test deck area of around 8.4 m x 4 m and a weight capacity of approximately 25 tonnes. The facility was used for a previous trial using deflagration charges reported elsewhere (Robinson *et al* 2020, Cheong *et al* 2020). As far as possible, the procedures detailed in the NPL Good Practice Guide (Robinson *et al* 2014) and the BEIS protocol were followed (though the latter are intended for offshore measurements (Cheong *et al* 2020).

The Limehillock Quarry facility is used extensively for in-water shock testing of structures for offshore marine applications and Thornton Tomasetti provided all the logistical support for the trial. The quarry has dimensions of approximately 250 m long by 125 m wide, is a little over 20 m deep on average and is filled with fresh water (Figure 4-1). The bathymetry between the position of the explosive source and that of the furthest hydrophone was 20.1 m ±1 m. During the trial, the average water temperature was stable at 8.6 °C for the shallowest 10m of the water column, but beneath this depth a thermocline can be observed with the temperature quickly decreased to 5.1 °C at the bottom.

Figure 2-1 Limehillock Quarry – hillside viewpoint

2.2 MEASUREMENT CONFIGURATION

In order to characterize the acoustic output from explosion and to evaluate the effect of the bubble curtain, acoustic measurements were recorded at three measurement locations with two nearfield measurements and a farfield measurement, all with sensors suspended from the water surface. These were: (i) close to the source (nominally 3 m and 13 m) and (ii) at a distance of 147 m (at the far end of the quarry). The closest nearfield sensor was placed inside the bubble screen in order to allow comparison of measurements with/without the presence of bubble screen. The configuration and deployment may be seen in Figure 2-2.

Thornton Tomasetti provided the instrumentation to measure the nearfield response from the explosion which were deployed from shoreside station. NPL and Loughborough University provided the farfield measurement equipment which consists of a four-elements vertical hydrophone array. This was deployed from a floating shock test vehicle (STV01) with an undercover area to provide weather protection to the data acquisition system and power supplies.

A sound particle motion sensor with bespoke underwater logger was also deployed to measure the particle motion of the signal from the explosive source. The sound particle motion measurements are not necessary for the characterization of the performance of the bubble curtain technique - the key metrics being peak sound pressure level and Sound Exposure Level (DIN 45653:2017), but the opportunity was taken to obtain data using new instruments and the experimental results will be reported separately.

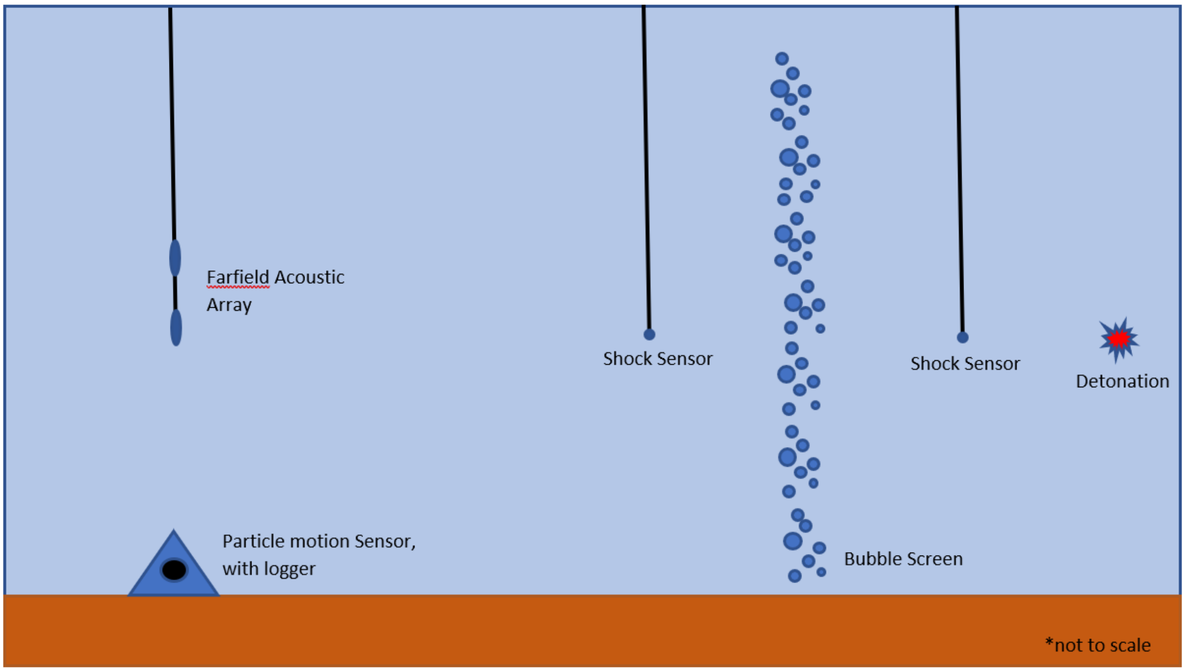

Figure 2-2 Schematic diagram of the measurement configuration in the trial (distances shown are not to scale).

2.2.1 Sound pressure measurement

For the nearfield measurements, two types of underwater shock transducers were employed: T11 transducers (manufactured by Neptune Sonar, nominal charge sensitivity: 0.07 pC/kPa; maximum pressure: 275 MPa) and 138A26 transducers (manufactured by PCB, nominal voltage sensitivity: 0.29 µV/Pa; maximum pressure: 172 MPa). The shock transducers were powered by a PCB 482C05 four-channel unity-gain signal conditioner with additional PCB 422E06 charge amplifiers being used for the T11 transducers. A 16-channel 1MHz Yokogawa DL750 data recorder was used for capturing the data. All data were sampled at 500 kilosamples per second giving a time base resolution of 2 µs. Each measurement was recorded for a duration of 5 seconds. The DL750 data acquisition system was triggered by a ‘Charge Probe’ which is fixed directly to the explosive and provided a voltage step at the time of detonation. The shock pressure sensors were suspended from floating pontoons (Figure 2-4) and due to a minor re-positioning of the source between detonations, their separation distances varied slightly between measurement sets. The distances were measured on the surface with a laser rangefinder (confirmed by the acoustic propagation delay). All four sensors were deployed at 7 m water depth, the same depth chosen for all of the source charges.

For far field measurement, a four-element hydrophone array was deployed from Thornton Tomasetti's shock test vehicle STV01 (Figure 4-4). The array consisted of two T50 hydrophones (manufactured by Neptune Sonar, with nominal sensitivity 28 µV/Pa) and two T11 shock sensors (manufactured by Neptune Sonar, nominal charge sensitivity: 0.07 pC/kPa; maximum pressure: 275 MPa). The line array was configured with only low-sensitivity hydrophones to avoid system saturation due to the expected high amplitude pulses generated during the high-order detonations. In addition to these acoustic sensors, a Soundtrap ST300 (manufactured by Ocean Instruments, with high gain nominal sensitivity -186 dB V/µPa) underwater recorders were deployed at mid-water column for the duration of the trial to determine the background noise level. The acquisition was made using a PicoScope 4824 sampling at 10 mega-samples per second (time resolution of 0.1 µs) recording for 5 seconds triggered electronically based on the level prediction of the charge size of the explosive.

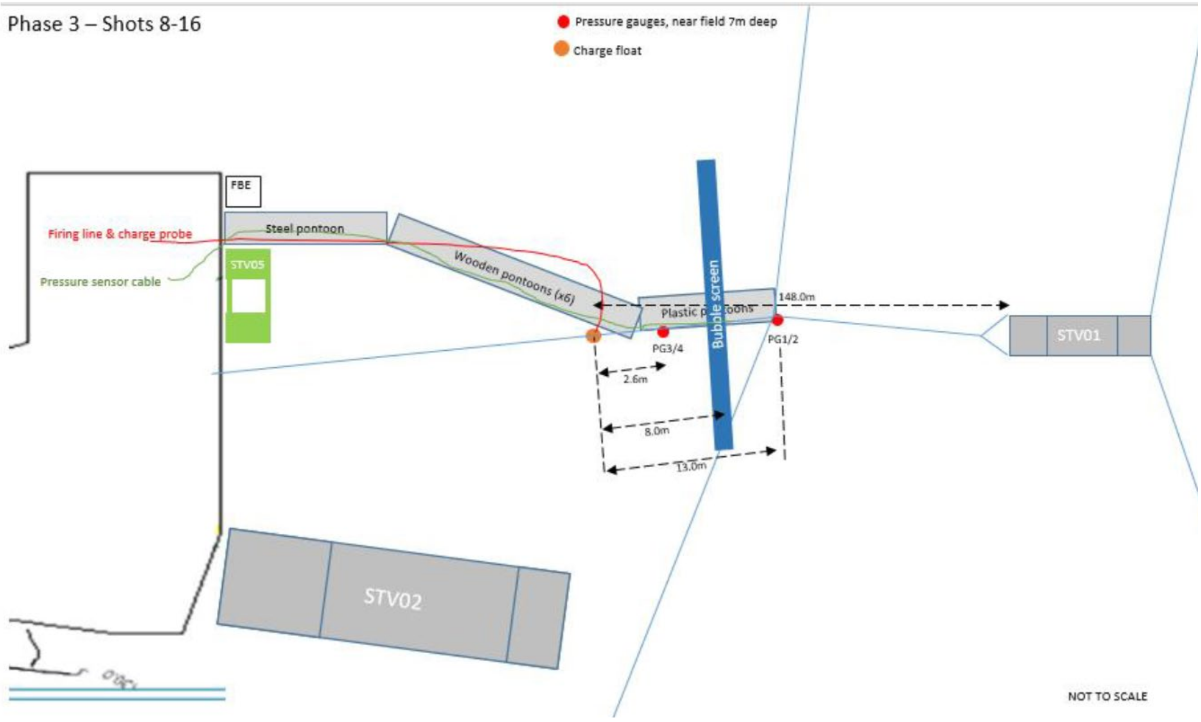

Figure 2-3 Measurement schematic with bubble curtain

NPL and Loughborough University instruments were completely independent and recorded by two different digitisers simultaneously providing some redundancy in order to avoid data loss by unexpected system failure.

The line-array hydrophones were calibrated traceable to national standards in the laboratory before the trial using the methods described in IEC 60565 (IEC 60565 2019 and 2020, Hayman *et al* 2017). This was done by comparison in a closed coupler in the range 5 Hz to 315 Hz. Free-field reciprocity was used to calibrate the T50 hydrophones over the frequency range 750 Hz to 200 kHz. Before and after deployment, the hydrophone sensitivities were checked at 250 Hz by use of a portable calibrated pistonphone (this enabled a full system sensitivity check as recordings were made on the acquisition systems of signals of known sound pressure level).

Figure 2-3 Left: Near field pressure gauge deployment pontoons; the buoy is used to mark the position of the explosive. Right: Far field acoustic array deployment on a shock test vehicle SVT01.

The sampling equipment was configured with the appropriate sensor sensitivities to ensure that as far as possible each individual system was configured to capture the acoustic waveform without distortion (including the high amplitude impulsive signals present during high order detonations). Preliminary calculations were performed to evaluate the likely sound levels to ensure the measurements can be carried out distortion-free. Background noise measurements were acquired before and after the test activities using a Soundtrap recorder, to allow the determination of the absolute noise level against background conditions.

2.2.2 Preparation of explosive sources

To simplify the test and maximise the usefulness of the data, nine charges were prepared as followed: 3x 465 g charges, 3x 250 g charges, 3x 45 g charges. The charge size corresponds to the maximum charge size used in the EODEX Technology's Pluton and Vulcan deflagration charges. The aim is to acquire data at three flow settings to evaluate the effectiveness of the bubble curtain. No surrogate shell or targets were used, the shaped charges were directly detonated using a shock tube as small freely-deployed charges to reduce complexity (rather than attempting a deflagration of a large surrogate munition).

EODEX Technology supplied the PE14 explosive and housings of the shaped charge used in the bubble curtain testing. Thornton Tomasetti prepared the shaped charges onsite and provided the means of deploying and detonating at the firing point for all testing.

Each test took approximately 30 to 90 minutes to complete; this was to allow safe deployment, recovery and required inspections pre- and post-test for the detonations. Tests involving bubble curtains switched on required longer time windows with the added operation of bubble curtain. The number of munitions/charges and order of the munitions used was agreed with the operators prior the start of the trial in order to prioritise the more important tests to ensure a comprehensive dataset. All test charges were successfully detonated according to the test plans.

The test schedule and associated details are described in Table 1 below:

Table 2-1 Bubble Curtain test schedule and parameters

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Date	17 Nov	17 Nov	17 Nov	17 Nov	17 Nov	17 Nov	17 Nov	17 Nov	17 Nov
Shot time	10:45	11:10	11:37	12:00	13:35	14:07	14:35	14:56	15:16
Shaped charge	465 g PE14	465 g PE14	465 g PE14	250 g PE14	250 g PE14	250 g PE14	45 g PE14	45 g PE14	45 g PE14
Detonation method	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube
Distance from charge float to STV01 aft (m)	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0	148.0
Distance from charge float to PG1 / PG2 (m)	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Distance from charge float to PG3 / PG4 (m)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Water depth (charge) (m)	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Charge depth (m)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Distance from charge to centre bubble curtain (m)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Bubble curtain output/ status	0% OFF	100% ON	50% Partial	0% OFF	100% ON	50% Partial	0% OFF	100% ON	50% Partial

2.3 BUBBLE CURTAIN OPERATION

The interaction of bubbles and sound has been the subject of study for some time (Leighton 1994) and some examples of the use of bubble curtains have been already reported for use in mitigating the noise from underwater explosions (Loye and Arndt, 1948; Domenico, 1982; Schmidtke, 2010; Schmidtke, 2012; Croci *et al*., 2014; Bohne *et al*, 2019). For the implementation used here, the basic principle of the EODEX bubble curtain involves the creation of a barrier of bubbles in the water column from the quarry floor to the water surface using a large air compressor. The system uses a perforated hose or pipe, which releases compressed air into the water to form the curtain of bubbles. The tests for EODEX were to investigate the effects of air bubble curtains on received signal levels with different charge sizes and bubble quantities in the curtains.

A 60 m long air hose drilled with holes was laid in two straight lines in parallel between the charge and two pressure gauges (PG1 and PG2) and hydrophone and vector sensor arrays. The holes in the hose were approximately 0.5 mm diameter and they were set 15 mm apart along the tube length at positions of “3 o’clock” and “9 o’clock” respectively, and reasonably spread along the length to avoid compromising the strength of the hose. Technical details of the bubble tubing are provided in Annex 1.

One set of pressure gauges (PG3 and PG4) were placed between the charge and the bubble curtain so the direct acoustic signals from the explosion of the charges could also be measured. The difference in the received signal levels with and without the bubble curtain was measured with three charge sizes at 45 g, 250 g and 465 g respectively. Note the actual charge used differed slightly from the intended nominal charge sizes of 50 g, 250 g and 450 g during the deployment due to operational reasons.

An air compressor was used to generate the bubble curtains with three air flow rates. The first was at 4.2 m^3/min, referred to as **full**, the second was at 50% of the full referred to as **half**, and the last with no air referred to as **off**. The bubble screen hose was lifted and lowered using a crane from the floating pontons, with the aid of a RIB boat to help positioning, before setting its final position. The bubble curtain system was activated several minutes prior the detonations to establish a wall of bubbles between the explosion points to measuring stations.

Figure 2-6 Bubble curtain assembly

Figure 2-7 Bubble curtain with air compressor at fully output.

Figure 2-8 Bubble curtain with air compressor at fully output – close up

3 RESULTS

3.1 TIME DOMAIN WAVEFORMS

The time waveforms received by the NPL hydrophone are shown in Figure 3-1 for the EODEX tests. The hydrophone was 147 m from the explosions. The waveforms for the tests without bubble curtain are in the left hand column for the 465 g on the top, 250 g is in the middle and 45 g is shown at the bottom (data were measured for the half bubble curtain for only a 250 g charge due to time constraints).. The y-axis scale is the same for all the plots in the figure to make comparison easy visually of the signal level. The two peaks in the three plots on the left column were from the initial explosion and the collapse of the first bubble.

It is clear from a purely visual inspection of the waveforms that the bubble curtain caused large reductions of the peak of the acoustic pulse. The high air flow rate to the bubble curtain (full) seems to increase the attenuation of the signal through the curtain compared to that with a lower rate at 50% (half).

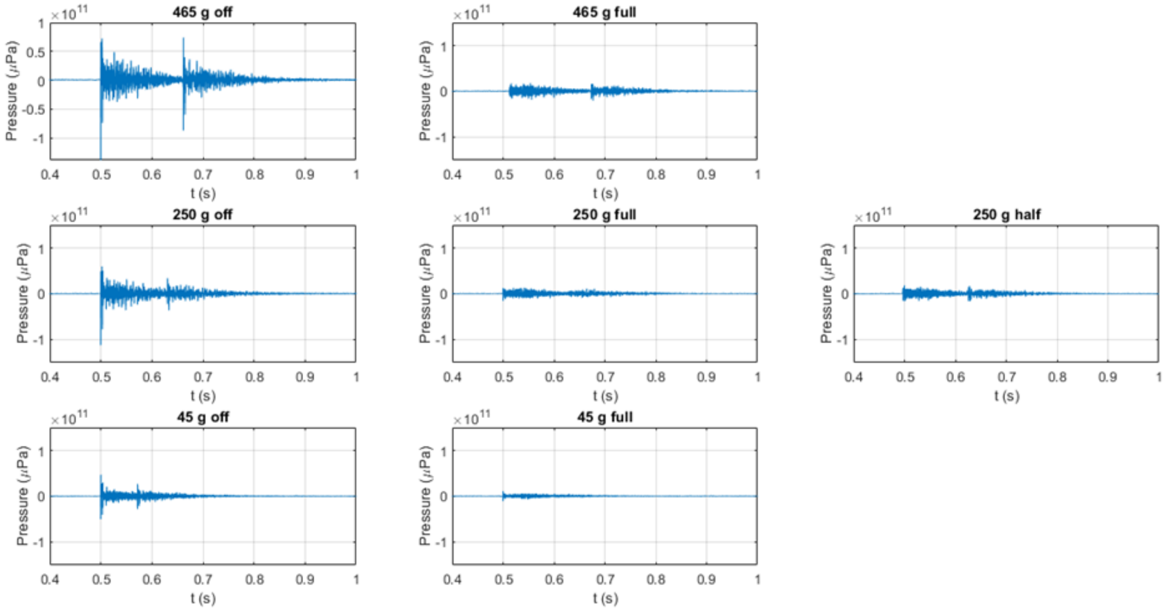

Figure 3-1 Time waveforms of measured signals with NPL's hydrophone at 147 m

The effects of the bubble curtain were also examined with Thornton Tomasetti's (TT) pressure gauges at a close range. Two of the four pressure gauges were placed at range 2.6 m from the charges before the bubble curtain, and the other two were at 13 m from the charges beyond the bubble curtain as shown in the Figure 2-7. The waveforms measured by PG1 at 13 m are plotted in Figure 3-2 for the 9 explosions. Similar to the data at 147 m in Figure 3-1, the attenuation effects with the bubble curtain are clearly demonstrated. Note that the received signals are highly impulse-like at this close range. The impulse spreading in time during propagation through the water column (as clearly shown in the Figure 3-1) is mainly due to the reflections from the water surface and bottom (essentially it is dominated by the impulse response of the water column).

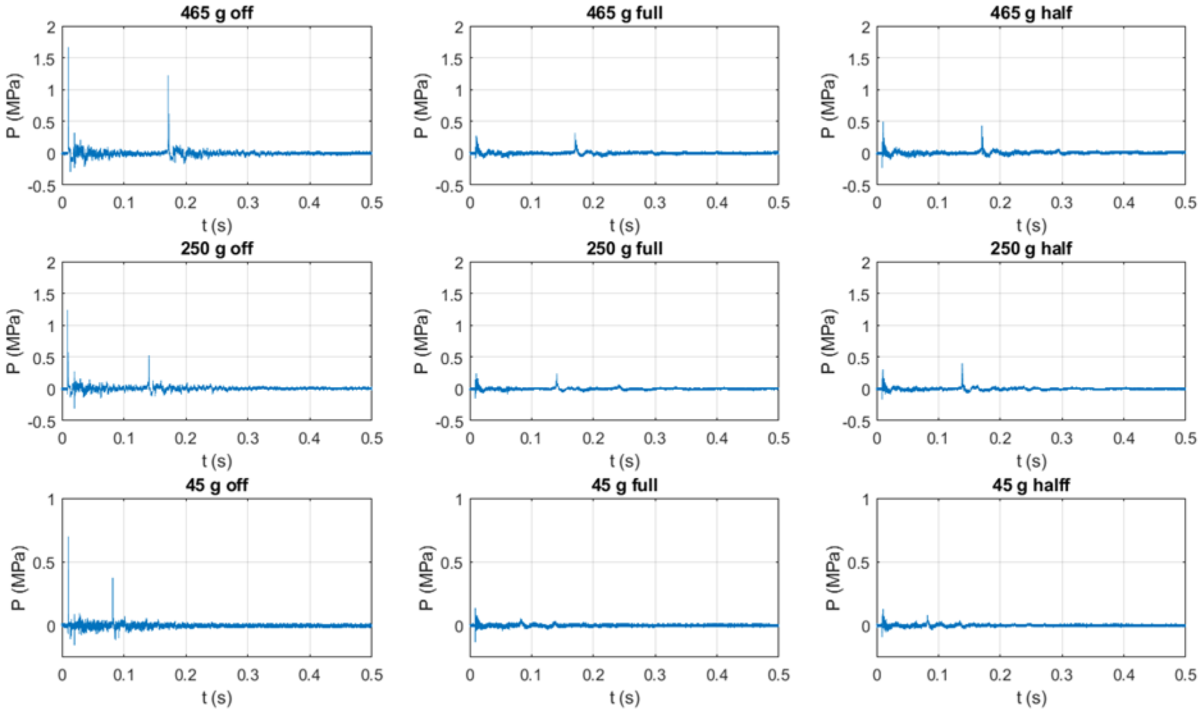

Figure 3-2 Time waveforms of signals with Thornton Tomasetti's pressure gauges at 13 m

3.2 FREQUENCY DOMAIN SIGNALS

The sound pressure level (SPL) for the signal waveforms in Figure 3-1 from 2 Hz to 200 kHz is shown in the first two columns in Figure 3-3. The data are calculated in decidecade bands (ISO 18405) the correct nomenclature for what are effectively the same as one-third octave frequency bands when calculated using base 10 arithmetic (IEC 61260-1:2014). In the following analysis, the terminology used in ISO 18405 and ISO 18406 was used unless otherwise stated (ISO 18405 and 18406: 2017). Transmission loss (TL) calculated as the difference in SPL between the signal without the bubble curtain and signal with bubble curtain is plotted in the right column of the figure. The column on the right shows the TLs with three charge sizes, and two air flow rates, full and half. The spectrum peak is around 200 Hz for all three charge sizes. The TL is just below 10 dB from 100 Hz to 10 kHz. The TL decreases outside the frequency range. Noise effect becomes noticeable with the smallest charge at high frequency as in the bottom right plot.

Figures 3-4, 3-5 and 3-6 show the detailed spectrum of SPL in 1 Hz resolution, and the decidecade band data on the same plot for the three charge sizes. The high resolution data exhibits very large fluctuations in sound pressure level vs frequency. The peak at around 160 kHz was due to the resonance of the hydrophone. TL is frequency dependent as illustrated in these figures.

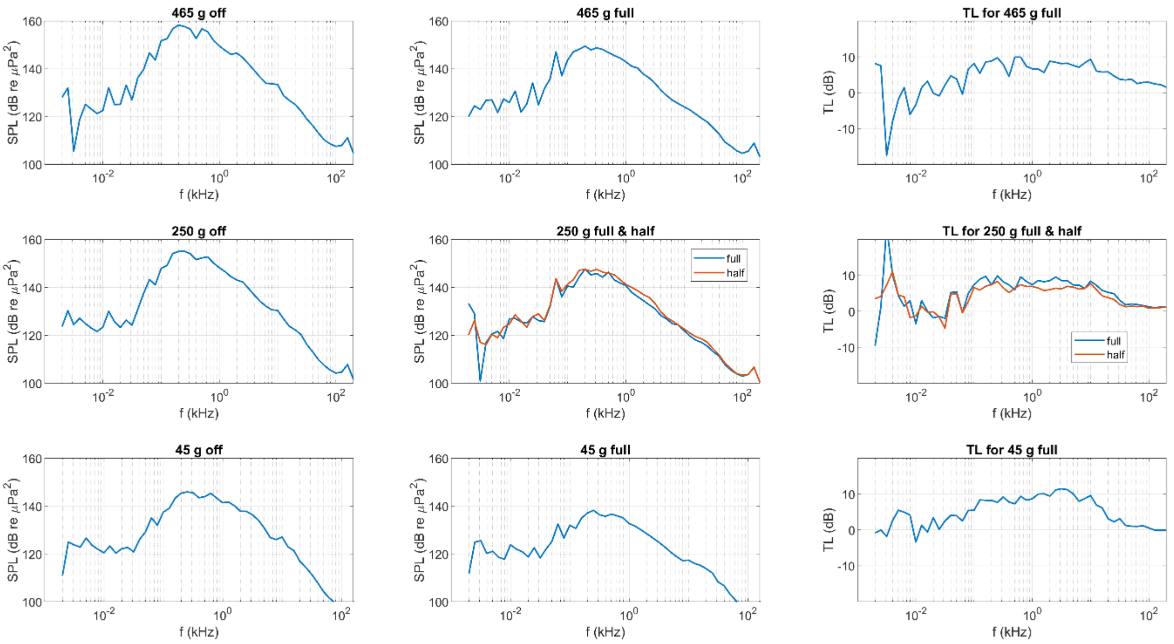

Figure 3-3 The sound pressure level (SPL) for the signal waveform in Figure 3-1 in decidecade bands in the first two columns. Transmission loss (TL) with bubble curtain on the right column.

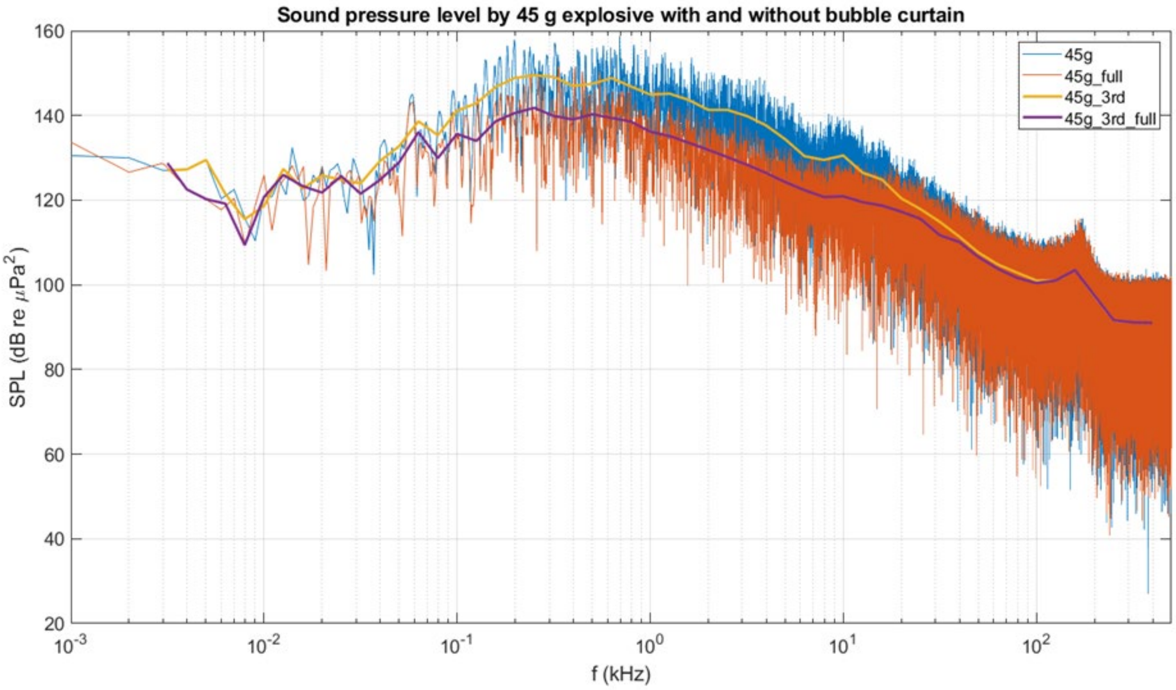

Figure 3-4 The sound pressure level (SPL) for the signal waveform in Figure 3-1 in decidecade bands (labelled “3rd”), and in 1 Hz resolution for 45 g charge.

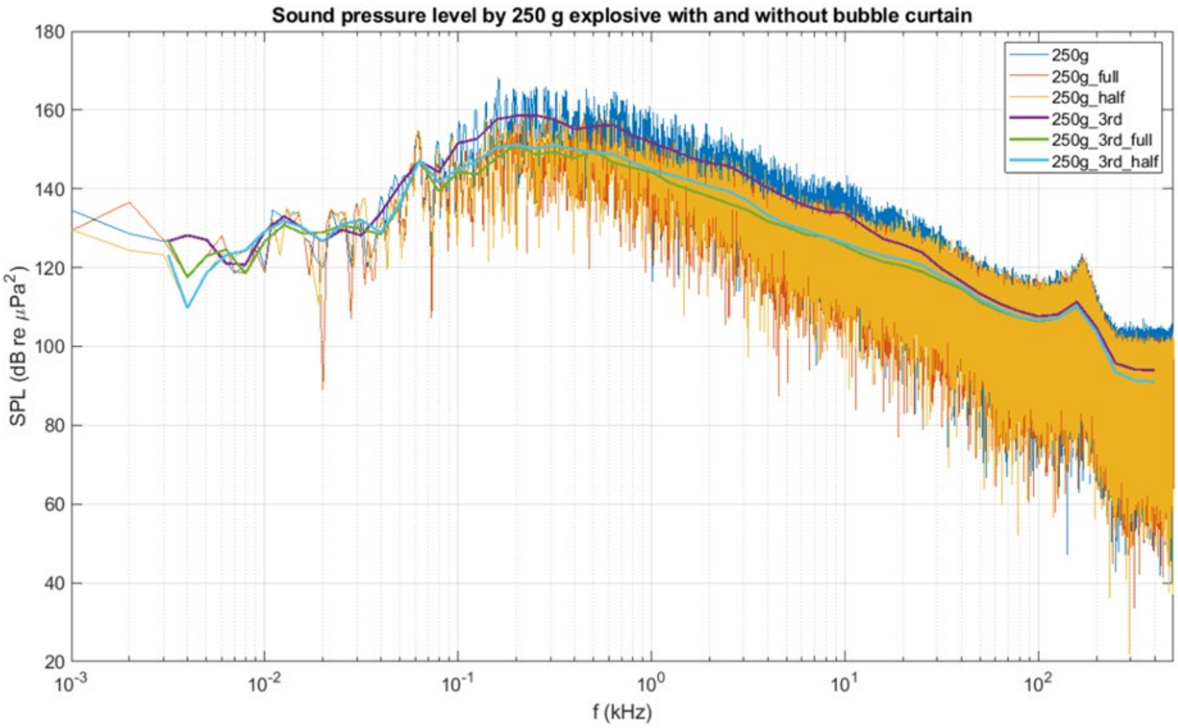

Figure 3-5 The sound pressure level (SPL) for the signal waveform in Figure 3-1 in decidecade bands (labelled “3rd”), and in 1 Hz resolution for 250 g charge.

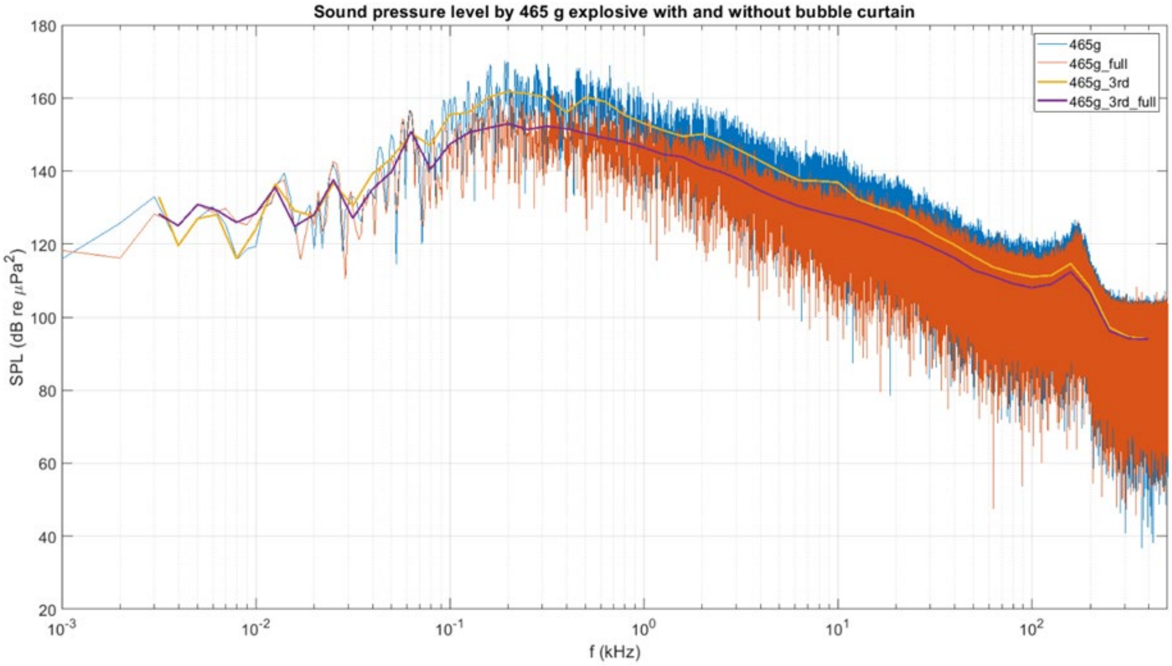

Figure 3-6 The sound pressure level (SPL) for the signal waveform in Figure 3-1 in decidecade bands (labelled “3rd”), and in 1 Hz resolution for 465 g charge.

Figure 3-7 shows the comparison of the sound pressure at two ranges of 13 m for the PG1 data and 147 m for the NPL hydrophone data from the 9 explosions. The SPL at close range were much higher at low frequencies (below 200 Hz). The low frequency components were attenuated due to propagation loss over a large range in this case as shown by the red curves.

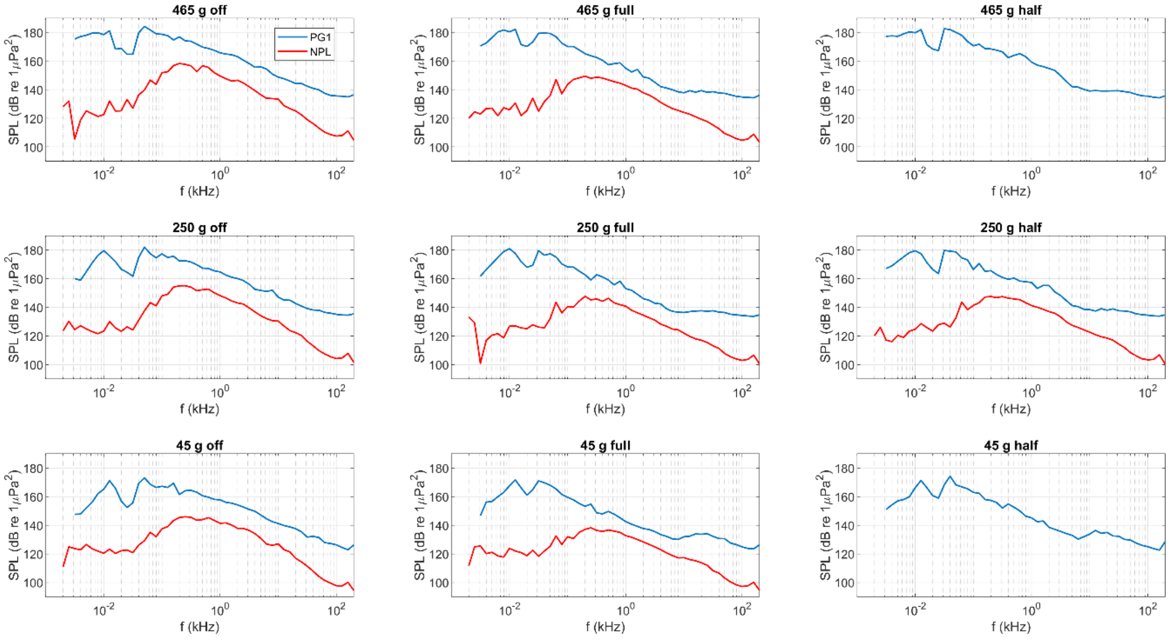

Figure 3-7 The sound pressure level (SPL) for the signal waveform in Figures 3-1 and 3-2 in decidecade bands.

3.3 ATTENUATION BY BUBBLE CURTAIN

The attenuation introduced by bubble curtain is estimated by comparison between the pulse peak sound pressure level and Sound Exposure Level (SEL) (ISO 18406: 2017; Robinson *et al* 2014) measured at the same location with and without the bubble curtain operational. The measured transmission loss in decidecade bands from (nominal) centre frequencies of 3.15 Hz to 200 kHz for 6 explosions with bubble curtain at close range (13 m) is shown in Figure 3-8. The higher airflow provides higher transmission loss by as much as 5 dB more through the bubble curtain at some frequencies. The overall effective frequency range is between 50 Hz and 2 kHz. There are variations in transmission loss with different charge sizes, mainly over higher frequency for higher charge sizes at 250 g and 465 g, but lower frequency with 45 g charge. There is a negative peak at 31.5 Hz. This only appears for the near field pressure gauge where the surface reflection might be the cause.

3.4 MEASURED SPL AND SEL WITH AND WITHOUT BUBBLE CURTAIN

Table 3-2 and Table 3-3 list the SPL and SEL measured with NPL hydrophone and Thornton Tomasetti pressure gauges as a function of range for three charge sizes with and without bubble curtain.

The bubble curtain introduces attenuation of acoustic signal in terms of additional transmission loss (TL). Table 4 shows measured TLs of the shock wave signals with three charge sizes and two levels of air flow through the bubble curtain. The TLs are the difference between the levels of the peak sound pressure and SEL with and without bubble curtains.

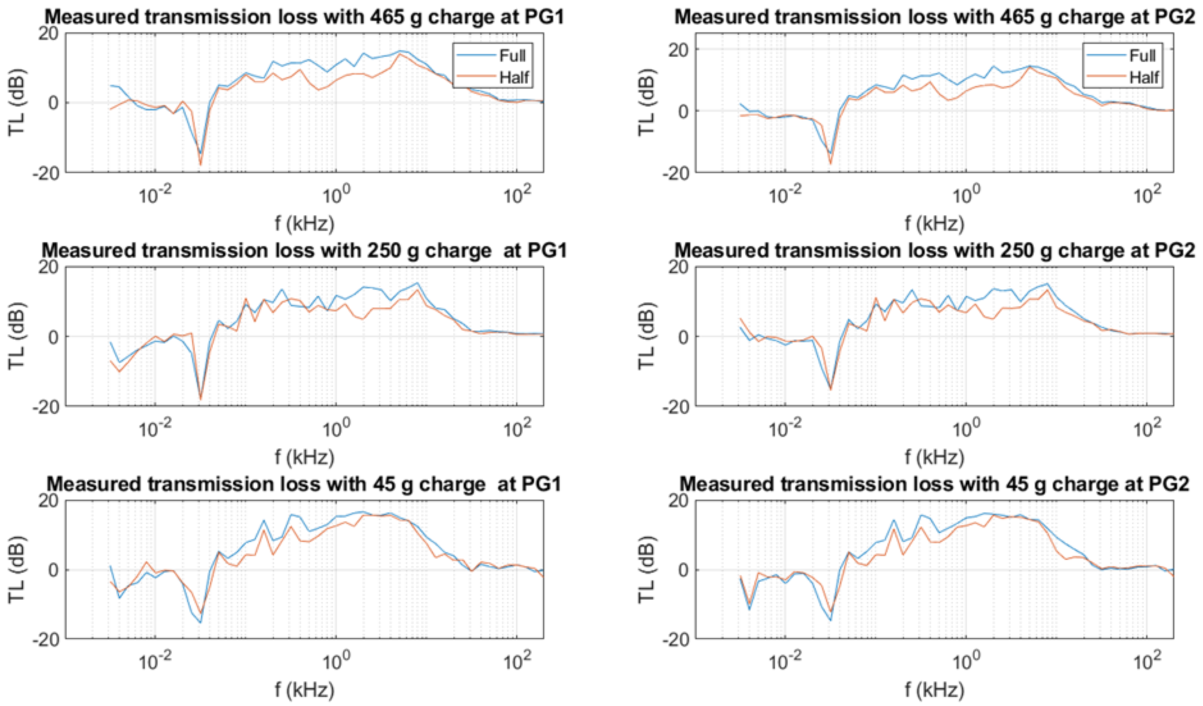

Figure 3-8 Measured transmission loss through bubble curtains obtained from pressure gauges (PG1 and PG2)

It is seen from Table 4 that at the close range (13 m) between the explosions and pressure gauges, the full air flow (4.2 m^3/min) generates higher attenuation on the peak pressure level for the two large charge sizes at 250 g and 465g of about 14.4 dB, while the low air flow at half rate (2.1 m^3/min) achieves about 10.3 dB. However, the TLs are comparable with both air flow rates at about 15 dB for the smallest charge size at 45 g. There are clear increases of TLs for the larger charges at the largest distance at 147 m compared with the results at close range (13 m). There is a decrease of TL at this distance for the 45 g charge compared with that at close range.

The TL for the SEL is much less in comparison with the peak pressure level. This is simply due to the fact that the bubbles in the curtain have a very large size distribution, so they absorb sound energy very effectively over a large frequency range through bubble resonance [Leighton, 1994]. The explosive signals contain very large signal bandwidth around the peak. The high frequency components are attenuated more by the bubbles resulting in greater attenuation of the peak. However, the acoustic energy of the explosive signal is greatest in the lower frequency band so that SEL decreases are much smaller in comparison with the peak pressure level.

It should be noted that the bubble curtain used the in trial consisted of two bubble layers in parallel and the results presented are therefore for **two** closely-spaced bubble layers. If a single bubble curtain layer were used, the attenuation produced would be reduced, though it is hard to say if the effectiveness would scale linearly.

The data in Table 3-1 and Table 3-2 are also plotted in Figures 3-9 and 3-10. There was very little spread of SPL and SEL for the data from the pressure gauges at range 2.6 m, where the bubble curtain had no effects on the received signals. For the signals measured after passage through the bubble curtain (received by the sensors at range 13 m and 147 m), the spread of the received signals was much greater due to the fact that bubble distribution in the bubble curtain were not always stable with time with between shots. When no measured data are available, this is indicated in the tables by N/A.

Table 3-1 Peak sound pressure level for EODEX tests

	NPL	PG3	PG4	PG1	PG2	Description
Shot no/range	**147 m**	**13 m**	**13 m**	**2.6 m**	**2.6 m**	
8	222.8	244.5	244.7	257.0	257.4	465g off
9	206.2	230.0	230.5	260.1	259.1	465g on
10	N/A	233.9	234.9	259.5	260.3	465g half
11	221.0	241.9	243.1	257.0	256.5	250g off
12	203.8	227.7	228.4	260.4	259.6	250g on
13	205.6	232.1	232.4	259.3	258.8	250g half
14	214.0	236.9	236.6	249.2	248.9	45g off
15	201.3	222.7	221.2	254.3	254.3	45g on
16	N/A	222.0	221.3	253.1	253.0	45g half

Table 3-2 SEL for EODEX tests

	NPL	PG3	PG4	PG1	PG2	Description
Shot no/range	**147 m**	**13 m**	**13 m**	**2.6 m**	**2.6 m**	
8	194.0	209.4	209.7	218.9	218.3	465g off
9	186.4	203.8	204.1	220.9	220.7	465g on
10	N/A	206.3	206.0	221.6	220.7	465g half
11	191.6	207.5	207.6	217.4	217.1	250g off
12	184.0	201.5	201.9	220.6	220.1	250g on
13	185.2	202.4	202.8	220.2	219.2	250g half
14	185.3	201.3	201.2	208.4	207.9	45g off
15	178.7	198.0	197.5	212.1	211.7	45g on
16	N/A	197.0	196.8	211.2	210.9	45g half

Table 3-3 Transmission loss of peak pressure level and SEL with bubble curtains

	13 m	147 m	13 m	147 m
Shot (air flow)	**TL_SPL**	**TL_SPL**	**TL_SEL**	**TL_SEL**
465 g (full)	14.3	16.7	5.6	7.7
465 g (half)	10.2		3.5	
250 g (full)	14.5	17.2	5.8	7.6
250 (half)	10.3	15.4	4.9	6.4
45 g (full)	14.8	12.7	3.5	6.6
45 g (half)	15.1		4.4	

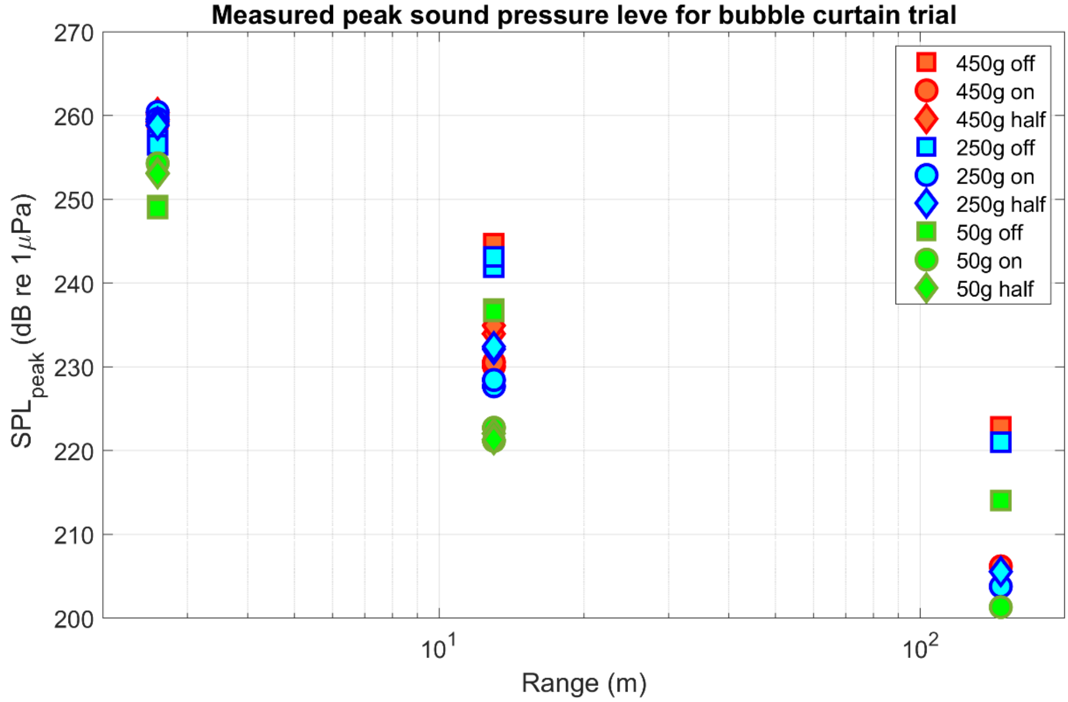

Figure 3-9 Measured peak sound pressure level vs range with and without bubble curtain

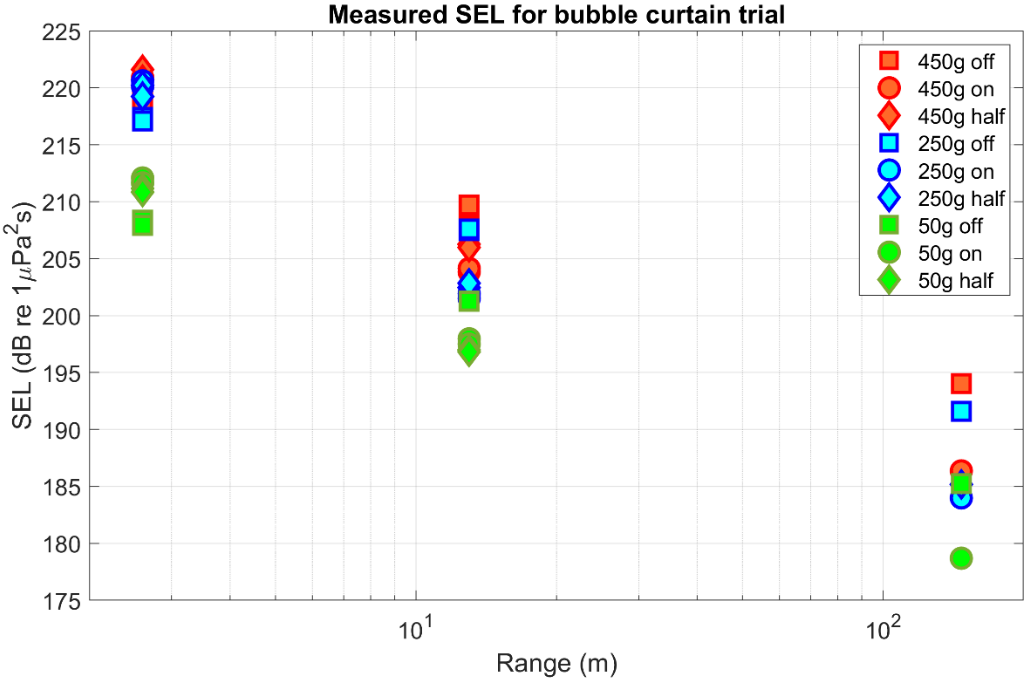

Figure 3-10 Measured SEL vs range with and without bubble curtain

4 CONCLUSION

4.1 SUMMARY

A total of nine explosive tests were undertaken during a 2 day trial at the Limehillock Quary test facility in order to assess the effects of a small bubble curtain on the acoustic signal generated by explosions of similar size to those used in low-order deflagration. Three charge sizes were used: 45 g, 250 g and 465 g respectively. The bubble curtain was used with two air flow rates of 2.1 m^3/min (50% or half-flow) and 4.2 m^3/min (100% or full-flow) compared to no curtain (0%, off or no flow). The bubble curtain consisted of two layers of bubbles generated by hoses a few metres apart. The holes in the hose were approximately 0.5 mm diameter and they were set 15 mm apart along the tube length at positions of “3 o’clock” and “9 o’clock” respectively, and reasonably spread along the length to avoid compromising the strength of the hose. Technical details of the hose are provided in Annex 1.

The results demonstrate that the bubble curtains can achieve an acoustic attenuation (reduction in signal amplitude) for peak sound pressure level of between 13 dB and 17 dB, and in broadband Sound Exposure Level of between 7 dB and 8 dB for detonations ranging in charge size from 45 g to 465 g.

Some dependence on air flow was observed, the full air flow (4.2 m^3/min) generating higher attenuation on the peak pressure level for the two large charge sizes at 250 g and 465 g of about 14.4 dB, while the low air flow at half rate (2.1 m^3/min) achieves about 10.3 dB.

4.2 DISCUSSION

The results of the trial can be regarded as a successful demonstration of the principles so far as they go, with up to 17 dB reduction in peak sound pressure level and 8 dB reduction in SEL achieved. Such a reduction would be valuable in further mitigating the effects of noise from low-order disposals, for example those using deflagration charges. However, there are some contingent factors that should be considered when evaluating the results.

Firstly, the test environment was relatively controlled with much less variation that would be observed in an offshore deployment. Offshore, the effects of tidal flow can distort the bubble curtain and limit the effectiveness. There was no tidal flow present in the quarry experiment and it is not known how resistant the method would be to such flow local to a UXO on the seabed. However, the flow on the seabed tends to be lower than in mid-water column, which would be helpful.

Secondly, the charge was not placed on the floor of the quarry but in the mid-water column (due to restrictions in the operational procedures at the quarry). This is not realistic for a UXO in an offshore location, which would be on the seabed (or even partially buried). However, the placement of the charge on the seabed may not in practice reduce the attenuation of the bubble curtain because the hoses would also be on the seabed, and there would possibly be less chance for tidal flow to influence the rising bubbles. The position of the UXO on the seabed is considered to produce a slight “muffling effect” on the explosion compared to mid-water explosions [Robinson *et al* 2022], and so a trial using a mid-water charge (as undertaken here) may well be more challenging for the bubble curtain method.

It should also be noted that the bubble curtain used consisted of two bubble layers a few metres apart. The results are representative of this configuration and cannot easily be extrapolated to other scenarios (with only one layer, for example). It should also be noted that the trial tested the principle of the method, but the hardware was not a commercial-off-the-shelf product. The compressed air generation was provided by the compressors supplied by the quarry operators (Thornton Tomasetti Ltd) and the hoses were configured to provide a barrier along the axis of the quarry to attenuate the sound propagating toward the sensors (pressure sensors and hydrophones). In real-world application, the hoses would need to surround the UXO in a circular or spiral configuration to provide equal reduction for all bearing angles (generating a cylindrical or spiral curtain). The authors understand that this is the intended configuration for the final product, but this is not how the curtain was implemented in these tests. In a real-world application, the compressed air supply would need to be either on a nearby vessel or supplied using gas bottles activated remotely just before the triggering of the explosion. Such a portable system is feasible for UXO as opposed to pile driving because the explosive event is very short-lived (unlike pile driving which can last for hours and require a bubble curtain to be sustained for the whole piling period). However, such a portable system was not tested here and would require further in-situ trials before the feasibility could be assessed. Similarly, it was not possible to systematically test different hose and hole size combinations to determine the optimal combination (this being too time-consuming for the scheduled work programme). A commercial bubble hose was utilised for the experiment, with details provide din Annex 1.

In summary, the use of a bubble curtain shows promise in providing additional attenuation of the noise from disposal of UXO using low-order charges (such as those used for deflagration). It should be noted that even the small charges used for deflagration, though they result in much quieter explosions than high-order detonations, are still quite noisy, being of a similar source level to that obtained from much marine pile driving activity (though admittedly much shorter in duration as they are essentially a one-off event). An extra 17 dB reduction of peak sound pressure level and 8 dB of SEL would be highly valuable. However, there are a number of further tests that would be required to demonstrate its feasibility for real-world offshore scenarios, including demonstrating the portable nature of the system including deployment at sea with provision of compressed air, determining the optimal hose and hole sizes, demonstration of the stability to tidal-flow conditions, and its effectiveness for real-world UXO located on the seabed.

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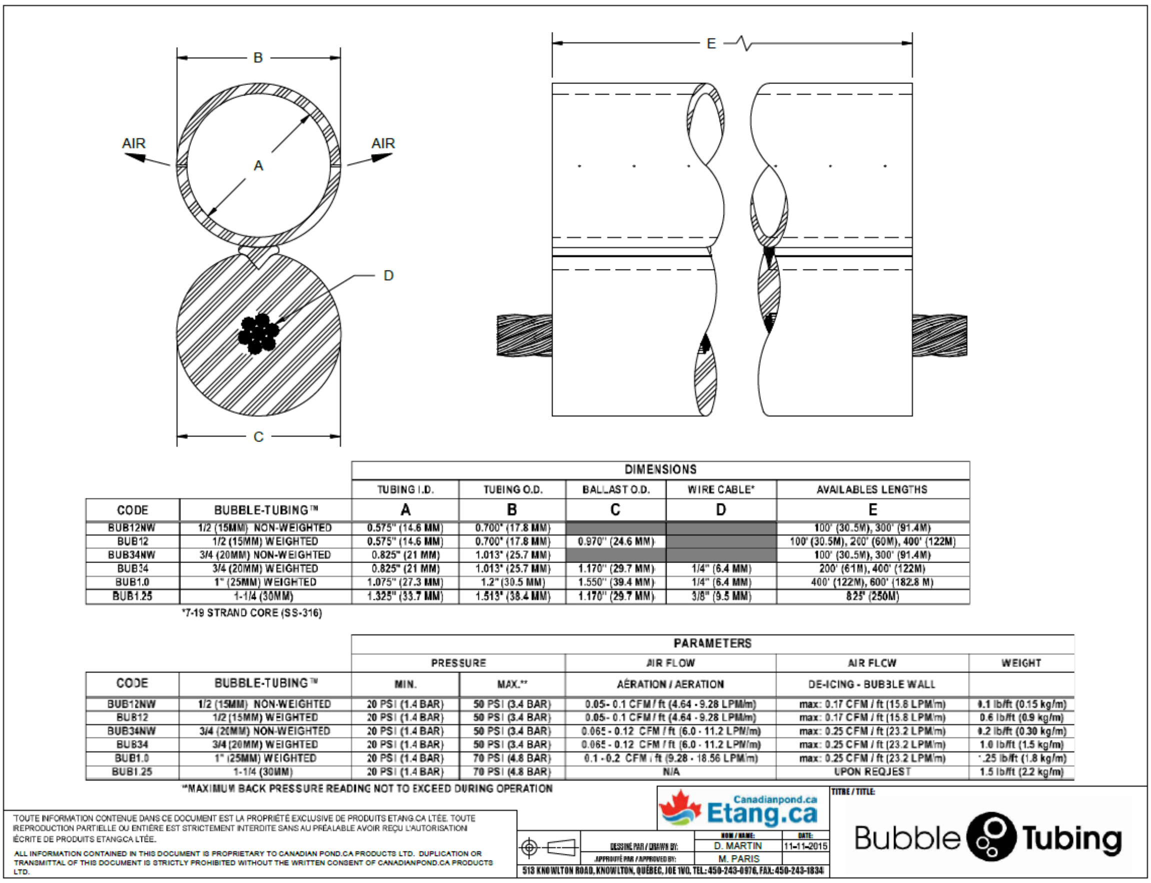
6 ANNEX 1 BUBBLE TUBING – TECHNICAL SPECIFICATION



		DIMENSIONS				
		TUBING I.D.	TUBING O.D.	BALLAST O.D.	WIRE CABLE*	AVAILABLES LENGTHS
CODE	BUBBLE-TUBING™	A	B	C	D	E
BUB12NW	1/2 (15MM) NON-WEIGHTED	0.575" (14.6 MM)	0.700" (17.8 MM)	▨	▨	100' (30.5M), 300' (91.4M)
BUB12	1/2 (15MM) WEIGHTED	0.575" (14.6 MM)	0.700" (17.8 MM)	0.970" (24.6 MM)	▨	100' (30.5M), 200' (60M), 400' (122M)
BUB34NW	3/4 (20MM) NON-WEIGHTED	0.825" (21 MM)	1.013" (25.7 MM)	▨	▨	100' (30.5M), 300' (91.4M)
BUB34	3/4 (20MM) WEIGHTED	0.825" (21 MM)	1.013" (25.7 MM)	1.170" (29.7 MM)	1/4" (6.4 MM)	200' (61M), 400' (122M)
BUB1.0	1" (25MM) WEIGHTED	1.075" (27.3 MM)	1.2" (30.5 MM)	1.550" (39.4 MM)	1/4" (6.4 MM)	400' (122M), 600' (182.8 M)
BUB1.25	1-1/4 (30MM)	1.325" (33.7 MM)	1.513" (38.4 MM)	1.170" (29.7 MM)	3/8" (9.5 MM)	825' (250M)

*7-19 STRAND CORE (SS-316)

		PARAMETERS				
		PRESSURE		AIR FLOW	AIR FLOW	WEIGHT
CODE	BUBBLE-TUBING™	MIN.	MAX.**	AÉRATION / AERATION	DE-ICING - BUBBLE WALL	
BUB12NW	1/2 (15MM) NON-WEIGHTED	20 PSI (1.4 BAR)	50 PSI (3.4 BAR)	0.05- 0.1 CFM / ft (4.64 - 9.28 LPM/m)	max: 0.17 CFM / ft (15.8 LPM/m)	0.1 lb/ft (0.15 kg/m)
BUB12	1/2 (15MM) WEIGHTED	20 PSI (1.4 BAR)	50 PSI (3.4 BAR)	0.05- 0.1 CFM / ft (4.64 - 9.28 LPM/m)	max: 0.17 CFM / ft (15.8 LPM/m)	0.6 lb/ft (0.9 kg/m)
BUB34NW	3/4 (20MM) NON-WEIGHTED	20 PSI (1.4 BAR)	50 PSI (3.4 BAR)	0.065 - 0.12 CFM / ft (6.0 - 11.2 LPM/m)	max: 0.25 CFM / ft (23.2 LPM/m)	0.2 lb/ft (0.30 kg/m)
BUB34	3/4 (20MM) WEIGHTED	20 PSI (1.4 BAR)	50 PSI (3.4 BAR)	0.065 - 0.12 CFM / ft (6.0 - 11.2 LPM/m)	max: 0.25 CFM / ft (23.2 LPM/m)	1.0 lb/ft (1.5 kg/m)
BUB1.0	1" (25MM) WEIGHTED	20 PSI (1.4 BAR)	70 PSI (4.8 BAR)	0.1 - 0.2 CFM / ft (9.28 - 18.56 LPM/m)	max: 0.25 CFM / ft (23.2 LPM/m)	1.25 lb/ft (1.8 kg/m)
BUB1.25	1-1/4 (30MM)	20 PSI (1.4 BAR)	70 PSI (4.8 BAR)	N/A	UPON REQUEST	1.5 lb/ft (2.2 kg/m)

**MAXIMUM BACK PRESSURE READING NOT TO EXCEED DURING OPERATION

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