IMCSE Technical Publication Series, 1 October 2022

ARE LOW-YIELD EXPLOSIVE ORDNANCE DISPOSAL METHODS VIABLE?

Authors: Alford R, Hazael R, Critchley R

Contact email: roland.alford@cranfield.ac.uk

Cranfield Forensic Institute, Cranfield University, Shrivenham, Swindon, SN6 8LA

EXECUTIVE SUMMARY

In 2021 reports began to appear online regarding a new underwater UXO clearance tech that produced a “low-yield” result. It claimed that the technology used did not cause deflagration (burning) but resulted in the munitions breaking up and scattering, causing the explosives to dissipate. The system used was referred to by the brand name Hydra-Jet.[1]

Review of available material shows that at Seagreen Offshore Wind Farm, currently being constructed 27km off the Scottish coast in the North Sea [2], three sea mines were attacked using the Hydra-Jet and all three interventions either caused a detonation or a partial detonation. It is unlikely that this technology is 100% reliability and appears to show no improvement over proven low-order techniques such as shaped charges that use low-density reactive liners.[3]

It is thought likely that the disruptive effect is produced by overpressure from the charge, placed at close range to the target causing high pressures that are designed to result in physical break-up of the munition rather than any more complex mechanism. The pressure readings taken of the events show that they strongly indicate that at least some of the explosives detonated.

The published pressure measurements, indicating that there had been at least partial detonations, were reported to have presented a risk of harm to wildlife (harbour porpoise within approximately 4km) despite the results not having breached the operator’s licence thresholds.[4,5] The latest data from trials conducted by the national Physical Laboratories and Loughborough University might offer guidance for more stringent but achievable thresholds for future work.[6]

BACKGROUND

A new term has recently been promoted as a method of environmentally friendly UXO clearance. The term “low-yield” is being used to describe the effects of a charge commercially branded as “Hydra” and “Hydra-Jet” which is claimed to use a new disposal mechanism, distinct from established low-order mechanisms. This product should not be confused with the similarly named Hydra-Jet disruptor produced by Cheery Engineering in the US.[7] The marketing literature for the Hydra charge claims that its use “is a Low-Yield technique that 100% guarantees that High-Order will not occur”.[8] This is unlikely to be an accurate use of terminology considering that EOD is not an exact science and absolute guarantees of results can never be made.

The Field Operations Report UXO ID & Disposal document for Seagreen [9] states that the "HYDRA-Jet Disrupter system can guarantee a low yield result when prosecuting the UXO target candidate. The HYDRA technique uses a high-pressure water jet instead of a high temperature plasma jet to achieve the penetration and disruption. The unwanted high order can therefore be guaranteed since no heat is introduced."

There are further claims that the explosive will either be disintegrated into "thousands of minute pieces" which dissipate over a few months or produce an "emulsion of tiny fragments of material, which forms a cloud and dissipates almost immediately". [1] This is contradicted in a recent newsletter from one company using the system stating that an "Explosive Free certificate issued on completion, with debris recovered on completion." [10]

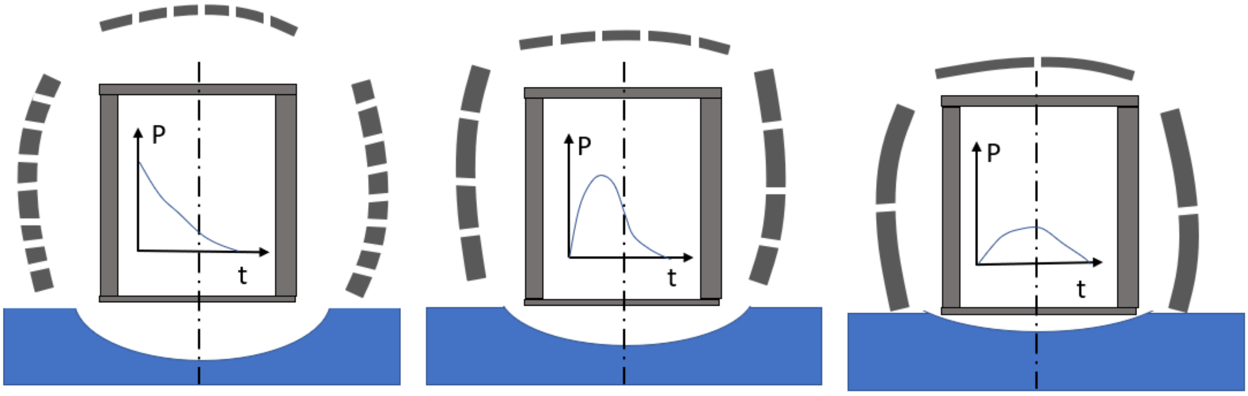
WHAT IS LOW-YIELD?

Open-source literature investigation for the term Low-Yield gives two relevant definitions. The first relates to the Hydra Program in the 1960s which was a facility to simulate underwater nuclear explosions on a small scale.[11] There does not appear to be any reference or link to low-yield and UXO clearance before 2021 when it started to be used in the context of the Seagreen Offshore Windfarm project. [12]

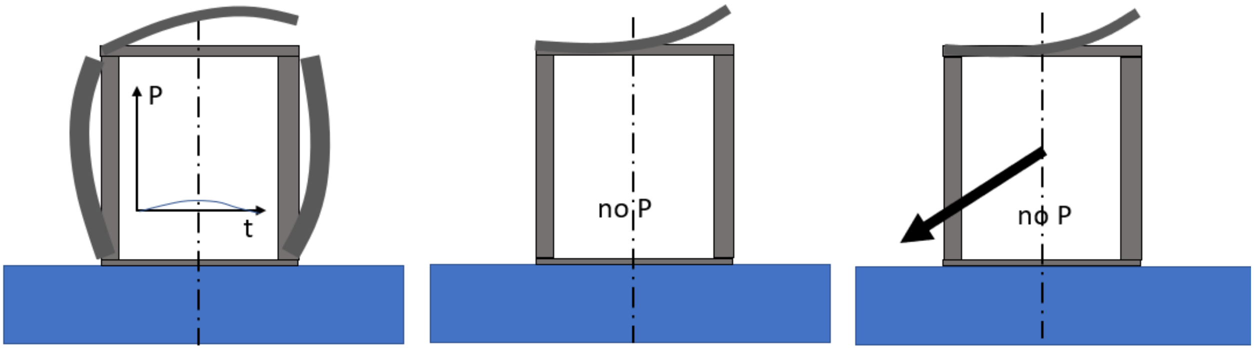
When a question was asked in the Scottish Parliament [13] about the proposed means of disposal, the answer was that "a low-yield method which disrupts and disintegrates the UXO without combustion of the explosive material" would be used. The next line in the response described a low-order method as one "which disrupts the UXO by deflagration without an explosive combustion of the main explosive filling". Specific terminology for explosive combustion was not defined in that context.

In their licence application, Seagreen Wind Energy Ltd [1] give more detail saying the system produces "high-pressure water jets targeting the vulnerable components and main explosive filling of the UXO. This will result in the rupture or split of the UXO casing and disintegration of the primary energetic component without combustion of the explosive material within the UXO."

There are a number of scales for measuring the reaction levels for explosives, mostly related to impact tests rather than low-order deflagration, but they do give a useful set of scales against which reactions can be measured. Perhaps the best is from Manfred Held, the inventor of Explosive Reactive Armour in which he has six levels. [14]



Type I. Detonation Type II. Partial Detonation Type III. Explosion



Type IV. Deflagration Type V. Burning Type VI. Propulsion

Fig. 1. Explosive Reaction Levels (adapted from Professor Dr M. Held. Deutsche Aerospace)[14]

On this scale, a low-order would be considered Type III or Type IV, although a result that starts as a Type V and transitions to Type VI or which starts as Type IV and transitions to Type II and even has a component of Type III would also be a low-order. The claims for low-yield appears to fit only Type VI, however this level is for propulsion which is not a commonly observed reaction identifiable by the munition having only a small rupture but being propelled some distance by venting gases. More typical EOD results would be either no-reaction at all or physical break-up of the case and explosive without burning or other chemical reaction of the explosive commonly termed "disruption" and defined in EOD terminology by physical break-up and separation of components.[15]

It is worth noting that in Types I-III a crater is shown below where the charges were. These correspond to detonation reactions whereas Types IV-VI, which are all non-detonation events do not have any craters.

While the terminology used to publicise the Hydra is generally imprecise the key phrase is "without combustion" which implies physical break-up and separation of the munition. In EOD terms, this would be a classic "disruption". In air, this would normally be achieved using a disruptor and underwater an overpressure (OP) charge.[15]

The term low-yield appears to have been adopted as a new phrase to describe disruption and enable the approach to be considered new and independent of previous work such as existing low order techniques.

WHAT IS LOW-ORDER?

The more conventional options for disposal of UXOs are either to detonate them, which is commonly referred to as a high-order, or to deflagrate them, commonly referred to as a low-order. Deflagration is a term that simply means to burn. The rate at which an explosive burns depends on various factors but if the rate increases, the reaction becomes more violent until a shockwave is produced resulting in a detonation. If the pressure within the munition increases due to the combustion gases generated not being able to escape, the bomb case will eventually burst before there is a transition to detonation. (Fig.2) This is commonly termed a low-order.

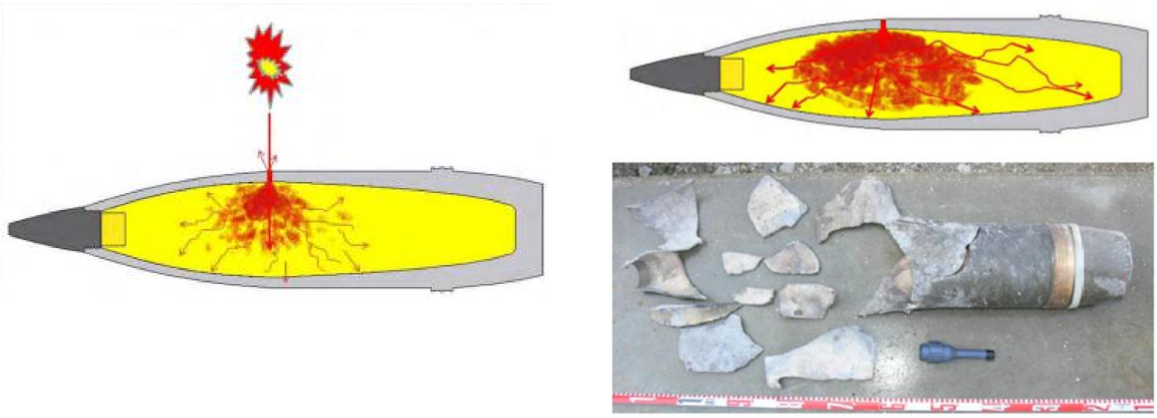


Fig. 2. Low order: Shaped charge injects burning reactive liner material into munition causing localised burning and cracking

Deflagration occurs generating gases rapidly which pressurize the bomb case which eventually fails, scattering the unburnt explosive

Results in air and underwater are very similar. (Fig. 3)

While there were references to low-order detonation as far back as 1958[16] the modern definition of low-order was being described in various explosive impact tests that were developed as a means of categorising explosive reactions in the development of insensitive munitions. The Lawrence Livermore National Laboratory in the US developed the LLNL Oblique Impact (skid) test in which they had seven levels from a detonation to no reaction in which the middle level was “Mild, low-order event with flame or light; charge broken up or scattered.”[17]. This would seem to be a good definition for a low-order event for a UXO.

Fig.3. Typical low-order of a bomb underwater (Image courtesy of Alford Technologies)

Partial low-order on a thin-skinned mine shows that a larger charge was needed to cause pressure to build up within the entire mine before bursting. (Image courtesy of Royal Norwegian Navy)

There are a number of means for triggering a low-order event in a munition, each with greater or lesser reliability.[18] None can offer a 100% guarantee of success, but some have a typical reliability of approximately 70% while the best systems have been found to offer low-order reliability in the high 90% range. For example, in field trials of the Vulcan charge system in conjunction with Mines Advisory Group (MAG) in Saravan Province in Laos fired the charge against Mk 80 series (mostly 500lb) bombs on 136 occasions and only caused detonations on four occasions.[19]

In late 2020 a WW2 Tallboy bomb that had been dropped on an attack on the German cruiser “Lützow” in April 1945 in Poland, was successfully neutralised using a low-order technique. This was widely reported at the time and has since wrongly been used as an example of a low-order with the implication that it is what a typical low-order is like [20] . In fact, it actually represents the successful neutralisation of the largest UXO ever attempted [3] in addition to successful low-order interventions on 12 historic British, US and German.

WHAT IS THE HYDRA

In the Seagreen UXO Clearance Noise Monitoring report [4] the HYDRA is described as having a “hyper high pressure water jet disintegration technique” in which a 750g explosive charge is placed such that its intended effect will be a high-pressure water jet which splits the UXO casing without causing a high-order explosion.” It then adds that “the explosive material of the target UXO should then *dissipate*.” Forming high-speed water jets using explosives is a well-known and established method first patented in 1982 by Sidney Alford[21] although it was not published until 1996 when its secret classification was lifted.

The expression “hyper high pressure” is a non-specific and loosely defined term but appears to be used to imply a high velocity without any quantification. In air, high-speed water jets are formed using explosives in several EOD tools (such as Vulcan, DemiMod[22] and Hydra-Jet[7]), in which case the velocities produced are typically 500-1500m/s. These water jets are not generally capable of disrupting thick-skinned munitions such as air-dropped bombs, but if suitably matched to the target, could conceivably disrupt and burst a thin-skinned munition.

To form any shaped charge jet, including those using water as the projectile, it is essential that there is a stand-off in front of the projectile for the jet to form fully. They physics of shaped charge jet formation has been extensively studied and is well established.[23] In devices for underwater use the cavity in front of the cone and the stand-off space must be sealed to exclude the water as any dense medium will reduce the shockwave power, through transfer of momentum, required for the jet to form.[24] The void in front of the cone is essential to the formation of the jet whereas a jet can penetrate through a flooded stand-off space but it’s performance will be negatively affected.

A publicity photo of the Hydra[25] shows the charge stood off from the mine, effectively introducing a water barrier in front of the water projectile that will degrade its performance. The degree to which the jet will be degraded will depend on the profile and velocity of the jet and the length of water column it is travelling through.

Unlike a typical copper jet, a water jet has the same density as the water it is travelling through so will be retarded faster than a jet made from a higher density material as an equal mass of projectile material will have a far greater surface area to be ablated and is not a solid so will lose mass to the surrounding water.

Introduction of the gap between the charge and the mine will reduce its ability to penetrate the target but will also decouple the shock from the charge from the target, reducing the peak pressure and thus the probability of the target detonating sympathetically. This is the principal on which Over Pressure (OP) charges are used in EOD.[15]

Fig. 4. Cutaway image of Barracuda charge which appears to share many similar external features as the HYDRA but the internal geometry has not been made public[26].

In Seagreen Wind Energy Ltd’s licence application[1] they say “this technique involves using two nonelectric Barracuda systems which will generate two counteracting high-pressure water jets targeting the vulnerable components and main explosive filling of the UXO. This will result in the rupture or split of the UXO casing and disintegration of the primary energetic component without combustion of the explosive material within the UXO." While a single Hydra was eventually used, this application confirms that the Hydra is based on the Barracuda charge body (Fig. 2.) with a reduced and different explosive configuration inside.

In a presentation on the system by UXOControl[27], illustrations that seem to be from a patent application show multiple charges being used to shoot water jets completely through a bomb's long axis, exiting the other end. It is recognised that illustrations in patents may not always be accurate but do tend to give an idea of what the author of the patent believes is occurring. This degree of penetration is very unlikely as explosively driven water jets have far lower performance than higher-density metal jets and are generally only capable of penetrating thin-skinned munitions up to approximately 25mm.[28]

PROPOSED "LOW-YIELD" MECHANISM

It can be inferred from available literature that discussions of hyper-velocity water are ambiguous and likely a commercial term. The most likely mechanism is detonation of a donor charge close enough to a target to cause it to break up without bringing it so close that it causes sympathetic detonation of the target. This observation can be substantiated using Equation 1, to predict the peak pressure from a charge in water: [29]

$$p_{pk} = k\left(\frac{W^{\frac{1}{3}}}{R}\right)^{\alpha}$$

where
p_{pk} = peak sound pressure (MPa)
W = charge mass (kg)
R = distance from explosion (m)
k, α = shock and pressure coefficient

Equation 1

In the Seagreen Final Noise Analysis Report [7] ***k*** is given as **52.4 x 10^6** and α **is -1.13.**

These constants are the same as those given in Swisdak [30] who gives the equation a range of validity of 3.4-138MPa. The equation above therefore does not hold true at very close distances where the pressure is likely to exceed 138MPa.

There is data for pressures at similarly close ranges [30] which can be used for comparison. This gives the pressure from 1kg TNT at 0.44m to be 135MPa. (Note that 0.75kg of PE has a TNT equivalency of 1.03kg so this figure is very relevant.)

By way of comparison, an Over Pressure (OP) charge historically used by the Royal Navy for breaking up underwater mines without causing detonation would produce a peak pressure in the region of **55MPa** based on the equation above[29].

A 0.75kg charge would clearly produce a high enough pressure at close range to cause physical break-up of thin-skinned historical ordnance. In fact, without the air gap, we can say that the pressure is **approximately 2.5 times greater** than was considered required to cause disruption and might be close to the detonation pressure. In fact, the risk of detonation is not purely from peak pressure, but also from impulse which is a measure of the pressure over a period of time.

If Pressure is plotted against Impulse there are three regions in which an object will fail or break called Impulsive Loading, Dynamic Loading and Quasi-static loading[31]. The final result will depend on the combination of the pressure and impulse. (Fig. 5) At close range, the Hydra is likely to be in the dynamic Loading region in which minor changes to the geometry can have a large impact. This is because the pressure and impulse are a function of charge size and stand-off distance. For a large charge at a large distance, minor changes in distance will be proportionately very small and will not affect either the pressure or impulse. Conversely, with smaller charges at close range, many factors such as the charge size, shape and distance, as well as things such as the presence of an airgap, will have a proportionally great impact. With the Hydra, both the pressure and impulse levels will be very sensitive to minor changes in these factors placing them in the dynamic loading zone. (Fig. 5)

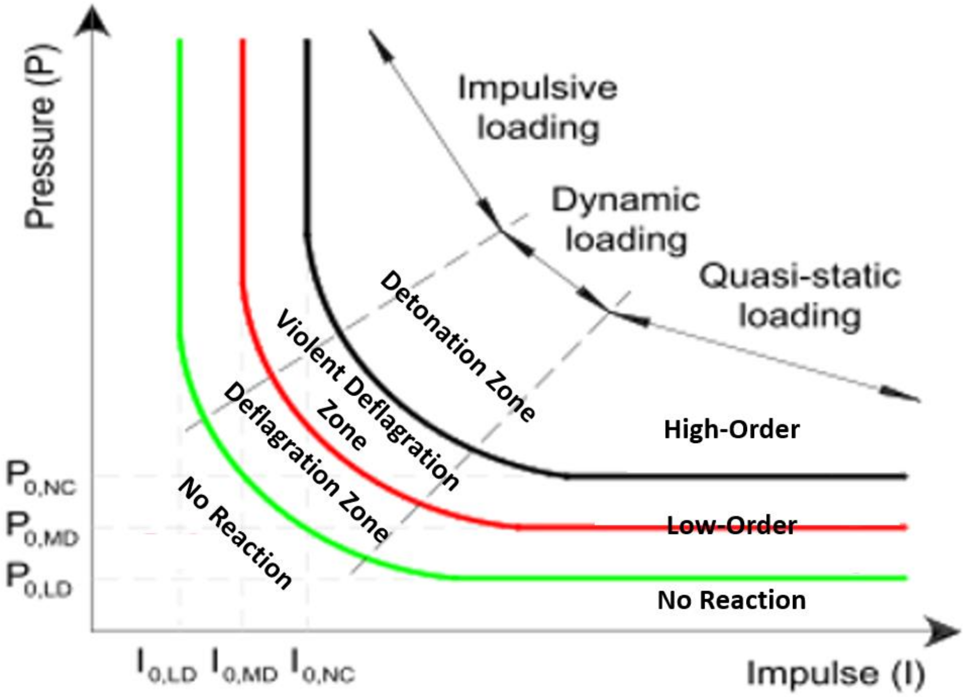


Fig. 5. Pressure against Impulse curves showing different reaction zones. (Adapted from Parisi F, Balestrieri C, Asprone D)

DOES THE EXPLOSIVE DISSIPATE?

It is reported that the explosive "dissipates", explaining why little or no explosive residue is found afterwards [1]. On the face of it, having a system that causes no chemical reaction of the explosive (detonation or deflagration) would be expected to leave the explosive in-situ. In the licence application this is further elaborated upon by explaining that the explosive is either disintegrated into thousands of pieces that dissipate over a few months or forms an emulsion of tiny fragments that dissipates almost immediately.

Both scenarios imply that a very violent event has occurred to fragment the explosive this completely compared with the normal degree of break-up associated with a typical Type IV reaction. The energy to break up the explosive must come from somewhere and it is not credible that it could come from and be delivered by a high-velocity water jet which would only be capable of gross break-up of the explosive in a munition into chunks rather than the more complete fragmentation described. Sidney Alford described hydraulic disruption leading to mechanical break-up of small UXOs which could be achieved by explosive injection of water into a munition to pressurize it enough for it to burst.[32] Such a result was found to burst the munition's casing but not significantly breaking-up the explosive. To achieve this result with a large target such as a sea mine, a large volume of water would be required, or the result is likely to be limited to a localized effect. (Fig. 3b) The low-yield method must, therefore, involve an explosive reaction to fragment the explosive.

After a typical low-order event, it is normal to find unreacted lumps of explosive in the vicinity.[18] These range in size from 20mm x 20mm x 20mm to approx.150mm x 150mm x 150mm. They will have undergone either deflagration or break-up. How much deflagration has occurred, as indicated by the size of the fireball, and how large or small the remaining explosive fragments are often a highly useful indicator that the event was, indeed a low-order and the more explosive found remaining, the less violent the event is deemed to have been.

If all the explosive is gone and there is no residue seen (as has been reported in the Seagreen reports), it indicates that the explosive has either detonated, all been consumed through deflagration or broken up and scattered so widely that they cannot be seen. This appears to have been misinterpreted as "dissipation" which could only occur after a reaction violent enough to completely break-up and scatter all the explosive. Fig.6 shows the typical size of explosive fragments after a low-order event in which the explosive deflagrates, increasing the pressure inside the target leading to it bursting. Reducing the fragment size further would require more energy, indicating a more violent reaction. In Held's scale, this would be at least a Type IV reaction. (Fig. 1)

Fig. 6. Typical fireball from low-order of a 1000lb Mk 82 bomb

Remaining explosive collected afterwards shows typical size of fragments (Source. Alford Technologies)

WHAT HAPPENED AT SEAGREEN OFFSHORE WINDFARM?

The reports from the Seagreen project[4] give a lot of detail about how the charges were used and the general conclusion is that the noise and pressure readings obtained were less than would be expected for detonations. The executive summary states that the use of the HYDRA is a “safer and lower noise alternative to simply detonating or deflagration.”

The noise measurements showed that the readings were higher than predicted and offers no explanation.

The conclusion admits that the measurements show that there was a potential for injury to harbour porpoise within 4km, to minke whales within 1.1km, to seals within 560m and to dolphins within 130m.

A graph was produced showing three curves, one showing the predicted noise levels at different distances from the 0.75kg HYDRA charge, another for a 25kg mine and a third for a 227kg mine (Fig. 7). This was plotted on a log scale for distance and with SPL (dB) on the other. As dB is, itself, a log scale, the curves appear parallel and relatively close together. Data from Seagreen [4] was plotted on the graph.

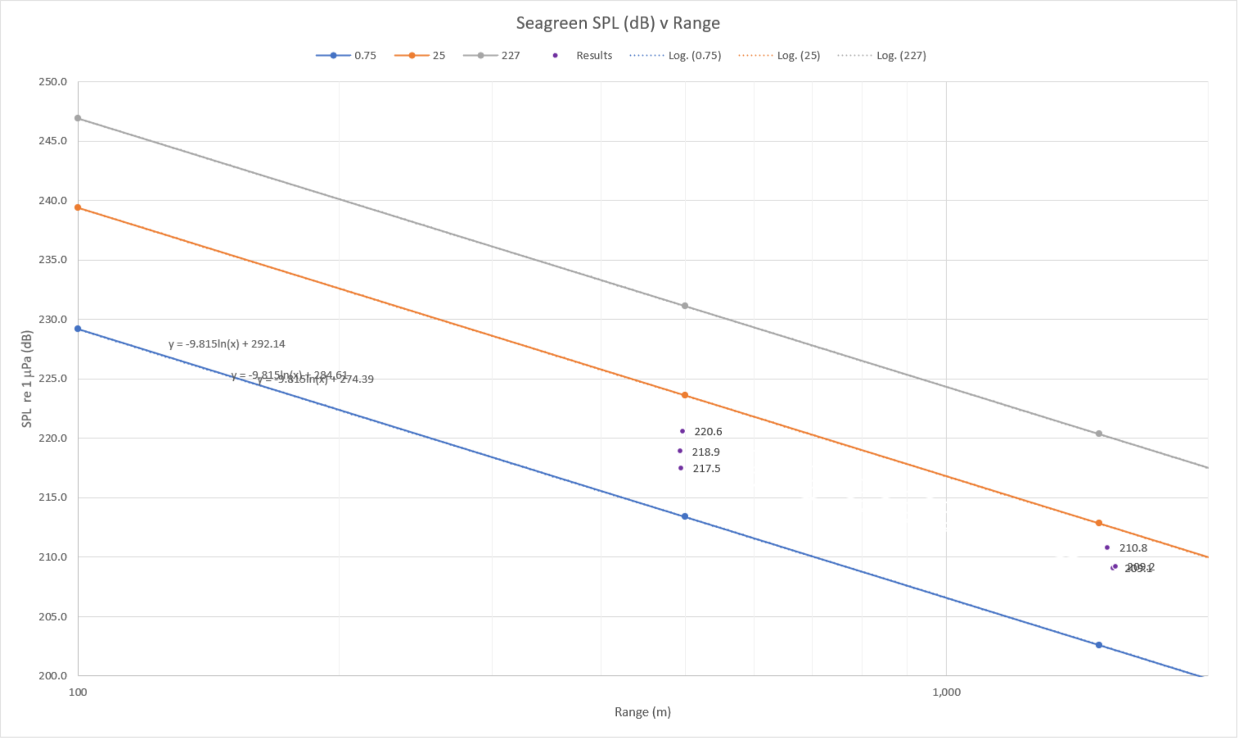


Fig. 7. Plotting noise levels against range could be misconstrued as it seems to show that a 0.75kg charge is nearly as loud as a 227kg charge

The noise readings for the detonations taken at 500m and 1500m are plotted on the graph. To anyone unfamiliar with log-log graphs, it would appear that the noise readings were slightly above the predicted levels but that there is actually little difference between the noise from a 0.75kg charge and a 227kg mine.

If the same data is used to plot the pressure in kPa against distance it becomes very apparent that at closer distances the peak pressure from each of the three sizes of charge are vastly different. (Fig.8) When the actual readings are then plotted on that graph it becomes clear that the explosive events measured cannot be explained by the HYDRA charges alone but also a significant amount of high explosive detonating.

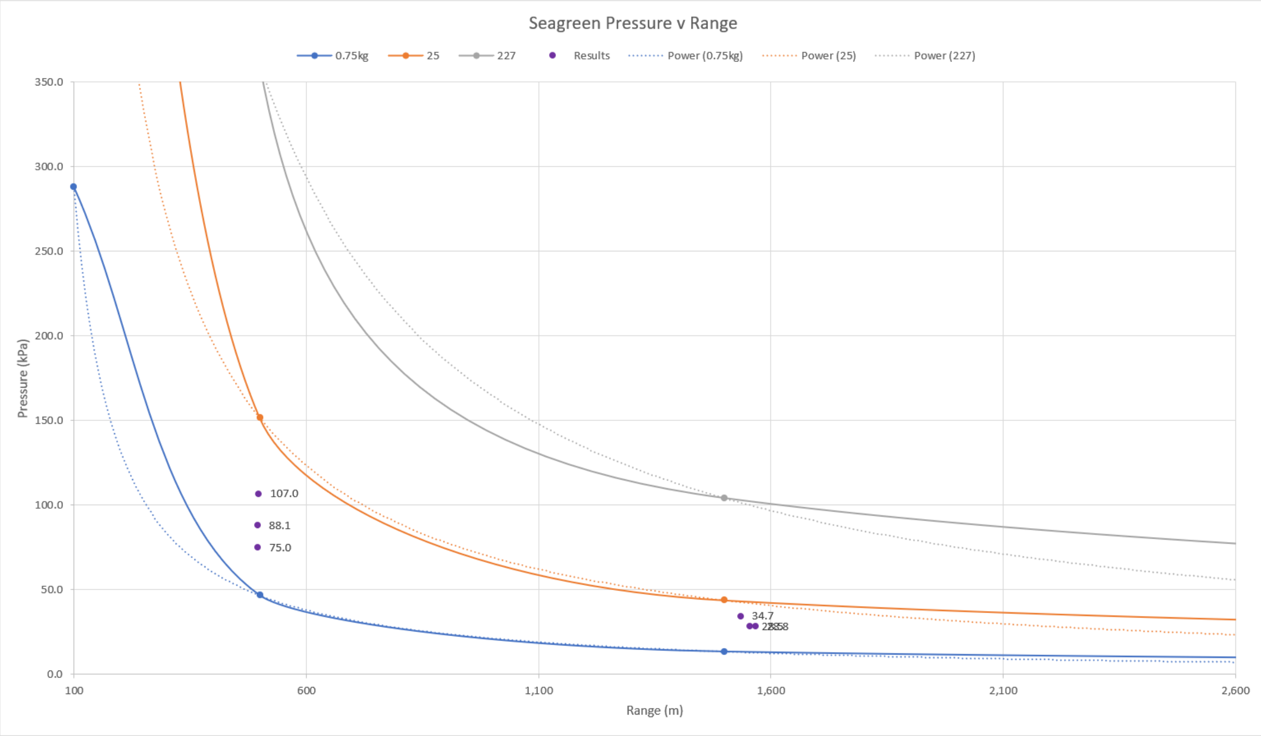
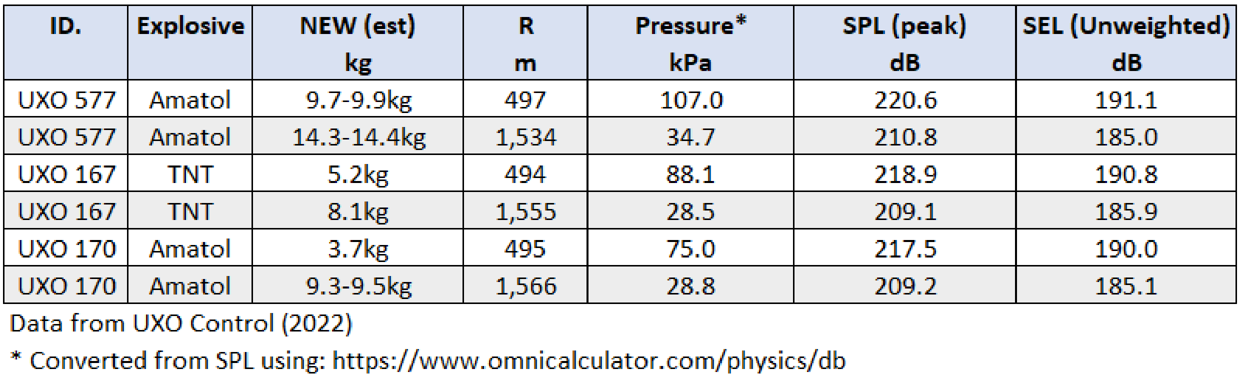


Fig. 8. Plotting the same data as pressure against range shows how the three curves diverge exponentially closer than 1.5km, offering a more understandable view of the readings

Equation 1 was then used to work out how much explosive was likely to have detonated. There was a discrepancy between the readings taken at 500m and those taken at 1500m. While it is possible that there were some additive effects from reflections of the shockwaves from the surface and bed of the sea, it is more likely that the higher readings are the correct ones.

The results indicate that the actual amount of explosive that detonated for each shot was not 0.75kg but actually between 8kg and 14.5kg. This means that the low-yield events were in fact partial detonations. This is further corroborated by reports of shallow craters being left after the interventions. According to Held's scale (pg. 3) craters are only formed when there has been a detonation, partial detonation or explosion.

Table 1. Derived Net Explosive Weights based on the noise measurements from Seagreen



ID.	Explosive	NEW (est) kg	R m	Pressure* kPa	SPL (peak) dB	SEL (Unweighted) dB
UXO 577	Amatol	9.7-9.9kg	497	107.0	220.6	191.1
UXO 577	Amatol	14.3-14.4kg	1,534	34.7	210.8	185.0
UXO 167	TNT	5.2kg	494	88.1	218.9	190.8
UXO 167	TNT	8.1kg	1,555	28.5	209.1	185.9
UXO 170	Amatol	3.7kg	495	75.0	217.5	190.0
UXO 170	Amatol	9.3-9.5kg	1,566	28.8	209.2	185.1

Data from UXO Control (2022)

* Converted from SPL using: https://www.omnicalculator.com/physics/db

The National Physical Laboratory, Loughborough University and Aarhus University conducted some recent trials with the Royal Danish navy in which a selection of historical UXOs (seamines) were selectively high-ordered underwater using a donor charge or low-ordered using a shaped charge. [33]

It was found that low-order events gave a greater than 20dB reduction for high to low order and 10km or 1/100th of the energy. (Fig. 9) Note that the measured SEL noise levels measured at 1.5km can be extrapolated to be approximately 165dB for a high-order and 145dB for a low order whereas the levels measured at Seagreen ranged from 185dB to 191dB at 0.5 to 1.5km.

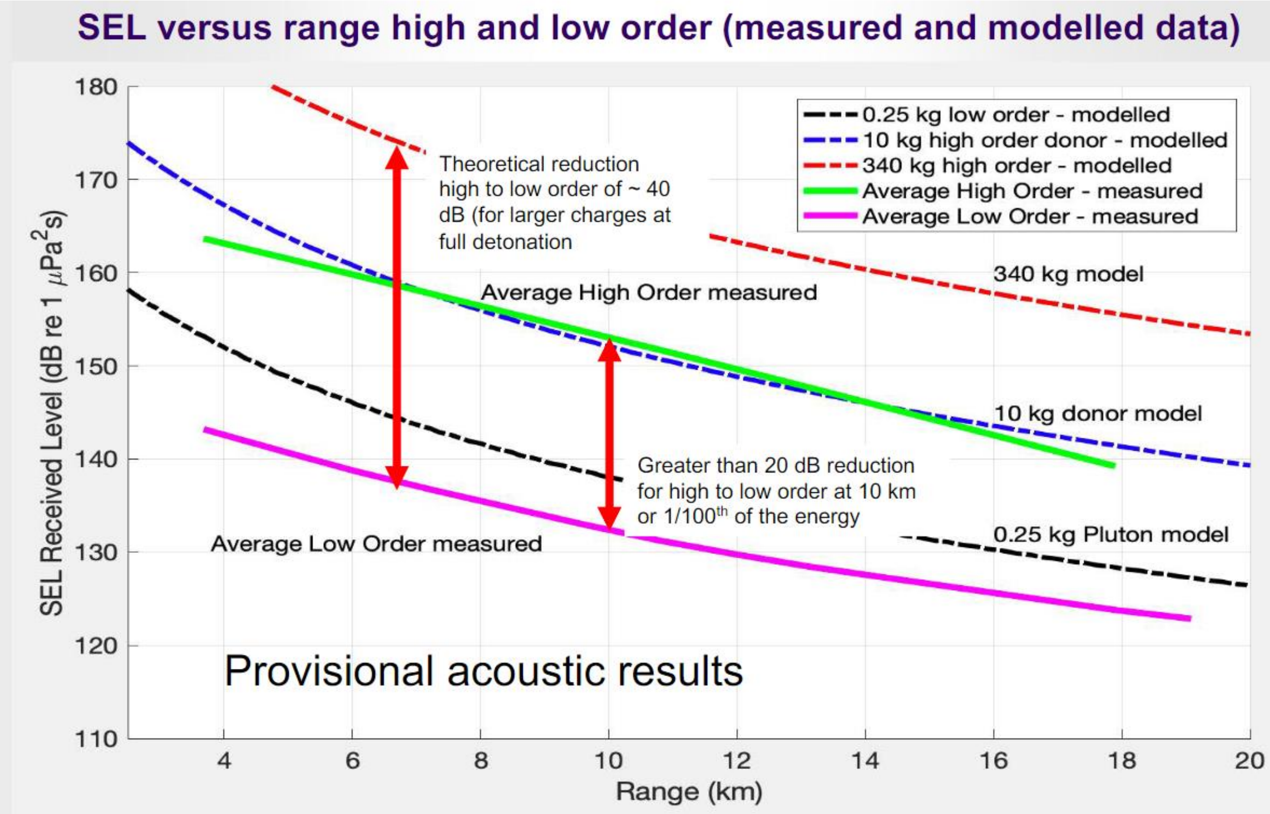


Fig. 9. Data from NPL report for high and low-order results (Reprinted with permission)

Claims of 100% success rate [10] are very unlikely. It is impossible to be sure how much explosive was in the mines when they were disposed of, but images showed that they were in very poor condition with large sections of the steel corroded away leaving the bare explosive exposed and eroded over time.[4] One image shows the base plate of one of the mines and shiny steel around the edge where it had been separated and sheared from the rest of the mine.[34] This was significantly more violent than would be expected from a typical low-order event which it has been claimed the HYDRA is an improvement on.

CONCLUSIONS

The noise pressure readings made during the three events show clearly that they were all more violent than the HYDRA charges could have produced alone. It is known that when a munition is low-ordered in water, the highest-pressure peak is due entirely to the charge used to cause the low-order and that the deflagration process does not register at all in the time pressure curves (NPL (2020) Final Report: Characterisation of acoustic fields generated by UXO removal). This indicates that the elevated pressure readings from Seagreen were the result of the partial detonation of at least some of the explosive in the mines.

Comparison with the recent data for low and high-order events by the NPL show that a low-order generally gives a reduction of approximately 20dB and that the noise levels measured at Seagreen were more consistent with those from high-orders than low orders.

Images taken before the firings show the mines to have been in very poor condition with large sections of the mine casing corroded away leaving the explosive directly exposed. There is no way to confirm the amount of explosive in the mines before the reaction so it is entirely possible that the two smaller mines underwent full detonations of all the remaining explosive.

The absence of any explosive after the shots and the presence of craters in the seabed further indicates that there was a partial detonation of the munitions in order to have broken the explosive into small enough particles to be scattered and lost. The presence of remains of parts of the charge deployment system is not surprising but the severely damaged condition is also an indication of a reaction far more violent than the mine breaking apart in the way described in the Hydra marketing literature.

ACKNOWLEDGEMENTS

Tom Burkey

REFERENCES

1. Soubies H. Seagreen Alpha and Bravo Site UXO, boulder and debris clearance - Marine Licence Application Supporting Environmental Information. ; 2021.
2. Seagreen Wind Energy Limited. Seagreen Wind Energy. 2022. Available at: https://www.seagreenwindenergy.com/ (Accessed: 27 September 2022)
3. Miętkiewicz R. High explosive unexploded ordnance neutralization - Tallboy air bomb case study. Defence Technology. Elsevier; 1 March 2022; 18(3): 524–535. Available at: DOI:10.1016/J.DT.2021.03.011 (Accessed: 20 April 2022)
4. Cook S., Banda N. Seagreen UXO Clearance Noise Monitoring: Underwater Noise Analysis Final Report. 2021.
5. SMRU Consulting. Seagreen Alpha and Bravo Site UXO clearance - Noise monitoring and mitigation summary. 2022;
6. Robinson SP., Wang L., Cheong SH., Lepper PA., Marubini F., Hartley JP. Underwater acoustic characterisation of unexploded ordnance disposal using deflagration. Marine Pollution Bulletin. Elsevier Ltd; 1 November 2020; 160. Available at: DOI:10.1016/J.MARPOLBUL.2020.111646 (Accessed: 4 April 2022)
7. Cherry Engineering. Hydra-Jet - Cherry Engineering, INC. 2022. Available at: https://cherryengineeringinc.com/?attachment_id=119065 (Accessed: 16 September 2022)

8. UXOControl Ltd. Neutralisation / Disintigration of live UXOs using the Hydra Jet Technique. 2021. Available at: https://uxocontrol.com/neutralisation-disintegration-of-live-uxos-using-the-hydra-jet-technique/ (Accessed: 25 July 2021)
9. Triputra I. Seagreen Offshore Windfarm Pre-Construction Site Survey: PUXO Identification and Disposal Operations and Results. 2021.
10. James Fisher. Unexploded Ordnance (UXO) Newsletter. Newsletter Edition 1. 2022;
11. Buntzen R R. HYDRA PROGRAM. THE NRDL LOW-YIELD UNDERWATER EXPLOSION TANK AND ASSOCIATED INSTRUMENTATION. May 1963. Available at: https://www.osti.gov/biblio/4693262 (Accessed: 17 September 2022)
12. www.seagreenwindenergy.com.
13. McLennan P., Matheson M. Scottish Parliament Question ref. S6W-01913. Question ref. S6W-01913. 2021.
14. Zukas J., Walters W. Explosive Effects and Applications. ,. 1998.
15. MoD. JSP 364: Joint Service EOD Manual Vo. 1 & 2. 2007; 1 & 2.
16. Cook M. The science of high explosives. New York: Reinhold; 1958.
17. Lee P., Zukas J., Walters W. Explosive Reaction Levels. Chapter 8;
18. Alford Sidney. WO 30-058155A1 Device for the disruption of Explosive Ordnance. World Intellectual Property Organization; 2002.
19. Alford Technologies., Mines Advisory Group. Vulcan Mk80 Series Low-Order Results Database - Saravan Province LDR. 2013.
20. Dirk van de Vleuten., UXOControl Ltd. Neutralisation / Disintegration of Live UXO's using the "HYDRA" © 'Hyper High-Pressure Liquid Jet'. 2020. Available at: https://www.youtube.com/watch?v=BmFO2to2HXQ (Accessed: 27 September 2022)
21. Alford Sidney. 2292445: GB2292445B Device and method for generating a liquid jet of very high velocity. GB: UK Patent Office; 1982.
22. Alford Technologies. C-IED/IEDD Products — Alford Technologies. Available at: https://www.explosives.net/cied-iedd (Accessed: 16 September 2022)
23. Cooper PW. Explosives Engineering. 1996.
24. Ridgeway J J. US4151798 Shaped explosive charge device for underwater use. 1979.
25. UXOControl Ltd. Hydra-Jet UXOControl. 2020. Available at: https://www.portalmorski.pl/bezpieczenstwo-granice/46800-niewybuchy-pod-pelna-kontrola (Accessed: 17 September 2022)
26. Event Horizon. Barracuda 88. Available at: http://www.precisionenergetics.co.uk/Docs/Barracuda.pdf (Accessed: 17 September 2022)
27. UXOControl Ltd. Hydra 'Low Yield' disposal Technique - Company Presentation. 2021.

28. Gale C. Low Observable Neutralization of Underwater Mines and Waterborne IEDs using Explosive Shaped Charges without Collateral Damage (ONR BAA Submission). 2020.

29. Cole RH. Underwater Explosions. Dover Edition (1965). Dover Publications Inc.; 1948. Available at: DOI:65-22737 LCCN

30. Swisdak MM. Explosion Effects and Properties: Part II - Explosion Effects in Water. 1978.

31. Parisi F., Balestrieri C., Asprone D. Out-of-plane blast capacity of load-bearing masonry walls Masonry View project Special Issue of Engineering Failure Analysis on 'Damage and Failure Analysis of Civil Structures and Infrastructures: Physics-based versus Data-driven Methods' View project. 2016. Available at: https://www.researchgate.net/publication/301673947

32. Alford Sidney. The Theory & Application of Low-Order Techniques for Conventional Munitions Disposal. Sidney Alford Ltd; December 2001.

33. Lepper P., Robinson S., Choeng S-H., Wang L., Tougaard J., Griffiths ET., et al. DEFLAGRATION: A method for lowering noise from underwater unexploded ordnance (UXO) clearance operations. Sixth International Conference on The Effects of Noise on Aquatic Life, Berlin. July 2022;

34. UXOControl. Seagreen: Field Operations Report UXO ID & Disposal. 2021.

Are low-yield explosive ordnance disposal methods viable?

Alford, Roland

2022-10-01

Alford R, Hazael R, Critchley R. (2022) Are low-yield explosive ordnance disposal methods viable?, IMCSE Technical Paper, October 2022

https://imcse.org/technical-papers/