

Detonation Performance of Urea-Hydrogen Peroxide (UHP)

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Abstract: Carbamide Peroxide, an adduct of Urea and Hydrogen Peroxide, is commonly used in the cosmetic and pharmaceutical industries as a solid source of hydrogen peroxide. However, it exhibits explosive properties and can be easily manufactured from readily available household chemicals, making it a potential emerging threat. We carried out a detailed performance assessment, combining experiments, thermochemical calculations and numerical simulations and highlighted a good level of agreement between experimental data from lab, field and underwater firings. A maximum detonation velocity of 3.65 km/s was recorded for unconfined 25 kg UHP charges at 0.85 g/cm³ (200 mm charge diameter). We determined in these conditions an infinite diameter detonation velocity of 3.94 km/s. These results are also consistent with previous results obtained at small scale under heavy confinement. Airblast measurements highlighted an average 40% TNT equivalence for impulse and 55% for peak overpressure at short distance, which are in good agreement with the 57% (Power Index) calculated from Explo5, while 50% for bubble energy (explosive power) and 20% for shock pressure (brisance) were obtained from underwater experiments. The use of different experimental approaches has proven useful to characterise the performances parameters of a non-ideal explosive for risk assessment purposes.

Keywords: Urea hydrogen peroxide, Detonation, Non ideal explosive, Performance

1 Introduction

Carbamide Peroxide or Urea Hydrogen Peroxide (UHP) is commonly used in the dental, cosmetic and pharmaceutical industries as a solid source of hydrogen peroxide. This adduct can also be easily manufactured from readily available household chemicals. Like other oxidisers such as ammonium perchlorate [1] or ammonium nitrate [2], UHP exhibits explosive properties [3, 4] and could represent a potential emerging threat. Determining UHP detonation performance parameters is hence important for safety purposes.

Because there is a need to predict large-scale explosive behaviour from small-scale experiments [5], our previous work demonstrated UHP detonability at small scale under heavy confinement, providing an initial lab-scale characterisation of detonation performance parameters, including velocity of detonation (VoD) records consistent with literature values from large-scale experiments [6]. UHP charges non-ideality was further studied by VoD dependence on charge diameter and confinement [7], a behaviour typically observed for charge diameters in the 10 cm range with explosives detonating at a lower regime, such as ANFO explosives, and particularly emphasised by recent research at small-scale [8, 9].

As extensive experimental data is particularly desirable to accurately evaluate the detonation parameters of non-ideal explosives [10], we present in this paper a detailed performance assessment supported by thermochemical calculations and numerical simulations. Initial lab characterisation is completed and complemented by field and underwater instrumented firings using scaled-up charges (Figure 1).

The level of agreement between small-scale and large-scale, between field and underwater experimental

performance parameters and between experiment and numerical simulation has been investigated. To that end and for each performance parameter under consideration, we made use of experimental TNT equivalences [11-13], knowing the limitation of the concept [14-16], especially when comparing non-ideal and ideal explosives [17]. However, for both academic and safety purposes, we found necessary to compare UHP detonation performance with well-known and documented standards, TNT or plastic explosives such as C4 (91% RDX), which were, for direct comparison, detonated in identical experimental conditions, with particular care for charge configuration (shape, initiation, confinement) and (scaled) distances.

2 Experimental Section

We used commercial lab grade Urea Hydrogen Peroxide - UHP (97%) purchased from ALFA AESAR. Average particle size was determined by dry sieving with 85% of the particles retained in the 600 µm mesh and 15% in the 1000 µm mesh. The standard enthalpy of formation of UHP was calculated from calorimetric measurements and we used the thermodynamic code Explo5 (V6.06.02) to determine UHP ideal detonation parameters. Following our previous work [6], the

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theoretically based equation of state (EoS) molecular fluid EXP-6 was selected to calculate UHP VoD and detonation pressure (P_{det}), together with its Jones-Wilkins-Lee (JWL) coefficients, required for further modelling of our experimental firing setups in Ansys Autodyn V14.0. For comparison purposes, we also calculated VoD and P_{det} using the Modified Becker-Kistiakowski-Wilson (M-BKW) EoS, as this equation of state is known to lead to a better accuracy when dealing with explosives showing a high dipolar molecules content in the detonation products and a low detonation temperature [18].

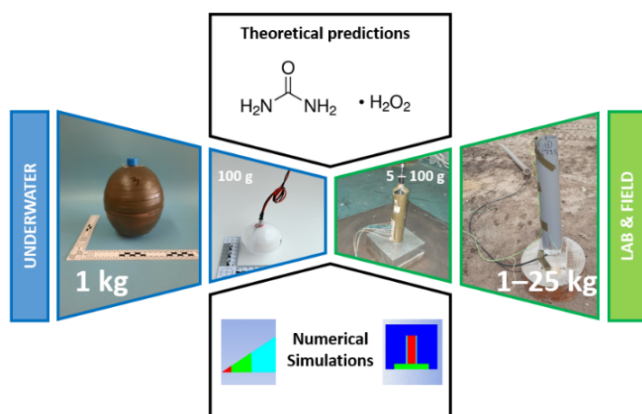


Figure 1. UHP Detonation Performance Assessment.

In the following subsections, we successively present the respective experimental methods and set-ups used for the lab, field and underwater firings.

2.1 Lab Firings

The firing setup basically consists of 80-120 g UHP cylindrical charges at loading densities ranging from 0.75 to 1.1 g/cm³, under heavy confinement (stainless steel walls), with an outer diameter (OD) of 38 mm, an inner diameter (ID) of 30 mm and a length equal to 5 inner diameters. 40 UHP charges were initiated by a standard N°8 military detonator and an 8 g C4 booster. Initial performance assessment [6] included Al 6082 T651 witness plate dent and detonation velocity measurements (Optimex 64 – OZM research). VoDs were determined using arrays of passive optical fibre probes to record arrival times and a known distance between probes. P_{det} was further estimated from VoD and loading density (ρ_0) using the following empirical correlation [7]:

$$P_{det} = \rho_0 \cdot (VoD)^2 \cdot (1 - 0,7125 \cdot \rho_0^{0,04}) \quad (1)$$

Complementary firings were carried out in the lab. The confinement sleeves were filled by 4 g UHP increments to obtain the following charge densities (theoretical maximum density 1.43 g/cm³ [3]), calculated from mass and volume UHP: 0.75 (loose) and 0.85 g/cm³, i.e. slightly compacted by vibration to achieve more uniform loading and homogeneity. The VoD setup [6] was duplicated (Figure 2) and included a total of 16 optical fibre probes, divided in two rows of 8 probes, with 7.5 mm between probes, and the first

probe of each row located 90 mm (3 x ID) from the booster charge. The setup was also slightly adapted in an attempt to capture improved signals by reducing the thickness of confinement material between the optical probes and the energetic material under investigation, while avoiding any early triggering from the light preceding the detonation wave due to translucency of the explosive. Instead of inserting the probes in 2 mm deep, non-through (blind) holes drilled in the confinement sleeve, like in previous work [6], we used all-through holes sealed by a piece of 30 μ m thick aluminium tape glued inside the sleeve. Finally, we recorded the VoD and measured witness plate indentation from two 120 g pressed TNT charges (1.61 g/cm³) prepared and detonated in the same conditions in an attempt to assess UHP relative brisance (%) based on plate dent depth [19].

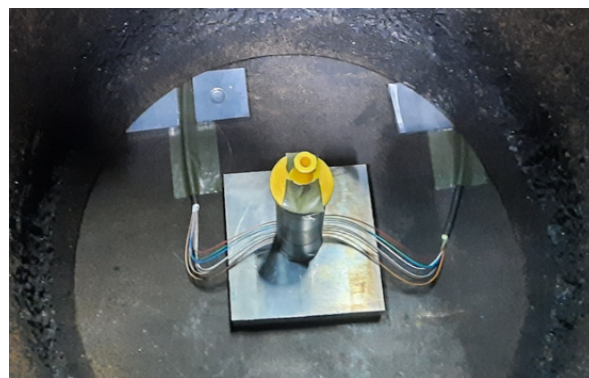
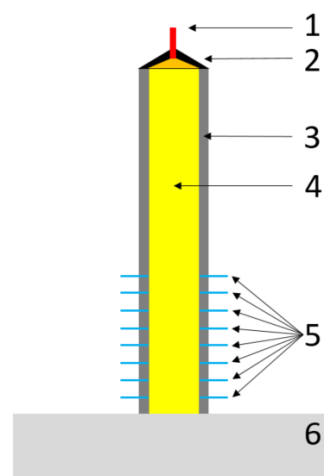


Figure 2. 100 g UHP – heavy confinement : (1) N°8 detonator; (2) C4 booster in bespoke holder, (3) Confinement sleeve, (4) UHP charge, (5) 2x8 Optical probes, (6) Al witness plate

2.2 Field Firings

The field firings consisted of two separated experimental campaigns in order to measure the VoD to determine a nominal charge diameter for studying UHP performances (1) and record the airblast characteristics in a selected setup, for which non-ideal effects are considered as limited enough to not significantly influence the performance of the charge, in

an attempt to provide a performance characterisation independent of the setup and valid for very large charges (2). Both experimental setups are depicted in Figure 3, while Table 1 describes the test program. Upscaled kg-size UHP charges without confinement (PVC casing) were filled in 25 increments and vibrated at each step to achieve a reproducible $0.85 \pm 0.02 \text{ g/cm}^3$ loading density at large scale, avoiding self-compaction phenomenon and density gradient observed at loose density (0.75 g/cm^3) for large charges.

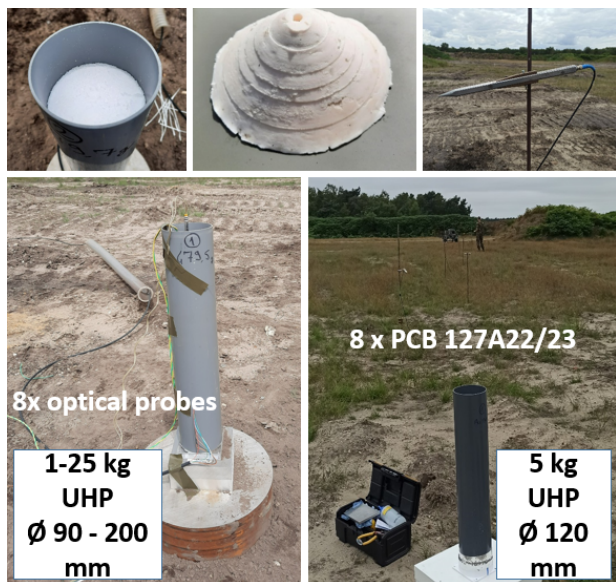


Figure 3. 1 to 25 kg UHP: VoD (left) and blast (right).

Table 1. Field Firings – UHP (0.85 g/cm^3 ; $L=5 \times ID$)

OD (mm)	ID (mm)	Mass UHP (kg)	Mass Bstr C4 (kg)	Target data	# shots
90	86.4	1.97	0.10	VoD	2
110	105	3.72	0.22	VoD	2
125	120	5.45	0.35	VoD	2
160	153.6	11.50	0.73	VoD	2
200	193	22.73	1.42	VoD	1
125	120	4.89	0.35	Blast	10

First, in order to determine the nominal charge diameter, 9 UHP charges (average loading density 0.85 g/cm^3) in PVC tubes of outer diameters ranging from 90 to 200 mm, were initiated using a standard N°8 military detonator and a bespoke moulded C4 booster (Figure 3, top middle) to fit the inner diameter of the tube and distribute the initiation wave over the entire charge diameter. VoD were measured using passive optical probes inserted in holes drilled in the PVC casing and sealed from inside the pipe by aluminium tape, as previously described (section 2.1). The recorded experimental detonation velocities were then plotted

against reciprocal diameter in order to determine unconfined VoD at infinite charge diameter.

Secondly, building upon previous results on nominal diameter, we selected a charge diameter of 120 mm for airblast measurements, a trade-off between the impact of the diameter on the performance characterisation and the practical charge size. With regard to atmospheric conditions, the test site was located 77 m above the sea level, the ambient pressure on the day of the tests was 102.35 kPa (according to the Meteorological Wing of the Belgian Defence). The temperature was 23°C and the relative humidity 60%. We recorded the pressure history and determined incident overpressure and positive phase impulse as a function of scaled distance ($Z=R/W^{1/3}$, with R the radial distance from the charge, and W the charge weight), using 8 blast pencils PCB 127A22/23 respectively positioned at 4.5 ($Z > 2 \text{ m/kg}^{1/3}$, to avoid short distance effects), 10, 15, 21, 26, 32, 37 and 43 meters distances, and compared them to a TNT reference to determine equivalences, using the airblast parameters from TNT surface burst by Kingery & Bulmash [20]. We fired 10 cylindrical charges containing approximately 5 kg UHP and initiated by a 350 g C4 booster and a standard N°8 military detonator. To limit energy dissipation due to cratering and ground shock, the charge was placed on a 45 cm high wood support. As the height of burst was higher than 3 times the charge diameter, the energy loss to crater formation was considered as negligible [7]. This was further supported by the fact that no significant crater formation was observed after detonation. In these conditions and assuming that the ground was a perfect reflector, an ideal hemispherical burst was considered with an effective yield of 200%.

2.3 Underwater Firings

The underwater test campaign was conducted at *Braboplas* range, a military underwater demolition site (available depth 9 m), and consisted of two phases, 25 shots at small scale [21] and 15 shots at larger scale, using respectively 100 g and 1 kg UHP charges. The experimental setup is depicted in Figure 4.

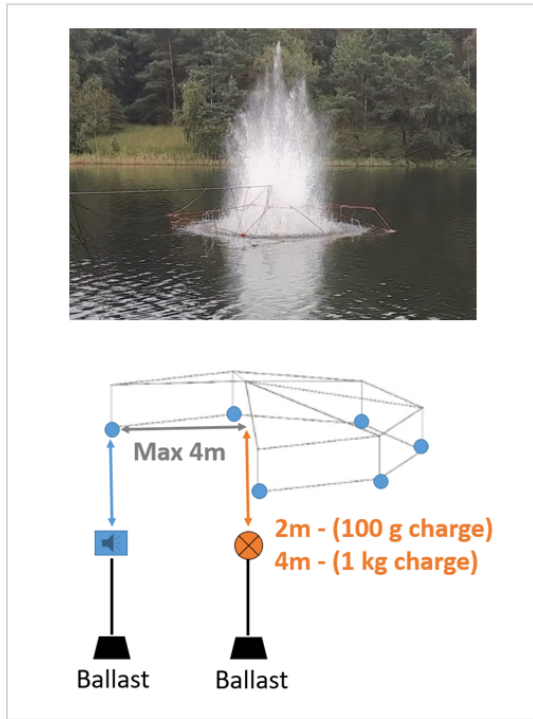


Figure 4. 100 g to 1 kg UHP – floating structure.

Explosive charges were suspended in the centre of a floating structure at a depth of 2 m for the 100 g charges and 4 m for the 1 kg charges. Eight voltage mode tourmaline pressure sensors type PCB 138A05 were placed at the same depth (D), respectively at 1 m, 1.50 m, 2 m and 2.5 m range (R) for 100 g charges and 2 m, 3 m and 4 m for 1 kg charges. According to recommendations in [22], pressure sensors were positioned at the depth of the centre of the charge and respectively outside the calculated maximum bubble radii of 0.75 m for a 100 g C4 explosive charge and 1.5 m for a 1 kg [23], considered as maximum dimensioning charges for the design of our experimental setup.

Unconfined spherical charges of 100 g loose UHP (0.75 g/cm^3) in plastic casing (1 mm thick, 70 mm OD), as shown on Figure 5, were initiated by an explosive train comparable to the one used in the lab (section 2.1), i.e. a standard N°8 military detonator and a central spherical 8 g C4 booster. We also fired, in the same conditions, spherical 100 g C4 charges for reference and comparison purposes. In an attempt to better assess the influence of the booster [24] on UHP detonation performance (equivalent shock pressure and bubble energy), we finally fired 8 g C4 booster charges alone.



Figure 5. 100 g UHP charge configuration.

Upscaled unconfined spherical charges of 1 kg UHP (loading density 0.80 g/cm^3 , slightly compacted to improve homogeneity) in plastic casing (1 mm thick, 140 mm OD) were initiated by a standard N°8 military detonator, inserted in a bespoke channel to detonate a central spherical 60 g C4 booster (Figure 6). Additionally and similarly to the small-scale campaign, the performance of the C4 booster alone was separately investigated. Finally, we fired 1 kg spherical C4 for reference and comparison purposes.

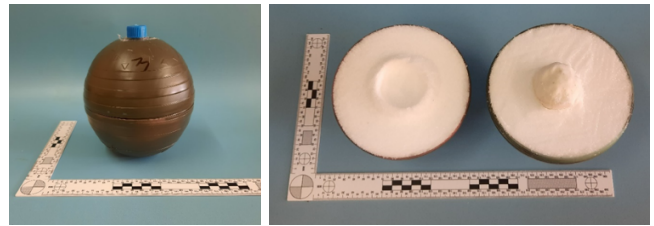


Figure 6. 1 kg UHP charge configuration.

Using the procedure described in [25-27], we recorded the pressure history to determine underwater shock pressure and first pulsation period (t_b). Because the firings were standardised (same explosive masses, depth, range, water properties) for comparison purposes in order to assess UHP underwater performance, we made use of the so-called shock energy ($E_{s, equ}$) and bubble energy ($E_{b, equ}$) equivalents:

$$E_{s, equ} = \int_{t_0}^{t_0 + \theta} P^2(t) dt \quad (2)$$

$$E_{b, equ} = t_b^3 \quad (3)$$

where:

t_0 : time of arrival of the shock wave
 θ : time at which the pressure has decreased to $P_\theta = P_{\max} \cdot e^{-1}$
 t_b : first pulsation period

We simulated both set-ups in Ansys Autodyn V14.0 in order to model and compare peak overpressure ($P_{\max}$) and equivalent shock energy of the different

charges to experimental values. A 1D Euler multi-material model was used, representing a spherical geometry. For UHP, the JWL parameters previously calculated with Explo5 [6] were fed into Autodyn. Models from Autodyn's standard library were used for C4 and water.

3 Results and Discussion

3.1 Lab Firings

Complementary lab campaign results are available in Table 2, while theoretical calculations from Explo5 are presented in Table 3. As expected, VoD and indent depth measurements are in excellent agreement with previous measurements [6]. For our reference TNT charges pressed at 1.61 g/cm³, we recorded a detonation velocity of 6.90 km/s, a value in very good agreement with the 6.91 km/s predicted from LASL explosive properties data [28] and very close to the theoretical maximum 6.95 km/s at 1.64 g/cm³ [7]. Using experimental VoD recorded at small scale under heavy confinement to estimate P_{det} , we determine a relative brisance (based on P_{det}) of 9% for loose UHP (0.75 g/cm³) and 14% at 0.85 g/cm³ loading density with respect to TNT.

Table 2. UHP – 30 mm ID, 4 mm steel confinement (VoD $\pm$ max 0.026 km/s for 95% confidence interval)

UHP Loading Density (g/cm ³)	0.75	0.85
Average VoD (km/s)	2.954	3.454
Estimated P_{det} (GPa)	1.93	2.96
Relative brisance (%) vs TNT* from P_{det}	9	14
Average indent depth (mm)	5	6
Relative brisance (%) vs TNT* from indent depth	30	35

*TNT at 1.61 g/cm³ loading density

We measured a maximum indentation of 17.3 mm for the TNT charges and determined a 30-35% relative brisance from indent depth measurements for UHP. This value should however be treated with care. Even if the correlation between the result of a plate dent experiment and the experimentally determined detonation pressure [19] is generally accepted and widely used to assess relative brisance of high explosives [29], this correlation was actually only demonstrated for conventional military explosives [19]. It was later pointed out that this correlation was a consequence of similar expansion of the detonation products of most conventional military explosives down to about 1 GPa, the pressure range of interest of the test, making the peak detonation pressure the major difference between them and leading to the observed linear correlation [10]. However, UHP (CH₆N₂O₃) differs from conventional CHON explosives, like TNT, by a high water content in the detonation products and a very low detonation temperature (1500 K, calculated, Table 3). Noting that water is a triatomic polar molecule, a significant impact on the isentrope slope between the

detonation pressure and 1 GPa is expected. In these conditions, the linear correlation observed between the plate dent result and the detonation pressure of conventional CHON explosives should not be extrapolated to UHP without additional external validation based on the measurement of the UHP detonation pressure, which will be part of future work.

Table 3. UHP – Explo5 calculations with EXP-6 and M-BKW EoS

	EXP-6	M-BKW	EXP-6	M-BKW
Loading density (g/cm ³)	0.75	0.75	0.85	0.85
VoD (km/s)	3.66	3.96	4.11	4.37
P_{det} (GPa)	2.43	2.95	3.31	3.98
T_{det} (K)	1600	1467	1606	1483
Q_{det} (kJ/kg)	1588	1548	1624	1582
V_{gas} STP (l/g)	1.06	1.07	1.05	1.06

As shown in Table 3, the choice of EoS influences the calculation of the detonation parameters, such as VoD or P_{det} , and consequently the Autodyn numerical model. Due to the relatively low detonation pressure, it was only possible to achieve a fitting of the JWL equation parameters based on the calculated detonation gases isentrope with the EXP-6 EoS of the Explo5 software. Calculating the Q_{det} (4349 kJ/kg) and V_{gas} (0.67 l/g) values from M-BKW for TNT (1.63 g/cm³), we derived a 57% TNT equivalence by Power Index (PI) [14] for UHP (0.85 g/cm³). Table 3 also emphasises the surprisingly low detonation temperatures of UHP as previously mentioned, potentially out of the EoS validation ranges [18] and hereby questioning the overall accuracy of the calculation.

3.2 Field Firings

Looking at field firings (no confinement), the recorded UHP VoD value (max $\pm$ 0.025 km/s for 95% confidence interval) in the field are summarised in Figure 7, with a maximum of 3.65 km/s at 200 mm charge diameter and the possible beginning of a plateau observed from 160 mm charge diameter. The observed deviation is likely due to density variations, the charge preparation method being only accurate to ± 0.02 g/cm³ at this scale. Based on the recorded data, VoD at infinite charge diameter is about 3.94 km/s, namely 96% and 90% of the ideal VoD predicted from Explo5 using EXP-6 and M-BKW EoS, respectively, indicating a non-ideal character [10] typically observed with explosives detonating at a comparable regime [7]. This result is also consistent with the 3.78 km/s recorded by Matyas [3] in comparable charge diameter (206 mm) but higher loading densities (0.93 g/cm³) and heavier (steel) confinement.

Urea-Hydrogen Peroxide

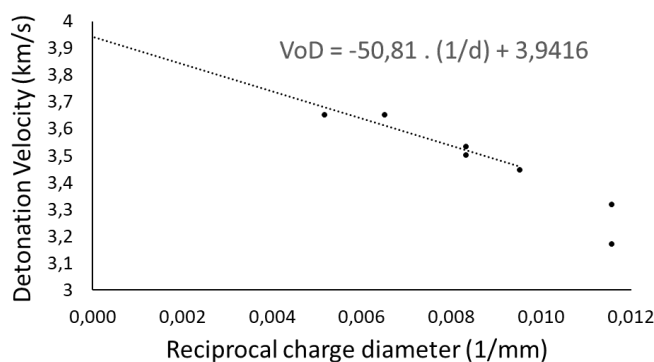


Figure 7. UHP Detonation Velocity vs reciprocal diameter ($0.83 \leq \text{loading density (g/cm}^3) \leq 0.87$).

As far as airblast parameters are concerned, reproducible pressure-time histories were recorded (as illustrated on Figure 8), enabling side-on peak overpressure and positive impulse to be determined and compared to TNT data.

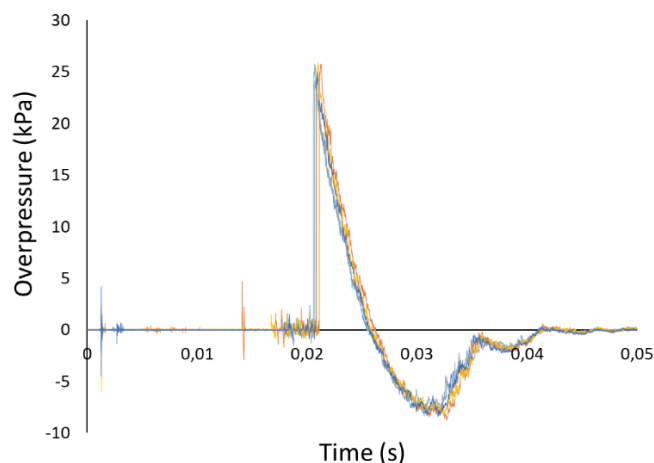


Figure 8. 5 kg UHP (0.85 g/cm^3) – 10 m standoff (5 shots).

Figure 9 summarises the TNT equivalences for overpressure and impulse as a function of UHP scaled distance. As expected, TNT equivalences are dependent on scaled distances [12, 13], which could be explained by the rather large distance interval considered [15] and the significant difference between the composition of TNT and UHP detonation products, as previously discussed. An influence of the charge shape at a lower scaled distance cannot be excluded [15].

Even if the same trend is observed, TNT equivalences from overpressure are higher than those from impulse. The order of magnitude is however comparable to commercial blasting explosives detonating at a similar regime [30-32] and in good agreement with the 57% TNT equivalence (PI) calculated from Explo5 (section 3.1).

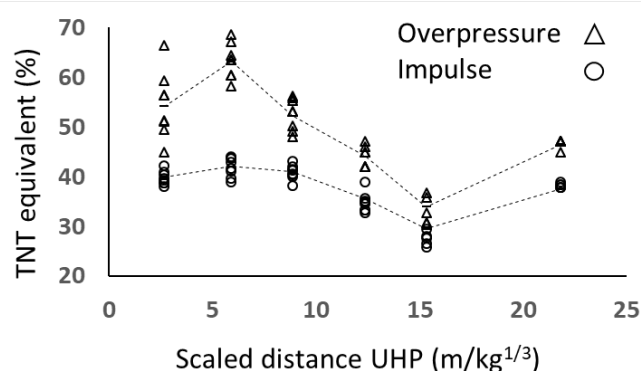


Figure 9. TNT equivalences for UHP airblast parameters at 0.85 g/cm^3 (line with average values as a visual guide).

3.3 Underwater Firings

The experimental average shock wave parameters and calculated equivalent shock ($E_{s, \text{equ}}$) and bubble ($E_{b, \text{equ}}$) energies from the underwater firings are summarised in Table 4. As far as UHP is concerned, these values include the contribution of the respective C4 boosters (bstr). Additionally, predictions based on numerical simulations with Autodyn (using Explo5 parameters calculated with EXP-6 EoS) for peak overpressure and equivalent shock energy are mentioned.

Table 4. Underwater Firings – Small and large scale – mass (M), depth (D), range (R), peak overpressure (P_{max}), first pulsation period (t_b), equivalent shock ($E_{s, \text{equ}}$) and bubble ($E_{b, \text{equ}}$) energies.

	M (g)	D (m)	R (m)	P_{max} (MPa)	t_b (ms)	$E_{s, \text{equ}}$ (kPa^2s)	$E_{b, \text{equ}}$ (10^{-3}s^3)
UHP ^a 100	2	1.5		5.67 ± 0.7	81 ± 2	450	0.5
				8.12^c		2360 ^c	
C4 ^b 8	2	1.5		4.07 ± 0.4	48 ± 1	162	0.1
C4 100	2	1.5		12.93 ± 0.9	121 ± 1	4590	1.8
				12.97^c		4670 ^c	
UHP ^a 1000	4	3		8.21 ± 0.7	178 ± 4	2192	5.6
				8.70^c		4660 ^c	
C4 ^b 60	4	3		4.87 ± 0.4	90 ± 2	587	0.7
C4 1000	4	3		14.22 ± 1.4	220 ± 2	11381	10.6
				14.06^c		10930 ^c	

^a main charge with C4 booster; ^b booster charge; ^c Autodyn

On the one hand, C4 has proven a good reference explosive for underwater experiments. Experimental results and simulations for C4 are in good agreement for both small-scale and large-scale campaigns, and consistent with literature data related to underwater performance of RDX-based compositions [33, 34], giving us confidence in the experimental setup and the recorded results. As expected, P_{max} for the 100 g and 1 kg, respectively at 1.5 m and 3 m standoffs, are within the same order of magnitude as they have been

measured at comparable scaled distances (3.23 vs 3 m/kg^{1/3}). Considering the 8 to 150 g C4 charges fired at 2 m depth, the linear regression (Figure 10) of experimental first pulsation periods against the cubic root of the explosive mass is in good agreement with Reference [35] where 95% RDX charges (6 to 10 g) were detonated at the same depth.

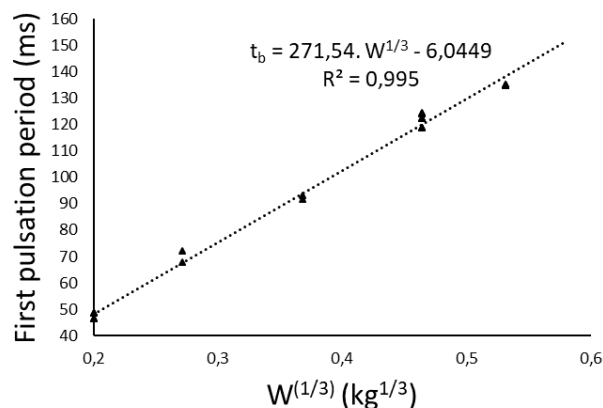


Figure 10. 8 to 150 g C4 (1.63 g/cm³) – experimental first pulsation period at 2 m depth.

On the other hand, UHP experimental data for equivalent shock energy ($E_{s, equ}$) differ significantly from the Autodyn simulation, particularly at small scale (Table 4). Even if the numerical predictions for P_{max} for the 100 g (8.12 MPa) and 1 kg charges (8.70 MPa) are in good agreement as they are calculated at comparable scaled distances, this scaling is not observed experimentally (5.67 MPa vs 8.21 MPa) and suggests that strong non-ideal effects affect the detonation of the 100 g charge. However, the numerical values from Autodyn for UHP should also be treated with care, as the JWL coefficients used in the model and calculated from Explo5 have not been validated experimentally, which would require large-scale cylinder expansion testing [36]. Further investigations would also be required to first characterise the actual detonation regime of UHP at small scale, and assess its non-ideality. Considering the rather small charge radius (35 mm) and the absence of confinement, the detonation of the 100 g UHP charges in this configuration may have not achieved a steady state. UHP experimental performance parameters are however somehow closer to numerical predictions when considering the 1 kg charges, especially for P_{max} . The experimental equivalent shock energy is about 50% of the numerical prediction. This difference between experiments and simulation could hence be attributed to the non-ideal behaviour of UHP in these conditions, to the limited accuracy of the model, taking into account UHP specific detonation products discussed in section 3.1, or to a combination of both.

The 1 kg charge with a larger charge radius (70 mm), the mass being limited by the actual experimental setup, is therefore considered as more suitable to characterise the UHP detonation performances, which could be compared to C4. However, the equivalent shock and bubble energies of UHP available in Table 4 have been calculated for a 1 kg UHP charge and a 60 g C4 booster, while the 1 kg C4 did not require any booster. Assuming additivity effect [24], we subtracted the relative contribution of the 60 g C4 booster from the equivalent shock ($E_{s, equ}$) and bubble ($E_{b, equ}$) energies of UHP (Table 4) in order to compare identical explosive quantities and derive TNT equivalences (Table 5). Using literature data [37] for TNT first pulsation period, we obtain a 50% TNT equivalence for bubble energy (explosive power). When it comes to shock pressure, we eliminate the contribution of the booster and calculate a 14% equivalence with respect to C4. Using a 1.3 TNT equivalence for C4, consistent with literature data related to underwater shock performance of RDX-based compositions [33, 34] and calculated from the ratio of the respective estimated detonation pressures [7] (section 2.1), which best characterise the shattering effects [16] of explosives, we derive an estimated maximum 20% TNT equivalence for brisance for UHP. As expected for explosives detonating at a lower regime, the TNT equivalence of UHP for brisance is rather low.

Table 5. Underwater Firings – TNT equivalences (%).

Charge	Brisance	Explosive Power
1kg UHP	20	50

3.4 Detonation Performance Assessment

Integrating all the results obtained from different experimental approaches presented above, we were able to characterise the detonation performance of UHP:

1. As expected for an energetic material detonating at a rather low regime, the brisance of UHP, its destructive fragmentation effect on its immediate vicinity [38], has proven weak (20%) when compared to conventional explosives. A good level of agreement was found between TNT equivalence from underwater shock energy and TNT equivalence based on detonation pressure calculated from VoD, either in the lab or in the field. Future work should enable us to further correlate these results to the brisance determined by indirect measurement of the detonation pressure.
2. UHP explosive power is rather limited (50%) as demonstrated by TNT equivalence based on underwater bubble energy or TNT equivalence based on airblast characteristics (long distance

blast wave), which have proven consistent and in good agreement with the 57% (PI) calculated from Explo5.

The validity of the small-scale setups used to characterise detonation parameters has been investigated. VoD measurements carried out in the lab are consistent with results from the field (95%). Further improvements might include optimisation of charge geometry and reproducibility of loading densities. When it comes to explosive power, the airblast data from the field are in good agreement with results from the kg-size underwater campaign, while smaller charges could not adequately describe large-scale steady behaviour.

4 Conclusion

We carried out a detailed performance assessment, combining experiments, thermochemical calculations and numerical simulations and highlighted a good level of agreement between experimental data from lab, field and underwater firings. A maximum detonation velocity of 3.65 km/s was recorded for unconfined 25 kg UHP charges at 0.85 g/cm³ (200 mm charge diameter). We determined in these conditions an infinite diameter detonation velocity of 3.94 km/s. These results are also consistent with previous results obtained at small scale under heavy confinement. Airblast measurements highlighted an average 40% TNT equivalence for impulse and 55% for peak overpressure at short (scaled) distance ($Z=2$), which are in good agreement with the 57% (PI) calculated from Explo5, while 50% for bubble energy (explosive power) and 20% for shock pressure (brisance) were obtained from underwater experiments. The use of different experimental approaches has proven useful to characterise the performances parameters of a non-ideal explosive for risk assessment purposes. Future work includes experimental measurement of UHP P_{det} to better assess its non ideal character and a detailed analysis of the accuracy of the related thermodynamic calculations.

Symbols and Abbreviations

ANFO	Ammonium Nitrate Fuel Oil
Bstr	Booster
D	Depth
$E_{b, equ}$	Equivalent bubble energy
EoS	Equation of State
$E_{s, equ}$	Equivalent shock energy
ID	Inner Diameter
JWL	Jones-Wilkins-Lee
L	(charge) Length
LASL	Los Alamos Scientific Laboratory
M	Mass
M-BKW	Modified Becker-Kistiakowski-Wilson
OD	Outer Diameter
PCB	PicoCoulomb
P_{det}	Detonation pressure
PI	Power Index
P_{max}	Side-on peak overpressure

PVC	Polyvinyl chloride
Q_{det}	Heat of Detonation
R	Range
RDX	Research Department Explosive
t_b	First pulsation period
T_{det}	Detonation temperature
TNT	Trinitrotoluene
UHP	Urea Hydrogen Peroxide
V_{gas}	Volume of gas
VoD	Velocity of Detonation
Z	Scaled distance

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