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Methodology for determining the initiating capabilities of detonators using an underwater explosion test
Metodyka określania zdolności inicjowania zapalników przy użyciu testu wybuchu podwodnego

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Abstract: *Currently, detonators are considered the initial source of detonation in almost all blasting operations. The possibility of developing and implementing many modern and innovative detonators into production requires conducting appropriate tests which will determine their safety in use or impact on the environment. It needs to be borne in mind that the explosive charge in a detonator, needs to be sufficient to provide an appropriate energy impulse to initiate the explosive material. In order to determine the initiating capability of detonators, an underwater explosion test can be used. Underwater detonation leads to rapid expansion of gaseous products, which results in the formation of a gas bubble which undergoes successive collapse. This article presents the methodology of an underwater explosion test based on testing carried out on selected detonators.*

Streszczenie: *Obecnie zapalniki są traktowane jako źródło inicjowania detonacji niemal we wszystkich operacjach strzałowych. Możliwość opracowania i wdrożenia do produkcji wielu nowoczesnych i innowacyjnych zapalników wymaga przeprowadzenia odpowiednich testów, które określą bezpieczeństwo użytkowania czy ich wpływ na środowisko. Należy mieć na uwadze, iż przy pobudzaniu ładunku niezbędne jest dostarczenie odpowiedniego impulsu energii, który zainicjuje dany materiał wybuchowy. W celu określenia zdolności inicjalnej zapalników można wykorzystać test wybuchu podwodnego. Podwodna detonacja prowadzi do uformowania pęcherza gazowego, w wyniku gwałtownej ekspansji produktów gazowych, który to ulega kolejnym kolapsom pod wpływem ciśnienia hydrostatycznego. W artykule przedstawiono metodykę testu wybuchu podwodnego na podstawie przeprowadzonych badań dla wybranych zapalników.*

Keywords: *underwater explosion test, initiating capability, detonator*
Słowa kluczowe: *test wybuchu podwodnego, zdolność inicjowania, zapalnik*

Symbols and abbreviations

E_B	Bubble gas energy equivalent [s^3]
E_{BW}	Bubble gas energy equivalence [J]
E_S	Shock energy equivalent [Pa^2s]
E_{SW}	Shock wave energy equivalence [J]
e	Euler's number
HMX	1,3,5,7-Tetranitro-1,3,5,7-tetrazocane (octogen)
PETN	Pentaerythritol tetranitrate (pentrite)
RDX	1,3,5–Trinitro-1,3,5-triazacyclohexane (hexogen)
p_{max}	Maximum pressure [MPa]
p_θ	equals p_{max}/e
t_b	Time interval between shock-wave pressure peak and first collapse of the gas bubble [ms]
θ	Time to reach p_θ [μs]

1. Introduction

The origins of the invention of detonators date back to the 18th century. The first mention of a detonator dates back to 1745, when British physician and apothecary William Watson proved that an electric spark from a friction machine can ignite black powder which has been mixed with a flammable substance [1-3]. Then in 1750, American scientist and inventor Benjamin Franklin contributed to the creation of a detonator in the form of a paper tube filled with black powder, with guide wires running through both sides and wadding sealing up the ends. His entire experiment consisted of a large electrical spark discharge between two wires which caused the detonator to fire [4]. Further, in 1832, an American chemist and professor, Robert Hare, constructed a hot wire detonator. The construction consisted of a multistrand wire passing through gunpowder inside a tin tube. The fine strand of multistrand wire served as a hot bridge wire which, when subjected to a strong current, became incandescent and ignited the gunpowder charge [5, 6]. In 1863 Swedish chemist, Alfred Nobel, conducted research on the detonation of nitroglycerine using a fuse. Unfortunately, the fuse itself did not initiate the detonation process of nitroglycerine. As early as 1864, Nobel had added mercury fulminate to the gunpowder based detonators [7]. In 1867 he used small copper shells, filled with pressed mercury fulminate and coupled with a fuse, which caused the nitroglycerine to detonate [8, 9]. In 1868, an American inventor, Henry Julius Smith, invented the first electric detonator combining a spark gap ignitor and mercury fulminate. To complete the historical review, in 1875 Smith and then in 1887 Perry G. Gardner, developed electric detonators which combined a hot wire detonator with mercury fulminate explosive [10-12]. Today, modern detonator design is based on the invention of Smith and Gardner.

Detonators are used to initiate the detonation of charges composed of secondary explosives [13-15]. Typically, a detonator consists of a copper or aluminum shell, inside of which, from the bottom, are successive layers of: high-density secondary explosive (e.g. PETN, RDX, HMX), low–density secondary explosive (e.g. PETN, RDX, HMX), a layer of primary explosive (e.g. lead(II) azide), all protected by a pressed aluminium cap. The shell is sealed with an initiation source – typically a detonation tube or a fuse head located inside a screwthread, which is permanently bonded to the shell in such a way as to ensure the integrity of the detonator. Triggering of the fuse head or detonating tube leads to the initiation of detonation in the primary explosive layer, which is transmitted to subsequent layers of the secondary explosives leading to the shock impact on the initiated charge [16-20].

Basic techniques for testing the initiating capability of detonators include: the lead plate test and the underwater explosion test. In the first case, it should be noted that it is a comparative test only, not providing high quality data and requiring the use of harmful lead [15].

During an underwater explosion, a gas bubble is formed by the gaseous products of the explosion, which expands until the process is inhibited by hydrostatic pressure at which point a collapse of the gas bubble

occurs, which generates another shock wave at the site (pulsation). This is followed by another pressure–limited expansion of the gas bubble and another collapse (Figure 1). This process strongly depends on the parameters of the explosive, the depth of immersion, the geometry of the charge and the parameters of the environment [21-34, 37].

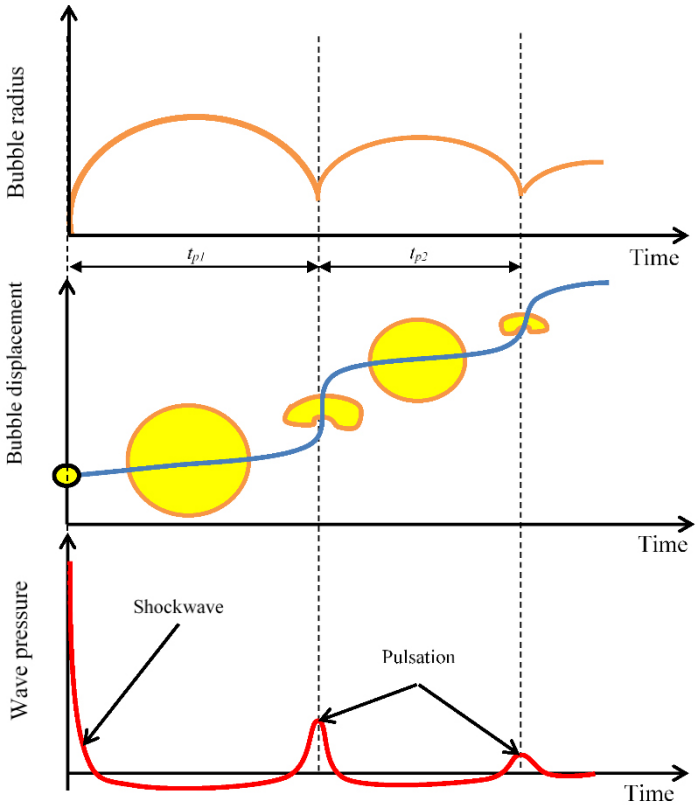

Figure 1. Changes of gas bubble radius, displacement and wave pressure during an underwater explosion (Reprinted from [37] under the terms and conditions of the Creative Commons 4.0 Attribution (CC BY) license.)

This article describes the methodology of the underwater explosion test as per the European Standard [35], and a presentation of the obtained results for detonators manufactured by Nitroerg S.A. (Bieruń, Poland).

2. Underwater explosion test methodology

The purpose of the underwater initiating capability test is to measure the pressure changes at a given distance, as a function of time. By measuring the pressure of the shock wave and pressure changes resulting from gas bubble collapse (the time interval between the first shock and the first collapse–related shock), the value of the output energy of the detonator can be determined.

The water tank should have a minimum capacity of 500 dm^3. The tank should be constructed of a robust and corrosion resistant material (e.g. stainless steel frame), at the same time, the design should take into account the prevention of the reflection of the shock wave from the wall, which could affect results (e.g. filling the walls with high–density polyurethane sheets to absorb the energy). A mounting frame is placed on the tank, which allows for the appropriate placement of the detonator and pressure sensor in the tank. According to

the standard, the distance between the sensitive element of the pressure sensor and the detonator should be 400 ±5 mm and both elements should be placed in the water at a depth of at least 400 ±5 mm, and not less than 200 mm from each of the tank walls. During the test, the environmental conditions must be taken into account. The water temperature must not change by more than ±2 °C, while the atmospheric pressure must not change by more than ±5 kPa.
First, reference detonators prepared in accordance with the afore-mentioned standard, are tested. In order to test the initiating capability of detonators, it is necessary to prepare 20 detonators of a specified type, which will be characterized by the same construction, i.e. casing made of the same material, the same appearance, quantity and type of both primary and secondary explosive charge. The detonators need to be mounted in the tank in the same way as the reference detonators.
The energy equivalence of a shock-wave (E_{SW}) is given by the following equation [21]:

$$E_{SW} = \frac{4\pi R^2}{\rho_w C_w} \int_{t_0}^{t_0+\theta} p^2(t)dt \tag{1}$$

where: E_{SW} – shock–wave energy equivalence [J], R – distance between detonator and pressure sensor [m], ρ_w – water density [kg/m^3], C_w – sound velocity in water [m/s], θ – time to reach p_θ [μs], p_{max} – maximum value of the pressure [MPa].
The gas bubble energy equivalence (E_{BW}) (in J) is given by the following equation [21]:

$$t_b = \frac{1.135 \cdot \sqrt[3]{E_{BW}} \cdot \sqrt{\rho_w}}{\sqrt[6]{p_h^5}} = \frac{1.135 \cdot \sqrt[3]{E_{BW}} \cdot \sqrt{\rho_w}}{\sqrt[6]{(g \cdot h \cdot \rho_w + 101.325)^5}} \tag{2}$$

where: t_b – time interval between the shock-wave pressure peak and the first collapse of the gas bubble [ms], ρ_w – water density [kg/m^3], p_h – total hydrostatic pressure [Pa], g – gravitational acceleration constant (9.81 m/s^2), h – immersion depth of detonator [m]. Equation 2 for constant measurement conditions can be simplified to Equations 3 and 4.

$$t_b = K1 \cdot \sqrt[3]{E_{BW}} \tag{3}$$

$$\frac{t_b}{K1} = \sqrt[3]{E_{BW}} \tag{4}$$

where:

$$K1 = \frac{1.135 \cdot \sqrt{\rho_w}}{\sqrt[6]{(g \cdot h \cdot \rho_w + 101.325)^5}} \tag{5}$$

The total output energy (E) in water is assumed as the sum of the E_{SW} and E_{BW} [21].

$$E = E_{SW} + E_{BW} \tag{6}$$

3. Materials and methods

The underwater explosion test was performed on two types of electric detonators, NITRODET 0,45A and ERGODET 0,2A WZI (produced by Nitroerg S.A., Bieruń, Poland). Details of these detonators are shown in Table 1. Reference detonators had been prepared and tested in accordance with [35] with the results reported in [36]. A schematic of the water tank used for the underwater explosion test is shown in Figure 2.

Table 1. Selected details of the test detonators (compiled from [38])

Parameters	Type of detonator	
	NITRODET 0,45A	ERGODET 0,2A WZI
Primary charge	lead(II) azide	lead(II) azide
Secondary charge	PETN	RDX
Ignition head resistance [Ω]	0.4-0.7	1.2-2.2
Actuation time [ms]	max. 10	max. 10
Shell	aluminium	copper
Wires	copper	steel

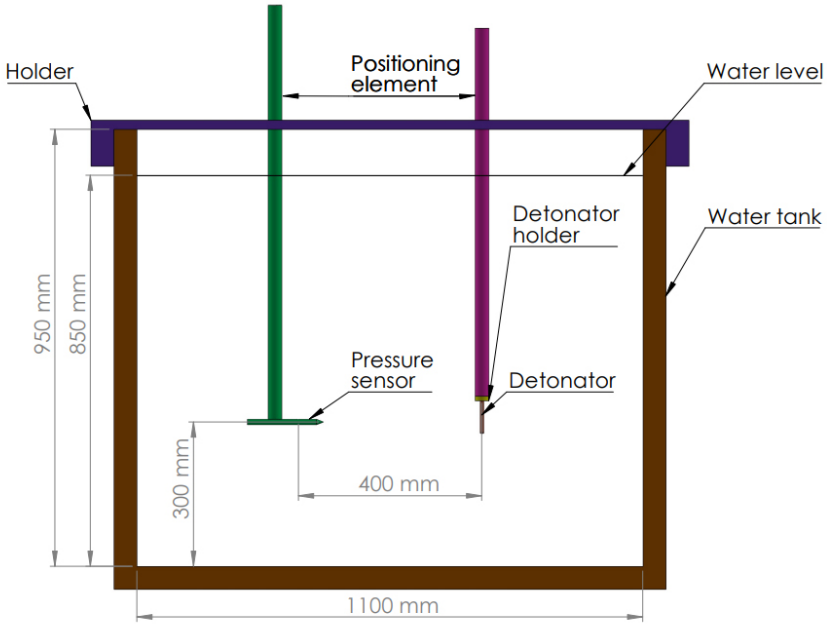

Figure 2. Schematic of the underwater explosion test set-up

The positioning stand for the detonators and pressure sensor was mounted on the tank. A tourmaline pressure sensor (PCB Piezotronics 138A10, sensitivity 73.15 mV/MPa, PCB Piezotronics, Depew, NY, USA) was used to measure the shock–wave in water and the second pressure peak related to the collapse of the gas bubble, and was placed 400 mm from the charge axis and 550 mm below the water surface. Sensor data were recorded using an AMC VIBRO CONDITION 8000D signal conditioner (AMC VIBRO, Cracow, Poland) coupled with a Textronic TBS2401B digital oscilloscope (Tektronix, Beaverton, OR, USA). The recorded waveforms were analyzed using OriginPro software 2024. The test conditions during the measurements were constant; the water temperature equal to about 19.5 °C, and the atmospheric pressure equal to 1029 hPa.

4. Results and discussion

Detonation of the tested charge in the underwater explosion test generated pressure waves in the water. The obtained signal was recorded on a digital oscilloscope, as the voltage change as a function of time ($U = f(t)$). Knowing the characteristics of the pressure sensor, the collected data was converted into a pressure-time relationship ($p = f(t)$). Based on the profile of the generated shock wave in the water, the maximum

pressure, p_{max}, was determined, as well as the moment at which the sensor signal dropped to a value equal to $p_\theta = p_{max}/e$. Additionally, the time between the pressure peak and the first collapse of the gas bubble, t_b, was established based on the obtained data. Figures 3 and 4 show examples of pressure-time outputs from which the above-mentioned parameters of the tested detonators were determined. The values of p_{max}, p_θ, θ, and t_b are presented in Table 2.

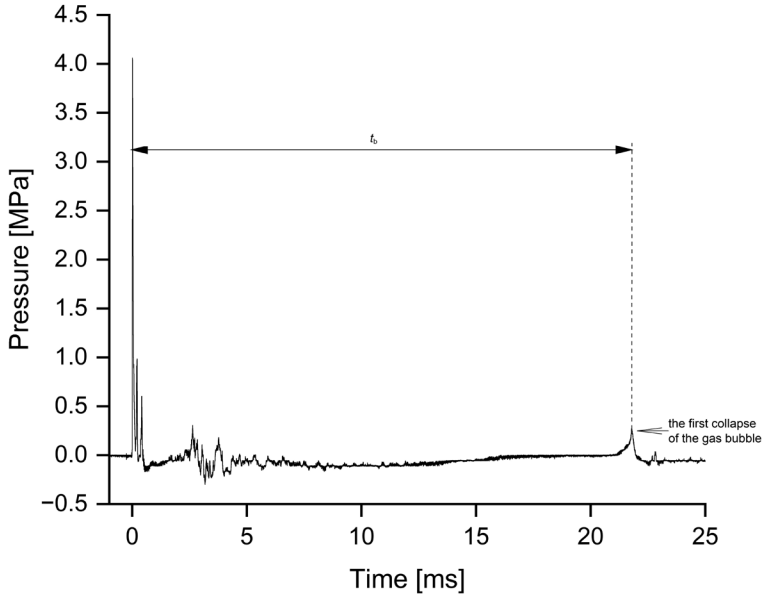

Figure 3. Pressure vs time of shock wave for NITRODET 0,45A detonator

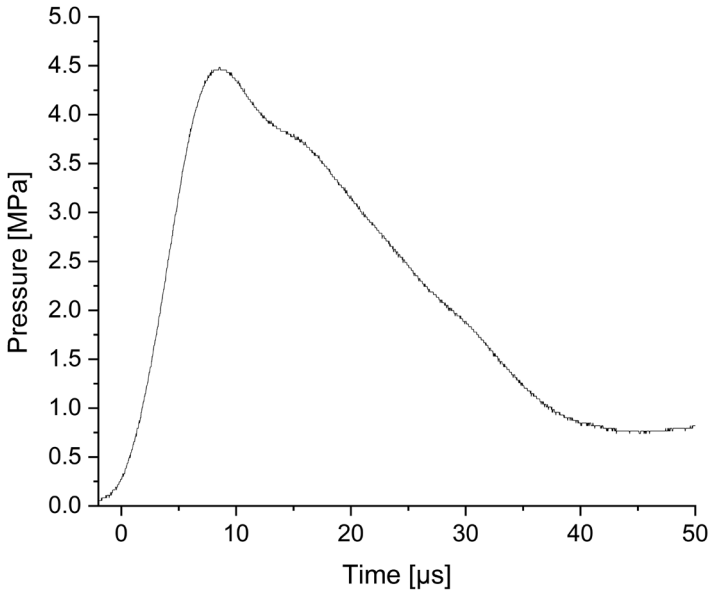

Figure 4. Pressure vs time of shock wave for ERGODET 0,2A WZI detonator

Table 2. Values of experimental shock wave parameters for the reference [36] and tested detonators

Detonator	p_{max} [MPa]	p_θ [MPa]	θ [µs]	t_b [ms]
Reference [36] (m_{PETN} = 600 mg)	9.67 ±0.34	ND	ND	21.21 ±0.11
NITRODET 0,45A	4.08 ±0.05	1.50 ±0.02	41.29 ±1.15	21.72 ±0.06
ERGODET 0,2A WZI	4.14 ±0.23	1.52 ±0.08	38.60 ±3.95	21.23 ±0.05

ND – no date

The reference detonators are characterized by the highest maximum pressure of 9.67 MPa. In contrast, the tested detonators, NITRODET 0,45A and ERGODET 0,2A WZI, achieved significantly lower average maximum pressure values compared to the reference detonator (41.8% and 42.4%, respectively). In terms of pressure decay time to the value p_θ, the results do not differ significantly from each other. This indicates that the shock waves generated by the detonation of NITRODET 0,45A and ERGODET 0,2A WZI have a similar nature, even though PETN is used as the secondary charge in the first detonator and RDX in the second.
The opposite trend is observed in the time of the first bubble collapse, where the t_b value for the reference detonator is close to the values obtained for the test detonators. The highest t_b was obtained for NITRODET 0,45A. On the other hand, the t_b values obtained for NITRODET 0,45A and ERGODET 0,2A WZI differ from the t_b for the reference detonator by no more than 3%.
The E_{SW}, E_s, E_{BW}, and E_B values were calculated based on the data recorded by the pressure sensor. The total energies were also calculated as the sum of shock wave energies and gas bubble energies for the tested detonators. The calculated results are presented in Table 3.

Table 3. Values of the calculated E_S, E_{SW}, E_B, E_{BW} and E for the reference and tested detonators

Detonator	E_{SW}, $\cdot 10^8$ [Pa^{2}s]	E_S [J]	E_{BW}, $\cdot 10^{-6}$ [s^3]	E_B [J]	E [J]
Reference [36] (m_{PETN} = 600 mg)	4.63 ±0.11	629 ±15	9.54 ±0.13	770 ±10	1399 ±16
NITRODET 0,45A	3.56 ±0.09	485 ±12	10.25 ±0.09	827 ±7	1312 ±17
ERGODET 0,2A WZI	3.43 ±0.23	467 ±31	9.57 ±0.66	772 ±5	1239 ±36

The highest shock wave energy value was obtained for the reference detonator (629 J). In comparison, the NITRODET 0,45A detonator (77.1% of the reference detonator's value) and ERGODET 0,2A WZI (74.2% of the reference detonator) have similar E_{SW} values. In the case of gas bubble energy, the highest value was obtained for the NITRODET 0,45A detonator, which represents 107.4% of the reference detonator's value. However, the ERGODET 0,2A WZI detonator also has a higher E_{BW} value (100.3%) than the reference detonator, though the difference could be neglect. The total energy values obtained in the study are as follows: Reference (100.0%) > NITRODET 0,45A (93.8%) > ERGODET 0,2A WZI (88.6%). For the NITRODET 0,45A and ERGODET 0,2A WZI detonators, the contribution of shock wave energy to the total energy is 37.0% and 37.7%, respectively. In turn, the gas bubble energy for the tested detonators constitutes 63.0% and 62.3% of the total energy, respectively. The differences between the total energy values are not significant, and it can be surmised that the NITRODET 0,45A detonator possesses a higher relative work capacity than the ERGODET 0,2A WZI detonators.
The significant difference in the parameters of test and reference detonators is, most probably, related to the various masses of secondary and primary high-energy materials in each detonator. In the reference detonators, prepared in accordance with European standard [35] the mass of PETN was equal to 600 mg, whereas the mass of lead(II) azide was equal to 300 mg. In the tested detonators produced by Nitroerg S.A., accurate data for the high-energy materials contained in each detonator are not available. On the basis of the results, the authors suggest that the total amount of high-energy material is not higher than 300-400 mg per detonator.

5. Conclusions

This paper presents the methodology of underwater explosion testing based on tests performed on NITRODET 0,45A and ERGODET 0,2A WZI detonators. From the performed studies, the shock wave energy and gas bubble energy of the detonators were determined. Ultimately, this allowed the initiating power of the tested detonators to be estimated and their energetic parameters compared. The studies, conducted in accordance with European standard [35] led to the following conclusions:

- The underwater explosion technique can be used on a small scale to determine and compare the energetic parameters of different explosives.
- The underwater explosion test allows an assessment to be made of whether an explosive meets the prescripted requirements and whether they can be used as basic charges in detonators.
- The NITRODET 0,45A and ERGODET 0,2A WZI detonators demonstrated significantly lower maximum pressure values compared to those of the reference detonator, but the bubble collapse times were very close to the reference values.
- The tested detonators provided a lower shock wave energy than the reference detonator, but their gas bubble energy values were higher, which may affect their effectiveness in various applications.
- The NITRODET 0,45A detonator was characterized by a higher initiation power and relative work capacity than the ERGODET 0,2A WZI detonator.

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