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Initiation Strength of Detonators – Air Gap Test Method

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Abstract: The present paper describes a new method of Air Gap Test used for determination of initiation strength of detonators. Factors influencing initiation strength of detonators are stated. Results of the experiments performed at the Institute of Energetic Materials are summarized.

Keywords: detonator, Gap Test, initiation

Introduction

In general, the detonators are used as a source of shock wave to initiate detonations of other explosives, most often low explosives. When assessing the utility value of detonators, one has to evaluate their handling safety, stability, ignition sensitivity, water resistance etc. However, the most significant factor can be seen in their initiation strength (hereinafter I.S.; I.S.D. = initiation strength of detonator), i.e. the ability to bring to detonation a low explosive of certain sensitivity.

Standard detonators for a comparison of I.S. are being prepared at present. Weights of their secondary charges in the detonators are equivalent to the I.S. grade. Originally TNT was used as the secondary charge but it has been replaced by PETN nowadays.

It is well-known that the detonation proper of the detonator consists of:

1. Activation of the primary charge.
2. Transfer of detonation from the primary charge to the secondary charge of the detonator.

3. Stable detonation of the secondary charge.

When a detonator adjusted in an explosive material detonates, the explosive material is exposed to the action of detonation wave of the secondary charge of detonator, to a compression shock wave of detonation products of the secondary charge, and to that of destruction products of the metal shell of detonator. Hence there are three basic initiation mechanisms combined: the initiation by a compression shock wave due to the impact of a fast flying body – the initiation by the shock wave transferred into the explosive being initiated from the detonating secondary charge – the initiation by a detonation wave transferred into the explosive being initiated from detonation of another explosive. The combination of action of these three mechanisms is summarily called "reactive compression shock wave" (R.C.S.W.).

From the point of view of detonator construction the I.S. is affected by the following factors [1, 2]:

a) the detonator shell;
b) the secondary charge;
c) the effect of orientation of detonator.

Practically, the I.S. value is determined on the basis of the deformation and destruction effects produced on a defined type of material. The test methods can be direct or indirect [3-8]. The Barrier test (Gap test) [9, 10] (belonging among the direct methods) and breakdown test [11] (one of the indirect methods) are important from the point of view of the experiments realized in this paper. This paper deals with the evaluation of influence of the construction material of detonator shell, specifically we have studied the difference between aluminium and copper.

In practice, the axial and the lateral components of I.S.D. are summed up because the detonator, as an initiator, is inserted in the explosive. In order to quantify the individual components, it is necessary to adopt a method that evaluates them separately and thus enables determination of the dominating factor in I.S.D.

With this aim, a team of IEM began the I.S.D. measurements by means of Air Gap Test, and this method was (for evaluation of individual factors affecting I.S.D.) complemented by the breakdown test, measurements of detonation velocities of secondary charges, and measurements of parameters of air shock waves.

Experimental

We have used a modification of Air Gap Test which was developed at our Institute [12-15] (see below). Also breakdown test [11], measurement of detonation velocities [11] and measurement of parameters of air shock waves were used as the complementary (orientational) methods for solving the problem of the I.S.D.

Air Gap Test

In principle, the Air Gap Test is a modified Gap Test (Barrier Test) [9, 10]. This modified arrangement does not use the partition formed by poly(methyl methacrylate) plates (hence the partition is the air only), no primer particles being used either (hence the detonator tested is the donor and the explosive charge is the acceptor). Semtex 1 was used as the acceptor explosive: it was located in a plastic tube case of 20 mm inner diameter and 20 mm height. The weight of charge was not constant, ranging from 8.5 g to 9 g. Its density was approximately 1.43 g cm^{-3}. The explosive was taken from a single manufacturing batch, and its sensitivity to initiation by shock wave was verified by means of the Small Gap Test. It was found that the sensitivity slowly drops with time, but within comparable experiments in one time period the relative informative value of measurement results remained unaffected. The results are presented in Table 1 [12-14].

Table 1. Results of measurements of Small Gap Test for Semtex 1A

Year of measurement	**1999**	**2000**	**2001**
Distance of 50% initiation, y_0 [mm]	16.50	17.90	12.45
Standard deviation, s_y [mm]	0.60	1.30	2.65

The measurement proper was carried out on an instrument devised at the IEM and made by Austin Detonator, Vsetín (Figure 1).

In the measurement of axial effect the detonator centre was directed to the centre of acceptor charge while in the measurement of lateral effect the centre of secondary charge was oriented towards the centre of acceptor charge. The quantity measured was the distance between the detonator and acceptor charge. This distance was adjusted with the help of insert gauges.

The values measured were treated by means of a statistical method (RUN DOWN) to give the mean value of $\mathbf{H_{50}}$ [mm] and standard deviation **s** [mm]. The application of this method necessitates that the values followed should exhibit normal distribution.

In this way, both axial and lateral effects of detonators were evaluated.

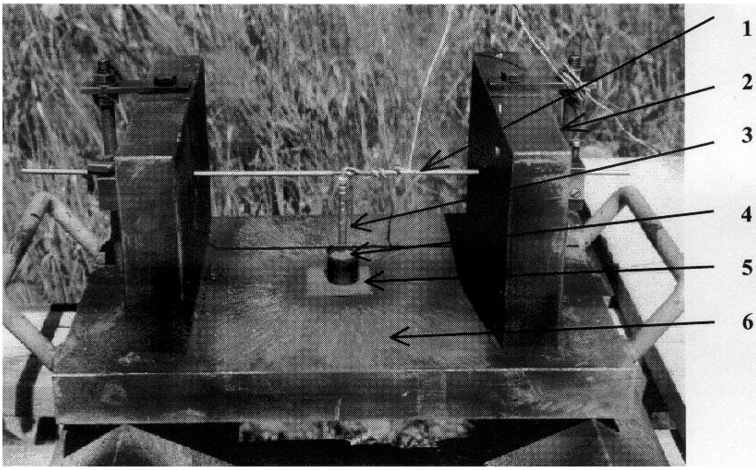


Figure 1. Measurement of I.S.D. – arrangement for axial effect. 1 – Fixation wire, 2 – adjustment of distance between the detonator tested and acceptor charge, 3 – detonator tested, 4 – acceptor charge, 5 – reference plate, 6 – instrument for I.S.D. measurements.

Breakdown Test

The Breakdown Test was realized according to the test described in Appendix 26 of Decree Czech Mining Office 246/1996 except for the thickness of reference plate. In our case the plate thickness was 6 mm and the material was lead of 99.5% purity with hardness H_B (10/100/60) = 3.5 to 5.5. The plate dimensions were 40 × 40 mm. The test was carried out on the same apparatus as that used for measuring I.S.

The bottom part of detonator is placed immediately on the reference plate, and after firing the diameter of hole (Diameter [mm]) and the amount of material torn out from the reference plate (M [g]) are evaluated. The results are presented in Table 2.

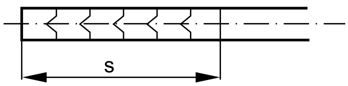
Measurement of detonation velocities

The detonation velocities were measured in the same way as that used for measurements of detonation velocities of low explosives (time method [11]). The arrangement only differed in the dependence on the type of detonators measured. The values obtained (D [m s^{-1}]) are given in Table 2

In order to eliminate the error resulting from the short length of the secondary charge of detonators, we prepared detonators in which six doses of secondary charge were pressed (Figure 2).

For measuring the detonation velocity of commercially produced detonators the arrangement used was modified. The detonator was fixed in the apparatus for measurement of the Air Gap Test, the start sensor was wound around the detonator several millimetres from the point of beginning secondary charge, the stop sensor was placed on the steel reference plate and the detonator was pressed on it by its bottom.

WS-Cu



NP2, 6 × 0.3 g

140 kg pc^{-1}, s = 36.4 mm

d = 1.58 g cm^{-3}

220 kg pc^{-1}, s = 35.5 mm

d = 1.63 g cm^{-3}

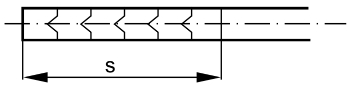
D^{140} = 7755 m s^{-1}

D^{140} = 1092 m s^{-1}

D^{220} = 7881 m s^{-1}

D^{220} = 1180 m s^{-1}

WS-Al **scale 1:1**



NP2, 6 × 0.3 g

140 kg pc^{-1}, s = 36.3 mm

d = 1.59 g cm^{-3}

220 kg pc^{-1}, s = 36.03 mm

d = 1.60 g cm^{-3}

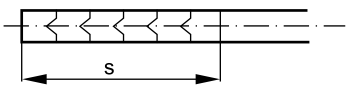
D^{140} = 8046 m s^{-1}

D^{140} = 461 m s^{-1}

D^{220} = 8369 m s^{-1}

D^{220} = 326 m s^{-1}

BL-Cu



140 kg pc^{-1}, s = 36.45 mm

d = 1.58 g cm^{-3}

220 kg pc^{-1}, s = 36.3 mm

d = 1.59 g cm^{-3}

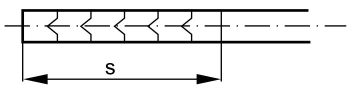
D^{140} = 7521 m s^{-1}

D^{140} = 139 m s^{-1}

D^{220} = 7730 m s^{-1}

D^{220} = 525 m s^{-1}

BL-Al **scale 1:1**



140 kg pc^{-1}, s = 36.40 mm

d = 1.58 g cm^{-3}

220 kg pc^{-1}, s = 35.9 mm

d = 1.60 g cm^{-3}

D^{140} = 8126 m s^{-1}

D^{140} = 638 m s^{-1}

D^{220} = 8276 m s^{-1}

D^{220} = 277 m s^{-1}

Figure 2. Preparation of column of secondary charge for measuring the detonation velocity. Weighing Np 2, 6 x 0.3 g, WS-detonator, BL-detonator.

Measurement of the parameters of air shock waves

The measurement of parameters of air shock waves was made in a shock tube of 210 mm diameter (in VVÚU Ostrava-Radvanice) and in free air (in the test facilities of the IEM). In the former case, the detonator tested was placed at the beginning of the shock tube and made to detonate. The distances of sensors (piezoelectric, Kistler) from the beginning of shock tube were 6.25, 8.75 and 11.25 m. The signal from sensors was led *via* an amplifier to oscilloscope, where the data were stored and subsequently treated by means of a special program. The most distinct record was obtained from the sensor nearest to detonator front (5.25 m).

The measurement in open air was based on the same principle. The sensors (piezoelectric, Kistler) were placed at the distances of 3 m and 5.2 m from the detonating detonator. The sensors and the detonator were located in the same plane. The mean values of the measured quantities p_{max} [kPa] and I [Pa·s] obtained from the sensors placed at 6.25 m (VVÚU Ostrava) and 3 m (IEM) from detonator are presented in Table 2.

Test initiators

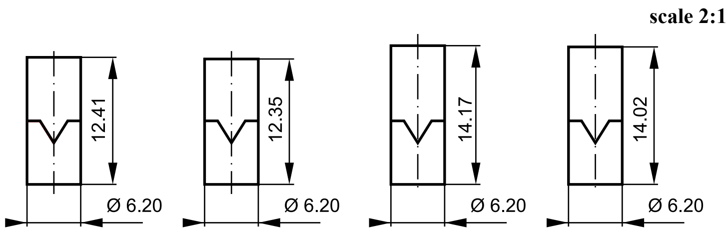
Whole-shell detonator (WS-Al, WS-Cu)

The aluminium (Al) and copper (Cu) shells, degree 0 of electric initiators (Austin Detonator, Vsetín) were filled with 2 × 0.3 g Np 2 (a low explosive material based on pentrite phlegmatised with 2% wax), each portion being pressed by means of a hand-operated press at 140 kg/ks (48.2 Mpa) or 220 kg/ks (76 Mpa). The material Np 2 was chosen because of the possibility to press on independent bodies of secondary charge.

The initiation element (a metal cup with lead azide and Np) was pressed on the pre-pressed secondary charge.

Shell-less detonator (SL-Cu)

The bodies of secondary charge were prepared at the same conditions of pressure and weight (the 6.20 mm diameter corresponds to the inner diameter of detonator shell). The resulting values were 1.55 and 1.66 g cm^{-3}, respectively (Figure 3). Subsequently, the initiation elements were stuck on these bodies.



NP 2.2 × 0.3 g	NP 2.2 × 0.3 g	NP 2/Al 2 × 0.3 g + 0.1 g Al 14.3% Al	
140 kg pc^{-1}	220 kg pc^{-1}	140 kg pc^{-1}	220 kg pc^{-1}
d = 1.55 g cm^{-3}	d = 1.61 g cm^{-3}	d = 1.60 g cm^{-3}	d = 1.65 g cm^{-3}
D = 7678 m s^{-1}	D = 7886 m s^{-1}	D = 7052 m s^{-1}	D = 7306 m s^{-1}
ΔD = 247 m s^{-1}	ΔD = 121 m s^{-1}	ΔD = 197 m s^{-1}	ΔD = 377 m s^{-1}

Figure 3. Pressing of bodies of secondary charge for shell-less detonator.

Shell-less detonator with aluminium (SL with Al)

Aluminium (14.3% Al Albo 90) was admixed to Np 2, the next procedure being identical with that used for the shell-less detonator.

Bottomless detonator (BL-Al, BL-Cu)

After cutting off the bottom of shell by means of a modified support mandrel, the pressing of charge was identical with that used for whole-shell detonator.

Other detonators tested

For comparison, the described tests were also applied to standard detonators No 3 and No 8 with TNT as secondary charge, industrial ignition detonator No 8 Al type II (produced by Sellier & Bellot, a.s., Vlašim), and detonators Nonel Surface 0.2 g Np, No 6, and Nonel Indetshock 0.72 g Np, No 12 (produced by Austin Detonator, a.s., Vsetín).

Results and Discussion

An initiation of explosive by a detonator that is inserted in it or placed immediately near to it represents a complex process involving effect of shock wave, of expanding products and effect of fragments of the detonator shell. With regard to the test methods adopted, the following parameters of a detonator were varied:

Orientation: axial, lateral.

Shell type: whole shell, shell-less, copper, aluminium.

Pressure used for pressing the secondary charge: 140 and 220 kg/ks.
Admixture of Al in the secondary charge body of shell-less detonator.

The explosion transformation of secondary charge is finished within 1.5-1.7 μs, and the detonation wave together with the pressure of products cause an increase of shell body from initial R_0 to $2R_0$ along the secondary charge. After exceeding the strength limit, the initial velocity of shell fragments is proportional to the detonation velocity of the secondary charge and to the ballistic ratio [16]. It can be presumed that the shock wave separates from the reactive wave (from detonation products) at about 10-14 multiple of charge diameter. Before this limit, the measured distances of Air Gap Test describe the action of reactive compression shock wave.

There is no large difference between the temperature coefficients of copper and aluminium ($a^{Cu} = 1.14$ cm^2 s^{-1}, $a^{Al} = 0.99$ cm^2 s^{-1}). At the conditions of contact of the shell metal with the detonation products (t ~ 2500 °C) it is possible to presume an initial reaction of aluminium with the detonation products and with air oxygen.

The values of p_{max}, I^+ and I^- measured for the shell-less detonator with aluminium, as compared with those of the whole-shell aluminium detonators, are only slightly higher, which supports the presumption about the exothermal reactions of aluminium predominantly outside the detonation wave. An admixture of 14.3% Al to Np 2 is unable to completely react in the detonation wave and decreases the detonation parameters (the detonation velocity drops by 500-700 m s^{-1}).

The bottomless detonators exhibit an increased lateral effect when I.S.D. is measured by the Air Gap Test, as well as a larger breakdown of lead reference plate in the breakdown test.

The markedly lower transfer distance in axial effect of Air Gap Test (comparable with those of shell-less detonator) proves a positive effect of particles of the metal bottom of detonator shell upon I.S.D.

Still another conclusion can be made from the results of the measurements made by the Air Gap Test: The lateral effect of both whole-shell and bottomless detonators is always higher than the axial effect. In the lateral effect, the amount of fragments from the part detonator shell, which is oriented to the acceptor, is higher, and so it can be presumed that the probability of occurrence of fragments with velocities $v > v_{crit}$ will be higher.

Table 2. Results of tests with the test initiators mentioned

Detonator tested	Air Gap Test H_{50} [mm] s [mm] Axial effect	Air Gap Test H_{50} [mm] s [mm] Lateral effect	Break-down test M [g] Diameter [mm]	Det. velocity D [m s^{-1}]	VVÚU Ostrava Sensor 6.25m P_{max} [kPa]	VVÚU Ostrava Sensor 6.25m I^+ [Pa·s]	IEM Sensor 3.00m P_{max} [kPa]	IEM Sensor 3.00m I^+ [Pa·s]
WS-Al (2 x 0.3 g Np 2.140 kg/ks)	15.8 1.0	32.4 8.24	1.08 5.07	8046	63.0	171.5	2.50	0.62
WS-Al (2 x 0.3 g Np 2.220 kg/ks)	18.2 2.4	31.2 3.92	1.2 6.77	8369	71.4	164.3	2.26	0.56
WS-Cu (2 x 0.3 g Np 2.140 kg/ks)	10.2 2.32	25.2 2.99	2.07 10.35	7755	35.2	61.8	2.25	0.43
WS-Cu (2 x 0.3 g Np 2.220 kg/ks)	10.6 1.50	28.8 5.31	2.58 11.67	7881	35.6	62.3	2.11	0.45
SL-Cu (2 x 0.3 g Np 2.140 kg/ks)	statistical treatment was not possible		1.48 7.1	7678	52.9	105.2	2.42	0.62
SL-Cu (2 x 0.3 g Np 2.220 kg/ks)	3.8 1.0	not eva-luated	1.55 7.63	7886	59.6	109.7	2.43	0.48
SL with Al (2 x 0.3 g Np 2.140 kg/ks)	not evaluated		1.18 5.21	7052	73.1	154.7	2.83	0.74
SL with Al (2 x 0.3 g Np 2.220 kg/ks)	not evaluated		1.28 5.48	7306	73.3	151.3	2.84	0.68
BL-Al (2 x 0.3 g Np 2.140 kg/ks)	not eva-luated	35.6 9.76	1.8 8.5	8126	62.5	165.7	2.19	0.62
BL-Al (2 x 0.3 g Np 2.220 kg/ks)	3.8 0.98	34.4 11.2	2.23 10.35	8276	69.4	163	2.45	0.61
BL-Cu (2 x 0.3 g Np 2.140 kg/ks)	not eva-luated	28 7.6	2.85 12.97	7521	42.3	72.7	2.23	0.51
BL-Cu (2 x 0.3 g Np 2.220 kg/ks)	not eva-luated	32 8.76	3.05 12.95	7730	40.2	72.7	2.13	0.50
Standard detonator No 3 (Cu)	3.8 2.72	not eva-luated	0.9 without breakd.	5385	20.8	22	1.42	0.23
Standard detonator No 8 (Cu)	not evaluated		1.4 5.22	5692	41.7	62.2	2.01	-
Ind. ign. detonator No 8, Al type II.	21.1 3.5	15.9 4.52	1.3 4.3	7276	87.1	205.7	2.82	0.64
Nonel Surface 0.2 g Np, No 6	7 1.26	3.4 0.8	0.69 1.68	9408	not measured		not measured	
Nonel Indetshock 0.72 g Np, No 12	not eva-luated	67.8 2.04	1.62 6.88	9342	not measured		not measured	

The grater I.S. value of aluminium detonators (WS and BL, lateral effect) can be interpreted by a higher velocity of fragments of the aluminium shell. This presumption can be supported by calculation. The calculation of velocities of fragments from whole-shell aluminium and copper detonators starts from the ballistic ratios $B_{Al} = 0.64$ and $B_{Cu} = 1.49$ and, furthermore, from the Gurney constant (1) or by introducing the detonation velocity for a particular density (2):

The Gurney constant for Np 2 was calculated with the help of parameter Φ, and then from Ref. [17]: it follows that $\mathbf{v_g^{Al} = 2508\ m\ s^{-1}}$ and $\mathbf{v_g^{Cu} = 1897\ m\ s^{-1}}$.

According to Ref. [18] for ρ = 1.58 g cm^{-3} (which is an average value for the pressures of 140 and 220 kg/ks) it is then $\mathbf{v_g^{Al} = 2259\ m\ s^{-1}}$ and $\mathbf{v_g^{Cu} = 1956\ m\ s^{-1}}$.

Hence, from the given facts it follows that the I.S.D. value made by the Air Gap Test method is substantially affected by the fragmentation effect of decomposition of the metal shell of detonator and by the number and velocity of fragments accelerated by the detonation products.

The results obtained with the industrial detonators mentioned in the paragraph Other Detonators and their comparison with standards (the normalised detonators No 3 and No 8), Sellier & Bellot, a.s., Vlašim and detonators Nonel, (Austin Detonator, a.s., Vsetín) indicate high quality of the commercially produced detonators.

Conclusion

The following conclusions can be drawn from the experiments conducted and discussion:

Breakdown Test

- This test is not distinctly affected by the value of pressure of press.
- Comparison of the individual detonator types (WS, BL, SL) shows higher values of the quantities monitored only in the case of BL detonator.

Measurement of detonation velocities

- As for the shell material, the Al-shell detonators exhibit higher detonation velocities than the Cu-shell detonators.

Measurement of air shock waves

- The effect of press pressure on the secondary charge upon the values of $\mathbf{P_{max}}$ and $\mathbf{I^+}$ was only observed with detonators WS-Al, SL-Cu, BL-Al.

- The Al-shell detonators measured in shock tube exhibit higher values of $\mathbf{P_{max}}$ (in the range of 13-36 kPa) and $\mathbf{I^+}$ (in the range of 90-110 Pa·s) than the Cu-shell detonators in all the cases of specially prepared detonators.
- The values of $\mathbf{P_{max}}$ and $\mathbf{I^+}$ decrease in the series of detonators: SL with Al, WS-Al, BL-Al, SL-Cu, BL-Cu, WS-Cu (measured in shock tube).
- The values of $\mathbf{P_{max}}$ and $\mathbf{I^+}$ measured on free surface decrease in the series of detonators: SL with Al, WS-Al, SL-Cu, BL-Al. The values of $\mathbf{P_{max}}$ and $\mathbf{I^+}$ of detonators WS-Cu and BL-Cu are, in average, identical.
- The measurements on free surface were basically of preliminary nature.

Air Gap Test

- The detonators pressed at 140 kg/ks exhibit lower or almost identical axial and lateral effects.
- Al-shell detonators exhibit, on average, 5.3 mm higher axial and lateral effects as compared with Cu-shell detonators. The magnitude of both axial and lateral effects depends on the shell material.
- The magnitude of lateral effect of bottomless detonators (BL) compared with that of whole-shell detonators (WS) is higher by 3.1 mm on average.
- Addition of aluminium to the secondary charge (SL with Al) lowers I.S.
- Axial and lateral effect of shell-less detonators (SL) exhibits a small transfer distance. At the given experimental conditions, the evaluation of $\mathbf{H_{50}}$ was only possible in a single case. This fact fully confirms the effect of detonator shell, as packaging and source of fragments, upon the I.S. value of detonator measured by means of Air Gap Test.
- These conclusions are also supported by the values of initial velocities of shell fragments calculated according to Gurney's approximation:

  $\mathbf{v_g^{Al} = 2508\ m\ s^{-1}}$, $\mathbf{v_g^{Cu} = 1897\ m\ s^{-1}}$ [17]

  $\mathbf{v_g^{Al} = 2259\ m\ s^{-1}}$, $\mathbf{v_g^{Cu} = 1956\ m\ s^{-1}}$[18].

The detonators listed in the set of "Other detonators tested" were measured by the methods given only for comparison. All the conclusions given are in accordance with the theoretical premises.

The Air Gap Test appears suitable for evaluation of equivalent I.S. It provides well-reproducible results, is simple in principle and is not expensive. A certain drawback can only be seen in its higher time demands.

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