Initiation of Explosives by Ultrasonics*

C. O. Leiber, Institut für chemisch-technische Untersuchungen
(CTI), Bonn, W-Germany

Summary: Explosives may be initiated by ultrasonics of proper frequency range and sufficient intensity. Papers concerning this field are cited and the different results may be understood by considering the interaction of the bubbles with the surrounding medium, only possible within a frequency range defined by the cinematic viscosity of the surrounding medium and the diameter of the bubbles. The eigenfrequency of the explosive container and the frequency of initiation are the coupling members between explosive and confinement important in respect to safety consideration. Also the impact sensitivity varying with the diameter of the bubbles may be understood in these terms.

In Germany (FRG) permitted explosives must show a transmission of detonation of at least 3 cm in a confinement similar to practical conditions. As such approximations of practical confinements for testing this, coal/concrete mortars 2/1 and 20/1 are used representing inclusions and borc holes of different strength[1].

At Berggewerkschaftliche Versuchsstrecke, Dortmund-Derne, an experimental arrangement according to fig. 1 had been established for proofing this condition. Since such mortars are expensive and a lot of waste arise after experiments, a belgian institution[12] suggested to use a steel tube of proper dimensions for such tests. These tubes are for repeating use. In fig. 2 this steel tube arrangement is shown. The dimensions of it had been altered until the results matched for one fixed type of explosive (class III permitted explosive in W-Germany).

It must be suggested that this method isn't applicable for explosives in general, since their detonation velocity of 1,500 to some thousond m/s is less or may be less than the shock, respective sound velocity in steel of about 5,000 m/s. According to this the receptor "knows" about the initiation of the donor just before the detonation front travelled to it, as the following experiment proofes:

Enlarging the distance D between the cartridges from a maximal distance no detonation of the second cartridge occured. But introducing in the mid of the tube a tight closing loam plug, detonation of the second cartridge occured again, even by enlarging the maximal distance D. Precautions had been taken to prevent possible initiations by impact of loam particles. Finally the detonation transfer failed by axial isolation of the second cartridge by soft materials like absorbent cotton. In this case

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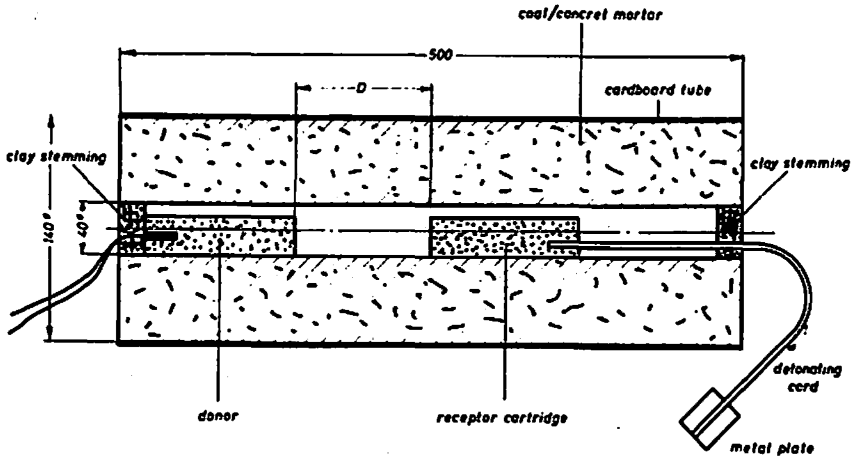
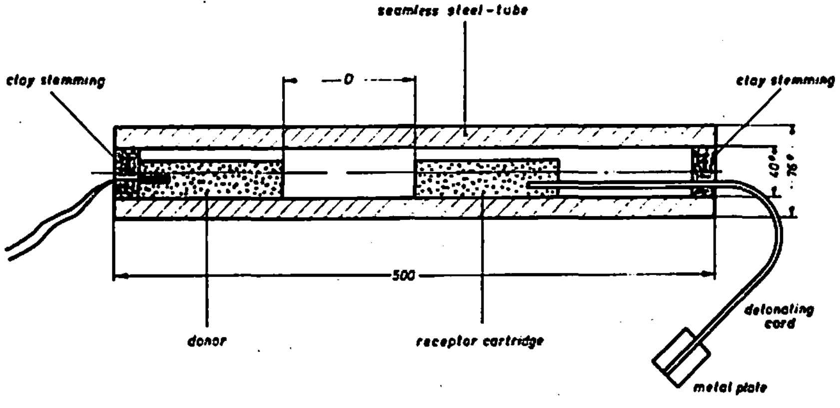
* Improved version of Explosivstoffe 19 (1971) 153-161



Dimensions in mm.

Fig. 1 Coal/concrete mortar for determination of the transmission of detonation according to Berggewerkschaftliche Versuchsstrecke, Dortmund-Derne[1].



Dimensions in mm.

Fig. 2 Seamless steel tude arrangement for determination of the transmission of detonation similar to[12]. The difference to the original is the stemming at the ends, as common in Germany, see fig. 1.

no direct contact between the inside surface of the tube and the outside surfaec of the cartridge had been possible.

According to this it is assumed that radial vibrations of the steel-tube are responsibel for initiation.

Acoustic vibrations of the steel-tube (fig. 2)

G. S. Field[2] investigated the possible vibrations of a pushed rod. The result is, that the possible vibrations and modes are extraordinary numerous and complex. He observed bending vebrations with a lot of not harmonic overtones, longitudinal vibrations, plate vibrations (even for long rods similar to the tube according to fig. 2), and a constant vibration independent from the length of the rod. The frequencies of all vibrations didn't exceed 50 kc/s for an aluminium rod of 6.5 cm in diameter and 44 cm length. The frequencies of longitudinal and bending vibrations are below 30 kc/s. He found that the vibrations are very sensitive to the condition of excitation.

According to the condition of excitation in fig. 2 it is assumed that a longitudinal vibration of the tnbe is not very reasonable. The possible frequencies of the bending vibrations of the tube (assumed as a rod, differences between rod and tube are small) are 250 c/s, 2.3; 6.3; 12.2; 20; 30; and 42k c/s or more. The frequencies are low and the vibrations are dampened by sand in this experiment.

According to the excitation of the tube by the inside detonating cartridge, one should expect intense radial modes. This could be checked by initiation of a secondary charge outside the tube.

G. S. Field[8] treated the case of radial modes of a tube with arbitrary wall thickness. For the radial frequencies f_i he obtaines

$$f_i = \frac{x_i}{2\pi r_1}\sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

with

E Youngs modul,
ν Poisson rate,
ρ density,
r_1 outside diameter,
r_2 inside diameter,
x_i order of vibration mode.

Introducing

$$m = \frac{1-2\nu}{1-\nu} \tag{2}$$

one obtaines x_i from the intersection of the functions F_5 and F_6:

$$F_5 = -\frac{xN_0(x) - mN_1(x)}{xJ_0(x) - mJ_1(x)} \tag{3}$$

$$F_6 = -\frac{\left(\frac{r_2}{r_1}x\right)N_0\left(\frac{r_2}{r_1}x\right) - mN_1\left(\frac{r_2}{r_1}x\right)}{\left(\frac{r_2}{r_1}x\right)J_0\left(\frac{r_2}{r_1}x\right) - mJ_1\left(\frac{r_2}{r_1}x\right)} \tag{4}$$

J_0 ( ) and J_1 ( ) are the Bessel functions and N_0 ( ) respective N_1 ( ) the Neumann functions of different order which are tabulated see for example[4].

In fig. 3 the functions F_5 and F_6 with $r_2/r_1 \approx$ o.5 (see fig. 2) and $m=0.572$ are plotted and one obtaines

$x_1 = 1.28$
$x_2 = 6.5$
$x_3 = 12.6$……

with equation (1) one obtaines for the radial eigenfrequencies

$f_1 = 1.28 \times 25.8 =$ 33.0[kc/s]
$f_2 =$ 167.7 kc/s
$f_3 =$ 325.1 kc/s……

According to the condition of excitation of the tube (see fig. 2) it is assumed that f_2 should be favoured because the initiated cartridge is eccentric probably causing more intense vibrations with one nodal plane. If so, in the nodal plane the maximum dynamic force is to be expected. After some experiments the steel tube had been destroyed and in fact the area of fracture had been in the center of the cylinder. It is therefore assumed that initiation of the second cartridge occured by intense vibrations of the frequency of about 170 kc/s.

Recent results about the initiation of explosives by ultrasonics:

W. T. Richards and A. L. Loomis[5] firstly are reporting in 1927 about such experiments. They had an ultrasouie generator producing 100 to 500 kc/s and 2 kVA **electrical** output. They reported that nitrogen iodide exploded by sufficient exposing to sonics and they failed detonating Ammonium nitrate.

N. Marinesco[6] found 1935 that ultrasonics of 1 Mc/s and an intensity of 5.8 W/cm² in the system detonated nitrogen iodide, crystalline silver fulminate and Berthollet powders on the basis of peroxides with and without perchlorates in the case that acoustic coupling between the oscillator crystal and the explosive

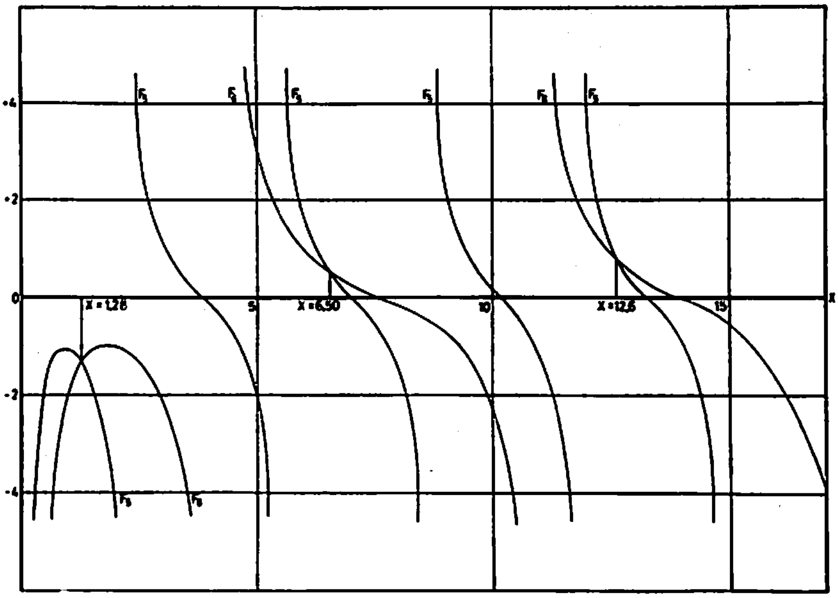


Fig. 3 Determination of x_i-values for the radial frequencies of the steel tube of fig. 2. x_i are given by the intersections of the functions F_5 and F_6 according to equ. (3) and (4)

had been performed by a not wetting inert liquid. If the substances had been pressed or had been submerged in paraffin oil, only nitrogen iodide and the shock sensitive Berthollet powder detonated since air had been absent. She didn't succeed in initiating nitrocompounds, even by overstressing the oscillator crystal.

But P. Renaud7) 1951 couldn't find any initiation by ultrasonics of 1 Mc/s and in the case of dynamite additionally at 20 kc/s, with an estimated acoustic intensity of the oscillator of about 100 W/cm². The investigated substances had been: mercury fulminate, cyanuric triazide, lead azide, nitroglycerine, diazocompound of m-nitroaniline, hexamethylenetriperoxidediamine (HMDT), gelatinous dynamite containing air bubbles between 0.1 and 1 mm diameter, lead picrate, ammonium picrate, and ammonium nitrate. The results of Marinesco he pointed out to be the effect of mechanical pushing by the oscillator, since the first 6 explosives listed above are very sensitive to mechanical treatment.

Some additional comments and investigations are cited in the monograph of F. P. Bowden and A. D. Yoffe8).

Further own experiments

Pure nitroglycerine, dynamite with bubbles of 0.1 to 1.5 mm diameter and a very sensitive explosive consisting of 90% rock salt and 10% NG/EGDN 60/40 had been treated with frequencies between 22 and 25 kc/s and an oscillator*) acoustic intensity of about 500 W/cm². Using an exponential horn of aluminium a good acoustic adaption to the explosive had been obtained, resulting in an acoustic intensity of about 220 W/cm² in the explosive.

Nitroglycerine didn't detonate in spite of the fact that it had been blackened by the experimental treatment, caused by abrasion

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* [Dr. Olaf from Bergbauforschung GmbH, Elssen-Kray] I am indepted to [ ] for making availabe his oscillator arrangement.

of the aluminium horn. Cavities had been formed by cavitation of about 1 to 2 mm diameter. Also the horn pushed to the bottom of the vessel containing thg nitroglycerine. The acoustic pressure had been about 33 bar.

The acoustic impedance had been similar in the case of dynamite and rock salt explosive. In no case a detonation had been observed in spite of the fact that during acoustic treatment of dynamite and salt explosive fumes were observed resulting from the burning. After experiment the salt had been sintered. No burning had been observed after removing of the oscillator. This result is due to the break down of acoustic coupling for the case of arising gases from burning. Only very small acoustic intensities may come into the system (about 10^{-4}W/cm^2 according to the acoustic impedance).

Assuming an adiabatic exponent κ of 1.4 respective 1.25 for an acoustic pressure of 33 bar a temperature of more than 500℃ respective 300℃ should be obtained resulting a thermal decomposition observed.

Discussion of the results:

According to the own experiments and the cited earlier investigations it is possible that initiation by ultrasonics may or may not occure, depending on the circumstances, such as exciting frequency, intensity, and structure of the explosive (bubbles).

According to a recently treated initiation model[9)10)] small bubbles in respect to the wave length show different behaviour whether they are fixed by viscous forces in the matrix or get a mobility in respect to the surrounding medium. This behaviour depends on Roth's number Ω.

$$\Omega = \frac{f}{f_g} = \frac{f}{\dfrac{3\eta/\rho_m}{2\pi R^2}} \qquad (5)$$

f frequency of sonic attack,

f_g characteristic frequency

R radius of the bubble

ρ_m density of the medium

η viscosity of the medium.

As shown[9)10)] an interaction of the bubble is possible to be mentioned for values of Ω between about 0.1 and 50, see fig. 4. The interaction is possible by the vibrations of the bubbles and their mobility in respect to the matrix and detonation may become possible.

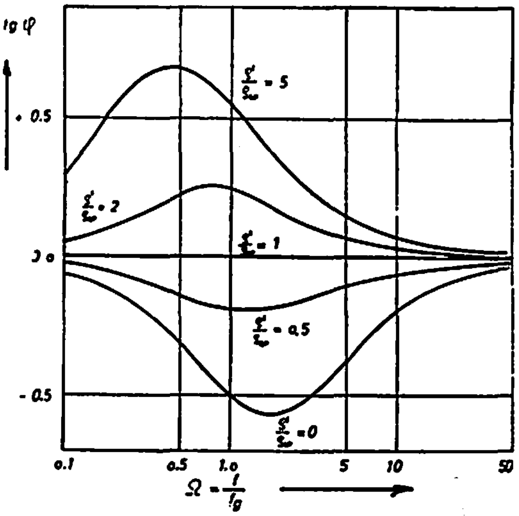

Fig. 4 Loss tangent tg φ for the interaction of a bubble with the surrounding medium as function of Roth's number Ω. Since the loss tangent for a bubble of zero density is negative, gains are obtained. Gains are realized by two-wave configuration. This means that the "bubble-wave" is a precursor to the stimulating frequency f with the phase angle $+\varphi$.

Assuming a consistence of roofing asphalt at 55℃ for dynamite and the salt explosive one may calculate with a kinematic viscosity of the order of 10^3 St. The viscosity of the salt explosive is not determined by the salt particles themselves but by their fluidity in respect to each other.

In tabel 1 for nitroglycerine and dynamite respective salt explosive the characteristic frequencies f_g and Roth's numbers are calculated as function of the radius R of the bubbles and the exciting frequency f. Moreover the wave-length assuming a sound velocity of about 2,000 m/s is noted. According to the assumptions $\lambda \gg R$ is realized.

Table 1

	Nitroglycerine			Dynamite, salt explosive		
Viscosity (P)	0.36					
Density (g/cm^3)	1.6					
kinematic viscosity (St)	0.225			$\sim 10^3$		
characteristic frepuency f_g (R in cm)	$0.108/R^2$			$\sim 500/R^2$		
(25kc/s) in cm	~ 8			~ 8		
(170kc/s) in cm	~ 1.2			~ 1.2		
f_g fūs $2R =$	f_g	Ω (25kc/s)	Ω (170kc/s)	f_g	Ω (25kc/s)	Ω (170kc/s)
1cm	0.43 c/s	58000	400000	2kc/s	12.5*	85
5mm	1.6 c/s	15500	100000	8kc/s	3.5*	21*
1mm	43 c/s	580	4000	200kc/s	0.13*	0.85*
0.5mm	160 c/s	150	1000	800kc/s	0.06	0.2*
0.1mm	4.3kc/s	6	40	20Mc/s	$1.3\ 10^{-3}$	$8\ 10^{-3}$
0.01mm	430kc/s	0.06	0.4	2Gc/s	$1.3\ 10^{-5}$	$8\ 10^{-5}$

* shows possible interaction

In fig. 4 the loss tangent, characterising the interaction of the bubble with the medium, as function of Ω is plotted for a bubble of zero density ρ'. According to fig. 4 and the numeric values of tabel 1 a reasonable interaction of the bubbles with the surrounding medium is possible only for bubble-diameters of about 0.1 to 0.05 mm in nitroglycerine (25kc/s), but the bubbles formed by cavitation had shown diametesr between 1 and 2 mm and no interaction had been possible of reasonable magnitude.

In the case of dynamite and salt explosive a weak interaction by 25 kc/s should be possible for the case of bubble-diameters of about 0.5 to 1 mm, but a strong one for 170 kc/s. This result of the outlined calculations agrees with experimental facts: Burning and sintering only during ultrasonic attack with frequencies of about 25kc/s, but detonation initiated by frequencies of about 170 kc/s.

The interdependence of the sensitivity of an explosive with bubble-diameter and the viscosity isn't new, J. F. Roth[11] 1966 had shown this for some systems by experiments. He filled some liquid explosives in bags by varying the amount of air in it. He got bags with bubbles of varying diameters in the liquid explosive and found a strong dependence of the critical impact energy by treating these in the falling weight test.

Taking as a measure for the exciting frequency the speed of fall of the weight, it is possible to introduce a relative Roth's number approximately. His results considered by this model are shown in fig. 5. Since the steepness of the impact depends on the amount of air in the bags, the exciting frequency cann't be considered constant, but one may see that the sensitivity of the explosive nearly depends on R^2 according to equation (5), assuming that reaction occures for a definite range of Ω.

Experiments had been done at Berggewerkschaftliche Versuchsstrecke, Dortmund-De-

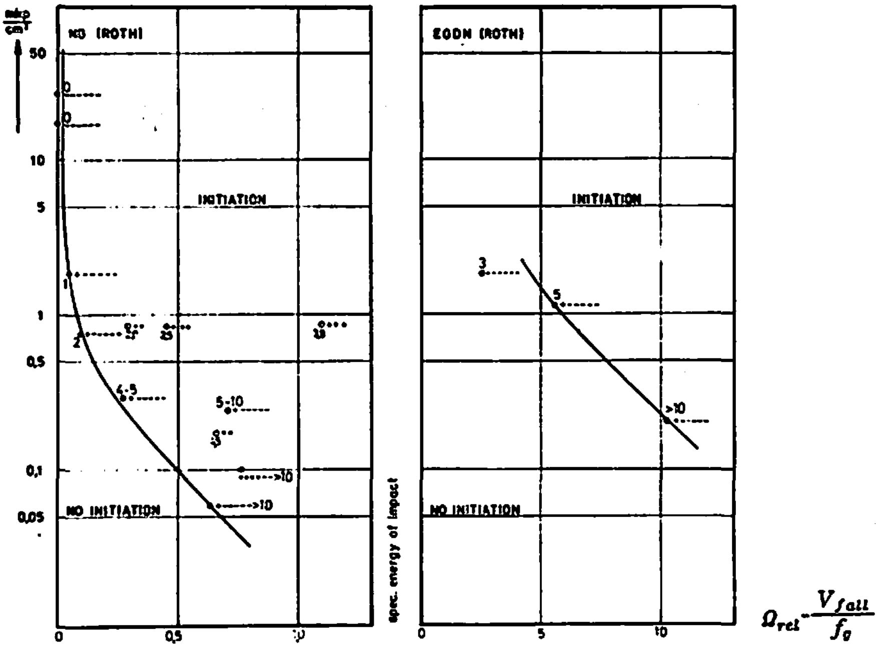

Fig. 5 Results of the falling weight test from Roth¹¹⁾. The numbers in the figure are the diametert of the bubbles in mm. The different markings of the results correspond to his two different experimental arrangements. The limit between initiation and no initiation had been defined here by 5 no initiations in 6 experiments.

rne. My collegues there and here I owe many interesting discussions and hints.

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