

EVALUATION OF THE PERFORMANCE OF EXPLOSIVES
BY UNDERWATER EXPLOSION.

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Summary

In order to evaluate the performance of explosives, an experimental set-up was installed at Vinterviken, Stockholm, at the beginning of 1972. Arrangements and measuring equipment are described, as well as an experimental method for determining the effect of water-container boundaries on the oscillation time of the gas bubble. With this method determination of the bubble energy becomes simple, even in cases where the effect exerted by the water-container boundaries is appreciable and difficult to calculate theoretically. The maximum pressure P_m , impulse density I , and shock wave energy E_S , in the water shock wave as well as the bubble energy E_B , can be determined accurately enough to serve as a good basis for predicting the performance of an explosive, e.g. in rock blasting. Control experiments with 100 g TNT balls yielded values of P_m , I , E_S and E_B in good agreement with those quoted by R H Cole /3/.

Introduction

When an explosive detonates under water, the main part of its energy is primarily released to the water as shock wave energy, and as energy in the oscillating system formed by the gases in the reaction products and surrounding water. Recordings of the period of oscillation (the bubble period) and the pressure-time profile in the direct water shock wave, enable us to determine the bubble pulse energy, as well as maximum pressure, impulse and energy in the direct water shock wave. These values yield information as for the energy of the explosive, and how quickly this energy was released.

1. Experimental

Charge and pressure gauge were suspended in a crane, which could be turned 90° to the quay edge as in Fig 1, which shows the arrangement in a section perpendicular to the quay edge. Charge and pressure gauge were placed 2,50 m below the surface, the pressure gauge being 2,00 m from the centre of the charge.

2. Recording equipment

On the whole, the recording equipment is in accordance with that used in /2/. The pressure gauge consisted of a 1/4" tourmaline crystal gauge, made by Crystal Research Corp, with a sensitivity of 28,2 pC/bar. Together with its coaxial cable type Amphenol 21541, the tourmaline gauge was attached to a supporting L-profile, 160 cm length, which was then attached to the crane with two 1 mm nylon cords. By this arrangement, the tourmaline gauge was kept at a distance of 2,00 m from the charge (see Fig 1). Cable length between gauge and charge amplifier was 42,5 m. The total capacitance of cable and gauge was 2735 pF.

The gauge was connected to a charge amplifier made by Kiestler, model 568. The amplifier was adjusted to give an output voltage of 0,01 volt/bar. According to the manufacturer, the frequency response is then almost flat from near direct current up to 150 kHz. A block diagram of the measuring equipment is shown in Fig 2.

The pressure-time profiles were recorded by two oscilloscopes with polaroid cameras. The oscilloscopes were of the type Tektronic 535, with sweep velocities of 20 $\mu\text{s}/\text{cm}$ and 200 $\mu\text{s}/\text{cm}$ respectively. The oscillation time of the gas sphere (the bubble periods) could be measured by recording the pressure-time curve separately on a UV-recorder made by SE-Laboratories. The paper velocity was chosen to 500 mm/s with time-marking of 100 Hz. In order to prevent the low impedance of the UV-recorder to load the charge

amplifier so much that the output voltage of the latter drops below the adjusted value, an impedance raising, damping arrangement (Fig 3) was connected in between charge amplifier and UV-recorder. The system was earthed by connecting the chassis of the charge amplifier to a copper plate submerged in the water.

3. Evaluation of the primary data

The recorded pressure-time profiles have the appearances shown in Fig 4. The first pulse to reach the tourmaline gauge originates from the detonation of the charge and has an amplitude of 90-170 bar in case of a 300 g charge. The high pressure gas sphere, formed after the detonation, expands rapidly, reaches a maximum and is then compressed to a minimum, followed by a new expansion and implosion, and so forth. Each minimum of the gas sphere is accompanied by emission of energy in the form of a pressure pulse in the water, which contributes to a gradual damping of the oscillations, while the gas sphere rises towards the surface because of its buoyancy. Recording of these pressure pulses will yield the oscillation time of the gas sphere (the bubble period), from which the bubble pulse energy E_B can be determined. Besides that, maximal pressure P_m , impulse density I , and shock wave energy E_S are determined from the direct water shock wave.

3a. The maximum pressure P_m

For the present experimental conditions, the direct water shock wave has a very steep front (rise time $< 1 \mu s$) to its maximum value P_m , after which, according to [3], the pressure near the front decreases:

$$P = P_m \exp(-t/\theta) \quad (3a.1)$$

where θ is the time constant.

The error in the recording of P_m can be divided into

- a. Error because of the extent of the tourmaline crystal.
- b. Error because of limitations in the high frequency response of the charge amplifier.

The relative response R_{P_m} of the tourmaline crystal for reproduction of the maximum pressure P_m because of errors according to a/above, will be

$$R_{P_m} = 1 - \frac{a}{c_o \theta} \quad (3a.2)$$

$$\text{where } \begin{cases} a = \text{radius of tourmaline crystal} \\ c_o = \text{sound velocity in water} \\ \theta = \text{time constant in the water pressure wave defined according to (3a.1)} \end{cases}$$

if, for example, $a = 4,5 \text{ mm}$, $c_o = 1,5 \text{ mm}/\mu\text{sec}$, and $\theta = 60 \mu\text{sec}$, we get $R_p = 1 - 4,5/1,5 \cdot 60 = 0,95$, that is, the value of P_m will be 5% too low because of the extent of the crystal.

The error in $b/$ can be determined, if the form of the pulse from the tourmaline crystal as well as the frequency response of the charge amplifier are known. For the equipment used in these experiments, we may expect it to give a P_m value which is too low, but the error will be smaller than that in $a/$.

The real maximum pressure has been determined by plotting $\log P$ as a function of t from the oscilloscope recordings (Fig 5). For times t , where $t < \theta$, there ought to be a straight line in the diagram except in the vicinity of $t = 0$, where the limitations of the equipment, discussed above, will affect the reproduction. The real maximum pressure P_m is obtained by extrapolating the straight line in the diagram to $t=a/c_o$. From the recording from a 103 g TNT-ball (see Fig 5), P_m was thus determined to 98 bar, the time constant being $\theta = 54 \mu\text{sec}$, while a direct reading gives 89 bar.

3b. Impulse density

The impulse density I (impulse/unit of area) is defined by

$$I = \int_0^t P(t) dt \quad (3b.1)$$

Since the contribution to the integral from the tail of the pressure-time curve is difficult to determine accurately, the time of integration must be limited /3,8/. The integration time $6,7 \theta$, which has been used by R.H. Cole /3/ in most cases, is a compromise, and has been used in the practical calculations. (The time θ is the time after which the pressure P has dropped to P_m/e , that is, to 37% of P_m).

3c. The shock wave energy E_s

The shock wave energy E_s that is present in the water when the shock wave passes the pressure gauge, and which later can not be transformed into energy in the oscillating system formed by the gas sphere and the water (bubble pulse energy), can be calculated from the formula (3c.1) below with good accuracy, if we assume the water shock wave to propagate spherically and the pressure P to be below $c:a$ 400 bar, where the water shock wave can be assumed to be acoustic /2/.

$$E_S = \frac{4\pi R^2}{\rho_o c_o} \int_0^t P^2(t) dt \quad (3c.1)$$

$$\text{where } \begin{cases} R = \text{distance between charge and pressure gauge} \\ c_o = \text{sound velocity in water} \\ \rho_o = \text{density of water} \end{cases}$$

As in the case of 1, the integration time t is chosen to 6,7 θ .

3d. The bubble pulse energy E_B

If the maximum extent of the gas sphere is small as compared to the distance from gas sphere to ~~the~~ water surface and to the bottom and the walls of the container (ideal water-container), the energy in the oscillating system formed by the water and the gas sphere can be determined from /3,4/:

$$E_B = K \cdot T^3 \quad (3d.1)$$

where

$$K = \frac{0.683 p_o^{5/2}}{\rho_o^{3/2}} \quad (3d.2)$$

$$\text{and } \begin{cases} E_B = \text{bubble pulse energy} \\ p_o = \text{static absolute pressure at charge depth} \\ T = \text{time for a complete oscillation of the gas sphere} \end{cases}$$

The constant 0,683 is dimensionless

For experiments in the water-container described in Fig 1, the charge must be appreciably smaller than 1 g, if the effects from the surface, the bottom and the walls on the oscillations of the bubble shall be small enough to enable a determination of E_B from formula (3d.1) with satisfying accuracy. In practice it is necessary to use charge sizes which are not below the critical dimensions for propagation of detonation and which permit simple calculations of the influence from the primer. If the experiments are not carried out in a very deep and wide container, where the charge can be placed far away from bottom, walls, and surface, the effect from the container boundaries on the oscillation of the gas sphere must be calculated in order to determine the bubble pulse energy from the oscillation time recorded.

Being able to determine this ideal bubble pulse energy makes it possible to compare explosives which have yielded essentially different bubble pulse times at one experimental site and to compare tests carried out at different experimental sites where the water-container boundaries have been affecting the oscillation of the bubble differently.

Cole /3/ gives a formula, determined by Friedman, by means of which the influence on the bubble period from the water surface and the bottom can be calculated. It is of the form.

$$T = aE_B^{1/3} + bE_B^{2/3} \quad (3d.3)$$

where E_B stands for the "ideal" bubble pulse energy and a and b are constants, depending on the water-container in question as well as on the location of the charge therein.

Nils Lundborg /4/ gives a formula, with which it is possible to compute the effect on the bubble period from the walls only, provided the charge is placed symmetrically in the water-container:

$$T = aE_B^{1/3} + bE_B^{2/3} + cE_B + dE_B^{4/3} \quad (3d.4)$$

where a, b, c , and d are constants depending on the dimensions of the container. In case there is a simultaneous effect from bottom, water surface and container walls, the total effect of the container on the bubble period becomes very difficult to calculate theoretically. The situation may become still more complicated when the form of the bottom and the walls can not be described mathematically in a simple way, and also when the charge **can** not be placed symmetrically in the water-container. Yet the effect of the container on the bubble period can be determined and described by a number of constants, by measuring the bubble period for one explosive in a certain container, the charge size being varied within a sufficiently wide range.

4. Calculation of bubble pulse energy in a water-container, where the boundaries disturb the oscillations of the bubble.

Let us consider a given water-container, in which there is a charge of a specific explosive s , its location being given. If we record the bubble period T for different masses m_s of this explosive, we will be able to determine $T = F(m_s^{1/3})$.

By plotting $T = F(m_s^{1/3})$ in a diagram with T and $m_s^{1/3}$ along the axes (see Fig 6) we can draw the tangent to the curve at origo. The tangent can be written:

$$T' = \left[\frac{dF(m_s^{1/3})}{d(m_s^{1/3})} \right]_{m_s^{1/3} = 0} \cdot m_s^{1/3} \quad (4.1)$$

For an "ideal" water-container we have according to (3d.1), $T \sim m/s^{1/3}$ since $E_B \sim m_s$.

Thus T' stands for the bubble period we should have got in the given container and with the given location of the charge, should the container boundaries not have disturbed the oscillations of the bubble. The bubble pulse energy of the explosive s of a given mass m_s can thus according to (3d.1) be written

$$E_B = e_{B_s} \cdot m_s = k(T')^3 \quad (4.2)$$

The bubble pulse energy per mass unit of the explosive s , e_{B_s} , being a constant independent of m_s , can thus be determined:

$$e_{B_s} = \frac{k(T')^3}{m_s} \quad (4.3)$$

T can thus be plotted as a function of $E_B^{1/3}$ (see Fig 6). This curve gives us the possibility to determine E_B from a measured bubble time T for an arbitrarily chosen explosive.

In practice owing to normally occurring fluctuations in the atmospheric pressure, the total static pressure p at the charge depth h will vary during the experiments for determination of the points (m_s, T) . Consequently, the measured values of T for charges located at the depth of h below the water surface, should be corrected to values of T which are valid at the same total pressure p_N . If this pressure constitutes the total pressure at the charge depth h at an atmospheric pressure of p_{Nl} , where p_{Nl} is most conveniently set at 1 normal atmosphere = 760 mm Hg, p_N can be written:

$$p_N = (p_{Nl} + \rho_O gh) \quad (4.4)$$

The times T_p which were valid at the total pressure of p , are corrected to times T , valid at the total pressure of p_N , by means of the relation

$$T = T_p \cdot (p/p_N)^{5/6} = T_p \left[(p_{Nl} + \rho_O gh) / (p_{Nl} + \rho_O gh) \right]^{5/6} \quad (4.5)$$

which can be obtained from (3d.1) and (3d.2), and where p_{Nl} stands for the actual atmospheric pressure and g means the acceleration due to gravity. The explosive s used for determining the points (m_s, T) should have a small critical diameter; be safely initiated by a detonator to a well-defined detonation velocity; the explosive should be easily formed into a desired shape; it should not change its properties at a prolonged direct contact with water.

The procedure above for the determination of E_B can be transformed into a mathematical form as follows.

Since $E_B \sim m_s$ (3d.3, 3d.4), the function $T = F(m_s)$ can be considered as a polynomial of the form

$$T = F(m_s) = am_s^{1/3} + bm_s^{2/3} + cm_s + dm_s^{4/3} \quad (4.6)$$

where a, b, c , and d are constants valid for the explosive s , the given container and the location of charge in the latter. The constants can be determined by fitting to the experimental points (m_s, T) , e.g. by means of the least square method.

According to (4.6) and (4.1), the bubble period T' , which should have been obtained in case of no influence from the container boundaries on the oscillation of the bubble, will be

$$T' = am_s^{1/3} \quad (4.7)$$

Then, according to the formula 3d.1, E_B can be calculated from

$$E_B = k(T')^3 \quad (4.8)$$

which, in accordance with the relation 4.7, will be

$$E_B = ka^3 m_s \quad (4.9)$$

Since, in practice, $F(m_s)$ will be monotonously rising, the inverse $F^{-1}(T)$ of $F(m_s)$ exists, and m_s can be written

$$m_s = F^{-1}(T) \quad (4.10)$$

and the bubble energy E_s can be written

$$E_B = ka^3 \cdot F^{-1}(T) \quad (4.11)$$

In the case of the particular water-container and charge location described in Fig 1, $T = F(m_s)$ can be satisfactorily described by the polynomial

$$T = am_s^{1/3} + bm_s^{2/3} \quad (4.12)$$

(see Fig 6). According to (4.10), m_s will be

$$m_s = \frac{a^3}{8b^3} \left[\sqrt{1 + 4bT/a^2} - 1 \right]^3 \quad (4.13)$$

According to the formulas (4.9), (4.13), and (3d.2), the bubble energy E_B can then be written as

$$E_B = \frac{0,683p_N^{5/2}}{\rho_o^{3/2}} \cdot \frac{a^6}{8b^3} \left[\sqrt{1 + 4bT/a^2} - 1 \right]^3 \quad (4.14)$$

where p_N is the absolute pressure at the charge depth, to which the times T have been corrected according to (4.5) when determining (m_s, T) .

The time T in (4.14) is the bubble period measured for an explosive at the total pressure of p_N at the charge depth.

Using the relations (4.4) and (4.5) the formula (4.14) can be written

$$E_B = \frac{0,683}{\rho_o^{3/2}} (p_N + \rho_o gh)^{5/2} \frac{a^6}{8b^3} \left[\sqrt{1 + \frac{4bT}{a^2} \cdot \left(\frac{p_N + \rho_o gh}{p_N + \rho_o gh} \right)^{5/6}} - 1 \right]^3 \quad (4.15)$$

where T_p is the bubble period recorded at the total pressure of $p = (p_N + \rho_o gh)$. Since the constant 0,683 in (4.15) is dimensionless (3d.2), the units can be chosen in any consistent system of units, e.g. the SI system.

4a. Experimental determination of the constants a and b

Sprängdeg (explosive paste) (86 PETN/14 oil), a plastic explosive made by Bofors, taken from one and the same package, was used at the determination of the points (m_s, T) . Initiation was by a detonator No 8, except for the two smallest charges, where a detonator type GT 1 was used. The explosive charge of the detonators No 8 and type GT 1 were considered to be equivalent to 1 and 0,4 g of sprängdeg respectively. For the water-container and charge location described in Fig 1, the bubble period T of the first oscillation of the gas sphere could, with satisfying accuracy, be described by a polynomial of the form $T = am_s^{1/3} + bm_s^{2/3}$, where m_s stands for the mass of sprängdeg. Using the least square method the constants a and b were fit to the experimental points (m_s, T) including the point $(m_s = 0, T = 0)$ (see Table 1 and Fig 6). The first bubble period could then be written

$$T = 0,2562 m_s^{1/3} - 0,0293 m_s^{2/3} \quad (4a.1)$$

$$a = 0,2562 \text{ sec/kg}^{1/3}$$

where

$$b = -0,0293 \text{ sec/kg}^{2/3}$$

Table 1. The first bubble period T for sprängdeg.

Shot nr	m_s (kg)	T (sek)
103	0,0150	0,0612
104	0,0289	0,0757
105	0,0289	0,0759
33	0,0900	0,1087
32	0,0935	0,1104
106	0,102	0,1138
34	0,182	0,136
35	0,183	0,136
85	0,310	0,160
86	0,318	0,161
36	0,381	0,170
37	0,386	0,171

atmospheric pressure
 $p_{NL} = 760 \text{ mm Hg}$

5. Evaluation of the performance of explosives

For a comparison of maximum pressure, impulse density, shock wave energy and bubble pulse energy values between shots where different charge weights and/or distances between charge and pressure gauge have been used, it is convenient to use the reduced values of the same parameters instead, that is, p_m , i , e_s and e_B . /3,5/

$$p_m = \frac{P_m \cdot R}{m^{1/3}} \quad (5.1)$$

$$i = I \cdot R/m^{2/3} \quad (5.2)$$

$$e_s = E_s/m \quad (5.3)$$

$$e_B = E_B/m \quad (5.4)$$

where $\begin{cases} R = \text{distance between charge and pressure gauge} \\ m = \text{charge weight} \end{cases}$

The integration time t for impulse and shock wave energy is 6,7 θ .

In a given explosive, e_B is a constant independent of m for such values of m that changes in the detonation velocity are negligible and the total reaction time in the charge is small as compared to the first bubble period,

while p_m , i and e_s , with good accuracy, can be considered as constants independent of R and m , provided the reduced radius $r = \frac{R}{m^{1/3}}$ is kept within the range $2,5 \lesssim r \lesssim 3,3$ [meter/kg^{1/3}] /3/.

For a given experimental setup one has to restrict m so that the surface of the gasbubble at its maximum extension is kept well away from the container-boundaries in order not to make the bubble unstable when it approaches its minimum /3/. The distance between charge and container-boundaries should not be less than ≈ 2 maximum bubble radii a_m where a_m can be estimated from

$$a_m \approx \left(\frac{1.3 E}{1+h/10} \right)^{1/3}$$

$$\text{where } \begin{cases} a_m = \text{maximum bubble radius} & [\text{meter}] \\ h = \text{charge depth} & [\text{meter}] \\ E = \text{explosion energy in explosive} & [\text{MJ}] \end{cases}$$

The shock wave amplitude near the charge, as well as the temperature and composition of the reaction products, may vary for different explosives.

As a consequence of this, e_B/Q , e_s/Q and $(e_s + e_B)/Q$ where Q stands for the total energy released per massunit in the explosive, will vary for different explosives. Using the experimental setup and evaluation technique described above, we normally obtain $e_B/Q = 40-60\%$, $e_s/Q = 20-30\%$, and $(e_s + e_B)/Q = 70-80\%$.

Predictions of the performance of an explosive from underwater data at, say, rock blasting, will become more accurate if the results are complemented with such data as detonation velocity, density, expected temperature of explosion, and gas volume of the reaction products at normal pressure and temperature.

6. Control Experiments

As a check on the procedure of determining the bubble pulse energy as described in section 4, the bubble pulse energy per mass unit in shots with different charge weights of sprängdeg was calculated. For these calculations, formula (4.15) and data from table 1 were used.

Besides that, the values of p_m , i , e_s , and e_B as defined in section 5, were determined using data from tests with balls made of pressed TNT ($\phi = 50$ mm, weight ≈ 100 g, drilled with $\phi = 7,3$ mm, 40 mm deep for initiation with a detonator No 8), whereafter these values were compared with those given by Cole /3/. The result is shown in Table 2 below. The weight stated includes that of the detonator, which was considered equivalent to 2 g of TNT.

Table 2.

Shot No	Explosive	Weight _m kg	Density kg/m ³	Atmospheric pressure P mm Hg	bubble period T, sec.	P _m bar	I bar·sec.	P _m $\frac{\text{bar} \cdot \text{m}}{\text{kg}^{1/3}}$	i $\frac{\text{bar} \cdot \text{sec} \cdot \text{m}}{\text{kg}^{2/3}}$	e _S $\frac{\text{MJ}}{\text{kg}}$	e _B $\frac{\text{MJ}}{\text{kg}}$
103	spr-deg	0.0150	1480	760	0.0612	-	-	-	-	-	2.02
35	"	0.183	1480	760	0.136	-	-	-	-	-	2.04
37	"	0.386	1480	760	0.171	173	$19.5 \cdot 10^{-3}$	475	$73.6 \cdot 10^{-3}$	1.21	2.04
49	TNT	0.103	1580	762	0.113	99	$7.5 \cdot 10^{-3}$	422	$68.2 \cdot 10^{-3}$	0.98	2.01
91	TNT	0.103	1580	749	0.114	98	$7.6 \cdot 10^{-3}$	418	$69.2 \cdot 10^{-3}$	0.99	2.01
	TNT(Cole)	0.103	1520	-	-	-	-	433	$67.5 \cdot 10^{-3}$	0.96	1.99

7. Estimation of errors

Determination of the maximum pressure on the oscilloscope screen gives an error in the individual measurement which may be estimated to $\pm 1.5\%$ when the amplification is so adjusted that the entire screen is used.

The error in the individual measurement of impulse density and shock wave energy is composed of errors in x- and y-directions on the oscilloscope screen, errors in the integration, which was carried out graphically, and errors in determining the time constant θ . Altogether this will give an error in I and E_S of about $\pm 3\%$. As for the bubble period, the error in the individual measurement of time will be about $\pm 0.5\%$, which is equivalent to an error of about $\pm 1.5\%$ in the bubble pulse energy.

Conclusions

The average values of maximum pressure, impulse density, shock wave energy and bubble pulse energy obtained by means of a number of experiments with an explosive, should have so small total errors as to serve as a solid basis for an estimation of the performance of an explosive e.g. at rock blasting /7/.

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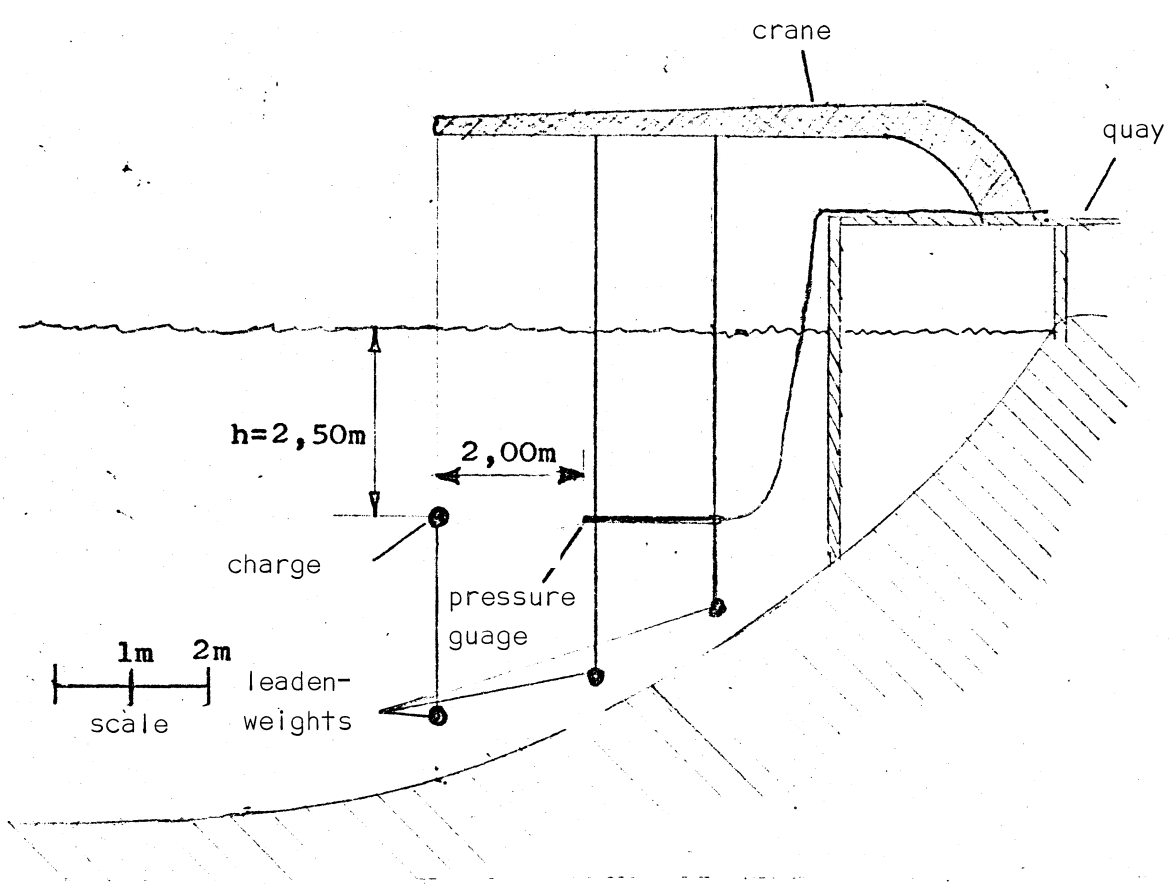


Fig. 1. Experimental site.

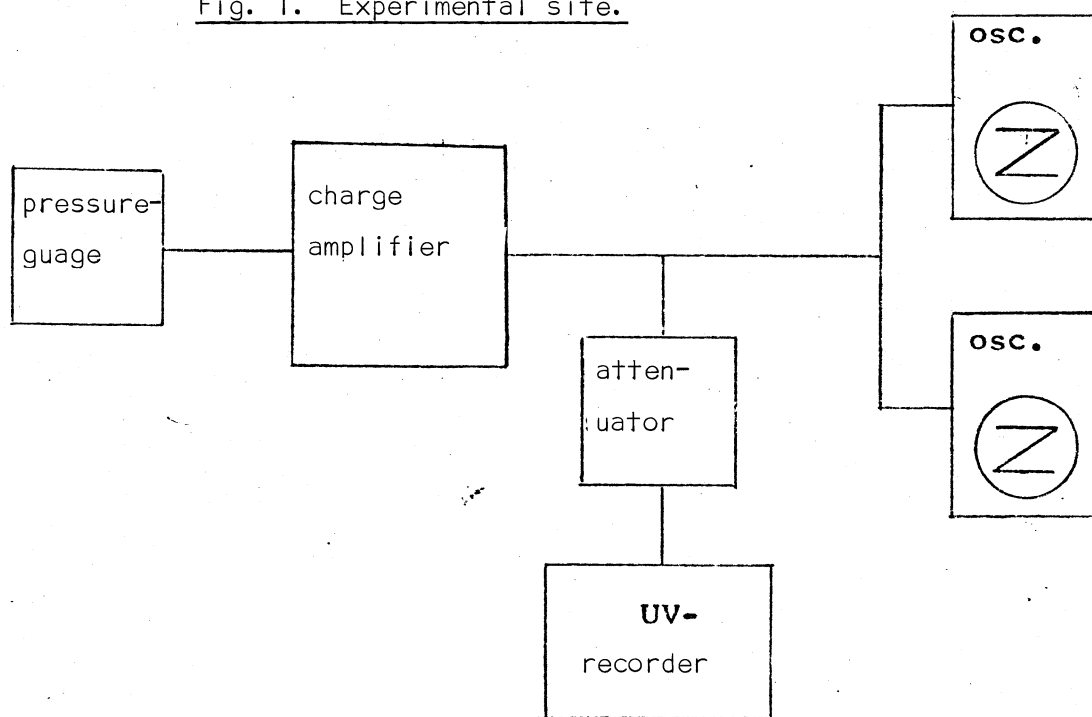


Fig. 2. Blockdiagram of measuring equipment.

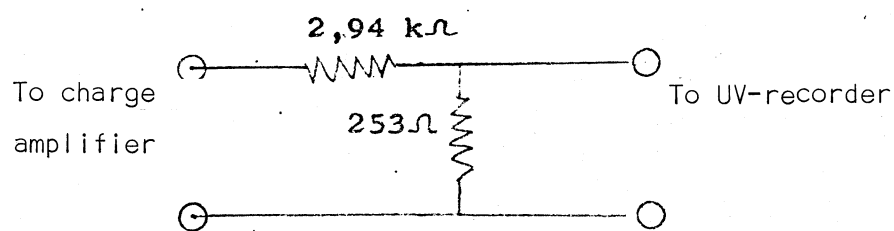
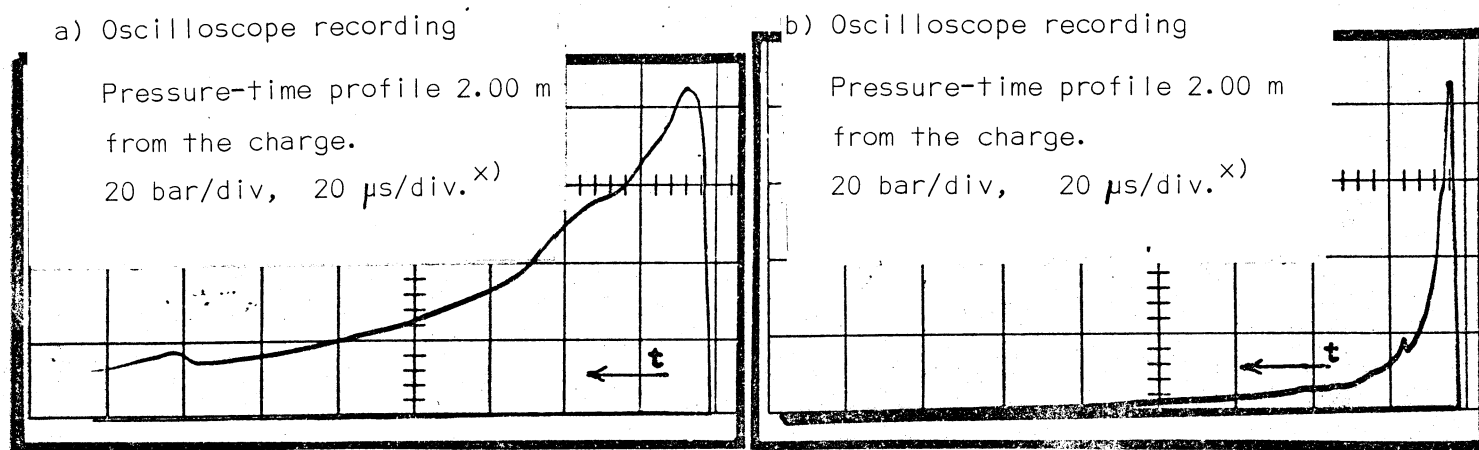


Fig. 3. Attenuator.

Fig. 4. Recordings from a 103 g TNT ball.



x) calibration gave for a) 20.6 bar/div, 20.0 $\mu\text{s}/\text{div}$ and for b) 20.6 bar/div, 196 $\mu\text{s}/\text{div}$.

b) UV-recording.

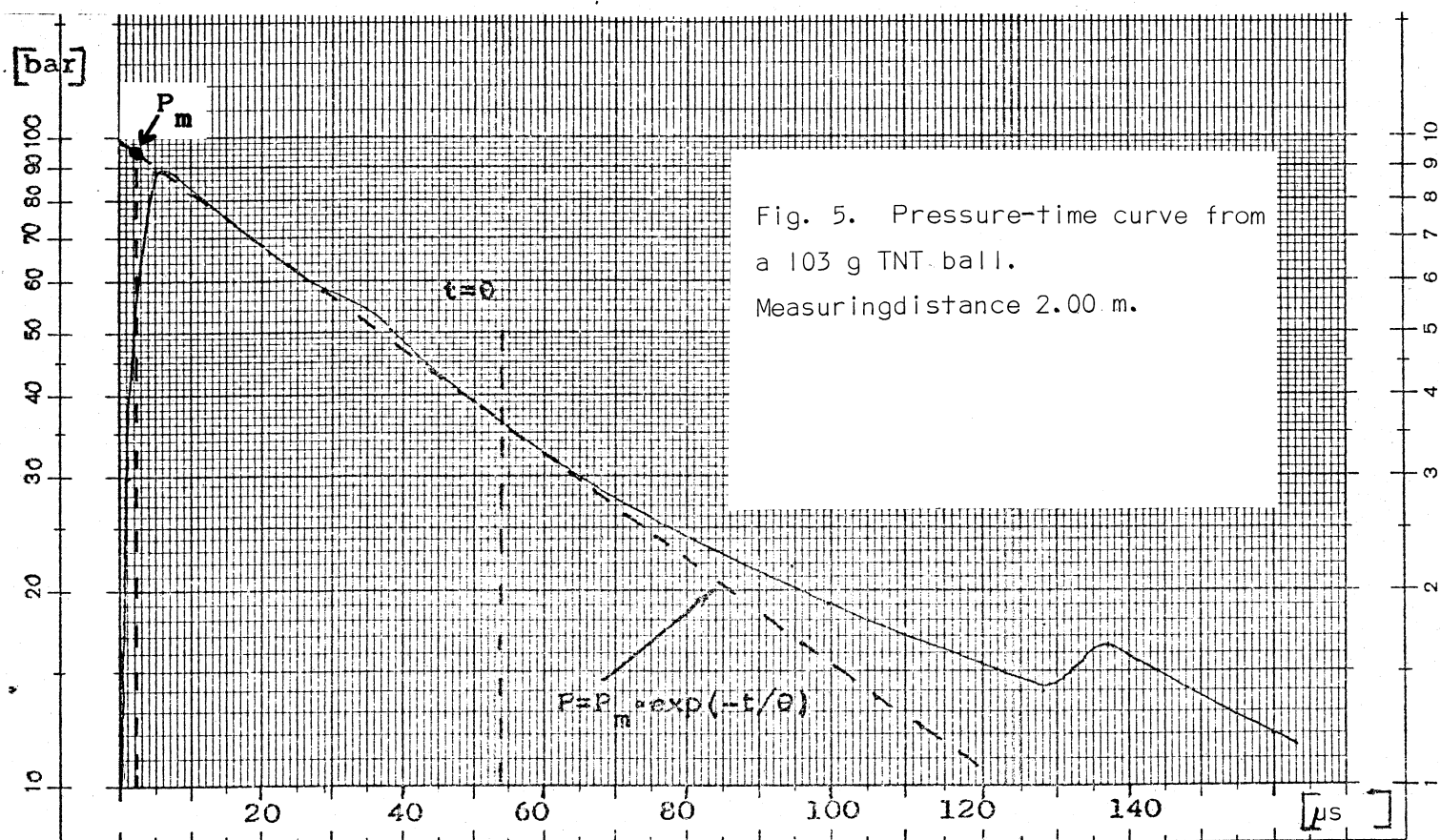
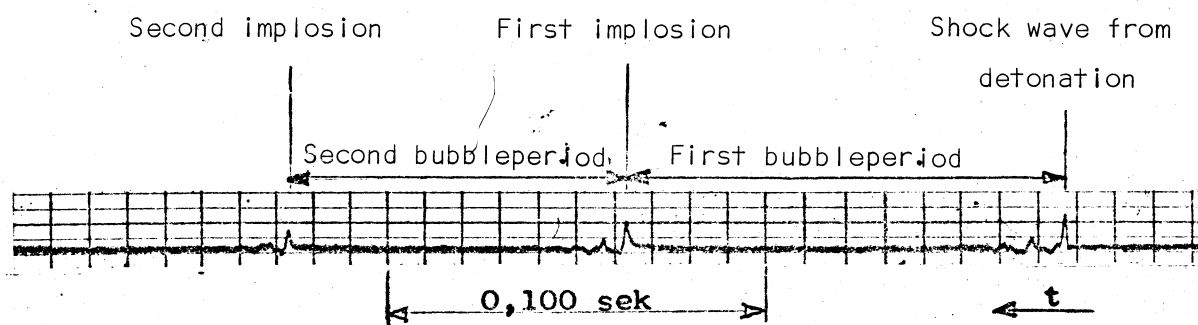


Fig 6. $T=F(m_s^{1/3})$, $T=F(E_B^{1/3})$ and

$$T' = \left[\frac{dF(m_s^{1/3})}{d(m_s^{1/3})} \right]_{m_s^{1/3}=0} \cdot m_s^{1/3}$$

T [sec]

0,20

○ = experimental points

 m_s = mass of sprängdeg (86 PETN/14 oil) T = first bubble period at 760 mm Hg at the experimental site in fig. 1.

0,15

$$T' = 0,2562 \cdot m_s^{1/3}$$

0,10

$$T=F(m_s^{1/3}) = 0,2562 m_s^{1/3} - 0,0293 m_s^{2/3}$$

0,05

 $E_B^{1/3} [MJ^{1/3}]$

0,1

0,2

0,2

0,4

0,3

0,6

0,4

0,8

0,5

0,8

0,6

0,7

 $m_s^{1/3} [kg^{1/3}]$