THEORY OF DESIGN OF THE ELECTRIC DETONATOR AND THE CONDENSER DISCHARGE EXPLODER

Shirô Kinoshita*

(1) Design of the Electric Detonator

The purpose of this study is to establish the fundamental formulas necessary for the design of electric detonator, condenser discharge exploder and electric blasting.

(1. 1) The relations between the number of electric detonators and the firing current.

Elwyn Jones[1)2)] has found that the energy (E) required to fire a low-tension electric detonator is as follows:

$$E=A+Bt \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where t is the excitation time, A and B being constants. And he has found also that there is the following relation between the excitation time (t) and the standard deviation thereof (σ_e).

$$\sigma_e=\alpha_t \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

And he has found on the basis of the theory of probability that the critical firing current necessary for the excitation of a series of n detonators increases as the number of the detonators increases.

But he has not established the relation between the critical energy equation $E=A+Bt$ and the critical firing current of a series of the detonators. Therefore when we want to design electric detonators of better characters, that is, the one for single firing, series firing or safe from stray current and so on, we cannot determine which factors of the electric detonator should be controlled. The present paper is an attempt to find these relations.

Received 24 Feb., 1960

* Orio Factory, Nippon Kayaku Co, Ltd. (Fukuoka-ken)

The relation between the reaction time (τ) and the excitation current (i) is $\tau=f(i)$ and the large the excitation current, the smaller τ, but τ may be considered constant when the excitation current is below about 2 ampere.

The distribution of the excitation time is normal. When we denote the range of excitation times of n detonators by R, the critical condition of the series firing can be expressed as follows.

$$R \leqq \tau \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

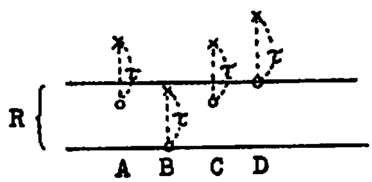

Fig. 1

As shown in Fig. 1 when the reaction time τ is shorter than the range of the excitation time (B in the Fig. 1), the serial firing without misfired detonators cannot be expected.

From equation (1) and (2)

$$i^2 r=\frac{1}{\sigma_e}\beta+B \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where

$\beta=A\alpha$

r, β, B are constant for a given lot of detonators

from equation (4)

$$i^2=\frac{\tau}{\sigma_e}\xi+\eta \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where

$$\xi=\beta/r\tau \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

$$\eta = B/r \quad \cdots\cdots(7)$$

The relation between w, the mean of the range of a set of n samples divided by the standard deviation (R/σ), and n has been tabulated by E. S. Pearson[3]. In the present paper the relation between w and n has been expressed in a form of an approximate equation as follows;

$$\log w = 0.490 + 0.7 \log(\log n) \quad \cdots\cdots(8)$$

or

$$w = 3.091(\log n)^{0.7} \quad \cdots\cdots(9)$$

Table 1 shows the values obtained from the statistical table[3] and from equation (9).

From equation (9) and (5)

$$i^2 = 3.091(\log n)^{0.7}\xi + \eta \quad \cdots\cdots(10)$$

From equation (10), (6), (7)

Table 1

n	2	3	4	5	10	20	50	100	1,000
from statistical table	1.128	1.693	2.059	2.326	3.078	3.735	4.498	5.015	6.483
from equation (9)	(1.333)	(1.841)	(2.166)	2.445	3.091	3.717	4.479	5.020	6.667

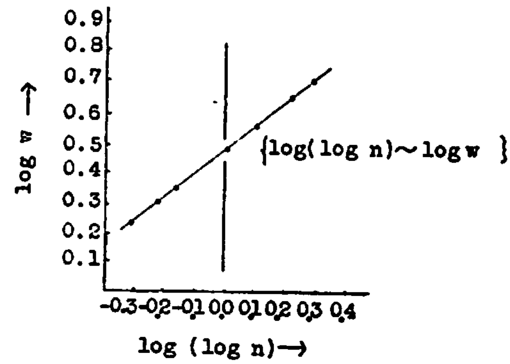

Fig. 2

$$i^2 = 3.091(\log n)^{0.7} A\alpha/r\tau + B/r \quad \cdots\cdots(11)$$

The equation (11) shows the relation between the excitation current (i) and the number of detonators (n) in a series which can be fired simultaneously without misfired detonators.

As the quantities A, α, r, τ, B can be obtained by measurement the value of n can be found from equation (11).

(1.2) The maximum firing number of the detonators in a series

The relations among the potential of the electric source (V), the firing current (i), the number of the detonators(n)in a series, the bridge wire resist ance of one of the electric detonator(r)can be expressed as follows:

$$V = nir \quad \cdots\cdots(12)$$

Table 2

Sample	No. of detonators in Series	Mean detonator resistance	Mean Firing Current Observed	Mean Firing Current Calculated	
No. 1	2	1.2	0.45	0.46	
	4		–	0.56	
	5		0.60	0.60	
	10		0.60	0.66	
	20		0.85	0.72	
	50		–	0.78	
	100		–	0.82	
No. 2	2	0.7	0.65	0.67	
	5		0.70	0.86	
	10		0.80	0.96	
	20		1.10	1.04	
	50		–	1.12	
	100		–	1.17	
No. 3	2	1.4	0.54	0.53	0.52*
	5		0.67	0.70	0.68
	10		0.81	0.77	0.76
	20		0.82	0.83	0.81
	50		0.88	0.90	0.90
	100		0.93	0.95	0.95

* These values are obtained from Jones' equation.

Equation (11) and (12) give:—

$$V^2 = r\{n^2(\log n)^{0.7}\frac{A\alpha}{\tau} \times 3.091 + n^2 B\} \quad \cdots\cdots(13)$$

When the quantities V, r, A, τ, B and α are obtained by experiments the value n can be obtained from equation (13).

This is the fundamental equation for the design of the electric detonator and the exploder, and it enables us to design them theoretically.

As an example, if we intend to increase

the firing number of the detonators in a series for given voltage (V), we should reduce the values of A, α, B and r, and increase that of τ.

The quantities A, B, α, τ and r are described by the following relations[4].

$$A=C(T-T_0)$$

$$C=ladk$$

$$B=H+Jl$$

$$=4\lambda_1 a\,\frac{T+T_0}{l'}+\frac{(T-T_0)2\pi\lambda_2}{2.3\log\frac{d_2}{d_1}}\,l$$

$$r=\rho\,\frac{l}{a}$$

where

l : length of bridgewire

a : cross-sectional area of bridgewire

d : density of bridgewire

k : specific heat of bridgewire

λ_1 : heat conductivity of bridgewire

T : ignition temp. of match head

T_0 : room temp.

l' : a part of bridgewire where heat loss occurs at the both ends

λ_2 : heat conductivity of match head

d_1 : diameter of bridgewire

d_2 : diameter of match head

ρ : specific resistance of bridgewire

In terms of these variables the formula (13) can be expressed as follows;

$$V^2=\rho\,\frac{l}{a}\,n^2(T-T_0)\left\{(\log n)^{0.7}\,\frac{lakd\alpha}{\tau}\times 3.091+4\lambda_1\,\frac{a}{l'}+\frac{2\pi l\lambda_2}{2.3\log\frac{d_2}{d_1}}\right\}\cdots\cdots(14)$$

This formula shows that to increase the serial firing number (n), the values of T, α, l, λ_2 should be decreased and that of τ increased. In this equation the values ρ, a, d, k and λ of the bridgewire and the diameter of the match head are constant.

(1.3) Single shot firing of an electric detonator.

When we design the electric detonator, the character of the serial firing and that of a single shot should be considered discriminatingly.

The ignition energy for a detonator may be represented by $E=A+Bt$.

The energy which is supplied by the current i to the bridgewire during time t is i^2rt, where r is the resistance of the bridgewire.

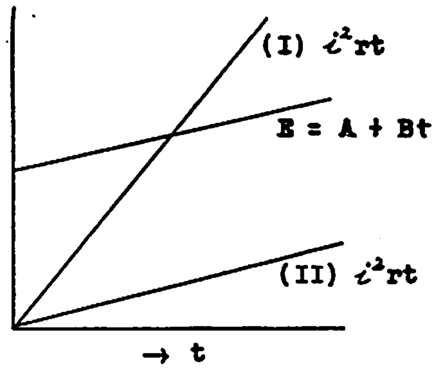

Fig. 3

As shown in Fig. 3, the ignition of an electric detonator occurs when the cuave i^2rt intersects the curve $E=A+Bt$. (curve I)

When the curve i^2rt and the curve $E=A+Bt$ do not intersect (curve II), the ignition of an electric detonator does not occur. So the following relation is needed for the ignition to occur.

$$i^2r>B$$

where

$$r=\rho\,\frac{l}{a}$$

$$B=H+Jl$$

That is

$$l>\frac{H}{i^2\frac{\rho}{a}-J}\cdots\cdots\cdots\cdots\cdots(15)$$

To ignite an electric blasting cap by the current i, the bridgewire should be longer than the value $\dfrac{H}{i^2\frac{\rho}{a}-J}$.

(2) Design of the condenser discharge exploder

In the design of a condenser type exploder, the characteris·tics of the electric detonators exploded by it should be taken into consideration.

The capacity of a condenser type exploder is determined by the microfarad of its condenser and the charged electric voltage. There is a relation between these two characteristics. For instance, if we fix the microfarad of a condenser, the charged electric voltage is determined. But from the point of view of safety against the ignition of methane-air mixture, the microfarad and the charged electric voltage of a condenser have their allowable limits.

(2.1) Fundamental formula for designing a condenser type exploder.

The total discharge energy of a condenser is

$$\int_0^t i^2 R dt = \frac{CV_0^2}{2}\left(1-e^{-\frac{2t}{RC}}\right) \cdots\cdots(16)$$

where

C : capacity of condenser in microfarad
V_0 : charged electric voltage in volt
t : time in second
R : resistance of circuit in ohm

As has been shown in the equation (11) the relation between the series firing number of the electric blasting caps (n) and their firing current (i) is

$$i^2 r = 3.091(\log n)^{0.7}\frac{A\alpha}{\tau} + B \cdots\cdots\cdots\cdots(11)$$

Therefore the total energy necessary to ignite n pieces of electric detonators is

$$ni^2rt = \left\{3.091\ (\log n)^{0.7}\frac{A\alpha}{\tau} + B\right\}nt \cdots\cdots\cdots\cdots(17)$$

The energy which is consumed in the leading wires and in the leg wires is

$$E_W = \frac{CV_0^2}{2}\left(1-e^{-\frac{2t}{RC}}\right)\frac{R_W}{R} \cdots\cdots\cdots(18)$$

where

R : total resistance of the firing circuit
R_W : sum of resistance of the leading wires and leg wires

Combining to equations (16), (17), with (18) we can obtain the fundamental equation for the condenser discharge exploder, that is

$$\left\{3.091\ (\log n)^{0.7}\frac{A\alpha}{\tau} + B\right\}nt + \frac{CV_0^2}{2}\left(1-e^{-\frac{2t}{RC}}\right)\frac{R_W}{R} = \frac{CV_0^2}{2}\left(1-e^{-\frac{2t}{RC}}\right) \cdots\cdots\cdots(19)$$

(2.2) An example of calculation

In the calculation we use the electric detonator which has the following characteristics.

A = 0.0029 joule
α = 0.075
τ = 0.0016 second
B = 0.09 joule/sec

In this example we want to design a 50 shots condenser discharge exploder. Taking into consideration the safety factor 2 we design in practice a 100 shots exploder in this case. The firing current necessary to fire 100 detonators in a series is 0.82 ampere and excitation time t is 0.0045 second. The sum of the resistance of the leading wires and leg wires (R_W) is 34 ohms and the total resistance of the firing circuit (R) is 160 ohms. When the value of C is 200 microfarad. the equation (19) gives V_0=134 volts (type 1) and when C is 20 microfarad V_0= 216 volts (type 2).

These two types exploder may be used for firing 100 shots, but from the standpoint of ensuring the safety against the methane air ignition, the type 1 (200 microfarad with 134 volts) seems not to be adequate.

(2.3) Safety against methane-air ignition

Table 3 and Fig. 4 show the energy discharged from the two types of exploders.

Table 3 Exploder

time	200μF with 134V			20μF with 216V		
	A	$(E_W)_A$	$D_A = A-(E_W)_A$	B	$(E_W)_B$	$D_B = B-(E_W)_B$
ms	Joule	Joule	Joule	Joule	Joule	Joule
2	0.236	0.050	0.186	0.353	0.075	0.278
4	0.441	0.094	0.347	0.439	0.093	0.346
8	0.777	0.165	0.612	0.465	0.099	0.366
20	1.360	0.289	1.071	0.467	0.099	0.368
40	1.690	0.359	1.331	0.467	0.099	0.368

A : The total energy discharged from the condenser with the capacity 200μF and the potential 134 volts. (equation (16))

$(E_W)_A$ and $(E_W)_B$: The energy which is consumed in the leading wires and in the leg wires (equation (18))

$D_A=A-(E_W)_A$: The energy feeded to the 100 fuse-heads by the condenser with the capacity 200 μF and the potential 134 volts.

B : The total energy discharged from the condenser with the capacity 20μF and the potential 216 vols.

$D_B=B-(E_W)_B$: The energy feeded to the 100 fuse-heads by the condenser with the capacity 20μF and the potential 216 volts.

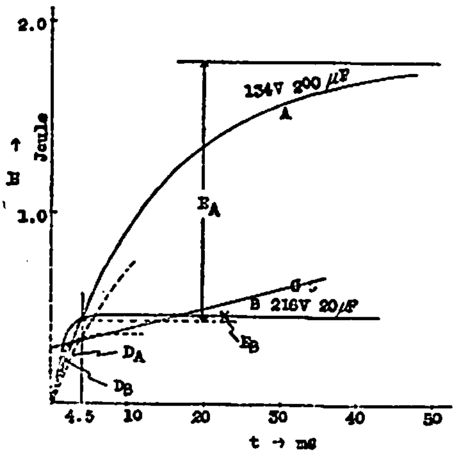

Fig. 4

In Fig. 4 the curve A shows the energy discharged from a condenser with the capacity 200μF and the potential 134 volts, and the curve B is for a condenser with the capacity of 20μF and the potential 216 volts. The curve C shows the energy needed to fire 100 fuse-heads. The curve D_A shows the energy feeded to the 100 fuse-heads by the condensers A, where the value of D_A is the difference between those of A and $(E_W)_A$. $(E_W)_A$ is the value of the energy which is consumed in the leading wires and in the leg wires. The curve D_B shows the energy feeded to the 100 fuseheads by the condenser B, where the value of D_B is the difference between those of B and $(E_W)_B$. $(E_W)_B$ is the value of the energy which is consumed in the leading wires and in the leg wires. E_A and E_B show the energy which remain in the condenser after 100 shots firing has taken place.

The superiority of the condenser-discharge exploder of this type is determined not only by its firing capacity but also by the degree of its safety against methane-air ignition, that is, the greater the energy that remains in the condenser after the firing has taken place, the lower is the safety. In this example the 20μF, 216 volts condenser is safer than that of 200μF 134 volts. In general, it may be said that the smaller the microfarad of the condenser is, the safer is the exploder against methane-air ignition.

(3) Firing electrically

Parallel series circuits fired by a condenser discharge exploder.

Example of calculation : —

The electric detonator which has the following characteristics is used.

Table 4

method of connection		firing current for one series (from Table 2, Sample No. 1)	excitation time (t) (from Fig. 5)	energy needed to fire 100 detonators (100 E where $E=0.0029+0.09t$)	resistance of circuit	exploder			
						200μF with 134V		20μF with 216V	
N						total energy discharged in time t	total energy supplied to 100 fuseheads	total energy discharged in time t	total energy supplied to 100 fuseheads
pcs		A	ms	Joule		Joule	Joule	Joule	Joule
$N_1=100$	100 series	0.82	4.5	0.330	$4+150\Omega = 154$	0.456	$0.456\times\frac{150}{154}\times\frac{120}{150}$ $=0.355$	0.442	$0.442\times\frac{150}{154}\times\frac{120}{150}$ $=0.344$
$N_1=N_2=50$	50 series 2 parallel	0.78	5	0.335	$4+\frac{1}{\frac{2}{75}}$ $=4+37.5$ $=41.5$	1.260	$1.260\times\frac{37.5}{41.5}\times\frac{37.5}{75}$ $\times\frac{1.2\times50}{75}\times2$ $=0.911$	0.467	$0.467\times\frac{37.5}{41.5}\times\frac{37.5}{75}$ $\times\frac{1.2\times50}{75}\times2$ $=0.337$
$N_1=N_2=\cdots=N_5=20$	20 series 5 parallel	0.72	5.7	0.340	$4+\frac{1}{\frac{5}{30}}$ $=4+6$ $=10$	1.790	$1.790\times\frac{6}{10}\times\frac{6}{30}$ $\times\frac{1.2\times20}{30}\times5$ $=0.859$	0.467	$0.467\times\frac{6}{10}\times\frac{6}{30}$ $\times\frac{1.2\times20}{30}\times5$ $=0.224$*
*$N_1=N_2=\cdots=N_{25}=4$	4 series 25 parallel	0.56	10	0.380	$4+\frac{1}{\frac{25}{6}}$ $=4+0.24$ $=4.24$	1.800	$1.800\times\frac{0.24}{4.24}\times\frac{0.24}{6}$ $\times\frac{1.2\times4}{6}\times25$ $=0.081$*	0.467	$0.467\times\frac{0.24}{4.24}\times\frac{0.24}{6}$ $\times\frac{1.2\times4}{6}\times25$ $=0.023$*
$N_1=N_2=\cdots=N_{50}=2$	2 series 50 parallel	0.46	17	0.440	$4+\frac{1}{\frac{50}{3}}$ $=4+0.06$ $=4.06$	1.800	$1.800\times\frac{0.06}{4.06}\times\frac{0.06}{3}$ $\times\frac{1.2\times2}{3}\times50$ $=0.040$*	0.467	$0.467\times\frac{0.06}{4.06}\times\frac{0.06}{3}$ $\times\frac{1.2\times2}{3}\times50$ $=0.010$*

* indicates the case of the misfire due to smaller energy supply

$E = 0.0029 + 0.90\,t$

resistance of a bridge wire: 1.2 ohms
resistance of leg wires: 0.3 ohms
resistance of leading wires to a power source: 4 ohms

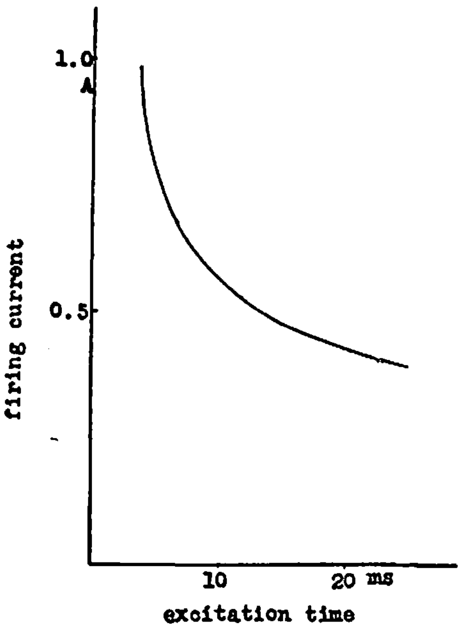

Fig. 5

Fig. 5 shows the relation between the firing current and the excitation time.

Two kinds of condenser discharge exploder are discussed. and one is a $200\mu F$, 134V condenser, and the other is a $20\mu F$, 216V condenser.

In the following calculation 100 electric detonators are to be fired in several parallel series circuits, where $N_1+N_2+N_3+\cdots\cdots+N_n=100$ and $N_1=N_2=N_3=\cdots\cdots=N_n$.

The result of the calculation is shown in Table 4.

Table 4 shows that when we explode 100 electric detonators by a $20\mu F$ 216V exploder, there is no misfire only in the cases of the 100 series circuit and the 50 series of the 2 parallels circuit. But when we use the $200\mu F$ 134V exploder, the 50 series of the 2 parallels or the 20 series of the 5 parallels are superior to the other circuits. The energy supplied to the 100 fuse-heads by these circuits are several times larger than the energy needed to fire 100 detonators, so these series parallels circuits minimize the possibility of misfires due to the current leakage.

Acknowledgements—

The author wishes to express his thanks to Dr. K. Hino. Chief, Explosives Research Section of the Nippon Kayaku Co. Ltd.. for many helpful advices during the preparation of this paper.

References

1) Elwyn Jones and H. P. Stout: Colliery Engineering, October and November, 1948.
2) Elwyn Jones: Proc. Roy. Soc, A 198 (1949).
3) Poul G. Hoel: Introduction to Mathematical Statistics., (Translated into Japanese by Taguchi pp. 186∼7).
4) Shirô Kinoshita: Study of Manufacture of the electric detonator: Journal of the Industrial Explosives Society, Japan: Vol. 15, No. 3, pp. 167∼169 (1954.9) (In Japanese).

---

p. 133 より

（山下）