On Group Misfiring in Series Circuit Electric Blasting

By

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In an electric blasting circuit where a large number of electric detonating caps are hooked up in a straight series, several instances have been reported in which a group of detonating caps situated in the vicinity of the middle part of the circuit were apt to misfire, and the cause of this kind of misfire has been ascribed to the leak of igniting current.

Every misfire will ultimately be traceable to the lack of the amount of electric power given to the detonating cap, while in this paper, to account for one of the factors leading to the cause of such misfire, the time required for the progressing current wave to arrive at the middle part of the circuit and also the gradual decay of the intensity of current during the transition are investigated.

Consequently, the intensity-time curves of igniting current and the amount of accumulated heat energy for detonating caps placed at the middle part and both ends in the circuit were studied and discussed under several feasible circuit conditions, and next, it was suggested that both the higher and the lower limits of the intensity of igniting current should be considered in order to reduce the possibility of misfire in such situations.

1. Introduction

It is often experienced that a group of electric detonating caps placed at the middle part of a circuit is prone to misfire in a straight series circuit which includes a lot of electric detonating caps.

It was provisionally said that those misfires were caused by the electric standing wave developed in the switching transient state giving uneven distribution of igniting current[1]. But recently the principal cause of such misfire has been attributed to a lack of igniting current derived from leaking in some spots in the circuit[2].

When the leaking paths are scattered in the blasting circuit, it can be taken for granted that the farther detonating caps will get the less current from the source of igniting current[3),4], but sometimes we have experienced such a group misfire as mentioned above, even though the circuit is kept in a well insulated condition.

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Now, we studied theoretically the intensity and the state of the transient igniting current at the middle part and also at both ends of the electric blasting series circuit, and in consequence we have tended to consider that the difference of the transient current distribution between them could affect group misfire in such a series circuit consisting of many detonating caps.

In a extremely long series circuit consisted of a lot of detonating caps, when the igniting current can not be affected by the reflection of the progressing current wave, the differences in the intensity and the arrival time between the surge currents at both ends and at the middle part of the circuit are so remarkable that we can hardly succeed in simultaneous blasting using such a circuit.

And yet, in practical blasting circuits, the igniting current wave form will become more complicated one in response to the reflection of the progressing current waves at both ends and/or the interferences between the progressing and the reflected waves.

Then, taking into consideration of the reflection of the current waves, we considered the heat energy distributed to the fuse-heads by these currents for several circuit conditions in which the blasting circuit consisted of 200, 400, and 800 electric detonating caps connected in straight series.

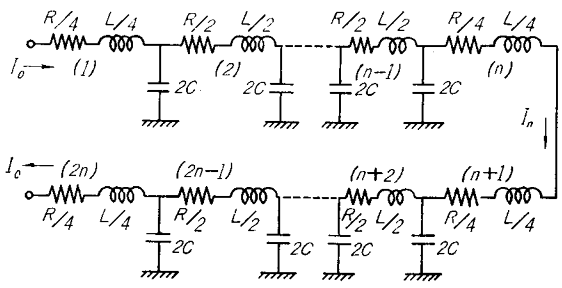

Fig. 1. A blasting circuit consisting of many electric detonating caps connected in series.

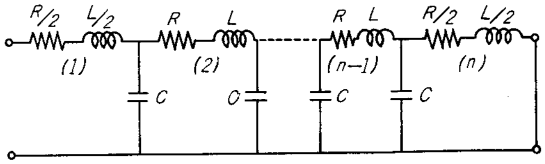

Fig. 2. Equivalent circuit corresponding to the circuit shown in Fig. 1.

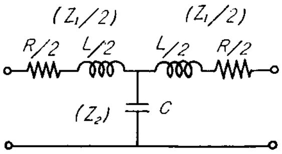

Fig. 3. An elemental four-terminal network.

2. Transient current in blasting circuits.

Now, in calculating the intensity of current, it is valid to regard these blasting circuits as those in which the electrical constants are lumped together at their respective positions rather than regarding them as those in which they are distributed uniformly along the overall length of the circuit, Then, such a series circuit as is shown in Fig. 1 may be regarded as the cascade connection of four-terminal networks, that is, because the symmetry of the blasting circuit shown in Fig. 1 is equivalent of the circuit shown in Fig. 2 which consists of n elements of the four-terminal network shown in Fig. 3.

Accordingly, the igniting currents at both ends and at the middle part of the circuit shown in Fig. 1 are respectively identified with the current at the sending end and the current at the receiving end in the equivalent circuit shown in Fig. 2.

In the equivalent network shown in Fig. 2, the voltages and the intensities of current at both ends can be represented as follows:

$$\left.\begin{aligned} V_0 &= V_n \cosh n\gamma + I_n Z \sinh n\gamma , \\ I_0 &= \frac{V_n}{Z} \sinh n\gamma + I_n \cosh n\gamma , \end{aligned}\right\} \tag{1}$$

where, V_0 and I_0 are the voltage and the intensity of current at the sending end, V_n and I_n are the respective quantities at the receiving end which corresponds to the middle part in a real blasting circuit, and Z and γ are the image impedance and the propagation constant respectively. Equation (1) is the so-called Telegraph Equation and Z and γ can be represented using four-terminal constants related to the elemental network shown in Fig. 3.

The relations among these constants can be written as follows:

$$Z = \sqrt{\frac{AB}{CD}} = \sqrt{\frac{B}{C}}, \quad \gamma = \log\left(\sqrt{AD} + \sqrt{BC}\right) = \log\left(A + \sqrt{BC}\right), \tag{2}$$

$$\left.\begin{aligned} A &= 1 + Z_1/2Z_2, \quad B = (Z_1^2/4 + Z_1 Z_2)/Z_2, \\ C &= 1/Z_2, \quad D = A, \quad AD - BC = 1, \end{aligned}\right\} \tag{3}$$

whereby

$$\left.\begin{aligned} Z_1 &= (R + j\omega L)/2, \quad Z_2 = 1/j\omega C, \quad j = \sqrt{-1}, \\ \omega &= 2\pi f, \quad f: \text{frequency}. \end{aligned}\right\} \tag{4}$$

L, C, R in formula (4) are linked with the inherent electrical constants of individual electric detonating caps such as self inductance l, earth capacitance c, and resistance r through the following relation

$$l = L/2, \quad c = 2C, \quad r = R/2. \tag{5}$$

As mentioned above, the detonating cap which has the worst current condition in the series blasting circuit consisting of twice n detonating caps is the one placed at the center of the circuit, that is, the n-th detonating cap, because of the delayed arrival of the igniting current wave and the certain decrease of its intensity, even in the circuit having no leaks.

The igniting current passing through the middle part of the blasting circuit in question is identical with the current passing through the receiving end of the equivalent circuit shown in Fig. 2, and this end has obviously been shorted as shown in the same figure. Accordingly, putting $V_n=0$ in equation (1) and taking formulae (2) and (3) into consideration, we can solve for current I_n, giving

$$I_n = \frac{V_0}{Z\sinh n\gamma} = \frac{V_0}{Z_2\sinh\gamma\cdot\sinh n\gamma}. \tag{6}$$

Equation (6) shows a steady current when an alternating voltage is applied to the sending end, and in another way, when a constant direct voltage is applied, the current in the steady state can be naturally expressed by $I_0=I_n=V_0/2nr$. Now, the transient igniting current under discussion, when a constant direct voltage is applied suddenly across the sending terminals of the circuit, can be obtained by applying Heaviside's operational method[5], giving the operational form for I_n

$$I_n = \mathfrak{H}\frac{V_0\mathbf{1}}{Z(p)}. \tag{7}$$

In equation (7), $\mathfrak{H}$ is a transforming symbol[6] between the function of time and the function of operator. Symbol $\mathbf{1}$ means a unit function which is noted as follows;

$$\text{when time } t<0,\ \mathbf{1}=0; \qquad t\geqq 0,\ \mathbf{1}=1.$$

$Z(p)$ is the so-called p-function of impedance, and it is equivalent to the denominator in equation (6). That is, putting $j\omega$ to p, we obtain

$$Z_2 = 1/j\omega C = 1/pC,$$
$$\gamma = \cosh^{-1}(1+Z_1/2Z_2) = \cosh^{-1}\{1+(R+pL)\,pC/4\}.$$

Then, writing $Z(p)$ in the following form

$$Z(p) = Z_2\sinh\gamma\cdot\sinh n\gamma,$$

and applying Heaviside's Expansion Theorem to equation (7), we obtain equation (8) in which we can find the igniting current I_n, including also its transient state, as the function of the number of detonating caps $2n$, and of the time t together.

$$\left.\begin{aligned} I_n &= \frac{V_0}{nR}+\frac{2V_0}{nL}\cdot e^{-\alpha t}\cdot\sum_{k=1}^{n-1}\frac{\sin(\beta_k\cdot t)}{\beta_k\cdot\cos(k\pi)}\cdots\cdots(t-n\sqrt{LC}>0), \\ I_n &= 0\cdots\cdots\cdots\cdots\cdots\cdots(t-n\sqrt{LC}\leqq 0), \end{aligned}\right\} \tag{8}$$

where,

$$\left.\begin{aligned} &\alpha = R/2L, \quad \beta_k = \sqrt{\frac{2[1-\cos(k\pi/n)]}{LC} - \alpha^2}, \\ &k = 1, 2, 3, \cdots, n-1. \end{aligned}\right\}$$

On the other hand, the intensity I_0 of igniting current which is being fed by the source, or just passing through both initial and final detonating caps in the blasting circuit, is equal to the intensity of a supplying current in the equivalent circuit shown in Fig. 2 as described above, and from equation (1) it is expressed in the form

$$I_0 = I_n \cosh n\gamma = V_0/Z_2 \sinh \gamma \cdot \tanh n\gamma. \tag{9}$$

Therefore, the transient current can be calculated by the following equation (10).

$$\left.\begin{aligned} &I_0 = \frac{V_0}{nR}(1-e^{-2\alpha t}) + \frac{2V_0}{nL} e^{-\alpha t} \cdot \sum_{k=1}^{n-1} \frac{\sin(\beta_k' t)}{\beta_k'}, \\ &\text{where,} \\ &\alpha = R/2L, \quad \beta_k' = \sqrt{\frac{(k\pi/n)^2}{LC} - \alpha^2}, \\ &k = 1, 2, 3, \cdots, n-1. \end{aligned}\right\} \tag{10}$$

β_k and β_k' comprised in equations (8) and (10), may take the $(n-1)$'s different values, therefore it is necessary to repeat those calculations $n-1$ times to evaluate each of the 2nd term in these equations for every value of t.

3. Electrical constants of a detonating cap.

The transient behavior of the igniting current treated in this paper arises from a result of the accumulation of electric reactive components consisted of self-inductance of leg wires and of heating bridges, and also the earth capacitance and the capacitance formed between a pair of leg wires, because if they were composed of only pure resistances, transient phenomena could not manifest itself.

To provide the universal values for those reactive components is still difficult since they are affected by the various local surroundings and handling conditions in which detonating caps are used.

Therefore, for convenience, in calculating the intensity of the transient igniting current, we employed values of the earth capacitance derived from the experimental results made on a piece of detonating cap and also for the self-inductance of leg wires we estimated the reasonable values taking the geometrical shape of leg wires and of a round of series circuit into consideration.

For instance, the earth capacitances under the various conditions measured by M. Yamada and H. Ohara[7] are shown in Table 1 which shows how the surrounding medium seriously affects the value of the earth capacitance. However, in arranging an actual blasting circuit some portion of the leg wires is often laid apart from the face or from the ground, so we adopted the values of 600 $\mu\mu$F and 4,000 $\mu\mu$F for the earth capacitance of a detonating cap.

Table 1. Earth capacitance of leg wire (Length of leg wire is 1.5 m each).

Type of leg wire	Surrounding conditions	Earth capacitance [$\mu\mu$F]
Paraffined cotton-covered wire	in air	4.6
	in damped ore dust	16,250
	in water	8,750
Vinyl insulated wire	in air	1.1
	in damped ore dust	400
	in water	1,000

It can be regarded that 600 $\mu\mu$F is the value for a detonating cap which has a pair of leg wires insulated by polyvinyl and placed in very moist underground, and that 4,000 $\mu\mu$F is suitable for a detonating cap with paraffin-covered leg wires in a fairly moist place.

Next, the self-inductance of leg wires has been considered. After a detonating cap has been used to connect up the circuit, the remaining parts of the leg wires are customarily coiled up into a lump and slightly tightened together between the adjacent blasting holes so that they will not tend to sag. It makes the inspection of the blasting circuit easy, and is helpful to prevent the tearing off of the leg wires and, also to prevent any accidental pull on them. But the coil itself thus formed, assuming 5 cm in diameter and 10 turns in 1 cm width, has the effect of adding an extra inductance of about 8 μH. On the other hand, the inherent inductance of a detonating cap with stretched leg wires is said to be 2~3 μH [8], and we must also take into consideration that the leg wires mentioned above may possibly be wound up into non-inductive coils.

Furthermore a loop blasting circuit which is formed by hooking up all detonating caps in straight series may have also a certain inductance. Taking all these facts into consideration, we have made a final estimate for the inductance of a detonating cap to be 10 μH each.

In the next, a heating bridge assembled into any detonating cap is prepared with the electric resistance of 0.7 Ω, and the single leg wire has a resistance of about 0.1 Ω per meter of length. Then, completed detonating caps have slightly different values of resistance depending on the length of leg wires attached, and the resistance of the heating bridge also increases with its temperature rise.

Consequently, we estimated the resistance of a detonating cap to be 1 Ω each in this paper.

The electrical constants of a detonating cap thus estimated are shown in block in Table 2.

Table 2. Electrical constants of detonating caps estimated for use in the calculations (Length of leg wire is 1.5 m each).

	Case (I)	Case (II)
Self-inductance [H]	10×10^{-6}	10×10^{-6}
Earth capacitance [F]	600×10^{-12}	$4{,}000\times10^{-12}$
Resistance [Ω]	1	1

4. Results of calculations

Applying the values of the electrical constants for each of the two circuit conditions shown in Table 2 to equations (8) and (10), we calculated the variation of the intensity of igniting current against time taking the total number $2n$ of detonating caps 200, 400, and 800 respectively.

Current-time curves obtained for each case are shown in Figs. 4～8 respectively and the times when the wave fronts of current arrive at the middle part of the circuit are shown in Table 3 with peak intensities of the surge current at the points in question.

Table 3. Peak intensity and arrival time of surge current.

Case	Electrical constants of a detonating cap	Numbers of caps in series	Peak intensity of surge current (%)		Arrival time of surge current at the middle part [μ sec]
			at both ends	at the middle part	
(I)	$l=10\ \mu$H	200	—	—	8
	$c=600\ \mu\mu$F	400	192	178	16
	$r=1\ \Omega$	800	360	174	32
(II)	$l=10\ \mu$H	200	225	166	20
	$c=4{,}000\ \mu\mu$F	400	445	128	40
	$r=1\ \Omega$	800	880	100	80

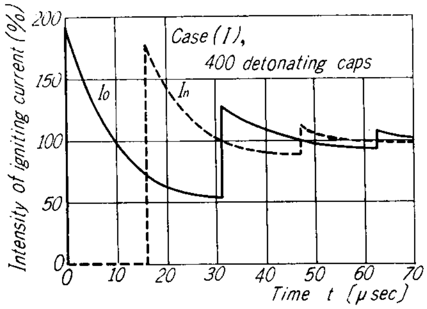

Fig. 4.

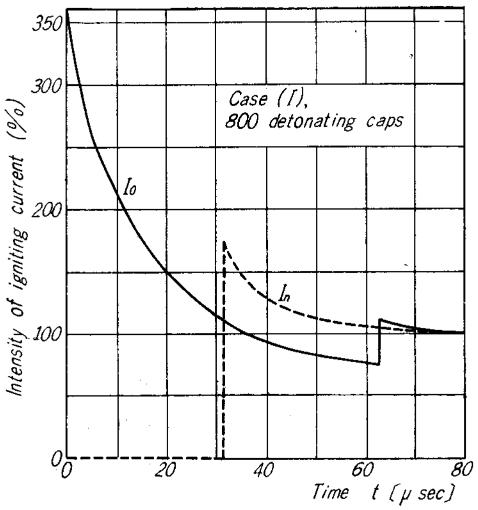

Fig. 5

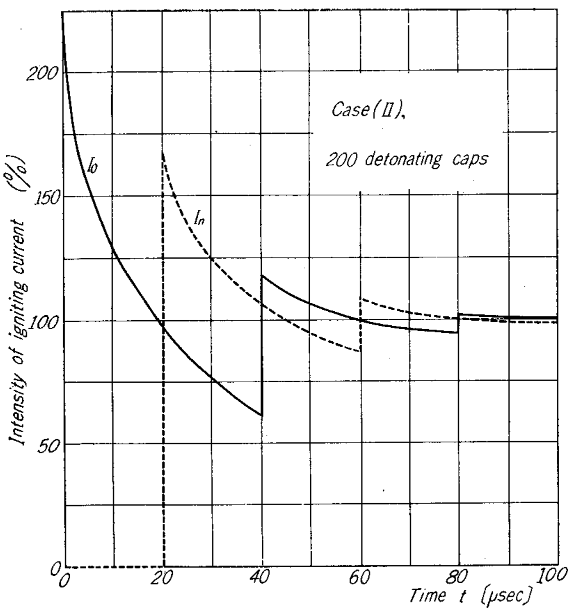

Fig. 6.

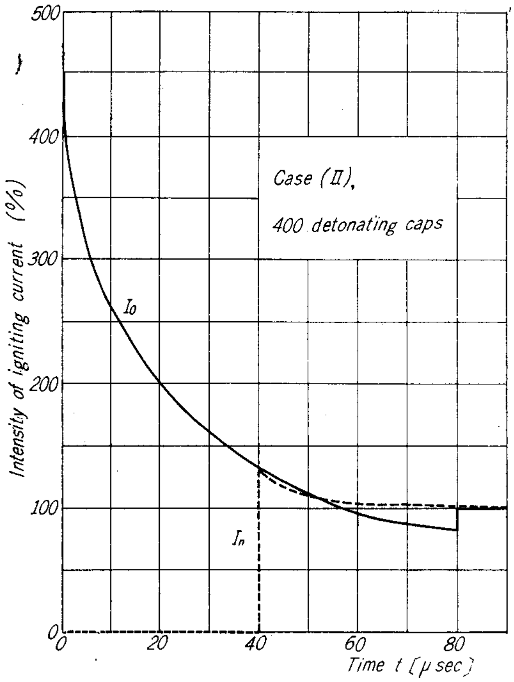

Fig. 7.

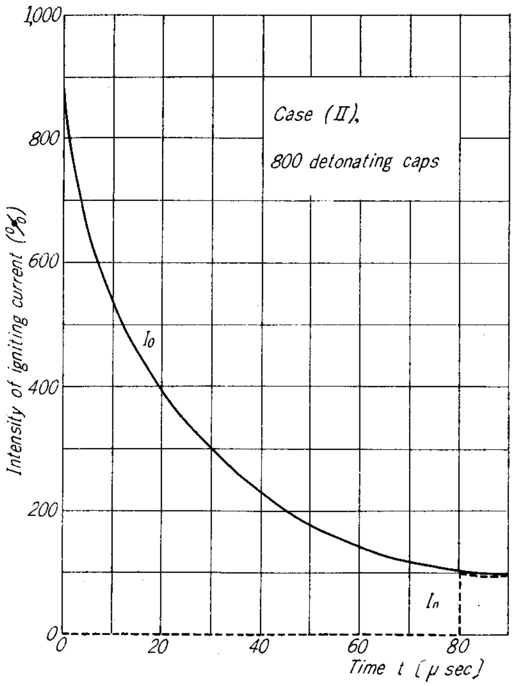

Fig. 8.

Figs. 4~8. Variation of igniting current against time.

In Figs. 4~8, each ordinate showing I_0 or I_n is arranged to indicate the current intensity by percentage based on the intensity of current at the steady state which is attained finally after some voltage is applied to the circuit. Accordingly the value 100% means the expected intensity for the case when both the earth capacitance and inductance are set nothing.

In Figs. 4~8, we can find that the current passing through both ends of the circuit grows occassionally to a remarkable intensity, and especially when the circuit contains 800 detonating caps, under the conditions shown in case (II), it approaches the intensity of 900%. After that, the intensity decreases gradually to the value in steady state, but such variation in the intensity of current gives a serious influence on the heating of fuse-heads during the activating period, because the quantity of heat given to fuse-heads increases in proportion to the square of the intensity of current.

The notable transient state in the intensity of current mentioned above is caused by the convergence and passing with a rush of charging current at both ends of the circuit as the distributed earth capacitances are charged up, being accompanied with the arrival of the progressing wave front of the igniting current, and thereafter, it becomes the steady state corresponding to the sufficient charge of all capacitances resulting from the entire progression of the wave front.

The propagation velocity of the current wave w and also the surge impedance Z_s are related to both the earth capacitance c and the inductance l as noted below.

Propagation velocity per detonating cap $w = 1/\sqrt{lc}$ [sec^{-1}],

Surge impedance $Z_s = \sqrt{l/c}$ [Ω].

Accordingly the time t_a for the current to propagate from the end terminal to the middle point along a circuit consisting of $2n$ detonating caps is shown as follows:

$$t_a = n/w = n\sqrt{lc} \quad [\text{sec}].$$

Therefore, in such circuits, the reflection of current takes place at the middle part and then at the end terminals, and consequently at those positions the current is intensified suddenly. It appears repeatedly with a period fitted to the propagation velocity and to the number of detonating caps as shown in Figs. 4~8. In a circuit which contains not so many detonating caps, it appears remarkably and frequently, but in the case where a circuit consists of more detonating caps, it is weakened to a certain degree by a decrement of the intensity at the wave front in proportion to the propagating distance along longer circuits.

5. Consideration

In Figs. 4～8, we can understand that the igniting current arrives at the middle part with a little lag from the exact time when a voltage has been applied at both ends, and furthermore that the current passing through both ends possibly comes to have a heavier intensity than the current at the middle part. Such differences in the intensity of igniting current at various positions of the circuit should be considered carefully to ensure against misfire in simultaneous firings.

In a very extreme case, it could possibly happen that the detonating cap placed at the middle part of the circuit remains in a state receiving no current in spite of the fact that a heating bridge of a detonating cap placed at both ends has sufficient heat energy to catch fire and has been fused. Indeed, we regard that the electric current which arrives at the middle part through the circuit has the same duration as the current which has passed both ends. But the former has naturally less intensity than the latter due to the gradual decay from its long distance of travelling as mentioned above.

Then, to investigate the phenomena in question in detail, we made some comparisons for the amount of heat energy given to the detonating cap under several circuit conditions for which the current-time curves had been obtained, and we studied the intensity of igniting current up to which a detonating cap placed in the middle will just miss firing.

Now, taking a common value I in the steady state, we expressed the relation between the current and the time for both ends and for the middle part in the following form,

$$I_0(t) = I \cdot f_0(t)\,, \quad I_n(t) = I \cdot f_n(t)\,. \qquad (11)$$

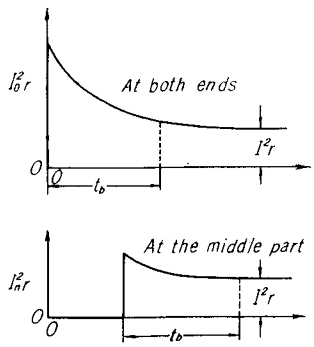

Fig. 9. Variation of electric power against time.

Then, the electric power-time curves which play an important role in heating the detonating caps placed at the respective positions can be derived from the current-time relations shown in equation (11), and the results are represented in Fig. 9. In both curves in Fig. 9, the duration of progressing current until the break down of circuit is expressed t_b, then the given heat energy to the detonating cap E_0 and E_n are written respectively as,

$$\left.\begin{aligned} E_0 &= r\int_0^{t_b} \{I_0(t)\}^2 dt = rI^2\int_0^{t_b} \{f_0(t)\}^2 dt\,, \\ E_n &= r\int_0^{t_b} \{I_n(t)\}^2 dt = rI^2\int_0^{t_b} \{f_n(t)\}^2 dt\,, \end{aligned}\right\} \qquad (12)$$

where, time 0 means the time when the detonating cap at the respective positions just gets the current.

Here, if we introduce the following intermediary functions X_0 and X_n

$$X_0 = \int_0^{t_b} \{f_0(t)\}^2 dt\,, \qquad X_n = \int_0^{t_b} \{f_n(t)\}^2 dt\,, \tag{13}$$

then X_0 and X_n can be considered as the functions of time which are necessary to convert the heat energy given to the respective detonating caps during the time t_b into the heat energy which will be given by the current in the steady state.

From equations (12) and (13), the heat energy E_0 and E_n may be written as shown in equation (14), and when the values X_0 and X_n have been calculated for a given circuit, the values of E_0 and E_n can be obtained using the intensity of the steady current which can be estimated easily corresponding to the applied voltage of the source and total resistance of the circuit.

$$E_0 = rI^2X_0\,, \qquad E_n = rI^2X_n\,. \tag{14}$$

Now, let us consider that the amount of heat energy E_0 attains to E_m by receiving the current continuously during the time t_b and just then the heating bridge of the detonating cap is fused stopping the current in the circuit from passing. Then the duration of the igniting current for the middle part of the circuit is limited to the same value of t_b. In the common duration t_b the heat energy E_n supplied to the detonating cap placed at the middle part of the circuit will attain to E_i, and if E_i is a value with which a detonating cap is barely able to catch fire, this case is a critical one in which the detonating cap placed at the middle part is just falling into misfire.

Consequently, in the first place, the values X_0 and X_n in equation (13) are calculable for successive time t from the current-time curves, $I_0(t)$ and $I_n(t)$. In the next, giving special values of E_m and E_i to E_0 and E_n in equation (14) respectively, and drawing the curves in which the intensity of steady current and its duration satisfy the relation given by equation (14), we can find the critical intensity of current and the critical duration from the intersecting point of both curves. Though this critical intensity is, of course, an imaginary one which can be expected in the steady state, it is very effective for fusing the bridge wire in its real intensified period at both ends of the circuit and hence it can activate the fuse-head so as to barely catch fire at the middle part of the circuit with its decayed intensity in the common duration. Indeed, though the currents fed to respective detonating caps have common duration as mentioned above, it must be remembered that the time when the detonating caps placed at the middle part of the circuit can catch fire critically will be delayed from the time when the detonating caps placed at end parts of the circuit are fused, depending on both the propagation velocity of igniting current and the number of detonating caps connected in series.

The properties of the heating bridge wire which is applied to the calculation in this paper are shown in Table 4 and they are identical with those of the heating bridge in actual use[9]. The fuse-head around the bridge wire is composed of a mixture of lead rhodanate, lead dinitrosoresorcinate, and potassium chlorate, and the ignition point of this mixture is reported to be 300~700°C[10].

Table 4. Properties of a heating bridge.

Composition	Pt: 90%, Ir: 10%
Diameter	0.03 mm (S.W.G. #49)
Length	2 mm
Density	21.5 g/cm^3
Specific heat	0.0323 cal/g·°C
Electric resistance at normal temperature	0.7Ω±0.1Ω
Temperature coefficient of electric resistance	+0.0013
Heat capacity	0.928×10^{-6} cal/°C
Melting point	ca. 1,750°C

The heat energy necessary to ignite this fuse-head in a comparatively short period has been recognized as 3~5 millijoules[11~13]. By the way, when the heat energy amounting to 7 millijoules has been given to the fuse-head by sudden heating under adiabatic conditions, it is considered from Table 4 that the bridge wire will be fused.

Consequently we employed the values of 3 millijoules and 7 millijoules as those which are necessary to ignite the fuse-head and to break the circuit respectively.

Based on the former current-time curves shown in Figs. 4~8, Figs. 10~14 are prepared in order to find the critical relation between the current and the time when the values of heat energy E_m and E_i attain to 7 millijoules and 3 millijoules respectively.

Each intersecting point in Figs. 10~14 shows a critical intensity of steady current and also a critical time mentioned above for respective circuit conditions. Here, in Figs. 10 and 12, both curves did not cross within the range of practicable igniting current, and in such cases all detonating caps will not misfire due to the cause under discussion.

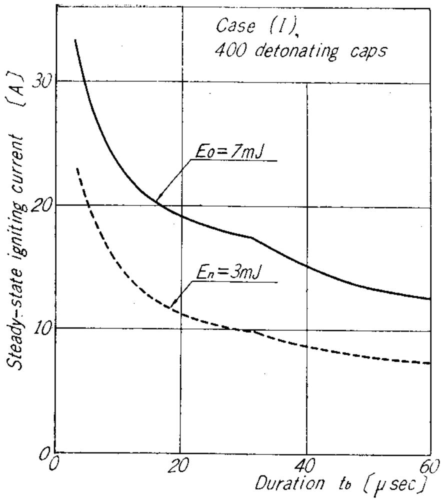

Fig. 10.

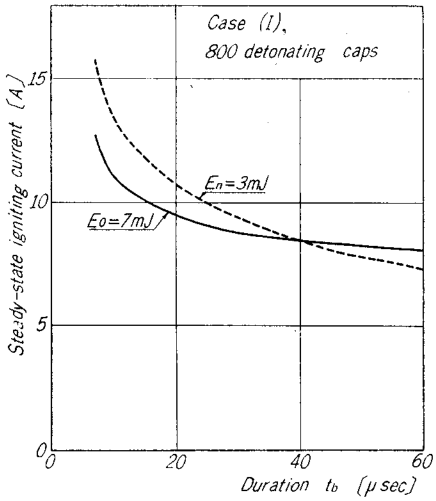

Fig. 11.

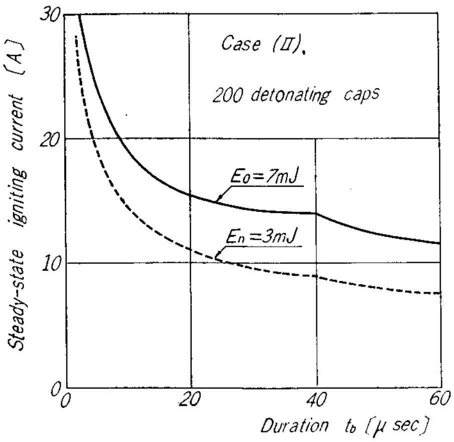

Fig. 12.

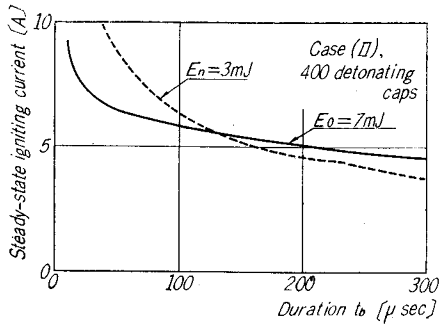

Fig. 13.

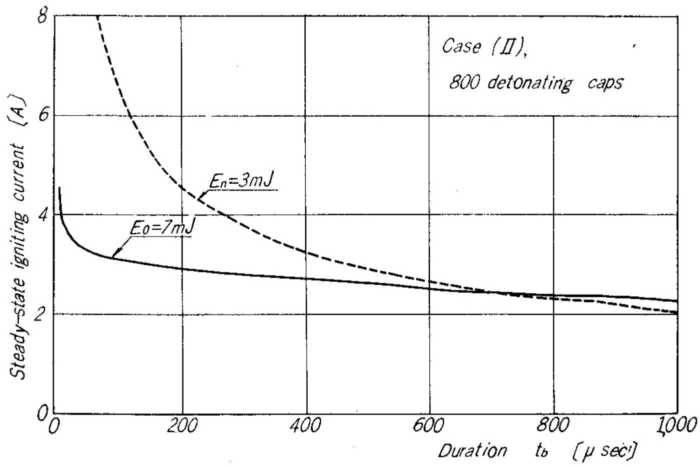

Fig. 14.

Figs. 10~14. Relation between the steady-state igniting current and the duration.

Accumulated heat energy E_0 and E_n for the case shown in Fig. 11, by way of example, are represented against time in Fig. 15. From this figure we can understand that the current is intercepted after 40 μsec from the beginning of current supply when the heat energy E_0 attains to 7 millijoules.

On the other hand, at the middle part of the circuit, the current arrives 32 μsec after the voltage was applied to the circuit, and it continues flowing during the period of 40 μsec as shown in Table 3.

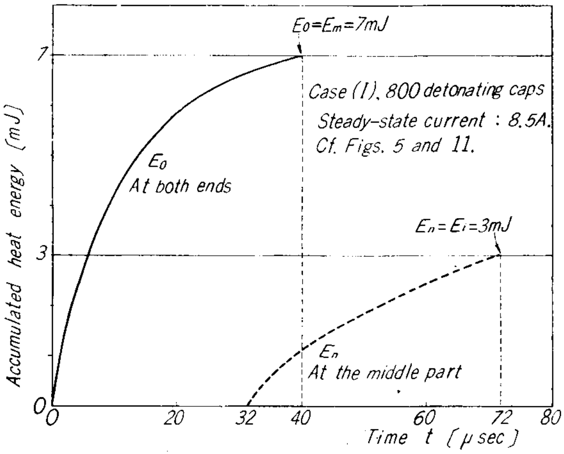

Fig. 15. Variation of accumulated heat energy against time.

Fig. 15 shows the just case in which the heat energy E_n given by this current for the detonating cap placed at the middle part comes up finally to 3 millijoules. In the same example, the critical intensity of current which brings such a delicate state is found to be 8.5 amperes as shown in Fig. 11. Then, under this circuit condition, when a higher voltage is applied to the circuit, that is, when the estimated current, disregarding earth capacitances and inductances, becomes heavier than 8.5 amperes, the detonating cap placed at the middle part of the circuit will remain misfired.

Now let us inquire into the critical intensity. To carry the current of 8.5 amperes in this circuit, the source of current is in need of a tension of 6,800 volts since the resistance of the circuit is 800 Ω, and it seems to be an unpractical tension. Therefore when a more practical tension less than the above voltage is applied to this circuit, the misfire ascribed to the logical necessity under discussion will not happen.

But we must not overlook a fact that the duration t_b in which the heat energy will be accumulated to the value of E_m may certainly be shortened because the heat of combustion may attack the bridge wire together with the heat supplied by the igniting current[14], and in consequence the heat energy E_0 given to the bridge wire may increase remarkably after the fuse-head has caught fire and attain to the value of E_m more quickly than expected. Moreover, taking into consideration that the measured values of E_m and E_i are generally expected to scatter within a considerable extent, we should regard such a circuit as the kind which still involves a considerable hazard of misfiring.

In Fig. 13, the critical current is found to be 5.6 amperes and accordingly the corresponding tension becomes 2,240 volts.

Fig. 14 shows a worse condition in which the critical current intensity is reduced to the value of 2.5 amperes. In the same figure, the duration t_b is found to be 710 μsec and it is greater than the values obtained for the other cases, and in this case the fusing of the fuse-head will surely be promoted by the additional heat of combustion. Consequently this case is considered to be in a more hazardous condition.

The important values calculated for the respective cases treated in this paper arranged in block in Table 5.

Table 5. Maximum intensities of current and other important critical conditions.

Case	Electrical constants of a detonating cap	Total number of caps connected in series $(2n)$	Source voltage [volts]	Intensity of steady current [amperes]	Duration of current (t_b) [μ sec]	Time when a cap placed at the middle part catches fire (t_a+t_b) [μ sec]	Corresponding curves	
							current-time curves	curves for critical condition
(I)	$l=10\ \mu$H	200	—	—	—	—	—	—
	$c=600\ \mu\mu$F	400	—	—	—	—	Fig. 4	Fig. 10
	$r=1\ \Omega$	800	6,800	8.5	40	72	Fig. 5	Fig. 11*
(II)	$l=10\ \mu$H	200	—	—	—	—	Fig. 6	Fig. 12
	$c=4{,}000\ \mu\mu$F	400	2,240	5.6	130	170	Fig. 7	Fig. 13
	$r=1\ \Omega$	800	2,000	2.5	710	790	Fig. 8	Fig. 14

$E_m=7$ millijoules, $E_i=3$ millijoules.
* Diagram of accumulating heat energy is shown in Fig. 15.

6. Conclusion

In a series blasting circuit consisting of a lot of electric detonating caps, the igniting current at both ends is remarkably intensified with a rush as compared to the other parts of the circuit during the switching transient state, and furthermore because of the delayed arrival and the gradual decay of progressing current wave at the middle part, a detonating cap or a group of them placed at the middle part tend to misfire even if the circuit is free from leaks.

In this paper, the igniting current forms and the amounts of accumulated heat energy are calculated for two circuit conditions which have different electrical constants and the total numbers of detonating caps used in the calculation for each condition are 200, 400, and 800. After investigating the results of those calculations we have tended to infer the logical existence of misfire in such blasting circuits disregarding any leakage.

In making up a blasting circuit with fairly many detonating caps in practice, it has been recommended hitherto to connect up the detonating caps into series-parallel, and connecting all of the detonating caps into straight series has not been recommended. However, it seems rather advice based on experience chiefly, and has still remained unexplained for its reason.

Moreover, the circuit having some leaking paths may result in a misfire which can not be distinguished from the one in this paper. Consequently if a misfire happened in a well insulated circuit, then the cause is usually ascribed to leakage, and we are apt to be led astray in considering an effective counter-move.

After discussing about misfires which belong to indistinct causes as mentioned, we have found out that the intensive current possibly causes the misfire at the middle part of the circuit under certain conditions, though it has been said that the heavier the current is, the more the reliability of ignition in a simultaneous blasting is increased.

A weak igniting current is always unsuited to simultaneous blasting. Then, a circuit which have a comparatively small critical intensity of steady current should be considered to have a narrower allowance in regard to the reliable intensity of the igniting current.

Consequently we may guess that in a certain circuit, both the higher and the lower limits in the intensity of igniting current stated above may come to approach and keep close to each other. Then the maximum number of detonating caps which can be fired simultaneously will be in existence, in relation to the circuit condition derived from the respective values of electrical constants for the detonating cap used.

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