The design of circuits for electric shotfiring

by P. C. SELIGMANN*, B.Sc. (Wits.) (Visitor)

SYNOPSIS

The theory of firing of electric detonators is developed insofar as it affects the design of blasting circuits. Practical values for the firing conditions suited to detonators of local manufacture are tabulated. The design principles of blasting circuits are outlined. This information can be used by mine management to ensure that electric blasting will be done efficiently and economically.

SAMEVATTING

Die teorie van die ontsteking van elektriese springdoppies is ontwikkel sover dit die ontwerp van ontstekingskringe betref. Praktiese waardes van die ontstekingsvoorwaardes vir springdoppies van plaaslike vervaardiging is getabuleer. Die ontwerpbeginsels van ontstekingskringe is breed beskrywe. Die inligting kan gebruik word deur mynbestuur om te verseker dat elektriese skietwerk so doeltreffend en ekonomies moontlik gedoen sal word.

Introduction

In some blasting patterns, particularly in massive orebodies, it is necessary to fire several hundred or thousand electric detonators distributed over a complex topography. The detonators, like any other electrical apparatus such as motors or lamps, must be supplied with electrical energy within specified limits if they are to give satisfactory performance. The need to ignite many detonators within a short period of time — commonly less than 5 ms — implies a very high peak power in the firing circuit. Rates of 100 to 200 kW at 1 kV are not unrealistic. Proper electrical connection of the detonators therefore requires wiring of voltage and peak-power capability comparable with those of the fixed wiring in the mine. At the same time, the temporary nature of the blasting wiring necessitates a cheaper type of installation than for permanent wiring. However, it is essential that the electrical integrity is not compromised to the extent that the detonators do not receive the correct firing energy. High-resistance joints or leaky insulation will jeopardize the blast.

For mine supervisors to be able to judge properly what level of care and attention (and therefore cost) should be given to connecting up, it is important that they should be aware of the electrical requirements of the detonators. Blasting circuits can be designed accordingly, and will provide the required electrical input with sufficient margin to allow for reasonable electrical efficiency at acceptable cost.

Electrical Characteristics of Detonators

The heart of the electric detonator is the fusehead, which consists essentially of a bead of incendiary material surrounding a thin filament of resistance wire called the bridgewire. The bridgewire is heated by the passage of an electric current and, upon reaching a certain critical temperature, ignites the incendiary composition. The duration of current that will just cause a specified percentage of fuseheads to ignite is called the kindle time.

As shown in the Addendum, the steady direct current i_k and time t_k required to kindle a fusehead are related by

$$1-\frac{i_0^2}{i_k^2}=\exp(-\beta t_k), \quad (1)$$

where i_0=minimum firing current (see below)

β=a constant describing the thermal properties of the fusehead.

The kindle times at various currents of fuseheads[1] made in South Africa have been measured. Equations of the above type were fitted to the results, using values of i_0 from the routine quality-control measurement on each batch of fuseheads. The method of least squares was used to determine the values of β that would make the equation best fit the observations. These values are tabulated with other data in Table I. The observed values for type 1 fuseheads, and the graph of the kindle-time equation that was fitted to them, are plotted in Fig. 1. It will be seen from this graph that the equation gives a very accurate representation of the measured kindle characteristics of the fuseheads. The agreement for types 0, 2, and 3 fuseheads was found to be equally good. It is therefore permissible to use equation (1) for generalizing the behaviour of these fuseheads.

Expanding the exponential in equation (1), we get

$$i_k^2\left(-\beta t_k+\frac{(\beta t_k)^2}{2}- \quad \ldots\ldots\right)=-i_0^2 \quad (2)$$

The product βt_k is always considerably less than unity at practical values of firing current, so that $(\beta t_k)^2$ and higher powers can be neglected. It follows that

$$i_k^2 t_k\approx\frac{1}{\beta}\, i_0^2, \text{ which is constant.} \quad (3)$$

The quantity $i_k^2 t_k$ represents the firing energy per unit resistance and is called the *firing impulse* (*FI*). Since β and i_0 are known constants for any particular type of fusehead, the impulse needed to fire the fuseheads is approximately constant (i.e. independent of the applied current) for each type.

At lower current when t_k becomes comparable with the thermal time constant β^{-1}, the firing impulse increases owing to the relatively more important effect of heat losses from the bridgewire. This is of no practical significance at recommended firing current or impulse; it does,

*Research Group, Explosives Division, AECI Limited, Johannesburg.

however, dictate that there is a finite current below which the fusehead will not fire no matter how long the application time. This is the i_0 of equation (1).

After the fusehead has kindled, the temperature of the bridgewire rises faster because heat of combustion is now added to the electrical heat. When the bridgewire reaches its melting point, it breaks, assisted by mechanical forces from the vigorously burning composition, and the flow of current is interrupted. The time until this occurs is the *break time*. The observed break times below which not more than 0,4 per cent of bridgewires will rupture are shown for type 1 fuseheads in Fig. 1. These observations do not fit an exponential function. They are reasonably well described by a power law that has no theoretical justification but is useful for calculation. Similar results were obtained for types 0, 2, and 3 fuseheads. The amount of energy that can be transferred by the bridgewire before it ruptures increases with increasing current.

When fuseheads are to be fired in series, it is necessary to ensure that every fusehead will be kindled before any one ruptures the circuit. Fig. 2 shows in generalized form the impulse that will ensure that at least 99 per cent of fuseheads will fire, as a function of the applied (steady) current. It also shows the energy that will be passed by at least 99 per cent of fuseheads before they break. If the

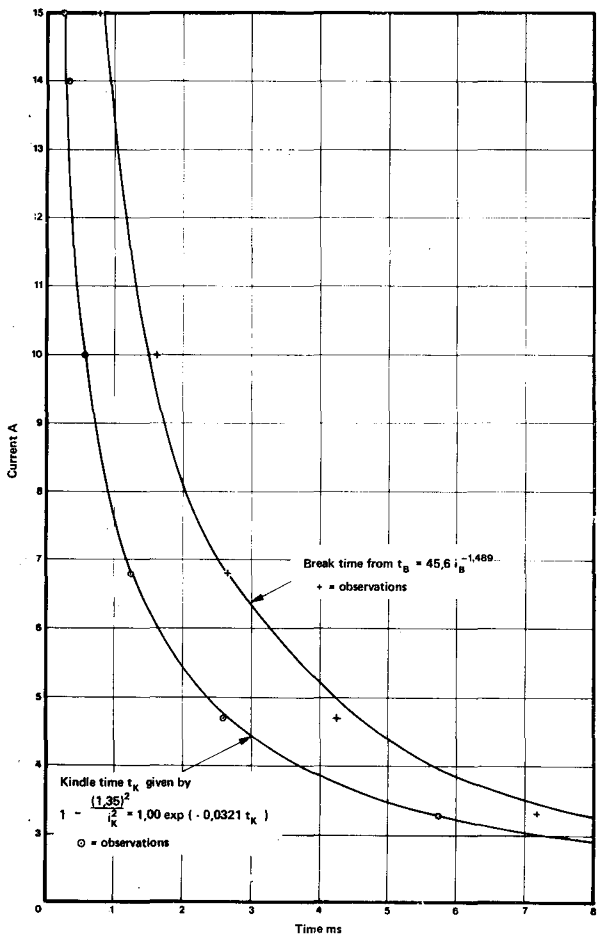

Fig. 1—The kindle and break times of service type 1 cerium fuseheads

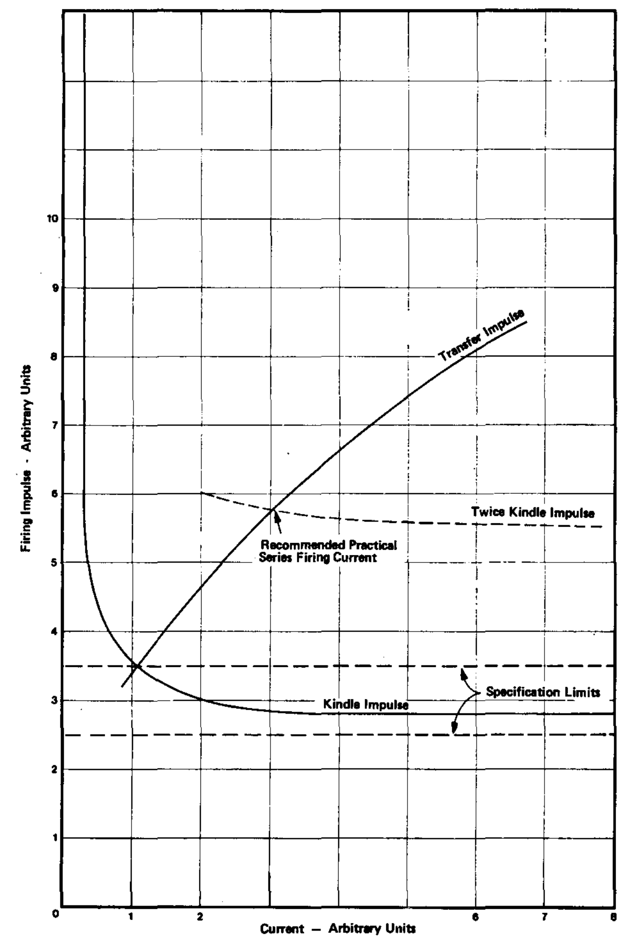

Fig. 2—Generalized characteristics of fuseheads

TABLE I

FIRING CHARACTERISTICS OF FUSEHEADS

Fusehead type*	i_0 A	β ms^{-1}	Specified firing impulse mJ/Ω Minimum	Specified firing impulse mJ/Ω Maximum	Recommended firing conditions for long series† Impulse mJ/Ω	Recommended firing conditions for long series† Current‡ A	Recommended firing conditions for long series† Time ms
0	0,45	0,055	3	5	7,4	2,30	1,4
1	1,35	0,032	50	70	120	6,55	2,8
2	3,2	0,035	300	500	700	14,1	3,5
3	6,7	0,039	1200	2000	2500	25,0	4,0

*See reference 1.
†Impulse, current, and time are related by equation (3). Safety margin of 2 applied as described in text.
‡Steady direct current.

operating current is chosen so that the 'break' curve is above the 'kindle' curve, more than 99 per cent of the shots will be satisfactorily energized.

In practice it is usual to allow a margin of safety in the choice of firing conditions. A conservative recommendation is a factor of 2 for long series (i.e. more than about 30 shots); this can be relaxed to 1,5 for fewer shots in each series of a series–parallel combination circuit. The firing current must therefore be chosen so that the impulse passed by the circuit before any fusehead breaks is twice that required to fire a fusehead. The recommended level is also shown in Fig. 2.

Table I lists the characteristics of the various types of fuseheads normally marketed in South Africa.

Firing Fuseheads with Varying Currents

In the above discussion, it was assumed that a steady direct current was applied to the fuseheads. This is seldom possible for large blasts in the field since it requires a d.c. mains supply or a large bank of accumulators. It is therefore more usual to fire the round from the a.c. mains or from a capacitor-discharge shot exploder. In the latter case, the current through the fuseheads decreases exponentially with time after switch-on at a rate depending on the time constant of the whole blasting circuit. When the shots are fired from a.c. mains, the current may increase or decrease in the first few milliseconds, depending on the phase angle of the supply at the instant of switch-on. It is shown in the Addendum that the energy required to initiate a fusehead does not change much from the d.c. value when the fusehead is supplied with current varying within practical limits: at worst, an increase of about 5 per cent in the required energy is found. This can be neglected in view of the safety factor usually applied, and the values of recommended firing impulse given in Table I for d.c. firing can safely be used for a.c. or capacitor-discharge initiation.

The impulse delivered by a varying current is given by:

$$\text{Impulse}=\int_0^{t_k} i(t)^2\, dt, \quad \ldots\ldots\ldots\ldots \quad (4)$$

where $i(t)$ is the time-varying current.

The current must be chosen so that the impulse given by this equation is at least equal to the recommended firing impulse in the recommended kindle time.

The solution of the equation in the case of a.c. mains leads to the conclusion that there is one situation in a.c. firing that is particularly unfavourable: that in which switch-on occurs on the falling wave at a phase angle of 150 to 175 electrical degrees. With random switching this will occur about 20 per cent of the time. In these circumstances, an r.m.s. value of the a.c. current several times as large as the tabulated d.c. is needed to ensure that the requisite energy is delivered to the fusehead in time. Values of the factor that must be allowed to take care of the effects of random switching and still deliver the energy specified in Table I are presented in Table II.

Impracticably large r.m.s. currents are needed to ensure the firing of a long series of detonators on a.c. mains when random switching is allowed. If a special phase-controlled switch[2] is used to ensure that the circuit is closed at the most favourable point in the cycle, a.c. firing can be done at an r.m.s. current of only 80 per cent of the equivalent d.c. The mains circuit must still, of course, be able to supply the required peak power, and this requirement usually makes the use of a mains-powered capacitor-discharge exploder a preferred choice. Where unassisted mains firing is essential, published practice[3] should be closely followed.

TABLE II

Fusehead type	Ratio of r.m.s. a.c. to steady d.c. required to deliver specified firing impulse to fusehead in worst conditions
0	5
1	3
2	2,5
3	2

When a capacitor-discharge exploder is used, the current becomes

$$i(t)=\frac{E_0}{R}\exp\left(-t/RC\right), \quad \ldots\ldots\ldots\ldots \quad (5)$$

where E_0=starting voltage of exploder at t=0
R=resistance of blasting circuit seen by exploder
C=capacitance of exploder.

This value can be substituted in equation (4) and the integral evaluated to determine the firing impulse since normally E_0, t, R, and C will be known. If the firing impulse so found is insufficient, one of the variables, usually R, must be changed to suit. These calculations are quickly done on a programmable calculator but are nevertheless a nuisance to do in the field. As there is a fixed standard range[1] of exploders available, C and E_0, which are predetermined by the exploder design, can only take a limited number of values. It is therefore possible for the capability of each of the 'standard' exploders to be calculated over a wide range of combinations of detonators in series–parallel array and for the results to be presented in graphical form.

Typical plots of this type are presented in Figs. 3 and 4. These show the capability of a type 823 exploder for type 0 and type 1 fuseheads respectively. (The 823 exploder is a large machine having an output of 800 V and a capacitance of 2000 μF. It is intended for use in underground caving and pillar-wrecking operations.) The procedure is as follows. Select the plot appropriate to the type of detonator (say, type 0) and exploder (823). Locate the leading wire length (6 m) on the left-hand vertical scale. Choose a convenient number of detonators for each series circuit (35 with iron wire). Lay a straight line from the leading wire length through the number of detonators to intersect the resistance per circuit scale (240 Ω). Run another straight line horizontally from the resistance point to the curve corresponding to the total buswire resistance (1 Ω). Drop a perpendicular to the horizontal axis, and find that up to 80 parallel circuits can be fired in these conditions.

These charts are supplied with the exploders or are otherwise available on request from the makers.

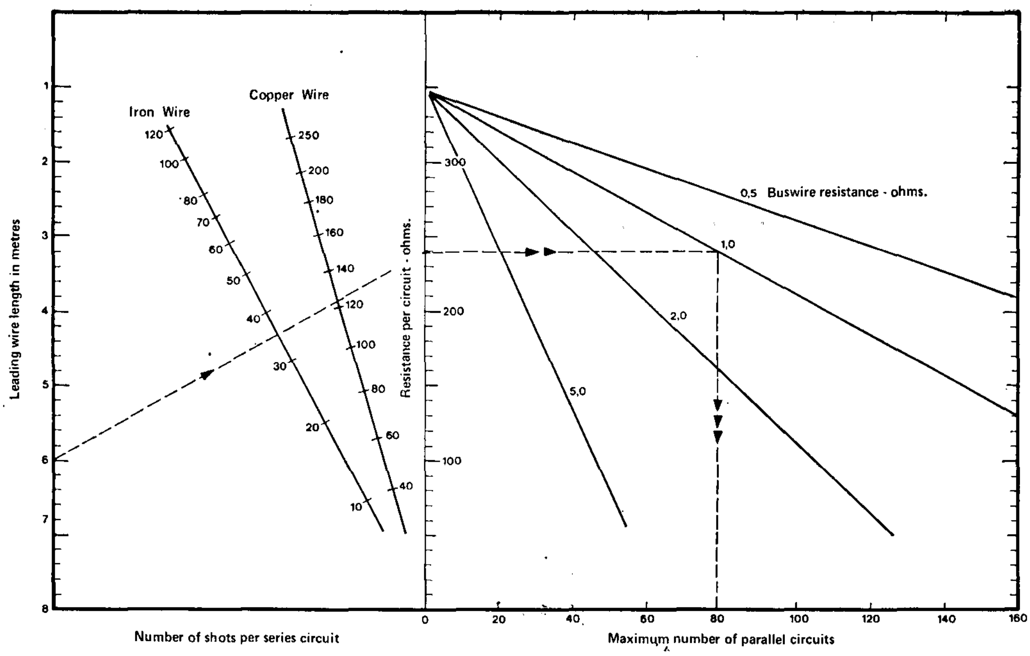

Fig. 3—Firing capabilities of type 823 exploder with type O fuseheads

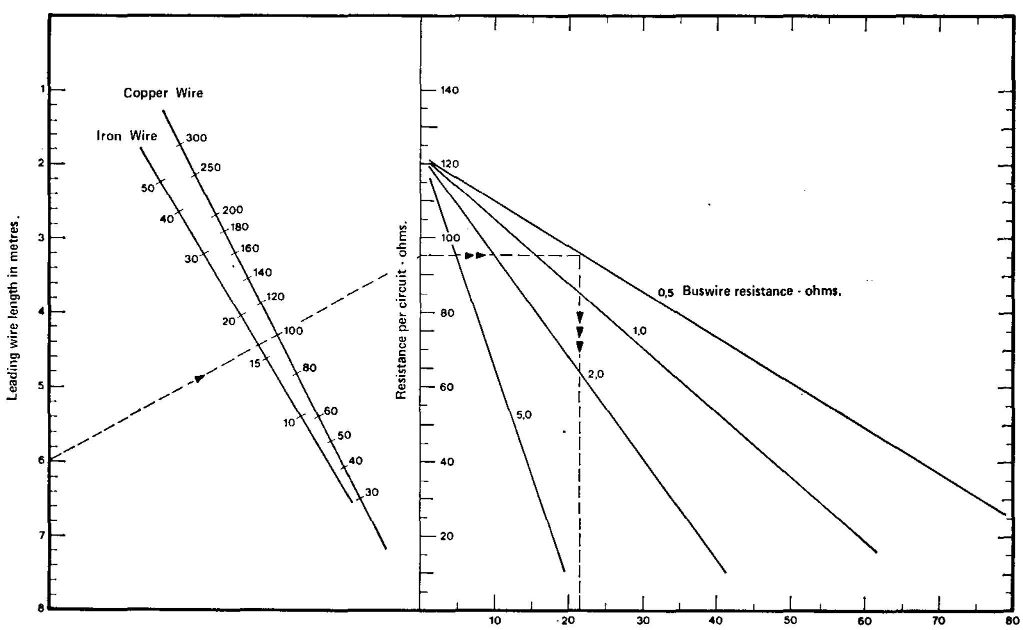

Fig. 4—Firing capabilities of type 823 exploder with type I fuseheads

It will usually be found possible to fire the required number of detonators in different series--parallel combinations. The selection of the best combination will depend on the layout of the blast, the thickness of available buswires, and the amount of effort that can be put into the testing. At one extreme the detonators may be connected into the largest series that can be fired by the exploder, leading to the smallest number of parallel circuits. This connection, which provides for the easiest testing and places the smallest demands on the capacity of the buswires, is the most susceptible to malfunction as a result of bad connecting up and current leakage to earth (see below). It is usually inadvisable to divide a single series circuit between two different areas of the blast so that in some cases long series cannot be arranged.

At the other extreme the detonators may be arranged in the largest number of parallel circuits each of relatively few detonators in series. This type of connection is very flexible in regard to blast layout, and is the most favourable arrangement to minimize the effect of earth leakage. It requires much heavier buswires and is much more trouble to test unless a special distribution panel is used.

Precautions

Careful design of the blasting circuits must be followed by equal care in executing them. There are two major reasons why a design may not perform as intended: high resistance joints between detonators, and current leakage to earth.

Although various thimbles and similar devices for joining wires are used overseas, and a plug-and-socket system is being developed locally, most blasting circuits are connected up by twisting together the detonator wires. This gives a satisfactory low-resistance joint if done tightly enough, and it is necessary to ensure that anyone helping with the connecting up is trained in effective technique. Incorrect methods lead to loose joints, particularly in the later stages of connecting up when the operators' fingers become tired. Each series circuit must be tested with an approved ohm-meter capable of reading up to about 500 Ω with single-ohm resolution. Circuit resistance should be between $\pm 0{,}5$ per cent of the value calculated from the number of detonators and the lead wire length. Greater resistance indicates faulty jointing; less resistance indicates the omission of one or more detonators from the string. These faults are readily corrected. Bad jointing may to some extent be overridden by overdesign of the output of the shot exploder.

The effect of earth leakage is much more deleterious than the mere loss of energy, which can be compensated for by an increase in the power of the exploder. If a series string of detonators has an earth-leakage resistance comparable with the string resistance, the current through the ends of the string may be twice that in the centre. When this occurs, all the detonators in the ends will break before any one in the centre is kindled, and gross misfires in the centre of the string will result. Earth leakage results from damage to the insulation of the detonator wires during charging up or from contact between the uninsulated wire at the joints and the rock face. Damaged insulation can be rectified only by recharging the hole, and must preferably therefore be precluded by good practice during charging up. Joints that cannot be held away from the face must be insulated with plastic tape or sleeves. All the circuits must be tested for leakage with an approved earth-leakage tester: the leakage resistance should be at least ten times the series string resistance. Since the effects of earth leakage cannot be compensated for by an increase in the exploder output, they must be prevented from occurring. In difficult cases — very highly conductive and abrasive orebodies — it may be preferable to shorten the series strings and use more parallel paths, even to the extreme of using parallel connection, to ensure successful blasting.

Conclusion

It has been shown that the electrical requirements for successful firing of many detonators can be met in several ways. Blasting circuits should be individually designed to meet their specific circumstances rather than relying on generalized recommendations. The investment in a large blast is so great that the costs of optimizing the design and of testing to ensure that the circuits agree with the plan are negligible in comparison with the whole. The effort in doing this will be minimized by making use of the aids to design and measurement that are available for the purpose.

Addendum: Theory of Firing of Fuseheads

This theoretical treatment is derived and extended from that of Silver and Morris[4]. It assumes that the incendiary material in a thin shell surrounding the bridgewire of a fusehead will ignite when the temperature reaches a critical value. The critical temperature does not depend on the rate of heating, and the other physical properties of the system are also regarded as constant during the heating period. These simple assumptions lead to an equation that describes the behaviour of fuseheads with more than sufficient accuracy for practical mining and industrial purposes. The more rigorous treatment by Davenport and Reynolds[5], intended for military and aerospace applications, does not give any practical improvement although it involves considerable cost in computational effort.

It is assumed that

- T = temperature of bridgewire
- T_k = critical temperature of bridgewire at which fusehead will ignite
- T_0 = ambient temperature
- l = length of bridgewire
- a = radius of bridgewire
- r = resistance per unit length of bridgewire
- c = heat capacity of bridgewire per unit length
- p = rate of heat loss from bridgewire to surrounding shell of incendiary per unit area of bridgewire surface
- t = time
- t_k = kindle time, i.e. time for which current must flow for bridgewire to reach T_k
- i = instantaneous value of current
- i_0 = minimum firing current for the fusehead type
- I_{dc} = steady value of direct current
- I_{rms} = rms value of alternating current
- I_{t0} = starting value of capacitor discharge current.

Then, by consideration of the heat flow into and out of the bridgewire and by reduction to unit length,

$$\frac{dT}{dt}=\frac{ri^2}{c}-\frac{2\pi ap}{c}(T-T_0).$$

By substitution of $\beta=\frac{2\pi ap}{c}$ and rearrangement of the terms,

$$\frac{dT}{dt}+\beta T=\frac{ri^2}{c}+\beta T_0 \quad \ldots\ldots\ldots\ldots (6)$$

The term β represents the ratio of thermal conductance from the bridgewire to its thermal capacity: it is thus the inverse of the thermal time constant.

The complete solution of this differential equation depends on whether i is a function of t. Three cases are of practical interest.

(a) *Constant-current firing*, i.e. $i=I_{dc}$

The solution of (6) is

$$rI_{dc}^2=\frac{\beta c\,(T-T_0)}{l-\exp(-\beta t)}$$

and, at the critical condition where the fusehead just kindles,

$$ri_k^2=\frac{\beta c(T_k-T_0)}{1-\exp(-\beta t_k)} \quad \ldots \ldots \quad (7)$$

As $t \rightarrow \infty$, the critical current is, by definition, i_0 so that

$$ri_0^2=\beta c(T_k-T_0) \quad \ldots \ldots \quad (8)$$

By substitution of this boundary condition (8) into (7) and rearrangement of the terms,

$$1-\frac{i_0^2}{i_k^2}=\exp(-\beta t_k) \quad \ldots \ldots \quad (9)$$

Since β and i_0 are measurable constants, equation (9) is a sufficient description of the relationship between kindle time and applied constant current.

(b) *Capacitor-discharge firing*, i.e. $i=I_0 \exp(-\alpha t)$, where α=the inverse time constant of the firing circuit.

The solution of equation (6) becomes

$$rI_{t0}^2=\frac{\beta^{-2\alpha}c(T-T_0)}{\exp(-2\alpha t)-\exp(-\beta t)} \quad \ldots \ldots \quad (10)$$

If (8) is substituted into (10) under conditions at the critical point,

$$\frac{i_0^2}{I_{t0}^2}=\frac{\exp(-2\alpha t_k)-\exp(-\beta t_k)}{1-{}^{2\alpha}/_{\beta}} \quad \ldots \ldots \quad (11)$$

(c) *a.c. firing*, i.e. $i=\sqrt{2}\, I_{rms} \sin(nt+\lambda)$

The solution of equation (6) becomes, with the same boundary conditions as before,

$$\frac{i_0^2}{I_{rms}^2}=\cos\phi\Big\{\exp(-\beta t_k)\cos(2n\lambda-\phi)-\cos(2n\lambda+2nt_k-\phi)\Big\}+1-\exp(-\beta t_k) \quad \ldots \quad (12),$$

where λ=tne phase of the a.c. supply at the instant when the current is switched on

$\phi=\tan^{-1}(2n/\beta)$.

For each of these cases we can now calculate the magnitude of the current that is needed to fire the fusehead in time t_k as a function of time.

The firing impulse in each case can then be calculated from

$$\mathrm{FI}=\int_0^{t_k} i^2 dt \quad \ldots \ldots \quad (13)$$

by substitution of the appropriate function for i.

If the time required to kindle the fusehead is short compared with the thermal time constant β^{-1}, it wouldbe expected qualitatively that the effects of heat loss would be small and thus the time-dependence of the applied current would have relatively little effect. Since β^{-1} is of the order of 20 ms for ordinary fuseheads, this will usually be the case. Table III shows the calculated ratio of firing impulses for different conditions, and it will be seen that at kindle times up to 4 ms the effect of current waveform is negligible.

TABLE III

FIRING IMPULSE RELATIVE TO d.c. FIRING

Kindle time ms	Capacitor discharge circuit: Time constant of 2 ms	Time constant of 4 ms	Time constant of 8 ms	50 Hz a.c. mains firing (worst phase)
1	1,005	1,005	1,000	1,001
2	1,018	1,010	1,005	1,002
3	1,023	1,020	1,010	1,002
4	1,028	1,026	1,012	1,005

Acknowledgements

The author thanks the Management, Explosives Division, AECI Limited for permission to publish this paper. The assistance of I. C. Roselman in the preparation of the Addendum is also gratefully acknowledged.

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