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EXPLOSIVE INITIATORS*

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ABSTRACT

Design characteristics of the two major detonator types, hot wire and exploding bridgewire, are presented. The theory of operation of each detonator type is developed and related to practical firing set systems. Handling safety and frequently encountered hazard situations are discussed.

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I. INTRODUCTION

A problem encountered in all explosive operations is that of initiating the detonation wave in the explosive. This problem is complicated by the fact that it must be done easily, safely, and often with precisely controlled timing at widely separated points. A variety of devices, called detonators, have been developed to perform the function of initiation. Two common detonator types, appropriate for the sort of applications to which this symposium is devoted, are discussed in this article. Each of these detonators employs electrical energy to initiate relatively sensitive explosives from which the detonation can be transferred through a sequence of explosives (an "explosive train" or "lead") of decreasing sensitivity and increasing output until a detonation of sufficient strength to fire the main charge has been developed.

The first detonator type to be discussed, the hot-wire detonator, has an explosive train starting with a very sensitive primary explosive, and thus employs only a very small amount of electrical energy, which can be delivered by such simple sources as batteries or magnetos. Electric blasting caps are examples of this type of detonator. The second detonator type, called the exploding bridgewire or EBW detonator has an explosive train starting with a less sensitive secondary explosive but requires a more elaborate power source to vaporize ("explode") a wire by extremely rapid deposition of electrical energy to initiate detonation in this material. The hot-wire detonator has the advantages of lower cost (35¢ to \$5.00) and easier firing, whereas the EBW detonator (~ \$7.00) is safer and can be fired with more precise timing. Brief mention will be made of other special purpose initiators -- primarily to afford the opportunity of suggesting that most of them not be used.

This article is directed toward two very different groups of readers. First, there are those applying explosives to commercial, military, or research problems, who must select and make proper use of commercially available detonators. The second group consists of those designing explosively-actuated devices and who may actually have to design their own special detonator.

In Section II of this article the design and operation of the various types of initiators is discussed. Section III is devoted to some remarks on hazard situations involving detonators, and to some mention of safe handling practice. Since the use of EBW detonators necessitates having a special (although relatively simple) "firing set" to provide the electrical pulse that fires the detonator, we discuss the design of such a firing set in Section IV. Finally, since standard detonators often either do not provide sufficient output to initiate detonation in insensitive main-charge explosives, or additional explosive elements are required for wave shaping, Section V provides a brief summary of explosive train design.

Unfortunately, in a survey article based largely upon the work of others, it is difficult to properly reference all sources. Consequently, where directly applicable, specific references are provided; on points of general background interest, however, the reader is referred to several excellent texts and conference proceedings on the subject (see in particular references 4, 8, and 16).

-3-

II. DETONATORS

Even within the limited field of the work discussed in this symposium so much diversity exists that it is difficult to set precise guide lines for detonator selection. For this reason it is the intent of this report to provide a general description and a simplified theory of operation of hot-wire and EBW detonators. The theory developed can then be utilized to relate detonator characteristics to properties of the firing source and as a guide to safety requirements. The best detonator to use in a given application can then be selected on the basis of system considerations.

Hot-Wire Detonators

The oldest and most familiar detonator type is the hot wire detonator similar to electric blasting caps such as DuPont type ELA(6) or Hercules No. 4EB electric detonators.^{1,2} Construction details of an idealized hot wire detonator are shown in Fig. 1. Three major explosive components are generally present: an easily-ignited ignition or flash charge in close contact with the bridgewire, a primary explosive primer charge of sufficient strength to initiate a secondary explosive output or base charge. Typically, lead styphnate may be used as the ignition charge. The ignition charge reacts slowly in comparison to the detonation reaction of the lead azide primer charge. For applications requiring very accurate timing, detonators utilizing lead azide ignition charges are generally selected. A word of caution is in order, however; many such detonators were developed for military applications and may be overly sensitive in comparison to blasting caps. For example, the Atlas T2OE1, which utilizes a lead azide

ignition charge, has an all-fire* energy level of only 5000 ergs,³ hence must be used with care.

Because of the high sensitivity to initiation of the primary explosives used in hot-wire detonators, one of the main jobs of the detonator designer is to package the explosive in such a way that its effective sensitivity is reduced to an acceptable level, i.e. it must be sufficiently difficult to initiate detonation of the package that it can be handled and used safely. This section is devoted principally to a discussion of how this is accomplished, and what the results have been in the case of a common commercial blasting cap.

Most researchers view the ignition of primary explosive compounds as strictly a thermal process.⁴ Quantitatively, the ignition of primaries occurs as a result of raising the temperature of a very small critical volume (on the order of one or two cubic mils) to approximately 300°C.⁵ Since the critical volume of primaries is so small, the analysis of hot wire detonator behavior is generally based on the assumption that, if any portion of the bridgewire can be heated to the 300°C critical temperature, initiation will result. Thus, the analysis of initiation behavior of hot-wire detonators is reduced to a simple thermal calculation of the wire temperature. Among the earliest studies utilizing these concepts is

* There is, of course, some statistical variation in the amount of electrical current, energy, etc. required to fire samples selected from a lot of nominally-identical detonators. Three levels are frequently mentioned: (1) The all-fire level is that at which some desired reliability (say 0.9999) of firing is achieved, (2) the threshold level is usually taken to be that at which 50% of a sample of detonators will fire, and (3) the no-fire level is that level of stimulus that the detonator can tolerate for an extended period of time with some high assurance that it will not fire.

the work of Rosenthal⁶ who, from energy balance considerations, proposed that hot wire detonator behavior could be described by the differential equation

$$C_p \frac{dT}{dt} + aT = P(t) , \quad (1)$$

where T is the increase in heater-wire temperature, C_p is the heater-wire heat capacity (which depends on the volume of the wire and the material of which it is made), a is a heat loss factor which depends on many details of the detonator design, and $P = I^2 R$ is the input electrical power to the heater wire. The current $I(t)$ in the heater wire depends principally on the type of power source. The wire resistance, which we take to be of the form $R = R_0(1+bT)$, depends on the size of the wire, the material of which it is made, and on its temperature. Resistance variation with temperature is usually small and can often be neglected.

Equation(1) says simply that two things happen to the input electrical power $P(t)$: Part of it goes to heat the resistance wire, and part of it is dissipated through heat conduction from the wire through the leads or the explosive charge to the case, and thence to the environment. To study the dependence of detonator performance on the various parameters, we examine solutions of Eq. (1) for several situations of particular interest.

Firing by Low-Level Direct Currents

In ordinary use, hot wire detonators are fired by connecting them to a constant current source such as a battery. (We assume the battery and firing lines to be of sufficiently high impedance that the current delivered to the detonator doesn't vary significantly due to the temperature-induced change in heater-wire resistance.) In this case Eq. (1) takes the form

$$C_p(dT/dt) + aT = I^2 R_0(1+bT) \quad , \quad (2)$$

where I is constant, and has the solution

$$T = \frac{I^2 R_0}{a - I^2 R_0 b} \left[1 - \exp \left(- \frac{a - I^2 R_0 b}{C_p} t \right) \right] \quad , \quad (3)$$

for the case where heating starts from ambient temperature at $t = 0$.

When the parameters are known, this solution gives the temperature history of the heater wire, and can be used to infer the time required for the detonator to fire at various current levels. Discussion of a practical case is given later in this section. Before dealing with this example, however, we may usefully examine Eq. (3) to see the effect of changing various parameters. In ordinary use, detonator firing takes place in times short compared to the characteristic time, C_p/a , in Eq. (3), so we can approximate the equation as

$$T = \frac{I^2 R_0}{C_p} t \quad . \quad (4)$$

We see that the loss factor has little influence on ordinary firing, and that such firing takes place in a time proportional to the rate of energy deposition and inversely proportional to the heat capacity of the wire. At long times after the beginning of current flow, the heating transient will vanish, leaving the wire at an equilibrium temperature T_∞ given by

$$T_\infty = \frac{I^2 R_0}{a - I^2 R_0 b} \quad . \quad (5)$$

When this equation is written in the form

$$I = \sqrt{\frac{T_\infty a}{R_0(1+bT_\infty)}} \quad (6)$$

it lends itself to determination of the no-fire current for the detonator, i.e. the steady current the detonator can carry without the temperature exceeding the critical value for firing. We see that a detonator having a large no-fire current must be designed to have low resistance and a large loss factor. We have seen previously that decreasing the wire resistance may increase the function time of the detonator but the loss factor, insofar as it can be changed without altering the ratio R_0/C_p , has little influence on the function time under normal operating conditions.

If there is no heat loss from the wire, i.e. if $a = 0$, then the solution of Eq. (1) is

$$T(t) = \frac{1}{C_p} \int_0^t P dt \quad , \quad (7)$$

which can be written

$$T = E/C_p \quad , \quad (8)$$

since $\int P dt$ is just the deposited energy E . Thus we see that, in this case, the firing criterion is one of energy. One must supply enough energy to heat the wire to the critical temperature of the explosive. Since the assumption of no heat loss is conservative, this criterion can safely be used to estimate no-fire levels for various transient current waveforms.

Capacitor-Discharge Heating

In applications where precise timing of detonator firing is important, a capacitor-discharge firing circuit is used. In this case the power source term $P(t)$ in Eq. (1) is that obtained by discharging

a capacitor of capacitance C charged to a voltage V_0 through the heating-wire resistance, and the solution of Eq. (1) is

$$T = \frac{V_0^2}{RC_p \left(\frac{a}{C_p} - \frac{2}{RC} \right)} \left[\exp \left(- \frac{2t}{RC} \right) - \exp \left(- \frac{at}{C_p} \right) \right], \quad (9)$$

where, for simplicity, we have neglected circuit inductance and assumed the heater-wire resistance to be constant. The behavior of this solution is discussed below in connection with a specific example.

Example

A fairly wide range of values of the various parameters can be achieved by proper detonator design. It may be of general interest to evaluate Eqs. 2 through 9 for the DuPont No. 6 blasting cap. From the published specifications the parameters of interest are, or can be estimated to be,

I (No Fire) -----	0.1 ampere
I (All Fire) -----	0.5 ampere
R_o -----	1.1 ohm
T (Explosion Temp.) -----	300. °C
a -----	400. erg/°C sec
b -----	$1.3 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$
C_p -----	$16 \times 10^{-6} \text{ watt sec/}^\circ\text{C}$

Plots of Eqs. 3 (using the above parameters) are shown graphically in Figs. 2 and 3. Figure 2 presents bridgewire temperature histories for various constant current levels from the 0.1 A (no fire) value to above the 0.5 A (all fire) current. Evaluation of Eq. 6 yields a "maximum" steady state value ($T = 300^\circ\text{C}$) of 0.1 A in agreement with the listed "no fire" current specification. The relatively low bridgewire temperature is also evident in Fig. 2. Note also that the no-fire level corresponds to a power input of 120,000 erg/sec = 12 milliwatts. Finally, Eq. 8 may be evaluated to yield an estimated minimum firing energy of 48,000 ergs.

Figure 3 depicts the expected firing behavior of the No. 6 blasting cap when fired by a one microfarad capacitor charged to various voltages, assuming a circuit resistance, including bridgewire, of one ohm. It is apparent that temperatures exceeding the minimum initiation temperature can be achieved in sub-microsecond times. Although the styphnate-containing No. 6 blasting cap would be unsuitable for very precise timing, it is reported that capacitor discharge systems, when coupled to hot wire detonators containing lead azide ignition charges, can produce detonator firing simultaneities (i.e. the standard deviation in output from a group of detonators fired simultaneously) approaching 0.1 μsec .

In summary, Eqs. 2 through 9 and Figs. 2 and 3 provide a straightforward and logically consistent method for estimating hot wire detonator performance and, for safety considerations, maximum permissible no-fire energy and power input values. In considering safety problems, however, it is important to note several additional points which, though implied, were not directly stated in the analysis. Although a firing energy of 48,000 ergs was derived for a common detonator type, this relatively high energy is in actuality the result of the designer's skill in packaging the explosive, and is a minimum firing energy, only if it is deposited in the wire. The very small critical volume of primary explosives and their purely thermal initiation dependence, results in a very small true explosive initiation energy threshold. Although the exact specification of this threshold is a complex problem, it nonetheless cannot exceed a few ergs for primaries such as lead azide. These low firing energies are clearly demonstrated by high-resistance detonators such as the carbon bridge and conductive mix types, which may exhibit detonations at stored energies of less than 10 ergs when fired by capacitor discharge. It is clear that such detonators should only be used by trained personnel in special situations; they have no place in ordinary engineering operations.

The important point being made is that hot-wire detonators must be considered as devices containing a 1 erg explosive desensitized 3 to 4 orders of magnitude by the bridgewire. If, however, thermal energy can be coupled directly to the explosive, say by an internal electrostatic spark from the wire to the case, an explosion will in all likelihood occur even though the available energy is extremely small.

Exploding Bridgewire Detonators

The newest and perhaps least familiar detonator of practical importance is the exploding bridgewire or EBW detonator. Typical of EBW detonators are the Type RP.1 and RP.2 units produced by Reynolds Industries.⁷ Construction details of an idealized EBW detonator are shown in Fig. 4. It can be seen that the major construction difference between the EBW and the hot wire detonator is that secondary explosives are utilized in the EBW in replacement of the primary explosive ignition and primer charges. From the standpoint of safety, the elimination of primaries is very significant. This follows since secondary explosives, unlike primaries, require more complex stimuli than simply elevation of their temperature to detonate.⁸ For example, the application of a flame to secondaries under most situations produces only a relatively slow burning. For prompt detonation, secondary explosives require not only a relatively high energy input, but in addition, the rate of delivery of this energy to the explosive must be extremely rapid. Such rapid delivery rates are usually achieved only as the output from other explosives. In other words, secondary explosives are typically initiated by the shock wave generated by the detonation of another explosive. In hot wire detonators this shock wave is produced by the primer charge. In EBW detonators this initiating shock wave is generated by the electrical explosion of the bridgewire, i.e. the rate of energy deposition into the bridgewire is so rapid that energy densities approaching those of explosives can be realized within the wire.^{9,10} As a consequence of this rate requirement on the energy deposition for a bridgewire explosion, the possibility of accidental initiation of an EBW detonator is greatly reduced.

It should be noted that, whereas hot wire detonators utilize an overly sensitive explosive and in effect degrade this sensitivity by proper detonator design, the problem in EBW detonators is to find a secondary explosive sufficiently sensitive to be initiated by the small, highly divergent shock developed by an exploding wire. This problem has been resolved by utilizing an intrinsically sensitive secondary explosive, generally PETN (pentaerythritol tetranitrate), loaded as a low density granular powder of controlled particle size and shape. These latter properties are of great importance since order of magnitude increases in sensitivity are observed in low-density powder compacts as compared to high density explosives. Even though the effective sensitivity of secondary explosives may be increased by the proper selection of physical parameters, such materials are still 3 to 4 orders of magnitude less sensitive than primary explosives.

Typically EBW detonators must be fired by a fast capacitor discharge (LRC circuit) in which the observed detonator current and bridgewire resistance waveforms appear as shown in Fig. 5. As the wire temperature increases due to I^2R energy deposition, its resistance increases and reaches a maximum during vaporization of the wire.¹¹ The increase in resistance in the circuit (which causes the dip in the current waveform shown in Figure 5) is actually terminated by the occurrence of a spark breakdown at the bridgewire-explosive interface. The spark breakdown drives a shock wave which causes initiation of the granular explosive.

Several EBW detonator firing criteria have been proposed; the burst current criterion is the simplest of these to utilize in field situations.

Consider Fig. 5. If the bridgewire current flowing at the time of peak wire resistance is denoted as the burst current I_b , then it has been experimentally observed that for a given detonator type there exists a particular value of I_b , designated the threshold burst current I_{bth} , which if realized will produce 50% firing of a given detonator sample.^{9,12} Expressed another way, EBW detonators can be characterized in terms of an I_{bth} threshold that is a property only of the detonator and is independent of any particular current profile or firing system. This I_{bth} criterion may be theoretically justified and extended to include wire parameters through the following analysis. Assume there exists a critical peak power input, P_{crit} , which must be exceeded if explosive initiation is to result, i.e. the maximum power P_{max} delivered to the detonator must be such that

$$P_{max} = I_b^2 R_{max} \geq P_{crit} \quad (10)$$

It follows from Ohm's law that

$$I_{bth} = \frac{d}{\sqrt{\ell}} \sqrt{\frac{P_{crit}}{\rho_{max}}} = K \frac{d}{\sqrt{\ell}} \quad (11)$$

where ρ_{max} is the maximum wire resistivity, d and ℓ are the bridgewire diameter and length respectively, and $K \equiv \left[P_{crit} / \rho_{max} \right]^{1/2} = \text{constant}$.

The coefficient, K, has been experimentally shown to be dependent on several parameters, and when this dependence is inserted in Eq. (11),

I_{bth} for gold bridgewires in PETN can be expressed as⁹

$$I_{bth} = \frac{d}{\sqrt{\pi}} \left[850 + 35.5 \frac{(l d s_o^P \times 10^{-3} - 120)}{(l d s_o^P \times 10^{-3})^{3/2}} \right] \left[\frac{1}{(1.88 - \delta)^3} \right] \left[1 - \frac{2 \times 10^{-2}(T-24)}{\sqrt{\pi}} \right] \quad (12)$$

where d and l are in mils,

s_o^P = specific surface of the granular PETN explosive in cm^2/g , δ = explosive density in g/cm^3 , and T = temperature in °C. For most properly designed EBW detonators Eq. 12 may be approximated as $I_{bth} = 850d/\sqrt{\pi}$.

For the most common EBW detonator bridgewire (1.5 mil diameter by 40 mil length gold wire), the approximate equation predicts I_{bth} to be 201 amperes as compared to an observed value of 225 amperes.

In the above analysis we have derived a measure of EBW detonator sensitivity. For firing set design the question which must now be answered is: For a given detonator, will a given choice of firing set parameters result in a burst current meeting or exceeding the required threshold burst current? To answer this question it will be necessary to introduce one additional concept, the concept of bridgewire action input. If it is assumed that the energy required for adiabatic heating of the bridgewire from a nominal ambient temperature to complete vaporization is unique, then from energy conservation it follows that

$$I^2 R_o(e) dt = M de \quad , \quad (13)$$

where $R(e)$, the dynamic bridgewire resistance, is an unique function of the specific energy e and M is the bridgewire mass. The integration of Eq. 13 yields

$$\int_0^{t_b} I^2 dt = M \int_0^{e_b} \frac{de}{R(e)} \quad (14)$$

From Ohm's Law Eq. 14 can be written as

$$\int_0^{t_b} I^2 dt = \frac{DA\ell}{\ell/A} \int_0^{e_b} \frac{de}{\rho(e)} \quad (15)$$

where D , A , and ℓ are the bridgewire density, cross-sectional area and length respectively and $\rho(e)$ is the dynamic wire resistivity. The specific energy integral appearing in Eq. 15, although complex, can be evaluated and within practical limits is single valued. Consequently, all of the terms in the right side of Eq. 14 may be evaluated. Defining the quantity $\int_0^{t_b} I^2 dt$ as the burst action, G_b , we may write Eq. 15 in the form

$$G_b = g d^4 \quad (16)$$

where g is the action coefficient to burst, a function only of wire material. For gold, $g = 0.022 \text{ A}^2 \text{ sec/mil}^4$, thus for a typical 1.5 mil diameter bridgewire

$$G_b = (0.022)(1.5)^4 = 0.11 \text{ A}^2 \text{ sec.} \quad (17)$$

Equation 17 then specifies that for a 1.5-mil diameter gold bridgewire, burst (vaporization) of the bridgewire will occur when the time integral of the input current is $0.11 \text{ A}^2 \text{ sec}$, independent of the current waveform utilized.

These two concepts, action and burst current, are utilized in firing set design as follows. First, sufficient energy must be supplied to the bridgewire to vaporize the wire, i.e. to produce bridgewire burst. The analysis of a firing set is simply the determination of a solution to a differential equation describing the electrical circuit in terms of circuit current and time. Action, a quantity equivalent to energy, also involves only current and time, and thus provides the simplest method of predicting the occurrence of burst. The second requirement for initiation, as previously discussed, is that the circuit current at the time of burst exceed the detonator threshold burst current, I_{bth} . Since the solution of the circuit equation also yields the burst current when the action requirement is satisfied, all parameters required for predicting the behavior of an EBW firing set system are known. To illustrate the method we consider a capacitor discharge firing circuit described by the differential equation.

$$L \frac{dI}{dt} + I(R_w + R) + \frac{1}{C} \int I dt = 0 \quad (18)$$

In this equation L , R , and C are the circuit inductance, resistance, and capacitance respectively and R_w is the dynamic bridgewire resistance. The behavior of such a circuit is shown in Fig. 5. Although the peak bridgewire resistance is relatively high (~ 10 ohms), it is much lower for most of the heating cycle and is negligible in comparison to circuit resistance. For many practical circuits, bridgewire resistance thus may be neglected, allowing Eq. 18 to be solved analytically (if R_w cannot be neglected a numerical solution is generally necessary) yielding a predicted circuit current of

$$I = \frac{V_0}{L\omega} e^{-\frac{Rt}{2L}} \sin \omega t, \quad (19)$$

where

$$\omega = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}},$$

and

V_0 = the initial capacitor voltage,

L = stray inductance of the circuit (which must be kept as low as possible)

R = circuit resistance,

C = circuit capacitance,

I = instantaneous current,

t = time.

Integrating the square of Eq. 19 to compute the burst action G_b yields

$$G_b = \frac{\frac{V_0^2}{L\omega}}{(R/L)^2 + \omega^2} \left\{ \frac{2\omega^2}{R/L} \left[1 - \exp\left(-\frac{Rt_b}{L}\right) \right] - \left[(R/L) \sin \omega t_b + 2\omega \cos \omega t_b \right] \exp\left(-\frac{Rt_b}{L}\right) \sin \omega t_b \right\} \quad (20)$$

Typical EBW circuit parameters are,

$$G_b = 0.11 \text{ A}^2 \text{ sec (1.5 mil dia. gold wire)}$$

$$L = 1.0 \text{ } \mu\text{H}$$

$$R = 1.0 \text{ ohm}$$

$$C = 1.0 \text{ } \mu\text{F}$$

$$V_0 = 2.0 \text{ kV.}$$

Plots of Eqs. 19 and 20 utilizing the above parameters and various values of V_0 are shown in Fig. 6. Also shown in the figure is the I_{bth} value (225 A) for the 1.5 mil-diameter by 40-mil long gold bridgewire EBW detonator. Estimated burst currents (neglecting the current dip

that occurs concurrently with wire vaporization) are given by the intersection of the dashed curve denoting attainment of the burst action ($G = 0.11 \text{ A}^2\text{sec}$) and the various current curves shown. It is recommended that only systems producing burst currents several times greater than threshold should be utilized operationally ($V = 1000$ volts for example). At these current levels bridgewire burst occurs in sub-microsecond times and, as a result of the prompt initiation of the PETN by the resulting shock wave, produce highly reliable actuation and excellent timing simultaneity (within $0.1 \text{ } \mu\text{sec}$).

The approximate effect of various parameters upon burst currents can be more clearly seen by a further simplification of Eq. 18. If it is assumed that the current input to the bridgewire is simply a "ramp" with a rate of rise equal to the initial rate of current rise in an LRC circuit then

$$I = \frac{V_0}{L} t \quad , \quad (21)$$

and

$$G_b = \left(\frac{V_0}{L} \right)^2 \frac{t_b^3}{3} \quad . \quad (22)$$

Substituting Eq. 21 into 22 yields

$$I_b = \sqrt[3]{\frac{3V_0 G_b}{L}} \quad . \quad (23)$$

Thus we see, in approximation, that the burst current is directly proportional to the cube root of the product of the initial capacitor voltage and burst action, and is inversely proportional to the cube root of the circuit inductance. A brief discussion of some of the details of the design of a suitable firing circuit for EBW detonators is given in Section IV of this article.

III. SAFETY CONSIDERATIONS

Hazard conditions most commonly encountered in the handling of explosives are listed in Table 1.¹³ Also tabulated are the associated critical parameters and probable response of detonators subjected to these hazards. As a result of the purely thermal initiation characteristics of primary explosives the only possible response to significant extraneous energy inputs is an explosion. It follows that the best method of achieving safety with hot wire detonators is simply to exclude all such energy inputs. In contrast, EBW detonators requiring both a minimum energy and a high rate of energy input can "dud", i.e. at current levels below threshold, the bridge-wire can melt and create an open circuit with no resulting detonation. Moreover, since EBW detonators contain only secondary explosives, exposure to high temperatures (fire) typically result in burning rather than detonation.

Let us consider individually the hazards tabulated in Table 1. Hot wire and particularly EBW detonators are remarkably insensitive to impact. Under ordinary handling situations impact would appear to be a minor hazard.

Lightning (or for that matter any storm nearby) can constitute a hazard by producing high ground and atmospheric potentials and currents. Handling of all explosives and most particularly primary explosives generally should be terminated during storm conditions.

Radio frequency hazards depend upon the output power and distance to the transmitter. Recommended minimum distances for hot wire detonators are listed in Table 2.¹³ As indicated in Table 1, EBW detonators do not present a problem in that the ~ 4 ampere current required even to melt the bridgewire (far short of the "explosion" necessary to initiate detonation) would be difficult to achieve.¹⁴

For electrostatic safety calculations, the human body is normally assumed to be a 500-pF capacitor charged to 18,000 volts thus storing 810,000 ergs. Although the body is thus capable of storing sufficient energy to fire a hot wire detonator by bridgewire heating, the usual body resistance (~ 3000 ohms) precludes the deposition of the firing energy into a 1-ohm bridgewire. An internal spark breakdown from heater-wire to case, however, can and has resulted in accidental explosions. Similarly, detonators with high "bridgewire" resistances, the carbon bridge and conductive mix types, for example, also represent more of a hazard since they not only exhibit greater sensitivity but, because of their higher resistance, accept a greater fraction of the source energy. In contrast, the direct spark initiation of granular secondaries as used in EBW detonators, although possible, requires an extremely low-impedance firing circuit, a condition not met by the human body¹⁵ or, indeed, any source short of a very closely coupled, low-inductance capacitor.

Because of the possible utilization of detonators in industrial applications, machine-generated static electricity should also be considered as a current source. It must always be kept in mind that any moving insulators such as vehicles with rubber tires, power-transmission belts, and even fluid and wind blown dust streams, are capable of developing large static voltages.

Induced current on firing lines can occur as a result of the proximity of an unshielded firing line to an AC power line. The current induced in a loop containing the detonator is proportional to the mutual coupling between circuits and the rate of change of current in the power line.¹⁴ Fortunately in most field situations the mutual coupling should be small. Nevertheless conditions could exist in which hot wire detonators would be initiated.

In industrial applications, stray currents due to differences in ground potentials of various items of electrical equipment are certainly not infrequent. Again such currents are typically low level and at worst should produce burnout of EEW bridgewires but could produce a detonation in hot wire detonators.

Finally, many common items of test equipment such as standard ohmmeters can also produce sufficient currents for the initiation of hot wire detonators.

IV. FIRING SET DESIGN

Conventional firing circuits and firing techniques for hot-wire detonators are well described in the literature and should be considered prior to the construction of special firing circuitry.¹³ Unfortunately, very little information is available on EBW firing circuits or for hot-wire systems coupled to complex auxiliary equipment such as high speed cameras and oscilloscopes. Although a number of alternative firing set designs are possible, it is the intent of this report to describe one firing set which has proved to be suitable at our own laboratory. In addition, the discussion of Sec. III will be used to develop design features common to many firing sets.

Although simplifications are possible, generally at the expense of versatility, a firing set for engineering applications should at least exhibit the following:

1. Fire reliably
2. Produce reproducible output current waveforms.
3. Minimize prefiring.
4. Trigger precisely and reproducibly with a short delay time.
5. Fire a variety of detonator combinations, including firing through relatively long firing lines.

To meet these requirements the circuit shown in Fig. 7 has been found satisfactory. Major components include the firing capacitor C_4 , and ignitron output switch I_1 , and trigger thyratrons V_2 and V_3 . Thyatron V_1 disarms the circuit following a firing operation. The firing set requires an input trigger of between 1 and 2 volts developed across the relatively low (50 ohm) input impedance;

FIG. 7 EBW FIRING SET SCHEMATIC.

thus, triggering by electrical noise transients is unlikely.

In Sec. II it was shown that the burst current could be estimated from Eq. 23,

$$I_b = \sqrt[3]{3V_0 G_b / L}.$$

From this relationship we see that if the inductance of a firing set is increased by the use of long firing lines,* for example, the voltage must be increased proportionally to maintain a constant value of I_b . The 5 kV rating of the circuit shown is adequate for most test situations. One final point on general circuit design should be discussed. The ramp approximation invoked in Eq. 23, although convenient, neglects to decrease in the voltage on the firing capacitor as it discharges during the firing cycle. This approximation thus predicts a burst current that is too high. Proper selection of the necessary firing capacitance can be estimated as follows: Given the assumed ramp current waveform, the voltage remaining in the firing capacitor C at the time of bridgewire burst is given to good approximation by,

$$V = V_0 - \frac{Q_b}{C}, \quad (24)$$

where

$$Q_b = \int_0^{t_b} I dt = \frac{V_0}{L} \frac{t_b^2}{2} \quad (25)$$

is the charge delivered up to the time of burst. Combining Eqs. 23, 24, and 25 yields

*The inductance of coaxial cable is generally between 0.03 and 0.07 microhenries per foot.

$$\frac{V}{V_0} = 1 - \frac{1}{2CV_0^{4/3}} \sqrt[3]{9G_b^2 L} \quad (26)$$

For the circuit shown in Fig. 7 ($C = 3.5 \mu\text{F}$, $V_0 = 5 \text{ kV}$, $L = 1 \mu\text{H}$, and $G_b = 0.11 \text{ A}^2\text{sec}$) the evaluation of Eq. 26 indicates that at burst the voltage remaining on C is 96% of the initial voltage V_0 .

Although it would appear that C is excessively large it must be recalled from the definition of action that if multiple detonators are fired in parallel, the total action required increases with the square of the number of detonators, i.e.

$$G_t = \int_0^{t_b} I_t^2 dt = \int_0^{t_b} (nI_b)^2 dt = n^2 G_b \quad , \quad (27)$$

where G_t and G_b are total action and branch action respectively, I_t and I_b are the associated total and branch currents, and n is the number of branches. By comparison of Eqs. 26 and 27 it can be seen that the second term in the right hand side of Eq. 26 will increase as $n^{4/3}$. Consequently, if multiple detonator firing is contemplated, considerable excess capacitance should be included.

All of the discussion of this section has been directed toward EBW firing. If hot wire detonators are to be used for similar applications, basically similar firing sets, operating perhaps at lower voltages, are required. Although the reduction in voltage may result in other alternatives in component selection, the basic firing set design should be very similar.

Finally, standard safety features should be included in any firing set design. These should at least include a locked access to the firing switch, provision for disconnecting and grounding of the firing lines when connecting detonators, and automatic disarming of the fire set following a firing operation.

V. EXPLOSIVE TRAIN DESIGN

An explosive train is defined as a series of explosive components, generally of increasing size and decreasing sensitivity, either in contact or interconnected by inert barriers or air gaps. Thus a detonator itself is an explosive train, as are various combinations of output components which might be combined with it. For example a detonator, followed by a MDF link, a booster charge, and a line wave generator might constitute a typical train. Obviously not all train combinations can be considered or even anticipated here, thus it is the intent of this section to simply denote some of the more important aspects of explosive train design and to provide the reader with additional references on the subject. Most of the work covered in this literature is primarily directed toward the propagation of a detonation and not, as is often of importance in engineering studies, toward timing reproducibility.^{16,17,18} Consequently, for most of the techniques described in the references, it must be assumed that the factors of importance for the continuity of detonation also enhance the reproducibility of timing.

Prior to discussing these factors several almost obvious points should be noted. First, in almost all cases, the best reliability is achieved by minimizing the number of interfaces, gaps and barriers in the train. Whenever interfaces are necessary, great care should be taken to insure that these are reproducible. Secondly, unless designed to meet specific military specifications, commercially manufactured explosive components, i.e. blasting caps, MDF, etc., may differ between manufacturers, or even between production lots from a single manufacturer. Consequently, reproducibility requires careful selection and testing of individual train components.

The basic requirement for initiation of any explosive is that the rate of energy input to some small volume be sufficiently great that a self-sustaining explosive reaction occurs, i.e. the energy released in the growing reaction exceeds all losses from the volume.

The volume considered is that contained within a small hemispherical shock driven into the end of a cylindrical "receptor" charge by an adjoining cylindrical "donor charge." Two complex situations where timing performance is difficult to predict are immediately apparent. First, the utilization a donor charge whose diameter is less than the critical diameter* of the receptor charge may result in failure of the detonation to propagate, or at best results in a complex and poorly understood detonation growth process in the receptor. Such a situation should be avoided.

As a second example, the situation wherein the radius of the initiating shock hemisphere is less than the reaction zone length** of the receptor charge leads to incomplete reaction within the volume and should likewise be avoided.

Given that the dimensions of the shocked volume in the receptor charge are satisfactory, the growth of detonation in the receptor is strongly dependent upon the pressure profile of the shock pulse from the donor.

* Critical diameter is defined as the minimum column diameter that will sustain a steady detonation.

** Reaction zone lengths of most high explosives, TNT, RDX, etc., are usually less than one millimeter, and thus do not pose a serious limit. Blasting agents, however, may exhibit reaction zone lengths of several inches. For particular explosives the reader is referenced to the manufacturer's specifications or the explosives literature.^{8,16}

Any method of sustaining the applied pressure pulse is generally of value. Within limits, increasing the donor charge length and particularly its diameter contributes to sustaining the pressure. However, because of radial expansion of the product gases, a point of diminishing returns is soon reached at which further increases in charge length no longer serve to increase the shock pulse duration. Consequently, donor charges with approximately a one-to-one length to diameter ratio are commonly utilized. The transfer of detonation is significantly improved by the containment of the explosives in a strong material case of high acoustical impedance, i.e. "tamping" of the charges in steel or lead sleeves.

If detonation is to be transferred through a barrier (the detonator case, for example), the barrier should be of a high shock-impedance material such as metal, which can efficiently couple the shock into the receptor explosive.

Initiation of a receptor charge may also result from impact by fragments from a metal barrier traversing (and, for a short distance, accelerating across) an air gap between the barrier and the receptor charge. Dynamites, for example, appear to be particularly susceptible to this type of initiation. As a result, metal barriers combined with small air gaps (~ 0.1 ") may offer advantages from the standpoint of initiation. Considering timing reproducibility, however, the use of this type of relatively uncontrolled projectile initiation is questionable.

In brief summary, then, this section has pointed out that good explosive train design involves minimizing discontinuities, reducing losses, avoiding situations involving long growth to detonation processes, and maintaining high, sustained shock pressures during propagation

down the train. In practical design additional factors such as the chemical and physical properties of the explosive may also be of importance. For particular problems, the reader is referred to the literature, and perhaps of even greater importance, to a strong experimental program of his own.

SUMMARY

In this report the two major detonator types in common use, hot wire and exploding bridgewire, have been described. Operating characteristics of hot wire detonators were developed from solutions of the Rosenthal equation coupled to the concept of a critical initiation temperature of primary explosives. Operational properties of EBW detonators were developed in terms of the burst current and action concepts. These concepts were utilized to specify firing set requirements and a practical EBW firing set was presented. It was pointed out that the reliable performance of an initiation system was also dependent upon the proper design of the explosive train coupling the detonator to the main explosive charge. General explosive train design guidelines were discussed.

It was indicated that safety in hot wire detonators depends upon the exclusion of all extraneous energy inputs from the very sensitive primary explosives. In contrast EBW detonators, because of their inherent energy rate dependent restriction for initiation, appear to offer greater safety.

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TABLE 1

TYPICAL HAZARDS AND DETONATOR RESPONSE				
HAZARD	DET. TYPE	PROBABLE RESPONSE	CRITICAL PARAMETERS	COMMENTS
Fire	Hot Wire EBW	Explode Burn	Temp. Temp.	~ 280°C ~ 200°C
Impact	Hot Wire EBW	Explode Explode	Hot Spot Hot Spot	Relatively small hazard in intact detonator Relatively small hazard detonator
Lightning	Hot Wire EBW	Explode Dud	I, V I	5 mile minimum storm distance B.W. Burnout, direct strike might detonate
RF Transmitter	Hot Wire EBW	Explode Dud	I, V I	Heating of bridgewire or explosive Bridgewire burnout
Body Static	Hot Wire EBW	Explode None	V	Pin to case breakdown Estimated firing voltage exceeds 80,000 volts
Machine Static	Hot Wire EBW	Explode None	I, V	Pin to case breakdown Detonation conditions difficult to achieve
Induced Current	Hot Wire EBW	Explode Dud	L, dI/dt L, dI/dt	Bridgewire heating Bridgewire burnout
Stray Current	Hot Wire EBW	Explode Dud	I I	Bridgewire heating Bridgewire burnout

TABLE 2

RADIO TRANSMITTER POWER VS. MINIMUM DISTANCE*

POWER WATTS	MINIMUM DISTANCE FEET
5 to 25	100
25 to 50	150
50 to 100	220
100 to 250	350
250 to 500	450
500 to 1,000	650
1,000 to 2,500	1,000
2,500 to 5,000	1,500
5,000 to 10,000	2,200
10,000 to 25,000	3,500
25,000 to 50,000	5,000
50,000 to 100,000	7,000
MOBILE FM TRANSMITTERS	
1 to 10	5
10 to 30	10
30 to 60	15
60 to 250	30

* BLASTERS' HANDBOOK, 14th Ed.

BRIDGEWIRE	- RESISTANCE ALLOY; $R \approx 1 \text{ OHM}$
IGNITION CHARGE	- LEAD STYPHNATE OR COLLOIDAL LEAD AZIDE
PRIMER CHARGE	- LEAD AZIDE
BASE CHARGE	- PETN; #6 (~4.9 GRAINS) #8 (6.9 GRAINS)
DIMENSIONS	- ~0.28" DIAMETER, 1.25" LENGTH

Fig. 1 Construction Details of a Typical Hot Wire Detonator

FIG 2 COMPUTED HOT WIRE DETONATOR BRIDGEWIRE TEMPERATURE VERSUS TIME FOR DC INPUT CURRENT LEVELS FROM 0.1 TO 1.0 AMPERES.

FIG 3 COMPUTED HOT WIRE DETONATOR BRIDGEWIRE TEMPERATURE VERSUS TIME FOR CAPACITOR DISCHARGE HEATING AT VARIOUS LEVELS OF INITIAL CAPACITOR VOLTAGE.

BRIDGEWIRE	- GOLD; $R \cong 0.05 \text{ OHM}$
LOW DENSITY EXPLOSIVE	- PETN, $\sim 0.5 \text{ CRYSTAL DENSITY}$
BOOSTER CHARGE	- TETRYL, PEX 9407
DIMENSIONS	- $\sim 0.375'' \text{ DIAMETER, } 1.25'' \text{ LENGTH}$

Fig. 4 Construction Details of a Typical Exploding Bridgewire Detonator.

TYPICAL EBW CURRENT AND RESISTANCE WAVEFORMS

Fig. 5 Typical EBW Current and Resistance Waveforms.
A typical value for t_b is $\sim 0.5 \mu\text{sec}$.

FIG 6 COMPUTED EBW DETONATOR CURRENT VERSUS TIME FOR A TYPICAL CAPACITOR DISCHARGE FIRING SYSTEM. DELIVERY OF BURST ACTION FOR A 1.5 MIL DIAMETER GOLD WIRE ($G=0.11 \text{ A}^2 \text{ SEC}$) SHOWN AS DASHED LINE.