Conf-9106187--2

UCRL-JC-105644
PREPRINT

Received by OSTI

MAY 30 1991

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This paper was prepared for the
The 16th International
Pyrotechnics Conference
June 24-28, 1991

April 1991

Lawrence Livermore National Laboratory

UCRL-JC--105644

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ELECTROSTATIC DISCHARGE EFFECTS ON EBW DETONATORS

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Abstract: With appropriate circuit resistance and inductance and sufficient stored energy, discharging a charged human body or component through an exploding bridgewire (EBW) detonator may cause the detonator to function or may damage the detonator. We have studied the effects of electrostatic discharge (ESD) on a number of exploding bridgewire detonators which were subjected to discharges which passed directly through the bridgewires (pin-to-pin), as well as discharges which passed from the bridge to the metal case of the detonator (pin-to-case).

We have performed calculations to determine the values of inductance and resistance for which burst and melt may occur for given ESD sources, using a phenomenological model of bridgewire burst in a computer code called FIRESET (1). Bridge melt was computed using the same computer code, but using experimental values of bridge resistivity and specific heat up to melt.

EXPERIMENTAL ARRANGEMENTS

ESD Sources: Possible ESD threats to a detonator depend on how a detonator is handled and its local environment. Perhaps the most probable threat to an isolated detonator is the charged human body. As an electrical model for the charged human body we used a series RLC circuit with a 600 pF capacitor charged to 20-30 kV in series with 500 Ohms, as shown in Fig. 1a.

A severe human ESD model has been proposed by Fisher (2). The circuit is shown in Fig. 1b. Fisher's model gives a spike on the leading edge of the discharge waveform, which Fisher and others (3,4) take to be the worst-case ESD waveform. We did not use Fisher's model for any experimental tests, but used it in some calculations of energy and power delivered to an electric spark.

We also considered the ESD threat which occurs when a detonator comes in contact with a charged metal object (component) in an assembly operation. The severity of the threat depends on the range of capacitances and charging voltages, as well as the circuit R and L. The two worst-case threats we considered were series RLC circuits containing 600- and 1000-pF capacitors charged to 25-30 kV.

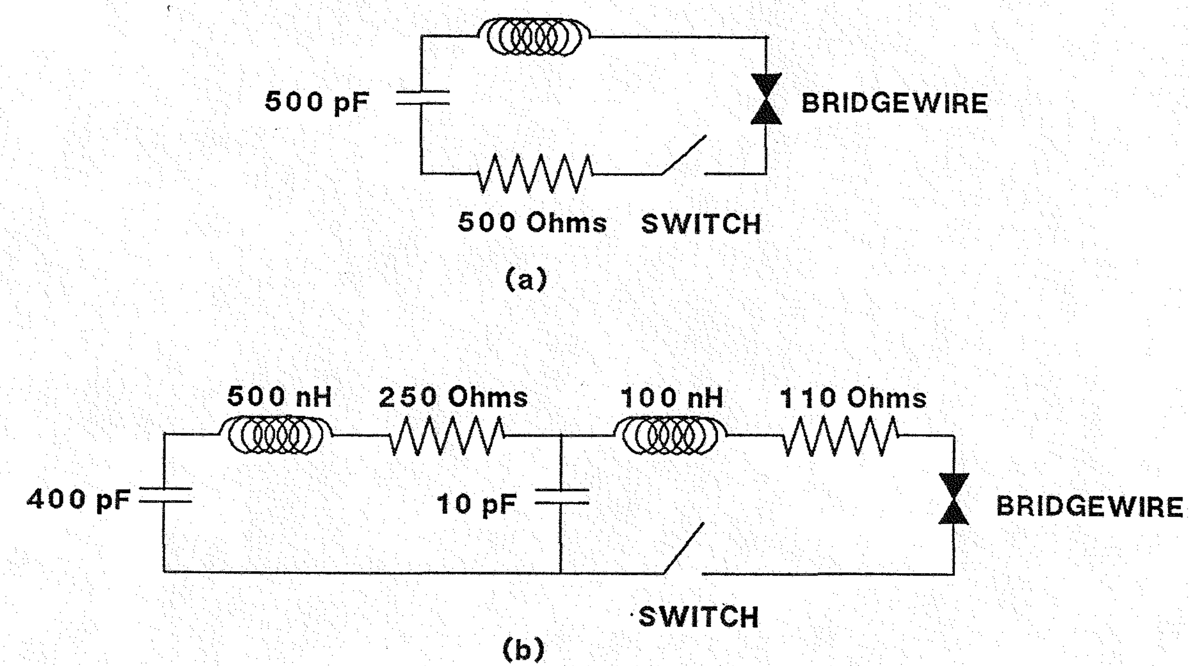

Figure 1. Circuits which simulate the discharge of a charged human body.

The ESD sources were connected to the detonators in either a pin-to-pin or pin-to-case configuration. It should be recognized that in the actual threat environment, the circuit will include one or more sparks which will either occur as a charged object approaches the detonator leads, or internally in the detonator.

We performed some tests to estimate the resistance of a small spark in series with one of our threat sources. This was done by charging a RLC circuit until breakdown occurred across a variable-length gap. By measuring the current-time waveform, the circuit inductance and spark resistance can be calculated. For gaps in the range 0.5 - 10 mm, we observed a roughly-linear relationship between circuit resistance and spark length as shown in Fig. 2. Spark resistance is an important consideration when the electrostatic discharge is from pin-to-pin, because spark resistance will limit the fraction of the stored energy that can be deposited in a bridgewire. When two spherical electrodes with a potential difference of 25 kV are brought together, a spark will occur at a separation of the order of 10 mm (5). If one of the electrodes is needle-like, the spark will occur at a larger separation. The data of Fig. 2 imply that an electrostatic discharge from one of our threat sources into a detonator will involve a spark resistance of the order of 1 Ohm or more.

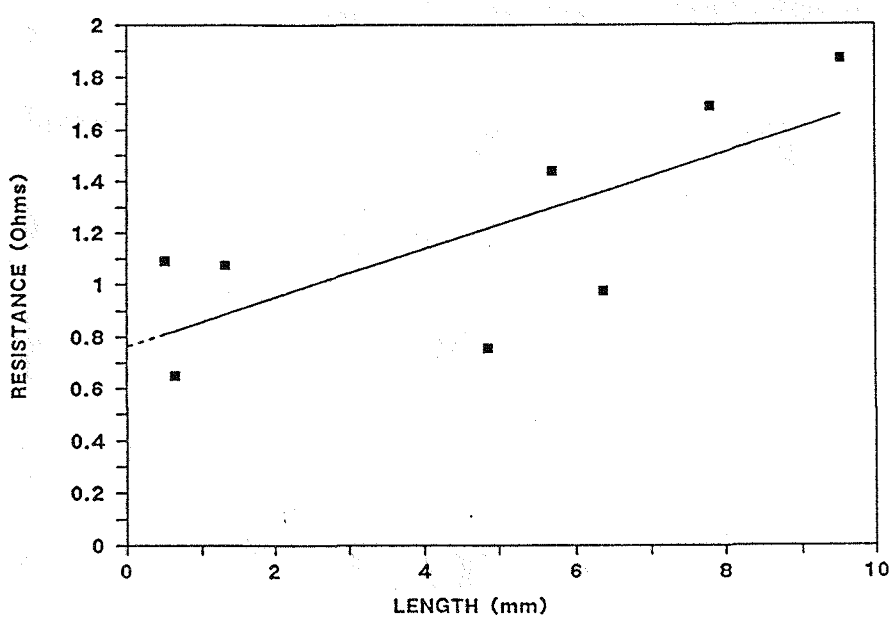

Figure 2. Spark resistance vs. spark length in air.

Firing System and Diagnostics: In the construction and characterization of the circuits which simulated the ESD threats it was necessary to keep inductances and resistances low to simulate worst-case conditions. The switch was a troublesome component. It is not easy to find a low-inductance, low-resistance switch which will stand off 20-30 kV and turn on in a few ns. For most of our work we used solid dielectric switches which closed when a detonator blew a hole in a sheet of Kapton dielectric, which was holding off the voltage. To further facilitate conduction, the detonators which closed the switches had conical Cu liners which formed a jet to aid penetration and conduction. The switch was laminated as part of a short, parallel-conductor flat cable. The cable capacitance was used to store the charge and the detonator was connected to the cable, keeping the inductance and resistance as low as possible. Current was measured using a low-inductance, current-viewing resistor and a current-viewing transformer and recorded on a digital oscilloscope.

MODELING ESD EFFECTS

There are two, very different ways in which an electrostatic discharge may deposit energy in a detonator. The first, which occurs in the pin-to-case mode or if the bridgewire is open, is the production of an electric spark. Spark initiation of explosives is an exceedingly complex phenomenon, which we will not attempt to model for a number of reasons. The path of the spark will depend critically on the geometry and materials of the detonator. The physics of an electric spark is complex and its interaction with high explosive is, at best, poorly understood.

The second way that an ESD can deposit energy in a detonator is by heating the bridgewire. This occurs when the discharge is from pin to pin, and is much more amenable to modeling. The short duration of the discharges from the sources we consider means that the energy deposition will be adiabatic, which considerably simplifies the job of determining the state of the bridgewire after the discharge. Some of the possible final states of the bridge lead to predictable outcomes. If the current in the discharge is high enough to cause the bridge to explode at or above the threshold burst current of the detonator, the detonator will function with full output. If the bridgewire melts, the detonator may be rendered non-functional (dudded). Finally, if the temperature of the bridge does not reach a temperature at which the explosive melts or decomposes, it is unlikely that the detonator will be damaged in any way.

<u>Bridgewire</u> <u>Heating</u>: Before we proceed to a discussion of the simulation of dynamic heating of bridgewires it will be useful to consider some of the general features of adiabatic electrical heating. Assuming a uniform current, $I(t)$, flowing through a conductor initially at a temperature T_o, the temperature, T, of the conductor is given by the energy

balance equation,

$$I(t)^2 R(T)dt = MC(T)dT, \tag{1}$$

where R(T) is the electrical resistance, M is the mass, and C(T) is the specific heat of the conductor. Writing I, M and R in terms of the current density, J, mass density, D,

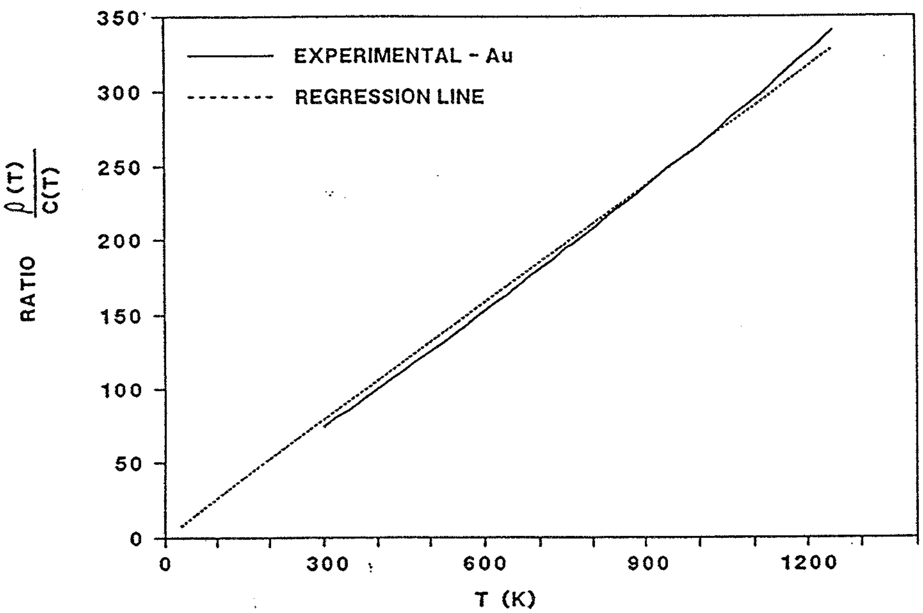

Figure 3. Resistivity/specific heat ratio for gold.

and resistivity, $\rho(T)$, we obtain

$$J(t)^2 dt = D(C(T)/\rho(T))dT. \tag{2}$$

The variation of density with temperature is small and we ignore it. The specific heat of metals increases slowly with temperature above room temperature, and resistivity has a significant, nearly-linear dependence on temperature. The ratio of resistivity to specific heat also turns out to be nearly linear. Figure 3 shows $\rho(T)/C(T)$ of Au as a function of temperature using experimental data from the compilation of Touloukian (5). Similar curves are obtained for Al and Cu. If we approximate the temperature dependence of $\rho(T)/C(T)$ as a linear function, we can write

$$C(T)/\rho(T) = 1/\alpha T, \tag{3}$$

and Eq. (2) becomes

$$J(t)^2dt = D/(\alpha T)dT, \quad (4)$$

with solution

$$T(t) = T_o\exp(\alpha\, g(t)/D), \quad (5)$$

where

$$g(t) = \int_0^t J^2 dt. \quad (6)$$

The quantity g(t) is called specific action. Specific action plays an important role in both the heating of conductors and the electrical explosion of conductors. Equation (5) states that under adiabatic conditions and in materials for which Eq. (3) is valid, the temperature of a conductor carrying electrical current depends only on α and the specific action through the conductor.

Bridgewire Explosion: A typical ESD source deposits electrical energy in a bridgewire in a fraction of a microsecond. The deposited energy may exceed the cohesive energy of the material, leading to a rapid buildup of temperature and pressure of the conducting material and the subsequent violent explosion of the conductor. EBW detonators utilize these electrical explosions to directly initiate low-density secondary explosives. Exploding conductors are also used to initiate high-density secondary explosives in slapper detonators (6) and in shock wave generators which can produce pressures into the 100 GPa range (7).

A detailed computer simulation of an exploding conductor requires a magnetohydrodynamic computer code, detailed knowledge of the equation of state of the conductor at high temperatures and low densities and a model of the resistivity as a function of temperature and density (8). Fortunately, it is possible to make a much simpler empirical simulation of the electrical behavior of an exploding conductor.

It has been shown experimentally that the specific action required to cause an electrical explosion in a conductor (action to burst) is approximately constant, independent of the current waveform (9).

To calculate the electrical characteristics of exploding bridgewires, we have used an empirical model developed by Lee (10,11) where the dynamic resistance is simulated by assuming that the resistivity is a function only of specific action. Lee (10) used a Gaussian function to model the resistivity peak and a hyperbolic cosecant function to model the initial heating and post-burst resistance. His expression for resistivity is given by

$$\rho(g) = A[1-\text{sech}\{g/g_o\}] + B \exp[-\{(g-g_o)/S\}]^2, \qquad (7)$$

where the four model parameters are A, the post-burst resistivity, B, the height of the resistivity peak, S, the width of the resistivity peak and g_o, the specific action to burst. The use of the Gaussian function ensures that the resistivity peak will occur at $g = g_o$. Expansion of the conductor is ignored in computing the resistance.

We have observed experimentally that specific action to burst is only approximately constant. Specific action to burst increases with the rate of deposition of electrical energy, and it is necessary to scale the values of g_o and S to account for this fact (10,11). The initial rate of current rise, V_o/L, is used as the scaling parameter. The scaling equations are

$$g_o = G_o(V_o/KL)^P, \qquad (8)$$

$$S = S_o(V_o/KL)^P, \qquad (9)$$

where the quantity $K = 2(10^{11})$A/s and $P = 0.19$.

A computer code, FIRESET, has been developed to numerically calculate current versus time for a RLC circuit containing exploding conductors (1). The circuit equations are solved numerically using a fourth-order Runge-Kutta method with Gill's modification (12). During each time step, the specific action through the conductor is computed and resistance of the conductor is updated, using Eq. 7.

Model parameters had previously been determined for Al and Cu bridges (1), but not for Au and the Au/Pt alloy used in some of the bridges we studied, so it was necessary to determine model parameters for the Au and Au/Pt. The first step was to select an appropriate capacitor discharge unit

(CDU). The CDU was discharged into a shorted load, and the values of R, L and C were determined for the CDU by analysis of the current-time waveform. Au and Au/Pt bridges were then exploded at various charging voltages and the current-time waveforms were measured. Model parameters were then adjusted until the FIRESET code gave a reasonable simulation of the experimental waveforms. Model parameters for Au and Au/Pt are given in Table I along with the model parameters for Al and Cu from Ref. (1).

Table I. FIRESET model parameters.

	Al	Au	Au/Pt	Cu
A (μOhm-cm)	90	120	70	100
B (μOhm-cm)	140	400	320	200
G_o ($10^9 A^2 s/cm^4$)	0.9	2.5	1.5	2.5
S_o ($10^9 A^2 s/cm^4$)	0.18	0.15	0.75	0.25

Bridgewire melt: An electrostatic discharge can damage an EBW detonator by melting the bridgewire or by raising it to a temperature sufficient to cause decomposition of the powder around the bridgewire. In cases where an electrostatic discharge does not vaporize the bridgewire, it is straightforward to calculate the temperature of the wire from the known thermal properties. We have used the FIRESET code described above to perform such calculations, substituting a table of resistivity vs. temperature values for Eq. (7) and adding Eq. (2) to the system of equations to be solved. Specific heat values are accessed by the code from a table of specific heat vs. temperature. The code will indicate when the bridgewire reaches a temperature which is specified as input to the code.

DETONATORS STUDIED

We studied a number of different types of detonators, both commercially available detonators and detonators which are built to LLNL specifications. We will discuss the results of tests on three different types of EBW detonators. Separation into the various types is made according to geometry and details of construction.

Type 1 detonators had metallic cases of 7.62-mm diameter or less with 0.038-mm-diameter gold bridgewires and a plastic header. The explosive pressings were cylindrical or had cylindrical symmetry. When a spark breakdown occurred, the path from the bridge to the case was through low-density powder and the spark path was typically short.

Type 2 detonators had metallic cases of approximately 12.7-mm diameter, plastic headers, and 0.027-mm-diameter, 70%/30%, Au/Pt bridgewires (Type 2a) or 0.038-mm-diameter gold bridgewires (Type 2b). The bridgewires were surrounded by low-density powder, but a spark to the case had to pass around or through a higher-density pressing and the spark path was longer than for Type 1 detonators. The high explosive pressings were hemispherical and the detonators are designed to give an output with hemispherical symmetry.

Type 3 detonators were hemispherical with metallic cases. The major difference between Type 2 and Type 3 detonators was that the Type 3 detonators had flat, aluminum bridgewires deposited on ceramic headers. Bridgewire dimensions were 0.127-mm-wide and 0.010-mm-thick or 0.254-mm-wide and 0.015-mm-thick for the Type 3 detonators. Other dimensions were about the same as for Type 2 detonators. The length of the spark paths varied, but all sparks had to pass through or along a high-density HE pressing.

RESULTS AND DISCUSSION

We tested over 100 detonators of various types, using both charged human and charged component sources. The results of the tests are summarized in Table II. The pin-to-case discharges were clearly the most damaging. Generally speaking, the shorter the breakdown path from the bridge to the case, the lower the threshold for dudding or inadvertent detonation. This is apparently due to a higher energy density deposited in shorter sparks. We show in Fig. 2 that the resistance of a spark in air is proportional to its length. One would expect the same to hold true in the powder. At the discharge frequency of the charged components, the internal resistance of the source is quite low, so one would expect maximum power transfer to low-resistance sparks.

For the charged human source, however, the internal resistance of the source is so high that one would not expect the power transferred to the spark to depend much on spark resistance. If we assume that a typical spark has a constant resistance of 1 Ohm, the calculated energy deposited in the spark by the circuit of Fig. 1a is 0.23 mJ with a peak power of about 1.5 kW. We did no testing with the circuit of Fig. 1b, but a calculation for 20 kV charging voltage indicates an energy deposition in a 1-Ohm spark of about 0.21 mJ with a peak power of about 10 kW. Tucker et al. report that they were able to produce detonations in PETN with as little as 10 mJ of energy deposited in a spark at an average power of about 330 kW over 30 ns (13). The charged component sources we considered stored up to 0.45 J, far in excess of the minimum energy required for spark detonation. In a low-inductance circuit, the charged-component sources are also capable of supplying the high power needed for spark initiation of detonation.

Table II. Summary of electrostatic discharge tests.

	Charged human: 500 Ohms, 20 kV 600 pF	Charged component: Low resistance, 30 kV, 0.6, 1 nF
Pin-to-Pin	No Effect	Some detonations with Type 2, Au/Pt Bridges; Dudding in all types with low circuit R.
Pin-to-Case	Type 1 dudded @ $\geq$ 20 kV.	Type 1 detonated or dudded; Types 2,3 showed powder displacement, but still functional.

The Type 1 detonators showed poor resistance to pin-to-case discharges. They fulfilled two conditions which appear to favor damage or inadvertent detonation from ESD. First, a typical spark path from the bridgewire solder post to the case was the order of 1 mm in length. Second, the entire spark path was in low-density powder. Dudding from the charged-human-body source was possible, due to displacement of powder near the bridge by the spark. Confinement may also play a role, as the Type 1 detonators generally had smaller confinement volumes.

Spark breakdown paths in the Type 2 and Type 3 detonators were longer, and part of the spark path was along the surface of a high-density (1.60 g/cm^3) pressing. High-density HE pressings are very insensitive to spark initiation, compared to the low-density PETN near the bridgewire. Inspection of the Type 2 and 3 detonators after testing with charged component sources showed displacement of the low-density powder, but the detonators still functioned.

The detonators we tested were all resistant to ESD damage from a charged human source connected pin-to-pin. This is not surprising, considering the high series resistance in the charged-human body simulators. All of our charged-human testing was done using the circuit shown in Fig. 1(a). At 20 kV charging voltage, the capacitor stores 100 mJ of electrical energy. This amount of stored energy is sufficient to initiate a small EBW detonator in a low-inductance, low-resistance circuit, but with the charged-human source, most of the energy will be deposited in the 500-Ohm resistor. A dynamic calculation using the FIRESET model, (Eq. (7)), indicated that the temperature of a 0.038-mm-diameter gold bridgewire rose only about 10°C during the discharge. The charged component sources we used represent a much greater hazard. At 20 kV, the 600 pF and 1 nF sources store 120 mJ and 200 mJ of energy, respectively. In a suitable circuit, they are capable of initiating small EBW detonators. We conducted tests up to 30 kV and observed detonation only in Type 2 detonators with Au/Pt bridges. Dudding could be produced in any of the types of detonators by the mechanism of bridgewire melt.

The range of circuit parameters which could cause bridgewire melt or detonation was determined using the FIRESET computer code (1), described above. Two limiting cases were considered. First, it was assumed that detonation would occur if the bridgewire bursts above the measured threshold current for detonation. For a given inductance, the fixed circuit resistance was varied in the calculation until the bridgewire burst current was below the threshold for detonation. The threshold values of resistance were plotted against inductance, giving a sort of "phase boundary". Values of L and R below the "phase boundary" will produce a detonation. Figure 4 shows the detonation threshold curves for 0.0028-mm, Au/Pt bridgewires using the 1 nF source. Also shown are R and L values from experimental shots, with firing voltage denoted by the symbol used for the corresponding threshold curve. Calculated curves were consistent with the experimental results.

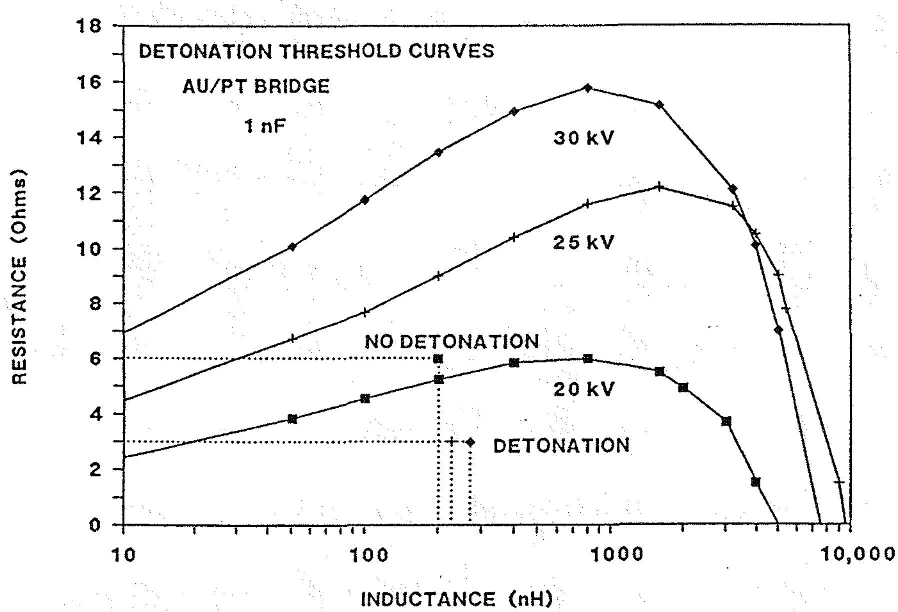

Figure 4. Detonation threshold for a Type 2 detonator with a 0.28-mm-diameter Au/Pt bridgewire. Also shown are R and L values of experimental shots with firing voltage denoted by the symbol for the corresponding threshold curve.

We used the FIRESET computer code to compute another limiting case of certain damage, i.e. bridgewire melt. For a given inductance, the fixed circuit resistance was varied in the calculation until the bridgewire no longer melted. Plotting threshold values of resistance and inductance gives another "phase boundary". Melt is predicted for values of R and L which lie below the boundary. Figure 5 shows both the detonation and melt threshold curves for 0.038-mm-diameter Au bridgewires, using the 600 pF source. Note that a resistance well below 1 Ohm is required to produce a detonation. It is unlikely that either of our charged-component sources would produce a detonation with the 0.38-mm Au bridges because at these voltages the circuit would be completed by an air spark which would have a resistance of 1 Ohm or more. The sources can easily dud the bridgewires, however, and Fig. 5 shows that at 2 Ohms and 180 nH, the bridgewire melts as predicted.

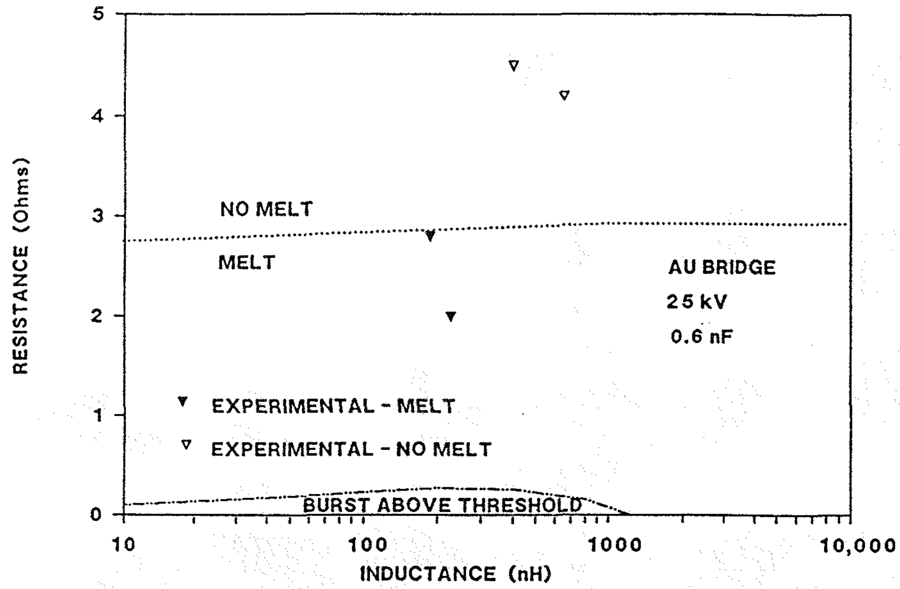

Figure 5. Detonation and melt thresholds for 0.38-mm-diameter gold bridgewires. Also shown are the R and L values of an experimental shot with the firing voltage denoted by the symbol used for the corresponding threshold curve.

SUMMARY AND CONCLUSIONS

We have studied the vulnerability of various types of EBW detonators to electrostatic discharge from sources which simulate a charged human body and charged metallic components. We tested over 100 detonators and divided them into three classes according to size and internal construction. Type 1 detonators were small, cylindrical detonators with round Au or Au/Pt bridgewires. The spark path from a bridgewire solder post was typically the order of 1 mm and passes through low-density powder. Type 2 detonators were hemispherical with round Au or Au/Pt bridgewires. Spark paths were longer and passed around or through a high-density HE pressing. Type 3 detonators were hemispherical with flat, Al bridgewires. Dimensions and construction were about the same as for Type 2 detonators.

When the discharge passed from a pin to the detonator case we found that the charged human body source can dud the Type 1 detonator. The charged component sources we used can dud or detonate the Type 1 detonators. After pin-to-case exposure to the charged-component sources, the Type 2 and Type 3 detonators showed powder displacement, but were still functional

When the discharge passed through the bridgewire, (pin-to-pin), no effect was observed in any of the detonators using the charged-human-body source. The charged component sources were capable of detonating or dudding the Type 2 detonators with Au/Pt bridgewires and could dud the other types of detonators with sufficiently low values of circuit resistance and inductance. The mechanism for dudding appeared to be powder removal from the bridge region. We did not attempt to calculate this effect.

In the pin-to-case mode, calculations were made of energy and power deposited in a 1-Ohm spark. Calculations indicated that the charged-human-body source is insufficient to cause detonation, in agreement with our experimental findings. With proper circuit parameters, calculations showed that the charged-component sources deposited energy and power in a spark capable of producing detonations

Calculations were made of the threshold circuit parameters for producing detonation or bridgewire melt in the pin-to-pin mode. These calculations were consistent with our experimental findings. The mechanism for detonation is bridgewire burst at a current above the detonator threshold level and the mechanism for dudding is bridgewire melt.

EBW detonators are very insensitive to electrostatic discharge, compared to conventional, low-energy detonators, but they are not invulnerable. In assembly operations, where ESD might occur, some degree of ESD protection is needed to assure safety and reliability. This should not be difficult to achieve. Charging sources sufficient to charge our charged component sources to hazardous voltages should be obvious and easily eliminated. The charged human body does not represent a safety hazard, and can be controlled as a threat source by the usual precautions of conductive flooring and wrist straps.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the able assistance of Todd Bullock in conducting the experiments.

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