A view on the functioning mechanism of EBW detonators - part 1: electrical characterisation

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Abstract. Exploding Bridgewire (EBW) Detonators are in widespread use and have proven reliability and performance characteristics. Since their invention there have been numerous studies to identify the mechanism by which the exploding bridgewire initiates the explosive. However, there is still not a universally accepted mechanism. This paper is the first of three characterising the initiation of PETN in an exploding bridgewire detonator to understand the underlying mechanism. The approach taken was to understand the transfer of energy through the system, beginning with the fireset / bridgewire interactions. The measurement of current, time to bridgewire burst and the transient voltage across the bridgewire at burst have enabled the determination of the energy used in bursting the bridgewire. This in turn has led to the calculation of the energy efficiency of the fireset bridgewire system and an estimate of the energy delivered post bridgewire burst. The results of the experimental work will be presented, together with the implications for the initiation mechanism of PETN in an exploding bridgewire detonator.

1. Introduction
Fundamental to determining the initiation mechanism of an EBW detonator is an understanding of the processes by which the plasma, generated by the bridgewire explosion, interacts with the explosive to establish a detonation wave. However, this is a complicated phenomenon and must therefore be split into multiple steps to allow the processes to be identified and quantified. The approach adopted was to track the energy through the system, beginning with the transfer of energy (quantity and rate) from the fireset capacitor to the bridgewire.

To monitor the amount of energy in the system, and the rate of delivery, measurements of current and voltage with respect to time are required. In a circuit with transient effects (the voltage is of very short duration, of the order of a 100 ns) the energy stored on the fireset capacitor is not the energy delivered to the bridgewire as a result of complex electrical interactions. For many applications voltage monitoring is routine and does not present any particular challenges. This is not the case when applied to the exploding bridgewire in an EBW detonator due to both the required timescales and the positioning of the monitor. The complex, transient interactions are such that the voltage must be monitored as close to the bridgewire as possible.

The electrical characteristics of the bridgewire at burst were studied as a function of fireset energy by varying the energy stored on the fireset capacitor. The firing voltages selected were intended to span from sub-explosion levels, through threshold voltages to the all-fire level and in some cases beyond.
2. Experimental and Results
A detonator assembly, filled with an inert simulant (sucrose), was used, rather than bursting the bridgewires into air, to ensure that the burst characteristics were as representative of the detonator as possible. Sucrose has been used elsewhere [1] as a PETN simulant for wire explosions. Unconfined bridgewires do not exhibit the same characteristic burst point on the current trace as confined bridgewires – see figure 1 for comparison of confined (sucrose) and unconfined (air) wire explosions.

The firing system comprised a capacitor discharge unit (CDU) with a capacitance of 50 nF and an inductance of 100 nH. The current monitor was a wrap-around double transformer, with attached co-axial cable and BNC connector, attached to the stripline cable. The voltage across the bridgewire during firing was measured using a voltage probe (Tektronix Model P5210 High Voltage Differential Probe) attached to the two pins on either side of the bridgewire.

Typical current and voltage traces at all fire level are shown in figure 1. Once the firing voltage exceeds the level required to explode the bridgewire, changing the firing voltage did not change the shape of the current and voltage traces. However, the peak currents and voltages did change with a change in firing voltage.

![Figure 1](image.png)

**Figure 1.** Example Current and Voltage Traces for an All-Fire Level.

Figure 1 shows the burst point on the current trace, with the peak in the voltage corresponding to the bridgewire burst.

3. Discussion
The high voltage differential probe, by design, only recorded a voltage when the bridgewire burst. Therefore voltage-time profiles were only recorded for those experiments where sufficient energy was delivered to burst the bridgewire. The results (see figure 2) show that initially the voltage at burst increases rapidly with an increase in fireset energy. The rate of increase then slows with an additional increase in fireset energy. A less pronounced trend is observed in the current-time profiles as shown in figure 3.
The data in figure 3 show that as the fireset energy increases the burst current increases. The final parameter directly measured from the current and voltage traces was the time taken for the bridgewire to burst once the current began to flow i.e. the time from $I_0$ to $I_{burst}$ on the current trace. The relationship between this time and the fireset energy is shown in figure 4.

With an increase in firing energy, the time to burst decreases but asymptotes to a time of approximately 50 ns. The 50 ns minimum will be limited by the “rise rate” of the fireset discharge. This rise rate is determined by the inductance and capacitance of the system.
The direct measurement of the current and voltage across the bridgewire at burst allowed a number of other parameters to be calculated. The delivered energy required to burst the bridgewire was calculated using equation (1):

\[ E = \int_0^{t_b} IV \, dt, \quad (1) \]

where \( I \) = current, \( V \) = voltage and \( \Delta t \) = time between \( I_0 \) and \( I_{\text{burst}} \).

Figure 5 shows the energy required to burst the bridgewire with respect to the energy on the fireset.

Examining figure 5 in isolation could lead to the conclusion that the greater the energy stored on the fireset capacitor, the greater the energy required to burst the bridgewire. To fully explain this it is necessary to consider equation (1) which demonstrates the time dependence of the energy required to burst the bridgewire. Referring back to figure 4 it is clear that the burst occurs faster with higher fireset energy, thus reducing the time available to deliver the energy and therefore necessitating a higher energy. The energy required to burst the bridgewire begins to plateau as the burst time asymptotes. This phenomenon can be further explained by considering the efficiency of the bridgewire with respect to the fireset energy – figure 6.

In figure 6 it is clearly shown that the efficiency of the bridgewire decreases as the fireset energy increases. The efficiency of the bridgewire was calculated using equation (2).

\[ \text{Efficiency} = \left( \frac{E_b}{E_{fs}} \right) \times 100, \quad (2) \]

where \( E_b \) = energy required to burst the bridgewire and \( E_{fs} \) = fireset energy.

The maximum power transfer theorem [2] shows that the maximum theoretical efficiency is 50%; therefore a maximum experimental efficiency of 45% shows an efficient electrical system in terms of power transfer.

The bridgewire does not actually become less efficient at higher fireset energies; rather the reduced time to burst leads to a lower percentage of the fireset energy being used in bursting the bridgewire. This can be demonstrated using the schematic in figure 7.
The energy that is considered to be ‘useful’, i.e. the energy that contributes to bursting the bridgewire is denoted, in figure 7, by the cross-hatching. It is clear that as the time to bridgewire burst decreases, less of the total energy delivered is used in bursting the bridgewire due to the time dependence factor of the energy required to burst the bridgewire.

The power of the bridgewire at burst was calculated using equation (3):

$$ P_b = I_b \cdot V_b, \quad (3) $$

where $I_b$ = burst current and $V_b$ = bridgewire burst voltage.

The final parameter calculated from the experimentally measured current and voltage was the resistance at burst. The peak resistance of the bridgewire at burst can be calculated using equation (4):

$$ R_{\text{peak}} = \frac{V_b}{I_b}. \quad (4) $$

Figure 8 shows that the power delivered to the bridgewire to induce burst increases linearly with increasing fireset energy, supporting the theory explained earlier in figure 7. Due to the increased rate of energy delivery, the cumulative energy is lower and therefore in order to successfully burst the bridgewire the power delivered must be higher.

Figure 9 shows that, for fireset energies above the level required to burst the bridgewire, the peak resistance of the bridgewires remains approximately constant as the firing voltage increases because the initial dimensions of the bridgewire are constant therefore the volume of plasma does not change with increasing firing voltage.
4. Conclusion
The electrical response of a bridgewire system has been characterised over an extended voltage range (sub-explosion through to detonator all-fire levels). From this characterisation it is clear that the energy conversion efficiency of the system decreases but the rate of energy delivery increases over that voltage (fireset energy) range. Increasing the fireset voltage, and therefore the fireset energy, decreases the energy efficiency of the system; less of the total energy is useful in bursting the bridgewire. However this increase in fireset energy does increase the peak power delivered to the bridgewire. The energy required to burst the bridgewire has been shown to be material and rate dependent.

The results obtained, particularly the energy required to burst the bridgewire, suggest that there is an optimum fireset energy for energy transfer efficiency and detonator performance. Initial increases in fireset energy result in a reduction in the time required to burst the bridgewire. However, further increases in fireset energy have a limited effect on the electrical characteristics of the bridgewire. Therefore it could be postulated that there is no advantage to EBW detonator performance in increasing the firing (fireset) energy further. By evaluating the bridgewires’ electrical performance or response over a range of fireset energies they have effectively been characterised over a range of dynamic conditions. This is the fundamental understanding required to progress in determining the initiation mechanism by tracking the energy through the system. This understanding is required in order to understand how the explosive (PETN) responds to the bridgewire.

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References
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