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Power and Energy of Exploding Wires

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Abstract. Exploding wires are used in many high-energy applications, such as initiating explosives. Previous work analyzing gold wire burst in detonator applications has shown burst current and action metrics to be inconsistent with burst phenomenon across multiple firing-sets. Energy density better captures the correlation between different wire geometries, different electrical inputs, and explosive initiation. This idea has been expanded upon, to analyze the burst properties in power-energy space. Further inconsistencies in the understanding of wire burst and its relation to peak voltage have been found. An argument will be made for redefining the definition of burst. The result is a more broad understanding of rapid metal phase transition and the initiation of explosives in EBW applications.

INTRODUCTION

Exploding Bridgewire (EBW) detonators were first invented in the 1940's[1] for use in the first atomic weapons. Their use has since proliferated into many DoE, DoD, and commercial applications. Despite their use for more than seventy years, the physics underlying EBW burst behavior has yet to be fully understood. Tucker is credited with discerning the most about EBW characteristics through his work on action[2] and burst current[3]. Action is defined as

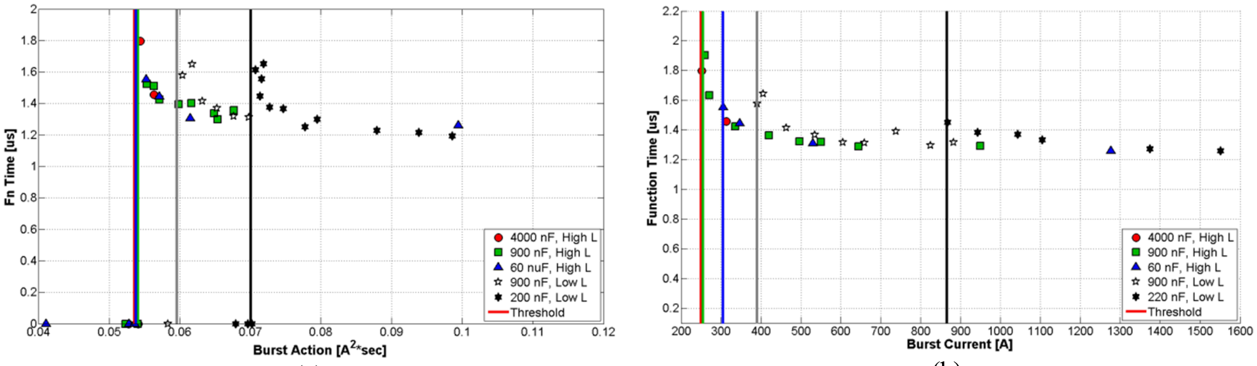
$$A = \int_{t_0}^{t_b} I^2 \, dt \tag{1}$$

where t_0 is the start of current, t_b is the time of burst (defined as peak voltage) and I is the measured experimental current. Tucker originally created this criterion as a means of discerning when bridgewire burst would occur. He notes that action until burst should be constant for a given bridgewire size regardless of firing circuit parameters. In reality, action has been used sparsely as a performance metric. Tucker's burst current has been ubiquitously applied as a performance metric within the detonator community. Burst current is defined as

$$I_b = I(t_b)$$

where I_b is burst current, and $I(t_b)$ is the experimentally measured current at the time of burst. Tucker's experiments utilized a cable discharge system, which is an effectively infinite capacitance and infinite inductance firing-set, as well as a few high capacitance, high inductance firing-sets. Through these tests, Tucker found that performance of EBW detonators did collapse onto a single performance curve when related by burst current.

Recently, these ideas were retested with modern equipment and 0.0012 inch diameter by 0.020 inch long gold bridgewires inside detonators loaded with hexanitrohexaazaisowurtzitane (CL-20) (FIGURE 1). In this paper, function time is defined as the point of peak power until the start of rise in the PVDF signal (FIGURE 2), indicating output from the EBW.



(a)

(b)

FIGURE 1. (a) Function time versus burst action. (b) Function time versus burst current. Neither metric is capable of comparing explosive performance across different firing-sets.

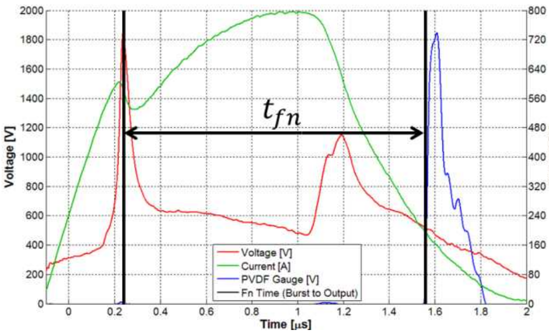


FIGURE 2. Definition of function time: time from peak power until output from the EBW is detected in the start of the PVDF signal.

Two important results are observable in FIGURE 1: neither burst action (a) nor burst current (b) allow for adequate comparison of function time across different firing-sets. Tucker's observations regarding action were derived from using high capacitance and high inductance firing circuits. Apparently, the action to burst changes as the charge voltage on the capacitor changes. Thus, Tucker's assertion that action is a constant to burst is not true for lower-inductance or lower-capacitance firing-sets. Additionally, burst current has the same failings, and is unsuitable as a means to compare detonator performance across different firing-sets.

INITIAL OBSERVATIONS AND MOTIVATION

After no direct correlation between detonator performance and either action or burst current could be found, the problem of correlating electrical impulse to explosive performance needed to be re-examined. To begin, a common point of performance was found: a detonator that performed with a 1.30 μs function time using all five firing-sets. The current traces for each of these tests were plotted against each other for comparison (FIGURE 3).

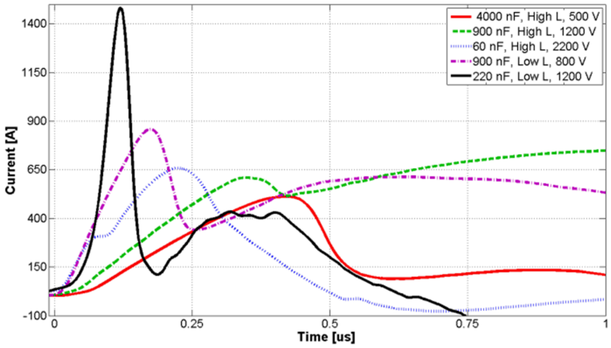


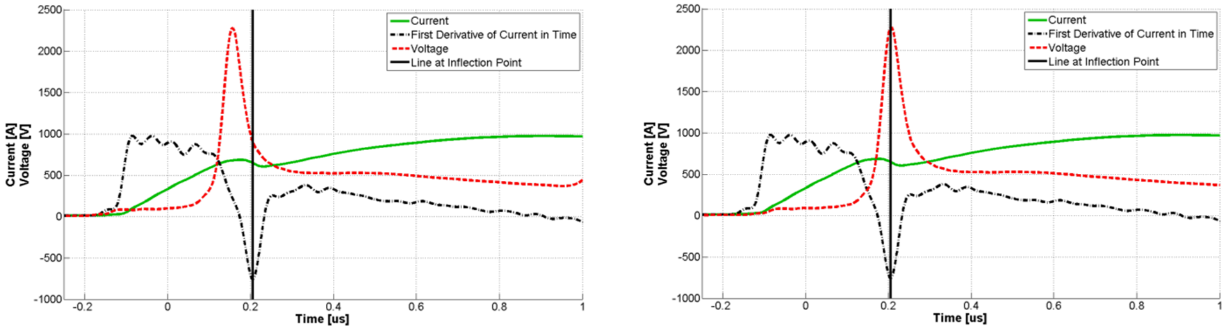
FIGURE 3. Current traces from experiments using different firing-sets with different voltage settings that resulted in the same detonator performance.

From FIGURE 3, it can be inferred the action and burst current from each of these tests is different. Additionally, the current pulses have different widths and amplitudes. However, each of these tests must have something in common to produce the same detonator performance.

To understand how these different current profiles can result in identical detonator performance, it is necessary to obtain accurate measurements of voltage, current, and function time. From there, the new information can be analyzed to try and find a better correlation between electrical impulse and detonator behavior.

DATA ANALYSIS

All data gathered from experiments was analyzed in the same manner using an automated MATLAB program. The purpose of the program was to remove error introduced by typical analysis techniques that require human interaction. The program runs through a large number of necessary post-processing steps required to obtain repeatable results, the most important of which is aligning the peak in voltage with the current inflection point, defined as the point where $\frac{d^2I}{dt^2} = 0$, which can also be defined as the local extremum in $\frac{dI}{dt}$. The voltage probe has its own cables and connection to the oscilloscope, but the signal from the current-voltage transformer (CVT) is routed using a Bayonet Neill-Concelman (BNC) cable. The two cables produce different delays, resulting in the voltage and current arriving at the scope at different times (FIGURE 4). Depending on the length of the BNC cable, the current can arrive before, or after, the voltage. Numerical derivatives are notoriously noisy. Thus, to correctly identify the current inflection point, low-pass filtering must be employed.



(a) (b)

FIGURE 4. (a) The time difference between bridgewire inflection point and voltage peak. (b) The correctly aligned voltage and current signals.

Mathematically, it can be shown that the current inflection point and the voltage peak need to align. The voltage measured by the voltage probes is not directly at the bridgewire, so there are corrections dues to the measurement circuit

$$V_{measured} = V_c + V_b + L_c \frac{dI}{dt} \tag{2}$$

where V_c is the voltage added by the constant circuit resistance between the measurement point and the bridgewire, V_b is the actual voltage at the bridgewire, and L_c is the inductance between the measurement point and the bridgewire. Correcting for V_c is trivial, and was done prior to other analysis. This leaves

$$V(t) = I(t)R_b(t) + L_c \frac{dI}{dt} \tag{3}$$

where $V(t)$ is measured voltage, $I(t)$ is measured current, and $R_b(t)$ is the bridgewire resistance, which changes with time and is not directly measured. As the inflection point is approached, $L{\sim}10^{-7}$, $\frac{dI}{dt}{\sim}10^{10}$, $I{\sim}10^3$, and $R{\sim}10^{-2}$. This results in $L\frac{dI}{dt}{\sim}10^3$ and $IR{\sim}10^1$, or

$$L\frac{dI}{dt} \gg I(t)R(t) \tag{4}$$

and the measured voltage becomes

$$\frac{dV}{dt} \approx L\frac{d^2I}{dt^2} \tag{5}$$

Thus, at the inflection point

$$\frac{dV}{dt} \approx L\frac{d^2I}{dt^2} = 0 \tag{6}$$

and $\frac{dV}{dt} = 0$ is the peak in voltage. Therefore, mathematically, the inflection point in current and voltage peak must coincide. Aligning the voltage peak and current inflection point through post processing is unique to this analysis.

EXPERIMENT DATA

Since neither burst current nor action can correlate detonator performance across a wide range of firing circuit parameters, a new metric was created. Analysis, up until now, has relied solely upon current for determination of performance. In the same manner that electric fields and magnetic fields are codependent, it was hypothesized the measurement of current is dependently linked with voltage. Power is one such way through which current and voltage are codependent variables:

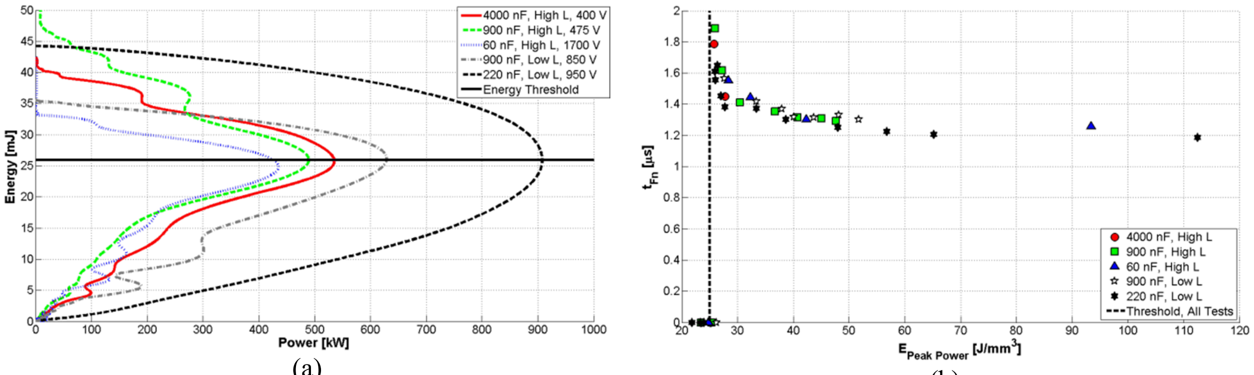
$$P = I(t)\,V(t)$$

where P is power, and V is voltage. Another way is through energy:

$$E = \int_{t_0}^{t_f} P(t)\,dt = \int_{t_0}^{t_f} I(t)\,V(t)\,dt$$

where E is energy, and t_0 and t_f denote the start and end, respectively, of integration in time.

Initially, tests near threshold were compared in power-energy space (FIGURE 5a). Each firing-set produces a different power, but at peak power each firing-set has the same energy threshold. When function time versus energy at peak power is plotted, the detonator threshold and performance is similar for each firing-set (FIGURE 5b). Energy is important for comparing detonators across multiple firing circuits.

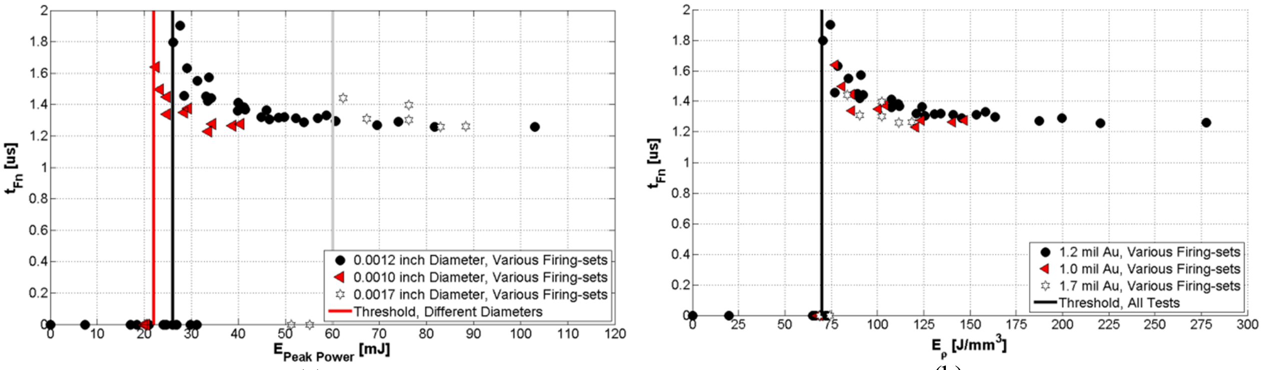


(a)

(b)

FIGURE 5. (a) Firing-set traces through power-energy space for detonators tested near threshold. Each firing-set produces a different power, but at peak power each firing-set has the same energy. (b) Function time versus energy at peak power. The total energy input to the bridge until peak power shows similar performance for 0.0012 inch (30.5 µm) diameter, 0.020 inch (0.508 mm) long gold bridgewires independent of the firing circuit.

Now that performance of a single gold bridgewire has been correlated across multiple electrical inputs, an attempt was made at comparing performance across various bridgewire diameters. When function time is compared to energy at peak power of different wire diameters (FIGURE 6a), smaller wires require less energy to initiate the explosive and larger wires require more energy for equivalent performance.



(a) (b)

FIGURE 6. (a) Comparison of function time versus energy at peak power for various sized gold bridgewires. (b) The same comparison using energy density. Energy density can collapse performance across multiple bridge dimensions and multiple firing-sets.

In an attempt to correlate the data of various bridge dimensions, the energy was divided by the initial volume of the wire. A new variable was created: energy density at peak power,

$$E_\rho = \frac{E_{Peak\ Power}}{Bridgewire\ Volume} = \frac{\int_{t_0}^{t_{Peak\ Power}} I(t)\, V(t)\, dt}{\pi\, r^2\, \ell}$$

where E_ρ is energy density at peak power, r is the radius of the wire, and ℓ is the length of the wire. Energy density at peak power was used to compare the data from multiple bridge diameters (FIGURE 6b). Dividing the energy at peak power by the volume of the wire correlates the detonator performance of any bridgewire diameter to any electrical input.

This analysis has carefully preserved the distinction between peak power and the traditional definition of bridgewire burst. Traditionally, bridgewire burst is defined as the peak in voltage or the inflection point in current. This analysis has uniquely placed peak voltage and the current inflection point at the same point in time. The performance comparisons demonstrated use energy until peak power, which is not the same as traditional bridgewire burst. If the analysis is performed on the energy density until peak voltage (FIGURE 7), the performance of the detonator is no longer comparable across firing circuits.

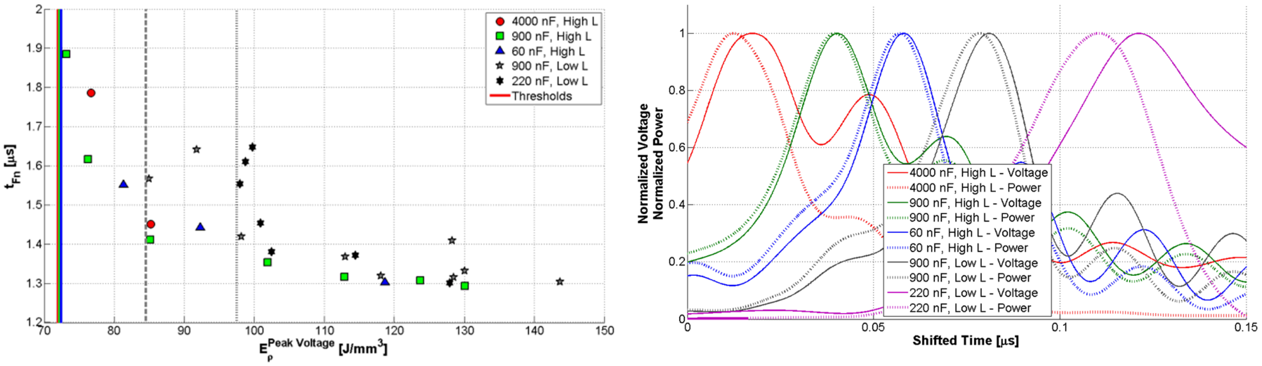


FIGURE 7. (a) Function time versus energy density at peak voltage, which does not correspond to detonator performance. (b) Timing differences between peak power and peak voltage in experimental measurements.

Looking at the waveforms for the low power configurations (FIGURE 7), there is little difference in timing between peak voltage and peak power. As the power of the firing circuit increases, the time difference between peak power and peak voltage becomes larger. The peak in power always occurs before the peak in voltage in these tests.

The energy density at peak power correlates to performance of an explosive component across multiple firing circuits and multiple bridge diameters. Energy density at peak voltage produces no such correlation. Perhaps the community definition of burst is incorrect. Perhaps burst is actually occurring at peak power.

CONCLUSIONS

Burst current and action are incapable of comparing explosive performance across multiple electrical signals. This realization has necessitated the creation of a new metric capable of comparing electrical parameters to initiation and performance of explosive components. Through experimentation, it was found that energy density at peak power is the only known metric capable of comparing any bridgewire dimension and any electrical signal to explosive performance. Further study found that peak voltage does not allow performance to collapse. Analysis of the signals shows peak power occurring before peak voltage, and peak power corresponds to explosive performance. The community definition of burst may be incorrect. Burst may actually occur at peak power.

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