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# PETN Exploding Bridgewire (EBW) Detonators: A Review

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(September 2020)

## **Abstract**

Exploding bridgewire (EBW) detonators have been used in weapon systems since the 1940s but there is huge debate surrounding how energy is transferred throughout the EBW firing system and the mechanism by which the exploding wire leads explosive detonation.

This report summarizes the underpinning technologies and physical processes that are currently understood and reviews the various efforts to quantify the mechanism by which the PETN is initiated.

The behavior of the firing system is very well understood and predictable. The energy delivered to the wire has been empirically modelled but further investigation is required to understand the role of material heterogeneities and their effect on initiation. The energy delivered by the exploding wire has been quantified in many studies but it is not possible to correlate these to a particular design or firing regime and thus definitive conclusions are impossible. The energy absorbed by the PETN is also not well understood.

Therefore, the initiation mechanism within the PETN EBWs has not been determined for EBW detonators. There is strong evidence that a shock-to-detonation (SDT) mechanism is not the sole cause of initiation. There is insufficient understanding of how electrical sparks transmit energy to PETN to make any judgement regarding the role gas ionization plays. Deflagration-to-detonation (DDT) seems like the most likely candidate for initiation but there is still a great lack of evidence for the presence of this mechanism.

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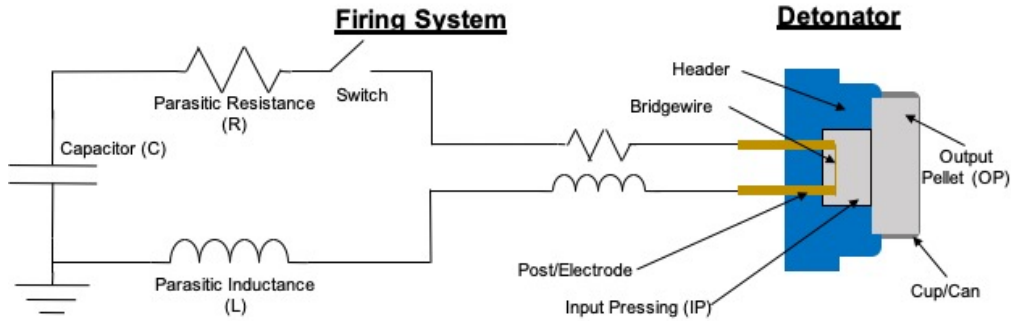
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## **1. Introduction and Scope**

This report aims to summarize the state-of-the-art in understanding of how Exploding Bridgewire (EBW) Detonators use electrical energy to initiate low-density Pentaerythritol tetranitrate PETN explosives. A good, and more general, review of EBW detonators is given by Rae [1]. Many EBW detonators utilize other explosives for the initiating fill (IP) but they are not the focus of this report. The report will also recommend research that will aim to understand these physical processes better with the aim of generating tools that enable the critical aspects of initiation in these devices to be predicted and quantified.

EBW detonators were invented at Los Alamos National Laboratory in the 1940s [2] specifically to initiate nuclear weapon explosive charges. This invention was due to the need for an electronic detonator that had a very repeatable function time compared to those that existed prior to that era. Typical EBW detonators have standard deviations in function time less than 25 ns [2]. Function time is defined as the time taken from the application of a current pulse to the time at which the detonation wave reaches the outer surface of the detonator. Before this invention, detonators usually were of a “hot-wire” design: application of a low-voltage electrical pulse causes heating of a wire that creates a thermal reaction within the explosive. Hot-wire detonators can have an variability, or jitter, in function time of milliseconds which is vastly unsuitable for nuclear weapon initiation. This is due to inherent variability within the timescales that manufacturing tolerances have upon the thermal conduction and subsequent thermal initiation processes. The physical differences between EBW and hotwire detonators are relatively minor and, in fact, the EBW concept was proven by initiating a hotwire detonator using a capacitive discharge unit (CDU) [2].

The solutions to improve timing jitter were to reduce the uncertainties within the physical processes within the system that deliver energy to the bridgewire, and from the bridgewire to the explosive fill. To reduce the uncertainty in the energy transfer to the bridgewire, a pulsed CDU, charged to thousands of volts, was employed that caused the wire to explode in a very repeatable manner rather than heat up on a slower, and more variable, timescale. This explosion then caused a repeatable initiation of the explosive fill but, unfortunately over 70 years later there is still no conclusive theory that describes this process. A schematic of a typical EBW detonator system is shown in Figure 1.



**Figure 1 - Schematic of and EBW detonator and firing system**

In addition to the increased repeatability (reduced timing jitter), EBW detonators offer advantages in safety and reliability over hotwire detonators [2, 3]. This is because EBW detonators do not require primary explosives and there is less variability in energy transfer from the bridgewire to the explosive fill. The electrical characteristics of hot wire, EBW and EFI (exploding foil initiator) detonators are shown in Table 1. This table shows that EBW detonators lie somewhere between hot wire and EFI detonators in terms of electrical safety as shown by threshold current, voltage and power. Typical threshold energy appears the same for all three devices but it is important to note that other criteria must also be satisfied such as current and power.

**Table 1 - Threshold electrical characteristics for typical hot wire, EBW and EFI detonators. Table reproduced from [2].**

	Hot Wire	EBW	EFI
<b>Current (A)</b>			
Threshold	1	200	2000
Operating	5	500	3000
<b>Voltage (V)</b>			
Threshold	20	500	1500
<b>Energy (J)</b>			
Threshold	0.2	0.2	0.2
<b>Power (W)</b>			
Threshold	1	100,000	300,000
<b>Function Time (µs)</b>			
Typical	1000	1	0.1

Many of the physical processes involved within the functioning of an EBW detonator are well understood and quantifiable. The general processes of how energy is transferred between the various subsystems is described:

- 1. The firing system delivers a current pulse across the bridgewire.** EBW detonators require a firing system that involves stored, high-voltage electrical energy. This is typically achieved by a capacitive discharge unit (CDU) but other devices can generate firing pulses with sufficient electrical characteristics. This report will only focus on CDUs as they are ubiquitous for detonator applications. The capacitor is charged to a high voltage (>500

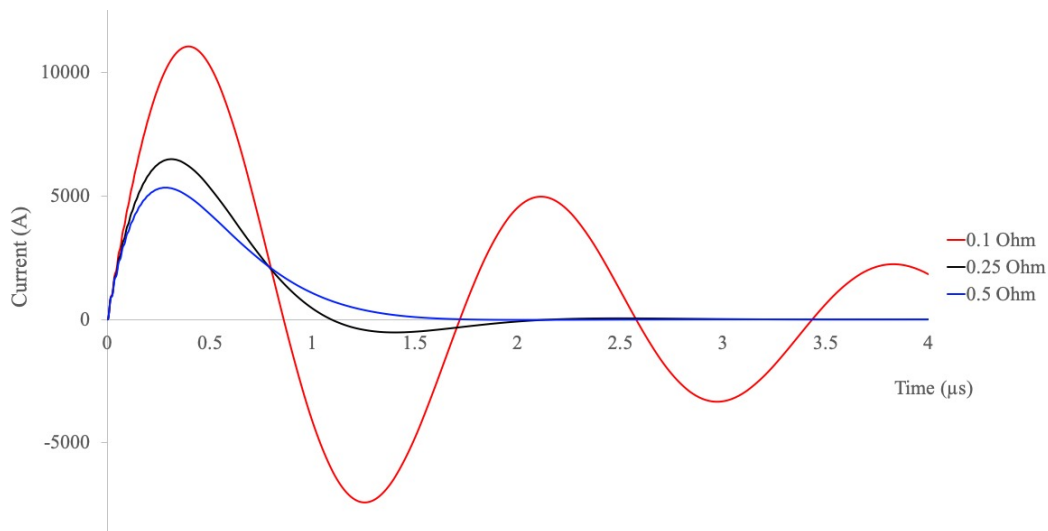
V) as shown in the circuit in Figure 1. Upon firing, an ultrafast switch closes that releases the charge on the capacitor through the detonator electrodes and across the bridgewire.

2. **The bridgewire heats and explodes.** Electrical energy from the firing pulse is absorbed within the entire electrical circuit due to resistance. The thinner and shorter bridgewire has lower cross-sectional area than the larger cables in the circuit and thus heats at a faster rate than the large cables. Due to resistive heating the bridge melts, vaporizes and, potentially, ionizes during the explosion process.
3. **Energy is deposited within the initial pressing (IP).** The energy from the exploding bridgewire and energy generated by continued conduction through the expanded wire, and spark within the air, is transferred into the explosive IP. This energy emanates in the forms of EM radiation (x-ray [4], UV [5], visible [6], IR [7]), electrical [2], and mechanical (shock-waves) [8].
4. **The IP explosive initiates.** This process has not yet been quantified, or understood, and is the subject of this report. It has been studied by many researchers and many claim to understand it, however.
5. **The IP explosive causes a detonation in the OP.** The output from a detonator is a detonation wave from the OP. The transition from initiation of the IP to detonation in the OP can be variable between different designs and, often, not well understood.

## 2. Firing Circuit Description and Operation

EBW detonators must be operated by a pulsed power source. This source is typically a capacitive discharge unit (CDU). A schematic of a CDU is shown in Figure 1. This unit consists of three elements: a capacitor, a switch and a resistive load (the bridgewire). The capacitor is charged to a high voltage before a fast-acting switch closes and causes the electrical charge to be released to the firing circuit and through the detonator bridgewire. Parasitic resistance and inductance inherently exist in CDUs, and detonator cables, and are required to be optimized due to their detrimental effect on detonator performance. CDUs are often referred to as RLC (resistance, inductance and capacitance) circuits.

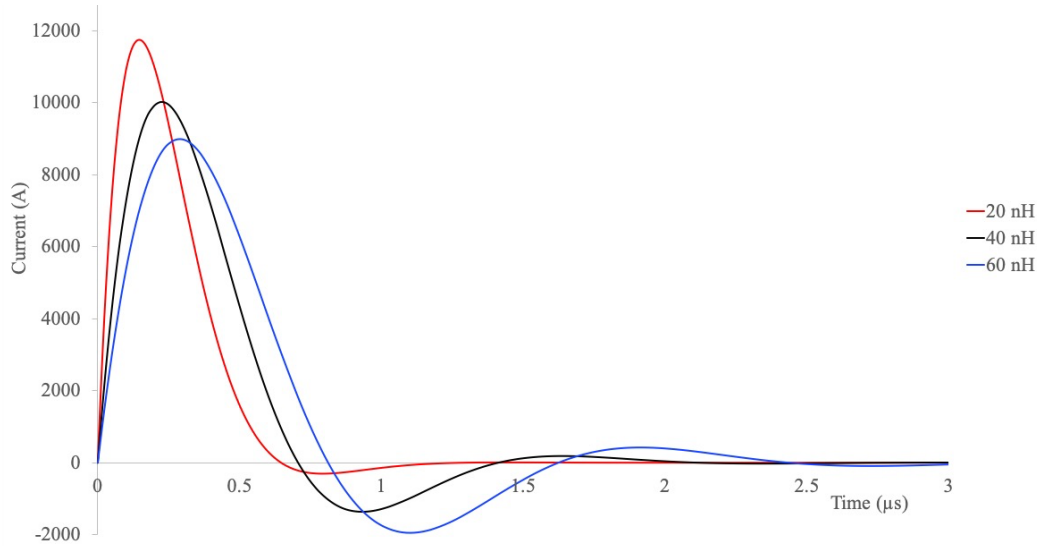
If a fixed resistive load is placed on the output of the system, instead of a detonator bridgewire, the current in the circuit following the behavior of an underdamped, critically damped, or overdamped sinusoid, depending on the circuit resistance. This mode of operation is usually called a ringdown, and can be used to characterize the circuit and extract RLC parameters. Typical ringdowns are shown in Figure 2.



**Figure 2 - Ringdowns showing the effect of increasing firing circuit resistance.**

The resistance of the firing circuit is an important parameter to minimize. Figure 2 shows the effect of increasing circuit resistance. The maximum current decreases with increasing resistance which will limit the available energy to explode the bridgewire and therefore initiate the detonator IP [9].

The inductance of a firing circuit is also a critical parameter to minimize to ensure proper detonator function. It can be harmful to the energy input to the bridgewire and decrease the probability of detonation [10]. The effect of increasing inductance on the current profile is shown in Figure 3. It can be seen that relatively small increases in inductance decreases the peak current and also the rate of current change ( $di/dt$ ). Both of these characteristics are critical for bridgewire explosion and detonator function.



**Figure 3 - Ringdowns showing the effect of increasing firing circuit inductance.**

### 2.1. Transfer of electrical energy through firing system

This section describes the energy flow through a firing circuit and is a summary from [11]. This report gives a very thorough explanation of the process and is an excellent source for further understanding of the behavior of these circuits when connected to an EBW detonator.

The capacitor is charged to high a high voltage using a system external to the circuit shown in Figure 1. The energy stored on the capacitor ( $E_C$ ) is determined by:

$$E_C = \frac{1}{2} CV^2 \quad (1)$$

where  $C$  is the capacitance and  $V$  is the charge voltage. The operation of the fast-acting switch causes current to flow through the system and thus the discharge of the capacitor begins. The current flow ( $I$ ) depends on the rate of change of voltage across the capacitor ( $dv/dt$ ):

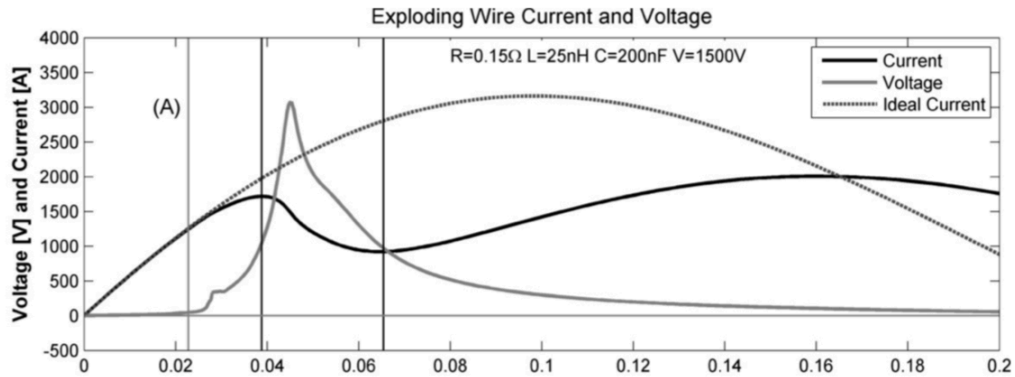
$$I = C \frac{dv}{dt} \quad (2)$$

This charge does not instantaneously flow through the bridgewire due to the natural inductance of the circuit. Instead, significant energy ( $E_L$ ) is intermittently stored in the magnetic field of the circuit:

$$E_L = \frac{1}{2} LI^2 \quad (3)$$

Where  $L$  is the inductance. Therefore, the energy stored in the magnetic field is dependent on the current flow and this allows energy to be released to other energy sinks (circuit resistance, bridge resistance) during the time-dependent operation of the circuit.

When the firing circuit is discharged through a detonator and explodes the bridgewire, there is no longer a fixed resistive load across the CDU circuit. The bridgewire changes resistance rapidly as it explodes. This process is called ‘burst’ and will be the focus of the next section. A typical current trace is shown in Figure 4.

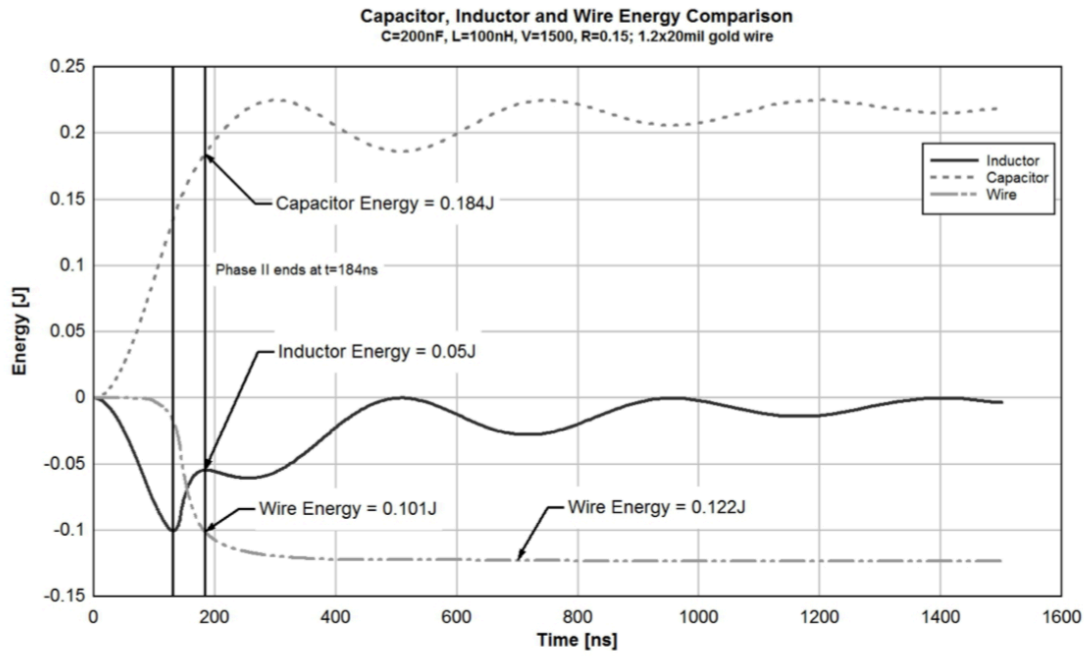


**Figure 4 - Typical Current and voltage traces of a bridgewire exploded by a CDU. This image is reproduced from [11].**

In Figure 4, it can be seen that the current profile up to point A is identical between the bridgewire case (‘Current’) and ringdown case (‘Ideal Current’). This is because the bridgewire has a relatively constant resistance as it is still in the solid phase. After point A, the explosion process begins and the bridgewire resistance increases. The voltage drop across the bridgewire increases and the current drops as seen in Figure 4. During this explosion process, the bridgewire is absorbing much of the energy that was stored in the capacitor and the magnetic field.

Figure 5 is reproduced from [11] and is an excellent description of how energy flows through an EBW firing system. Positive  $dE/dt$  indicates a component is releasing energy and negative  $dE/dt$  indicates that a component is absorbing energy. The black lines are at consistent points in the energy transfer process in both Figure 4 and Figure 5. As described previously, energy flows from the capacitor and into the inductor. A relatively small amount of energy resistively heats the bridgewire. This is small until the bridgewire increases in resistance and then absorbs more energy from the circuit. This energy is mostly supplied by magnetic field of the circuit.

It is important to note that not all of the energy on the capacitor is transferred to the bridgewire. In the example in Figure 5, only 54 % of the energy was transferred. Some of the remaining energy is absorbed through parasitic resistance of the firing circuit and the remainder is not delivered before the exploded wire creates an open circuit. In the latter case, the remaining energy is typically discharged through safety resistors within the firing system.



**Figure 5 - Energy within the general firing system components during the discharge of the CDU. This image is reproduced from [11].**

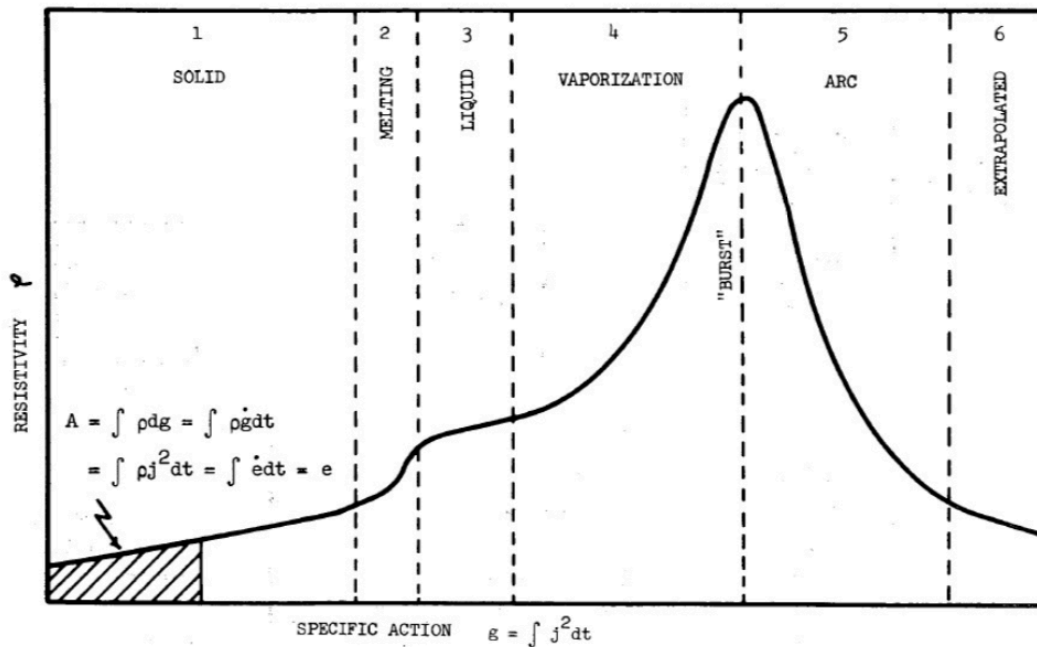
### 3. The Electrical Explosion of the Bridgewire

#### 3.1. General Theory

Dynamic changes in resistance of the bridgewire are caused by the explosion of the wire and the relative conductivities of different material phases. There has been consensus for some time that there is a minimum amount of energy and power level required to explode the wire [10] and that can mostly be explained by the theory of Tucker in 1972 [12] that detail the states of the bridgewire as it undergoes explosion:

1. **Solid Heating.** This is the resistive heating of the solid bridgewire until the onset of melt. Tucker states that this region is difficult to define: “the precise determination of the end of this region is often difficult to estimate from experimental data since no sharp discontinuity associated with the beginning of melting is observed” [12]. This is likely due to the well-known non-linearity of the resistance/temperature curve in metals.
2. **Melting.** During the melting phase, the wire material is a mixture of both solid and liquid. The end of this region is generally well defined and may be precisely identified for all metals thus far tested [12]. This is defined by the discontinuity in resistance that can be seen in Figure 6.
3. **Liquid Heating.** Tucker defines this as a region of little curvature, in which the slope may be relatively large for such metals as gold and copper or approach zero for many refractory metals [12]. It is also stated that the actual transition point from heating of the liquid phase to vaporization is difficult to define and he suggests that evidence exists that superheating of the liquid commonly occurs although this evidence is not referenced.
4. **Vaporization.** This region is characterized by a rapid increase in resistance as the liquid wire vaporizes. Tucker suggests that this is associated with a decrease in wire cross-section although it is known that the wire increases in cross-sectional area during this phase as it expands. It is more accurate to explain this by the increased resistivity of the gaseous phase of the material. He also explains that if system voltages are sufficiently high, the resistance rise is terminated by an arc breakdown through the wire vapor. He defines this point in the resistivity profile as “burst”, which is the peak resistance that the wire reaches during the explosion process.
5. **Arc Growth.** After the wire is vaporized, there is still sufficient potential across the wire vapor to cause an arc to form. Tucker characterizes this region as a rapid fall in resistivity associated with the growth of the arc channel; resistivity in this region depends upon both the current profile following burst and upon external confinement [12]. The general understanding of this portion of the curve seems to now include ionization of the gas surrounding, or within, the bridgewire although there is little to no direct evidence to suggest that ionization states are, in fact, reached within the expanded bridge material. It is likely that these states are reached, however, as electrical conduction remains after the air spark is suppressed [13] and they are regularly assumed to exist [14, 15].

6. **Extrapolating Resistance.** This region describes the continued conduction of the wire, or volume of exploded wire, after the decrease in resistance. Tucker notes that the limit of this region is well defined due to the limit in experimental recording time. The resistivity trend is caused by the current flowing through a mixture of the expanded wire and the ionized gas surrounding the wire [16]. Ionization of the surrounding gas has been suppressed by increasing the pressure of, or changing the, gas surrounding the bridgewire and therefore changing the position on the Pashen curve [13] thus demonstrating that both materials are conducting at this point. The probable terminus of this behavior is the inevitable decay of potential difference across the bridgewire volume needed to continue spark transmission caused by the decay of energy within the CDU circuit.



**Figure 6 - Tucker's theory of resistivity as a function of metal phase during the explosion of a metal wire. Image reproduced from [12].**

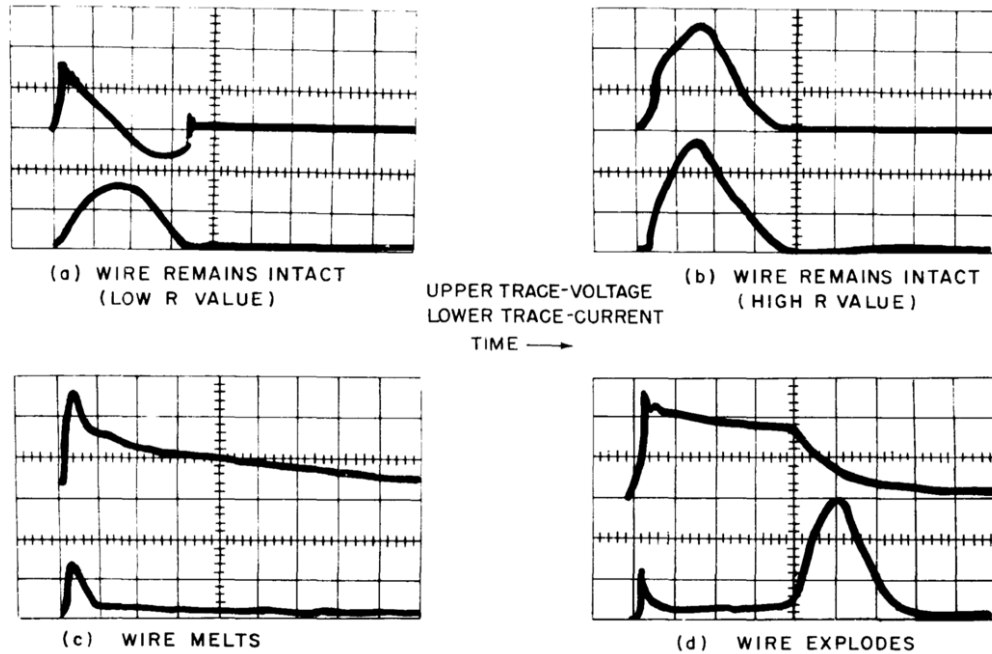
Figure 6 also shows the theory of the action integral [12]. It is hypothesized that there is a minimum action required to explode a metal wire, where specific action ( $g$ ) is defined as:

$$g = \frac{1}{A^2} \int I^2 dt$$

Where  $A$  is the initial cross-sectional area of the wire and  $I$  is the current history. The theory has been shown to capture the behavior of an exploding wire but relies upon an empirical calibration from existing data. Therefore the theory does not predict scenarios outside of the calibration regime where the minimum action has shown to be not constant [17], most notably by Valancius [18].

The key question then becomes “what are the thermodynamic properties of this minimum state and how do they transfer energy to the IP and affect EBW initiation probability?”

It has been shown that the energy and power affect the explosion response of the wire. If energy is too low or deposited too slowly, the wire may not explode or explode in a non-optimal way [10].

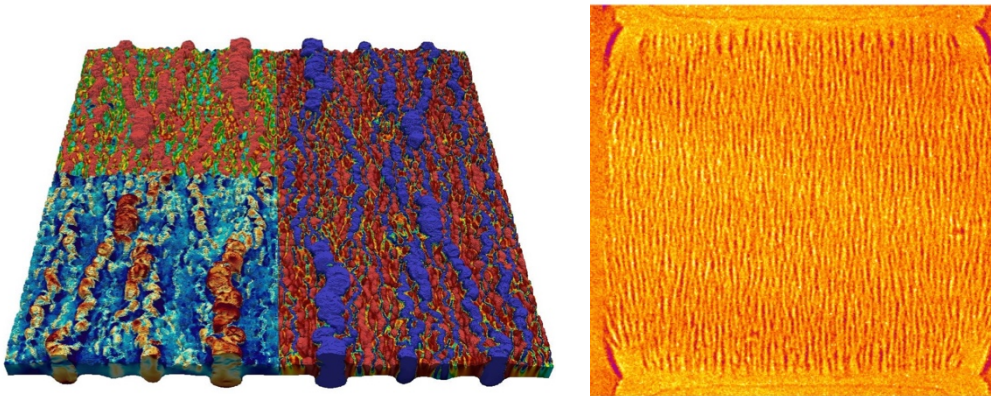


**Figure 7 - Wire behavior correlated to different electrical responses: voltage above and current below. Image reproduced from [10].**

The traces in Figure 7 (d) show a dwell event. This is where the wire begins to explode and then pauses as seen by the dip in current flow. After the pause, a current restrike drives it to full burst provided sufficient voltage remains across the wire length. Leopold has shown this phenomenon can be controlled by wire length provided that other circuit parameters remains constant [10] although the length is indirectly controlling energy density which is probably key to the root cause. Recently, dwell events have been shown to be caused by the wire material taking a pathway through the equation of state (EoS) that is at a particularly high-resistivity point while in the vapor phase. In this scenario the parasitic resistance of the firing circuit is relatively high and there is insufficient energy within the circuit’s magnetic field to drive the wire past this high-resistivity phase. The conductivity stalls until the material has expanded enough to reach a less resistive state and the energy within the capacitor can drive the wire and absorb energy quickly again [11].

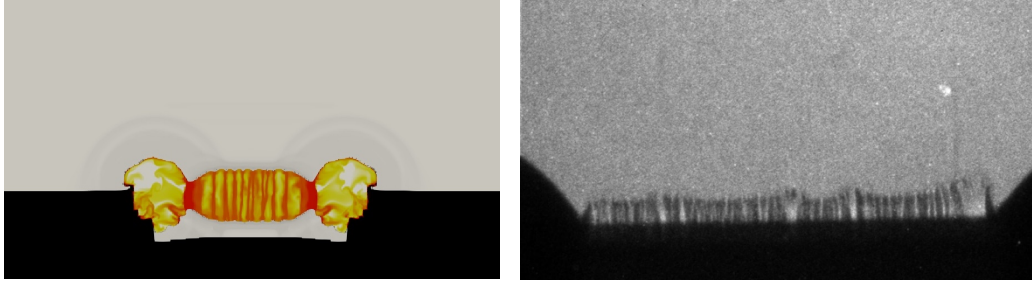
### 3.2. Electrothermal Instabilities

Tucker's theory of a phase-dependent pathway leading to burst is a very important theory and has led to valuable empirical models [19-21] that describe the electrically-driven explosion process within metals [21]. However, it is realized in a later publication that this assumption of phase homogeneity may not be valid and it is probable that solid materials exist at elevated temperatures and pressures [16]. The phenomenon of electrothermal instabilities (ETI) during electrically-driven metal explosions has been extensively studied [22-24] since the development of Tucker's theory. The principle states that instabilities propagate during the electrical explosion process due to the spatial differences in geometry, conductivity or microstructure. The increased resistivity, and therefore heating, of locations across the wire lead to a variety of thermodynamic states throughout the entirety of the wire. This phenomenon has also been witnessed in real detonator components; both EBWs [25] and EFI detonators [26, 27]. Figure 8 and Figure 9 show the results of these EFI and EBW studies respectively and it can be seen in both that the density varies dramatically during explosion as a result of ETI.



**Figure 8 - Electrothermal instabilities in an EFI foil with surface crystal structure. MHD simulation (left) and PCI radiograph of a copper-Kapton foil (right).**

In both Figure 8 and Figure 9, the MHD simulations of the components included quantified surface imperfections in the components. This produced qualitatively similar behavior to the experiments although the quantifiable resistive, thermal and volumetric response has not yet been studied. Therefore, Tucker's description of the resistive changes of an exploding wire compared to unique material states is not strictly accurate although it does provide valuable insight into the process.



**Figure 9 - Electrothermal instabilities in an EBW with surface defects. MHD simulation (left) and PCI radiograph of a SE1 detonator (right).**

One aspect of ETIs that have not been studied is their influence on explosive initiation. The local elevated temperatures and pressures produced by ETI are far higher than the assumed bulk behavior and these are favorable conditions for explosive initiation.

### **3.3. Energy emitted from the exploding bridgewire**

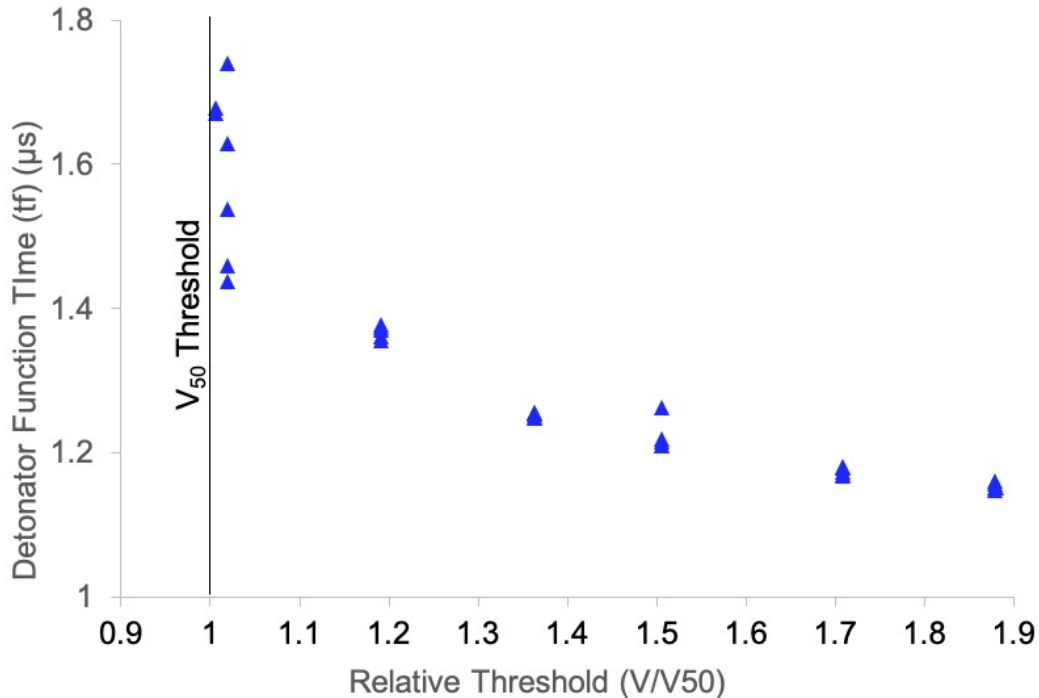
Many forms of energy have been demonstrated to emanate from exploding wires: EM radiation (x-ray [4], UV [5], visible [6], IR [7]), electrical [2], and mechanical (shock-waves) [8]. It is important to note that not all of these have been demonstrated in the regimes that EBW detonators operate but they are included in this review as data particular to EBW detonators is limited when it comes to the bridgewire output. Some studies have focused on quantifying the magnitude of these energies but it is naïve to assume that they are emitted at a constant ratio across all EBW designs. It is almost certain that their magnitude and prevalence is determined by the bridge material [28], bridge geometry and firing system parameters (R,L,C & V). These energies transmit to the IP and cause initiation; as far as a theory of understanding the EBW initiation mechanism, that is the only statement that the detonator community agree on!

#### 4. General Observations about EBW Initiation

There are general trends that are applicable across all EBW detonators and the trends can provide the restraints for determining a theory of initiation.

##### 4.1. Function time vs CDU charge voltage

The relationships between CDU charge voltage/energy and function time are constant across EBW detonators. Figure 10 shows a typical relationship and can be found in [25].

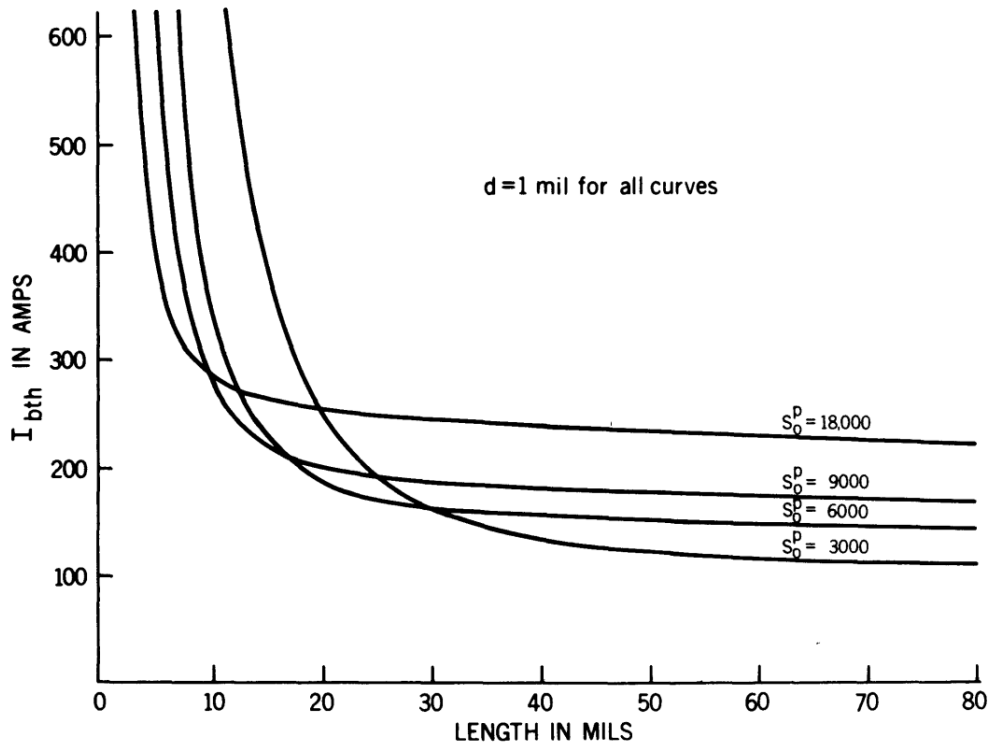


**Figure 10 – Typical relationship between EBW function time and CDU charge voltage. Image reproduced from [25].**

This relationship states that as CDU charge voltage decreases, the function time decreases asymptotically towards the  $V_{50}$  threshold.  $V_{50}$  is defined as the CDU charge voltage at which the probability of detonator initiation is 50%. This relationship is important when determining the ‘all-fire’ level of an EBW detonator which is the voltage at which a 99.9% (or other similarly high probability) of detonators will function. The function time is assumed to reach a constant value as charge voltage is increased although there is no published data to support this as a fact. It is therefore assumed that the amount of energy is responsible for the probability of detonator function given a repeatable manufacturing process for a particular component. There is no published evidence between the energy required to explode the wire and the energy required to initiate the detonator, although there have been suggestions within the detonator community i.e. it may be possible to explode the wire, but not initiate the detonator.

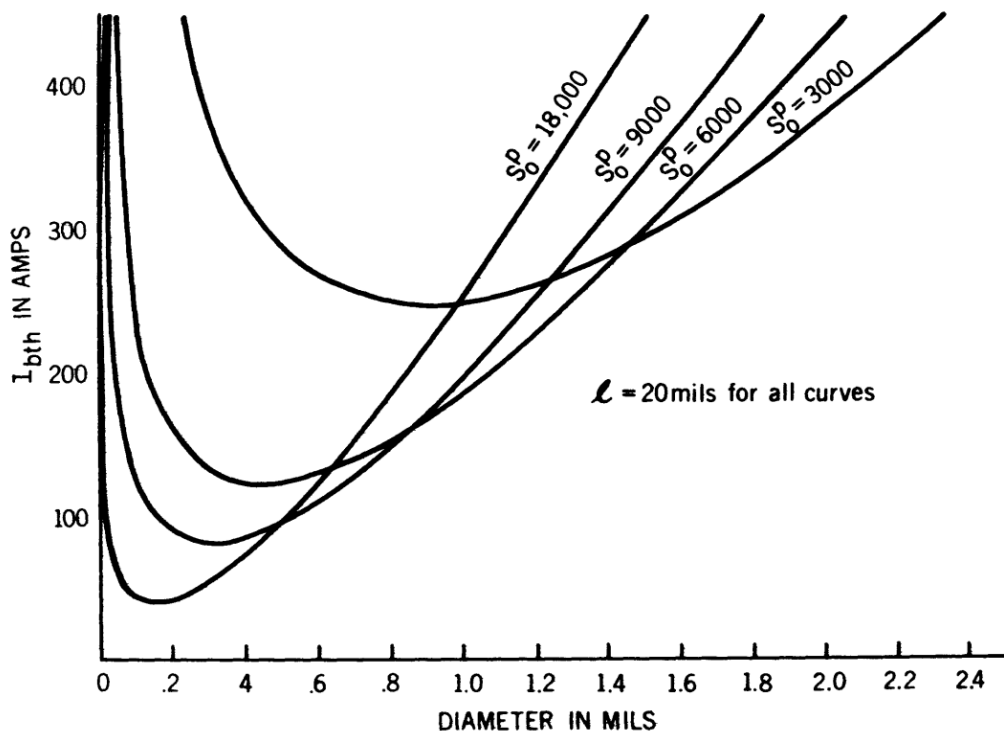
#### 4.2. Specific surface area (SSA) vs threshold

Another general trend in PETN EBW detonators is that lower specific surface area (SSA) PETN powders have lower  $V_{50}$  thresholds at wire diameters practical for detonator use ( $\sim 25 \mu\text{m}$ ) as shown in Figure 11. Typical EBW detonators have bridgewire lengths of  $\sim 1 \text{ mm}$  (40 mil) This study [19] used burst current ( $I_{\text{bth}}$ ) as the metric for describing threshold but the results should be analogous to  $V_{50}$  threshold.



**Figure 11 - Burst current ( $I_{\text{bth}}$ ) vs wire length for different surface area PETN. All wires were gold or gold alloy. Image reproduced from [19].**

The real situation is far more complicated as higher surface area PETNs have lower  $V_{50}$  thresholds for very small diameter wires approaching  $2 \mu\text{m}$  in diameter (Figure 12). This subtlety is probably due to the relative size of the particles compared to the bridgewire and is not particularly applicable to typical EBW bridgewire dimensions.

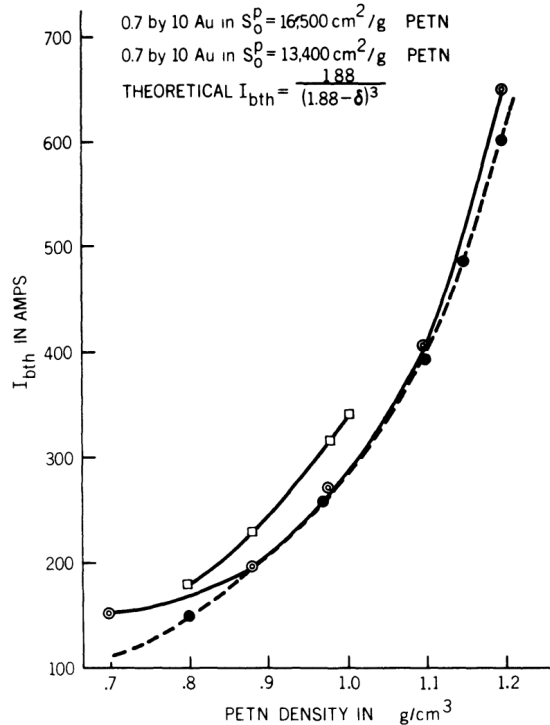


**Figure 12 - Burst current ( $I_{bth}$ ) vs wire diameter for different surface area PETN. All wires were gold or gold alloy. Image reproduced from [19].**

Practical considerations in detonator design prohibit the use of low SSA PETN in EBWs despite the advantage of reduced threshold and therefore increased performance margin. Rather, higher SSA PETNs are used because they offer more consistent initiation timing and increased repeatability [5].

### 4.3. Pressing density vs threshold

EBWs typically have IP densities on the order of  $0.8-1.0 \text{ g.cc}^{-1}$  but the optimal densities for minimum initiation threshold are lower as shown in Figure 13 [19]. They are typically higher because of practical considerations such as mechanical integrity and a compromise must be made between this and initiation threshold. Such degradation in mechanical integrity through the detonator lifecycle will detrimentally affect safety, reliability and performance. Additionally, the initiation through spark discharge has a lower threshold at lower densities [29] which has adverse consequences for detonator safety. Having a lower density powder could increase sensitivity of the detonator to electrostatic discharge (ESD) events.



**Figure 13 - Burst current vs PETN pressing density. All wires were gold/gold alloy. Image reproduced from [19].**

#### 4.4. Wire material vs initiation threshold

An EBW bridgewire can be composed of almost any solid metal and many have been investigated [28, 30, 31]. The most notable study was on varying wires of different materials and studying their thresholds in PETN [32]. The materials studied, and in order of lowest to highest threshold were: silver, copper, aluminum, platinum, tungsten and iron. The author states that these materials produce high peak electrical powers caused by a low boiling point and low heat of vaporization. A way to interpret this finding is that the bridge material needs to absorb a high proportion of its energy within the gaseous and plasma phases to transmit maximum energy to the explosive.

However, it is difficult to quantify how much energy is delivered by the bridgewire to the explosive that contributes to the initiation process. Studies that have focused on quantifying this have aimed to measure the expansion of the wire into air [33] and found that there is no correlation between the vigor of expansion of the bridgewire in air and the initiation threshold of PETN (see Table 2). Other studies have aimed to use the rate of expansion of the bridgewire into air and infer shock properties within the PETN [14, 15]. This method is incorrect and the results of those studies should be treated with caution.

**Table 2 - Ranking of wire diameters that gave the lowest threshold in PETN and the most vigorous expansions in air. Table reproduced from [33].**

	<u>To Effect detonation in PETN</u>	<u>Vigor of Exploding Wires in Air</u>
1	0.0020	0.0030
2	0.0015	0.0020
3	0.0030	0.0015
4	0.0010	0.0010

## 5. PETN Initiation: Deflagration to Detonation (DDT)

### 5.1. Definition of DDT

Deflagration to detonation transitions (DDT) explain the process of conversion of a subsonic deflagration (burning) reaction to a supersonic detonation reaction. There are a wide number of phenomena that are symptomatic of DDT and four major types exist ranked in order of lowest explosive solid fraction to highest in the system: burn area acceleration, type II, type I and wave coalescence [34]. There is no specific ‘cut off’ porosity between the regions, rather an overlap based upon the dominant phenomena that contribute to the DDT (see Table 3).

**Table 3 - Types of DDT and the phenomena that occur in each. Table reproduced from [34].**

Major types of DDT → Initial state (solid fraction) → Phenomenon ↓	Area acceleration		Type II		Type I		Wave coalescence
	Gas, vapor	Dusts, fogs	Very low-density beds	Pour-density beds	Packed beds	Pressed beds	Solids
Ignition	✓	✓	✓	✓	✓	✓	✓
Conductive burning (laminar)	✓	✓	✓	✓	✓	✓	✓
Turbulence	✓	✓	✓				
Flame folding	✓	✓					
Deconsolidative burning			✓-	✓	✓	✓-	✓-
Flame acceleration with pressure	✓	✓	✓	✓	✓	✓	✓
Flame intrusion			✓	✓	✓		
Channel formation			✓	✓			
Convective burning			✓	✓	✓-		
Thermal explosion			✓	✓	✓-		
Flame propagation in cracks						✓	✓-
Compaction			✓	✓	✓	✓-	
Compressive burning				✓	✓	✓	✓
Shock formation	✓	✓	✓	✓	✓	✓	✓
Detonation II (compacted material)			✓	✓	✓	✓	
Detonation I (pristine material)	✓	✓	✓-	✓	✓	✓	✓
Retonation (high-velocity rearward-going wave)			✓	✓	✓-		

If DDT is to occur in the low-density PETN IP in EBW detonators then it should be either type I or II based upon the porosity of the explosive fill.

Type 1 DDT typically occurs in explosive beds of 50-70% TMD [34]. The process begins by a thermal stimulus or the thermal energy generated by porous compaction. This energy then propagates through a wave to compact the material ahead of it thus depositing energy into the material through interparticle friction, heating through compression of the interparticle void gases, intraparticle shear/fracture and microkinetic energy [35]. The thermal energy deposited into this material then ignites the compact and an ignition wave propagates through the compacted powder. A compacted region (plug) then forms as a result of the pressure caused by the initial burning and the ignition wave. This plug material is close to 100% TMD [34] and intermittently restricts the ignition wave’s progress due to the increased density further increasing the pressure behind it. The pressure

behind the plug causes a shock wave to be released through it and into the compacted material ahead of it which eventually evolves into a detonation wave. Type I DDT has been observed and studied in coarse (~180  $\mu\text{m}$  particle) PETN [36].

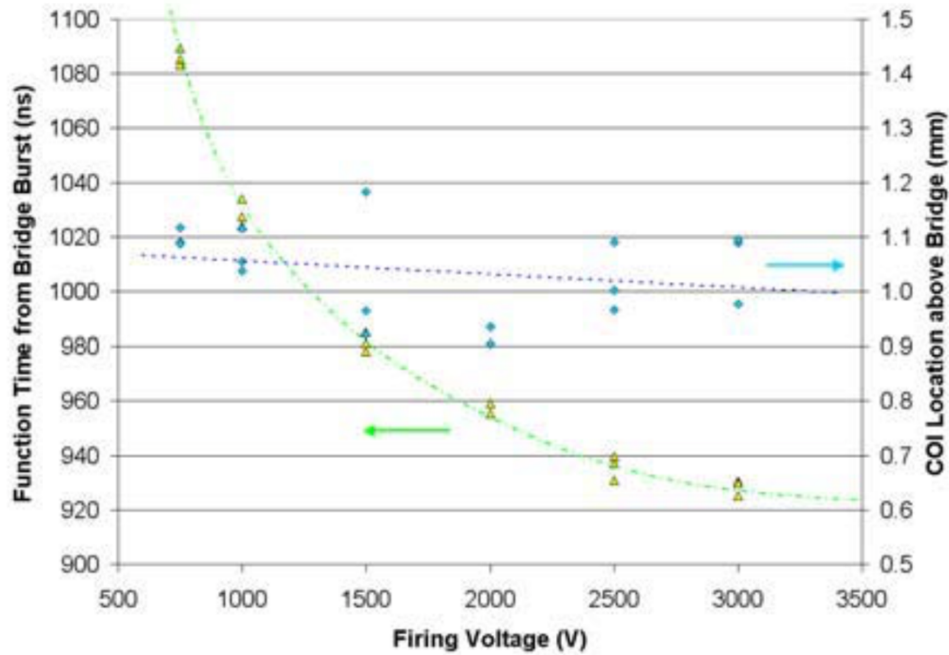
The classical description of type II DDT is given in [36]. In this paper, it is referred to as DXDT localized thermal explosion detonation transition. Initially, a burning wave propagates through the porous bed through conductive burning. The speed of this wave is on the order of 0.1-10s  $\text{mm}\cdot\text{s}^{-1}$  [34]. The conductive burning causes the release of gas that increases the pressure and drives the burning reaction through the intergranular voids ahead of the conductive burn front. In low density powders, there is a large amount of pore space available to allow the hot gasses to permeate the bed. The increased conductive burning causes further release of gas and subsequent heating/compaction of the bed. The wider powder system becomes pressurized and, once a critical pressure has been reached, the process of convective burning occurs and is a much faster process. This convective burning quickly heats a volume of porous explosive and a subsequent localized thermal explosion ensues. This explosion then creates shock waves that lead to detonation. These phenomena were explained around PETN at ~ 30% TMD with particle sizes on the order of 1  $\mu\text{m}$  [36, 37].

There are subtle differences in type I and II DDT as explained above. The similarity is that there is a burning reaction that causes pressure and this pressure causes shock waves within the material. The shocks then initiate the material through a typical shock-to-detonation transition (SDT). The above processes were determined and described in terms of a 1-dimensional column of powdered explosive with heavy confinement and, if either of these occur within PETN EBW detonators, then the mechanics are likely to be far more complicated.

## 5.2. DDT in EBW Detonators

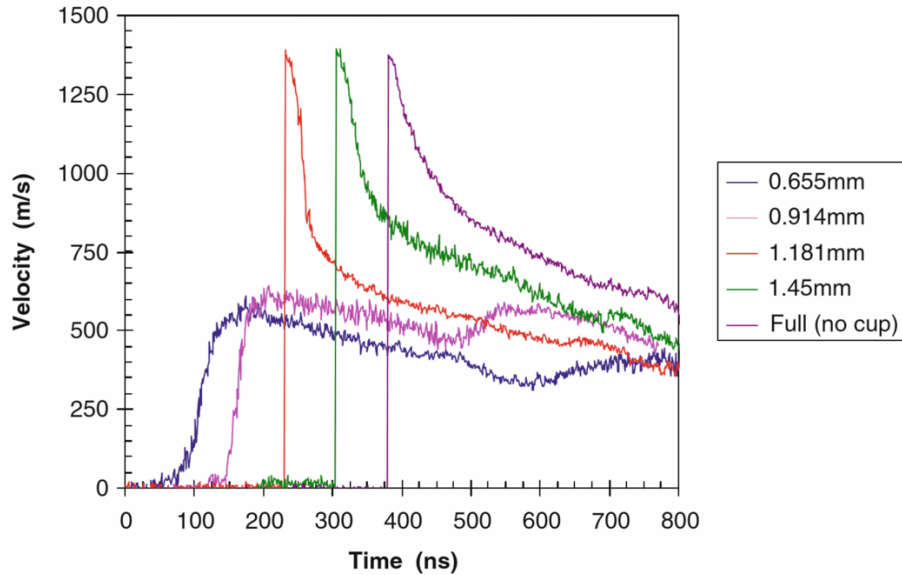
Most of the published work by LANL has concluded that DDT is the mechanism responsible for initiation of the IP in EBW detonators [38, 39] in addition to observations by other researchers [10]. However, none of the studies have narrowed down their conclusions with a suggestion of which type DDT is occurring.

There are two main pieces of evidence for the presence of DDT as the dominant mechanism for EBW initiation. Firstly, Martin [38] observed that there was no change in the center of initiation (COI) with CDU voltage across a series of ‘cutback’ experiments (see Figure 14). As previously discussed, the energy output from a bridgewire increases with CDU voltage and thus, more energy would be deposited into the IP. The conclusion from this is that if the PETN IP was being initiated by a shock-wave then the run-to-detonation distance would be shortened with increased pressure and the COI would therefore decrease with increased CDU voltage. This is evidence that disproves SDT rather than proves DDT as the dominant mechanism, however.



**Figure 14 - Function time and calculated COI from detonator breakouts as a function of CDU voltage. Image reproduced from [38].**

The most compelling evidence for DDT are the VISAR data from [38]. This experiment took an EBW detonator and removed material to produce IPs with different thicknesses, known as a cutback. Figure 15 shows the VISAR data at differing IP thicknesses. It can be seen that steady detonation has been achieved by 1.18 mm and the compression waves before this are very ramped in appearance. This data suggests that there is significant compaction occurring then almost instantaneous detonation after a point. This ramped wave aligns with the theory of DDT explained earlier although there is no other data available that would allow a description of the type of DDT occurring.



**Figure 15 - VISAR data from EBW cutback experiments showing the buildup to detonation. Image reproduced from [38].**

The cutback experiments listed in [38] provide the best insight into the shock-waves within an EBW IP leading to detonation. This technique has also been applied to laser EBWS but data were not presented in [38]. There could be significant insight into thermal initiation/DDT of PETN if input energies and powers were comparable as other energy forms could be omitted (shock, electrical).

Although not specifically listed as DDT, a thorough LANL study suggests that a thermal initiation is the cause of initiation in EBWs [7, 40, 41]. This thermal initiation of a volume of the PETN IP will probably lead to detonation through DDT. The authors claim that their data is inconsistent with a DDT response because there was no deflagration wave observed. However, the intensity of the ignition source (the EBW) could cause the deflagration, and subsequent thermal ignition in a very small volume that was not measurable on the scales of the investigators. Rae [1] also makes a similar observation that the convective burn part of the DDT process could be assumed to happen within the bursting of the wire.

It is convenient to assume that the dominant initiation mechanism in EBW detonators is DDT because, intuitively, the exploding wire produces a high-temperature gas/plasma that will permeate the low-density bed. There is a lack of data that describes the temperature output of an exploding wire within PETN and therefore it is difficult to compare the output from a 3-dimensional exploding wire to 1-dimensional columnar DDT experiment. The question of how is the energy transmitted to the bed is also an interesting question to be answered. Rae hypothesizes that UV emission from the bridgewire could be responsible for the thermal ignition of the IP in [1] based upon sensitivity data from [42] and is making progress on quantifying this output in [43].

HNS has been attempted as an EBW IP many times but there is no known, or documented, successes from the research of this author. It has been demonstrated possible using exploding wires at far higher voltages [44], however, but this is outside the regime for EBW detonators. This anecdote has some interesting connotations towards the conclusion that DDT plays a role in the initiation of EBW detonators. The connection was made in [1] that it was not possible to initiate HNS using direct optical initiation based upon data from [42]. A reasonable perception is that a purely thermal mode of initiation would not initiate a relatively thermally insensitive explosive. Therefore, if DDT was the dominant EBW initiation mechanism then HNS should not be a suitable EBW IP explosive.

## 6. PETN Initiation: Shock to Detonation (SDT)

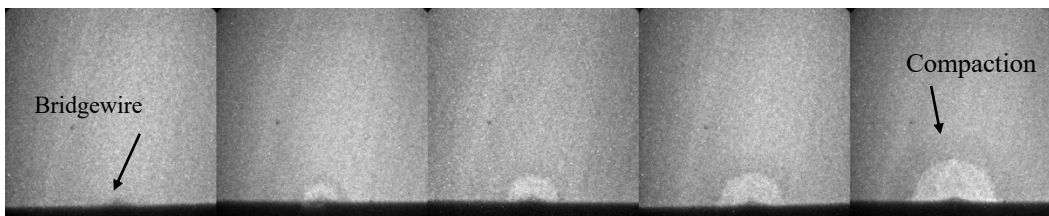
### 6.1. Definition of SDT

The shock-to-detonation transition (SDT) within low-density PETN can be assumed to be heterogeneous due to the complex microstructure and large pore volume. The initiation mechanism within heterogeneous detonation is hot-spot formation [45]. This is the process by which a transiting shock-wave collapses interparticle voids and deposits energy by, e.g.: adiabatic compression of the gas, intraparticle viscous/plastic heating, interparticle friction, adiabatic shear, particle fracture, etc. Therefore, the microstructure of the material intensifies the deposited thermal energy compared to that of a solid. This localized, higher intensity, thermal energy overcomes the activation energy required to initiate the explosive crystals. As the shock transits the porous explosive, it constantly gains energy from the explosive reactions to support the shock-wave and increase it into a steady detonation.

Empirical models can describe the SDT in planar impacts [46] and those typical of a thin shock, as produced by an EFI initiator [47, 48]. The models from thin shocks are inappropriate to apply to EBW detonators due to the 3-dimensional nature of exploding wires. The pop-plot can serve as a lower bound for this threshold in EBWs although the requirement behind it is a purely planar, steady shock.

### 6.2. SDT in EBW Detonators

SDT has been assumed to be the dominant mechanism for EBW initiation [15, 49, 50], probably due to the fact that it is the simplest explanation of how detonation could be achieved. Early attempts to correlate this were focused around correlating initiability of explosives in EBW configurations with drop weight sensitivity [51]. More advanced studies have focused around quantifying the pressure that could be generated by an exploding wire into low-density PETN. Data on the 1-dimensional shock-sensitivity of PETN are very sparse and only one study has reported it [46] but there are significant uncertainties in this data that were not investigated properly.



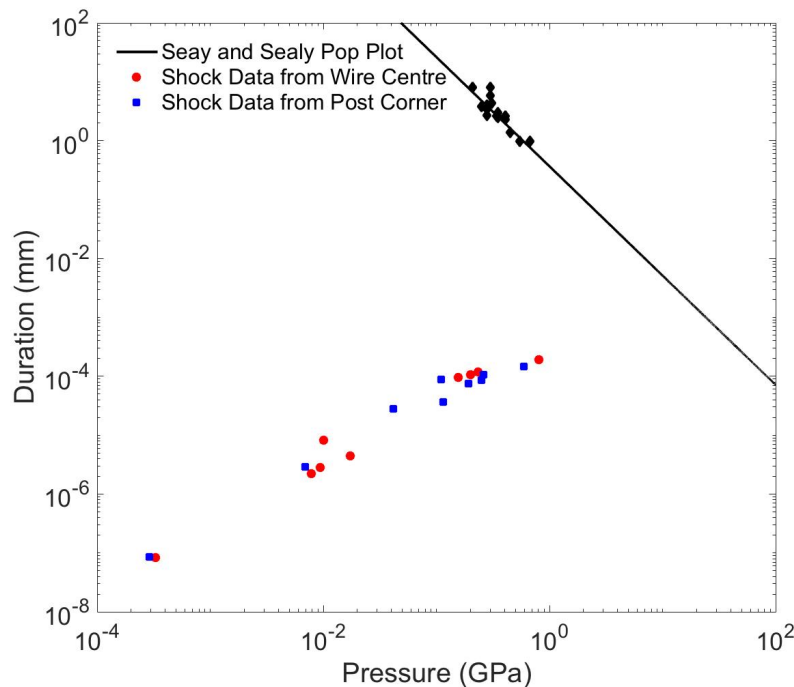
**Figure 16 – XPCI radiograph of an EBW explosion into a  $1.0 \text{ g.cm}^{-3}$  sucrose analogue for low-density PETN. Image reproduced from [25].**

Studies have shown that there are mechanical stress waves generated by exploding wires into a PETN bed [39]. Figure 16 shows this shock transmission in the form of a radiograph taken as a typical EBW bridgewire explodes into low density sucrose which appears to be a good analogue for PETN [25] with respect to its shock Hugoniot. This study showed that there was a supersonic shock-wave present

in a PETN type material but the diagnostic had insufficient temporal resolution to infer pressure from the unsteady wave.

The shock pressure generated by an exploding EBW bridgewire confined by water have been investigated by Frank [13, 52]. It was found that the pressures generated (0.5-0.7 GPa) were sufficient to initiate PETN although not on the length scales of a typical EBW detonator. They also realized that the planar vs line sources were not interchangeable as far as initiation was concerned and concluded that the measured shocks were not sufficient to determine that SDT was the mechanism behind initiation. Another point to note on this study is that the investigators assumed that the shock pressures were similar in water to PETN because they have similar densities ( $1.0 \text{ g.cm}^{-3}$ ). This is a very poor assumption because the two materials have very different shock Hugoniots due to the high compressibility of the porous PETN compared to the relative incompressibility of water.

Some investigators have concluded that the shock-wave generated by an EBW bridgewire is responsible for initiation [14, 15]. However, the authors made a similar mistake, to Frank [13, 52], by assuming that water has a similar shock response to PETN. In addition, the shock velocity in this study was calculated by assuming that it was twice the particle velocity of the wire surface as measured from explosions into air. The invalidity of this assumption is amplified by the fact that Hugoniots for water and PETN do not have a gradient of 2. Therefore, their calculated shock pressure of 1.5 GPa is incorrect, and disagrees with the correct calculations published by Frank [52].



**Figure 17 – ALEGRA MHD tracer particle pressure/duration from a typical EBW plotted against Pop Plot data [53] for low-density PETN. Image reproduced from [25].**

Other studies have focused on simulating the pressure output of an exploding EBW using magneto-hydrodynamics codes such as CALE and ALEGRA [25, 54]. By simulating the EBW's reaction to the firing system, over a range of CDU charge voltages, it was possible to calculate the pressure that an exploding wire exerted onto an analogue of PETN. The sucrose analogue was not a perfect match to that of low-density PETN but the uncertainties are reported in [25]. This study showed that the pressures (and durations) generated by the exploding wire alone were at least a factor of 100 too low to initiate PETN based upon published pop-plot data. This study assumed that there was no pressure generated by thermal expansion of the explosives during the explosion of the wire. This is the most recent proof that SDT is almost certainly not the cause of initiation of the IP fill in EBW detonators.

Although there seems strong evidence that SDT is not the dominant mechanism by which EBW IP fills initiate, the role of shock-compaction cannot be ruled out as a contributing factor. Type 1 DDT relies upon the energy generated by the compaction of the powder to heat the explosive material. It is possible, and probable, that shock-compaction contributes to this effect. Another uncertainty in the role of the SDT is the unreliability of the only published low-density PETN Hugoniot data [53]. Should a more accurate understanding of how this material behaves be obtained, a better data set should be measured. In addition, there has been little effort to understand how unsteady shock-waves initiate PETN; the current evidence relies upon the pop plot which is conservative although unrepresentative of the EBW regime. Even the early studies into EBW initiation disagreed with the notion that the amount of mechanical energy delivered from an EBW bridgewire was correlated to initiation. Leopold found that the wire diameters that gave the most vigorous expansions into air did not correlate with the wire diameters that were most favorable with initiation [33]. This anecdote must be taken in the context of the requirement of a duration/volume that is also necessary for initiation and that a particular diameter wire may not give the required volume to produce initiation even though the pressure is the highest.

## **7. PETN Initiation: Spark Initiation**

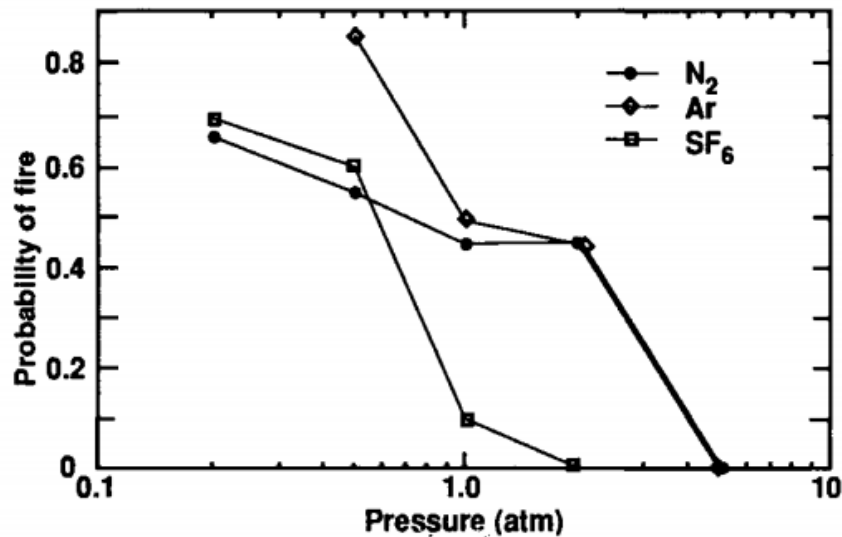
### **7.1. Definition of Spark Initiation**

Electrical sparks have demonstrated effective at initiating PETN. There are devices that have no bridgewire and are known as ‘arc’ or ‘spark-gap’ detonators [55]. These devices are similar to EBW detonators in firing circuitry and geometry. The energy required to fire these devices is substantially lower than EBW detonators and they are unsuitable for use in weapon systems due to their inherent susceptibility to electrostatic discharge (ESD) either by human body or furniture/tooling present in an operating environment.

As electrical sparks traverse a low-density explosive material, the spark channel flows through the interparticle void space as air has a lower dielectric constant than the explosive crystals [34]. This effect is proven to be dominated by the pressure of the gas and the type of gas within the voids [56]. Kennedy summarizes the ignition process as a heat-initiated and pressure-driven deflagration in a small volume in PETN [34] but little is understood about how a sparks transmit their energy to explosive beds, such is the case with EBW initiation in general. Some models have been proposed that allow initiation to be predicted [57]. Little is understood about which path a spark will take through a low-density PETN bed and experiments must be conducted to understand a component’s response to electrical sparks.

### **7.2. Spark Initiation in EBW Detonators**

The contribution of spark energy to overall EBW initiability was studied in [13]. Different gases ( $N_2$ , Ar and  $SF_6$ ), at different pressures, were imposed upon standard SE-1 EBW detonators to inhibit the formation of sparks around the bridgewire at the time of burst. The probability of initiation was measured and found to vary significantly. An increase in pressure resulted in a reduction in initiation probability in all cases. The results of this study can be seen in Figure 18. The study concluded that this effect was due to the reduction in ionization of the PETN crystals around the bridgewire during burst. The author suggests that the ionization causes either sensitization by direct interaction of the electric field or by localized initiation of chemical reactions within the PETN. There is still to be proof of this theory but it seems to be a reasonable assumption and does follow Kennedy’s analysis of spark initiation in porous explosives [34]. The effect of initiation probability was correlated with the dielectric strength of the gas indicating that it was not a simple effect caused by an increase in gas pressure. An increase in gas pressure would probably decrease the likelihood of initiation by inhibiting DDT and SDT mechanisms even if the spark were to be ignored.



**Figure 18 - Probability of initiation vs pressure for a SE-1 exposed to different gases. Image reproduced from [13].**

The initiation of PETN from a spark alone requires significantly less energy than that of an EBW. By using an identical EBW header with and without a bridgewire, the delivered energy for initiation was found to be 5-17 mJ for a spark gap and 15-28 mJ with a bridgewire [58] for a PETN at 1.0 g.cc<sup>-3</sup>. This implies that the spark discharge could be important in the initiation of EBW detonators and that there is more energy required to explode the wire to generate a spark. Therefore, the presence of a metallic bridgewire offers safety advantages in that it increases the minimum firing energy and it provides a short circuit to remove any stored charge across the cable conductors.

A damage scenario where the bridgewire has broken is a vulnerable state for an EBW detonator. With a broken bridgewire, the detonator's functioning mechanism then leans towards spark initiation and, as discussed earlier, the energy threshold for initiation is substantially lower. A study has investigated the thresholds for differing degrees of broken bridgewires but varying the gap size [59] and found the energy required for initiation was approximately 40% lower for detonators with no bridgewire (consistent with [58]). This study concluded that smaller gaps (<125 μm) in the bridgewire had higher energy thresholds than bridgewires with larger gaps. The author suggests that in detonators with smaller gaps, the energy deposited by the spark is small and the bridgewire absorbs most of the energy. In this case, the thresholds are closer to that of the intact EBW. For larger gaps (125-600 μm), the energy deposited into the spark channel is much higher and the energy absorbed by the wire is lower. They postulate that it was not clear whether the spark was initiation the PETN or just increasing the energy density of the remaining bridgewire which caused higher energies there. It was also noted that this study was not representative of real defective parts as the entire bridgewire is present and in this study, the wire was removed by laser ablation: the total volume of bridgewire was different.

Safety and performance are factors for concern when a spark is unintentionally transmitted through an EBW detonator. EBW detonators are considered insensitive to electrostatic discharge (ESD) compared to low-energy detonators [60] but not as insensitive as EFIs or laser detonators. This is mainly due to the higher density of the IP explosive and the electrical insulation/absence of the electrodes in those other designs. There are two paths that spark energy can take through an EBW detonator: pin-to-pin (PtP) and pin-to-cup (PtC). The path depends on the relative position of the charged object and the ground. The spark will form along the path of lowest resistance caused by the dielectric strength of the materials within the design. PtP ESD discharges travel through the cable conductors and therefore through the bridgewire. This is not a problem for HBESD [60] provided that the bridgewire is intact but larger sources can produce reactions or even detonations. PtC ESD travels from the metallic cup of the detonator and to the ground path which is through the bridgewire/electrodes. This is potentially a more severe scenario because the spark may travel through the low-density IP of the detonator and cause spark initiation of the explosive, i.e.: there is no bridgewire to transmit the energy. The low-density PETN is a preferential path for the spark [60] and has a much higher sensitivity than a high-density OP. It is possible to reduce the likelihood of PtC ESD discharges through the IP by grounding the cup to provide a preferential path for the discharge to ground [61].

The performance of EBW detonators have also been affected by ESD. A typical test is the human-body ESD (HBESD) test. A realistic requirement is that the detonator remains serviceable after being subjected to discharges that could be delivered by a human body interacting with the detonator. This is because humans will interact with that detonator many times within its lifespan and that should not degrade the component. Sources above HBESD level have been shown affect reliability [62] or to ‘dud’ a detonator meaning that it will no longer function as intended [60].

ESD safety considerations must be traded against performance characteristics for an EBW detonator; the higher the ESD initiation threshold, the higher the required energy to function the detonator. Therefore, it is important to focus efforts on designing features that increase the resistance to ESD while not increasing the minimum CDU energy required to function the device. As mentioned, this could be by grounding the cup or insulating electrodes with the aim of preventing a spark channel from forming within the IP.

## 8. Conclusions

This study aimed to report the current understanding of the physical processes that cause EBW detonators to fire: particularly the energy transfer from the bridgewire and the resulting initiation mechanism within the IP. The CDU behavior is the most well understood part of the EBW firing system, and can be predicted through analytical solutions provided that the L, C, R & V are well understood.

The absorption of electrical energy by the bridgewire and the physical states that the metal achieves are also fairly well understood. There exist empirical models to calculate resistance during a typical EBW firing and these models can be useful tools when developing bridge geometries and CDU constraints. The subtleties around the spatial variations in temperature/density during the bridgewire explosion are less well understood. These variations may play a crucial role in initiation of the IP due to localized high-intensity energies that are emitted but there is no understanding of this phenomenon. High-fidelity magneto-hydrodynamic (MHD) simulations could provide insight into these spatial variations and, in conjunction with phase-sensitive diagnostics, could provide a better understanding of this phenomenon.

This study demonstrates that there has been a lack of quantifiable data surrounding the energy that is emitted by the bridgewire. Different types of energy have been shown to emit (EM radiation, electrical, and mechanical) but there has been little effort to quantify the magnitude of these energies on a single bridgewire design. Most studies have measured one type of energy on a particular material/geometry. Therefore, the ratios of these energies are unknown and they will certainly depend on the energy density within the bridgewire, confinement, bridge material and etc. These emitted energies are potentially predictive through MHD but there is a large effort required to calibrate the necessary models. Without this understanding of the magnitude and ratios of these energies, the energy transmission to the IP cannot be understood therefore preventing the exact initiation mechanism(s) to be quantified and understood.

There is no good understanding of the energy emitted from the bridgewire so it stands to reason that there is not a real understanding of the energy absorbed by the IP explosive. It has been demonstrated that there is not sufficient shock energy emitted from the exploding wire to initiate the IP by SDT, however.

Therefore, the exact explosive initiation mechanism for EBWs has not been determined. It has been shown that SDT cannot be solely responsible. Two recent studies have suggested that a localized thermal explosion which is a reasonable assumption. Given this and the evidence of ramped wave behavior, it seems like this localized thermal explosion causes DDT within the IP although there is no direct evidence to back up this claim. It is currently safe to assume that the variety of energies emitted from an exploding wire contribute to initiation but it is very

unlikely that there is a single emitted energy or initiation mechanism that causes EBW initiation.

## 9. Recommendations

In order to better understand the energy transfer processes within an EBW detonator that can enable predictions regarding safety and performance, the following recommendations are made:

1. **Energies Emitted from Exploding Bridgewire.** The first priority is quantifying the amount and type of energy that is emitted during the explosion of bridgewires. This study should look at various materials, energy densities and track the rate of change of energy emission.
2. **Energies Absorbed by IP Explosive.** The amount of particular energies absorbed by the explosive powder should be studied with respect to their initiability. This is particularly important to understand how EM radiation are absorbed by the explosive. Then correlations can be made between the energy emitted by the exploding bridgewire and the sensitivity of the explosive to these types of energy. Rae suggests DOI-augmented EBW detonators for this purpose [1].
3. **Spark Formation and Spark Initiation.** One of the main safety implications for EBW detonators are ESD hazards but there is no existing capability to predict the formation of a spark and its effect on the IP. This is a large gap in the community's understanding and is important to investigate. This study should aim at using existing predictive models and quantify the energy delivered to the IP by a spark. Further investigation should then focus upon how this delivered energy initiates the IP.
4. **Further Investigation into DDT.** The study presented in [39] was incomplete and, if expanded to cover a larger CDU charge voltage space, could provide a more definitive answer to the role of DDT across the regime of EBW detonators.
5. **Electrothermal Instabilities.** The temperatures and pressures of the localized electrothermal instabilities should be studied. These matter states are likely of much higher intensity than the assumed bulk behavior of the exploding wire. Their effect on initiation is currently not understood.
6. **Magneto-hydrodynamic Tools.** Creating predictive models that use first-principle physics to calculate the state of the exploding bridgewire and its effect on its confining material will unearth new processes that haven't been considered in the context of EBW detonators. This capability, coupled with state-of-the-art experimental techniques, will be essential in solving most of the problems mentioned above.

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