

# CURRENT DIVERSION AROUND A FRAGMENTING WIRE DURING THE VOLTAGE SPIKE ASSOCIATED WITH EXPLODING WIRES

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## Abstract

This paper explores the physical processes that occur during the electrical explosion of fuse wires, particularly the voltage spike that occurs shortly after the wire melts in high-inductance circuits. The observations show that the physics is similar for a range of experimental parameters, discussed in detail. It would appear that the wire heats up and melts homogeneously. Following this, radiant plasma (with a brightness temperature of around 16 000 K in higher powered tests) is observed to form in a spot-like fashion along the length of the wire. The spots develop longitudinally along the wire length, merging to form a continuous plasma column. A dramatic increase in the electrical resistance of the exploding wire accompanies the plasma development, giving rise to the voltage spike. The rise in resistance is found directly proportional to the total length of the plasma column. X-radiography shows that, shrouded by the plasma, condensed wire fragments, with lengths of several centimetres, remain. This, and other evidence, indicates that current is diverted around the seemingly lower resistance fragments, preferring the plasma (flashover). An hypothesis is given to explain this phenomena.

**Keywords:** Exploding fuse wires, current diversion, flashover, copper vapour electrical conductivity

## 1. Introduction

The electrical explosion of metallic conductors (fuse wires) has been studied at QinetiQ for the purposes of understanding the generation of metallic plasma for the UK MoD electrothermal-chemical (ETC) gun programme. An understanding of the physical processes occurring during the electrical explosion is essential to allow predictive modelling of plasma generator operation.

Fuse wires studied were typically copper, with diameters of 0.5 to 1.0 mm and length in excess of 100 mm. In this work, one module was used of a ten module, 500 kJ, 800  $\mu\text{F}$  crow-barred capacitor based pulse forming network [1] with circuit inductance ranging from 26  $\mu\text{H}$  to 800  $\mu\text{H}$ . Charge voltages varied but all were less than 22 kV. The relatively high circuit inductance typically gave discharge durations from 2 to 10 ms. Peak currents were between around 10 and 36 kA. Current rise rates were between 20 and 200  $\text{MA s}^{-1}$ , which is low, compared to many other exploding wire studies. The inductance also ensures that current continually flows with no current 'dwell' much debated in earlier exploding wire work where circuit inductance was far lower [2]. The crow-bar diode fitted within the module ensures there is no current reversal.

## 2. Application

The idea of using electrical energy for gun propulsion is almost as old as the discovery of the electromagnetic force. In 1844, the newly invented electric gun "SIVA" (The Destroyer) was claimed by a Mr Benningfield to be able to fire a continuous stream of balls at a rate of more than 2000  $\text{min}^{-1}$  and kill at a distance greater than a mile [3]. Nothing much is known about the device or how it operated, but the concept is suggested used electrical energy to provide the propulsive force for driving projectiles in military applications.

Today, work is still progressing on a number of electric gun designs. The work reported within this paper was undertaken by QinetiQ on behalf of the UK MoD's effort for the ETC gun. The ETC gun utilises dense, non-ideal plasma for ignition and combustion control of otherwise conventional weapons [4]. The plasma propellant interaction is beneficial in terms of propellant ignition and combustion control [5, 6, 7, 8, 9]. The exploding wire studies described in this paper were undertaken in the context of developing capillary plasma generators (CPGs) for the ETC gun [10]. CPGs are typically polyethylene tubes in excess of 100 mm in length and 5 mm diameter, with a copper rear electrode and annular front electrode connected via a copper wire ranging in diameter from 0.5 to 1 mm [11]. It is the

metallic plasma, venting from the CPG, which is used for interaction with the energetic propellant.

Key to CPG development has been the generation of a computer model to simulate CPG operation [12]. The multi-species Eulerian hydrodynamics code currently supports a '1.5 dimensional' (1.5D) modular model called EDENET. This model has radial and axial components, which are executed separately but output from one component can be used as input to the other component. The physics of CPGs is strongly two dimensional (2D), with the physical properties having gradients both in the axial and radial direction. However, a fully 2D model would be expensive in computer processing time; the 1.5D approach allows simulations to be completed in a few hours on a conventional desk top personal computer. Each main model comprises a number of sub-models or sub-routines responsible for different sub-systems within the CPG, including an exploding wire sub-routine. The equation of state for copper utilised by the model is Cu\_3 from the SESAME database (Los Alamos National Laboratory, USA). These are supplemented with transport data (electrical conductivity) from experimentally validated [13] work by Desjarlais [14]. The exploding wire studies discussed within this paper are similar to those used to initiate plasma within a CPG, and CPG operation will depend upon the mode of wire vaporisation. The predicted mass and energy flux venting from the device will be strongly influenced by initial plasma conditions following the wire explosion phase.

Much effort has gone into the study of the plasma venting from the CPG. A tentative experimental energy budget has been made for the CPG and venting plasma [11]. The main finding from this and other studies [15] was that radiation is prevented from interacting with the CPG components or propellant by an optically thick condensing vapour boundary layer. The thermal characteristics of this boundary layer are thought to play a central role in the electrothermal ignition of energetic materials in ETC experiments. The electrical properties of this boundary layer are also thought to play an important role in the wire explosion process. This is discussed in detail later.

The next three sections describe the electrical characteristics, and photographic and x-radiographic investigations into the wire explosion event.

### 3. Wire explosion studies – (i) electrical study

The wire explosion studies reported within this paper were conducted in an open air environment. Work has also been performed with confined wires and wires exploded within a pressurised environment (several tens of megapascals). The confinement

and/or pressurisation is found to alter the properties of the plasma, but the initial wire explosion process, the subject of this paper, is largely unaffected.

Wires are contained between two copper electrodes in a semi-balanced field assembly to reduce the non-axial magnetic field produced by the supply cables, thus reducing the off-axis Lorentz forces on the current carrying material during the wire explosion process. Figure 1 shows a schematic of the assembly. The wires were attached in a number of different ways, including using tape to suspend the wires 2 mm from the electrodes. No significant difference in the mode of wire explosion was measured for any attachment method. Generally, the experimental copper wires were run through axial holes incorporated in the electrode design.

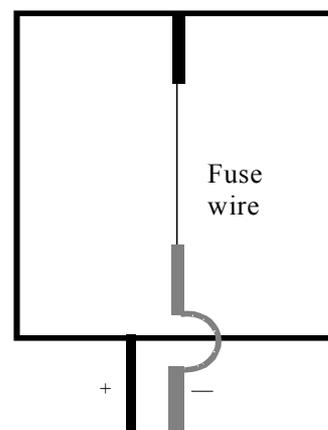


Fig. 1: Schematic of the semi-balanced field assembly used for open air exploding wire studies

Time resolved measurement of voltage across the wire was made using a calibrated 3000:1 voltage divider. Crocodile clips attached the terminals of the voltage divider directly to the wire ends in the case where the wire ran through the electrodes. These wire ends were found largely unaffected after the discharge, with the crocodile clips still firmly attached. Time resolved current flowing through the wire was deduced from measurement of the rate of change of current. This was achieved by use of a calibrated Rogowski coil around the electrical supply cables. From the time resolved voltage and current, the load resistance, discharged energy and power were deduced.

Figures 2 - 4 show the electrical data during ET165 Test 21: a 1 mm diameter, 175 mm long copper wire explosion in air, using the semi-balanced field assembly. The wire mass was 1.2 g. This was a relatively low powered test, utilising a single module fitted with the 800  $\mu\text{H}$  inductor. Recorded peak current was around 10 kA and peak voltage was around 16 kV. Peak power was around 15 MW with total energy discharged being around 15 kJ. Peak rate of rise of current for this test was around 20 MA s<sup>-1</sup>.

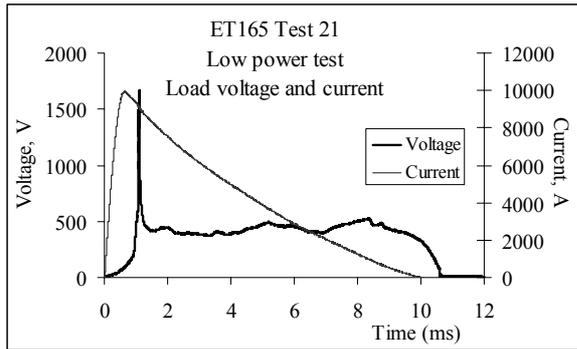


Fig. 2: Load voltage and current for low powered exploding wire in air test

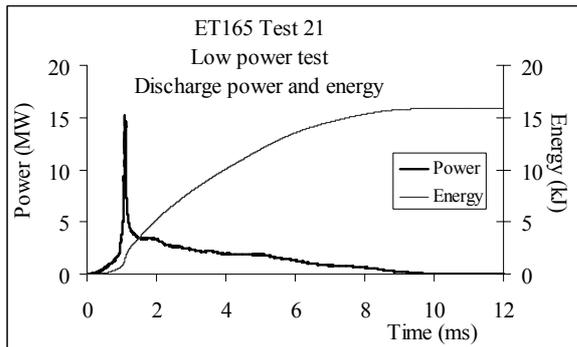


Fig. 3: Discharge power and energy for low powered exploding wire in air test

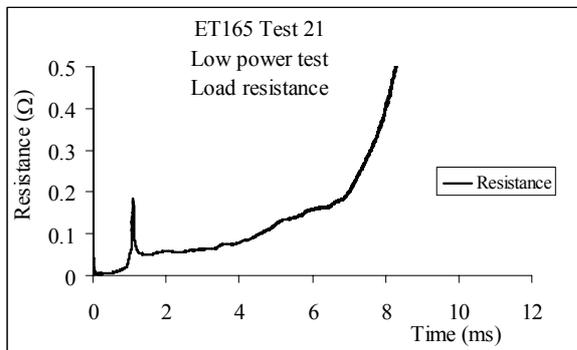


Fig. 4: Load resistance for low powered exploding wire in air test

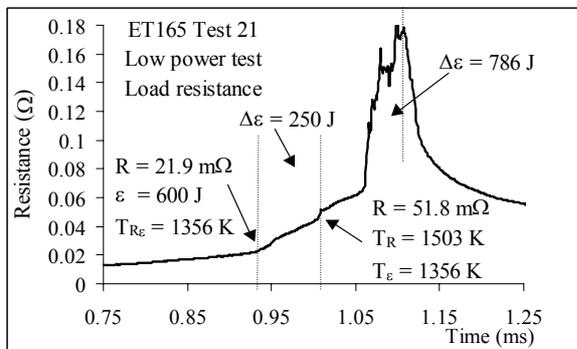


Fig. 5: Load resistance for low powered exploding wire in air test - detail of resistance spike

Several features, identifiable from Figures 2 – 5, are common to all the tests undertaken during these as well as many other similar exploding wire tests and are insensitive to the discharge power or experimental conditions (i.e. confinement or pressurisation). Initially, the resistance rise is smooth indicating an initial smooth heating period. Then, after two small discontinuities in the rate of rise in resistance, a sudden rise occurs. This can be seen shortly after 1 ms in this particular test. With the load current remaining reasonably constant during this period (more so for the high powered tests), this sharp rise in resistance causes a rise in load voltage and thus a rise in discharge power. Following this, the load resistance decreases, giving the characteristic resistance *spike*, and levels out at a plateau value, here, of around 50 mΩ. The plateau value is found to be sensitive to experimental conditions and can be maintained with the discharge of additional capacitor modules. However, as the available supply of power reduces, the load resistance increases towards open circuit conditions.

The most interesting feature is the resistance spike. This has been known about for many years. In earlier exploding wire work where circuit inductance was far lower [2], the current ceased to flow and a much debated current ‘dwell’ occurred. During this dwell, the current (and power) was found to reduce to very low values before resuming after a short period. The increase in resistance leading to either the dwell or the voltage spike is associated with the formation of a plasma discharge (flashover). The formation of plasma during these tests is discussed in detail later.

Figure 5 shows a detail of the resistance *spike* period. In this example, the first small discontinuity in the rate of change of resistance starts at 0.935 ms. At this moment, the value of resistance,  $R$  is 21.9 mΩ and discharged energy,  $\epsilon$  is 600 J. The wire temperature is calculated both from the resistivity,  $T_R$  and energy,  $T_\epsilon$  and is informative in understanding the relevance of this discontinuity. Assuming uniform heating, both the resistance [16] and energy indicate the wire to be at the melting point of 1356 K. Additionally, the wire is in the solid phase, showing that this feature is associated with the start of wire melt. This agrees with other findings that the onset of melting can be identified to a reasonable degree of accuracy on the resistance trace as a small ramp as the solid to liquid phase change occurs [17].

The resistance increases until at 1.013 ms when a second small discontinuity in the rate of change of resistance occurs. 250 J of additional electrical energy,  $\Delta\epsilon$  was discharged after the start of melt during this period. This is exactly the amount of energy required to melt the wire. However, the resistance is higher than might be expected from the molten wire at this temperature [18], and indicates that the wire temperature,  $T_R$  is more than 1500 K.

However, this temperature is based upon the assumption of homogenous heating, which may no longer be valid and/or the wire may no longer be continuous. Both explanations are supported from evidence discussed in the next sections.

The resistance spike occurs shortly after the second small discontinuity in the rate of change of resistance. The spike could be mistaken for wire vaporisation, but consideration of the energy shows this not to be so. The additional energy following the end of melt until the peak in resistance is 786 J. Assuming no heat loss and no bulk heating of the wire, this is enough to vaporise a maximum mass of 0.13 g of copper, around 10% of the total. Hence, 90% or so of the wire must still be in the solid phase close to the boiling point. High rates of radiative energy loss during this period indicate that the amount of vaporisation will be less than this.

#### 4. Wire explosion studies – (ii) photographic study

Visual images captured by a digital gated ‘Ultranac’ fast framing camera of an unconfined exploding wire in air show that a radiant discharge (flashover) occurs. This is first observed at the electrodes and wire centre, and then at random locations along the wire in a spot fashion, as shown diagrammatically in Figure 6. Here, the plasma is represented by negative images acquired from an actual wire explosion, but the wire location (discussed in more detail below) is shown for indication only as the wire location cannot be seen on the photographic images. Homogenous heating of the wire no longer applies once flashover begins.

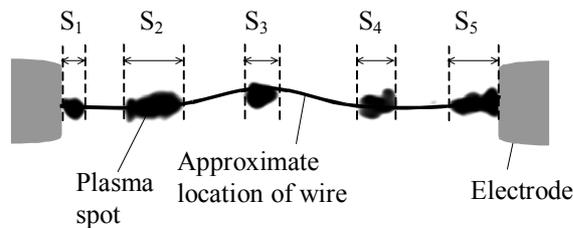


Fig. 6: Negative image of wire in air recorded prior to resistance peak in the visible with exposure time of 100 ns

The radiant emittance of the molten portion of the wire is low in comparison with the bright spots developing in the images. Spectra recorded from such spots [19] reveal that the radiant parts are from copper plasma, with a brightness and colour temperature of around 16 000 K for higher powered tests. The entire wire appears to be covered in radiant plasma at peak resistance.

The development of the plasma spots has been studied using photographic images. The development in the radial direction of the spots is characterised by

a sudden expansion to between 5 and 12 mm, often followed by a pause and then a slower expansion to many tens of millimetres. Individual spots develop apparently in a random fashion, although this can be controlled to a certain extent with small nicks in the wire. For high powered discharges, the initial rate of expansion was greater than  $1200 \text{ m s}^{-1}$  followed by a slower expansion of around  $400 \text{ m s}^{-1}$ . For low power discharges, the expansion was dramatically slower (around  $14 \text{ m s}^{-1}$ ) and the length of the pause considerable, although the spot diameter at the pause was similar. The pause at this spot diameter is thought to be due to a balance between spot temperature (resistivity), current and wire resistance.

With the axial development of individual spots, they tend to expand and coalesce at high velocities. The total length of the plasma (here called the shroud length) can be measured from the photographic images. This is shown in Figure 6 as the sum of the individual lengths of  $S_1$  to  $S_5$ . The edges of the plasma spot boundaries are poorly defined, but the digital images allow an edge to be objectively determined within one pixel of error. Integrated axial expansion in this example was  $13 \text{ km s}^{-1}$ .

From measurement of the shroud length, it is evident that there is a strong relationship between this and the resistance of the wire/plasma system. Figure 7 shows the normalised shroud length along with the resistance (spike region) for a high powered test. Figure 8 shows that the relationship between the resistance and the coverage of the wire is linear (with an  $r^2$  value of 0.9922).

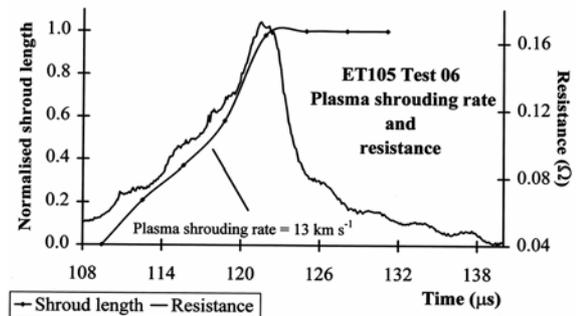


Fig. 7: Plasma shroud length versus resistance of exploding wire in air (high powered test)

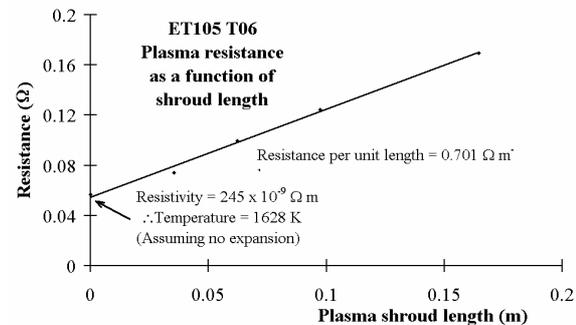


Fig. 8: Plasma shroud length versus resistance of exploding wire in air (low powered test)

The implication of the relationship between resistance and shroud length is that the rise in resistance of the wire/plasma system is associated with the plasma rather than with the unshrouded condensed portions of the wire. The temperature of the wire immediately prior to shrouding (of around 1628 K, given by the intercept in Figure 8 and assuming uniform heating), indicates that the wire temperature is below the boiling point (2840 K). Presumably, the unshrouded wire temperature does not increase much more, as this would lead to a non-linear relationship with shroud length.

The relationship shown in Figure 8 has been repeated for many tests, with a wide range of discharge powers. With the higher powered tests, the resistance and power profiles are very similar due to the current being reasonably constant for this period of the discharge. It could be argued from the results for the higher powered tests alone that it is the power (or indeed the voltage) that is proportional to the shroud length. For the low powered tests, the discharge power and resistance have very different profiles as the current changes over the ‘wire explosion’ period. The graphs of shroud length versus resistance derived from low powered tests indicate that the linearity between the two is maintained. No such relationship with power (or voltage) is maintained for these low powered tests.

Photographic evidence, together with the electrical considerations, suggests that at the peak in resistance the wire is largely in the condensed phase with plasma shrouding it. It is presumed from the linear relationship with shroud length and resistance that the electrical current is largely being conducted through this plasma. If it were not, then the linear relationship between resistance and shroud length, as well as the energy transfer processes required for the maintenance of the plasma temperature, would both need to be explained.

## 5. Wire explosion studies – (iii) x-radiographic study

To confirm the low condensed mass loss predicted during the wire explosion process from electrical considerations, and to gain further insight into the development of the condensed exploding wire material beneath the plasma sheath, pulsed x-radiological studies were performed. For these exploding 150 mm long, 1 mm diameter wire tests, around 14 kJ of energy was discharged in 0.7 ms, with a peak power of around 120 MW. The fast framing camera was again used to compare individual x-radiographs with photographs. Figure 9 shows six photograph and x-radiograph ‘montages’ and a further two photographs highlighting intermediate plasma development. The first image is a montage but not simultaneous, with the x-

radiographs being captured a few microseconds prior to the photograph. The two images that follow are enhanced digital images taken 1  $\mu$ s apart with an exposure time of 100 ns. The following five images are montages made from simultaneous x-radiographic and photographic images.

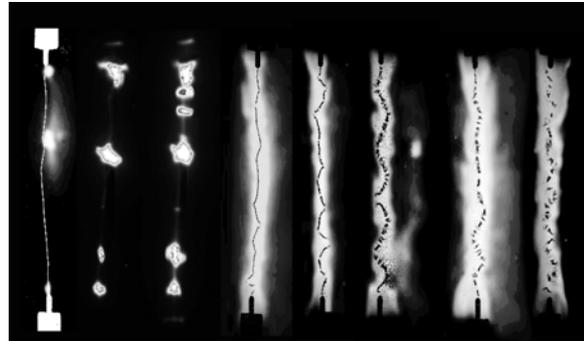


Fig. 9: Photographic and x-radiographic ‘montages’

The x-radiographic work [20] indicates that condensed fragments of the wire, several centimetres long, exist for a period after the peak in resistance. This fragmentation is similar to that reported throughout earlier exploding wire studies [2] as well as more recent literature [21, 22]. Two fragmentation processes seem to be occurring: a coarse process that occurs before the peak in resistance, and a finer process that seems to occur after peak resistance. The resolution in these images for condensed copper has been determined to be around 100  $\mu$ m, suggesting that the second process may have been underway before the peak in resistance if the initial breaks were less than 100  $\mu$ m wide.

The coarse process fragments the wire into pieces several centimetres long. The origin of the breaks in the (initially undamaged) wire has been shown [20] to be associated with kinks established during the buckling of the wire. Measurement of the individual wire lengths shows that buckling is consistent with thermal expansion. It was originally thought that the longitudinal confinement of the wire by the electrodes was responsible. However, recent work [23] has shown that freely suspended wires also suffer similar buckling, demonstrating that the wire’s own inertia is sufficient confinement. Excess heating at the kink locations leads to premature vaporisation at these sites. Further heating of these locations is thought to be radiative once covered in plasma; it has been shown [20] that the kink locations are coincident with the formation of plasma spots. The fine process fragments the wire into a random and increasing number of smaller pieces.

Other workers in this field often make no distinction between the coarse and fine structures. It has been suggested that thermally-induced stress or other wave phenomena cause the fragmentation, possibly while the wire is still in the solid phase [22, 24, 25]. Nasilowski first showed that it is possible for

the wire to fragment whilst still in the solid phase [26], repeated by Graneau [21] and others, although the experimental conditions were somewhat different. Examination of the recovered wire showed little evidence of melting. Molokov and Allen [22] reports that, for current densities in the range  $10^8 - 10^9 \text{ A m}^{-2}$ , solid phase fragmentation due to thermal stress waves is likely to occur. Lukyanov and Molokov [27] go as far as to predict the number of fragments expected by this process. Current densities reported here are somewhat higher at peak current, but pass through the range quoted above while the wire is still solid. Whether there is sufficient time for solid phase fragmentation to occur is debatable. Work at QinetiQ is ongoing to determine if solid phase disintegration of the wire is occurring under these conditions by interrupting the current through the wire during mid-explosion.

Shvetsov *et al* [28], among others [2], suggest that the fine structure may be due to 'magnetohydrodynamic (MHD) instabilities of the necking type' [28]. Here, the current flowing through the molten wire acts to cause the metal to flow into a series of globules and necks [26], or reinforces a similar pre-existing structure [28]. Once established, material flows from the necks to the globules, giving the fine structure appearance shown in Figure 9.

Close inspection of the x-radiographs pre-peak resistance (Figure 10) shows no indication of necking associated with the MHD effect. Further, the finer structure first occurs at the kink location, once plasma spot development is well underway. What appears to be vapour bubbles (appearing as 'smoke-rings' [29] on the x-radiograph) can be seen. It is feasible that micro-fractures occurring in the solid phase seed the vapour sites, by introducing local thermal gradients within the solid wire.

However, a striated appearance is expected with simple boiling without the need for invoking solid phase micro-fractures, as the forming vapour bubble is free to expand radially but constrained longitudinally. The fine structure is being formed at the inner side of the kink as shown in Figure 10. The plasma might be expected to be hotter in the inside of the kink, causing that side of the wire to boil first. Several of the fragments show curvature at their ends, presumably caused by localised pressure developed during the vaporisation.

Another important finding from images such as those shown in Figure 9, is that condensed material remains essentially at the same location until it has all evaporated away. This indicates that the Lorentz forces associated with the buckled wire are insufficient to drive the condensed fragments from their axial position, adding weight to the argument that very little current is being conducted through the fragments. Lack of Lorentz forces is also cited in reference [29] and x-radiographic images clearly

show it not to have any significant effect in reference [28]. Further, the confinement of the wire in a capillary [20] appears to make little difference to the physical mechanisms of the exploding wire.

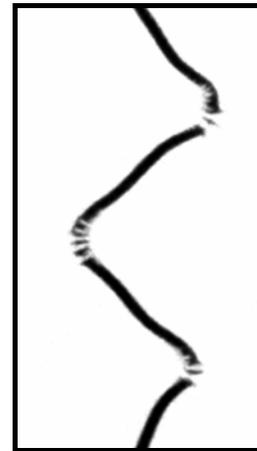


Fig. 10: Exploding wire in air magnified x-radiological image

## 6. Hypothesis for the diversion of current around condensed wire fragments

It has been argued above that current is being diverted around the condensed fragments of an electrically exploding wire (flashover) through the seemingly higher resistance plasma. This phenomenon is also reported on work conducted for the electric armour programme [29], for aircraft radome lightning segmented divertor strips [24, 30] and segmented strip ETC igniters [31]. Arguments are presented in [29] and [31] that the effect is essentially geometrical, limited to an aspect ratio of gaps and fragments of about unity. In the work described here, the fragment length is at least ten times that of the gap length. A physical mechanism that explains current diversion is still needed for these aspect ratios and the following argument attempts to provide one.

It is stated in [24] that the electrical conductivity of the metal vapour under exploding wire conditions was the most difficult part of the process to model. Recently published work by Desjarlais [14] has provided experimentally validated [13] electrical conductivity data in the liquid vapour transition region that may help to provide a solution to the current diversion. (The conductivity of liquid copper at atmospheric pressure as calculated from Desjarlais work is in excellent agreement with respect to that from Dyos [18]).

Copper vapour is a very poor conductor relative to the cool plasma and is often referred to as the 'insulation phase'. It is proposed that there might exist an electrically insulating vapour boundary layer that naturally forms as a result of thermal gradients at

the plasma/condensed wire fragment interface, assuming that there are no discontinuities in temperature at the interface. This idea is used to explore the current diversion phenomenon.

A simplified model of a copper fragment surrounded by a plasma has a condensed copper fragment of length,  $l_c$  diameter,  $d_c$  and temperature,  $T_c$  sited within a copper plasma column of length,  $l_p$  diameter,  $d_p$  and uniform temperature,  $T_p$ . A vapour boundary layer of thickness,  $t$  and at uniform temperature,  $T_v$  surrounds the fragment. Current is initially passing into the problem through the plasma due to an applied potential. It then has the option of continuing to conduct through the plasma, or pass through the copper vapour boundary into the condensed fragment. It would then conduct through the condensed fragment and re-enter the plasma by re-passing through the vapour boundary. The relative resistance of the plasma column and that of the vapour boundary together with the condensed fragment will determine the relative current density within the plasma and fragment. This problem is shown schematically in Figure 11. Apart from the application of the vapour boundary layer, the model is thus far similar to Powell's [31].

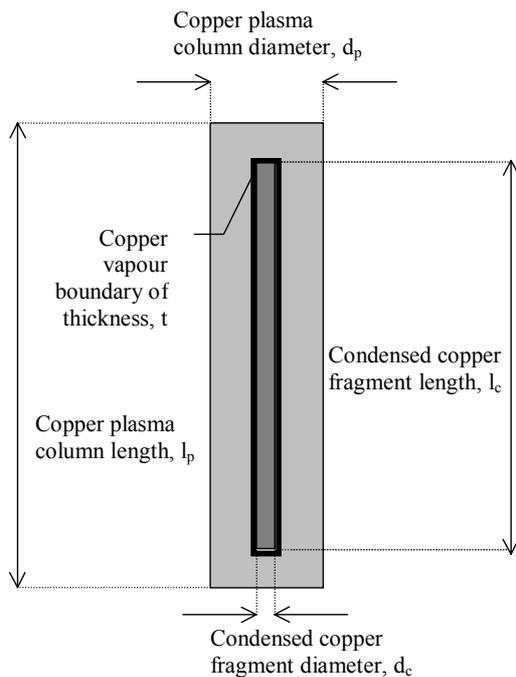


Fig. 11: Schematic of a plasma-shrouded exploding condensed wire fragment

Powell continued to solve the magnetic diffusion equation, restricted to a limited set of geometrical arrangements in an attempt to understand the experimentally demonstrable current diversion. Here, current diversion has been explained by use of a simple resistor network treatment without recourse to specific geometries, by putting the copper plasma in parallel with a copper vapour boundary and the

condensed copper fragment. The approach was to impose a value of resistance upon the vapour boundary layer to compel current to favour the route through the plasma. The thickness of the vapour layer,  $t$  would be the only variable for a given temperature,  $T_v$  that would allow the boundary resistance to be adjusted. The thickness would then be obtainable from the relationship between this imposed resistance and the vapour conductivity given by Desjarlais at  $T_v$ .

It was necessary to establish what complexity was required to model the current density through the vapour boundary along the length of the wire. It seemed obvious that the current passing through the vapour would not be uniform along the length,  $l_c$  but would be concentrated at the two ends. Simply treating the entire vapour boundary as two resistors (with cross sectional area  $\pi d_c l_c / 2$ ) would be unlikely to give a realistic solution for the vapour thickness. A process of mesh refinement was therefore applied to try to find an acceptable degree of complexity. This was achieved by modelling the plasma column and condensed fragment as an increasing number of series resistors. Each plasma and condensed copper resistor was connected together by a resistor representing the vapour. The values of each resistor representing plasma and condensed copper was calculated, with a total fragment length,  $l_c$  taken to be 50 mm, and diameter,  $d_c$  of 1 mm, and a plasma column diameter,  $d_p$  of 6 mm. There is no limit to the number of such fragments, shown in figure 12, which could be in series. However, in this case with a wire length of around 150 mm, there would be three such segments. A plasma temperature,  $T_p$  of 10 000 K, vapour temperature,  $T_v$  of 2850 K and condensed copper temperature,  $T_c$  at 2840 K was assumed. The values of the resistors representing the vapour were varied until sufficiently little total current was flowing through the condensed fragment at the mid-point  $l_c/2$  to be deemed as negligible with regard to the lack of experimentally observed effects (such as the Lorentz force). A circuit simulation package was used to determine the current at each point within the resistor network for each case as complexity increased. It was found that by dividing the plasma and condensed copper columns into first two, then four, eight, twelve and finally sixteen parts showed that increasing complexity reduced the thickness of vapour required by smaller increments, and that further complexity would little alter the value further.

Figure 12 shows a schematic circuit diagram of an example problem. Resistors R1 – R16 represent the plasma; R17 – R33 represent the vapour boundary and R34 – R49 represent the condensed wire fragment. The values of the resistance for each section of the sixteen part problem, which give around 95 % of the total current flowing through the plasma at the mid-point,  $l_p/2$  (i.e. between resistors R8 and R9 in figure 13) were for the plasma,

(R1 – R16) taken as 19 mΩ; for the condensed fragments, (R34 – R49) were 2.47 mΩ and those for the vapour boundary,  $R_v$  (R17 – R33) were 12 Ω. Under these conditions and with an arbitrary voltage of 300 V, the values of current in the plasma,  $I_p$  between R8 and R9 was 971 A, and the current in the condensed fragment,  $I_c$  between R40 and R41 was 56 A. The value of the vapour conductivity, (R17 - R33) using the Desjarlais conductivity of copper vapour at a temperature of 2850 K was  $3.83 \Omega^{-1} \text{ m}^{-1}$ . This gave a boundary layer thickness of around 30 μm, thought to be a reasonable order of magnitude for such a simple model. There was a maximum of 12.4 A flowing through the first (and last) sections of the boundary layers (R17 and R33). This diminished to 1.5 A through the centre sections (R24 and R26).

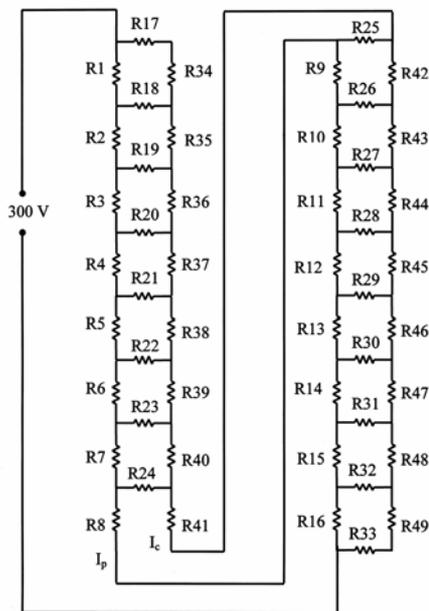


Figure 12: Schematic circuit diagram of a plasma-shrouded exploding condensed wire fragment

Maximum current densities based upon the arbitrary voltage of 300 V are for the plasma  $34 \text{ MA m}^{-2}$ , for the condensed fragment  $71 \text{ MA m}^{-2}$  and for the boundary layer  $1.3 \text{ MA m}^{-2}$ . Sensitivity analysis has shown this model to be insensitive to the condensed-phase temperature (conductivity), but highly sensitive to the plasma-phase temperature (conductivity), with a less thick vapour barrier being required for hotter plasma. This finding of plasma temperature sensitivity may go some way to explaining why the wire blow is so similar for a wide range of electrical discharge power levels: a thicker boundary layer is required for a less energetic event due to the cooler plasma. A thicker boundary layer would naturally form with lower plasma temperatures. Changing the voltage across the model from the arbitrary 300 V does alter the magnitude of the current density but not, of course, the ratio of the currents  $I_p$  to  $I_c$ .

A more complete model [32], taking into account radial resistance of the plasma, has shown the boundary layer thickness to be nearer 1 μm.

## 7. Summary and conclusions

This work has outlined experimental efforts to further understand the wire explosion process. The aim of the work was to provide data for the development and validation of computer codes that model the operation of capillary plasma generators for the electrothermal-chemical gun for the UK MoD. As such, much progress has been made and the code is capable of predictive operation within a range of discharge parameters.

Electrical, photographic and x-radiographic evidence has been used to build up this understanding over the course of several years and hundreds of tests, although much understanding is still required.

The main conclusion from this work is that a plasma sheath develops over the condensed (liquid) remnants of an exploding wire (flashover). The plasma is metallic in nature and originates from vapour issuing from small breaks along the wire length. The current is diverted from the wire and through the seemingly higher resistance plasma during the development of the sheath. This causes a steep rise in load resistance and the characteristic voltage spike seen in many exploding wire tests. The rate of rise in resistance is directly proportional to the length of plasma sheath. Peak resistance is defined when the entire wire length is shrouded. Further heating of the wire is thought to be mainly radiative. Attempts have been previously made to explain the counter-intuitive current diversion. These relied on the geometry of the fragmenting wire/plasma system and were not applicable to the fragmentation here. Hence, an alternative explanation has been put forward that relies on the properties of an hypothetical thermal vapour boundary layer existing between the condensed wire and plasma. This layer has a high resistivity and effectively increases the resistance of the wire fragments. The thickness of the boundary layer required to maintain the majority of the current through the plasma is found to be around one micron.

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