Experimental Investigation of wall-stabilised arc mechanisms of wires in fuse filler

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Synopsis: The paper reports on an experimental investigation into a fundamental aspect of arcing behaviour in HBC fuses [1]. The behaviour reported on is restricted to the case of silver uniform wire immersed in compacted silica sand subjected to a.c. short-circuit currents. The experimental findings indicate that arc formation and extinction processes in wires are basically simple sequential mechanisms for fuse operations characterised by wall-stabilised arc conditions. The findings lead to new explanations on how arcs behave in filled fuses and to a single mathematical expression for the arc voltage generated in HBC fuses over the complete arcing period.

1. Introduction

Many workers [2-10] have reported on the arcing mechanisms of fuse elements immersed in compacted silica fillers. This paper is restricted to a limited report on one aspect of a wide ranging research study into fundamental arcing behaviour in HBC fuselinks [1]. Although the results reported on here refer only to arc mechanisms occurring in silver wires immersed in compacted silica quartz filler they are applicable to other fillers and fuse elements.

2. Experimental Investigations

2.1 Methodology

The experimental investigations utilised crow-bar [10] and fibre-optic [11] experimental techniques to variously record and observe arc formations in uniform section silver wire within standard HBC fuse constructions during the arcing periods prior to and following the instant arc voltages reach their maximum value. Only the results of the crow-bar tests are reported on in this paper. All the tests were performed at the so-called I_2 'critical current' test setting for each fuse type, under standard test authority conditions. Each fuse sample was X-rayed to examine the fulgurites following fuse operation. Several hundred fuse samples were investigated in this work in this way.

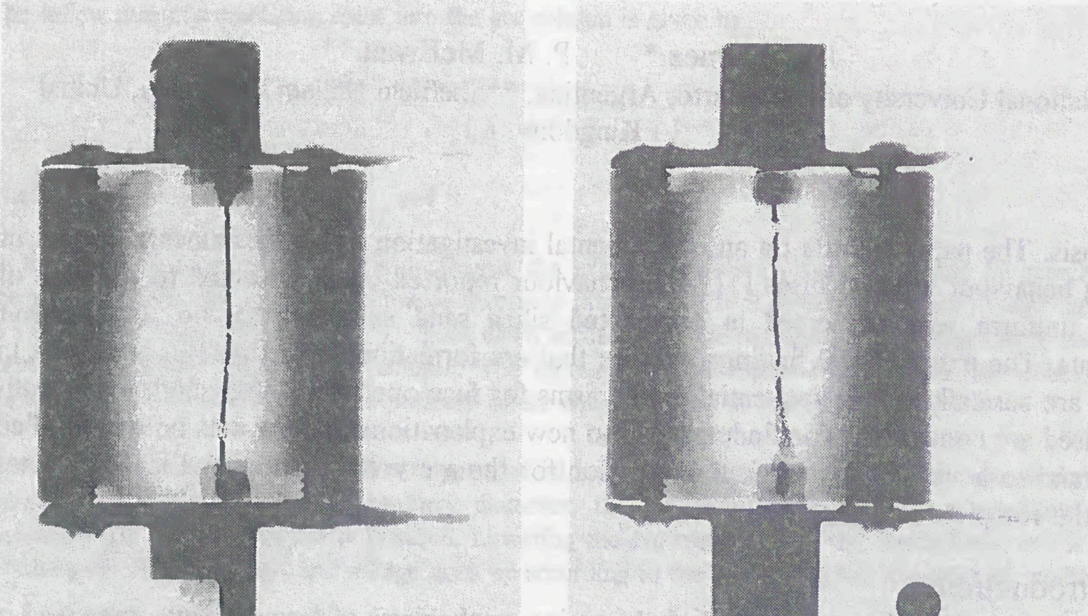
The a.c. test circuit voltage was 230 V. The length and diameter of the wire tested, corresponding to the critical arcing energy conditions, was 35 mm and 0.6 mm repectively. The filler material was standard fuse quartz sand, purity 99%. The grain size used was 300/180 μ (ASTM standard sieves) contained within a DIN 43625 standard (size 00) fuse construction.

2.3. Physical Observations from Crow-bar Tests

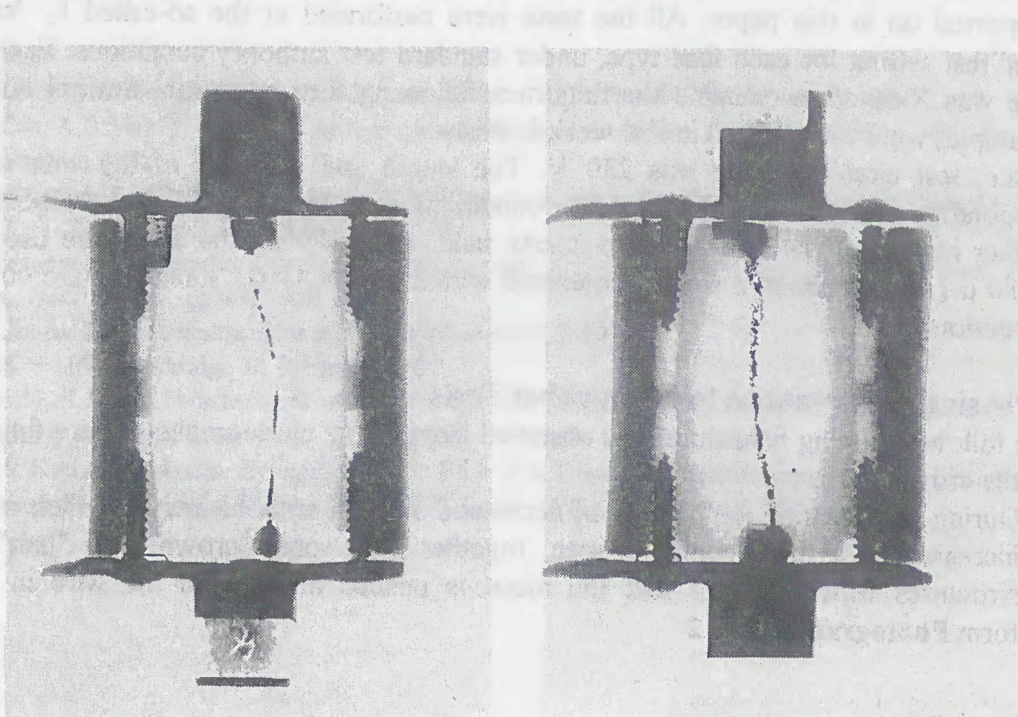
The following arcing behaviour was observed from X-ray photographs of wire fulgurites from the crow-bar tests:

- During wire melting the number of necks and swollen sections and how their number increased with time, could be seen, together with some "crown" and "hair" -like structures which suggest that the metal is pushed away from the wire in liquid form.**Photographs 1 & 2**

Photographs 1 & 2 - Examples of fuse wire disruption



Photographs 3 & 4 - Wire interruption showing long and short arc combinations



- At the beginning of the arcing period only one or two short arcs are observed. **Photograph 3.** although a short time later a few short and long arcs appear. **Photograph 4.**
- The arc phenomena continues sequentially producing an increasing number of short arcs and some longer arcs at the same instant.
- The number of arcs continue to increase until the arc voltage peak is reached.
- At, or just after, the peak arc voltage occurs the single short arcs begin to coalesce into long arcs.
- The fulgurite found after the arc is quenched constitutes a series of alternate uniform modules typified by white and dark grey rings. These modules generally differ only very slightly in length.
- Multiple arcs do not to merge into a single arc during the arc extinction period [5]

3. Proposed Arc Mechanisms

3.1 Basic Arc Mechanism for Rising Arc Voltage

As the number of arcs and arc voltage could be determined from the foregoing tests it was decided to examine the transient positive column voltage E(t) per arc (i.e. the transient arc voltage per arc less an assumed contant arc-root voltage (Vak) per arc) against both arc number and time. It was also decided to consider first the arcing behaviour in wires up to the instant the arc voltage reached its peak value.

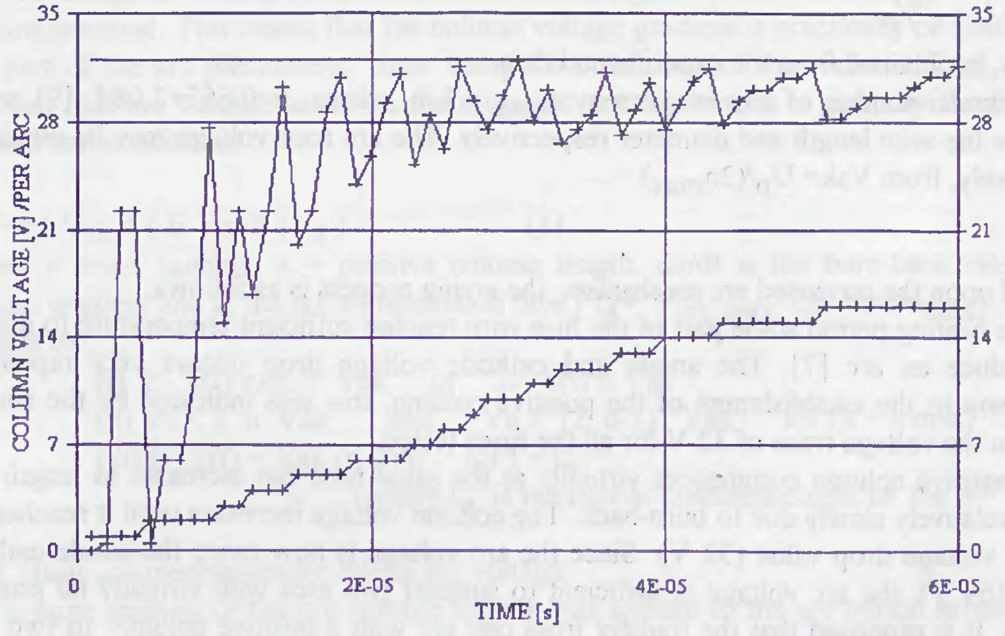


Fig. 1 - Transient Experimental Column Voltage per Arc

The plot of the transient positive column voltage per arc for this period is given **Fig 1**. The graph is very revealing as, in resembling a saw-tooth in shape, it indicates that the arcing process is a sequential arc mechanism which is characterised by the following behaviour if wall-stabilised arc conditions are assumed to apply:

- the positive column voltage E.x(t) increases from zero to a maximum value equal to the arc root voltage value (Vak) at each new arc ignition.
- the maximum voltage an arc can sustain is consequently 2Vak (i.e.which occurs when E.x(t) $\rightarrow$ Vak) after which a new arc is formed.
- the maximum arc voltage follows as Vak peak=$2n_{max}$ Vak.
- the time interval between arcs ignitions is a constant, for the period up to the instant the maximum value of arc voltage occurs.
- the arc voltage is a simple function of the number of arcs which can be expressed mathematically by the relation

$$V_{arc} = 2\,(n-1)\,V_{ak}$$

Data is required on the arc-root voltage drop, the maximum arc voltage and the slope, or speed, of voltage rise for relevant wires to be able to apply the formulae to wire fuses. The value of the arc-root voltage was estimated as 32 V from the experiments, which includes the anode and cathode voltage drops. The second data required is that of the maximum arc voltage, which is determined using Hibner's equation :[6]

$$U_p = k_1 \times l_z \times \sqrt{i0/S_z}$$

where k_1 is obtained from the experimental data.
The maximum number of arcs is given by n_{max} = L/h, where h=0.555+2.08d [9] and L and d are the wire length and diameter respectively. The arc root voltage may be obtained, alternatively, from Vak= $U_p/(2n_{max})$.

Based upon the proposed arc mechanism, the arcing process is as follows:
After the heating period some part of the fuse wire reaches sufficient temperature to disrupt and produce an arc [7]. The anode and cathode voltage drop occurs very rapidly in comparison to the establishment of the positive column, this was indicated by the sudden change in the voltage trace of 32 V for all the fuses tested.

The positive column commences virtually at the same time but increases in length and voltage relatively slowly due to burn-back. The column voltage increases until it reaches the arc-root voltage drop value (32 V). Since the arc voltage is now twice the anode-cathode voltage (64 V), the arc voltage is sufficient to support two arcs with virtually no positive columns. It is proposed that the transfer from one arc with a positive column to two arcs with minimal positive column voltdrops occurs without change in the total arc voltage. For this to happen the first arc column must virtually vanish by arc root merger and/or greatly expand in diameter. Both effects would account for the observed massive scatter of molten and semi-molten element products in filler. Irrespective of either effect the results indicate that the maximum voltage value for each arc is 2 x Vak (64 V) [7, 8]. The two arcs after a very short time re-establish their positive columns, and column extension, due to the burn back, recurs. This produces an increase of the column voltage at the same rate in both columns. The speed of positive column growth is, is therefore, halved. When the two separate positive columns reach 32V, a further arc occurs. The positive columns again 'reduce' but for this and subsequent cases the column voltage does not fall to zero.

For the example described, just before the third arc ignites the total voltage is 128 V (i.e. 64 V for each of the two arcs). When the third arc ignites the total arc-root voltage drop is 96 V (32V x 3) hence the remainder voltage (32 V) is shared between the three columns (i.e. 10.7 V across each positive column).

Physically the remainder voltage would be distributed across the columns in accordance with their prevailing physical properties and dimensions. Based on this averaging the column voltage of the first arc changes from 0 V to 32 V, then decreases to 0 V before increasing again up to 32 V. At the next ignition the column voltage per arc falls to 10.7 V before increasing to 32 V, and for the next ignition the column voltage per arc falls to 16 V rising to 32 V and so on. It follows, based on the results and above explanations that the positive column voltage decreases without change in the total arc voltage, the mechanism being solely an internal voltage redistribution

It is postulated that the mechanism is replicated until the maximum number of arcs occur. At this instant the arc voltage is equal to twice the sum of the individual arc-root falls since each column voltage fall will be equal to that of the arc root voltage. From a simple mechanistic viewpoint, the rate of the voltage increase (dv/dt) in each arc will diminish as the arc number increases. For example, the dv/dt associated with the first arc will be halved when two arcs are burning, and divided by three when the next (third) arc ignites, and so on, from which it is also postulated that the column dv/dt, **Fig. 1**, is inversely proportional to the number of arcs.

From these findings and tests, it is proposed that prior to the voltage peak, the positive-column voltage is virtually proportional to the arc length and that the column cross-section remains constant. This means that the column voltage gradient is practically constant during this part of the arc phenomena, these being the conditions of the wall-stabilized arc. The transient fuse arc voltage based on the proposed arc mechanism is given by the following relation and conditions:

$$V_a = n\,(V_{ak} + (E \;\, dx/dt)\; t_a) \qquad (1)$$

where n = arc number, x = positive column length, dx/dt is the burn-back rate, E the column gradient and t_a the arc commutation time (t_a= $V_{arc\ max}$ rise time/n_{max})

Subject to:

(i) E . x(t) max. = Vak or E . x(t) $\leq$ Vak

(ii) Va $\leq$ 2 n .Vak and Va $\geq$ (2 n-1) . Vak for (n = n max)

(iii) E . x(t) = Vak (n-2)/n for t = t_n

(where t_n is the time at commencement of the n^{th} arc)

3.2. Basic arc mechanism for falling arc voltage

The same analysis of the arc voltage per arc was applied to the arc period subsequent to the occurrence of the arc voltage peak. Based on the same wall stabilised arc assumptions, the transient positive column voltage wave-form shape is similarly obtained **Fig. 2.** This arc voltage shape is similarly distinctive except that the distance between the saw-tooth teeth (arc extinctions) is now not constant but, in contrast, to the corresponding pre peak arc voltage results **Fig. 1**, the slope of the column voltage per arc is constant. This new graph indicates (i) that at the instant the arc voltage falls the number of arcs will be a maximum, (ii) the number of arcs decrease as the arc voltage continues to fall by the simple process of two arcs merging, and (iii) that the arc extinction mechanism is governed by the same condition, as in the previous case, namely that the maximum voltage per arc cannot exceed 2Vak.

The arc extinction voltage wave-form shape, based on these assumptions, is explained as follows. The arcs continue to extend as the means of dissipating the circuit energy but cannot increase in number given that the whole wire is consumed. It follows, therefore, that two of the separated arcs must eventually merge. At this instant there is a loss of an anode/cathode arc root and, therefore, a corresponding intantaneous increase in the column voltage of value Vak.

As in the arc formation process the column voltage wave-form shape indicates that the positive column voltage per arc cannot exceed Vak, hence the net column voltage and arc voltage must fall by this amount whilst the overall arc column length remains essentially the same.

The proposed arc extinction mechanism is basically as follows. Given that the maximum arc chain length is that of the fuse wire, then as each arc column increases minutely in length with time the number of arcs decreases sequentially by the process of separated arcs merging.

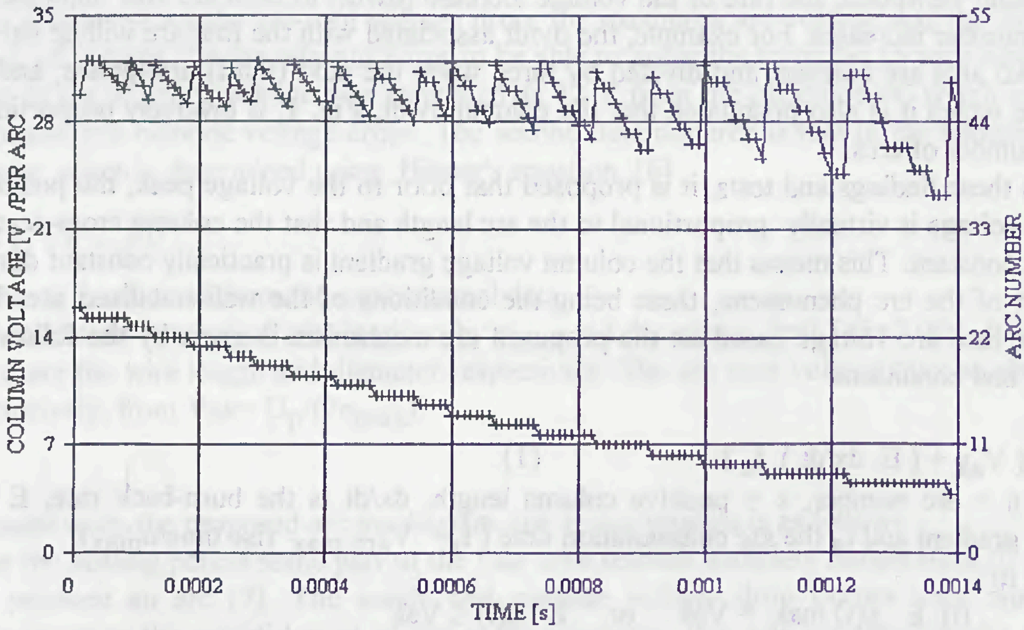


Fig. 2

Experimental Column Voltage per Arc

This mechanism involves a sequential quantum decrease in the net column voltage whilst the sum of the column lengths remains more or less constant during which, however, the corresponding decreases in current become progressively larger. For example, from Fig. 3 over the period 0.39 ms to 0.4 ms, the percentage change in current is 26% for a change in arc voltage of 17% and over the period .43 ms to .45 ms the corresponding percentage changes are 64% and 29% respectively. The fall in current, for these conditions, can occur only if the column diameter or the column conductivity decrease at ever increasing rates. For example the latter percentage change results in a doubling of the arc impedance corresponding to either a reduction in arc conductivity by a factor of 2 or a reduction in column diameter by a factor of 1.4. Either effect would lead to an accelerated deionisation of the arcs which is consistent with rapid arc extinction under wall-stabilised arc conditions as observed in the reported tests.

3.3 Transient Arc Voltage Prediction

Equation(1) is applicable for predicting the transient arc voltage for the pre- and post-peak arc voltage periods. The comparison of the experimental and predicted fuse arc voltage and current using the arc voltage equation for both periods is shown, **Fig. 3**.

4. Conclusions

The proposed arc mechanisms for wires immersed in compacted silica filler have been demonstrated to give consistent results with experimental findings, observations and analysis for the arcing periods up to and following the instant arc voltages reach their peak value, referred to as the arc formation (ignition) and arc extinction mechanisms respectively. Both mechanisms, in essence, are based on the proposition that the arc column voltage per arc cannot exceed the anode/cathode root voltage for a given fuse type. The mechanisms provide new explanations on how arcs behave under wall-stabilised arc conditions, typical of those encountered in successful HBC fuse current interruption.

The proposed mechanisms are expressed by a single, relatively simple, mathematical expression which enables accurate prediction the complete fuse arc current, voltage and I^2t characteristics.

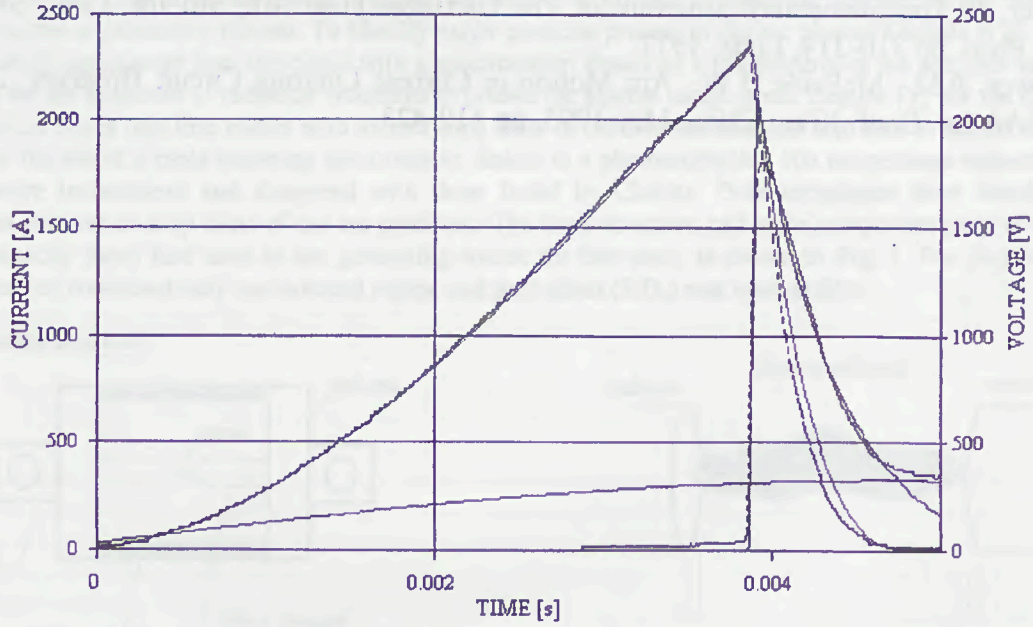


Fig 3 - Experimental and predicted arc voltage and current waveforms

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