CHAIN OF ARCS AS DETERMINING FACTOR IN ELECTRICAL EXPLOSION OF WIRES

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INTRODUCTION Electric fuses are without doubt the earliest practical application of the exploding wire phenomenon /EWP/ and, for that reason, research work on electric fuses has given many valuable contributions to the theory of EWP. In electric fuses one can observe phenomena known from physical experiments, e.g. undoloidal disintegration of wires into drops and striated disintegration of conductors as well. The shape of disintegration of exploding wire depends probably on the quantity of energy stored in the wire prior to disintegration.

Often electric fuses break off more energy than applied in physical experiments; e.g. in the case of a capacitor bank with 20 μF at 10 kV we have an energy of:

$$1/2CU^2 = 1/2 \cdot 20 \cdot 10^{-6} \cdot 100 \cdot 10^6 = 1 \text{ kilojoule}$$

which partially only can be evolved in the wire to be exploded. While in the case of an electric fuse which, when operating, cuts off the current at 10 kA in the circuit of 2 mH inductance, the energy evolved in the fuse element equals at least:

$$1/2\, LI^2 = 1/2 \cdot 2 \cdot 10^{-3} \cdot 1 \cdot 10^8 = 100 \text{ kilojoules}$$

The energy acting during the operation of the fuse can be greater than that in physical experiments. This fact is very important for development of a common hypothesis for all applications of EWP.

Considerations presented in this paper are based upon two assumptions:

1/ Short circuit current is broken by a fuse element due to the creation of many transversal arc gaps [1, 2, 3] with definite spacing [4]. Creation of these arc gaps is perfectly shown on published photografs [5, 6].

2/ Metal vapour in arc gaps has to some extent insulating properties[7].

PREBURST ENERGY It is a well known fact that preburst energy evolved in a fuse element can be more or less than the energy necessary for complete melting of its mass and it can be more or less than the energy necessary for complete vaporisation of this mass. The first possibility is considered by those who deal with electric fuses [1, 8] and the second by physicists [8, 9]. This difference cannot be caused by mistakes in evaluation results of test and it is why the process of electrical explosion should not be considered as a simple transition of phases.

Technicians use, in their experiments, low voltage sources of power with inductances measured in milihenries; physicists as a rule apply

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high voltage capacitors with inductances measured in microhenries. Therefore, the transport of energy occurs with different rates. In physical experiments the current increases very rapidly, however in technical experiments the current increase rate is small in accordance with the formula: $(di/dt)_o = U/L$.

Taking also into consideration the fact shown by Eiselt [10] that during dwell time the wires divide into parts, i.e. when energy input from the source has been interrupted, one can conclude that once the initiated process of disintegration is continued due to forces independent of the fresh energy input. It enables treatment of preburst energy as a result of competition of two processes:

1/ energy input from source with rate of current load,

2/ breaking action of energy input by increased number of arc gaps created along of the wire being disintegrated.

Preburst energy is therefore

$$E = f\left(\frac{di}{dt} / \frac{\Delta n}{\Delta t}\right)$$

where

di/dt - rate of current increase,

$\Delta n/\Delta t$ - rate of creation of elementary arc gaps.

Maury [11] has established creation of more than $1 \cdot 10^5$ arcs in a second.

The above considerations allow to conclude that the higher is the rate of the current increase, the more energy can be evolved in the wire untill the mechanical process of creation of arc gaps cuts off the path of the current.

Nash and Olsen [12] have established that the quantity of energy evolved depends on the wire diameter, too. Thick wires can consume more energy than fine wires of the same mass. This fact can be explained. Fine wires have finer spacing of disintegration than thick wires, thus they create more arc gaps per unit of length and per unit of time, so the current is cut off more rapidly than in the case of thick wires, which can also need more time for creation of transversal cracks [4] and arc gaps. This explanation makes clear why fine wires can win the competition described above.

PEAK CURRENT Data published by Leopold [13] enable to plot peak current and peak voltage versus wire length /Fig. 1/. The curve $I_{1max} = f/l/$ is peculiar if we assume that the wire cuts off the current due to melting. This seems to be evident if one assumes that the current is cut off owing to the creation of many arc gaps along of the wire. The longer is the exploded wire, the more arc gaps can be expected to come into existence and the more arc gaps can occur in a unit of time. Thus the longer is the wire, the more rapidly is the current cut off. Some deviations from this rule can be caused by dispersion of spacing of disintegration.

Considering the relation $U_{max} = f/l/$, one can point out that the measured peak voltage is a sum of voltage drops on elementary arc gaps [1, 2]. The longer is the wire the more arc gaps can exist and the higher voltage can be recorded. Saturation of the curve $U_{max} = f/l/$ at a definite level will be explained with Baxter's plots of the peak voltage.

PEAK VOLTAGE H.W. Baxter /1904-1962/ has given some important plots [1] of peak voltage across the wire in the medium of quartz sand grains as function of design parameters of the fuse and as function of circuit inductance /Figs. 2-5/.

Operation of a fuse in short circuit conditions can be considered as a rapid process. During this process the magnetic field energy $1/2\ LI^2$ is transformed into energy of the electric field $1/2\ CU^2$. Rapid process means here that time of arcing is reduced to zero and one can assume the equality:

$$1/2\ LI^2 = 1/2\ CU^2$$

where: U-overvoltage, I-cut-off current, L-inductivity of the circuit, C-capacity of the circuit.
The above formula gives: $U = I\sqrt{L/C}$.
Taking into consideration the fact that after attenuation of the overvoltage across the fuse the voltage U_o, equalling the open circuit voltage remains, we obtain $U_{max} = U_o + I\sqrt{L/C}$
Baxter's plot of $U_{max} = f/l/$ can be commented as follows /Fig. 2/.
It has been written earlier that proportionally to the wire length the peak voltage increases but in the circuit with constant circuit parameters /U_o, R, L, C/ the increase of peak voltage is stopped when the fuse wire is long enough. It means that the magnetic energy of the circuit has been exhausted and greater number of arc gaps cannot cause a further increase. Greater inductance of the circuit, however, results in saturation of the curve $U_{max} = f/l/$ at a higher level. The slant part of the curve displays that there can exist an average arc gap voltage u_1 and U_{max} cannot exceed: $U_{max} \leq u_1 \cdot n$, where n is the number of arc gaps.

Knowledge of the spacing of disinterration of copper wires in quartz sand [4] enables calculation of the average arc gap voltage as we know the total voltage /Fig. 2/.
The 0.022 in.dia. Cu wire has a spacing [4]:
$h_s = 0,555 + 2,08\ d$ /mm/
$h_s = 0,555 + 2,08 \cdot 0,022 \cdot 25,4 = 1,71$ mm
The average number of arc gaps along of a wire 6 inches long of this diameter is 89, so the average arc gap voltage:

$$u_1 = \frac{4100 + 4200}{89} = 46 \div 47,2 \text{ volts}$$

The next plot of $U_{max} = f/L/$ shown on Fig. 3, can be commented as follows:
The peak voltage increases with the increase of the inductance, initially, according to the formula $U_{max} = U_o + I\sqrt{L/C}$, because greater inductivity means greater magnetic energy of the circuit with other parameters being constant. The slant part of the curve $U_{max} = f/L/$ means that the wire of constant length, i.e. of constant average number of arc gaps will obtain higher voltage for each arc gap, but this voltage cannot exceed a definite value which should be considered as breakdown voltage of the chain of elementary arc gaps. When this breakdown voltage is reached the curve $U_{max} = f/L/$ stops its increase, because the wire of definite length cannot divide into more parts than it follows from the spacing of disintegration. When however longer wires were applied in Baxters experiments, the voltage reached accordingly greater values as it is shown in Fig. 3.

Data from Fig. 3 enable the following calculation of average arc gap voltage:

$$u_1 = \frac{3100}{\frac{4 \cdot 25{,}4\ \text{mm}}{1{,}71\ \text{mm}}} = \frac{3100\ \text{volts}}{59\ \text{arc gaps}} = 52{,}6\ \text{volts}$$

and

$$u_1 = \frac{1430}{\frac{2 \cdot 25{,}4\ \text{mm}}{1{,}71\ \text{mm}}} = \frac{1430\ \text{volts}}{29\ \text{arc gaps}} = 49{,}4\ \text{volts}$$

The above given three values of u_1 obtained from different experiments are similar. The differences are small and they can be explained as the result of dispersion of spacing.

Fig. 4shows a family of curves representing the relation $U_{max} = f/d/$. One can give the following explanation to the plot. The thicker is the wire the longer is the spacing of disintegration and at constant length of the wire the number of the elementary arc gaps decreases therefore, the value of the peak voltage decreases accordingly.

A reduction of the current in the circuit results in reduction of magnetic field energy, thus advantage of insulating properties of individual arc gaps is not wholly taken. This explains the observation that a reduction of the prospective current causes a reduction of the peak voltage. The results presented in Fig. 4 enable calculation of the average arc gap voltage for the highest curve as in table 1. The similarity of the obtained values cannot be accidental.

Table 1 Average arc gap voltage u_1 calculated after Baxters data [1/Fig. 55/] for prospective current of the circuit of 1500 amps.

Diameter of the wire inches	mm	Spacing x/ h_s mm	Average number of arc gaps xx/ n	Peak voltage U_{max} V	$u_1 = \frac{U_{max}}{n}$ V
0,036	0,9144	2,45	21	1100	52,4
0,028	0,7122	2,03	25	1350	54,0
0,022	0,5588	1,71	30	1600	53,3
0,0148	0,3759	1,33	38	2050	53,9

x/ after formula: $h_s = 0{,}555 + 2{,}08\ d$ /mm/

xx/ for two inches long fuse wires

The curve in Fig. 5 can be commented in the following manner. Spacing of disintegration for wires in quartz sand depends on the size of grains [4, Tabl.3]. The spacing is the finest for grains with dimensions 0,2 - 0,4 mm, so the fuse wire of definite length surrounded by such a sand will produce during disintegration the greatest number of arc gaps and thus the highest peak voltage. Finer and thicker grains will produce longer spacing and thus will lower the peak voltage.

It has been shown [20] that in other than Baxters test conditions the average arc gap voltage can be much higher.

DWELL TIME Finite dwell time is not recorded in the case of electric fuses because such an event would mean unsuccesful operation of this device. Nevertheless, sometimes during desinn tests of fuses one can observe two pulses of current. It is overcome by application of longer fuse elements, i.e. by increasing the number of arc gaps. The same result can be reached by decreasing voltage of the power source. In the case of current pause, not transient overvoltage but a stabilised voltage of the source or residual voltage on a capacitor bank is the acting factor. When the chain of arc gaps can withstand acting residual voltage, the second current pulse cannot occur and the current pause lasts infinitely. When acting voltage is high enough breakdown of arc gaps between metal striations can occur; therefore the dwell time should depend on the acting average value of arc voltage. Interesting papers about current pause and the restrike mechanism in exploding wire discharge in air are given by Vlastos [21, 22, 23].
In the case of electric fuses with quartz sand filler, intensive cooling of liquid metal particles stabilises arc gaps after radial explosion [4], but in the case of explosion in air or in vacuum, radial flow of metal striae can eliminate many of arc gaps due to direct contact of metal particles. On the other hand, infrapressure which should exist in the axial postexplosion duct/seen excellent in fulgurites [4]/, will facilitate voltage breakdown along of this duct. Investigation od fulgurites [14] has shown that the postexplosion duct is not a postarc duct in the case of correct operation of the fuse, but it is when breaking capacity has been exceeded. In this case the striated structure in fulgurite vanishes. When to Eiselts [10] data /Fig. 6/ one applies a hypothesis that the duration of the dark pause depends on the average value of the acting arc gap voltage and one converts Eiselts results making assumption that the spacing of striae in air is a linear function of the wire diameter, e.g. h = 5d, one will obtain a family of curves Fig. 7 instead of one curve seen on Fig.6.

The accepted formula h = 5d is probably not correct in this case, but it is applied only in order to show the manner of argumentation and not exact values. We have no other papers about spacing of striae in air except of works of Arnold and Conn [15] and Coffman [24], but theese papers do not give formulae for calculation of average spacing versus wire diameter. Dark pause depends on residual field intensity in a uniform manner for all diameters of tested wires [10]:

$$\tau = f\left(\frac{U_p}{l}\right)$$

where U_p is residual voltage on capacitor acting on chain of arc gaps in the fuse element with length l.

The results of the tests give a hiperbolical plot /Fig. 6/, so

$$\tau = \frac{k}{U_p/l}$$

When spacing of disintegration is h one can write that l = nh where n is number of considered arc gaps, so

$$\tau = \frac{k\,h}{U_p\,/\,n} = \frac{kh}{u_1}$$

When spacing of disintegration is a linear function of the diameter d of the wire $h = \alpha + \beta d$ we can write

$$\tau = \frac{k(\alpha + \beta d)}{u_1} = k_1 + k_2 \frac{d}{u_1}$$

Main properties of the dwell time are as follows:

1. Duration of the dwell decreases when the acting residual average voltage u_1 increases.
2. Current pause vanishes when in given test conditions the fuse element is shorter than l_{min}, i.e. when the number of arc gaps is smaller than a certain n_{min}, because in this case the chain of arc gaps cannot withstand transient increasing overvoltage.
3. Current pause lasts infinitely, when in given test conditions the fuse element of a certain diameter is longer than a certain l_{max}, i.e. when the number of arc gaps is greater than a certain n_{max}, namely when chain of arc gaps between striae is able to withstand residual voltage acting in the process.
4. The dwell time in the zone between l_{min} and l_{max} increases proportionally to the wire length, i.e. to the number of arc gaps. The above remarks give a picture as shown on Fig. 8, based on experiments of Cnare and Neilson [16].
5. Increase of wire diameter results in increassing of l_{min}, because in this case we have less arc gaps in the chain.

RESISTANCE ANOMALY Resistance of the wire as a function of energy input during pre-arcing time increases more rapidly for that wire in which energy is evolved slower [17, 18, 19].
Usually and traditionally we consider exploding wires in pre-arcing time as metallic continuum subjected to uniform changes along and across the wire. This is not correct because we know that the wire melts from surface inwards and that transversal cracs are created along of the wire prior to creation of arc gaps.
These facts show that the resistance calculated simply from oscilogrammes is a mean value and we do not take into account these zones of locally increased resistance. Creation of mechanical cracks in wires needs some time, so when transport of energy is rapid enough we can evolve more of it without an additional resistance increase.

SHORT CIRCUIT OPENING Knowing phenomena in electric fuses with quartz - and filler one can give grid - description of the process of short circuit opening by means of a fuse with a single wire melting element /Fig. 9/. Left hand column in this grid presents events in the melting wire. Central column presents alterations of the current and magnetic field, right hand column shows alteratione of the voltage across the fuse.

SOME ADDITIONAL REMARKS TO THE GRID DESCRIPTION Short- circuit heats the melting wire. In an accidental point of the fuse wire the first arc gap comes into existence, and mechanical vibrations of the fuse wire devides due to vibrations into segments and a chain of elementary arc gaps with short arcs is brought about.

Increasing current, causes in the melting wire increasing pinch pressure which /when the current is cut-off and reduced/ results in radial expansion of molten segments between quartz - sand grains and in transformation of the wire into a tube /Fig. 10/.Internal duct of the slag /or fulgurite/ is not a post-arc duct in case of a fuse which broke correctly the short - circuit current. The slag shows no electrical conductivity in the longitudinal direction but some parts of it shows this conductivity in the transversal direction.

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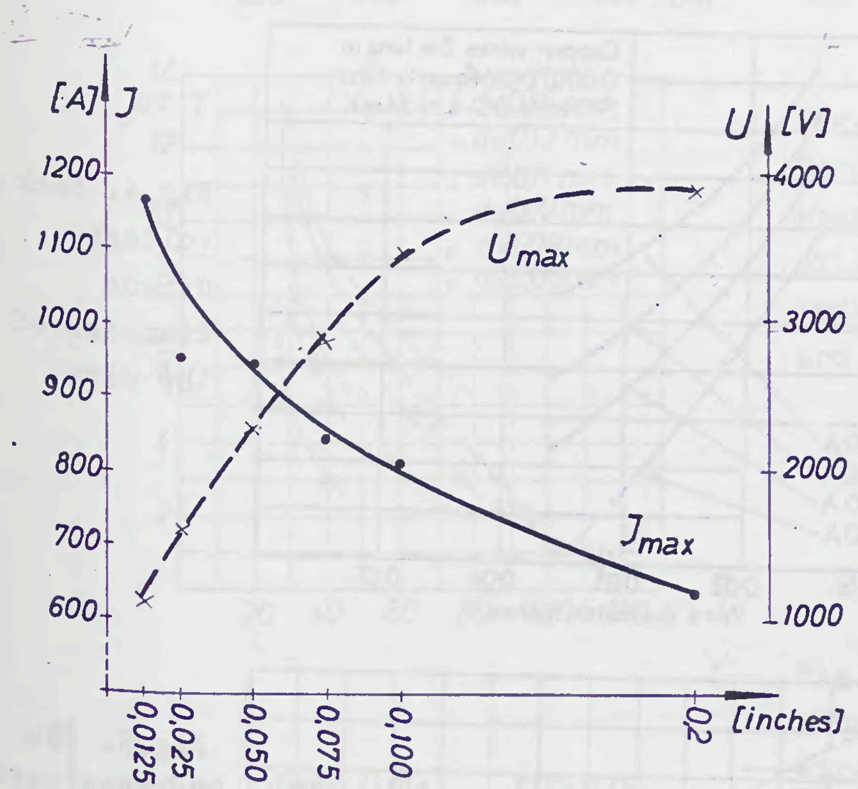

Fig.1.First pulse peak current and peak voltage as a function of the wire length

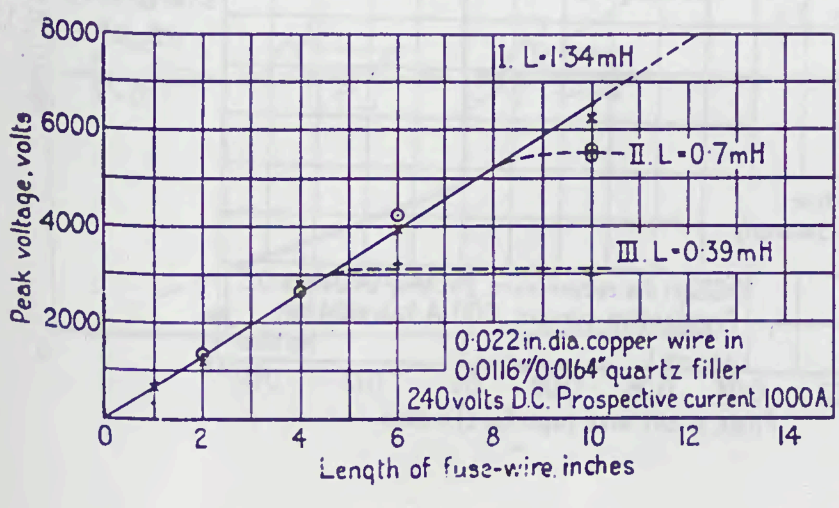

Fig.2.Peak voltage versus length of the fuse wire

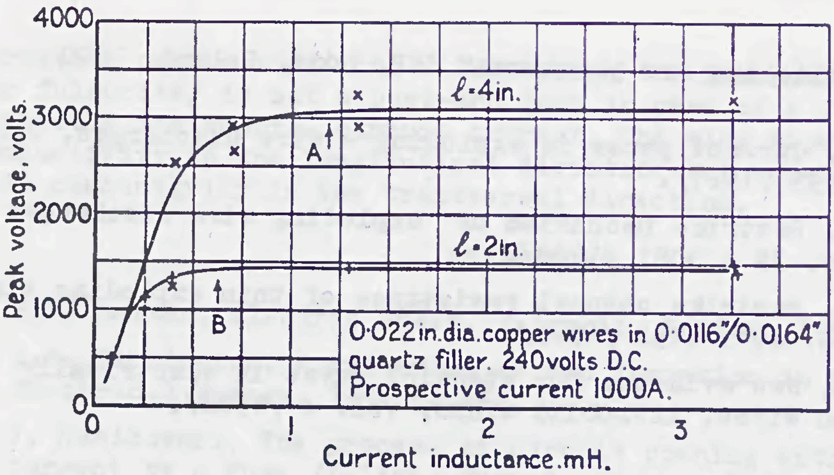

Fig.3. Peak voltage versus inductance of the circuit

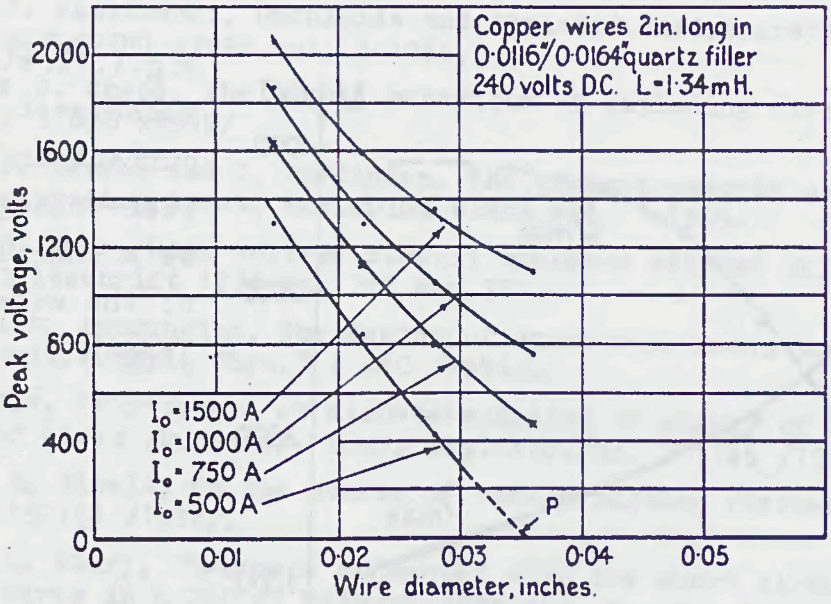

Fig.4. Peak voltage versus diameter of the wire

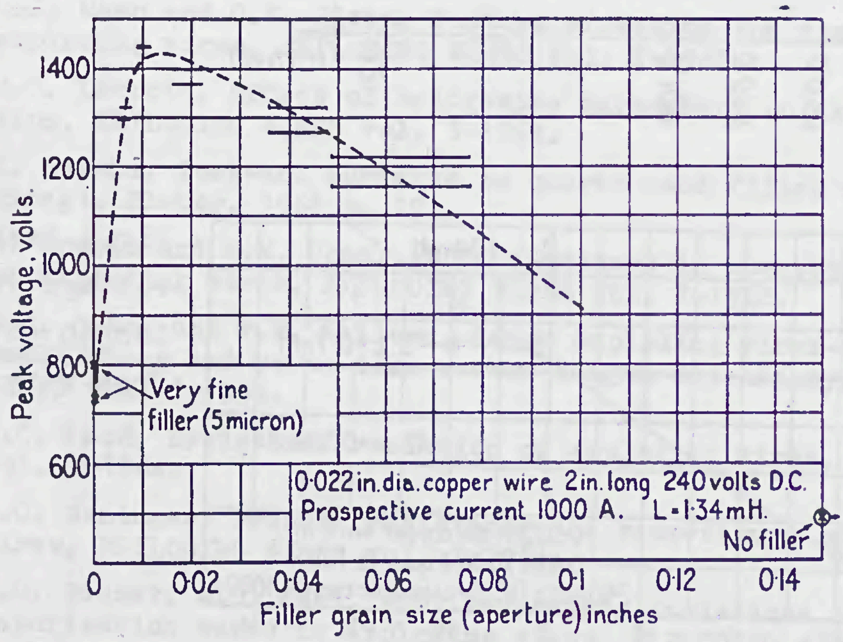

Fig.5. Peak voltage versus grain size of the filler

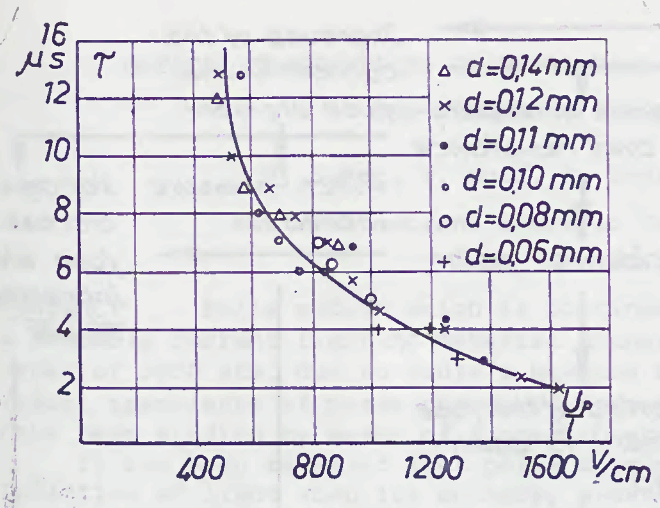

Fig.6. Dark pause duration versus residual field intensity

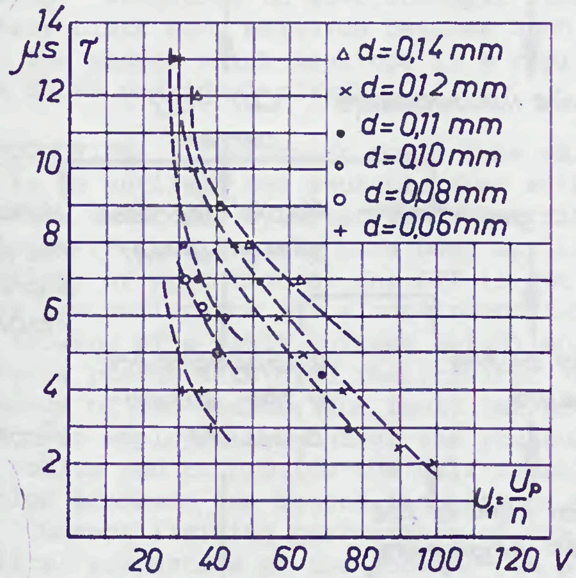

Fig.7. Dark pause duration versus average voltage acting on individual arc gaps

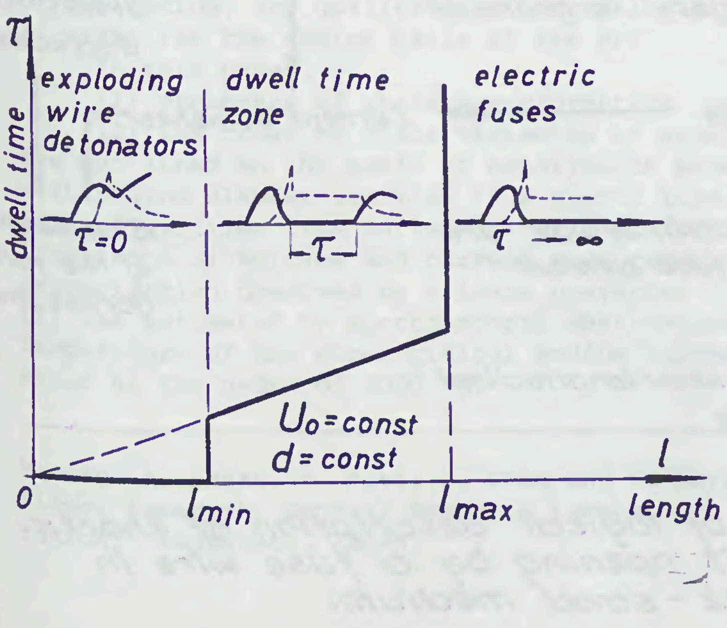

Fig.8. Application zones of exploding wires and dwell time zone as a function of wire length

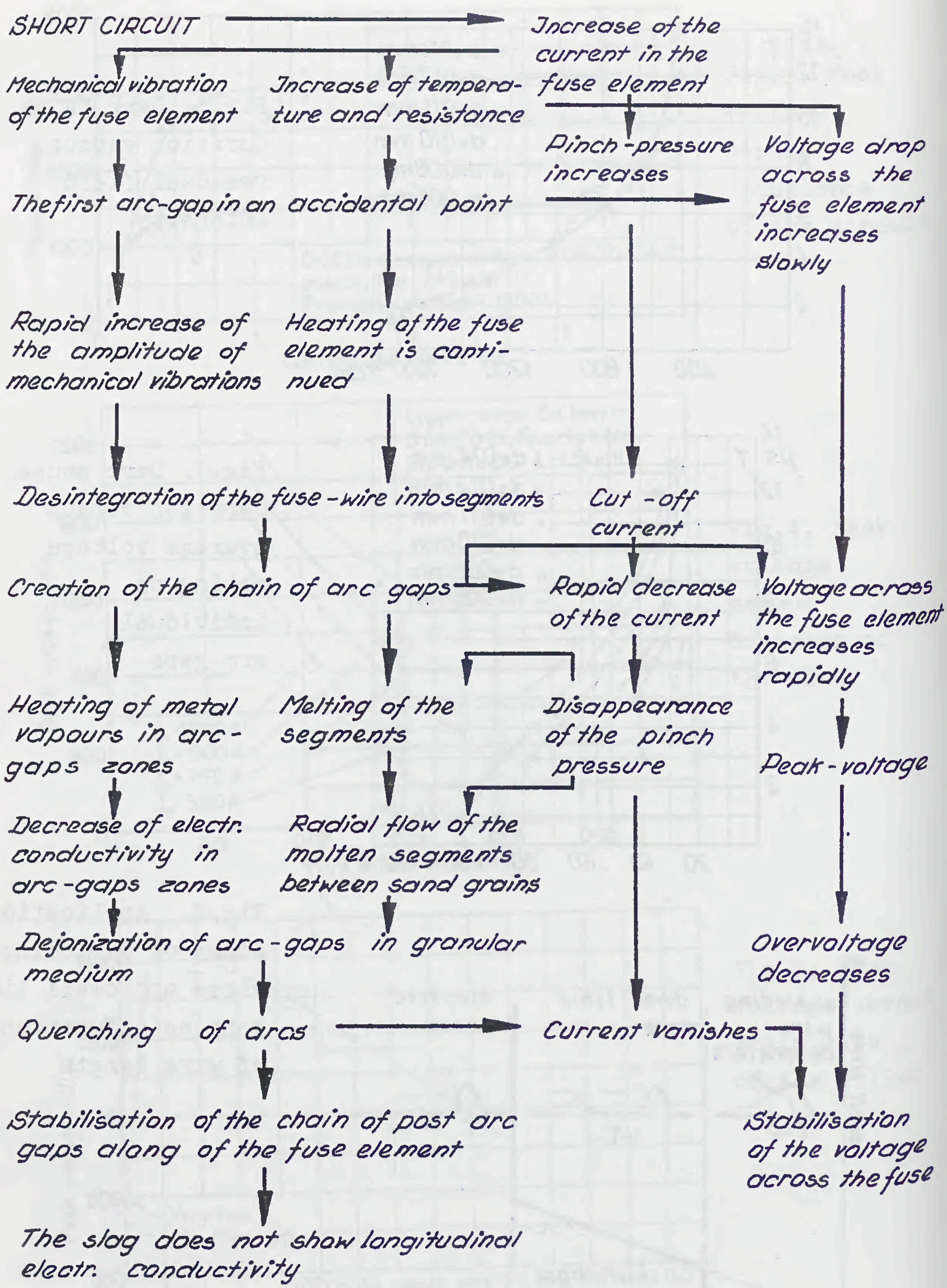

Fig. 9. Grid of logical description of short-circuit opening by a fuse wire in quartz-sand medium.