Arcing phenomena in high voltage fuses

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Arcing Phenomena in High Voltage Fuses

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Abstract

A study has been made of the variables which govern the arc voltage of high voltage fuses with sand as filler material. The measurements were carried out at constant current in a range of several kA. Experimental relations were obtained for the burn-back rate of fuse elements (silver and copper). It was observed that preheating of the fuse element due to Joule heating is generally of importance. A model based on the energy processes in the electrode regions and including preheating was developed and is capable of predicting accurately all recorded burn-back rate data. An analysis was made of the lumen increase due to arcing. For a constant current the lumen thickness increased with the root of the time for all currents investigated. Theoretically this observation was explained by a model in which the arc channel expansion is primarily due to the volume decrease of sand as a result of fusion. Flow of molten silica into the filler is an additional effect contributing to lumen expansion. A model was developed for a fully ionized quasistatic arc with rectangular cross-section. The predicted relation of arc voltage and current was proven by experiment. Calculation of the arc voltage as a function of time based on this arc model and including arc elongation by burn-back and arc channel expansion showed good agreement with the measured arc voltages. Results on the initial arc voltage generated by notch disruption and arc merging are compared with known data.

Daalder, J.E. and E.F. Schreurs
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Chapter 1: Introduction

Fuse links are protective devices which have been in use for more than one hundred years. They combine attractive features as a simple construction, a reliable and safe operation and a moderate price with fast interrupting and current-limiting capability. Fuse links are therefore of significance in a wide variety of power applications. During the last years there is an increasing interest in the development of models which describe the operation of fuses during current interruption. A proper fuse model can be a valuable tool in the search for materials which improve the fuse performance, in the development of new fuse designs or in the decrease of the costs of production. However in fuse modelling today a clear limitation is set by the scarce knowledge existing of the physical processes which occur during arcing. Empirical relations are available of arc voltage and current behaviour during the interrupting stage but only little is known of their coupling with the basic variables of arc plasma and filler material. This is not surprising because the arcing mechanism is complex and a range of variables are involved during interruption.

The models existing today can roughly be divided into static and dynamic models. In the static model the arc voltage is taken as a fixed function of time (e.g. a rectangular or triangular voltage pulse). Although these models are useful in explaining some basic interactions between the fuse link and the circuit (e.g. Boehne (1946)), their use in elucidating fuse behaviour or in fuse design is very limited. In dynamic models physical processes such as arc elongation, arc plasma behaviour and electrode effects play a role (e.g. Wright and Beaumont (1976); Ranjan and Barrault (1980); Gnanalingam and Wilkins (1980)). Mostly far reaching simplifications have been used as a constant electric field during arcing or a constant arc cross section. A first attempt of taking arc channel expansion into account has only recently been made (Gnanalingam (1979); Gnanalingam and Wilkins (1980)). The significance of the filler material, though appreciated for a long time, has hardly been incorporated in any existing model. The same applies for the first stage of arcing which in modern fuses is initiated by disruption of notches in the fuse link. Experimental results are conflicting and no clear picture exists of the arc initiating process.

1.1. Scope of the work

In this study a number of processes are analysed which occur if a large
current is conducted by a notched fuse element surrounded by sand (see fig. 1.1).

Fig. 1.1a: Fuse element with notch
1.1b: Situation during arcing.

After a period of current flow the notch will melt and an arc is generated. Due to the erosion of the fuse element the arc length increases. The arc energy melts the surrounding sand and a part of the molten silica will be pressed into the voids between the sand grains. As a result channel expansion occurs.

The arc voltage can be calculated from the equation (neglecting electrode effects):

\[
U_{\text{arc}} = \frac{1}{l} \int E \, dx = \frac{1}{A} \int \rho I \, dx
\]

Here \( E \) is the column field strength, \( \rho \) is the specific resistance of the arc plasma, \( I \) the current and \( A \) the crosssection of the arc channel.

The solution of this equation is complex as \( \rho \), \( l \) and \( A \) vary with current, position and time. Also the current may vary from several kA to zero in a few milliseconds.

In this study the current was taken as constant during each experiment and the other parameters were analysed for different current levels as a function of time. It was proven that in this way the coupling between
the different variables could be established, a process almost impossible if using a.c. current (to our knowledge only Kroemer (1942) has used (approximately) dc currents in his analysis of the burn-back rate).

In chapter 2 a model is developed relating the voltage gradient of a fully ionized arc with current and arc channel dimensions. In chapter 3 the burn-back rate of the fuse elements is analyzed and a theoretical description is given including the effect of preheating. In chapter 4 the channel expansion during arcing is experimentally investigated and a theoretical model is developed based on the properties of the arc plasma and the filler material. In chapter 5 the results obtained are combined in calculating the arc voltage as a function of time. Finally in chapter 6 the influence of notch disruption on the arc ignition voltage is discussed.
Chapter 2: Model of a fuse arc.

2.1 Introduction
During the process of interruption in a fuse an arc is generated enclosed by a wall consisting of a mixture of molten and granular sand. The arc can be treated as a wall-stabilized arc (Ranjan (1980)). The dimensions of the arc-channel vary during the interruption process. On the one hand the erosion of the fuse element leads to an increase in arc length. On the other hand the silica once molten diminishes in volume and will be pressed into the voids of the surrounding silica and this results in an increase of the arc channel cross-section. Arcing in fuses and the ensuing variations in the arc channel dimensions typically occur on a scale of milliseconds (cf also chapter 4) whereas the thermal time constant of the enclosed arc will be in the order of microseconds to tens of microseconds (Frind (1965); Browne and Strom (1951)). It seems reasonable therefore to consider the arc in fuses as being quasi-static.

The electrical behaviour of a quasi-static, wall-stabilized arc with fixed channel dimensions can be described with a voltage-current characteristic (Maecker (1960); Fraser (1964)) as shown in fig. 2.1

![V-I characteristic](image)

Figure 2.1: V-I characteristic for a wall-stabilized arc.

The characteristic can be divided into three regions:

region A) The voltage decreases with increasing current. This is due to an increasing ionisation in the arc plasma and an increase of the current conducting path of the arc.

region B) In this region a transition takes place from partly to fully ionized arc plasma. Here the arc-voltage is almost constant and independant of current (Edels (1965)).
The plasma is fully ionized and the voltage increases with current due to an increase in electron-ion interactions.

Few data are known on the parameters of arcs in sand. Literature shows that this type of arc has a positive voltage-current characteristic (Kroemer (1942), Lakshiminarashima et al. (1978), Gnanalingam (1979)).

The only spectroscopic observations known of arcs in sand are due to Chikata et al. (1976). They observed that at arc ignition the plasma consists of ionized silver vapour originating from the fuse element. However the period is very short (order of 10 μsec) and thereafter the arc burns solely in silica vapour. This is consistent with Kroemer's (1942) observation that the field-strength is largely dependant on the filler material and independant of the fuse metal. Chikata et al. (1976) measured in case of a 1000 A ac arc current an electron density of $10^{18}$ cm$^{-3}$ and an electron temperature of $2 \times 10^4$ K. From their data follows that the average ion charge is at least one; i.e. the silicon plasma was fully ionized.

Wheeler (1970, 1971) performed experiments on arcs in quartz capillaries initially filled with argon or hydrogen using current densities in the range of 30 - 100 kA cm$^{-2}$. An increasing arc voltage with current was observed. He concluded that apart from the initial stage of arcing the plasma consists of quartz vapour evaporated from the wall. Spectroscopic observations showed silicon ions to be present having ion charge numbers up to 4. He concluded to plasma temperatures of the order of $10^5$ K and electron densities of the order of $10^{19}$ cm$^{-3}$.

The results may be compared with the experiments of Maecker et al. (1951, 1955) on water stabilized arcs (Gerdien-arc). They measured for a current of 1450 A in a 2,3 mm diameter channel a maximum temperature of $5.2 \times 10^4$ K. We therefore conclude that for arcs in sand the voltage-current characteristic has a positive gradient for not too low currents and that the plasma is fully ionized, the ions having a charge number of at least one.

2.2 The high power constricted plasma discharge column with a rectangular cross section.

We consider a stationary power balance of a flat arc having a rectangular cross section.
The energy loss by radiation is neglected and the Joule heating is balanced only by thermal conduction:

\[- \text{div} (\lambda \ \text{grad} \ T) = G E^2 \]  

(2.1)

![Fig. 2.2: Dimensions of the flat arc.](image)

If the thickness of the channel is much smaller than its width, i.e. $D \ll b$ the energy balance can be written in a one-dimensional form:

\[\frac{d}{dx} (\lambda \frac{dT}{dx}) = -GE^2 \]  

(2.2)

A further assumption is that the degree of the ionization in the plasma is high; i.e. we consider currents which are not too low. In that case Spitzer's (1956) formulas for electrical and thermal conductivity are applicable:

\[\lambda = \lambda_0 T^{2.5}\]  

(2.3)

\[G = G_0 T^{3/2}\]  

(2.4)

$\lambda_0$ and $G_0$ are very weak functions of the temperature and are therefore taken independant of $x$; the form of eq. 2.3 and 2.4 implies that the inherent magnetic field is neglected in the transport processes.

The boundary conditions are:

\[x = 0 \quad \frac{dT}{dx} = 0 \]  

(2.5)

(for reasons of symmetry) and

\[x = \pm bD \quad T = 0 \]  

(2.6)
The system of equations 2.2 - 2.6 can be solved semi-numerically and analogous to a method used by Wheeler (1970) in his analysis of a cylindrical arc. The result is:

\[ E = \frac{p^{0.3} \lambda_{o}^{0.4}}{G_{o} 0.7 b^{0.4}} \]  

(2.7)

where \( p \) is a numerical constant: \( p = 1.458 \).

This result is in close agreement with Gnanalingam's (1979) analysis of the same problem.

The values of \( \lambda_{o} \) and \( G_{o} \) are given by Spitzer (1956):

\[ \lambda_{o} = \frac{\alpha}{Z \ln \Lambda} \quad \text{[Watt m K]} \]  

(2.8)

\[ G_{o} = \frac{\beta}{Z \ln \Lambda} \quad \text{[\Omega m]} \]  

(2.9)

Here \( Z \) is the ion charge and \( \Lambda \) the Coulomb cutt-off. \( \ln \Lambda \) varies slowly with \( Z \), \( T \) and the electron density. For the plasmas considered here values between 5 and 10 can be expected (Wheeler (1970)). The formulas are valid for a Lorenz gas (ions are at rest and have an infinite mass) with corrections for electron-electron interaction and thermo-electric effects. The numerical constants \( \alpha, \beta \), are dependant on \( Z \) (in case \( Z = 1 \), \( \alpha = 1.85 \times 10^{-10} \) and \( \beta = 1.53 \times 10^{-2} \)) (Spitzer (1956)). Introducing eqs. 2.8, 2.9 in 2.7 the result is:

\[ E = q (Z \ln \Lambda)^{0.4} \frac{I^{0.4}}{b^{0.4}} \quad \text{[Vm}^{-1}] \]  

(2.10)

In case of \( Z = 1, q = 3.4 \times 10^{-2} \); its value is substantially the same for higher values of \( Z \) (variation of less than 1%).

This result can be compared with Wheeler's result (1970) in case of a cylindrical arc with radius \( R \):

\[ E = 1.9 \times 10^{-2} (Z \ln \Lambda)^{0.4} \frac{I^{0.4}}{R^{1.4}} \quad \text{[Vm}^{-1}] \]  

If we use as an example the results of Chikata's (1976) fuse experiments (\( n_{e} = 10^{18} \text{ cm}^{-3}, T_{e} = 2.10^{4} \text{ K}, Z = 1 \)) the value of \( Z \ln \lambda \) amounts to (Spitzer 1956): \( Z \ln \lambda = 3.56 \).

Introducing this in eq. (2.10) it follows that

\[ E = 5.65 \times 10^{-2} \frac{I^{0.4}}{b^{0.4}} \quad \text{[Vm}^{-1}] \]  

(2.11)
In case of a fuse element of \(5 \times 0.2 \text{ mm}^2\) arced at 1000 A the fieldstrength will initially be \(E = 374 \text{ V cm}^{-1}\). If the channel increases to a thickness of \(D = 10^{-3} \text{ m}\) the fieldstrength will drop to \(E = 74.6 \text{ V cm}^{-1}\).

2.3 Measurements

In the previous section it was found that in case of a fully ionised and stationary arc the fieldstrength \(E\) is proportional to \(10^{0.4}\), provided the dimensions of the arc channel remain the same. In order to check if such a relation exists for arcs burning in sand a series of experiments were performed. Arcs were ignited by copper strips in compacted silica at constant current. After a specified time the arc was short-circuited and the ensuing current-voltage characteristic was recorded and analysed.

2.3.1 Experimental setup

Copper strips with a rectangular cross-section \((5 \times 0.2 \text{ mm}^2)\) were mounted in a sand filled cartridge. The cartridge had a bore diameter of 5 cm and a length of 12 cm as shown in fig. 2.3.

![Fig. 2.3: The experimental fuse link.](image)

Note: the probes were only used in the measurements as described in section 3.2.
The sand was compacted by a standard technique to a density of 1.69 gr/cm$^3$ in each experiment. The sand used roughly had the following composition:

(p: grain size)

0.125 mm < p < 0.25 mm : 78% by weight
0.25 mm < p < 0.5 mm : 22% by weight

The fuse current was generated by a RLC-circuit which was critically damped, see fig. 2.4. Both a circuit breaker and a thyristor were placed in parallel with the experimental fuse. The breaker was used for the commutation of the current $I_m$ to the fuse element and this occurred when the current reached its maximum value. As a result a current flowed through the fuse element which was constant within 5% for several ms. During the experiment this current was varied from 400 A up to 2600 A by a proper choice of the load voltage of the capacitor bank (0 - 15 kV). Arc initiation was obtained at a constricted section in the fuse element.

After a period of arcing the crowbar thyristor was fired and the current commutated into the thyristor circuit. The time $t_{com}$ the current needed to commutate was varied by an inductance $L_c$ in series with the thyristor.

![Diagram of experimental circuit](image)

Figure 2.4: a) Experimental circuit. $R = 4.4 \Omega; L = 45 \text{ mH}; C = 6.8 \text{ mF}$. b) Current flow.
During the experiments $L_c$ was chosen such that the time $t_{com}$ was significantly longer than the time constant of the arc, which lies in the range of several microseconds up to tens of microseconds. On the other hand we had to choose $t_{com}$ so short that the variation of arc channel dimensions during commutation were negligible. This is necessary because the relation $V \sim I^\beta$ can only be verified provided the arc channel dimensions remain constant.

The voltage and current signals were recorded and stored by a PDP-11 microcomputer and two transient recorders ("Le Croy" wave form analysers P 2256 and P 2264). The data thus obtained were stored on diskette and plotted on a X-Y-recorder. The input impedance of the system used amounted to $10^5 \Omega$.

2.3.2 Experimental results.

In figure 2.5-a a typical example of the voltage and current traces during commutation is shown. In figure 2.5-b the V-I-characteristic is drawn on a logarithmic scale. The constant $\beta$ in $V \sim I^\beta$ was determined from the slope of the V-I-characteristic.

The results of the measurements are collected in table 2-6 where: $l_x$ is the length of the fulgurite; $I$, $V$ the values of current and voltage at the onset of commutation. $I_\beta$ is the value of the current below which the formula $V \sim I^\beta$ does not apply any longer. It appeared that for $I < I_\beta$ the voltage will remain nearly constant. (Region B of the static V-I characteristic, see fig. 2.1).

2.3.3 Discussion of the results.

From the results it appears that the averaged measured value $\beta = 0.41$ ($s = 0.04$ ; $n = 15$). This result is close to the value $\beta = 0.4$ which is predicted by the theory. The spread in the $\beta$ values as given in table 2-6 are considered to be due to statistical variations from one experiment to the other. At any rate no dependency was found on the commutation times used nor on the current prior to short-circuiting or the length of the fulgurites. However care was taken to avoid the situation that as a result of long arcing times the fulgurite cross-section should become too large (particularly in the central parts). In that case the local drop in arc temperature due to low current densities may be such that no longer the condition of a fully ionised arc applies. This effect was probably observed for measurements where long fulgurites ($> 30 \text{ mm}$) were formed. In these cases $\beta$-values of less than 0.3 were measured (whereas the central parts of the fulgurite cross-section were $> 9 \times 2 \text{ mm}^2$).
Figure 2.5. Experimental proof of $V \sim I^{0.4}$

a) variation of $V$ and $I$ during commutation (Nr. of meas. 407)
b) $V-I$-characteristic of fig. 2.5-a.
Table 2-6

<table>
<thead>
<tr>
<th>Nr. of meas.</th>
<th>I (A)</th>
<th>V (V)</th>
<th>l_f (mm)</th>
<th>L_c (μH)</th>
<th>t_{Com} (msec)</th>
<th>β</th>
<th>I_β (A)</th>
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<td>2215</td>
<td>322</td>
<td>15</td>
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<td>2220</td>
<td>319</td>
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<td>0,39</td>
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<td>10</td>
<td>0,24</td>
<td>0,44</td>
<td>300</td>
</tr>
</tbody>
</table>
The lower $\beta$ values can be explained by a shift for the central parts of the arc to field strength values which are less dependant on current as shown in fig. 2.1 region B.

As stated before, the commutation time should be several times longer than the time constant of the arc. Otherwise a characteristic of a dynamic arc would be measured. A too short commutation time will have the effect that the resistance of the arc plasma will be "remembered" if the current decreases to zero. This results in a steeper slope of the V-I-characteristic than $\beta = 0.4$. This has indeed been observed in some experiments with very short commutation times ($< 60 \mu$sec). In figure 2-7 an example is shown of an arc which showed this behaviour.

Figure 2.7: The effect of a too short commutation time
--- static characteristic.
\text{\textbullet\textbullet\textbullet} measured characteristic of $t_{\text{COM}} = 25 \mu$sec is of the same order as the time constant of the plasma.
2.4 Conclusions

A theoretical model of the electrical behaviour of a stationary, rectangular arc has been developed. This model of a fully ionised arc predicts an arc-voltage dependency on arc current according to $V \propto I^{0.4}$. Experimentally this dependency has been observed for arcs in sand at not too low current values.

The limits for the model are:
- low arc current densities: full ionisation cannot be maintained under these circumstances.
- too high $\frac{di}{dt}$: in this case the condition of quasi-static behaviour is not fulfilled.

The model will be used for the explanation of the development of the arc voltage in fuses.
Chapter 3: The burn-back rate of fuse elements.

3.1 Introduction

In this chapter we deal with the burn-back rate of fuse elements. The measurements, except one series of experiments (series E, see annex 2) and the derivation of the model for the burn-back rate has previously been published by Daalder and Hartings (1981-b). The quantitative results of the experiments, given in this chapter show some minor differences compared with those given in the previous mentioned publication. This is due to the use of more accurate physical data of the fuse element material. Also another method of determining the average current $I$ during an experiment was used again improving the accuracy.

3.2 Measurements

3.2.1 Experimental setup

A similar setup, as described in chapter 2, is used. The differences are:
- A number of tungsten probes, having a diameter of 0.5 mm, was used to measure voltages with respect to anode and cathode potential at various positions along the arc.

The probes were inserted into the cartridge and placed at right angles to the fuse element as shown in fig. 2-3. The probes were spaced 5 mm apart and were positioned at both sides of the constriction where the arc was initiated.
- Instead of using the thyristor-link, a circuit breaker without inductance $L_c$ was used to short circuit the fuse link after a specified arcing time. (see fig. 2-4)

As a result the time $t_{com}$ needed for the current to commutate in the circuit-breaker link is negligible and a rectangular current pulse is obtained.

3.2.2 Experimental results

Five series of measurements were done: A) Ag 5 x 0,1mm$^2$; B) Ag 5 x 0,2 mm$^2$; C) Cu 5 x 0,1 mm$^2$ D) Cu 5 x 0,2 mm$^2$ and E) Cu 5 x 0,2 mm$^2$. The arcing times in series E were chosen longer than in series D.

The arc-voltage, probe-voltages and the current through the fuse-element were recorded. For each experiment the following variables were measured:
- $I$: the current;
- $t_{cur}$: the time the current flowed;
- $t_{arc}$: the arcing time
- $l_f$: the length of the fulgurite.
A typical example of a measurement is given in fig. 3.1.

![Diagram showing arc voltage, probe voltage, and current as a function of time for an arc in sand.](image)

**Fig. 3.1:** Arc voltage, probe voltage and current as a function of time for an arc in sand.

The pattern of the different probe voltages, in different experiments were almost identical.

From the time difference between the initial rise of the voltage of two successive probes and the distance between the probes, the anode- and cathode- burn-back rate was calculated.

In a second method employed the initial length of the fuse element at both sides of the notch was measured. After arcing the remaining length of the fuse element was subtracted and from this the burn-back rates at the anode- and the cathode-side were determined. Both methods showed that the anode- and cathode-burn-back were equal.

An average burn-back rate (single side) was therefore calculated using

$$V_f = \frac{1}{2} \frac{t}{t_{arc}}$$
A summary of the experimental results is given in Annex 2. From the experiments it was concluded that the burn-back rate of fuse elements is proportional to the current density in the fuse element. However for high current densities and/or long arcing times a more than linear increase in the burn-back rate with current density occurs. At high values of \( J^2 t \), multiple arcing was observed.

3.3. The model for the burn-back rate

Analysis showed that the fuse element for the greater part is eroded as liquid metal droplets which are subsequently pressed into the surrounding filler (cf. chapter 4).

Daalder and Hartings (1981-b) demonstrated that the erosion of fuse elements is mainly due to local electrode effects. By analysis of cathode processes, they derived a formula for the cathode burn-back of fuse elements according to:

\[
V_{th} = \frac{U_{\text{con}}}{C_s \rho_s (T_m - T_b) + L \rho_s + C_l \rho_s (T_d - T_m)} \cdot J
\]  

(3.1)

where \( U_{\text{con}} \) is the power loss per ampere arc-current to the cathode. This quantity was derived from vacuum experiments and is a constant for a specific metal (Daalder (1977, 1981a)).

The denominator \( H = C_s \rho_s (T_m - T_b) + L \rho_s + C_l \rho_s (T_d - T_m) \) is the enthalpy increase per unit volume needed to raise the temperature from the initial fuse element temperature to the temperature at which the metal droplets are removed from the strip.

In this formula:

- \( C_s, C_l \): the specific heat of the fuse element in solid and liquid state.
- \( \rho_s \): the specific density in the solid state.
- \( L \): the heat of fusion.
- \( T_b \): initial temperature of the fuse element.
- \( T_m \): fusing temperature.
- \( T_d \): temperature of liquid droplets.
- \( J \): current density.

Due to Joule heating the temperature \( T_b \) increases during arcing:

\[
T_b = T_o \exp \left( \frac{J^2 \cdot t_{\text{cur}}}{\alpha} \right)
\]

(3.2)

where

\[
\alpha = \frac{\lambda \cdot \rho_s \cdot C_s}{L_{\text{wf}}}
\]

(3.3)
and $T_o$ is room temperature, $\lambda$ is the thermal conductivity, and $L_{wf}$ is the constant of Wiedemann-Franz: $L_{wf} = 2.4 \times 10^{-8} \frac{k^2}{\Omega m}$. 

The equations 3.1, 3.2 and 3.3 describe the momentary burn-back rate (single side) as a function of time. In order to compare the results with the average burn-back rate $\bar{V}_f$ obtained from the experiments $V_{th}$ must be averaged by integration:

$$\bar{V}_{f,th} = \frac{1}{t_{arc}} \frac{t_{cur}}{t_{cur - arc}} \int_{t_{cur - arc}}^{t_{arc}} V_{th} dt$$   \hspace{1cm} (3.5)

where $\bar{V}_{f,th}$ is the theoretical averaged burn-back rate.

The result of the integration is given by equation (3.6):

$$\bar{V}_{f,th} = \frac{U_{con}}{H + C_p T_o} \left[ 1 - \frac{\alpha}{J^2 t_{arc}} \ln \left( \frac{H + C_p T_o}{H + C_p T_o - C_p T_0 \exp (\frac{J^2 t_{cur - arc}}{\alpha})} \right) \right]$$

Eq. 3.6 is valid as long as $T_d \leq T_m$ and thus

$$J^2 t_{cur} \leq \frac{\lambda \rho S C_s}{L_{wf}} \ln \left( \frac{T_m}{T_o} \right)$$   \hspace{1cm} (3.7)

3.4. The determination of the droplet temperature

In eq. 3.6 the quantitative values of all parameters, except $T_d$, are known (See Annex 1).

Assuming eq. 3.6 to be valid, an estimate can be made of the droplet temperature $T_d$. For various values of the droplet temperature, $\bar{V}_{f,th}$ (eq. 3.6) was calculated for all experiments and the temperature was chosen such that $\bar{V}_{f,th}$ showed the optimum correlation with $\bar{V}_f$. From these calculations it appeared that $T_d$ amounts to:
- 1700 K in the silver experiments,
- 1356 K (i.e. fusion temperature) for the copper experiments.

The good agreement between measured and calculated values of the burn-back rate is shown in fig. 3.2.
fig. 3.2.: Correlation between measured ($\bar{V}_f$) and calculated ($\bar{V}_{f.th}$) burn-back rates including the effect of Joule heating.

a) Silver  $T_d = 1700\,^\circ\text{K}$  \hspace{1cm} (N = 24)

b) Copper  $T_d = 1356\,^\circ\text{K}$  \hspace{1cm} (N = 40)
3.5. Discussion

It proved that for the majority of the experiments Joule heating of the fuse elements is a significant effect. As was previously noted [Daalder and Hartings (1981-b)], this effect may explain the difference in burn-back rates as measured by different authors. It is a customary procedure to plot the burn-back rate \( V_f \) as a function of current (density) [Kroemer (1942); Gnanalingam (1979); Dolegowski (1976); Wilkins et al. (1978)]. In case of linear approximations an erosion constant \( C \left[ \frac{m^3}{A \cdot s} \right] \) is obtained. However, if preheating of the fuse element occurs, such an erosion constant neither has a physical meaning nor is it constant as its value will depend on the set of experimental variables chosen (which are in most cases not explicitly stated). We will illustrate this by the following example.

The measured burn-back rate \( \tilde{V}_f \) is plotted as a function of \( J \) for two series of experiments (see fig. 3.3). An approximate linear relation \( \tilde{V}_f = C \cdot J \) can be found in both cases. One can observe that the value of \( C \) differs though the same fuse element material is used and the current densities are in the same range for both experiments. The difference is explained by the fact that in series E longer arcing times and thus larger \( J^2 t \) values were used than in series D. This is in accordance with equation 3.6 which predicts that \( \tilde{V}_f \) is not only a function of \( J \) but also of \( J^2 t \). In our opinion it is therefore only allowed to define a constant erosion rate \( C' \) for such values of \( J^2 t \) that Joule heating is negligible.

The erosion constant \( C' \) can be found by calculating \( V_{f,th}/J \) (eq. 3.6) for \( J^2 t_{cur} \to 0 \), i.e.:

\[
C' = \frac{U_{con}}{H}
\]

The result is:

\( C' = 1.06 \cdot 10^{-9} \ \left[ \frac{m^3}{A \cdot s} \right] \) for copper fuse elements and

\( C' = 1.03 \cdot 10^{-9} \ \left[ \frac{m^3}{A \cdot s} \right] \) for silver fuse elements.

The relation \( V_f = C'J \) is shown by the dashed lines in fig. 3.3 a and b. We conclude therefore that only for \( J^2 t_{cur}/a \approx 0 \) a linear relation exists between \( V_f \) and \( J \). If this is not the case eq. 3.6 is an accurate expression for the calculation of the burn-back rate for specific values of \( J \) and \( t_{cur} \), as was proven by experiment.

As a final remark it should be noted that the influence of preheating on the value of the burn-back rate will be frequently encountered in fuse practice.
Fig. 3.3: The significance of fuse element preheating in the determination of the erosion constant $C$.

a) series D: Cu $5 \times 0.2$ mm$^2$; $C'$ obtained from eq. 3.6 in case $J^2 t + 0$

b) series E: as a) but longer arcing times have been used.
A fuse element generally will have an (average) temperature substantially higher than the room temperature as it will be heated by load currents. This will lead to a higher burn-back rate than in case of a cold fuse. The difference may easily be a factor 2 or 3 (compare eq. 3.1 and 3.6). A similar situation occurs for the over-current range where heating during the pre-arcing period will enhance the burn-back rate.
Chapter 4: The arc-channel expansion

4.1. Introduction

For a calculation of the arc-voltage the change of arc-channel dimensions as a function of time must be known. During arcing a so-called fulgurite is formed around the discharge consisting of a coherent mixture of fuse-link material, molten silica and granular sand (see fig. 4.1).

In this chapter the structure of the fulgurite and the variations of the arc cross-section will be discussed.

4.2. The structure of the fulgurite

From figure 4.1 can be seen that the fulgurite has a symmetrical form. Arcing was initiated by a notch in the fuse element originally situated in the central part of the fulgurite (corresponding with the bulge in fig. 4.1 a and b).

The length of the fulgurite corresponds with the total length of the fuse element eroded during arcing. The fulgurite parts situated left and right of the origin are identical in form and length indicating that the anode- and cathode burn-off rates are equal.

The structure of the fulgurite wall was observed by casting the fulgurite in resin and by cutting slices perpendicular to the axis of the fuse element. Photographs of these cuts are shown in figures 4.2 and 4.3.

It can be seen that in case of copper the inner part of the fulgurite is hollow. This cavity is known as the lumen and we assume that the dimensions of this lumen correspond with the dimensions of the arc-channel. However, experiments with silver fuse-elements show an inner part filled with a foamy structure (fig. 4.3).

Probably a mixture of molten and evaporated silicon has filled the cavity during or after arcing. This is in clear contrast with the results of the copper experiments where the transition from wall to cavity could always clearly be seen (fig. 4.2).

The boundary layer of the fulgurite consists of sand grains fused together. Laying more inwards a region can be discerned with a considerable amount of metal droplets (cf. Lakshiminarashima (1978)). Apparently a large part of the fuse element is eroded in the form of liquid metal droplets which are subsequently pressed into the sand. The inner region consists of a mixture of sand grains and solidified molten silicon. Similarly a part of the silicon molten by the arc energy is pressed in the voids between the sand grains.
Fig. 4.1: The fulgurite
a) top view // y-axis
b) side view // z-axis
c) outline of the form of a fulgurite
Fig. 4.2/4.3: Cross-sections of fulgurites cut perpendicular to the arc-channel axis.
4.2 a) copper 5 x 0.1 mm$^2$
4.2 b) detail of a)
4.3 c) silver 5 x 0.2 mm$^2$
4.3 d) detail of c)
Fig. 4.5: X-ray pictures of fulgurite cuts

a) fuse element
b) place where originally the notch was situated.

c) No. of meas. 326 Cu 5 x 0.2 mm$^2$, I = 890 A; $t_{arc} = 11.6$ msec.
Although not verified by experiment one may speculate on the significance of this effect for the pressure containment in the arc-channel. Analysis of a series of fulgurite cross-sections showed that in case of copper fuse elements for the first few milliseconds of arcing the shape of the cavity is approximately rectangular, i.e. of the same form as the cross-section of the original fuse element, see fig. 4.6.

Fig. 4.6: Cross-section of the lumen.

4.3. Local channel growth

From experiment one can obtain the final dimensions of the lumen area. The local channel growth as a function of time can then be determined in the following way. We showed that if no preheating of the fuse element occurs the arc length will increase linearly with time at constant current. Experiment also showed that then during each experiment the voltages of successive probes were similar in form and magnitude. From these observations we conclude that the energy exchange during arcing dominantly occurs in the y-z plane (fig. 4.1). The increase of the lumen area for any position can then be described by the same function $F : F(t - t_1) U(t - t_1)$ where $U$ is the Heaviside function and $t_1$ the moment arcing starts at an arbitrary place (provided the current is constant). In other words the increase in the lumen area will become the same for two positions by a shift of the time axis corresponding with the time difference in the onset of arcing at these positions.

Using this model, first the channel dimensions were measured as a function of the distance $x$ from the fulgurite end. As a next step $x$ can be related to time by the burn-back relation $x = V_f \cdot t$ (ch. 3) and thus $F(t)$ is obtained.
4.4. Analysis of the arc channel expansion rate

Measurements showed that for the fuse elements investigated the variation of the thickness $D$ was dominating in lumen growth (cf. fig. 4.6). For instance at a current of 1500 A the initial thickness of 0.1 or 0.2 mm increased more than tenfold in around 3 ms whereas the width $b$ (initially 5 mm) increased by less than 20% in the same time. The latter effect is even of less significance if we consider eq. 2.10 which shows that the fieldstrength $E$ is proportional to $b^{-0.4}$ whereas $E$ is inversely proportional to $D$. For these reasons it is justified to analyse the channel growth by a one-dimensional model governed by the variation of $D$.

The increase of the lumen area is a complicated mechanism. Several processes are likely to contribute to the expansion of the channel and Gnanalingam et al. (1980) lists the following:

1. boiling off silica vapour from surface layers of quartz in contact with the arc.
2. melting of deeper layers of silica.
3. fusion of silica grains, reducing the air spaces and thus moving the fulgurite wall.
4. solidification of fuse element metal and condensation of silica vapour on the surfaces of particles in the outer part of the region of fusion, with the exchange of latent heat to the particles.

Analysis of fulgurite cross-sections obtained in our experiments showed that these processes indeed occur. However, no data are available on the significance of each process and its relative contribution to the channel growth. A detailed description of the channel increase is therefore not realistic and we will limit ourselves to a simple model in which the fusion of sand is considered to be a major process.

A prerequisite for the formation of an arc-channel is the melting of the silicon. Due to melting there is an increase in space as for compacted sand around 64% ($\rho_{\text{sand}}/\rho_{\text{quartz}}$) of each unit volume is occupied by quartz and the remainder is taken up by air. On melting quartz increases in volume by 7% (Wright et al. (1976)) and as a result the molten quartz will occupy 68% of the original sand volume. In the space formed the arc will expand. Due to arc pressure a part of the molten silica will be pressed in the voids of the solid sand in the outer regions. This leads to a further increase of the lumen area.

We will now calculate this increase for a constant fuse current. In fig. 4.7 a schematic drawing is shown of a part of the arc channel.
The colour of the fulgurite wall is red for the copper fulgurites and yellow-white in case of silver (cf. also Kroemer (1942)).

The distribution of metal droplets was analysed by X-ray photography, see fig. 4.4.

Fig. 4.4: a) X-ray picture of a fulgurite (top view //y-axis)
   b) X-ray picture of a fulgurite (side view //z-axis).
   No. of meas. 320 (Cu 5 x 0.2 mm²; I = 1240A; t_{arc} = 11.2 msec).

The black dots represent the metal droplets, whereas the sand is shown by varying shades of grey. X-ray pictures from successive cuts of a single fulgurite (fig. 4.5) show that the droplets for the greater part are pushed away in the y-direction (compare fig. 4.1). The pictures also show that the metal always can be found in the outer region of the fulgurite wall. An explanation of this effect is that during arcing the droplets will repeatedly become liquid again and are then pushed on by the silicon which is melted by the arc. This should mean that the position of the droplets roughly defines an isothermal surface with a temperature close to the melting point of the fuse metal and below the melting point of silicon.

The cross-section in the central part of the fulgurite, (i.e. through the plane were the notch was originally situated) consistently shows a capricious form and its size is relatively large if compared with the other cross sections. Due to the small size of the notch there is little metal present as is also verified by fig. 4.5 g. The effect is similar to the cavity formation which occurs after prolonged arcing times at the outer parts in the z-direction. In this direction again there is little metal present (see fig. 4.5) and generally after a few msec bulges are formed in the z-x plane leading to a deviation from the initially rectangular shape of the lumen.

It seems therefore that metal droplets increase the cohesion between the sand grains and improve, by a kind of glueing effect, the solidity of the wall around the arc.
The energy input $dW$ for an element having an axial length $\Delta x$ will be:

$$dW = E(x,t) \Delta x \, dt$$  \hspace{1cm} (4.1)

This arc energy will flow through an area $A$ into the sand where

$$A = (2b + 2D) \Delta x = 2b \Delta x$$  \hspace{1cm} (4.2)

provided $b >> D$.

As a result a volume of sand $dv_s$ will melt.

The energy per unit volume $H$ which is necessary to increase the sand from room temperature $T_o$ to a temperature $T_e$ beyond the fusion temperature is:

$$H = c_s \rho_s (T_m - T_o) + L_p + c_l \rho_s (T_e - T_m)$$  \hspace{1cm} (4.3)

The energy balance in the case of adiabatic heating will then be

$$E(x,t) \Delta x \, dt = H \, dv_s$$  \hspace{1cm} (4.4)

Once the sand is molten, its volume will attain a value:
where $\rho_1$ is the specific mass of quartz in the liquid state.

The increase of the lumen volume $dv$ is:

$$dv = dv_1 - dv_s = dv_s \left(1 - \frac{\rho_s}{\rho_1}\right)$$  (4.6)

This volume $dv$ can be further increased by a flow of the molten silica into the voids of the solid sand. A maximum volume will be attained, if the molten silica is entirely removed from the volume it occupies i.e. $dv = dv_s$. Because it is not known to what extent this flow of molten silica may occur we introduce a factor $\gamma$ in relation 4.6

$$dv = \gamma(1 - \frac{\rho_s}{\rho_1}) dv_s$$  (4.7)

where

$$1 \leq \gamma \leq \frac{\rho_1}{\rho_1 - \rho_s}$$

If $\gamma = 1$ no flow occurs, where $\gamma = \frac{\rho_1}{\rho_1 - \rho_s}$ depicts the situation for maximum flow.

Introducing now eqs. 4.7, 4.2 and 4.3 into eq. 4.4 together with $dv = AdD$ where $dD$ is the increase in lumen thickness, the result is:

$$E(x,t) I dt = \frac{H b dD}{\gamma(1 - \frac{\rho_s}{\rho_1})}$$

or

$$\frac{dD}{dt} = \frac{E(x,t) I \gamma(1 - \frac{\rho_s}{\rho_1})}{H b}$$  (4.8)

Introducing for $E$ eq. 2.10, one can write:

$$\frac{d^2 D}{dt^2} = \frac{q[Z \ln \Lambda]^{0.4} I^{1.4} \gamma(1 - \frac{\rho_s}{\rho_1})}{b^{1.4} H}$$  (4.9)
Provided the term on the right hand side of the formula does not vary with time during the expansion of the lumen area at a fixed current, the differential equation can be solved. The solution is:

\[
D = \sqrt{(D'_0)^2 + 2Bt}
\]  

(4.10)

where

\[
q(Z \ln \Lambda)^{0.4} I^{1.4} (1 - \frac{d}{D'})
\]

\[
B = \frac{1}{D^{1.4} H}
\]  

(4.11)

and \(D'_0\): the initial thickness of the arc channel.

Note that \(B\) has the dimension of the diffusion coefficient \([m^2 \text{s}^{-1}]\).

This result was checked by the measurement of lumen dimensions formed by arc currents ranging from 300 to 2600 A.

4.5 Experimental results on arc channel growth

4.5.1. Introduction

The variation of the arc channel width was measured from a series of cuts of fulgurites obtained with copper fuse elements. From each cross-section the average thickness \(D\) was found by microscopical measurement of the arc channel thickness at five different places. In order to check the validity of eq. (4.10) \(D^2\) was plotted as a function of the distance \(x\) from the fulgurite ends i.e. we took the transition planes from fuse element to arc channel as origins \((x = 0)\) (see fig. 4.8 and 4.9). In this manner the increase in thickness on both the anode and the cathode side for each fulgurite was obtained. The transformation \(t = x/V_f\) was done by using the averaged measured value \(V_f\) which was accurate enough for most measurements because of the low values of \(J^2t\) (see Chapter 3). (In case of the measurements nos. 212, 213 and 215 (see table 4.10) the effect of Joule heating was taken into account in the transformation. Here the values of \(J^2t\) could not be neglected).

By the method of the least squares straight lines were drawn through the data points as shown in fig. 4.8 and 4.9. From their slope \(B\) (eq. 4.10) was obtained. Establishing the initial value of \(D'_0\) of the arc channel proved to be difficult. Often the remaining part of the fuse element broke off during handling of the fulgurite. Also material was removed
Fig. 4.8. Increase in channel thickness for copper 5 x 0.1 mm² and
I = 385 A. (•) anode side; (x) cathode side.

Fig. 4.9. Increase in channel thickness for copper 5 x 0.2 mm² and
I = 2420 A (•) anode side; (x) cathode side.
Copper $5 \times 0.1 \text{ mm}^2$

<table>
<thead>
<tr>
<th>No. of Meas.</th>
<th>$I_\text{A}$</th>
<th>$\tilde{V}_f$ [m.s$^{-1}$]</th>
<th>$B_x$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
<th>$x$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
<th>$r_1$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
<th>$r_2$ [10$^{-3} \text{ s}$]</th>
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<td>1.0</td>
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<td>-</td>
<td>-</td>
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<td>0.81</td>
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* $\tilde{V}_f$ is not used for the $x$-$t$ transformation but the burnback rate increase due to Joule heating is taken into account (see text).

Copper $5 \times 0.2 \text{ mm}^2$

<table>
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<tr>
<th>No. of Meas.</th>
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<th>$B_x$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
<th>$x$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
<th>$r_1$ [10$^{-4} \text{ m}^2 \text{s}^{-1}$]</th>
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<td>2.7</td>
<td>0.89</td>
<td>3.1</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table 4.10: Experimental results of the measurements on arc channel growth.

By cutting the fulgurite which could lead to the disappearance of the transition area were fuse element and arc had met. The conditions made it difficult to establish the exact position of $x = 0$, however this did not interfere with the determination of the value of $B$ (a shift in the $x$-axis (or time axis) will not influence the slope of the straight line).
4.5.2. Experimental results

Table 4.10 compiles the results of the measurements. $r^2$ denotes the coefficient of determination for the regression line and shows that there exists a fair linear relation between $b^2$ and $t$. (The average value for all data is $r^2 = 0.85$). $\tau$ is the maximum time for which the linear relation holds. The value is at least several msec, i.e. a timespan relevant for actual fuse interruption. For higher values of time there is a significant decrease in channel expansion, this has not been further pursued.

The values of $B_y$ and $B_x$ attained for the anode and cathode side were averaged: $\bar{B}$, as we did not observe any particular dependency on either side.

4.5.3. The initial thickness $D'_o$ of the arc channel

It is unlikely that the initial thickness of the arc channel $D'_o$ is equivalent to the thickness $D_o$ of the fuse element used in an experiment. Between the flat fuse element and the silicon grains a volume of air can be found which may give a significant contribution to the thickness $D'_o$. Assuming that the silicon grains can be approximated by spheres each having a radius $R$, the average increase in thickness due to the air volume around the strip can be calculated (see fig. 4.10):

\[
D'_o = D_o + 2 \bar{d}_e
\]

\[
\bar{d}_o = (1 - \frac{\pi}{3})R
\]

Fig. 4.10: The influence of silicon grains on the value of $D'_o$

For the filler we used in our experiments $R = 0.1$ mm.

As a result we found: $D'_o = 0.18$ mm ($5 \times 0.1$ mm$^2$) and $D'_o = 0.28$ mm ($5 \times 0.2$ mm$^2$).
4.6 Discussion

The results on lumen expansion showed that for a considerable range of currents the thickness $D$ of the arc channel varies with time according to

$$D = \sqrt{(D')^2 + Bt} \quad (4.10)$$

Apparantly the theoretical model derived gives a proper prediction of the lumen growth. It follows that $H/\gamma$ in eq. (4.11) has a fixed value at least for a constant current.

In fig. 4.11 $B$ has been plotted as a function of $I^{1.4}$. A fair linear relation exists. No significant differences were found between the series of $5 \times 0.1 \text{ mm}^2$ and $5 \times 0.2 \text{ mm}^2$. This agrees with eq. 4.11 where $B$ appears to be independent of the initial thickness of the arc channel. The data points were approximated by:

$$B = 1.23 \times 10^{-8} I^{1.4} \quad (4.12)$$

Inserting this result in eq. (4.11) the result is

$$\frac{H}{\gamma} = \frac{q[Z \ln \Lambda]^{0.4}(1 - \frac{\rho_s}{\rho_1})}{b^{1.4} \times 1.23 \times 10^{-8}} \quad (4.13)$$

This shows that the quantity $\frac{H}{\gamma}$ is independant of current.

Eq. (4.13) can be evaluated introducing for $Z \ln \Lambda$ the numerical value of 11.5; a result obtained in the next chapter (ch. 5). Using also $\rho_s/\rho_1 = 0.68$ and $b = 5 \times 10^{-3}$ the result is:

$$\frac{H}{\gamma} = 3.90 \times 10^9 \quad (4.14)$$

We have demonstrated that $H/\gamma$ has a fixed value for our experiments. However it is not necessarily true that $H$ and $\gamma$ will have the same value during the experiments and for a range of currents.

$H$ is a temperature dependent function (eq. 4.3). It is likely that the same applies for $\gamma$. If the flow of silica into pores is Poiseuille dominated (Zwikker (1967)), $\gamma$ will be influenced by variables as the pore size of the filler material, the viscosity of the molten silica and the pressure of the arc, quantities which vary with the temperature. However, limitations can be imposed on the values of both $H$ and $\gamma$.

As we have seen the limits of $\gamma$ are:
In case of $\gamma = 1; H = 3.90 \times 10^9 \text{ J m}^{-3}$. This is equivalent with a temperature of $T = 2140 \text{ K}$; i.e. slightly above the fusion temperature of $T_f = 1996 \text{ K}$. For this situation no flow of molten silica occurs and the increase in lumen area is solely due to the fusion of sand.

Due to for instance increasing currents, higher temperatures can be expected in the molten silica. $H$ will become larger and thus $\gamma$.

This is a consistent picture as for higher currents the arc pressure will increase and the viscosity decreases leading to enhanced conditions for flow.

If we consider the extreme situation that the boiling temperature will be reached ($T = 2863 \degree \text{ K}$) $H = 5.4 \times 10^9 \text{ J m}^{-3}$ and $\gamma = 1.38$. This means that of the liquid silica 18% in volume will be removed. Higher values for $H$ are un-
likely. Although there is evaporation of the sand in order to sustain the arc, the amount is small in comparison with the amount of liquid silica.

We conclude therefore that for a range of currents (400 - 2600 A) the values of $H$ and $\gamma$ will vary between rather narrow margins. $0 - 10\%$ of the molten silica may flow into the voids between the sand.

It should be stressed that $\gamma$, being a material constant, will significantly be influenced by the choice of the filler material (pore-size, thermal conductivity and melting point). It is therefore our opinion that this variable is of importance in fuse design.
Chapter 5: Calculation of the course of the probe voltages.

5.1. Introduction

In this chapter the results of our study on the behaviour of a silicon arc, the burn-back rate and the expansion of the lumen area are combined to obtain an equation that predicts the value of the measured probe voltages as a function of time.

5.2. Theory

In figure 5.1 a schematic view is shown of a part of an arc, that has passed a probe at time \( t = 0 \).

![Schematic view of an arc in sand used in the calculation of probe voltage.]

Fig. 5.1: Schematic view of an arc in sand used in the calculation of probe voltage.

The voltage across this part of the arc can be calculated by solving

\[
V_{pr}(t) = \int_{0}^{l(t)} E(x,t) \, dx
\]

(5.1)

where: \( l = \text{length of the arc between the probe and the fuse element,} \)

\( t = \text{time taken from the moment the arc passed the probe.} \)
Here

\[ l(t) = \int_{0}^{t} V_f(t') \, dt' \]  \hspace{1cm} (5.2)

If the change in \( V_f \) due to Joule heating during the arcing period is neglected and we take the current constant during a measurement the burn-back velocity \( V_f \) is constant. Thus:

\[ l(t) = V_f \cdot t \]  \hspace{1cm} (5.3)

The thickness \( D \) of the arc channel at position \( x \) as a function of the time \( t' \) lapsed since the arc started at \( x \) may be written as:

\[ D(x,t) = D_o' \sqrt{1 + \frac{B}{(D_o')^2} \cdot t'} \]  \hspace{1cm} (4.10)

Using equation 5.3 \( t' \) can be written as

\[ t' = t - \frac{x}{V_f} \]  \hspace{1cm} (5.4)

Substituting eq. 5.4 in eq. 4.10 gives

\[ D(x,t) = D_o' \sqrt{1 + \frac{B}{(D_o')^2} \left( t - \frac{x}{V_f} \right)} \]  \hspace{1cm} (5.5)

In chapter 2 a formula for the electric field \( E \) in a rectangular arc-channel was derived:

\[ E = \frac{q \cdot \left( \frac{z \ln \Lambda}{b} \right)^{0.4} \cdot 1^{0.4}}{b^{0.4} \cdot D} \]  \hspace{1cm} (2.10)

Combining eq. 5.5 and eq. 2.10, gives

\[ E(x,t) = \frac{q \cdot \left( \frac{z \ln \Lambda}{b} \right)^{0.4} \cdot 1^{0.4}}{b^{0.4} \cdot D_o' \sqrt{1 + \frac{B}{(D_o')^2} \left( t - \frac{x}{V_f} \right)}} \]  \hspace{1cm} (5.6)

Here \( q = 3.4 \times 10^{-2} \).

In eq. (5.6) \( b \) is taken as a constant and equal to the initial width of the fuse element. Substitution of eq. 5.3 and eq. 5.6 in eq. 5.1 and after integration the following expression is derived for the probe-voltage as
a function of time (for a constant current I):

\[ V_{pr.th}(t) = \frac{0.068 [Z \ln \lambda]^{0.4} I^{0.4} D'_0 V_f}{B^{0.4} B} \left\{ \sqrt{1 + \frac{B}{(D')^2}} t - 1 \right\} \] (5.7)

5.3. Comparison between experimental and theoretical results

In order to calculate the probe voltage according to eq. 5.7 we start from the data of Chikata et al. i.e. we take \( Z = 1 \) and \( \ln \lambda = 3.56 \) (see chapter 2). Other data used are:

- \( D'_0 = 0.18 \times 10^{-3} \) m for Cu \( 5 \times 0.1 \) mm\(^2\) and
- \( D'_0 = 0.28 \times 10^{-3} \) m in case of Cu \( 5 \times 0.2 \) mm\(^2\).

For B the experimental result \( B = 1.23 \times 10^{-8} \) \( I^{1.4} \) was used.

For 17 of the experiments described in chapter 3, the theoretical probe voltage was calculated at intervals of 0.5 msec and compared with the measured probe voltage. The values of I and \( V_f' \), measured during each experiment, were used for the calculation of \( V_{pr.th} \).

The measured probe voltage was obtained by taking the average of a probe voltage on the cathode side and the anode side. From this average value, 10 V was subtracted, taking into account the anode- and cathode voltage drop, which we assumed to be 20 V equally divided over anode and cathode.

The ratio \( R \) between calculated and averaged measured probe voltage

\( R = \frac{V_{pr.th}}{[h(V_{pr.an} + V_{pr.cath}) - 10V]} \)

were plotted as a function of time. An example of such a calculation is given in fig. 5.2 and 5.3.

The plots of \( R \) as a function of time are shown in Annex 3.

Finally a table of the average \( \bar{R} \) and the standard deviation \( S_R \) for each experiment is given in table 5.4.

5.4. Discussion

From experiments with current densities less than 2 kA/mm\(^2\) the ratio \( R = V_{pr.th}/V_{exp} \) as a function of time lies close to the average value \( \bar{R} \) (see Annex 3). This demonstrates that the course of the theoretical and experimental probe voltage is the same and that the derived model is qualitative good. However, the average ratio \( \bar{R} \) does not equal one, but is less than one: the predicted probevoltage are lower than the measured ones. For the higher current densities (\( J > 2 \) kA/mm\(^2\)) \( R \) is decreasing with increasing \( t \) and so qualitatively there is less agreement between the calculated and the measured values of the probevoltages.
However, for current densities above 2 kA/mm$^2$ the effect of Joule heating is already significant in the burn-back rate as a function of time, whereas this effect was not taken into account. As an example see measurement 213 ($J = 3.17$ kA/mm$^2$). For short arcing times the burn-back velocity will be $3.17 \cdot 1.06 = 3.36$ m/s (see chapter 3). An average burn-back rate during arcing was measured of 3.96 m/s. The burn-back rate at the end of the arcing period will have reached about 4.6 m/s. This means that the burn-back rate has increased by 35% during the experiment.

Consequently $V_{\text{probe}}$ has to be calculated taking into account the effect of Joule heating. Doing this, a smaller ratio $R$ would be found for smaller values of $t$ and higher ratio $R$ would be found for high values of $t$. Therefore the ratios $R$ will lie closer to the averaged value $\bar{R}$ and for $J > 2$ kA/mm$^2$ a better agreement will be obtained between theoretical and measured values of the probe voltage.
Copper 5 x 0.2 mm²
No. of meas. 225.

<table>
<thead>
<tr>
<th>t[ms]</th>
<th>( V_{\text{calc}} ) [V]</th>
<th>((V_{\text{pr.cath}}-10 \text{V})(V_{\text{pr.an}}-10 \text{V}))</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>32</td>
<td>75</td>
<td>40</td>
</tr>
<tr>
<td>1.0</td>
<td>52</td>
<td>110</td>
<td>70</td>
</tr>
<tr>
<td>1.5</td>
<td>68</td>
<td>145</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>81</td>
<td>175</td>
<td>125</td>
</tr>
<tr>
<td>2.5</td>
<td>93</td>
<td>205</td>
<td>145</td>
</tr>
<tr>
<td>3.0</td>
<td>104</td>
<td>235</td>
<td>168</td>
</tr>
<tr>
<td>3.5</td>
<td>114</td>
<td>265</td>
<td>190</td>
</tr>
<tr>
<td>4.0</td>
<td>123</td>
<td>295</td>
<td>210</td>
</tr>
<tr>
<td>4.5</td>
<td>132</td>
<td>325</td>
<td>233</td>
</tr>
<tr>
<td>5.0</td>
<td>140</td>
<td>350</td>
<td>255</td>
</tr>
</tbody>
</table>

\( \bar{R} = 0.52 \)

\( s_R = 0.04 \)

Fig. 5.3: Method of calculation of R. No. of meas.: 225.
<table>
<thead>
<tr>
<th>No. of Meas.</th>
<th>$I$ [A]</th>
<th>$J$ [$10^9$ Am$^{-2}$]</th>
<th>$\bar{R} = \frac{V_{th, pr}}{V_{exp}}$</th>
<th>$S_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>204</td>
<td>385</td>
<td>0.77</td>
<td>0.80</td>
<td>0.03</td>
</tr>
<tr>
<td>326</td>
<td>890</td>
<td>0.89</td>
<td>0.66</td>
<td>0.02</td>
</tr>
<tr>
<td>203</td>
<td>495</td>
<td>0.99</td>
<td>0.68</td>
<td>0.02</td>
</tr>
<tr>
<td>217</td>
<td>1040</td>
<td>1.04</td>
<td>0.49</td>
<td>0.05</td>
</tr>
<tr>
<td>218</td>
<td>1240</td>
<td>1.24</td>
<td>0.55</td>
<td>0.05</td>
</tr>
<tr>
<td>201</td>
<td>660</td>
<td>1.32</td>
<td>0.64</td>
<td>0.03</td>
</tr>
<tr>
<td>220</td>
<td>1440</td>
<td>1.44</td>
<td>0.60</td>
<td>0.04</td>
</tr>
<tr>
<td>202</td>
<td>855</td>
<td>1.71</td>
<td>0.71</td>
<td>0.08</td>
</tr>
<tr>
<td>221</td>
<td>1890</td>
<td>1.89</td>
<td>0.57</td>
<td>0.03</td>
</tr>
<tr>
<td>325</td>
<td>1920</td>
<td>1.92</td>
<td>0.52</td>
<td>0.06</td>
</tr>
<tr>
<td>223</td>
<td>2250</td>
<td>2.25</td>
<td>0.53</td>
<td>0.04</td>
</tr>
<tr>
<td>206</td>
<td>1210</td>
<td>2.42</td>
<td>0.75</td>
<td>0.10</td>
</tr>
<tr>
<td>225</td>
<td>2420</td>
<td>2.42</td>
<td>0.52</td>
<td>0.04</td>
</tr>
<tr>
<td>226</td>
<td>2600</td>
<td>2.60</td>
<td>0.52</td>
<td>0.07</td>
</tr>
<tr>
<td>213</td>
<td>1585</td>
<td>3.17</td>
<td>0.63</td>
<td>0.12</td>
</tr>
<tr>
<td>212</td>
<td>1695</td>
<td>3.39</td>
<td>0.62</td>
<td>0.12</td>
</tr>
<tr>
<td>215</td>
<td>1885</td>
<td>3.77</td>
<td>0.69</td>
<td>0.12</td>
</tr>
</tbody>
</table>

$$\bar{x} = 0.62$$  
$$S_x = 0.09$$

Table 5.4: Results of the calculations of the probe voltages.

If one considers table 5.4 one can observe that the average value $\bar{R}$ for 17 experiments is $\bar{R} = 0.62$. However this value should equal one. Agreement between theory and experiment will be found if the constant $[Z \ln \Lambda]^{0.4}$ in eq. 5.8 should have a value which is a factor 1.6 higher than the value based on Chitaka's (1976) results, where $Z \ln \Lambda = 3.56$. From our results a value of $Z \ln \Lambda = 11.5$ seems more realistic, a result which is in good agreement with Wheeler's (1970/1971) finding on arcs in quartz capillaries or Maeker's (1960) results on water stabilized arcs. It seems therefore likely that for the arcs studied here both the arc temperature and the ion charge $Z$ is higher than in the experiments of Chitaka.
2.5. Conclusions

In this chapter an analytical solution of the probe voltage as a function of time is derived for constant current experiments. A good qualitative agreement exists between the theoretical and measured probe voltages. The deviations at current densities above 2 kA/mm\(^2\) are due to the assumption of \(V_f\) being constant. Taking the increase of the burn-back rate into account for current densities above 2 kA/mm\(^2\) the deviations between calculated and measured probe voltages will be minimized.

Quantitative agreement is largely dependent on the chosen values of the ion charge \(Z\) and the Coulomb cut-off. If a value of \(Z \ln \Lambda = 11.5\) is taken a good agreement is found between theory and experiment. Experimental data on high current wall stabilized arcs shows this value to be realistic. It is shown that the electrical behaviour of a fuse arc is largely dependent on a combination of the plasma parameters for a highly ionized (silicon) arc, the burn-back rate of the fuse element and the expansion of the arc channel. The expression derived for the voltage development over the fuse arc is shown to have a good predictive capability.
Chapter 6: The influence of the notch disintegration on the arc-voltage

6.1. Introduction

In the previous chapters a model has been developed, which predicts the probe voltage as a function of time. The total arc-voltage however, shows a sudden step-wise increase at the moment an arc is formed, in contrast with the probe voltage which at the onset shows a continuous voltage increase. The difference is caused by the processes which occur in the notch during arc ignition.

By several authors experimental work has been done and experimental expressions have been derived to describe the so-called arc-ignition voltage (Dolegowski (1970), (1973), (1976), Gnanalingam (1979), (1980); Hibner (1973); Onuphrienko (1977); Ossowicki (1970); Vermij (1969)). The results found are conflicting and it is not made clear to what kind of physical processes the arc-ignition voltage is related.

In this chapter some experiments on copper fuse elements with rectangular notches are described.

6.2. Experimental setup

Two types of experiments were performed:
Type a):
Fuse element with notches of a shape as shown in fig. 6.1 were investigated.

![Fig. 6.1: Shape of the notch in the fuse elements.](image)

The course of the arc-voltage at arc-ignition was measured with a high sensitivity (1V/sample unit) and a fast sampling rate (0.1 - 0.5 µsec/sample interval). About 0.1 - 0.2 msec after arc-ignition the arc was interrupted by short-circuiting and the shape of the fuse element after
notch-disintegration was studied.

Type b):
Using a double-notched fuse element as shown in fig. 6.2, two arcs in series were initiated. The voltage trace across the strip was measured.

Fig. 6.2: Double notched fuse element.

These measurements were performed because it was suggested by Gnanalingam (1979) that from these experiments the value of the anode-cathode voltage-fall could be measured from the voltage drop occurring at the moment the two arcs in series merged. The value of the electrode fall voltage is important because of its contribution to the total arc voltage at arc ignition and arc merging.

6.3. Experimental results

Type a):
In fig. 6.3a a typical example of the voltage trace during notch disintegration is shown. The current $I$ (1420 A) is constant up to the moment $t_c$ when the arc is short-circuited. Fig. 6.3b is an enlargement of fig. 6.3a at the onset of arc initiation. A sudden voltage increase $U_{in}$ in the voltage across the fuse element is observed. The voltage increases then more gradually and reaches a top value $U_{top}$. Subsequently the voltage decreases. Without firing the thyristor the arc voltage would increase again a few tenths of a millisecond after $U_{top}$ is reached (cf. fig. 3.1). Fig. 6.3c is an X-ray picture of the fuse element after arcing (the dashed lines indicate the original shape of the notch). In table 6.4 the results of our experiments are shown. (Here $I$ is the current which is constant until $t = t_c$).

The current densities in the notch varied between 3.8 and 14 kA/mm².

Type b):
In fig. 6.5 the arc voltage of a double-notched fuse element is shown.
Fig. 6.3:

a) voltage trace during notch disintegration
b) enlargement around arc-initiation
c) fuse element after the experiment

shape of notch before the experiment.
<table>
<thead>
<tr>
<th>No. of meas.</th>
<th>I [A]</th>
<th>Notch length [mm]</th>
<th>U$_{in}$ [V] ± 1V</th>
<th>U$_{top}$ [V] ± 1V</th>
</tr>
</thead>
<tbody>
<tr>
<td>364</td>
<td>730</td>
<td>0.3</td>
<td>8.6 - 12.4</td>
<td>37</td>
</tr>
<tr>
<td>357</td>
<td>780</td>
<td>0.3</td>
<td>--</td>
<td>48 ± 5</td>
</tr>
<tr>
<td>359</td>
<td>1010</td>
<td>0.3</td>
<td>--</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>351</td>
<td>1420</td>
<td>0.3</td>
<td>16.3</td>
<td>63</td>
</tr>
<tr>
<td>366</td>
<td>1690</td>
<td>0.3</td>
<td>10.5</td>
<td>61</td>
</tr>
<tr>
<td>362</td>
<td>450</td>
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<td>10.6 - 14.4</td>
<td>52</td>
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<td>358</td>
<td>750</td>
<td>1.0</td>
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<td>73 ± 5</td>
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<tr>
<td>360</td>
<td>1000</td>
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<td>22 - 28</td>
<td>78</td>
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<tr>
<td>353</td>
<td>1400</td>
<td>1.0</td>
<td>33</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 6.4: Summary of results on notch disruption.

Fig. 6.5: Voltage trace of an experiment with a double notched fuse element. 
$t_a$, $t_b$: initiation of arcs in the notches; $t'$: arcs merge; 
$t_c$: current commutation.
The initiation of the arc at the two notches occurs at \( t_a \) and \( t_b \). The arc voltage increases due to the elongation of the two arcs in series. Around \( t' \) the two arcs merge and a lower voltage increase results. No significant drop in the arc voltage can be seen during merging of the arcs (less than 3 Volt).

6.4. Discussion

If one analyses the voltage trace during notch disintegration (fig. 6.3), the following phases can be discerned:

a. initially the current is conducted by the metal and a constant voltage across the strip is measured (in our case this voltage is several volts due to the current-shunt in series with the fuse element);

b. just before disruption the voltage increases a few volts due to the increased resistance of the strip material in the notch caused by Joule heating;

c. after the melting temperature of the metal (in a part of the notch) is reached, disruption takes place and a voltage rise \( U_{\text{in}} \) occurs within 0.5 \( \mu \)sec. The value of \( U_{\text{in}} \) ranges from 9 to 33 Volts. The value of \( U_{\text{in}} \) is probably determined by a cathode voltage drop (\( \approx 10 \) Volts) and the arc voltage of the explosively generated "mini-arc" (including an anode voltage drop if present);

d. after the voltage step \( U_{\text{in}} \), there is a further increase of arc voltage due to the burn-back of the notch element. This process is very similar to the fuse element erosion as previously described. Due to the high current densities in the notch and preheating (at least a part of the notch has attained the fusion temperature) the burn-back rates are very high. From the oscillograms values of 25 msec\(^{-1} \) (single-side) were obtained for the higher currents.

If we assume that during arc elongation in the notch the variation of the cross-section is small in comparison with the high burn-back rate, one should expect that the maximum voltage \( U_{\text{top}} \) varies with \( I^{0.4} \) (cf. eq. 2.10). Fig. 6.6 shows that this is reasonably fullfilled for the limited number of experiments performed.

*Note: After arc initiation at \( t_a \) and \( t_b \) one can discern a dip in the arc voltage (\( \approx 30 \) V), in contrast with the voltage course as shown in fig. 6.3 and fig. 3.1, where no sudden drops can be seen. This effect is probably due to the fact that in the experiments of type b notches are used consisting of two parallel bridges (cf. fig. 6.2). Apparently, short-circuiting of the initiated arc takes place. This for instance may happen by a temporary resolidification of one of the bridges due to commutation of the current to the other bridge.
Fig. 6.6: The initial arc voltage in the notch related to the current.

In first approximation the notch disintegration can therefore be described by two phases. The first phase consists of arc formation and a voltage step of 10 - 20 Volts associated with the cathode (and anode) fall voltage. In the second phase the arc elongates and the voltage increases similar to the arc processes described previously. After the arc voltage has reached its maximum value it decreases again. This is most likely due to the increase in the arc channel cross-section. Once the notch has been eroded, there will be a transition to the burn-back rate of the fuse element which has a much lower value than the notch burn-back rate. This means that momentarily the increase in arc-channel cross-section is dominant and the voltage will then be decided by the variation of the lumen area. Once the arc elongates by erosion of the fuse element the voltage increases again.

In first instance one could expect that the ratio R between $U_{\text{top}} - U_{\text{in}}$ for a notch length of 1 mm and a notch length of 0.3 mm would be $1.0/0.3$ for a specific current because the voltage across the arc is related to the arc length. However, we find a value R of 1.6 - 1.9.

Probably this is due to the fact that the fast erosion process in the notch does not stop at the transition between uniform strip element and notch, but still continues in the uniform strip element due to the current concentration near the notch (fig. 6.7; cf. also fig. 6.3c).
The depth of erosion in the uniform strip element will be almost the same for elements with notches of 0.3 and 0.1 mm. This causes the value of R to be less than 1.0/0.3.

The processes during notch disintegration occur fast compared with the time scale of the uniform burn-back so that the total result is generally an almost rectangular voltage step in the arc-voltage.

6.5. **Comparison with other authors**

By several authors values of the ignition voltage are given, but little attention is paid to the processes which determine the initial arc voltage.

Hibner (1973) and Dolegowski (1970),(1973),(1976) derived expressions for the ignition voltage of notched strip elements by measuring the values of the ignition voltage. By extrapolation (e.g. the resistance gradient method) the occurrence of several processes during disintegration of the notch were established.

Hibner (1973) found that the voltage $U_p$ occurring during a sudden disintegration of (a part of) a fuse element was related to the current $I$ as:

$$U_p \propto I^{1-\gamma}$$

From the results of his experiments he found that $\gamma$ equalled 0.5. The influence of the anode-cathode fall voltage $U_b$ on the voltage $U_p$ was not taken into account. Hibner's formula lies close to the results of our description of an arc in fuses (chapter 2: $V \propto I^{0.4}$). This indicates that the processes occurring in the notch are analogous.

Dolegowski (1970),(1973),(1976) found that the ignition voltage $U_p$ could be described by an anode-cathode voltage $U_b$ and a voltage across the arc in the notch:
He concluded that $U_b$ consisted of a current independent and a current dependent part: $U_b = U_o + F(i)$. For $U_o$ and $F(i)$ Dolegowski found several values and expressions. In his most recent publication (Dolegowski (1976)) $F(i)$ is described as $F(i) \sim I^{0.39}$, which again is close to a dependency of $I^{0.4}$.

Gnanalingam (1979) proposed a method of determining the value of the anode-cathode voltage by measuring the voltage drop which should occur at the moment two arcs in series merge. However in our experiments no significant voltage drop is measured. In our opinion the method can not be used for the determination of the value of the electrode-fall voltages.
Chapter 7: Conclusions.

a) A fuse arc in sand can be described in terms of a quasi-static wall stabilized arc.

b) In case of fixed channel dimensions the arc voltage $U$ and arc current $I$ are related according to $U \sim I^{0.4}$; in agreement with theory and experiment.

c) The burn-back rate of fuse elements is governed by electrode processes. For moderate currents and arcing times the burn-back rate is proportional to the current-density of the fuse element.

d) Preheating of the fuse-element by Joule heating will increase the burn-back rate. The effect is mostly of significance, particularly for high current densities and for long arcing times.

e) The arc energy is dominantly converted into the heating and fusion of the surrounding sand. This and the flow of molten silicon result in an increase of the arc channel and a decrease of the arc voltage. For the (constant) currents investigated the arc channel expansion is around an order of magnitude lower than the burn-back rate.

f) The arc voltage of a fuse arc can be calculated on the basis of a model which incorporates the arc elongation by burn-back, the arc channel expansion by the fusion of sand and the plasma parameters of a highly ionized (silicon) arc.

g) Measurements on notch disruption indicate that the arc ignition voltage consists of an cathode-anode fall and an arc voltage build-up which is analogous to the arc voltage generation as follows from note f.
During the merging of arcs in series the arc voltage drop is negligible.
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Annex I

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Physical data of sand filler

$\rho_s$ : density of filler in solid state, used in the experiments 

$R$ : average grain size radius

$1.69 \times 10^3 \text{ kg m}^{-3}$

$1.10 \times 10^{-4} \text{ m}$

Data of quartz

$C_s$ : specific heat of solid (300 - 1996 K) 1) 

$C_l$ : specific heat of liquid (2000 K) 2) 

$T_m$ : melting point 3) 

$T_b$ : boiling point 4) 

$L$ : heat of fusion 5) 

$\rho_s$ : density in the solid state 6)

$1.18 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$

$1.25 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$

1996 K

2863 K

$1.42 \times 10^5 \text{ J kg}^{-1}$

$2.64 \times 10^3 \text{ kg m}^{-3}$

1) Landolt-Bornstein (1959).
2) Touloukian et al. (1970).
3) Campbell (1957).
4) Ražnjević (1977) and Weast (1975).
5,6) Weast (1975).
### Annex II

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* Eq. (3.6) is not valid, because $j^2 t_{cur} > \frac{\lambda \rho_S C_s}{L_{WF}} \ln \left(\frac{T_M}{T_o}\right)$.
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## Series E Copper, 5 x 0.2 mm²

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<th>No. of Meas.</th>
<th>( J ) ([10^9 \text{ A.m}^{-2}] )</th>
<th>( t_{cu} ) ([10^{-3} \text{ s}] )</th>
<th>( t_{arc} ) ([10^{-3} \text{ s}] )</th>
<th>( l_f ) ([10^{-3} \text{ m}] )</th>
<th>( \frac{1}{2} V_{arc} \cdot I \cdot dt ) ([10^7 \text{ Joule}] )</th>
<th>Weight of ( \bar{V}_f ) ([10^{-3} \text{ kg}] )</th>
<th>( \bar{V}_f ) ( \text{fulgurite m/s} )</th>
<th>( \bar{V}_f ) ( \text{th m/s} )</th>
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Annex III

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