

# ESTIMATION OF THE PLASMA'S PARTICLE DENSITIES DURING THE ARCING PERIOD OF A HIGH-VOLTAGE FUSE

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**Abstract:** We report in this paper the results of the estimated number densities for the plasma species during the arcing period in a model sand-filled high-voltage fuse. The model fuse was energized at 6 kV, using synthetic test circuit, and a prospective current of 1.25 kA, 50 Hz, was passed through it. The arcing period has been investigated using spectroscopic means. The fuse arc is supposed to be composed of O I, O II, Si I, Si II and Si III particles. Using the estimated values of electron density and temperature, and assuming the plasma to be in Local Thermodynamic Equilibrium (LTE), Saha's and Brunner equations are applied to determine the particle densities of ionized and neutral particles in the plasma. The model high-breaking capacity high-voltage fuse, under the given testing conditions, shows that its arc remains highly ionised throughout the arcing period.

**Keywords:** Fuse arc, Saha's equation, Plasma species, Particle density, Plasma Ionisation.

## 1. Introduction

A high-voltage high breaking capacity fuse is the most effective and economical device for the protection against short-circuit currents in medium-voltage systems. It is preferred over a circuit breaker for the protection against such heavy currents because of its much faster response time: it can reliably operate even within 5 ms (i.e., quarter of the time period for a 50 Hz AC system) from the onset of a short-circuit current. When it is used with a circuit breaker the system can be protected against all fault currents; the circuit breaker providing the protection against over-load currents.

A large gap exists between the theory and practice as regards manufacturing and applications of high breaking capacity fuses are concerned. To bridge this gap, extensive testing is essential during the development stage of a new fuse. In spite of tens of years of research there still is a lot of uncertainty, and the mechanisms on the operation of HBC fuses are

unclear. Though the pre-arcing time in high-voltage HBC fuses is fully understood and good models exist to simulate the behaviour of the fuses [1]-[3], this is not the case with the arcing period. The dynamic behaviour of the arcing period in current-limiting high-voltage fuses is not yet known [4]. This is primarily due to the difficulty in experimentation of the arcing period for two reasons; first the arcing period is very short i.e., of the order of a few milliseconds during short-circuit currents and second that the arcing takes place inside an opaque fuse cartridge and is surrounded by silica sand thus providing no optical window for diagnostics. To have a better understanding of the operation of the fuses research is now being conducted to determine the physical parameters such as pressure, electron density and current during the arcing phenomenon [5].

For understanding the arc dynamics we have conducted the diagnostics on the arcing period inside an experimental model HBC fuse. The constructed fuse, shown in Fig. 1, had 112 mm long cartridge and inner diameter of the cartridge being 60 mm. A uniform silver wire of diameter 0.55 mm, used as fuse element, was stretched in the middle along the axis of the cartridge. An optical fibre, supported inside a glass capillary, was made to just touch the fuse element: a hole had been drilled in the centre of the fuse cartridge for this purpose. The other end of the optical fibre was brought to a rapidly scanning spectrograph which was coupled to an optical multichannel analyser (OMA). The fuse was then filled with silica sand under vibration. The fuse was tested using a synthetic test circuit: the circuit was charged to 6 kV, and a prospective current of 1.25 kA, 50 Hz, was passed through the fuse. The temporal resolution of the arc was achieved by gating an image intensifier in front of the OMA: the gating could be delayed to record spectrum at different times during the arcing period. The shot-to-shot based spectra could be considered as were taken from one testing of the fuse at different timings during the arcing phase as these shots were conducted under identical conditions.

The arc temperature was determined by measuring the relative intensity of Si II spectral lines, and the electron density from the Stark broadening of these lines. These investigations have been reported in references [6]-[8]. In fact we have used the results from these experimental studies to calculate the number densities of the arc species. Preliminary results of the number densities for arc species had also been reported earlier [9] using a number of simplifying assumptions.

## 2. The Use of Saha's and Brunner Equations

If electron density and temperature are known and the plasma can be assumed to be in Local Thermodynamic Equilibrium (LTE), Saha's equation [10] can be used to determine number densities of the ionised and neutral species in the plasma. The collision rates between the various species present in the fuse plasma are sufficiently high (particularly compared with the timescale of the discharge and diffusion times), that thermodynamic equilibrium is a good approximation for our discharge conditions. Saha's equation is:

$$\frac{n_{r+1}n_e}{n_r} = 2 \frac{u_{r+1}(T)}{u_r(T)} \times \frac{(6.28m_0kT)^{1.5}}{h^3} e^{-\frac{E_r - \Delta E_r}{kT}} \quad (1)$$

where

$n_r$  = number density of all r-fold ionised atoms (e.g.,  $r = 0$  for neutral particles);

$n_{r+1}$  = number density of all (r+1)-fold ionised atoms;

$n_e$  = number density of electrons;

$u_r$  = partition function of r-fold ionised atom;

$u_{r+1}$  = partition function of (r+1)-fold ionised atom;

$m_0$  = electron rest mass,  $0.9107 \times 10^{-30}$  kg;

$h$  = Planck's constant,  $6.626 \times 10^{-34}$  J sec;

$k$  = Boltzmann's constant,  $1.38 \times 10^{-23}$  J/K;

$E_r$  = ionisation energy for ionisation process  $r \rightarrow (r+1)$ ;

$T$  = absolute temperature [K];

$\Delta E_r$  = lowering of ionisation energy.

The fuse arc is assumed to be composed of only Si I, Si II, Si III, O I and O II. These species were detected as reported in reference [11]. The mass of the SiO<sub>2</sub> evaporated by the arc discharge, as estimated in reference [8] was 2.8 g. The mass of the silver fuse wire (0.28 g) is 9% compared with the mass of the SiO<sub>2</sub> in the plasma and thus negligible. Furthermore, demixing processes [12] rapidly transfer the metal of the fusible fuse wire away from the hot plasma, so that the conducting medium in the arc is in effect a plasma in evaporated and dissociated SiO<sub>2</sub> filler material and any silver present in the arc was negligible as compared to that of Si and O and can be ignored.

The Saha's equation, for silicon and oxygen, can be written as:

$$(n_e n_{\text{Si II}})/n_{\text{Si I}} = f_1(T) \quad (2)$$

$$(n_e n_{\text{Si III}})/n_{\text{Si II}} = f_2(T) \quad (3)$$

$$(n_e n_{\text{O II}})/n_{\text{O I}} = f_3(T) \quad (4)$$

Since charge is conserved,

$$n_e = n_{\text{O II}} + n_{\text{Si II}} + 2 n_{\text{Si III}} \quad (5)$$

and assuming all O and Si atoms and ions are the result of decomposition of SiO<sub>2</sub>,

$$(n_{\text{O I}} + n_{\text{O II}}) = 2 (n_{\text{Si I}} + n_{\text{Si II}} + n_{\text{Si III}}) \quad (6)$$

Equations (2)-(6) can be solved to obtain the number densities of the plasma species present for a known temperature and electron density. The term  $\Delta E_r$  in Equation (1) can be calculated using the Brunner formula [10], which is:

$$\Delta E_r = 1.21 \times 10^{-6} \sqrt[3]{n_e [\text{cm}^{-3}]} + 2.5 \times 10^{-8} \sqrt{\frac{n_e [\text{cm}^{-3}]}{T [\text{K}]}} [\text{eV}] \quad (7)$$

## 3. Calculation of the Number Densities for the Arc Species

A computer program has been written in MATLAB which solves equations (2)-(7) and calculates the number densities of the fuse-arc species. It asks the user initially to provide the arc temperature [in K] and the electron density [in cm<sup>-3</sup>], and calculates  $\Delta E_r$  – the lowering of ionisation energy – from equation (7). The program then asks the user to provide the partition functions of Si I, Si II, Si III, O I and O II corresponding to the initially given temperature and the calculated value of  $\Delta E_r$ . These partition functions are given in reference [10]. The program then requires the values of ionisation energies for Si I (for transition from Si I to Si II), Si II (for Si II to Si III transition) and O I (for O I to O II transition): these values are also given in reference [10]. The program then prints the number densities of Si I, Si II, Si III, O I and O II.

The pressure in the arc could be calculated using the ideal gas law:

$$P = \Sigma n k T \quad (8)$$

Equation (8) was summed over all species including electrons and the temperature of all species could be approximated by the electron temperature.

Using these number densities, the percentage ionization of the arc is now calculated by:

$$\% \text{age ionisation} = 100 \times (n_{\text{O II}} + n_{\text{Si II}} + n_{\text{Si III}}) / (n_{\text{O II}} + n_{\text{Si II}} + n_{\text{Si III}} + n_{\text{O I}} + n_{\text{Si I}}) \quad (9)$$

The results are shown in Table 1 for the test fuse at 1.25 kA prospective current. The estimated values of electron density, given in reference [8], are reproduced in Table 1. The estimated temperatures as reported in references [6] and [8] were extrapolated to get the temperature values shown in Table 1 (the spectra were recorded at different timings for the temperature and electron density estimates e.g., the spectra for the temperature measurements were recorded at 0.368, 0.398, 1.203, 1.812, 2.148, 2.694, 4.138, 4.166 and 5.172 ms after the arc initiation).

#### 4. Discussion

The number densities of Si I, Si II, Si III, O I and O II as a function of time in the arcing period of the fuse are shown in Figs. 2-6. The number density of Si I in the fuse arc is typically quite low – of the order of  $10^{14} \text{ cm}^{-3}$  – and thus these particles were not detected in the fuse arc as had been reported in reference [11]. We had studied the fuse-arc spectrum using photographic films there and had established that Si II lines were best suited for further investigation of the arc as they had been detected throughout the duration of the arc. This was also verified in our study of the fuse arc using a sensitive equipment - Jarrell-Ash monochromator and optical multichannel analyser - the response of the system being highly sensitive to radiation between 520 and 650 nm.

It is evident from Table 1 that the concentrations of Si II particles is of the order of  $10^{17} \text{ cm}^{-3}$  and as majority of the spectral lines of these particles fall under the sensitive region (520-650 nm) of the equipment the fuse spectra were dominated by Si II lines which were used for the investigation in references [4], [6]-[7]. The concentrations of the oxygen lines, particularly O II, is very high in the arc, and these lines – between 415 and 500 nm – were detected in the arc as reported in reference [11]. As the spectrum recording equipment is not very sensitive in this range (415-500 nm), it was difficult to identify these lines in the studies reported in references [4], [6]-[7].

The results reported in reference [9] were approximate as  $\Delta E_r$  was ignored and average values of the partition functions at a temperature of 15000 K were used. The results of both these studies are slightly different; nevertheless they show similar trends.

The arc is highly ionised initially and for up to about 1 ms after the arc initiation: all the stored electrical energy of the circuit is suddenly dumped into the molten layer of silica sand (which results from this energy) and thus greatly ionises the arc. The ionisation of the arc then decreases as a function of time but still remains more than 50% toward the end when the last spectrum was recorded. The pre-arcing time of the fuse under these test conditions was 5.3 ms. Thus 4.1 ms time after the arc initiation - at which the last spectrum was recorded - refers to the point which is just 0.6 ms before the natural current zero (corresponding to 50 Hz). Toward natural current zero, the fuse arc is still highly ionised and this explains why the arc interruption did not take place under the given test conditions for the test fuse. The model fuse, unlike the commercial sand-filled current limiting fuses which are designed for automatic current interruption, was not intended for this purpose: it has been used to study the arcing dynamics in silica sand. To avoid a continuous flow of current through the arcing fuse, a crowbar – a pneumatically-operated switch which provided a parallel path for the current - was used. It started conducting between fifteen to twenty milliseconds after the fuse was provided electrical energy from the synthetic test circuit and the current had started flowing through it (i.e., at the beginning of the pre-arcing phase). This ensured that the test fuse remained in the arcing phase for a time between 10-15 ms (though we were only interested in the diagnostics of the arc before the first natural current zero).

The evolution of temperature and electron density (and hence the particle densities of the arc species) give useful information about the arc dynamics in high voltage sand-filled fuses. The plasma is highly ionised at the start of the arcing and should rapidly decrease its ionisation if the current interruption has to take place.

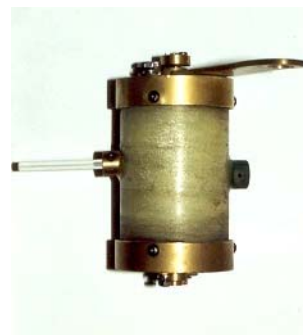


Fig. 1: Photograph of the model test fuse.

Table 1: The calculated plasma composition, corresponding to the estimated values of temperature and electron density, for the test fuse at 1.25 kA.

Time after arc initiation (ms)	0.157	1.121	2.105	2.470	2.673	3.360	4.100
Temperature (K)	21000	21000	18000	18000	18000	18000	15000
Electron density ( $10^{17} \times \text{cm}^{-3}$ )	3.5	2.1	3.0	2.5	2.0	2.7	1.2
$n_{\text{SiI}} (10^{17} \times \text{cm}^{-3})$	0.0068	0.0016	0.0250	0.0160	0.0092	0.0190	0.0180
$n_{\text{SiII}} (10^{17} \times \text{cm}^{-3})$	0.7300	0.3200	1.1400	0.8900	0.6500	0.9900	0.6500
$n_{\text{SiIII}} (10^{17} \times \text{cm}^{-3})$	0.3900	0.3100	0.1200	0.1100	0.1100	0.1100	0.0160
$n_{\text{OI}} (10^{17} \times \text{cm}^{-3})$	0.2700	0.0890	0.9300	0.6400	0.4000	0.7500	0.8400
$n_{\text{OII}} (10^{17} \times \text{cm}^{-3})$	2.0000	1.1700	1.6300	1.3900	1.1300	1.4900	0.5200
Pressure (bar)	2.0	1.2	1.7	1.4	1.1	1.5	0.7
%age ionisation	92	95	75	78	82	77	58

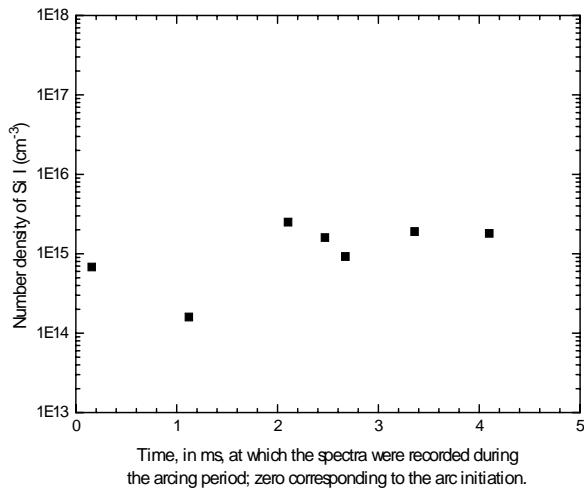


Fig. 2: Number density of Si I in the fuse arc as a function of time.

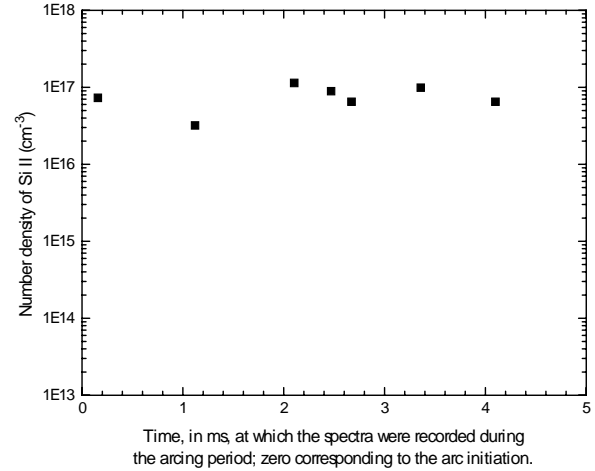


Fig. 3: Number density of Si II in the fuse arc as a function of time.

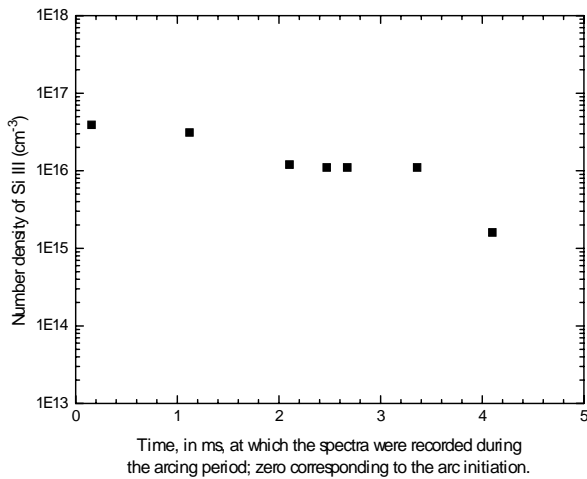


Fig. 4: Number density of Si III in the fuse arc as a function of time.

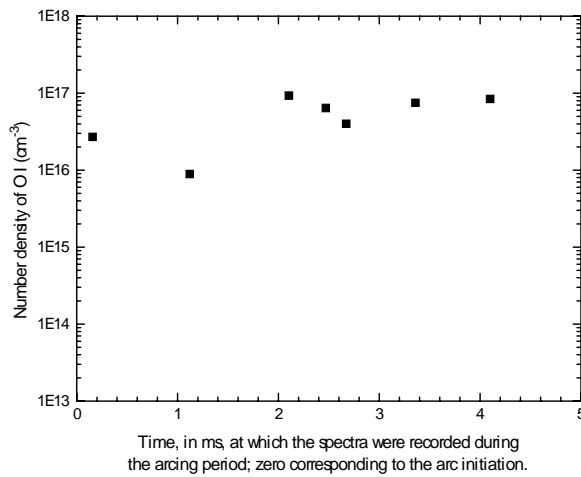


Fig. 5: Number density of O I in the fuse arc as a function of time.

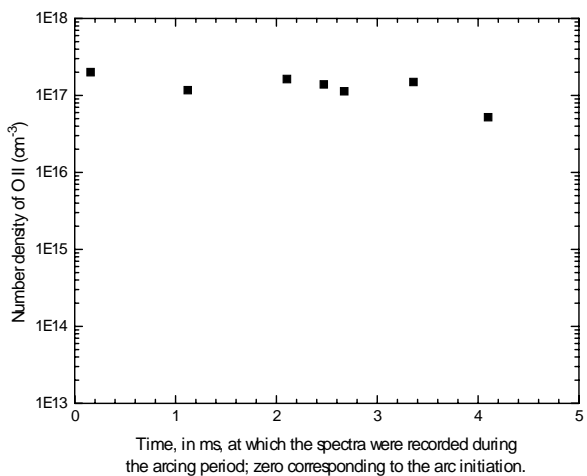


Fig. 6: Number density of O II in the fuse arc as a function of time.

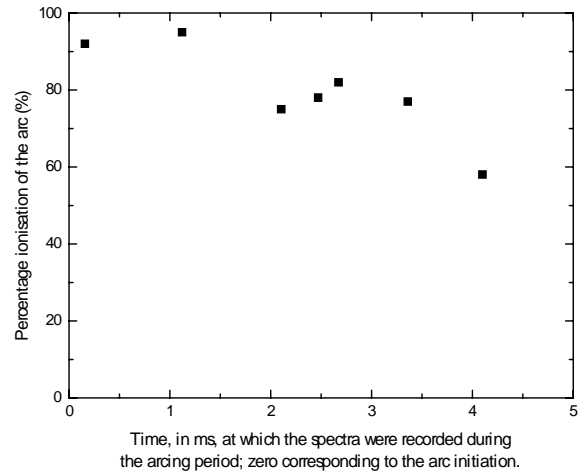


Fig. 7: Percentage ionisation of the fuse arc as a function of time.

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