SPECTROSCOPIC MEASUREMENT OF FUSE ARC TEMPERATURE

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Abstract: This paper describes an experimental spectroscopic technique to continuously investigate arc parameters, such as temperature, in high breaking capacity fuses. Difficulties concerning access to the fuse arc were overcome by the use of an optical fibre inserted into the fuse body, providing an ***optical window*** to the fuse arc. The spectroscopic technique consisted of the continuous acquisition of plasma emissions of radiation by an opto-electronic system. Using well stablished quantum-mechanics expressions for the computation of the results, the arc temperature was estimated to be about 20000K, which agrees with previous research. There was no signifcant variation of arc temperature with time. This piece of information is believed to be of great value for those developing dynamic representations of fuse arcs.

1 Introduction

The concealment of the hbc fuse arc within a solid dielectric [1] imposes important restraints to experimental diagnostic techniques such as the determination of the level of absorption of plasma radiation. This is an essential factor in the determination of the optical depth (or optical thickness) of the plasma. The formation of the fulgurite is so unique to this kind of device that it is almost impossible to directly compare the fuse arc to any other well-known industrial or laboratory plasma. To identify major particles present in the arc plasma Chikata et al. [2] used a specially built transparent fuse associated with a spectrometer. Based on a few pictures of the arc, they used time integration for the spectrum of radiation emissions to predict the plasma temperature. Barrow [3], for the first time, inserted optical fibres into fuse bodies with an end sited close to the element and was also able to record major arc radiation by the use of a rapid scanning spectrometer, linked to a photomultiplier. His temperature measurements, however, were inconsistent and disagreed with those found by Chikata. Both techniques were based on the recording of pictures or snap shots of the arc spectrum. The basic structure and main component parts of the high breaking capacity (hbc) fuse used as arc generating source for this study is shown in **Fig. 1**. For simplicity, the metallic element contained only one notched region and pure silica (SiO_2) was used as filler.

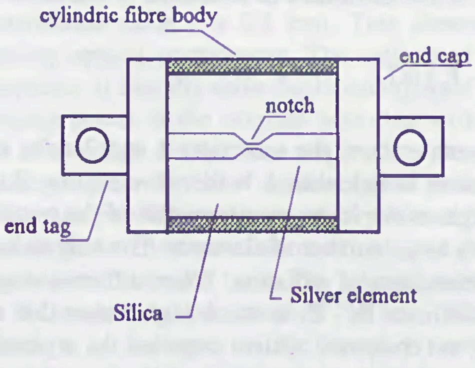

Figure 1 - Industrial fuse used as "arc source"

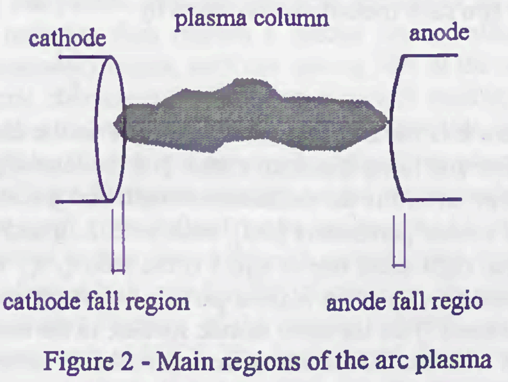

Figure 2 - Main regions of the arc plasma

2 The fuse arc

2.1 General

The arc [4] is characterised as a self-sustained electric discharge in which the plasma occurs at high temperature, high pressure and the medium is said to be in local thermodynamic equilibrium (LTE) implying, among other things, that the electron temperature is the temperature of the plasma. To sustain a high electron density a small electric field strength is needed and there is a small electrode fall of the order of 10 V, as illustrated in **Fig. 2**. The most important feature of the arc is thought to be its temperature field. The main plasma column is known as the thermal plasma or thermal layer in which most of the energy transfer takes place due to collisional processes involving free electrons and heavy ionised particles. The collisions are said to be elastic and most energy is used to heat the colliding ions. A hbc fuse arc is classified, to a first approxirnation, as a wall-stabilised by ablation, axisymmetric arc. The wall-stabilised definition is reasonable to indicate the presence of a barrier surrounding the arc at a different temperature from the plasma. The major diflference in the case of a hbc fuse arc, which greatly distinguishes it from all other types of ablation arcs, is the formation of a liquid barrier, which is entrained in the granules of silicon dioxide and held in position by surface tension. The chemical composition of such a structure has been discussed [1, 3] and it is basically formed of Si and Ag particles. The inner layers are very poor in Ag while its concentration tends to increase towards the outer layers. One of the reasons for this is thought to be a phenomenon known as ionic migration. Take a plasma rich in two vaporised particles, say neutral silver (Ag I) and neutral silicon (Si I). For a given axial temperature of the arc, T_a, only the particle with the lower ionisation potential is significantly ionised (in this case, Ag I). The ions and the atoms of this gas will then have the largest concentration gradients in the plasma. This will impose a flow of particles, as shown in **Fig. 3**, which implies an inward flow of atoms (neutral particles of Ag) and an outward flow of the recently ionised particles (Ag II, etc.) and electrons. Put differently, ionised particles of silver, if at all present near the axis of the arc, are likely to migrate to the outer boundaries of the plasma, being forced out by ionic migration.

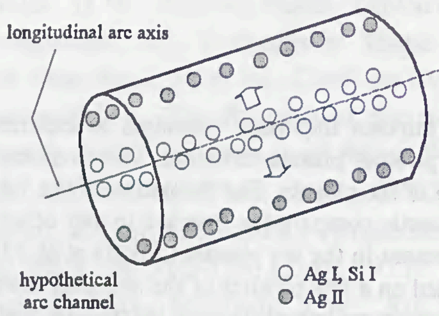

Figure 3 - Plasma particles migration

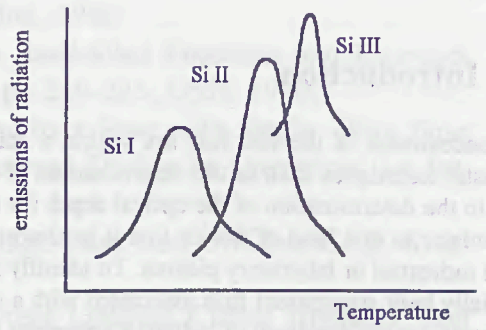

Figure 4 - Radiation from different stages of ionisation as a function of temperature

2.2 Atomic Emissions of Radiation from the Arc Plasma

Griem [5] derived an equation to calculate the thermal energy of the electron, on transition between specific quantum states, at atomic level. He went on to show that the ratio of the intensities of emissions of radiation from any two such transitions was given by

$$\frac{\xi_1}{\xi_2} = \frac{\lambda_2^3 g_1 f_1}{\lambda_1^3 g_2 f_2} e^{(E_2 - E_1)/kT} \tag{1}$$

where k is the Boltzmann's constant, T is the electron absolute temperature, the subscripts 1 and 2 refer to the higher and lower quantum states, ξ is the intensity of atomic emission of radiation, λ is the wavelengthg, E is the energy level, f is the oscillator strength and g is the statistical weight of the lower quantum state of the transition. The atomic parameters [6-8], such as E, λ, g and f are known for a large number of elements. The only unknown in the right-hand side of eqn.1 is the ratio ξ_1/ξ_2 of intensities of emissions of radiation. When different stages of ionisation of a given plasma particle are compared, the energy diflference $E_2 - E_1$ is much higher than that when radiations from the same atomic species, in the same ionised stage, are compared. Griem extended the argument to deal with atomic radiations from particles in subsequent stages of ionisation and derived the following expression, for a given atomic species :

$$\frac{\xi_2}{\xi_1} = \frac{\lambda_1^3 g_2 f_2 (kT)^{3/2}}{\lambda_2^3 g_1 f_1 \left[4\pi^{3/2} a_0^3 N_e E_H^{3/2}\right]} e^{\left[-\frac{E_2 + E_\infty - E_1 - \Delta E_\infty}{kT}\right]} \tag{2}$$

where the subscripts 1 and 2 refer to the lower and higher stages of ionisation respectively, a_0 is the Debye radius, E_H is the ionisation energy of the Hydrogen, E_∞ is the ionisation energy of the less ionised particle, ΔE_∞ is the reduction of the iozization energy of less ionised particle and all remaining parameters have the same meaning as in eqn. 1. Once the particles in subsequent stages of ionisation are selected, for a given plasma, all parameters, but the intensities ξ, can be found in tables of atomic quantum transitions. For both equations 1 and 2 the ratio between intensities of emissions of radiation can be found experimentally. Regarding subsequent stages of ionisation it is important to notice that at a given electron temperature, T, for a particular atomic species, one stage of ionisation will dominate all others. Cheim [9] also developed similar expressions and explained how eqns.1 and 2 can be used to assess plasma temperature based on a consideration of the local thermodynamic equilibrium and the optical thickness of the plasma. **Fig.** 4 gives an indication of the differences in the levels of emissions of radiation as a function of the temperature. In a silicon plasma, at low temperatures, one is supposed to find higher concentrations of neutral silicon (Si I) than two-fold Si II and so forth. There is a minimum temperature level to find a specific ionised particle, as there is a certain temperature above which only particles in an even higher ionised stage will be found. Away from these two extreme cases of temperature, one is likely to find two or more ionised stages, at the same time, but in diflferent concentrations and emitting radiation at various levels of intensity. A better estimate [5] of plasma temperature is achieved by using eqn. 2 than by using eqn. 1 because of the larger difference in the upper energy levels, making the spectroscopic technique more sensitive changes in plasma temperature. The experimental technique described in the next section allows for a continuous monitoring of the ratio of atomic radiations (ξ_1 / ξ_2) from the plasma, throughout the arcing period. The arc temperature can be calculated using eqn. 1 for the same stage of ionisation or eqn. 2 for subsequent stages.

3 Fibre Optic Continuous Spectroscopy (FOCS)

3.1 Fundamentals of FOCS

The FOCS experimental technique was developed from the ideas and previous experience discussed earlier in this paper. The novelty introduced here is the use of fast photodiodes associated with an optical fibre for the continuous recording of plasma radiations. FOCS combines the use of an optical fibre with an optoelectronic system which is able to choose and continuously monitor, from the main radiation beam, two and only two preselected frequencies of arc radiation (λ). This can be done without interruption, as long as plasma radiation exists or as long as it is observable. The optical probing takes place in the thermal plasma (plasma column) and it is supposed that the region under observation develops the highest temperatures.

3.2 Experimental Implementation of FOCS

The experimental implemtation of FOCS was achieved by the set-up of an optical system as shown in **Fig. 5**. Polychromatic plasma radiation exits the optical fibre through a special connector which yields a divergent beam with a clear image of the arc. The divergent beam is then collimated by a high quality camera lens. The distance between the fibre exit and the lens is carefully chosen so that the optical aperture of the collimated beam is set to a predetermined value ($\cong$ 0.5 cm). This dimension has to be compatible with the physical dimension of the remaining optical components. The collimated polychromatic radiation then reaches a special device called a beamsplitter. It literally splits the incoming light beam into two secondary beams, each one having 50% of the total impinging power of the original beam but with the same spectral characteristic. Using an electrical analogy, it works as a voltage divider. The amplitude of the signal is reduced but the waveshape is kept intact. After that, each secondary beam will follow similar optical paths. First, each will be filtered to a previously defined wavelength. This is made possible by the use of very narrow band interference filters. These are specially coated optical surfaces which allow for the transmission of only one frequency, with a small error defined by its bandwidth. All other frequencies are reflected back. The selected monochromatic radiation is then passed through a condensing lens to focus the monochromatic image of the arc. This image is then collected by a very fast PIN photodiode, the output of which is an analogue voltage signal, proportional to the impinging intensity of the plasrna radiation, at the selected frequency. An identical procedure is adopted for the other branch of FOCS. The fundamental difference is in the selected frequency of radiation (central line of the interference filter). It is now clear that the connection between FOCS and atomic radiations, in the plasma, is made possible by a proper selection of interference filters, corresponding to expected frequencies to be radiated by plasma particles. The next stage, as shown in **Fig. 6**, is the electronic amplification of the output of the photodiodes and posterior storage by a LeCroy 9400, 125 MHz digitial oscilloscope. From the scope data is transferred via a GPIB/IEEE-488 interface to a personal computer where the signals are stored and treated mathematically. The mathematical treatment comprises a simple division of the two signals on a byte-to-byte basis, using digital averaging. The result is a continuous curve of the ratio ξ_1 / ξ_2 of radiation emissions for the duration of the arc. Substituting this ratio in eqn. 1 or 2 (whichever is appropriate) the continuous temperature variation is calculated. To relate the waveforms captured by FOCS, as voltage signals, to fuse arcing, and to provide a time reference for these signals, one of the outputs from the photodiodes was recorded on another digital oscilloscope, simultaneousiy with the fuse test current.

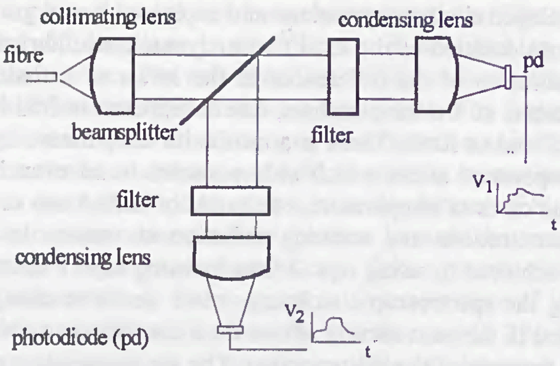

Figure 5 - FOCS experimental setup

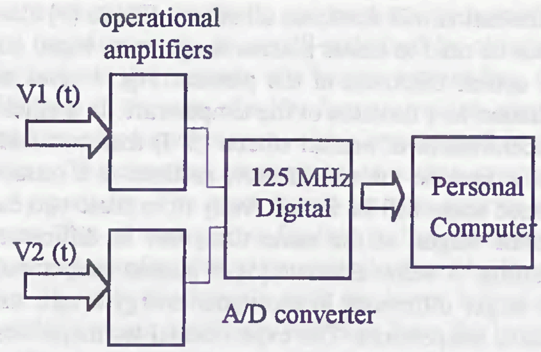

Figure 6 - Data transfer to a personal computer

3.3 Sample Fuses as Arc Sources for FOCS

A special effort was made to ensure that identical sample fuses were produced. A high level of quality control was adopted from the manufacturing stage of the main component parts, through the basic assembly line and to the final preparations in the laboratory. The sample fuses were manufactured without being filled with granular silica and without the two sealing pins shown in **Fig. 7**. All fuses were x-rayed to determine the precise location of the notches. A small hole was then drilled in the fuse body, immediately above the notch. A pure silica glass tube (diameter ϕ =1.0 mm) was pushed through the hole until its bottom end was approximately 3 mm from the pure silver metallic element. It was then glued to the walls of the hole. The cleaved tip of the pure silica optical fibre was inserted into the glass tube and allowed to rest on or very near the notch. This process was monitored by observation through a magnifying lens positioned near the pin hole. The fibre was then glued to the glass tube and the fuse filled with granular silica (mesh size 100/140, BS 410, 1976), having an average grain size of 100 μm. To minimise interference with the arc, the granular silica (SiO_2) was chosen to be approximately the average silica grain size. A good compaction was achieved by vibrating each fuse for 10min. To ensure consistent compaction, a metallic rod was pushed through the pin hole and pressed against the silica granules. When no more silica could be inserted the fuses were sealed and ready for testing. All fuses were tested in a one-phase, 250 V AC circuit, as shown in **Fig. 8**, with a prospective symmetrical current of 600 A RMS, at a power factor of 0.18 lagging.

4 Experimental Results

The results obtained by FOCS, from the power tests carried out on a number of sample fuses, are presented in two groups. The first group shows the patterns of radiation emissions from Si II (505 and 634 nm) while the second group shows different patterns from simultaneous emissions of Si II (413 nm) and Si III (457 nm).

4.1 Emissions of Atomic Radiation from Si II

Fig. 9 shows atomic radiations from Si II 505 nm (transition $3s^24p \Rightarrow 3s^24d$) and Si II 634 nm (transition $3s^24s \Rightarrow 3s^2 4p$). The time reference into the arc is shown in **Fig. 10**. An important effect visible in this example is the residual atomic radiation at 634 nm, after arc extinction. This effect was always present for this frequency and will be discussed in Section 6. The ratio of radiation intensities is given in **Fig. 11** and substituting this continuous ratio in eqn. 1, the variation of plasma temperature with time was calculated, as shown in **Fig.12**.

4.2 Emissions of Atomic Radiation from Si II and Si III

Atomic radiations from Si II 413 nm (transition $3s^2 3d \Rightarrow 3s^24f$) and Si III 457 nm (transition $3s4s \Rightarrow 3s4p$) are shown in **Fig. 13**. The respective arcing time references are given in **Fig. 14** and the correspondent ratio of radiation emissions are given in **Fig. 15**. Replacing the ratio of radiation intensities in eqn. 2, the plasma temperature was calculated continuously and the results are given in **Fig.16**.

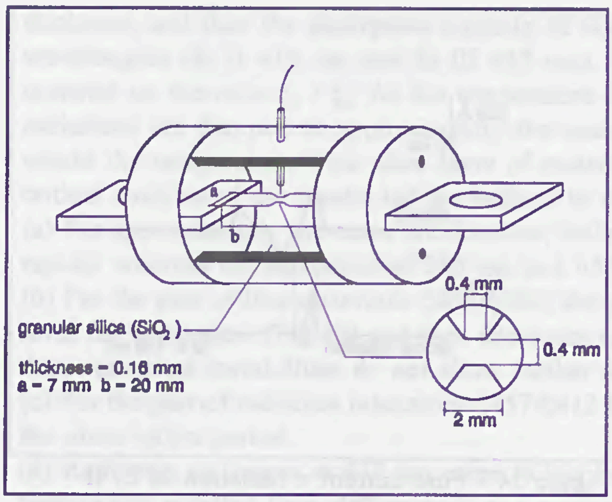

Figure 7 - Inserting optical fibre into fuse body

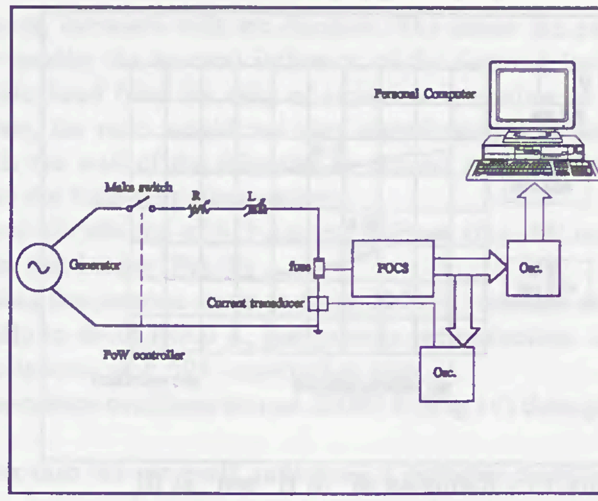

Figure 8 - Test circuit and optical-electronic set-up

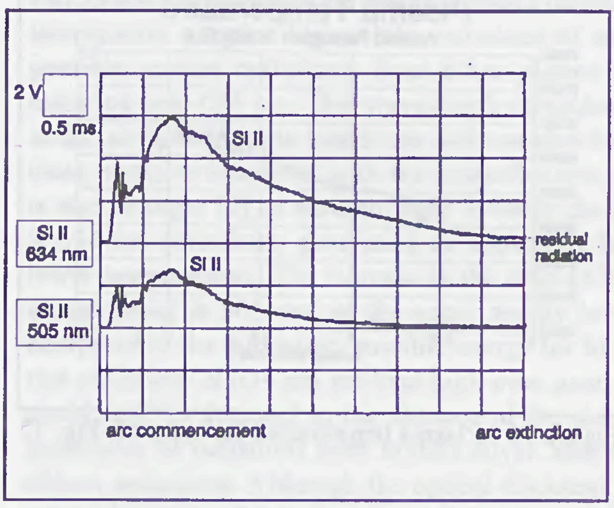

Figure 9 - Radiation of Si II 505 nm and 634 nm

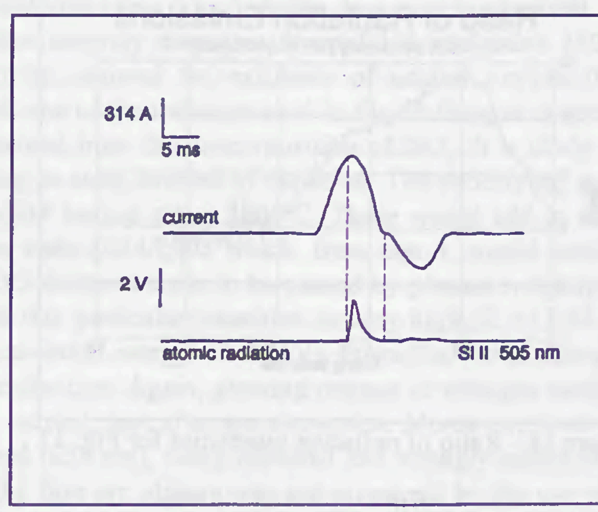

Figure 10 - Fuse current x radiation of Si II 505

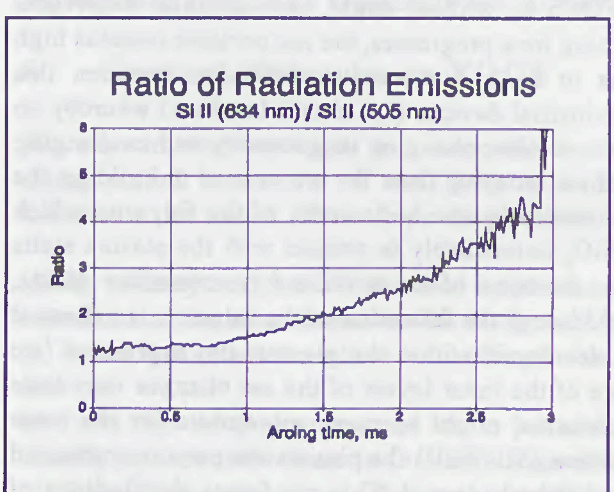

Figure 11 - Ratio of radiation intensities for Fig. 9

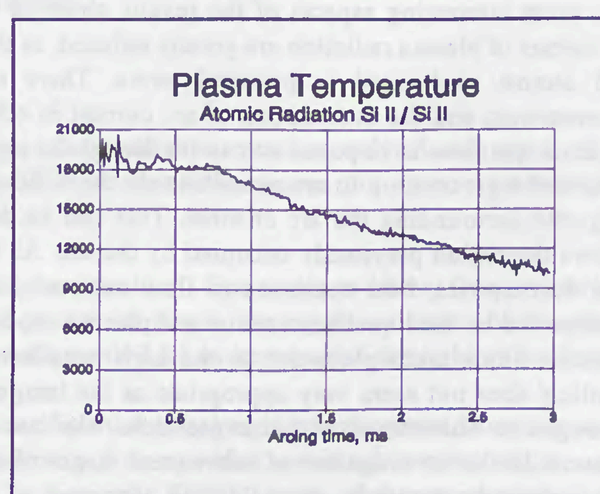

Figure 12 - Plasma temperature for ratio of Fig. 11

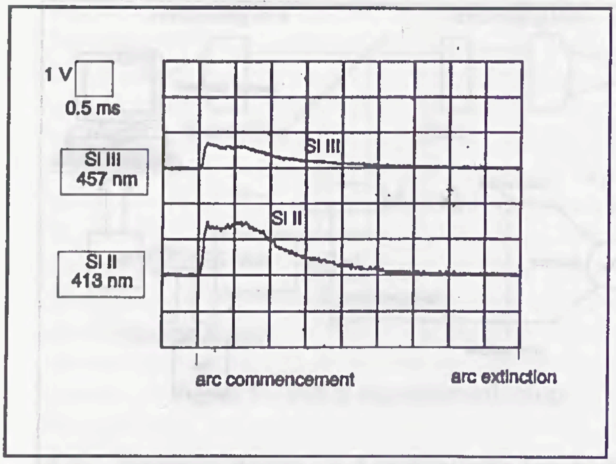

Figure 13 - Radiation of Si II and Si III

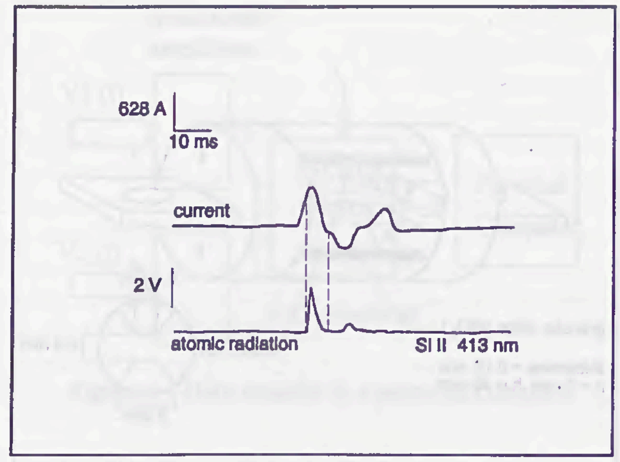

Figure 14 - Fuse current x radiation of Si II

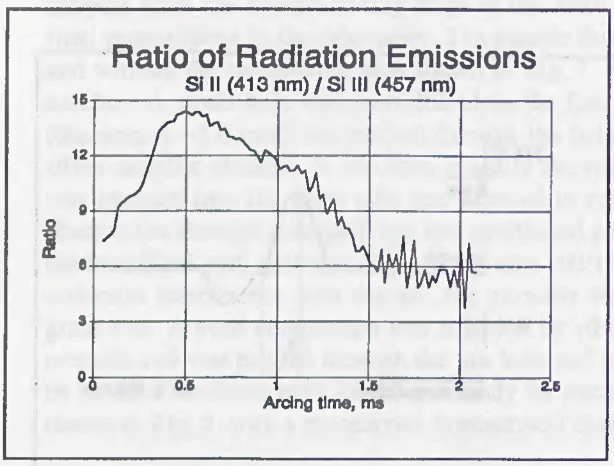

Figure 15 - Ratio of radiation intensities for Fig. 13

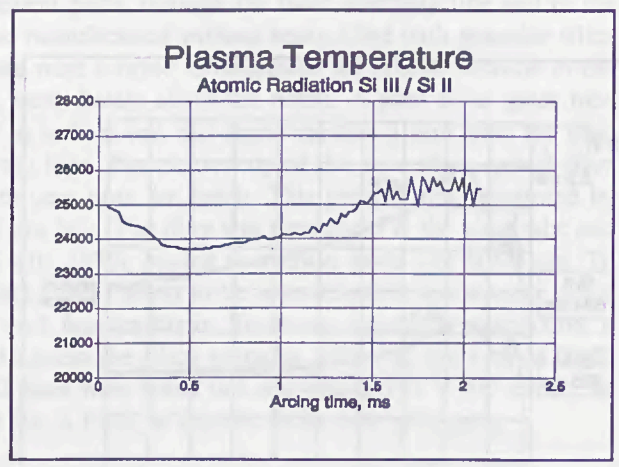

Figure 16 - Plasma temperature for ratio of Fig. 15

5 Discussion of Results

The most interesting aspects of the results obtained by FOCS is, without doubt, that although observable emissions of plasma radiation are greatly reduced, as the arcing time progresses, the temperature remains high and almost unchanged in practical terms. There seems to be a fundamental difference between this phenomenon and the interruption of arc current in other industrial devices (i.e. circuit breakers) whereby an external gas flow is imposed across (or along) the arc cross-section, changing its geometry and exchanging heat in the process, up to arc extinction. In the HBC fuse heat escaping from the arc is used to build up the fulgurite surrounding the arc channel. This can be demonstrated by the hollowness of the fulgurite which shows the region previously occupied by the arc. As the SiO_2 immediately in contact with the plasma melts and decomposes, heat continues to flow outwards, in the direction of the solid and remote silica quartz, transported by the liquefied material and plasma vapours. Although the formation of the fulgurite is a thermal process which takes place due to the high temperatures developed within the plasma, the expression 'arc cooling' does not seem very appropriate as the temperature of the inner layers of the arc changes very little throughout. This suggests that expressions like 'arc constriction' might be more appropriate for the inner plasma. In the investigation of subsequent stages of ionisation (SiII/SiIII) the plasma temperature remained approximately constant, about 25000K, for most of the observed interval. This reinforces the findings of Chikata [2] although he used a completely different spectroscopic technique and a time resolved approximation. Regarding the accentuated reduction in the intensities of emission of radiation, observed in both cases given in the Section 4, the present authors believe that radiations are damped by an absorbing layer of material, which progressively interposes itself between the plasma and the optical fibre. The thickness, and thus the absorption capacity of this layer, increases with arc duration. The closer the pair of wavelengths (Si II 413 nm and Si III 457 nm), the smaller the spectral influence of the forming layer of material on the ratio ξ_1 / ξ_2. As the temperature is calculated from the ratio of emission intensities, if both radiations are damped at approximately the same rate, the ratio would not vary significantly and neither would the temperature. This alien layer of material is the wall of the fulgurite, in process of formation. A critical analysis of the results led the authors to make the following observations :

(a) For approximately the same arc duration, emissions of radiation of 413 nm and 457 nm (Fig. 13) reduce rapidly whereas the emissions of 505 nm and 634 nm last longer (Fig. 9).

(b) For the pair of line emissions $\xi 634/\xi 505$, the plasma temperature starts at about 20000K, remains at that level for some time (Fig.12) and then decreases rapidly to about 10000 K, just prior to arc extinction. After this, numerical instabilities do not allow further calculations, as ξ 505 approaches zero.

(c) For the pair of radiation intensities $\xi 457/\xi 413$ temperature oscillates around 25000 K (Fig.16) throughout the observation period.

(d) Radiation emissions at 634 nm seem to last longer than the arc itself, indicating a probable coupling of frequencies radiated from different plasma particles.

There should be an explanation for the drastic reduction in the intensities of plasma radiation, observed in the rapid decline of the lines Si II and Si III, after 0.5 ms to 1 ms of arc commencement. High levels of temperature should indicate intense plasma radiation and vice versa. The opposite, however, is observed. The temperature remains high while emissions of radiation severely decrease. A careful investigation [10] of possible atomic radiations, from other plasma particles, showed the existence of neutral oxygen (O I) radiating near 634 nm. This wavelength coincides with one of the radiators used in Fig. 9. Oxygen is present in the air in the quartz interstices and can also be obtained from the decomposition of SiO_2. It is likely that these particles interfered with the measurements, acting as stray sources of radiation. The solidifying quartz is also thought [9] to emit strongly towards the red (634 nm) at about 2000°C. These would add to the Si II 634 nm emissions, generating an apparently higher ratio $\xi 634/\xi 505$ which, from eqn. 1, would result in lower temperatures. The increase in the ratio $\xi 634/\xi 505$ does not seem to be caused by plasma reabsorption of radiations at 505 nm, as the upper energy level of this particular transition is very high (E =12.53 eV) compared to the maximum possible energy for Si II (ionisation energy=16.35 eV). From Fig. 9 it is also clear that radiations at 634 nm are kept high even near arc extinction. Again, glowing oxygen or nitrogen particles could well be detected in the absence of the electric current, just after arc extinction. Moreover, there is a possibility of radiations from molten silver, near the red (634 nm), being captured and wrongly added to the silicon emissions. Although the optical thickness of the fuse arc plasma was not measured by the use of an external source of radiation, it can be estimated by the levels of energy involved in the atomic transitions. As stated earlier, radiations arising from higher quantum states are not expected to be reabsorbed and, as a consequence, the plasma is optically thin to those radiations.

6 General Remarks on FOCS

The experimental technique was successful in tracing plasma radiations continuously, during most of the arcing period. A number of steps have to be followed to successfully choose the atomic emissions of radiation to be traced. These steps are described below.

(a)The primary constraint is imposed by plasma particle composition. One needs to know, from a previous examination, the atomic species that are present and their ionised stages, during the existence of the plasma

(b) Select those particles whose levels of radiation are sufficiently high to be recorded throughout the desired interval.

(c) From this selected group, one has to put aside pairs of particles, belonging to the same atomic species, identifying those which are in the same stage of ionisation and those which are in subsequent stages.

(d) From these pairs, choose those whose differences in the upper energy levels, of the atomic transitions, are large enough [5, 11] (~ 2 eV) to yield accurate measurements of temperature from emitted radiation.

(e) Additionally, check whether or not the chosen wavelengths, for the particular pair of radiations, are present in radiations from other plasma particles, which would create the inconvenience of parasitic radiators, altering the results and possibly yielding incorrect conclusions.

(f) Finally, after a careful selection of wavelengths, one needs to specify the adequate interference filters, with good peak transmittance and narrow bandwidth, which are not always commercially available. The choice of wavelengths is extremely critical as it can be very difficult to meet conditions (a)-(e) simultaneously.
The error in the method can be discussed according to its classification as systematic or random error. Systematic errors are very difficult to detect as they are inherent in the measuring device itself or in the specific technique of measurement. The safest way to check [7] for the presence and scale of this type of error is to compare the results with those obtained by a different method. As mentioned before, there was excellent agreement between the results found in this project with those found by Chikata [2]. This is very much reinforced by the fact that the agreement was not only on the levels of arc temperature but also on its time pattern. Using time integration, Chikata was able to predict what has been confirmed by the continuous information registered by FOCS : the temperature stays very high (= 25000 K) and approximately constant near to the extinction of the arc. Although this is not an absolute guarantee of a negligible systematic error, it is a good indication of the accuracy of the results. It is important to remember that Chikata used photomultipliers with an external source of calibration, characterising a very different spectroscopic technique.
Random or statistical errors in the method, due to factors such as oscillations in the base line of oscilloscopes (for digital averaging), internal oscillations in the electronic amplifiers for the photodiodes, dark current of photodiodes etc., are overshadowed by a large error introduced by uncertainties in the atomic transition probabilities (oscillator strength). These uncertainties [5] are unavoidable and depend very much on the availability of data for the particular pair of atomic radiations. For the lines Si II 413 nm and Si III 457 nm, the uncertainty [6] is 25%. Unless more accurate information is available regarding atomic parameters, any spectroscopic technique will be subject to important errors originating from uncertainties in the fundamental atomic data. Taking all this into account, one can say that on the assumption of LTE and optical transparency of the plasma, FOCS gives continuously a good indication of arc temperature (~ 20000 K) which remains approximately stable through the arcing process. Validation was achieved by comparing the results obtained from two types of radiation (same stage and subsequent stages of ionisation) and results obtained by a different spectroscopic technique. The combination of the optical fibre with the photodiodes showed an excellent sensitivity to radiation in the visible range of the spectrum. The major advantage of FOCS is the continuous recording of emissions of atomic radiation, allowing for a continuous calculation of the plasma temperature. The major disadvantage lies with a difficult choice of wavelengths.

7 References

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