ARC TEMPERATURE MEASUREMENT IN A HIGH-VOLTAGE FUSE

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Abstract: We report measurements of the temperature at different times during the arcing period of an experimental model of a sand-filled, high-voltage, high breaking capacity fuse. An optical fibre is used to carry light from the fuse arc to a spectrograph which is used to isolate spectral lines of interest. The spectrum is recorded by an intensified photodiode array. By gating the image intensifier in front of the diode array a complete spectrum is recorded in several microseconds. By varying the timing of the gate pulse the arc spectrum can be obtained at any desired time during the arcing period. The arc temperature is determined from the relative intensities of Si II spectral lines. The arc temperature was found to be around 20,000 K.

I. INTRODUCTION

Accurate modelling of high-voltage, high breaking capacity (HBC) fuses requires better knowledge of the arc parameters of which the electron temperature of the plasma is a key parameter. Spectroscopic determination of the electron temperature and electron density has several advantages over other methods, such as the use of probes, as it does not disturb the plasma [1]. The use of spectroscopy to investigate the properties of a fuse arc was reported first by Chikata *et al* [2]. Using a transparent Pyrex glass tube as the fuse holder, they recorded a spectrum and from the relative intensity of two Si II lines estimated the arc temperature to be about 23,000 K. To obtain a more reliable picture of the arc plasma in a sand-filled non-transparent fuse-holder, Barrow and Howe [3] inserted optical fibres into the plasma to convey light to a rapidly scanning spectrometer. They observed three pairs of Si II doubletsaround 505.1 nm, 597.2 nm and 635.5 nm wavelengths. Their estimated temperature of the arc varied from around 3000 K to 7000 K. The applied voltage of the circuit was 255 V with the prospective fault current of 525 A. Cheim and Howe [4], who also inserted optical fibres into a fuse arc, deduced temperatures of about 20,000 K (throughout the arcing period) from the relative intensities of the Si II 413 nm and Si III 457 nm lines. The fuse was tested at 250 V(AC) and with a prospective symmetrical current of 600 A(rms). The result was inconsistent with that of Barrow and Howe [3], but comparable with those of Chikata *et al* [2] who tested the fuse with a prospective short circuit current of 1 kA (peak) at 1.3 kV. Although the technique used by Cheim and Howe [4] gave temperature values throughout the arcing period, it had inherent problems owing to the use of interference filters to isolate the spectral lines of interest. Saqib and Stokes [5] studied the fuse arc using optical fibre as light carrier and photographic film to record the spectrum. They found Si II lines to be most suitable for temperature estimates as they were detected throughout the lifetime of the arc plasma. They could however not estimate arc temperature due to the complexity of calibration of the photographic film for intensity measurements. Bezborodko and Fauconneau [6] used two Cu lines to measure arc temperature obtaining a result around 12000 K. The drawback of this technique was that Cu lines could not be used to measure temperature of the hot core, due to ionic migration. The high levels of continuum light background signal in studies [5] and [6] show the weakness of using interference filters to isolate spectral lines.

We report here an extension of this technique to the investigation of fuse plasma for higher applied voltage and prospective current, conditions more typical of those likely to be encountered in a commercial sand-filled fuse. Several Si II lines were used to estimate the temperatures, rather than just the two used by other researchers, in order to increase the reliability of the temperature measurement.

II. THEORY OF SPECTROSCOPIC TEMPERATURE MEASUREMENT

Emission spectroscopy involves the analysis of light that is emitted when an excited atom undergoes a transition to a lower energy level [7]. The intensity of the emitted light can be represented by the following relationship [8]:

$$I = \frac{PgA}{\lambda} e^{-E/kT} \qquad (1)$$

where I is the intensity of emitted light, λ is the wavelength of light, E is the energy of the excited level, g is its statistical weight, k is the Boltzmann constant, A is the transition probability for the transition, T is the electron temperature of the plasma, and P is a constant for lines from the same ionisation state. Equation (1) canbe written as

$$\log\left(\frac{I\lambda}{gA}\right) = -\frac{E\log e}{kT} - \log P \qquad (2)$$

When E is in electron volts and T in kelvin, the equation reduces to:

$$\log\left(\frac{I\lambda}{gA}\right) = -\frac{5040}{T} + const \qquad (3)$$

Thus a plot of log $\{I\lambda/(gA)\}$ versus E, for several lines belonging to the same ionisation level, should be a straight line, from the slope of which the arc temperatureis readily obtained. Values of the parameters g, A and E are available in references [9-14].

III. EXPERIMENTAL SET-UP

A simple experimental model of a high-voltage HBC fuse in which the current was forced to zero was used to study the fuse arc. Commercially available fuses are designed differently to ensure that the current goes to zero well before reaching its maximum value and that the reignition does not occur. The cylindrical holder for the experimental model HBC, of length 112.2 mm and internal diameter 59.6 mm, was filled with SiO_2 sand. The fuse was energised from a parallel-current-injection synthetic test circuit, as shown in Figure 1. The prospective current was 1.4 kA (peak), 50 Hz, at 6 kV. The fuse element was a 0.55 mm diameter uniform silver wire. In order to convey light to the spectrograph a multimode silica optical fibre with a core diameter of 62.5 μm was inserted through the wall of the fuse holder to touch the fuse element [3, 4, 5]. The other end of the fibre was mounted in the middle of the 25 μm entrance slit of a Jarrell-Ash MonoSpec 27 Monochromator [15]. The spectrum was recorded using a Princeton Applied Research model 1460 Optical Multichannel Analyser (OMA) with a 1024 element intensified photodiode array detector [16].

IV. RECORDING OF THE SPECTRUM

The OMA is operated in its gated mode in order to synchronise it with the fuse energising circuit. The initiation pulse, provided by the OMA, closes the mechanical make switch MS1 of the test circuit (Figure 1) which takes about 65 ms to close. A delay circuit enables the image intensifier to be triggered in order to record a spectrum at any chosen time during the arcing process. The exposure time, determined by the duration of the gating pulse, is several microseconds. A Nicolet Pro digital oscilloscope [17] is used to record the voltage across the fuse, the current flowing through the fuse and the time at which the spectrum is recorded. Figure 3 shows an example of these three traces. The voltage across the fuse is measured by Tektronix P6015, 1000:1, 20 kV, 100 MΩ resistive divider voltage probe (rise time 5 ns). Current is measured using a 190.8 A/V coaxial current shunt (rise time approximately 60 ns). A block diagram of the timing circuit is shown in Figure 2.

V. EXPERIMENTAL RESULTS

A low-pressure mercury lamp was used to calibrate the spectrometer wavelength scale. Relative calibration of sensitivity as a function of wavelength was accomplished using a calibrated tungsten ribbon lamp. The light from the tungsten lamp traversed the same optical path, including the optical fibre, as the light from fuse arc. Thus:

$$I_{lamp} \propto S_{lamp}$$

and

$$I_{arc} \propto S_{arc}$$

where I_{lamp} and I_{arc} are the intensities of the radiation from the tungsten lamp and fuse arc respectively, S_{lamp} and S_{arc} are the corresponding signals recorded by the OMA. Since the proportionality factor is same function of wavelength in both cases the relative intensity of the fuse arc spectrum is given by:

$$I_{arc} = (S_{arc} * I_{lamp}) / S_{lamp} \qquad (4)$$

Four pairs of Si II lines were identified in the arc spectrum. They were around 413 nm (412.8 and 413.1), 505 nm (504.1 and 505.6), 597 nm (595.8 and 597.9) and 636 nm (634.7 and 637.1). Because of partial overlap of the recorded line profiles the four doublets were treated as single lines with the signal value determined by calculating the area under the combined profile after subtraction of the background level. Average wavelength values were used for plotting $I\lambda/gA$, and $g\ A$ was replaced by $g_1A_1 + g_2A_2$ where subscripts 1 and 2 represent the first and second lines of each doublet. Figure 4 shows the spectrum of the tungsten lamp; Figures 5 and 6 show arc spectra taken at different times during the arcing period. A typical plot for determining the electron temperature is shown in Figure 7.

Table 1: Summary of measurements of arc temperature at different times during the arcing period.

Arc time (ms)	Temp. (K)	I_{arc} (Amps)	V_{arc} (volts)	Inst. MW_{arc}
0.090	21, 600	1365	2768	3.7783
0.833	19, 775	1183	1456	1.7224
0.925	19, 205	1170	1200	1.4040
1.965	18, 725	876	856	0.7499
2.263	17, 555	768	848	0.6513
2.302	18, 745	770	728	0.5606
2.979	17, 417	566	466	0.2638
3.650	16, 840	255	440	0.1122
4.102	15, 000	114.5	320	0.0366
4.400	18, 585	10.7	424	0.0045
4.446	19, 946	55	352	0.0194

A summary of temperature measurements as a function of time are shown in Table 1 which also gives the instantaneous arc current, instantaneous arc voltage, and instantaneous arc power. The arc time was obtained by subtracting the pre-arcing time for each shot (the average value around 5.3 ms) from the time at which the spectrum was recorded. Arc temperature as a function of time is also given in Figure 8.

VI. DISCUSSION

During the measurements care was taken to ensure that each sample fuse was identical and was energised under identical conditions so that a variation of temperature with time could be measured on a shot-to-shot basis. The spectrograph enabled us to record spectra from 300 nm to 800 nm. Since intensity calibration using the tungsten lamp was reliable above 420 nm only, we were forced to ignore the 412.8 and 413.1 Si II lines. As shown in Table 1 temperature varies in the range 15,000 K to 22,000 K. However it is clear from Figure 8 that the temperature falls slowly during the arcing period from a approximately 22,000 K at the start to around 18,000 K towards the end of the measurements. This contrasts with the findings of Chikata *et al* [2] and Cheim and Howe [4] who concluded that temperature remained constant around 20,000 K during the fuse arcing.

The fuse arc plasma was assumed to be in local thermodynamic equilibrium: this was confirmed by finding that plots of log $\{I\lambda/(gA)\}$ versus E did not deviate significantly from a line of best fit. According to Lochte-Holtgreven [18] there is no self-absorption in plasmas above 10,000 K, so the fuse arc plasma is optically thin. This has also been established experimentally by Bezborodko and Fauconneau [6].

As shown in Table 1, the arc temperature falls during the arcing period at a significantly slower rate than does the instantaneous power dissipation in the arc suggesting that other factors such as arc volume and arc density may be important.

Our investigation of arc temperature during fuse arcing gives arc temperatures significantly higher than those recorded by Barrow and Howe [3]. This is not inconsistent with the significantly higher power dissipated in the arc in our experiments. The values of temperature obtained by Bezborodko and Fauconneau [6] do not correspond to the hot region of the plasma and cannot therefore be compared with the results of the present study. Cheim and Howe [4] measured temperatures comparable with those reported here, even though they used interference filters which cannot be corrected for the presence of neighbouring lines and high background levels.

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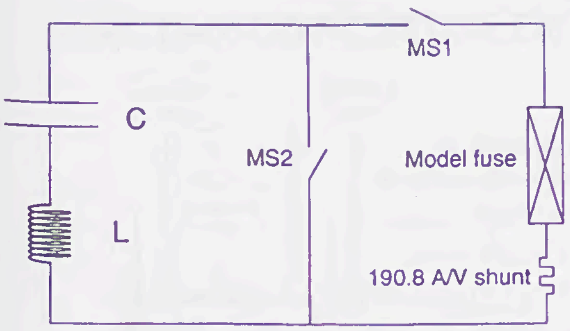

Figure 1: Electrical circuit to energise the test fuse.

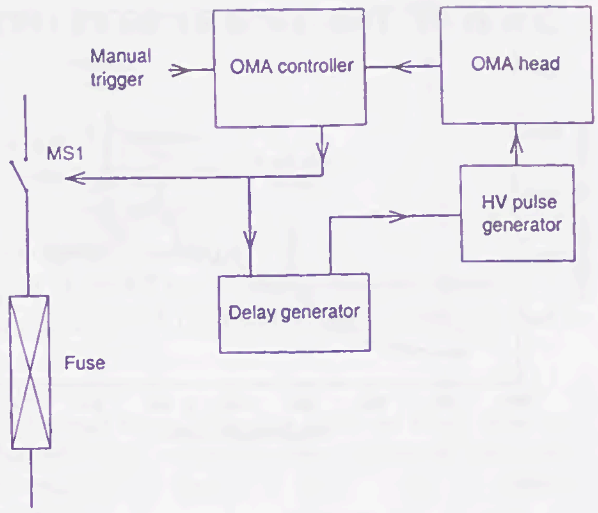

Figure 2: A simplified block diagram to synchronise OMA with the test fuse.

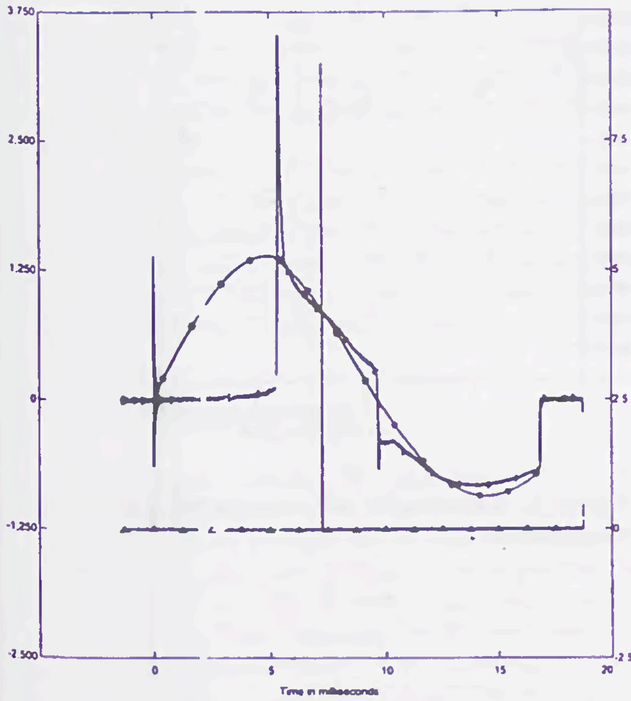

Figure 3: Plots for voltage across and current through the fuse. OMA head is opened at 7.265 ms to record the spectrum.

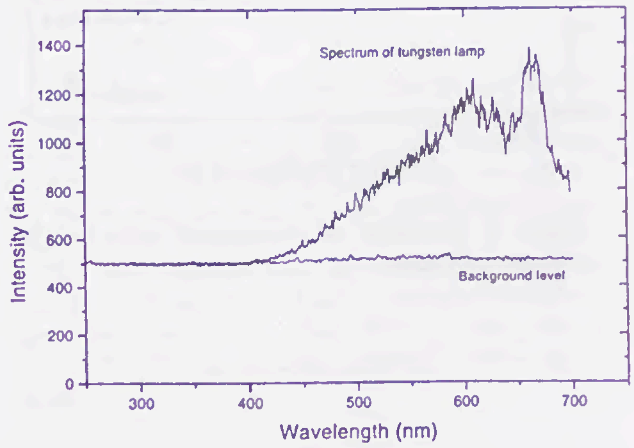

Figure 4: A spectrum of the tungsten lamp; background level is also shown.

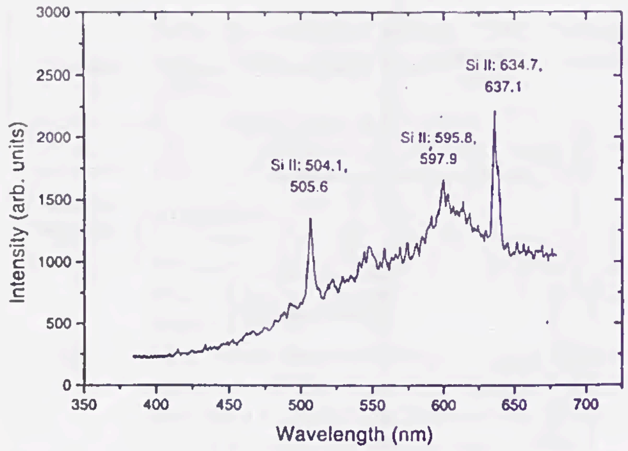

Figure 5: Fuse spectrum at 9.402 ms, ie, arc time of 4.102 ms.

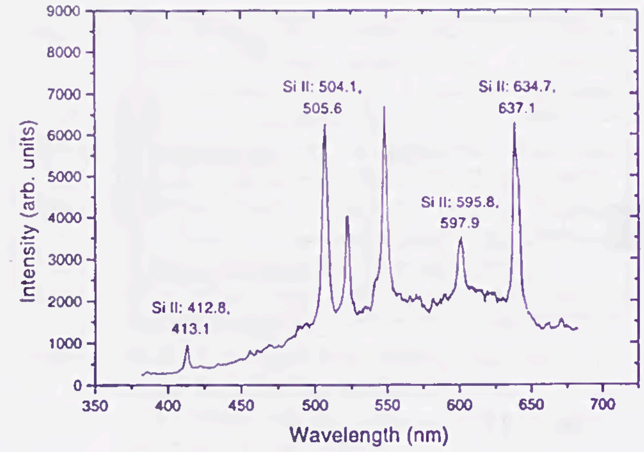

Figure 6: Fuse spectrum at 7.602 ms, ie, arc time of 2.302 ms.

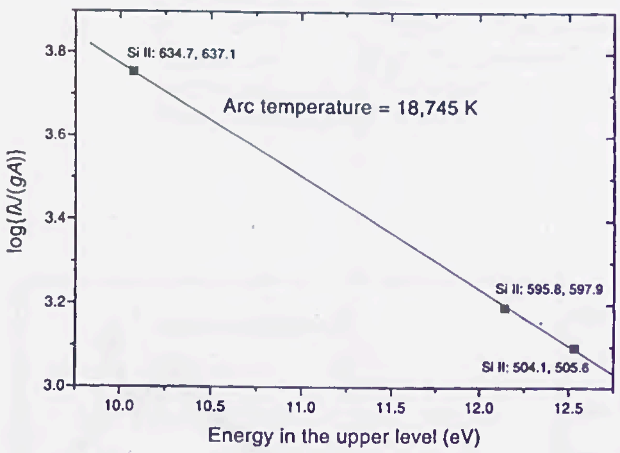

Figure 7: Deduction of temperature using relative intensity technique.

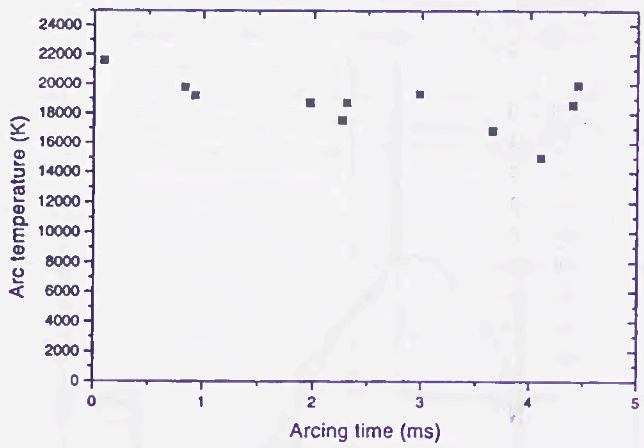

Figure 8: Variation of arc temperature during the arcing period.