Time-Resolved Measurement of Arc Temperature in a Sand-Filled High-Voltage Fuse

Muhammad A. Saqib, Anthony D. Stokes, Brian W. James, and Ian S. Falconer

***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. The cylindrical fuse-holder, containing a single-strand of uniform silver fuse-element, is tested at 6 kV, 50 Hz, and 1.25 kA prospective current is passed through it to generate the fuse arc. An optical fiber 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.**

***Index Terms*—Arc temperature, relative intensity of spectral lines, sand-filled high-voltage fuse, the fuse' arc spectrum.**

I. INTRODUCTION

ACCURATE modeling 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 in a sand-filled non-transparent fuse-holder, Barrow and Howe [3] inserted optical fibers into the plasma to convey light to a rapidly scanning spectrometer. They observed three pairs of Si II doublets around 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 fibers 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 fiber 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]:

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

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 ionization state. Equation (1) can be written as

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Fig. 1. Photograph of the test fuse: length is 112 mm and inner diameter of the cartridge is 59.5 mm.

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

When E is in electron volts and T in kelvin, (2) reduces to:

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

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

III. EXPERIMENTAL SETUP

A simple experimental model of a high-voltage HBC fuse in which the current was forced to zero, using a crow bar, was used to study the fuse arc. Commercially available fuses are designed to ensure that the current goes to zero at a time well before the fault current would have reached its maximum value had the fuse been replaced by a metallic link of negligible impedance. The current-limitation phenomenon is affected by a sudden rise of the voltage across the fuse at the initiation of the arcing: this voltage should be higher than the system voltage and is dependent upon the length of the fuse-element used. In commercial sand-filled fuses the fuse-element' length is thus kept very large compared with the length of the fuse holder. 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 (Fig. 1)]. The fuse was energized from a parallel-current-injection synthetic test circuit, as shown in Fig. 2. The fuse was tested at a prospective current of 1.25 kA (peak) at 6 kV, 50 Hz. The fuse element was a 0.55 mm diameter uniform silver wire. In order to convey light to the spectrograph a multimode silica optical fiber with a core diameter of 62.5 μm was inserted through the wall of the fuse holder to touch the fuse element [3]-[5]. The other end of the fiber 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 Multi-channel Analyzer (OMA) with a 1024 element intensified photodiode array detector [16].

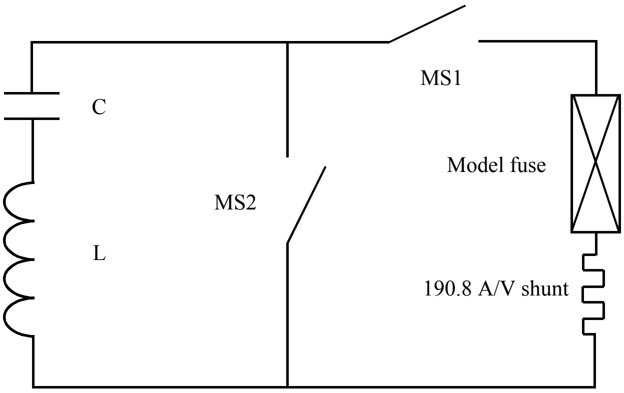

Fig. 2. Parallel-circuit-injection synthetic test circuit used to energize the test fuse.

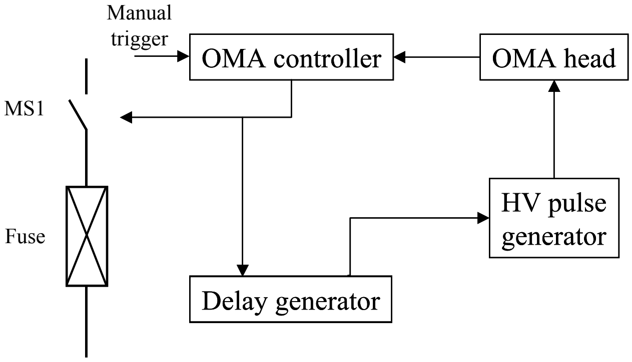

Fig. 3. A simplified block diagram to synchronize the OMA with the test fuse.

IV. RECORDING OF THE SPECTRUM

The OMA is operated in its gated mode in order to synchronize it with the fuse energizing circuit. The initiation pulse, provided by the OMA, closes the mechanical make switch MS1 of the test circuit (Fig. 2) 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 block diagram of the timing circuit is shown in Fig. 3. 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. 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).

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 fiber, as the light from fuse arc. Thus:

$I_{\text{lamp}} \propto S_{\text{lamp}}$ and $I_{\text{arc}} \propto S_{\text{arc}}$

where I_{lamp} and I_{arc} are the intensities of the radiation from the tungsten lamp and fuse arc respectively, S_{lamp}

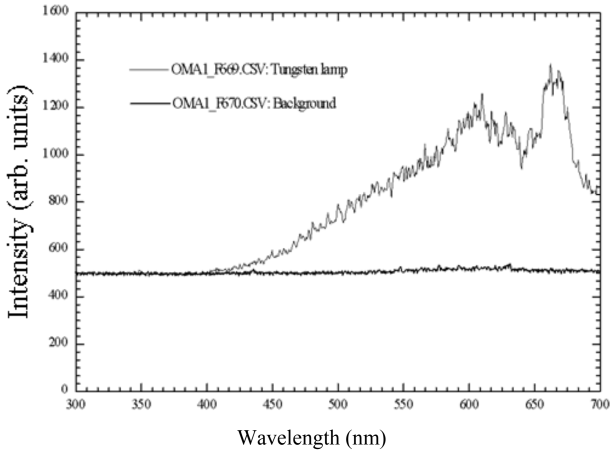

Fig. 4. Spectrum of the tungsten lamp and the background level, exposure time was 5 seconds at a current of 15.53 A, and the intensifier set in "continuous" mode.

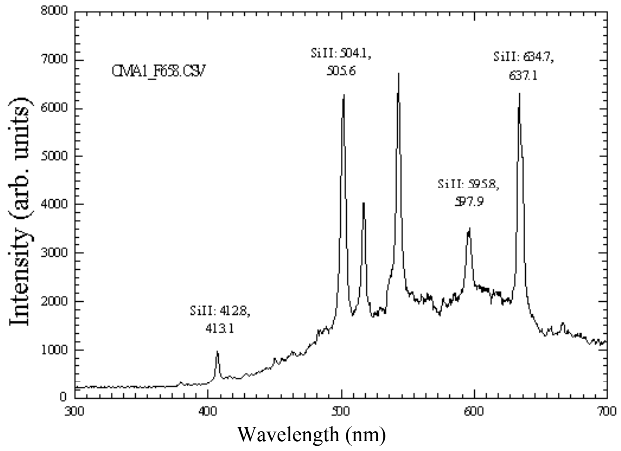

Fig. 5. The OMA head is opened and the fuse' arc spectrum recorded at 2.302 ms after the arc has struck (arcing time at which the spectrum is recorded is thus 2.302 ms).

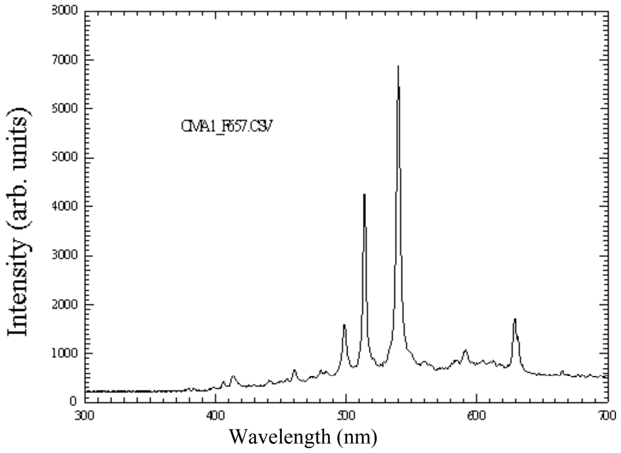

Fig. 6. The arc spectrum is recorded at an arcing time of 8.95 ms, i.e. 8.95 ms after the start of the arcing.

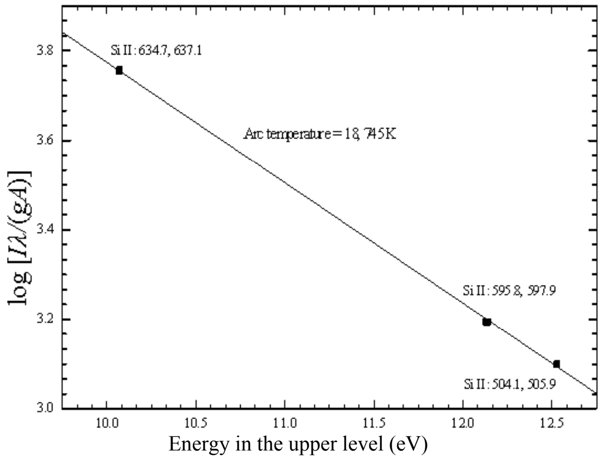

Fig. 7. Plot for the $\log[I\lambda/(g_1A_1+g_2A_2)]$ vs. upper level energy that is used to determine the electron temperature at arcing time of 2.302 ms (for the spectrum shown in Fig. 5): arc current is 770 A and arc voltage is 728 V.

TABLE I

SUMMARY OF MEASUREMENTS OF ARC TEMPERATURE AT DIFFERENT TIMES DURING THE ARCING PERIOD

Arc time [ms]	Temperature [K]	Arc current [A])	Arc voltage [V]	Arc power [MW]
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

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:

$$I_{\text{arc}} = (S_{\text{arc}} \times I_{\text{lamp}}) / S_{\text{lamp}} . \tag{4}$$

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 gA was replaced by $g_1A_1 + g_2A_2$ where subscripts 1 and 2 represent the first and second lines of each doublet. Fig. 4 shows the spectrum of the tungsten lamp; Figs. 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 Fig. 7.

A summary of temperature measurements as a function of time is shown in Table I which also gives the instantaneous arc current, instantaneous arc voltage, and

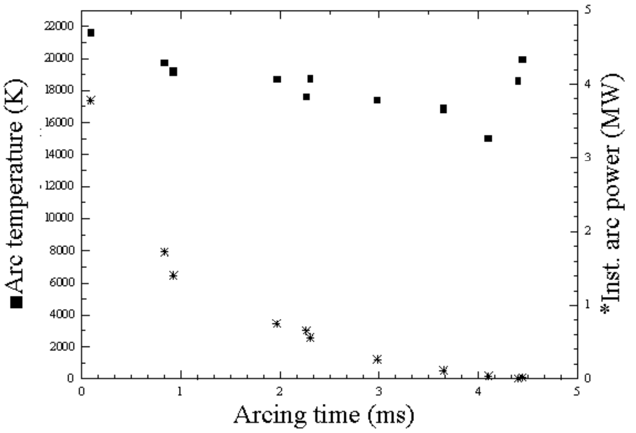

Fig. 8. Plots of arc temperature and instantaneous arc power for the test fuse at 1.25 kA.

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 Fig. 8.

VI. DISCUSSION

During the measurements care was taken to ensure that each sample fuse was identical and was energized 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 Fig. 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 plasma is optically thin. This has also been established experimentally by Bezborodko and Fauconneau [6].

As shown in Table I, 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 neighboring lines and high background levels.

VII. CONCLUSION

Our investigation shows that the temperature of the arc falls slowly from about 22,000 °K - at the arc initiation - to around 18,000 °K - at the end - during the arcing period when a 112.2 mm long (at internal diameter of 59.6 mm) model fuse was tested from a prospective current of 1.25 kA at 6 kV, 50 Hz. The arc was not extinguished by the fuse due to its current-limiting action, but in fact the fault current was carried by the crow bar (MS2, Fig. 2). The high temperature measured throughout the arcing period indicates that the arc probably had not cooled enough for successful current interruption by the fuse itself.

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Professor James' current research interest is in the experimental study of dusty plasmas, where his leadership has ensured that the University of Sydney team is a key contributor to this aspect of plasma physics.

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In 1966 Dr. Falconer accepted a position as Lecturer in the School of Physics at the University of Sydney, where he worked on laser diagnostics of plasmas, using lasers operating at wavelengths from the ultraviolet to the submillimetre regions. He has extended his interests from laser diagnostics to plasma spectroscopy, and from fusion-related plasma to gaseous electronics. He retired in 1997, but continues his association with the University of Sydney's School of Physics as an Honorary Senior Lecturer.

During his tenure at the University of Sydney, Dr, Falconer has traveled overseas to continue his researches at the University of Hull (UK), the MIT Plasma Fusion Center, the JET Joint Undertaking at Culham (UK), and the Laboratoire de Spectrometrie Physique in Grenoble. He has also worked for a period of several months at the CSIRO's Division of Applied Physics in Sydney.

Dr. Falconer's research interests are based around the application of laser and spectroscopic techniques to the measurement of the characteristics of plasmas ranging from fusion plasma to the dielectric barrier discharges that form the pixels of plasma screen TVs.