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# Dominant Spectra of Background Radiation in an SF<sub>6</sub> Post-Arc Channel

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**Abstract**—Composition of background spectra radiated from an SF<sub>6</sub> post-arc channel after current zero was investigated. The radiation intensity of background spectra at a wavelength of 455 nm around current zero was measured. Post-arc temperature was estimated from the intensity ratio of two spectral lines at 426.0 and 442.7 nm of iron used as an electrode material. Emission coefficients of not only continuous spectra but also S<sub>2</sub> spectra due to  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition were theoretically calculated as a function of temperature in the range of 3000–6000 K. The results indicated that the background spectra mainly consist of continuous spectra at temperatures above 4500 K, and of S<sub>2</sub> spectra at temperatures below 4500 K. The temperature dependence of the calculated emission coefficients of the background spectra agreed fairly well with that of the measured radiation intensity.

**Index Terms**—Background radiation, continuous spectra, S<sub>2</sub> spectra, SF<sub>6</sub> post-arc channel.

## I. INTRODUCTION

IN an SF<sub>6</sub> gas-blast circuit breaker, an arc discharge was established between the electrodes during current interruption processes. In order to elucidate the arc interruption phenomena, diagnosis of the arc temperature  $T$  and concentration  $X_M$  of metallic vapor ejected from the electrodes into the arc is of great importance. In measuring  $T$  and  $X_M$  in the arc column, spectroscopic observation is often performed to observe not only objective spectral lines but also background spectra near these spectral lines. Thus, it is necessary to investigate the background spectra. The background spectra at  $T > 6000$  K is usually considered to be continuous spectra. Until now, several studies have been done to find out various properties of the continuous spectra at  $T > 6000$  K [1], [2].

On the other hand, temperature of post-arc channel after current zero decays to magnitudes below 6000 K. However, very little is known about the continuous spectra at  $T < 6000$  K. In addition, there are few studies on the composition of the background spectra at  $T < 6000$  K.

The present paper describes the background spectra radiated from an SF<sub>6</sub> post-arc channel. First, time variation of radiation intensity  $I_{455}$  of background spectra at a wavelength of 455 nm was measured around current zero in a flat-type SF<sub>6</sub> gas-blast

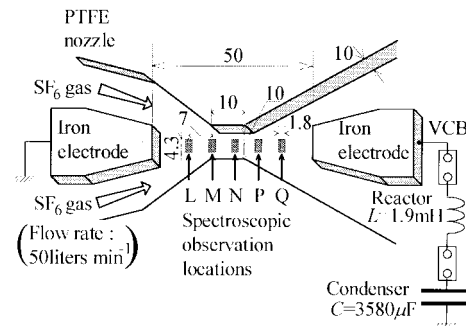


Fig. 1. Flat-type SF<sub>6</sub> gas-blast quenching chamber and spectroscopic observation position.

quenching chamber. In the chamber, we intentionally used iron electrodes, and observed Fe spectral lines at wavelengths of 426.0 and 442.7 nm together with the background spectra. This is because these Fe spectral lines have much higher radiation intensities than those of S<sup>+</sup>, F, or Cu at  $T < 6000$  K [3], [4]. Application of the two-line method to the measured two Fe spectral lines enabled us to estimate the post-arc temperature  $T$  up to 100  $\mu$ s after current zero for ac 5 kA<sub>peak</sub> arcs [3], [4]. As a result, the radiation intensity  $I_{455}$  of the observed background spectra was successfully obtained as a function of  $T$ . Second, to interpret the temperature dependence of  $I_{455}$ , integrated emission coefficient  $\epsilon'_{cont}$  of the continuous spectra at 455 nm was theoretically calculated as a function of  $T$  in the range from 3000 to 6000 K. However, the temperature dependence of  $\epsilon'_{cont}$  shows no agreement with that of the observed  $I_{455}$ . Finally, special attention was given to molecular spectra, where the integrated emission coefficient  $\epsilon_{S_2 455}$  of S<sub>2</sub> spectra due to  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition has to be taken into account for the background spectra at  $T < 6000$  K, since the temperature dependence of the sum of  $\epsilon_{S_2 455}$  and  $\epsilon'_{cont}$  agrees fairly well with that of  $I_{455}$ .

## II. MEASUREMENT OF RADIATION INTENSITIES OF IRON SPECTRAL LINES AND BACKGROUND SPECTRA

### A. Experimental Setup

Fig. 1 depicts the flat-type SF<sub>6</sub> gas-blast quenching chamber adopted in the experiment [3], [4]. In this chamber, we intentionally used two iron electrodes. A flat nozzle is made of polytetrafluoroethylene (PTFE) with a thickness of 10 mm. The nozzle throat is 10 mm wide and 10 mm long. The flat nozzle was sandwiched between two ceramic plates.

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Sulfur hexafluoride gas was supplied through tubes along the cathode to blow in the axial direction to the arc. The flow rate was adjusted to 50 l/min<sup>-1</sup> before arc ignition. Gas pressure in the chamber was always kept to be nearly 0.1 MPa.

A damping sinusoidal current with a frequency of 60 Hz was supplied from a capacitor bank (with capacitance  $C$  of 3580  $\mu$ F) through a reactor (with inductance  $L$  of 1.9 mH). Peak value of the current was adjusted to 5000 A. An auxiliary vacuum circuit breaker (VCB) was intentionally connected in series with this flat-type quenching chamber, thus interrupting the sinusoidal current at the first current zero. As a result, no transient recovery voltage (TRV) was applied between the electrodes in the flat-type quenching chamber.

### B. Spectroscopic Observation Along Nozzle Axis

Spectroscopic observation was carried out at five positions around the nozzle throat as denoted by the symbol L–Q in Fig. 1. At these positions, the ceramic plate sandwiching the flat nozzle has a rectangular hole of 4 mm  $\times$  1 mm. Through this hole, the arc radiation was observed with a bundle of four optical fibers made of quartz glass. Each fiber has a core of 0.8 mm in diameter, a clad of 1.0 mm in diameter, and a numerical aperture of 0.2. The bundle of fibers accepts arc radiation from a region with spatial dimensions of 4.3 mm  $\times$  1.8 mm.

This bundle of fibers transmits the arc radiation from the observation point to the entrance slit of a monochromator. The monochromator has a reciprocal dispersion of 0.8 nm  $\cdot$  mm<sup>-1</sup>. On the focal plane at the exit of the monochromator, a multichannel detector with three photomultiplier tubes was positioned. Use of this detector permits the simultaneous observation of radiation intensities at three different wavelengths. With the multichannel detector, we measured the radiation intensities  $I'_{426}$  and  $I'_{443}$  at wavelengths of 426.0 and 442.7 nm, respectively. Simultaneously, the radiation intensity  $I_{455}$  at a wavelength of 455.0 nm was also measured to obtain the intensity of background spectra. The wavelength of 455.0 nm is free from the spectral lines emitted from atoms and atomic ions. The observation width of each channel corresponds to 0.6 nm in wavelength. The relative spectral sensitivities of the overall optical system for the above three wavelengths were measured using a standard tungsten-halide lamp. Considering the sensitivities thus obtained, corrections were made to the three signals.

### C. Time Variations of Radiation Intensities of Spectra and Temperature around Current Zero

Numerical subtraction of background radiation intensity  $I_{455}$  from  $I'_{426}$  produces the net radiation intensity  $I_{Fe426}$  of Fe spectral line at 426.0 nm ( $z^7D^o-e^7D$ ). Similarly, the net radiation intensity  $I_{Fe443}$  of Fe spectral line at 442.7 nm ( $a^5D-z^7F^o$ ) was also derived. The top part of Fig. 2 illustrates the time variations of radiation intensities  $I_{Fe426}$ ,  $I_{Fe443}$ , and  $I_{455}$  at position M. As can be seen in this figure, all of  $I_{Fe426}$ ,  $I_{Fe443}$ , and  $I_{455}$  were detectable up to 100  $\mu$ s after current zero. It should be noted that  $I_{Fe426}$  and  $I_{Fe443}$  decay rapidly with time, while  $I_{455}$  of the background spectra almost

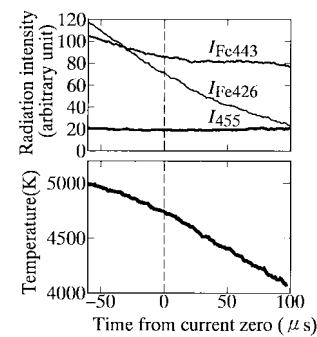


Fig. 2. Time variations of radiation intensity measured around current zero and temperature estimated at position M (Peak value of current, 5 kA; SF<sub>6</sub> gas flow rate, 50 l/min).

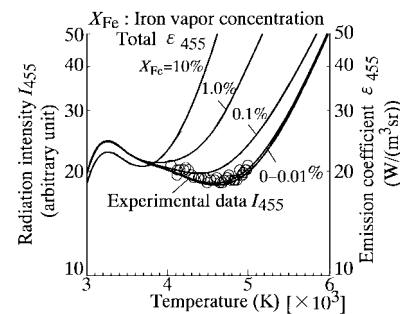


Fig. 3. Temperature dependence of the radiation intensity of background spectra at 455 nm measured at position M and those of emission coefficients calculated.

remain constant. A similar aspect was found at the other observation positions.

From the ratio  $I_{Fe443}/I_{Fe426}$ , temperature  $T$  around current zero was estimated by the two-line method on the assumption that the population of excited states in Fe follows a Boltzmann distribution and that the arc is optically thin. The validity of these assumptions was confirmed in additional experiments by measuring simultaneously Fe spectral lines at 430.8, 432.6, 438.6, 440.5, and 441.5 nm, as well as at 426.0 and 442.7 nm with an optical multichannel analyzer and by making a Boltzmann plot diagram for the seven lines. The bottom figure in Fig. 2 represents the decay process of  $T$  at the position M. Note that  $T$  is so-called an excitation temperature of Fe. The temperature  $T$  was estimated to be 4870 K at the current zero. It can be also seen that  $T$  decreases gradually with time, then reaching to 4140 K at 100  $\mu$ s after current zero.

### III. TEMPERATURE DEPENDENCE OF RADIATION INTENSITY OF BACKGROUND SPECTRA

Use of Fig. 2 permits us to obtain  $I_{455}$  as a function of  $T$ . Open circles in Fig. 3 designate  $I_{455}$  as a function of  $T$ . The intensity  $I_{455}$  decreases with  $T$  from 5000 to 4600 K, while  $I_{455}$  increases slightly with a reduction of  $T$  from 4600 to 4100 K. In order to interpret the above relationship between  $I_{455}$  and  $T$ , emission coefficient  $\epsilon_{455}$  of background spectra at 455 nm will be discussed in the next section.

#### IV. THEORETICAL CALCULATION OF EMISSION COEFFICIENTS OF BACKGROUND SPECTRA

##### A. Equilibrium Composition of SF<sub>6</sub>-Fe Mixture Plasma

The calculations of emission coefficients require the particle composition of SF<sub>6</sub>-Fe mixture. Thus, we calculated the equilibrium composition of SF<sub>6</sub> gas contaminated with iron vapor [3], [4]. The species taken into account were the molecular, atomic, and ionic species of SF<sub>6</sub>, SF<sub>4</sub>, SF<sub>2</sub>, F<sub>2</sub>, S<sub>2</sub>, F, S, F<sup>+</sup>, S<sup>+</sup>, F<sup>-</sup>, S<sup>-</sup>, F<sup>2+</sup>, S<sup>2+</sup>, Fe, Fe<sup>+</sup>, Fe<sup>2+</sup>, and electron. We obtained the composition by solving the simultaneous equations: Saha's equation for ionization reactions, Gulberg-Waage's equations for dissociation reactions, the charge neutrality equation, Dalton's laws of partial pressures, and the equation defining the iron vapor concentration  $X_{\text{Fe}}$ . In the present paper,  $X_{\text{Fe}}$  (in %) is defined as the ratio of the total mass of Fe, Fe<sup>+</sup>, and Fe<sup>2+</sup> to the sum of those of all particles:

$$X_{\text{Fe}} = \frac{m_{\text{Fe}}(N_{\text{Fe}} + N_{\text{Fe}^+} + N_{\text{Fe}^{2+}})}{\sum_j m_j N_j} \times 100. \quad (1)$$

##### B. Emission Coefficient of Continuous Spectra

Background spectra are usually considered to be continuous spectra, especially at  $T > 6000$  K. Thus, we calculated the emission coefficient of the continuous spectra taking into account four kinds of radiative mechanisms: 1) recombination radiation, 2) radiation by electron attachment, 3) bremsstrahlung, and 4) radiation by collision between electron and neutral species [5].

1) *Recombination Radiation*: The emission coefficient  $\varepsilon_{\text{fb}}$  (in  $\text{W} \cdot \text{m}^{-4} \cdot \text{sr}^{-1}$ ) of the continuous spectra due to recombination at a wavelength of  $\lambda$  is given by

$$\begin{aligned} \varepsilon_{\text{fb}} &= C_1 \frac{N_e}{T^{1/2}} \left[ 1 - \exp\left(-\frac{hc}{kT\lambda}\right) \right] \\ &\quad \times \sum_{j(\text{ion})} \frac{g_{1j} Z_{\text{eff}j}^2 N_j}{U_j} \xi_j \frac{c}{\lambda^2} \\ C_1 &= \frac{1}{(4\pi\epsilon_0)^3} \frac{16\pi e^6}{3C^3(6\pi m_e^3 k)^{1/2}} \end{aligned} \quad (2)$$

where  $e$  the electronic charge,  $m_e$  the mass of electron,  $h$  Planck's constant,  $c$  the velocity of light,  $k$  Boltzmann's constant,  $g_{1j}$  the statistical weight of the ground state of species  $j$ , and  $U_j$  the internal partition function of species  $j$ . The quantities  $N_e$  and  $N_j$  are the number density of the electron and the species  $j$ , respectively,  $Z_{\text{eff}j}$  is the effective ionic charge of the species  $j$ , and  $\xi_j$  is the Bibermann-Schlüter factor for nonhydrogenic particles [6]. The wavelength  $\lambda$  was taken to be 455.0 nm.

2) *Radiation by Electron Attachment*: Atoms such as F and S can capture a free electron to form negative ions F<sup>-</sup> and S<sup>-</sup> with the emission of a continuum similar to that of the recombination process. However, the attachment continuum of F<sup>-</sup> occurs at  $\lambda < 364.6$  nm because of the existence of the absorption edges [7], while that of S<sup>-</sup> at  $\lambda < 614.4$  nm [8]. Thus, the electron attachment to S mainly contributes to the

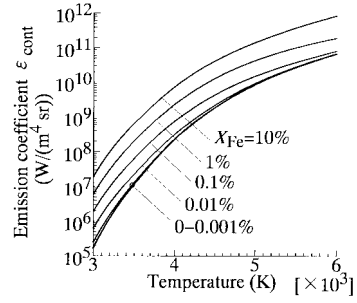


Fig. 4. Emission coefficient  $\varepsilon_{\text{cont}}$  of continuous spectra at a wavelength of 455.0 nm in SF<sub>6</sub> gas at 0.1 MPa as a function of temperature.

light emission at 455.0 nm. The emission coefficient  $\varepsilon_{\text{attach}}$  of the light at  $\lambda$  is expressed as

$$\varepsilon_{\text{attach}} = \frac{2hc}{\lambda^3} \exp\left(-\frac{hc}{kT\lambda}\right) N_{\text{S}^-} \sigma_{\text{det}}^{\text{S}^-} \frac{c}{\lambda^2} \quad (3)$$

where  $N_{\text{S}^-}$  is the number density of S<sup>-</sup>,  $\sigma_{\text{det}}^{\text{S}^-}$  is the photo-detachment cross sections for S<sup>-</sup>.

3) *Bremsstrahlung*: The emission coefficient  $\varepsilon_{\text{ff}}$  of the continuous spectra due to free-free transitions of electrons can be calculated by the following equation:

$$\begin{aligned} \varepsilon_{\text{ff}} &= C_1 \frac{N_e}{T^{1/2}} \exp\left(-\frac{hc}{kT\lambda}\right) \\ &\quad \times \sum_{j(\text{ion})} Z_{\text{eff}j}^2 N_j G_{\text{ff}} \frac{c}{\lambda^2} \end{aligned} \quad (4)$$

where  $G_{\text{ff}}$  is the temperature-averaged free-free Gaunt factor, which is close to unity [9].

4) *Radiation by Collision Between Electron and Neutral Species*: The emission coefficient  $\varepsilon_{\text{en}}$  of continuum due to collisions between electron and neutral particles is given as follows [5]:

$$\begin{aligned} \varepsilon_{\text{en}} &= \frac{32e^2}{3C^3(4\pi\epsilon_0)} \left(\frac{kT}{2\pi m_e}\right)^{3/2} N_e \exp\left(-\frac{hc}{kT\lambda}\right) \\ &\quad \times \sum_{j(\text{neutral})} N_j G_{\text{nj}} \frac{c}{\lambda^2} \end{aligned} \quad (5)$$

where  $G_{\text{nj}}$  is a factor depending on the cross sections of elastic electron-neutral collision.

The calculation results revealed that  $\varepsilon_{\text{attach}}$  is very much higher than  $\varepsilon_{\text{fb}}$ ,  $\varepsilon_{\text{ff}}$ , and  $\varepsilon_{\text{en}}$  in the temperature range from 3000 to 6000 K. For example, at  $T = 5000$  K,  $\varepsilon_{\text{attach}}$  is more than 130 times greater than those by the other three processes.

The summation of  $\varepsilon_{\text{fb}}$ ,  $\varepsilon_{\text{attach}}$ ,  $\varepsilon_{\text{ff}}$ , and  $\varepsilon_{\text{en}}$  yields the total emission coefficient  $\varepsilon_{\text{cont}}$  of the continuous spectra

$$\varepsilon_{\text{cont}} = \varepsilon_{\text{fb}} + \varepsilon_{\text{attach}} + \varepsilon_{\text{ff}} + \varepsilon_{\text{en}}. \quad (6)$$

Fig. 4 indicates  $\varepsilon_{\text{cont}}$  as a function of  $T$  in the range of 3000–6000 K at  $P = 0.1$  MPa with a parameter of  $X_{\text{Fe}}$ . As seen in this figure,  $\varepsilon_{\text{cont}}$  decreases markedly with reducing  $T$  for the same  $X_{\text{Fe}}$ .

The measured  $I_{455}$  included radiation intensities integrated in wavelength range of  $455.0 \pm 0.3$  nm. Thus, we calculated

the integrated emission coefficient  $\varepsilon'_{\text{cont}}$  (in  $\text{W} \cdot \text{m}^{-3} \cdot \text{sr}^{-1}$ ) of continuum in the range of  $455.0 \pm 0.3$  nm by

$$\varepsilon'_{\text{cont}} = \int_{454.7 \text{ nm}}^{455.3 \text{ nm}} \varepsilon_{\text{cont}} d\lambda \simeq \varepsilon_{\text{cont}} \times (0.6 \text{ nm}). \quad (7)$$

Although not being able to compare values of  $I_{455}$  with the absolute values of  $\varepsilon'_{\text{cont}}$ , we are able to compare the temperature dependence of  $I_{455}$  with that of  $\varepsilon'_{\text{cont}}$ , i.e., that of  $\varepsilon_{\text{cont}}$ . It should be noted that the temperature dependence of  $\varepsilon_{\text{cont}}$  greatly differs from that of  $I_{455}$  shown with the open circles in Fig. 3. This result indicates that background spectra include significant spectra besides the continuous spectra in the temperature range of 3000–6000 K.

### C. Emission Coefficient of S<sub>2</sub> Spectra Due to $B^3\Sigma_u^- - X^3\Sigma_g^-$ Transition

In the temperature range of 3000–6000 K, the high-temperature SF<sub>6</sub> gas has the molecules such as S<sub>2</sub>, F<sub>2</sub>, and SF<sub>2</sub>. Thus, particular attention to the molecular spectra was paid especially to S<sub>2</sub> spectra. The reasons are given below. 1) SF<sub>2</sub> has much lower number density than S<sub>2</sub>. 2) F<sub>2</sub> emits band spectra with marked low intensity, because F<sub>2</sub> has much higher electronic energy of upper state than S<sub>2</sub> [10].

Sulfur molecules S<sub>2</sub> emit very extensive band spectra mainly through  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition [11]. The emission coefficient  $\varepsilon_{\text{S}_2}$  (in  $\text{W} \cdot \text{m}^{-3} \cdot \text{sr}^{-1}$ ) for  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition of S<sub>2</sub> is written by

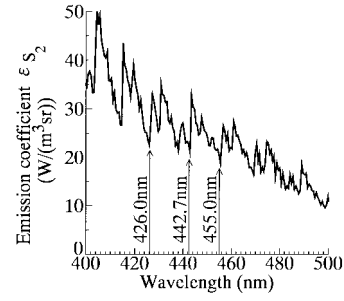
$$\varepsilon_{\text{S}_2} = \frac{hc}{4\pi\lambda_{v'v'',J'J''}} N_{n'v'J'} A_{v'v'',J'J''} \quad (8)$$

where  $n, v, J$  are the quantum numbers on electronic, vibrational, and rotational state, respectively. The prime (') denotes the upper state, and the double prime (') the lower state. Then,  $\lambda_{v'v'',J'J''}$  is the wavelength, and  $A_{v'v'',J'J''}$  the transition probability. The calculation was performed for vibrational transitions  $(v', v'') = (0, 0), (0, 1), \dots, (12, 25), (12, 26)$  and for rotational transitions including P and R branches with  $J' = 0, \dots, 500$ . Fig. 5 represents  $\varepsilon_{\text{S}_2}$  at  $P = 0.1$  MPa as a function of wavelength at  $T = 4000$  K. This figure reveals that S<sub>2</sub> has differences of 9% in emission coefficients at the wavelengths of 426.0, 442.7, and 455.0 nm. This difference may cause an error in temperature estimates. However, the error is only 20 K at current zero in Fig. 2 for example. Thus, emission coefficient of S<sub>2</sub> at 455.0 nm can be regarded as background spectra at the three wavelengths.

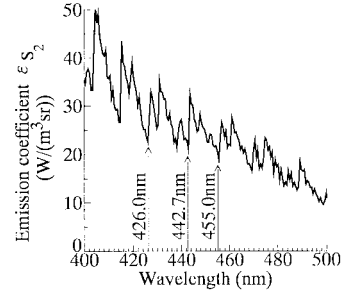
The integrated emission coefficient  $\varepsilon_{\text{S}_2 455}$  in the wavelength range of  $455.0 \pm 0.3$  nm was expressed as follows:

$$\varepsilon_{\text{S}_2 455} = \sum_{455.0 \pm 0.3 \text{ nm}} \varepsilon_{\text{S}_2}. \quad (9)$$

Fig. 6 represents  $\varepsilon_{\text{S}_2 455}$  as a function of  $T$  for  $X_{\text{Fe}}$  from 0 to 10%. As can be seen in this figure,  $\varepsilon_{\text{S}_2 455}$  increases gradually with reducing  $T$ . For example,  $\varepsilon_{\text{S}_2 455}$  has the magnitude of  $10.8 \text{ W} \cdot \text{m}^{-3} \cdot \text{sr}^{-1}$  at 6000 K, while  $\varepsilon_{\text{S}_2 455}$  is  $19.8 \text{ W} \cdot \text{m}^{-3} \cdot \text{sr}^{-1}$  at 3000 K. From Fig. 6,  $\varepsilon_{\text{S}_2 455}$  is also found to be almost independent of  $X_{\text{Fe}}$  in range of 0–1% for a given  $T$ .



(a)



(b)

Fig. 5. Dependence of emission coefficient due to S<sub>2</sub>  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition on wavelength in pure SF<sub>6</sub> gas at 4000 K at 0.1 MPa.

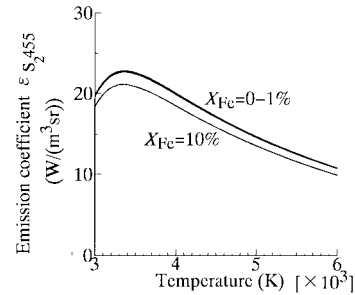


Fig. 6. Emission coefficient due to S<sub>2</sub>  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition in wavelength range from 454.7 to 455.3 nm in SF<sub>6</sub> gas at 0.1 MPa as a function of temperature.

## V. COMPARISON OF CALCULATED EMISSION COEFFICIENT WITH MEASURED RADIATION INTENSITY OF BACKGROUND SPECTRA

Let us calculate total integrated emission coefficient  $\varepsilon_{455}$  of background spectra in the range of  $455.0 \pm 0.3$  nm:

$$\varepsilon_{455} = \varepsilon'_{\text{cont}} + \varepsilon_{\text{S}_2 455}. \quad (10)$$

In Fig. 3, bold curves represent  $\varepsilon_{455}$  as a function of  $T$  at  $P = 0.1$  MPa. It should be noted that the temperature dependence of  $\varepsilon_{455}$  for  $X_{\text{Fe}} = 0$ –0.01% agrees fairly well with that of  $I_{455}$ . This agreement indicates that the background spectra at the wavelength of 455 nm mainly consist of not continuous spectra but S<sub>2</sub>S<sub>2</sub> spectra through  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition at  $T < 4500$  K. In addition, the agreement also suggests that  $X_{\text{Fe}}$  in the post-arc channel was probably of order of 0–0.01%.

## VI. CONCLUSIONS

We investigated background spectra in an SF<sub>6</sub> post-arc channel after current zero. Spectroscopic observations were performed to obtain radiation intensity  $I_{455}$  of the background spectra at 455 nm as a function of temperature  $T$ . The intensity  $I_{455}$  proved to decrease with  $T$  from 5000 to 4600 K, while to increase slightly with  $T$  from 4600 to 4100 K. To interpret the aspect of this temperature dependence, we first calculated emission coefficient  $\epsilon_{\text{cont}}$  of continuous spectra in the temperature range of 3000–6000 K. However, the temperature dependence of  $\epsilon_{\text{cont}}$  shows no agreement with that of  $I_{455}$  in the temperature range from 3000 to 5000 K. The emission coefficient  $\epsilon_{S_2 455}$  of S<sub>2</sub> spectra due to  $B^3\Sigma_u^- - X^3\Sigma_g^-$  transition at 455 nm were theoretically calculated as a function of  $T$ . Then, we derived the emission coefficient  $\epsilon_{455}$  of background spectra by summing  $\epsilon_{S_2 455}$  and  $\epsilon'_{\text{cont}}$  at 455 nm. The temperature dependence of  $\epsilon_{455}$  agreed fairly well with that of  $I_{455}$ . This result indicates that the background spectra mainly consist of continuous spectra at  $T > 4500$  K, while of S<sub>2</sub> spectra at  $T < 4500$  K.

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