

# A SPECTROSCOPIC ANALYSIS OF AN ARGON-FLUORINE PLASMA IN THE CASE OF TWO EMITTING LAYERS WITH APPLICATION TO THE ABSOLUTE TRANSITION PROBABILITIES OF VISIBLE FLUORINE LINES

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A double-section wall stabilized arc was observed axially, the temperature being about 14 500 K and the electron concentration of the order of  $10^{23} \text{ m}^{-3}$ . The contribution to the spectral line intensity of two emitting sections was analyzed and the plasma composition spectroscopically determined. The atomic concentration of fluorine, supplemented with absolute intensities was used in order to estimate the absolute values of the transition probabilities of the fluorine spectral lines 665.0 nm and 669.0 nm.

## *1. Introduction*

Techniques of the wall-stabilized arc frequently use gaseous mixtures which are prepared in a sandwich of layers with different gas compositions. We used an argon-fluorine plasma mixture placed in the central section of the arc column which was bounded by pure argon windows. This real structure can be substituted by the equivalent structure shown in Fig. 1. The experimental layout was described in detail elsewhere<sup>1)</sup>. During the experiment we were faced with the problem how to determine temperature in the central section by using the spectral lines of argon, which were emitted by the two sections which had different physical conditions. In order to solve the problem we kept the current constant (64.5 A) while varying the fluorine share in several steps beginning from zero flow.

Diagnosis of the physical conditions and the concentration of the plasma constituents was carried out exclusively by spectroscopic means.

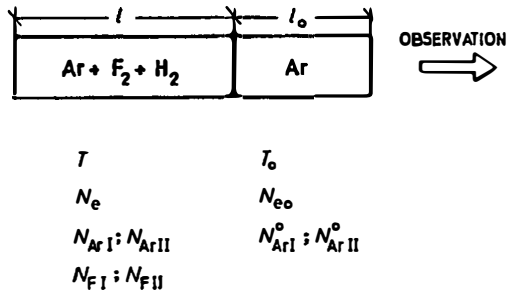


Fig. 1. The equivalent model of the arc column. Length of the central section  $l = 4$  cm, and the sum of the lengths of both window sections is  $l_0 = 3$  cm. The physical conditions of the sections are shown in the figure.

For the purpose we evaluated the *LTE* argon-fluorine plasma composition at atmospheric pressure, for a temperature range from 12 400 K to 14 800 K (in 200 K steps), and for the ratio  $M = (N_{Ar I} + N_{Ar II}) / (N_{F I} + N_{F II})$  from 1 to 100. Since for any temperature the concentration of plasma constituents depends on parameter  $M$ , the ratio of intensities of the spectral lines emitted by atoms of different ionization stages should also depend on parameter  $M$ . Thus for a simultaneous determination of temperature and argon fluorine ratio  $M$  (Fig. 2) we used electron concentration and spectral lines ArII 480.6 nm and ArI 430.0 nm. The ratio of ionic-to-neutral argon lines depends on temperature and electron concentration, and on the relative transition probabilities of lines *AII/AI* (for details, see Ref. 1). The parametric curves of constant temperature appear to be hyperbolas.

The electron concentration was measured by  $H_\beta$  half-width since a small amount of hydrogen was added only to the central arc section, thus  $H_\beta$  always indicates the conditions existing in that section. The behaviour of the electron concentration is shown in Fig. 3 and in Table 1. The error inherent in the electron concentration measurements amounts to 10%.

## 2. Analysis of the contribution of the central section to the intensity of the argon lines

In order to diagnose the physical conditions in a fluorine-argon mixture by using argon lines, one should first determine which part of the line intensity is contributed by the central arc section. Otherwise the derived physical parameters would have an average meaning for both the central and the window sections.

The measured line intensity of argon lines is equal to the sum:

$$J = I l + I_0 l_0$$

$$l + l_0 = L,$$

where  $I$  and  $I_0$  are the line intensities per unit length for the central and the window sections, respectively. The value of  $I_0$  can be found independently, since  $I_0$ , in the constant current regime, is also the intensity per unit length for the whole arc column and for pure argon:

$$J_0 = I_0 L.$$

Combining the relations, we obtain:

$$I = \frac{J - \frac{J_0 I_0}{L}}{l}.$$

Since the uncertainty of the plasma lengths and measured intensity lies within a range of 5%, the resulting error of the ratio of the deduced intensities  $I$  of lines 480.6 nm and 430.0 nm is in the domain of 15%. The ratio of deduced intensities  $I$  is plotted in Fig. 2 together with the ratio of directly measured intensities  $J$ . The temperature of the plasma increases with increasing the fluorine content. When using uncorrected intensities  $J$ , the established temperature has an effective meaning, as an average value for both plasma sections; this temperature shows a trend towards saturation, and is always less than the temperature in the central

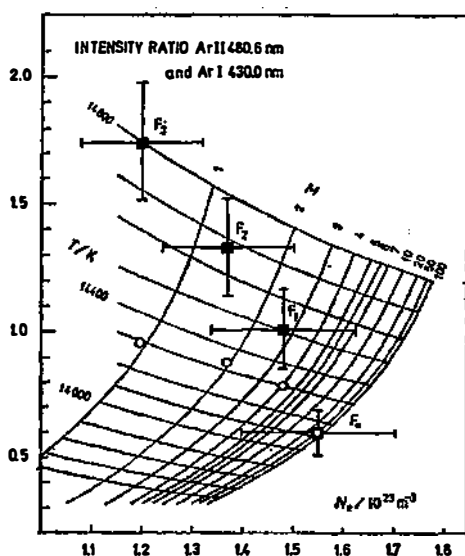


Fig. 2. Parametric dependence of mixture ratio  $M = N_{Ar}/N_F$  and temperature  $T$  on the ratio of the intensities of ionic and neutral fluorine lines, and on electron concentration.

Ratio of intensities  $J$  directly observed from the arc: ○.

Ratio of deduced intensities  $I$  per unit length of the central section: ■; the error bars amount to  $\pm 15\%$ .

The error bar of the electron concentration is  $\pm 10\%$ .

TABLE 1

Measurement	$F_0$	$F_1$	$F_2$	$F_3$
$N_e/10^{23} \text{ m}^{-3}$	1.55	1.48	1.37	1.20
$T(J)/\text{K}$	14 130	14 300	14 350	14 300
$T(I)/\text{K}$	14 130	14 500	14 680	14 800
$M$	$\infty$	$2.7 \begin{smallmatrix} + 4.3 \\ - 1.1 \end{smallmatrix}$	$1.4 \begin{smallmatrix} + 0.8 \\ - 0.5 \end{smallmatrix}$	$0.65 \pm 0.25$
Fluorine percentage %	0	27	42	60
$N_{F1}/10^{22} \text{ m}^{-3}$	0	$8.9 \begin{smallmatrix} - 4.6 \\ + 4.3 (\pm 50\%) \end{smallmatrix}$	$13.7 \begin{smallmatrix} - 3.9 (-30\%) \\ + 3.5 (+25\%) \end{smallmatrix}$	$19 \begin{smallmatrix} - 2.4 (\pm 15\%) \\ + 3 \end{smallmatrix}$
$A_{mn}(665.0)/10^6 \text{ s}^{-1}$	—	0.29	0.42	0.45
$A_{mn}(669. \text{nm})/10^6 \text{ s}^{-1}$	—	1.0	1.55	1.8

Data measured for four different argon-fluorine plasma mixtures,  $F_0, F_1, F_2$  and  $F_3$ .

$N_e$ , electron concentration as derived by means of the  $H\beta$  half-width.

$T(J)$ , temperature determined by means of uncorrected intensities of argon lines;  $T(I)$  temperature determined by means of deduced intensities. The error of temperature is equally sensitive to relative intensity errors as it is to the errors in electron concentration (see corresponding error bars).

$M$ , plasma mixture ratio. The error of the mixture ratio was estimated on the basis of a 10% error of the electron concentration and a 15% error of the relative intensities per unit of arc length. The error margins of neutral fluorine concentration  $N_{F1}$  follows closely the error brackets of mixture ratio  $M$  and temperature  $T$ , the concentration was derived from the calculated plasma composition.

$A_{mn}$ , the transition probabilities.

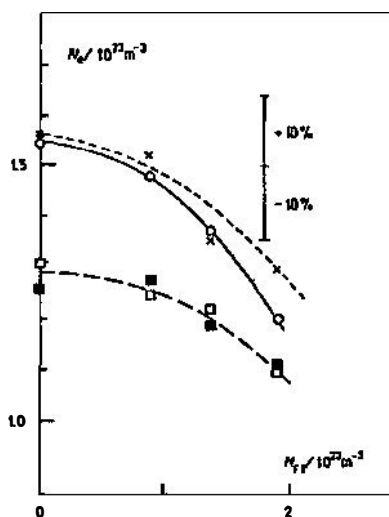


Fig. 3. Electron concentration versus neutral fluorine concentration. Data obtained by means of the  $H\beta$  half-width:  $\square$ ; by the ArI 430.0 nm half width:  $\times$ ; by ArII 480.6 nm:  $\circ$ ; by ArII 476.5 nm:  $\blacksquare$ .

For line 430.0 nm the published constant of proportionality<sup>7)</sup> between electron concentration and full half-width ranges generally from  $1.7 \times 10^{-18} \text{ nm cm}^3$  to  $2.2 \times 10^{-18} \text{ nm cm}^3$ . We took the value  $1.84 \times 10^{-18} \text{ nm cm}^3 = 1.84 \times 10^{-33}$  in order to obtain the best fit with the electron concentration derived by using  $H\beta$  in the pure argon plasma. For lines 480.6 nm and 476.5 nm we took the values given by Ref. 8 which amount to  $0.36 \times 10^{-18} \text{ nm cm}^3$  and  $0.42 \times 10^{-18} \text{ nm cm}^3$ , respectively.

section. The difference, however, is less than 4%. This corresponds to the temperature error mentioned in Ref. 1 and it is quite satisfying when measuring the relative transition probabilities of the spectral lines which have close upper energy levels.

The accuracy of determination of mixture ratio  $M$  — as clearly shown by the error bars in Fig. 2 — is influenced more by the error of the electron concentration measurements than by intensity error. Accuracy increases towards the lower values of  $M$  (see also Table 1). Temperature error remains within the 1.5% margin, even for the 15% error of the relative intensity measurement, and for the 10% error in electron concentration; this can be checked by using the analytical expression for the relative error and relation  $I(480.6 \text{ nm})/I(430.0 \text{ nm}) = f(T, N_e, AII/AI)$ .

The error of mixture ratio  $M$  cannot be further reduced without drastically improving electron concentration measurement, and it reflects the current situation in exclusively spectroscopic diagnostics.

Measuring the electron concentration, we also used the broadening of some argon lines. However, the constants of proportionality between electron concentration and full half widths of these lines are not known with the same precision as in the case of  $H_\beta$ , we present resulting electron concentration (Fig. 3) only for the sake of comparison. The widths of argon lines are influenced by the both sections of the arc, while hydrogen line width is determined only by the electron concentration of the central section.

### 3. Absolute transition probabilities

For given  $M$ , total gas pressure, and temperature, we can find the absolute concentration of the plasma constituents.  $N_{FI}$  obtained in this way (Table 1) was used in order to determine the absolute values of the transition probabilities of spectral lines FI 665.0 nm and 669.0 nm.

The absolute intensity of the spectral lines was measured by means of the internal intensity standard<sup>2)</sup>. Spectral line ArI 763.5 was found to be optically thick and its profile saturated. From the black body plateau, the equivalent width of the fluorine spectral lines,  $W_\lambda$ , was determined directly, knowing the relative spectral response. (In the far red, 2% uncertainty of temperature leads to the black body intensity uncertainty of 3%.)

The transition probability for the optically thin lines is given by:

$$A_{mn} = \frac{8\pi c}{l} \frac{W_\lambda}{g_m \lambda^4} \left[ \frac{N_{FI}}{u} \exp\left(-\frac{E_n}{kT}\right) \right]^{-1}.$$

The relative error of this is:

$$\frac{\Delta A_{mn}}{A_{mn}} = \left| \frac{\Delta W_\lambda}{W_\lambda} \right| + \left| \frac{\Delta N_{FI}}{N_{FI}} \right| + \left| \frac{\Delta l}{l} \right| + \frac{E_n}{kT} \left| \frac{\Delta T}{T} \right|.$$

The first term on the right side includes the error of the estimated black body level, but is mainly governed by the measured area under the profile and is close to 10% (in the case of the weaker line 665.0 nm it is rather 15%). The third term does not exceed 5%, and the last one 15% (considering 1.5% as temperature error). The main contribution to the error comes from the uncertainty in the concentration of fluorine neutrals  $N_{F1}$ , and even 15% in the case of flow  $F_3$  is an overoptimistic figure. Based on the three measurements (Table 1), the weighted mean value for the transition probabilities is equal to:

$$A(665.0 \text{ nm}) = 0.4 \times 10^6 \text{ s}^{-1} (\pm 60\%)$$

$$A(669.0 \text{ nm}) = 1.5 \times 10^6 \text{ s}^{-1} (\pm 50\%).$$

These values are 1.65—1.7 times higher than those published in Ref. 3,  $0.23 \times 10^6 \text{ s}^{-1}$  ( $\pm 35\%$ ) and  $0.91 \times 10^6 \text{ s}^{-1}$  ( $\pm 34\%$ ), respectively. Kurucz and Peytremann<sup>4)</sup> evaluated  $0.23 \times 10^6 \text{ s}^{-1}$  and  $1.27 \times 10^6 \text{ s}^{-1}$ , respectively. It should be mentioned that tables<sup>5,6)</sup> present generally more than twice higher values than were those given by arc measurements<sup>3)</sup>. Due to the very high error inherent in spectroscopic diagnostics of plasma composition, our estimate cannot be conclusive or solve the ambiguity, but our results indicate higher transition probabilities than previously found in the arc.

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SPEKTROSKOPSKA ANALIZA ARGON-FLUOR PLAZME U SLUČAJU  
DVOSTRUKOG SLOJA I ODREĐIVANJE APSOLUTNIH  
VJEROJATNOSTI PRIJELAZA LINIJA FLUORA U VIDLJIVOM

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Aksijalno je opažan zidom stabilizirani električki luk koji se sastoji od dva sloja s različitim fizičkim uvjetima. Temperature su se kretale oko 14 500 K, a koncentracije elektrona oko  $10^{23} \text{ m}^{-3}$ . Razdvojen je doprinos opažanom intenzitetu linija nastao od dva sloja, te je spektroskopskim putem određena kompozicija plazme. Mjerenjem apsolutnih intenziteta procijenjene su apsolutne vjerojatnosti prijelaza spektralnih linija fluora 665.0 nm i 669.0 nm.