Paper

Phenomenon of End of Life in a Fluorescent Lamp and By-Investigation of Alkali Metal Adsorption System

Minoru MYOJO
Matsushita Electric Industrial Co., Ltd.

Osamu FUKUMASA
Yamaguchi University

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ABSTRACT

The mechanism that causes the end of lamp life (EOLL) phenomenon in a fluorescent lamp should be clarified to achieve an effective measure for that. The EOLL phenomenon, including the tungsten sputtering from an electrode, is investigated. We observed the electron emission from a lead in the vicinity of the stem glass. The electron emission causes the intermittent pulse discharge that heats up the stem glass. The concentration of lamp current directly into one of leads is another factor to heat up a small glass portion around the lead. The comparison of the stem glass resistance and the glow discharge impedance between leads after the filament disconnection indicates whether or not the stem glass will begin to soften. It was shown that the heating of a small glass portion around the lead was a dominant factor that resulted in the final stage of EOLL, that is, a substantial overheating of a lamp end portion.

The way of operation for testing the life-ended fluorescent lamps is expected to contribute to the further understanding of the alkali metal adsorbate on metal surface.

KEYWORDS: fluorescent lamp, end of life, overheating, emissive coating, depletion, alkali metal adsorption

1. Introduction

In recent years, the high-frequency lighting systems of fluorescent lamps with electronic ballasts have contributed to a great improvement of the lamp efficacy and a distribution of value-added functions, such as dimming. However, it was found that the fluorescent lamp end portion could be sometimes overheated highly at the end of the lamp life (EOLL). The optimization of the whole system has become a new technical challenge.

A solution to this problem is to employ an EOLL detection circuit in the ballast having a function to shut down the fluorescent lamp operation[1]. The standardization of the test circuit that judges the propriety of the detection circuit in practical ballasts is being investigated by the IEC (International Electrotechnical Commission)[2] together with ANSI(American National Standards Institute), JELMA(Japan Electric Lamp Manufactures Association) and others. At the same time, other solutions by lamp design changes using a thermal cut-off[3], a pellet[4] to emit an arc-terminating gas, and ceramic[5][6] or glass[7] pieces mounted near electrodes have been introduced. They are expected to lower the probability of overheating at the lamp end portion.

To employ the above-mentioned measure effectively, it is important that one has a good understanding of the EOLL phenomenon in a fluorescent lamp. The main intention of this paper is to clarify the mechanism of the EOLL phenomenon and to present the difference in mode of discharge occurrence at a lead root according to the material combinations between surface metal of the lead and alkali component in the stem glass.

2. Outline of the EOLL Phenomenon

First of all, we considered the lamp operating condition to investigate the EOLL phenomenon. Fluorescent lamps were mated with the electronic ballast having the capacitor C1 of a filament heating system in **Fig.1** (here, we called the ballast C-type) and having no EOLL detection circuit. After disconnection of the filament the capacitor C2 is added by switching to the C-type ballast so that the ballast could maintain the lamp voltage highly at any time during operation. The reason why the C-type ballast is employed here is that the filament heating circuit of this type ballast

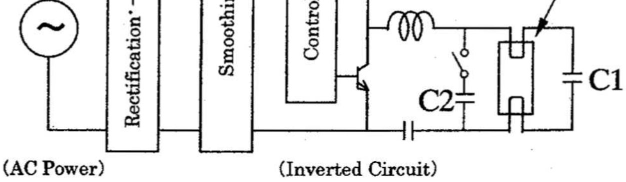

Fig.1 Electronic lighting ballast employed for the end of lamp life test

has a higher current-flow tendency than the winding transformer type. The characteristic relates strongly to the capability of flowing current in glass between leads after disconnection of the filament.

It is well known that after depletion of the emissive coating (alkaline earth triple-oxide of (BaSrCa)O) in a fluorescent lamp, the cathode fall voltage rises and the filament current increases. Both phenomena can result in the overheating of the lamp end portion such as a stem glass. At the same time metallic atoms spattered from metals near the electrode including a tungsten filament form a metallic film on the stem glass. When the lamp current between electrodes concentrates into one of leads directly, the glass portion near the lead will be extraordinarily heated up.

After one of the filaments is failed, what happens? The questions are as follows:

- Can the metallic film work electric conductivity between leads and participate directly in the role of melting the stem glass?
- In the case where the stem glass does not melt promptly, does the lamp keep the condition out of melting during the time up to turning off?

To reply on these questions, the paper will insist that the following two points :

(a) the process of beginning to melt the stem glass
(b) the generation mechanism of some intermittent pulse discharges from a lead-root portion should be clarified

3. Experiment for EOLL

3.1 Tested Lamp Type

The compact single-ended, double-straight tube fluorescent lamp FPL36 and the 28mm O.D. tubular, so called 2-foot length fluorescent lamp in Japan FL20SS/18 were examined. The lamps having a small amount or nothing of emissive coating on one of electrodes were prepared for the EOLL test. In those lamps, in general, the lead is made of plated nickel to core wire of iron and the sodium and potassium contents in the stem glass are about 8% of the weight of Na_2O and about 4% of the weight of K_2O, respectively. Two kinds of lamps were operated with the C-type electronic ballast in Fig.1. In the LC resonant system of the circuit, the capacitor C1 of 0.021μF and the capacitor C2 of 2200pF were adopted together with the inductance of 1.78mH. By using this ballast, the filament currents of FL20SS/18 having an emissive coating on both electrodes and only one electrode were measured to be 0.09A and 0.42A, respectively.

3.2 Measuring Apparatuses and Methods

The lamp voltage and current waveforms were measured by using an oscilloscope (Tektronix, TDS3014) and a current probe (Tektronix, TCP202). The current, voltage and electric power (effective value) between leads of the test side were measured with a high-frequency power meter (Yokogawa, WT1030). Those data were measured every 0.4 second and downloaded to a computer. The EOLL phenomenon was observed and sometimes recorded with a commercial digital camcorder if needed.

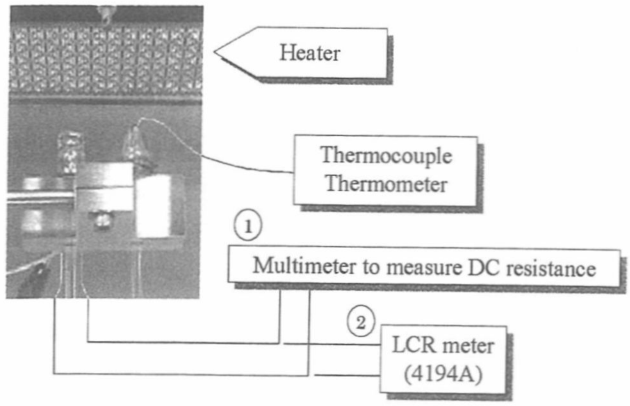

Fig.2 Apparatus that measures the electrical resistivity of a stem glass.

The configuration of the apparatus for measuring the electrical resistivity of a stem glass is shown in **Fig.2.** The object to support the stem was made of SUS304. The upper leads including a filament were removed. With heating by radiation from one direction, the DC resistance of the stem glass between leads was measured by means of a multimeter (H.P., 34401A). The temperature of a dummy stem glass was measured simultaneously. Moreover, the high-frequency impedance was measured by using a LCR meter (H.P., 4194A). A bakelite board for the stem-supporting object was employed to get rid of measurement errors at the high-frequency operation.

For the surface analyses of the lead-root portion including its neighboring glass, the Scanning Electron Microscope (Hitachi, S-2380N), the Auger Electron Spectroscopy (JEOL JAMP-10S) and the Electron Probe Micro Analyzer (JEOL, JZA-8900R) were employed.

4. Results and Discussions

In this chapter we will focus on the following two points:

(a) Process of beginning to melt the stem glass
(b) Generation mechanism of some intermittent pulse discharges.

4.1 Process of Beginning to Melt a Stem Glass

4.1.1 *I-V* Characteristic between Leads

Fig.3 shows the current and voltage variations between leads with the passage of time (a), (c) and their *I-V* characteristics (b), (d) of the lamp FPL36. The time variations show various patterns, whereas the *I-V* characteristic shows the fixed pattern that expresses each impedance of "the filament before disconnection → glow discharge after disconnection → the stem glass just after melting → the molten glass in progress."

Table 1 shows the electrical characteristics of each state. The measurements of 10 several samples gave almost the same results as this table or Fig.3. The insulating resistance between leads after disconnection of the filament and the existence of the site to intercept electronic conduction (see **Fig.4**) are evidences denying the electronic conduction

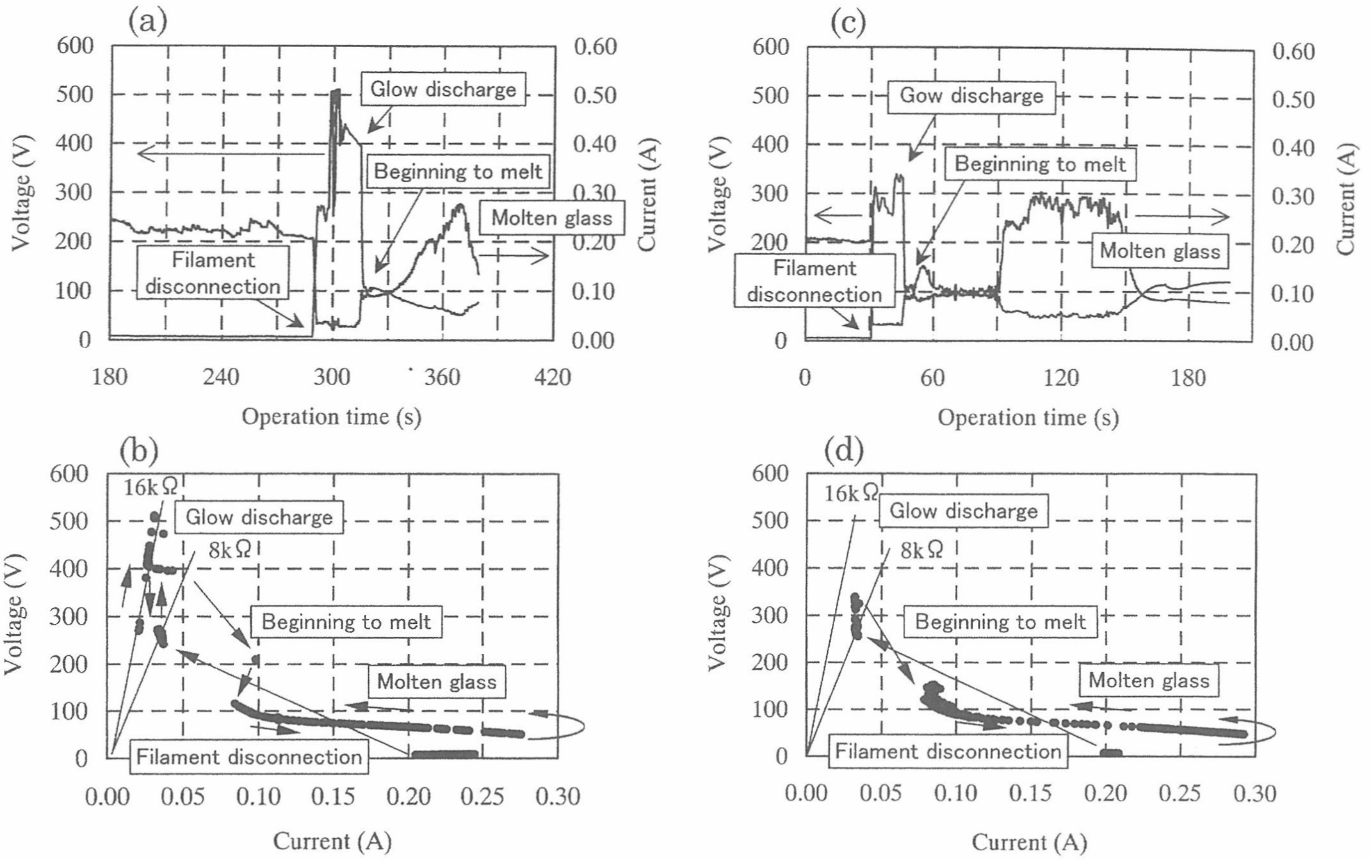

Fig.3 Time variations of current and voltage between leads (a),(c) and their *I-V* characteristics (b),(d) (FPL36).

between leads. The occurrence of the glow discharge just after disconnection of the filament can be taken as the collateral evidence. That is why the molten glass by way of electronic conduction does not indicate such a large impedance as the glow discharge.

As shown by the arrows in <Molten glass> in Fig.3 (b) and (d), the impedance of the molten glass was changed in both-way along the *I-V* curve. It can be supposed from the result that in the progression of the glass melting the cross-section area of ionic conduction would expand, and then the conduction distance would extend as reducing the cross-section area again. The shape of deformed glass also supports this idea.

The impedance values at the times before and after the stem glass melting shown in Fig.3 (b) and (d) will be helpful to the further discussion.

4.1.2 Ionic and Mixed Conductions between Leads

In order to evaluate the ionic and mixed (that is, ionic and electronic) conductions between leads, the effective cross-section area for ionic conduction inside the stem glass is investigated first. The DC value is assumed being also applied to that in the high-frequency impedance of the glass. After that, the ionic conduction distance will be calculated and the temperature of ionic conductive portion near the lead root just before the whole stem glass melting will be estimated.

Table 1 Electrical characteristics between leads of each state (FPL36).

State	Impedance (ohms)	Electric power (W)	Power factor
Filament coil	30-35	about 1.5	about 0.98
Glow discharge just after disconnection	8.0k-8.4k	6.8	about 0.73
Glow discharge	8.0k-16.0k	3.2-7.4	0.33-0.82
Stem glass just after melting	1.4k	9.7	0.99
Molten stem glass	1.4k→0.2k→1.2k	9.0-14.0	more than 0.99

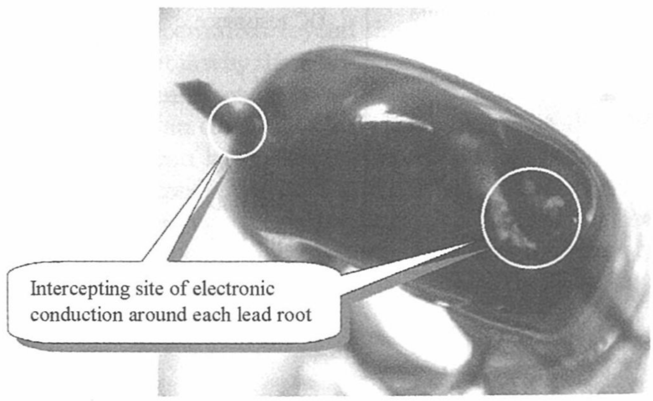

Fig.4 Intercepting site of electronic conduction around each lead root (FL20SS/18).

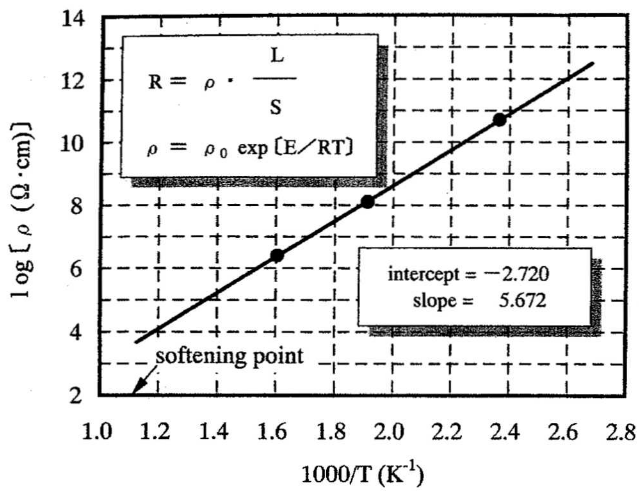

Fig.5 Electrical resistivity of the stem glass (FPL36).

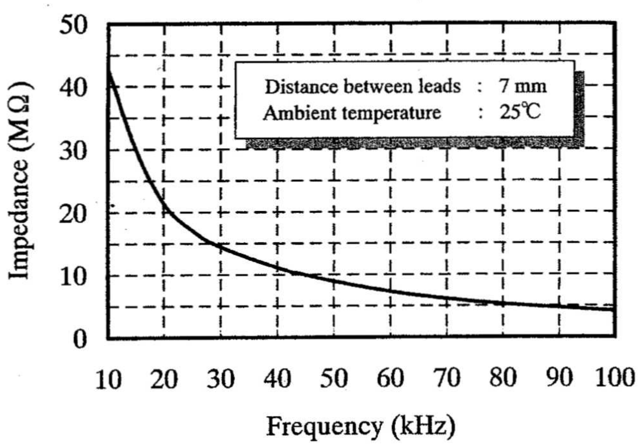

Fig.6 Frequency variation of impedance of the stem glass between leads (FPL36).

(a) Effective Cross-Section Area for Ionic Conduction

The electrical resistivity of the stem glass is given by the equation (1), which is derived from data brought by a glass manufacturer, as shown in **Fig.5**.

$$\log \rho = -2.720 + 5.672\ (1000/T) \quad (1)$$

where T is temperature[K] and ρ is electrical resistivity[ohm·cm].

On the other hand, the apparatus in Fig.2 provides the DC glass resistance between leads at each stem temperature (see **Table 2**). The glass resistance between leads**(ii)** measured at each temperature**(i)** can be converted into a certain value of electrical resistivity**(iii)** by multiplying by some S/L value (S is the effective cross-section area [cm^2] for ionic conduction and L is its distance [cm]) Using equation (1) the electrical resistivity**(iii)** can provide a corresponding value of calculated temperature**(iv)**. In order that the temperature of calculation**(iv)** corresponds to that of measurement**(i)**, the S/L value can be determined. As the value L is experimentally known as L= 0.70cm, the effective cross-section area S[cm^2] can be achieved.

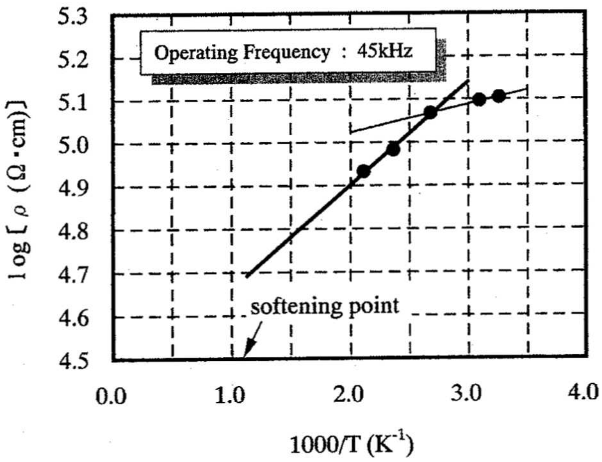

Fig.7 High-frequency electrical resistivity of the stem glass (FPL36).

Table 2 Estimation of the effective cross section area for ionic conduction (FPL36).

Temperature of stem glass (measured) (℃)	DC resistance (Ω)	Electrical resistivity log [ρ (Ω·cm)]	Temperature of stem glass (calculated) (℃)
450	7,590,000	4.989	**463**
500	2,954,500	4.580	**504**
550	1,364,000	4.244	**542**
600	500,000	3.808	**596**
(i)	(ii)	(iii)	(iv)

Conduction distance L = 0.70 cm (measured)

Effective cross-section area S = 0.009 cm^2 (Fitting)

From the result in Table 2, the effective cross-section area of the stem glass can be estimated to be S=0.009cm^2. The diameter when selecting the cross-sectional form circularly is about 1mm. We consider here the temperature and distance dependencies on the effective cross-section area. The temperature dependency seems to be small because a common value of the effective cross-section area could be given throughout the temperatures in Table 2. On the other hand, the uniform heating condition to the glass surface by radiation from one direction provides another condition that the distance dependency is small. That is why the ionic conduction path will be in the glass surface layer within 1mm. The value S=0.009cm^2 is assumed to be available on the high-frequency operating condition as well.

(b) High-Frequency Impedance of a Stem Glass

Fig.6 is an experimental result that shows the frequency variation of the stem glass impedance between leads at room temperature. The most is a resistance component because the capacity component is the minimum of several 100 fFs (femto Farads). The resistance component in 45kHz is estimated to be almost 10Mohms.

Fig.7 shows the electrical resistivity in 45kHz having two straight lines. Using the straight line of equation (2) in a higher region of temperature T[K] up to the softening point:

$$\log \rho = 4.422 + 0.240\ (1000/T) \quad (2)$$

the electrical resistivity ρ [ohm·cm] was estimated.

According to equation (2), the electrical resistivity at the softening point of 615 degrees C is $\log \rho$=4.69 in 45kHz. The electrical resistivity with a higher frequency of 100kHz was estimated as well because the operation frequency at the life end tended to increase. The value was obtained in the same way as almost $\log \rho$=4.34.

(c) Mixed Conductivity and Beginning of a Stem Glass Melting

We noted earlier that the electric conductivity on stem glass between leads did not come from only electronic conduction in a metallic film. Now then, is it possible that the stem glass would begin to melt only by ionic conduction in glass?

On assumption that the surface part of the whole stem glass between leads has reached up to the softening point of 615 degrees C, the high-frequency resistance between leads is calculated to be:

$$R = \rho \cdot (L/S) = 10^{4.69} \cdot (0.7/0.009) = 3.8[\mathrm{M\Omega}] \quad (3)$$

This value is quite larger than the glow discharge impedance of 8k-16kohms derived from the I-V charts in Fig.3 (b) and (d). This calculation means that the current of a filament heating circuit after the filament disconnection does not flows inside of the glass but flows selectively in glow discharge space. In other words, it means that the stem glass, of which surface being reached up to the softening point, cannot begin to melt only by ionic conduction.

These considerations require an idea that the initial electric conduction between leads should depend on the mixed conduction that includes both the ionic and electronic conductions simultaneously.

(d) Temperature of a Lead-Root Glass Portion

Here, the mechanism that begins to melt the stem glass should be clarified. In order to evaluate the temperature of the lead-root glass portion, we take here 2k-8kohms as the impedance between leads at the time after the glow discharge disappearance and just before the stem glass melting from the data of the I-V chart in Fig.3 (b). For the further discussion, moreover, the following three points:

- Resistance in the metallic film by electronic conduction is zero (actually the resistance of the metallic film on the stem glass indicated fairly small and various values, but "zero" value was employed here to make the calculation simple and the evaluation to be on the safe side.)
- Sum total of the distances for ionic conduction near each lead root is L= 0.1-0.2cm
- The cross-section area for ionic conduction is S=0.009cm^2

are assumed.

The electrical resistivity of the stem glass between leads is calculated by:

(i) When L=0.1cm, S=0.009cm^2, then

$$\rho = R \cdot (S/L) = (2000\text{-}8000) \cdot (0.009/0.1) = 180\text{-}720\ [\Omega \cdot \mathrm{cm}] \quad (4)$$

$$\log \rho = 2.26\text{-}2.86 \quad (4)'$$

(ii) When L=0.2cm, S=0.009cm^2, then

$$\log \rho = 1.95\text{-}2.56 \quad (5)$$

These values of electrical resistivity are less than each value of $\log \rho$=4.69 in 45kHz, $\log \rho$=4.34 in 100kHz and $\log \rho$=3.67 in DC at the softening point. This result indicates that the temperature of the lead-root glass portion is higher beyond the softening point and the glass body can move easily. Even if the 1/2 to 2 times values of the cross-section area are taken, there is no change to the conclusion.

As for the ionic conduction distance in the second assumption, there is no need that both lead-root portions have high temperatures beyond the softening point at the same time. That is why there is a possibility that the metallic film on the stem electrically coupled with one of the leads plays a role of an electrode across the lamp. Therefore, the electrode film can have a high temperature easily. In that case the ionic conduction part in the stem can extend from one to another via the glass part beneath the heated electrode film. The impedance change from glow discharge to molten glass in Fig.3 (b) and (d) may express the transition such a phenomenon as this.

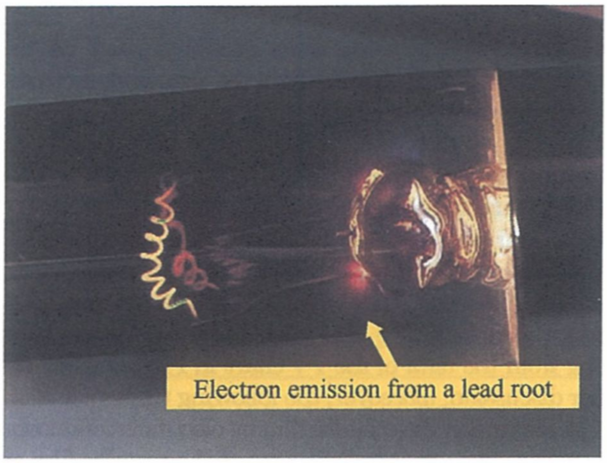

Fig.8 Electron emission phenomenon from a lead root (FL20SS/18).

4.2 Generation Mechanism of Intermittent Pulse Discharge

In Section 4.1, we emphasized the ionic conduction in glass around a lead root, and explained the process of the beginning to melt the stem glass.

In this section, we will consider a cause to heat up the glass portion around a lead root besides the heating by the lamp current that concentrates directly into one of leads. The cause we pick up here is the intermittent pulse discharge. The discharge results from the electron emission from a lead root (refer to **Fig.8**).

We observed two types of lamp current waveforms having a large amplitude as shown in **Fig.9** (a),(b) and considered that both waveforms were caused by electron emissions. However, the former waveform of Fig.9 (a) did not correspond well to the electron emission from a lead root because they were not always observed at the same time.

Therefore, the former waveform of Fig.9 (a) was dealt with out of consideration. On the contrary, the latter waveform of Fig.9 (b) always corresponded to the electron emission from a lead root. The electron emission phenomenon from a particular part in a lamp is more reasonable to be explained by an internal cause rather than an external one, such as a circuit driving.

In the following clauses, we will emphasize the phenomenon of reducing the work function by the alkali metal adsorbate on metal surface as an internal cause. As for the electron emission phenomenon in the discharge space, although the γ-mechanism of the adsorbate should be taken into consideration, it was not dealt with in this paper because it was still under investigation.

4.2.1 Alkali Metal Adsorbate on Metal Surface

After the first theoretical discussion of the alkali metal adsorption on metal surface by I.Langmuir[8] and R.W.Gurney[9], the question of the electronic structure of the adsorbate is still being discussed[10)-15)]. Although the theoretical picture is not clarified, the phenomenon of reducing the work function of about 3eV in Cu(001)-K system[10] may come out to the similar system of the alkali metal adsorbate on the lead surface in a life-ended fluorescent lamp. The analyses of the Auger Electron Spectroscopy (see **Fig.10**) and the Electron Probe Microanalyzer (see **Fig.11**) can verify the existence in plenty of alkali metal at the interface between glass and lead. The reduction in the work function at the lead-root portion will allow the electron emission from there.

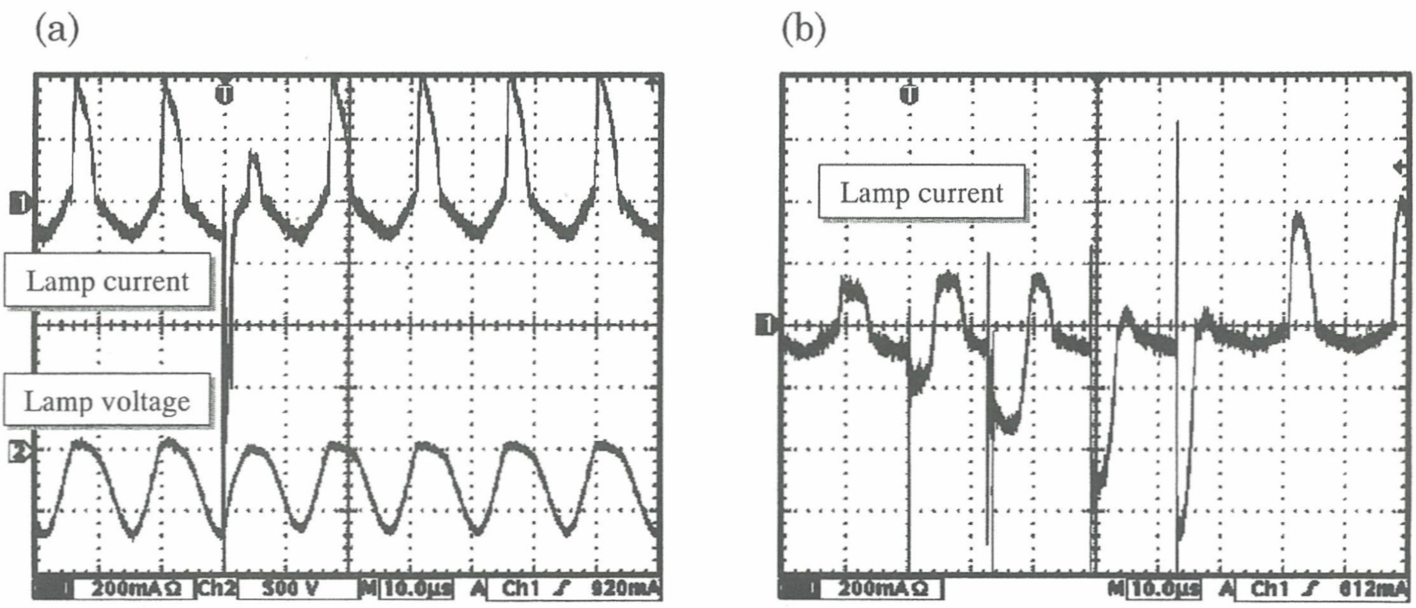

Fig.9 Lamp current waveforms having a large pulse amplitude of two patterns (a),(b) in a fluorescent lamp (FL20SS/18) having no emissive coating on one of electrodes (DC connection mode).

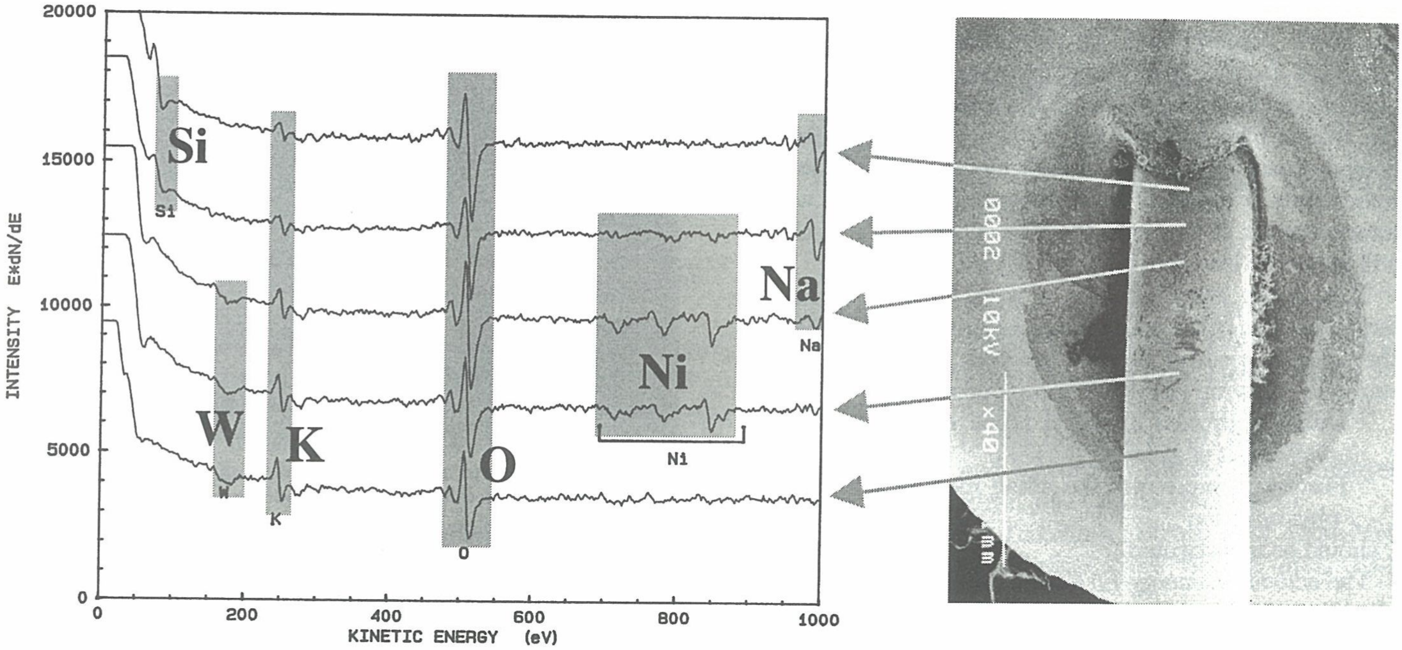

Fig.10 Surface analysis of the lead root by Auger Electron Spectroscopy (FL20SS/18).

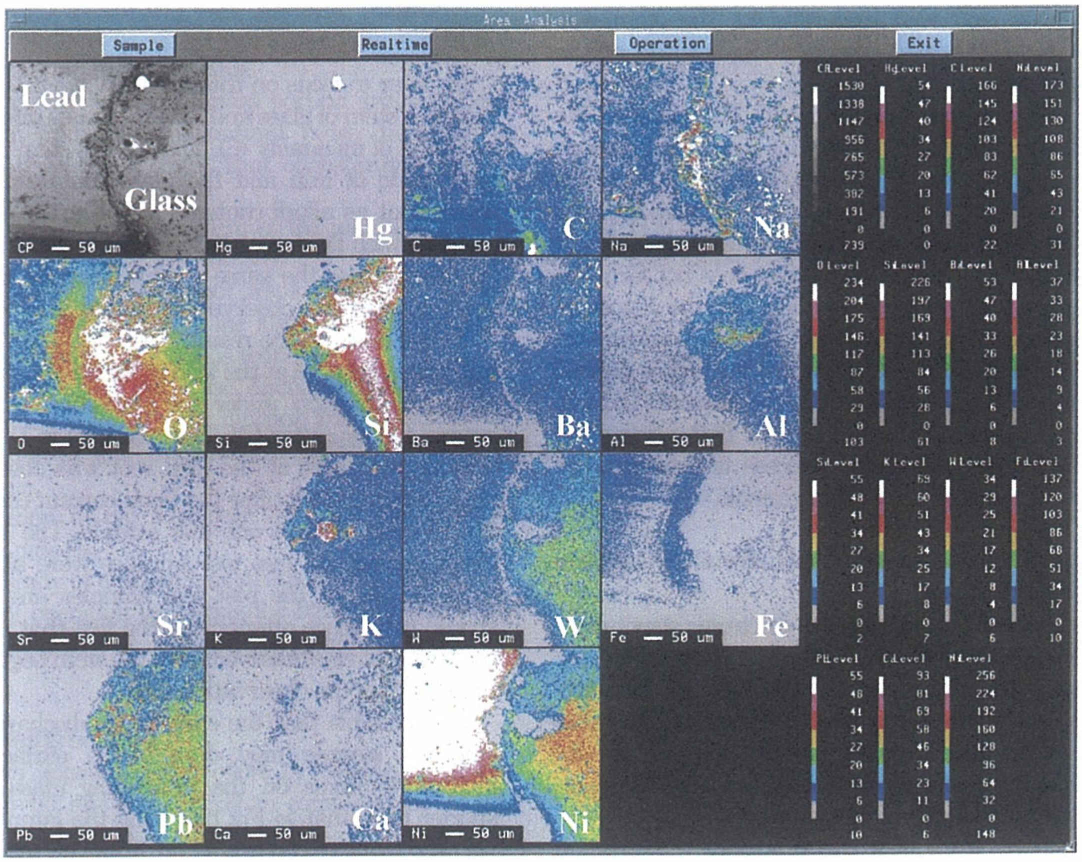

Fig.11 Surface analysis of the lead root including its neighboring glass by Electron Probe Microanalyzer (FL20SS/18).

4.2.2 Intermittent Pulse Discharge from the Lead Root

The intermittent or continuous mode of the electron emission may depend on the magnitude of the reduction in the work function and its decreasing rate. A halfway reduction in the work function may generate a great quantity of ion bombardment to the emission site because of the rather high cathode fall voltage at there. When the bombardment destroys the alkali metal adsorbate and its reformation is delayed, the electron emission mode will be intermittently. In that case the intermittent pulse discharge will make the lead-root portion heat up.

This is the story there is a need to think about the formation rate of the alkali metal adsorbate. It will relate to the decreasing rate of the work function. As for the formation rate, the following rate-determining process:

- Diffusion process in which alkali ions go to the lead surface out of glass
- Formation process of the alkali metal adsorbate after physisorption

should be investigated.

The activation energy E_D for the diffusion coefficient D of alkali ions in the stem glass is almost the same as that for the electrical resistivity, and is estimated to be 26kcal/mol (1.1eV) by using Fig.5 and equation (1). This value shows the ease of diffusion of the alkali ions in glass in terms of the common view.

On the other hand, when the lamp FL20SS/18 having conventional glass and lead materials for the stem was operated for the EOLL test, the first observation of the electron emission from a lead root was not obtained immediately but obtained after around 10 minutes. We think the fact is a good sign that there is room to discuss an activated-adsorption process concerning the formation of the alkali metal adsorbate on metal surface. That is to say, the fact means that the alkali atoms having already existed next to the lead surface prior to the EOLL test does not form the adsorbate that reduces the work function, and the adsorbate will be formed later by way of the activated adsorption process. The progress of the activation process seems depend on the impressed energy coming from the filament heating in the discharge space by the EOLL test. If the activation energy for the further adsorption process is obtained, the rate-determining process can be determined.

4.2.3 Further Discussion of Alkali Metal Adsorbate on Metal Surface

The discussing point concerning the electronic structure of the alkali metal adsorbate on metal surface is in the following. One is the adsorption theory based on the early picture of the Langmuir-Gurney model of ionicity, the other based on the recent picture of the modern *ab initio* density functional calculations of covalency. In the case of taking up the ionicity, the following condition:

Work function (W.F.) of a metal surface > Ionization potential (I.P.) of an alkali metal .... (6)

is required to the adsorption system.

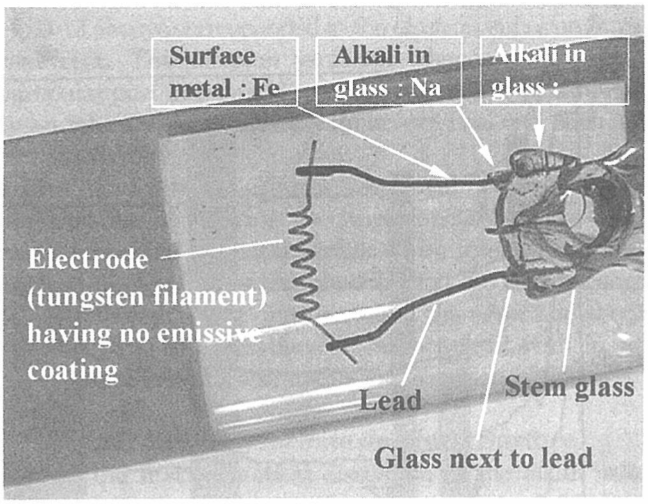

Fig.12 Configuration of the stem using the lead having an iron surface that contacts with the glass containing only sodium component as alkali contents (FL20SS/18).

Table 3 The first observation time of discharge at the lead root (n=5 each).

	Materials (W.F. 16) or I.P. 17) in eV)		First observation time (min.)
	Lead : Surface metal	Stem : Alkali in glass next to the lead	
This test	Fe (4.50)	Na (5.14)	(*) , average 51
Conventional	Ni (5.15)	Na (5.14) + K (4.34)	7-19, average 11

In order to focus on this question, we prepared the lamp having a stem of glass and lead materials under the opposite condition of inequality (6). That is, the stem consisted of the lead made of iron and the glass containing only sodium component as alkali contents (see **Fig.12**). The test lamps together with the lamps having conventional materials were operated under the same condition as the EOLL test and were examined to observe the discharge at each lead root.

Table 3 shows the result. The EOLL test was continued until the discharge at the lead root was observed or the stem glass was broken under the operation with the ballast having the capacitor C2. The mark (*) in this table means that no discharge at the lead root was observed until the stem begun to melt after the lamp current concentrated into one of leads besides one test sample. The lamp operation times among the rest test samples were almost one hour each. As far as the rest test samples are concerned, we should take more attention to the fact that no discharge at the lead root was observed until the stem begun to melt than the length of the observation time.

It is possible that the early pulse discharge observed by one test sample may due to the surface diffusion of potassium atoms on the protruding glass that is much shorter than that in Fig.12 during the lamp production. So we need to survey on this again, however, the table generally indicates that the discharge occurrences at the lead root of the test samples are much difficult than the conventional ones. We are not sure whether the reason for this result is dependent on the opposite condition of inequality (6), but sure that the material combination between glass and lead clearly provides the different discharge modes at a lead root and conjures the image of their different adsorption patterns. As is possible to provide some dynamic information concerning the alkali metal adsorbate on metal surface, the way of operation for testing the life-ended fluorescent lamps is expected to be useful for the by-investigation of the electronic structure of the alkali metal adsorption system.

5. Conclusion

Main two subjects concerning the phenomenon of a life-ended fluorescent lamp:

(a) The process of beginning to melt the stem glass

(b) The generation mechanism of the intermittent pulse discharge

were discussed. In addition, our approach to investigate accessorily the alkali metal adsorbate on metal surface was introduced.

The paper is summarized in the following.

As for the process of beginning to melt the stem glass,

(1) The glow discharge impedance between leads after disconnection of the filament and before the melting of the stem glass varied in the region of 8k-16kohms in the case where the distance between leads was about 7mm.

(2) The stem glass begun to melt at the time just after the impedance between leads reached to less than 2kohms.

(3) The mixed conduction that consists of ionic and electronic conductions plays an important role of the initial conduction between leads.

(4) The heating of the partial glass portion around a lead root results from the intermittent pulse discharge at there and the lamp current that concentrates directly into one of leads.

As for the generation mechanism of the intermittent pulse discharge,

(5) The discharge at the lead root results from the electron emission from the site where the alkali metal adsorbate is formed and the work function is reduced.

(6) The intermittence of the pulse discharge comes from a halfway reduction in the work function and the iteration of the destruction by ion bombardment and the formation of the adsorbate.

(7) The formation of the adsorbate will have the activated adsorption process.

As for the study of the alkali metal adsorption system,

(8) The way of operation for testing the life-ended fluorescent lamps is expected to be useful for the by-investigation.

6. Acknowledgment

The authors appreciate the effort by colleagues in the lighting field who are challenging to complete the EOLL measure in fluorescent lamp systems. We are pleased if the descriptions in the paper are referred to such engineers. We also thank Mr.S.Tabata who is a manufacturing manager of fluorescent lamp factory in Lighting Company of Matsushita Electric Industrial Co., Ltd. for assisting to make special lamps and thank Dr.H.Ogawa who is CTO in the company for sticking up for us.

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