The Effect of Mercury on Damage to Cold Cathode Fluorescent Lamp Electrodes

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ABSTRACT
Two kinds of the cold cathode fluorescent lamps (CCFLs) were operated at 5 mA as a life-test with Ni plate electrodes. One kind of CCFL contained Ne-Ar-Hg (Hg CCFL) and the other contained Ne-Ar (Hg-less CCFL). The results of the operations showed that the Hg CCFL’s voltage decreased with operating time continuously. On the other hand, the voltage of the Hg-less CCFL began to increase and its emitting light color changed from light violet to strong red after about 6000 hours operating time. The V-t and I-t waveforms of the Hg CCFL did not change during the life test, while those of the Hg-less CCFL at 6000 hours were different from those at 8000 hours. The waveform data seem to show that the Hg CCFL’s discharge was glow mode and that the Hg-less CCFL discharge changed from glow mode to arc mode after 6000 hours operating time. The authors then observed the electrodes of both kinds of lamps at 8500 hours operating time. The shape of Hg CCFL’s electrode at 8500 hours was the same as at 0 hours, but that of the Hg-less CCFL at 8500 hours was very different from at 0 hours. The tip of Hg-less CCFL’s electrode at 8500 hours operating time was gouged and U-shaped. The data show that the reason for the gouging of the electrode at lamp life end, or in very low temperature operation, was the sputtering of rare gases caused by the depletion of Hg.

KEYWORDS: CCFL, mercury, electrode, life test

1. Preface
In recent years, liquid crystal displays have often been used to display information on monitors, televisions, and signs. Since the liquid crystal module does not emit light, a backlight source is attached to the rear side of the liquid crystal module of liquid crystal displays to illuminate the screen. There are two main types of backlight sources: light emitting diode (LED) and cold cathode fluorescent lamp (CCFL). LED is used with mobile phones, notebook computers, car navigation devices, etc. Liquid crystal displays that use LED have three main features: they are thin, they do not lose brightness even in low-temperature atmospheres, and they do not lose life length even in low-temperature atmospheres. LED is often used as a backlight source for liquid crystal displays that may be used outdoors or in cold areas, such as displays for mobile phones and car navigation devices. Because of recent cost reductions, manufacturers have started to use LED in some liquid crystal televisions. On the other hand, liquid crystal displays that use CCFL have two main features. One is the low unit cost of the light source itself and the other is that optical design for backlighting is simple. In recent years, the price of liquid crystal televisions have continued to decrease, and the use of CCFL in backlight sources is being re-evaluated. A weak point of CCFL is that mercury vapor is used as the source of ultraviolet radiation so its characteristics change according to the surrounding temperature. This is particularly the case when CCFL is switched on in a low-temperature atmosphere such as at 0°C, as the quantity of light is reduced and the electrode is consumed in a short period of time. This reduction in the quantity of light is widely believed to occur because the mercury (Hg) vapor pressure drops, thereby decreasing the radiant intensity of ultraviolet rays (wavelength 254 nm) from the mercury. While the fast electrode consumption is believed to be related to the Hg vapor pressure, the details of this phenomenon are not yet clear.

The current study performed an evaluation through
life tests to investigate the effects of the presence of Hg vapor on electric discharge characteristics over time. This report covers the results of this study.

2. Experiment equipment and methods

2.1 Life evaluation testing

The specifications of CCFL used in this experiment will be described. Figure 1 shows the lamp structure and lighting circuit. The lamp tube diameter was 4 mm and the lamp length was 110 mm (distance between electrodes: 90 mm). The electrode was a Ni plate with a width of 1.7 mm, a length of 5.2 mm, and a thickness of 0.1 mm. Generally, a hollow-type Ni cup is used as the CCFL electrode. However, a Ni plate electrode was used in this study to allow visual observation of negative glow of the electrode surface. The lead wire was made of Kovar. The lead end was flattened and the Ni electrode was secured here using resistance welding. Two types of filler gas were prepared: Ne/Ar (8 kPa) and Hg vapor, and Ne/Ar (8 kPa). The ratio of Ne/Ar was 9:1. The Hg enclosed quantity was approximately 3 mg. This mercury was evaporated and CCFL was filled with Hg vapor. The lighting circuitry used was a type used in commercial products. The fundamental frequency was 35 kHz and the capacitor capacity was 12 pF.

With this lighting system, life testing was performed with an effective electric discharge current value of 5 mA and changes in lamp characteristics over time were investigated. Life testing was performed with six lamps each of the two lamp types (with and without Hg).

2.2 Observation of plasma around the electrode

A device to test the characteristics of cold-cathode tubes made by NF Corporation was used. The lighting frequency was 40 kHz and the output voltage waveform was a sine wave. This CCFL lighting system was observed using a high speed camera to investigate how the presence of Hg affected the spreading of electrode negative glow. The high speed camera used was a high resolution digital camera made by Princeton Instrument (PI-MAX: 512 (Gen III)).

Note that the filler gas pressure and electrode specifications of the lamp used for observation were the same as the lamp used in life testing. Lamps were aged at 5 mA for 20 hours or more before use. In addition, the electrical characteristics of the lamp were measured about 10 minutes after the lamp was switched on at an ambient temperature of 25°C.

3. Experimental results

3.1 Changes in electrical characteristics and luminescent state over time

Figure 2 shows the changes over time for the effective lamp voltage values (average of six lamps) for the CCFL with enclosed Hg (hereafter referred to as Hg-CCFL) and CCFL without Hg (hereafter referred to as Hg less-CCFL). Electric discharge current was 5 mA.

From Figure 2, it can be confirmed that the Hg-CCFL lamp voltage gradually dropped overtime and the Hg less-CCFL lamp voltage gradually rose after the elapsed time exceeded 6,000 hours. Each lamp voltage up to 8,000 hours had a variation of several percent. After 8,000 hours, lamps started to go out. While all 6 Hg less-CCFL lamps stayed lit up to 8,000 hours and aged data exists for this period, after this point the number of lamps still lit changed so the Hg less-CCFL lamp voltage can only be displayed in Figure 2 up to 8,000 hours. At the 10,000 hour point, all six Hg less-CCFL were out.

The luminescent state of the Hg-CCFL did not change at all over the entire lighting time. However, up until 6,000 hours, the emitted light of the Hg less-CCFL was a light violet (see Figure 3 (a)). From 8,000 hours, the...
emitted light changed to a luminance of a strong red (see Figure 3 (b)).

3.2 Changes in voltage and current waveforms over time

Figure 4 shows the Hg less-CCFL lamp current and voltage waveforms at 6,000 hours and after the lamp voltage rose (lit for 8,000 hours/effective lamp current: 5 mA). Figure 5 shows the Hg-CCFL lamp current and voltage waveforms at 6,000 and 10,000 hours (effective lamp current: 5 mA).

From Figures 4 and 5, it is possible to confirm that the Hg less-CCFL and Hg-CCFL lamp current and voltage waveforms change over time quite differently.

Figure 4 shows a large difference in the current and voltage waveforms changes at 6,000 and 8,000 hours. At 6,000 hours, the lamp current and voltage peak values (although slightly different) are at roughly the same time. However, at 8,000 hours, the voltage peak value has moved fairly far ahead of the current peak value. This lamp when out at approximately 9,500 hours.

Figure 5 shows there is no difference in the current and voltage waveforms changes at 6,000 and 10,000 hours. In both cases, the lamp current and voltage peak values (although slightly different) are at roughly the same time. This lamp has been lit with no problems for over 12,000 hours.

3.3 Difference in electrode shape at 8,500 hours

The electrode portion of an Hg less-CCFL lamp for which the voltage rose and the luminous color changed (at 8500 hours) was compared with a corresponding Hg-CCFL electrode using x-ray. Figure 6 shows the results of the observation of the electrode. From the diagram, it is possible to confirm that the presence of Hg causes a large difference in the exterior appearance of the electrode. The Hg-CCFL electrode retained its original shape and no electrode wear was observed. The tip of the Hg less-CCFL electrode appears to have been gouged off. These results show that when there is Hg, there is almost no electrode wear, but when there is no Hg inside the CCFL, the consumption is centered around one part of the electrode (the tip portion is gouged off).

In this study, the life test was performed at room temperature. However, at low temperatures, or in other words when the mercury vapor pressure is low, localized electrode wear may occur like with the Hg less-CCFL even in the case of Hg-CCFL.

This is related only to the life of the lamp, but while all six Hg-CCFL stayed lit even after 12,000 hours, all six Hg less-CCFL went out around 10,000 hours. The cause for the lamp going out is believed to be a (bulb) leak from the section near the electrode. The glass in the area of the electrode was heated and deteriorated heavily. It quickly breaks just by touching it. Figure 7 shows a photograph of this condition. From this information, it is assumed that immediately before the lamp went out, the temperature around the electrode rose a lot.
3.4 Observation of plasma around the electrode

As mentioned in Section 3.3, the tip of the Ni plate electrode is gouged out (forming a U shape) in the case of the Hg less-CCFL but not with the Hg-CCFL. The cause for this discrepancy may be the difference in plasma distribution around the electrode at the time of lighting. The change of the negative glow luminous state was photographed using a high speed camera. To light the lamp, a high-frequency power source by NF Corporation was used and this was connected in series to a 39 pF capacitor and the lamp in question (see Figure 1). The frequency was 40 kHz. The exposure time was 0.25 us. Figure 8 shows the photographs of the negative glow luminous state around the electrode. The times listed here indicate the time elapsed from the instant the cathode cycle was entered. The cathode cycle time was 12.5 us. Note that light emission around the electrode was not observed in the anode cycle.

The photographs of the electrode section on the right side of Figure 8 taught us the following. For the Hg-CCFL, light emission of negative glow was uniform from the time when negative glow was first seen on the electrode surface (2-4 us). As time elapsed, negative glow spread over the entire electrode surface. Next, after the peak value for the lamp current was exceeded, the lamp went out. In this case, the blackening of the glass of the electrode section was extremely small. On the other hand, for the Hg less-CCFL, light emission of negative glow was uneven from the time when negative glow was first seen on the electrode surface (2-4 us.). Strong light emission of negative glow appeared on the electrode tip and the negative glow did not spread uniformly over the entire electrode. The reason the light emission at the root section of the electrode grew stronger was that as the blackening of the glass near the electrode moved closer to the root of the electrode, it became thinner. If there was no blackening of the glass, it is believed that it would have been possible to more clearly observe the strong light emission at the tip by photographs.

4. Discussion of the experiment results summary

4.1 Changes in electrical characteristics and luminescent state over time

The change in luminous color at the 8,000-hour point for the Hg less-CCFL is considered to be due to changes in light emission from Ar light emission to Ne light emission. In addition, the rise in lamp voltage is believed to be due to the change from Ne-Ar electric discharge to Ne electric discharge inside the lamp causing the gas to be ionized changing from Ar to Ne, which has a high ionization voltage.

On the other hand, the reason the electrical characteristics and luminescent state of the Hg-CCFL did not change is that since it is in a saturated state with 3 mg of Hg enclosed, which causes ionization and light emission, even when Hg disappears from the electrode or tube wall, Hg atoms are constantly supplied and do not disappear in the space inside the tube.

4.2 Changes in voltage and current waveforms over time

Next, the reason for the large changes in current and voltage waveforms at 6,000 and 8,000 hours will be discussed. Figure 9 shows the electrical characteristics of
standard discharge lamps. Section D is the normal glow discharge range, section E is the abnormal glow discharge range, section F is the transient range from glow discharge to arc electric discharge, and section G is the arc discharge range. In Figure 4, the changes in current and voltage overtime were roughly the same in the case of 6,000 hours. They are similar to the discharge in sections D and E of Figure 9. However, the area outlined by the dotted line in the case of 8,000 hours shows that the current increased but the lamp voltage decreased. The discharge of this section is similar to the discharge in section F of Figure 9 (when corrected to direct current).

Here, Figure 9 shows the current and voltage characteristics of direct current electric discharge. The change from section D to section G is believed to be mainly due to a change in the mechanism of electron emission from the electrode. The discussion of current and voltage waveform for Figure 4 concerns the current and voltage characteristics at 35 kHz. Because the lighting frequency is different, the changes in current and voltage characteristics are not exactly the same but they are considered to be due to a change in the mechanism of electron emission from the electrode.

4.3 Difference in electrode shape at 8,500 hours

Figure 6 shows the observational results of the electrode of the Hg-CCFL and Hg less-CCFL by x-ray. For the Hg-CCFL, since deformation of the electrode did not occur, it is believed that when Hg is present, electrode metal scattering by sputtering is held back. Meanwhile, the hollowed out shape of the electrode of the Hg less-CCFL is believed to be due to Ni scattering by ion sputtering. This lamp contains Ar and Ne. Changes in the above mentioned electrical characteristics and lamp luminous color are considered to be as follows. Initially, there were two types of atoms. However, after the 6,000 hour point, Ne emission luminous color occurred and the lamp voltage started to rise. At this point, this caused ionized Ar⁺ to collide with the Ni electrode, leading to electrode sputtering.

4.4 Observation of plasma around the electrode

Figure 8 shows the changes of the negative glow emitting state around the electrode over time with lighting at 40 kHz sine wave alternating current. Since new lamps have unstable discharge characteristics, lamps that had been aged 20 hours were used in this experiment.

Figure 8 shows that negative glow spread over the entire electrode surface in the case of the Hg-CCFL. However, in the case of the Hg less-CCFL, negative glow did not spread over the entire electrode but remained focused on the tip. This is considered the cause of the difference in the spreading methods of plasma.

Ar⁺ and Hg⁺ are mentioned as possible ions in the vicinity of the cathode for Hg less-CCFL and Hg-CCFL, respectively. It is also possible that there are Hg²⁺ ions in the vicinity of the electrode for Hg-CCFL. Therefore, the role of the mobility of these ions will be considered next. The rare gases enclosed here are Ne and Ar (pressure ratio 9:1) and the ion types on the cathode front surface differ slightly from the case of pure Ar or Ne. Mobility in the case of mixed gas is expressed by Formula 1 below.

\[
\mu = \frac{1}{\mu_{Ne}} + \frac{1}{\mu_{Ar}}
\]

Here, \(\mu_{Ne}\) and \(\mu_{Ar}\) are the mobility of ions in Ne and Ar, respectively.

Table 1 shows Hg ion (Hg⁺, Hg²⁺) mobility in Ne gas and Ar gas. These mobility values are values cited from literature (760 Torr, 300 K) or calculated from drift velocity in inverse proportion to gas pressure. Table 2 shows Ar⁺ mobility in Ar and Ne gases. As in the case of Hg ions, the Ar⁺ mobility in Ar gas was obtained from literature. Since no data could be found for Ar⁺ mobility in Ne gas, it was calculated from theoretical formulas and the data of Table 1. Formula 2 is used to calculate ion mobility.

\[
\mu = \frac{e \lambda}{M_i \langle v_i \rangle}
\]

In this formula, \(e, M_i, \langle v_i \rangle\), and \(\lambda\) are electron charge, ion mass, mean speed, and mean free path. Here, Ar⁺ mobility in Ne gas and Ar⁺ mobility in Ar gas are written \(\mu_{Ar^{-}Ne}\) and \(\mu_{Ar^{-}Ar}\), respectively. When Ar⁺ ions are in Ne or Ar, \(e\) and \(M_i\) in Formula 2 do not change. Furthermore, when the pressure and temperature are the
same, \( <v_i> \) in Formula 2 can be considered unchanged. The item that changes is the mean free path \( \lambda_i \). Here, if the ion mean free path and atom mean free path are considered to be roughly equivalent, the mean free path of \( \text{Ar}^+ \) in rare gas is expressed by Formula 3\(^{30} \) and is dependent on collision cross-section \( \sigma \).

\[
\lambda_i = \frac{1}{\sqrt{2} n \sigma} \tag{3}
\]

Here, \( n \) is the atomic density, and if the pressure and temperature are the same, the value is the same. The collision cross-section \( \sigma \) of Ar and rare gas is expressed by Formula 4\(^{30} \). Note that in the case of Ar and Ne rare gases, they are \( \sigma_{\text{Ar},\text{Ar}} \) and \( \sigma_{\text{Ar},\text{Ar}} \), respectively.

\[
\sigma_{\text{Ar},\text{Ar}} = \pi (r_{\text{Ar}} + r_i)^2, \quad \sigma_{\text{Ar},\text{Ne}} = \pi (r_{\text{Ar}} + r_{\text{Ne}})^2 \tag{4}
\]

Here, \( r_{\text{Ar}} \) and \( r_{\text{Ne}} \) are the effective particle radii, which are presented below\(^{39} \).

\[
\begin{align*}
\lambda_{\text{Ar},\text{Ar}} & = 1.82 \times 10^{-10} \text{ m} \\
\lambda_{\text{Ar},\text{Ne}} & = 1.17 \times 10^{-10} \text{ m}
\end{align*}
\]

Consequently, the following is obtained when mean free path is compared.

\[
\frac{\lambda_{\text{Ar},\text{Ar}}}{\lambda_{\text{Ar},\text{Ne}}} = \frac{1}{\sqrt{2} n \sigma_{\text{Ar},\text{Ar}}} = \frac{\pi (r_{\text{Ar}} + r_{\text{Ne}})^2}{\pi (r_{\text{Ar}} + r_{\text{Ar}})^2} = 0.675
\]

First, the results of Table 1 are entered into Formula 1, and then \( \text{Hg}^+ \) mobility in mixed gas is calculated.

\[
\mu_{\text{Hg}^+,\text{Ne}} = \frac{\mu_{\text{Hg}^+,\text{Ar}} \times \mu_{\text{Hg}^+,\text{Ar}}}{\mu_{\text{Hg}^+,\text{Ne}} + \mu_{\text{Hg}^+,\text{Ar}}} = 6.16 \times 10^{-3}
\]

\[
\mu_{\text{Hg}^+,\text{Ar}} = \frac{\mu_{\text{Hg}^+,\text{Ne}} \times \mu_{\text{Hg}^+,\text{Ar}}}{\mu_{\text{Hg}^+,\text{Ne}} + \mu_{\text{Hg}^+,\text{Ar}}} = 1.23 \times 10^{-2}
\]

Next, the results of Table 2 are entered into Formula 1, and then \( \text{Ar}^+ \) mobility in mixed gas is calculated.

\[
\mu_{\text{Ar}^+,\text{Ne}} = \frac{\mu_{\text{Ar}^+,\text{Ar}} \times \mu_{\text{Ar}^+,\text{Ar}}}{\mu_{\text{Ar}^+,\text{Ne}} + \mu_{\text{Ar}^+,\text{Ar}}} = 2.90 \times 10^{-3}
\]

These calculations show that \( \text{Ar}^+ \) mobility is half or less of \( \text{Hg}^+ \) ions mobility.

The results of the calculations above suggest that the difference in ion mobility may be part of the reason for the variation in plasma spreading.

5. Summary

CCFL with and without Hg (Hg-CCFL and Hg less-CCFL) were observed for electrical characteristics under a life test with a constant high-frequency current. The results showed that while change over time of the effective lamp voltage for Hg-CCFL was stable, the voltage of the Hg less-CCFL began to increase and its luminous color changed from violet to red after about 6,000 hours. Furthermore, when the electrode shapes were observed at 8,500 hours, the Hg-CCFL electrode did not change at all while the shape of the tip of the Hg less-CCFL electrode changed greatly. In addition, when the current and voltage waveforms were observed, the Hg-CCFL waveforms did not change at all overtime while the Hg less-CCFL waveforms changed greatly between 6,000 and 8,000 hours. Glow discharge was seen at 6,000 hours but it had shifted to arc discharge by 8,000 hours.

Next, a high speed camera was used to observe the generation status of plasma in the vicinity of the electrode of the Hg-CCFL and Hg less-CCFL. The electrode material, gas type, and gas pressure of the lamps used were the same as those of the lamp for the life test. The lamps were aged 20 hours, and then observed. From the results, it could be observed that while plasma spread over the entire electrode for the Hg-CCFL, the plasma concentrated at the electrode tip for the Hg less-CCFL.

The following points were confirmed by these results.

(a) When there is Hg in the CCFL, there is no electrode damage. When there is no Hg, sputtering causes damage to the electrode. From this, it was learned that the sputtering rates of Hg and Ar ions are different.

(b) When Ar emission stopped, the tip shape of the Ni electrode changed and became hollow and the side edge portions became sharp.

(c) Measurement results from a high speed camera showed that when there was Hg, the plasma spread over the entire electrode. When Hg was not present, the plasma concentrated at the tip portion of the electrode. At the area where it concentrated, the electrode appeared to have been scraped away (and a U-shape was formed). It is believed that this means that plasma concentration causes changes in the shape of the electrode. In other words, the area where the plasma concentrates on the electrode scatters and dissipates with long-term operation.

The difference in Hg and Ar ions mobility is believed to be a possible cause for this plasma concentration.

The above confirmed that electrode wear occurs at the end of life of mercury or during very low temperature operation while the CCFL is lit because Hg ions in the vicinity of the cathode disappear, causing the negative glow of the electrode surface to shrink, and this portion to undergo ion sputtering. In other words, a deeper understanding was gained of the importance of having a sufficient number of Hg ions in the vicinity of the cathode in order to prevent abnormal wear of electrodes.

This experiment used plate-shaped electrodes. In practice, hollow cathodes in the form of cylindrical cups are used. Therefore, it is believed that electrodes wear...
not in one section only but wear gradually from the tip.

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