On the Use of Phosphors Excited by Low-Energy Electrons in a Gas-Discharge Flat-Panel Display

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Abstract—A gas-discharge flat-panel display device has been constructed in which the light output is white and the color is independent of intensity. The device is based on the Burroughs Self-Scan® structure. A white output was obtained by combining the orange glow of a gas mixture which is predominantly neon with the green emission of a ZnO:Zn phosphor (P15) deposited on transparent conducting anodes and excited by incident low-energy electrons. A peak spot intensity of 3000 fL in the white was achieved at a display-cell current density of 0.33 $A \cdot cm^{-2}$ and 180 V across the display cell. In a control region where no phosphor was deposited and the output was orange, the peak spot brightness was 7500 fL. Experiments on single-cell devices using helium, neon, argon, and xenon are described which demonstrate that the phosphor is indeed excited by low-energy electrons rather than by UV radiation from the gas discharge. The latter method had been used exclusively to date to obtain colors other than orange in gas-discharge flat-panel displays.

I. Introduction

IN DEVELOPING a flat-panel gas-discharge display system for a television type of application, there are at present two basically different approaches that can be considered. On the one hand, there are ac-operated panels with memory, such as the Digivue® marketed by Owens-Illinois [1]; on the other hand, there are dc gas-discharge display panels, and in this category, Burroughs' Self-Scan® [2] is perhaps the best known. The first approach has the virtue of providing memory within the panel and leads to high brightness without the requirement of high peak currents. A fundamental drawback of this type of display, however, is the difficulty of achieving gray scale. Where a gray scale is required, as in a video display system, the dc approach is favored. This consideration has been discussed by Van Houten, Jackson, and Weston [3], and the validity of their conclusions is substantiated by the most recent demonstration of real-time gas-discharge displays with gray scale. Both Chen and Fukui [4] of Bell Laboratories, and Chodil, De Jule, and Markin [5] of Zenith Radio Corporation have obtained real-time field-interlaced operation with gray scale using large Burroughs Self-Scan panels. Ikeda, Sakai, and Oishi [6] of Japan Broadcasting Corporation have achieved a similar operation using such a panel but have not demonstrated field interlacing. An exploded view of a Burroughs panel [2] is shown in Fig. 1. These panels are filled with a gas mixture which is predominantly neon, giving rise to a red–orange output. While this color may be adequate for alphanumeric displays, it is unlikely to be acceptable for a monochrome video display, where white is preferred. Furthermore, suitable means for achieving *full-color* displays must be developed if the gas-discharge flat-panel display is to compete seriously with the cathode-ray tube.

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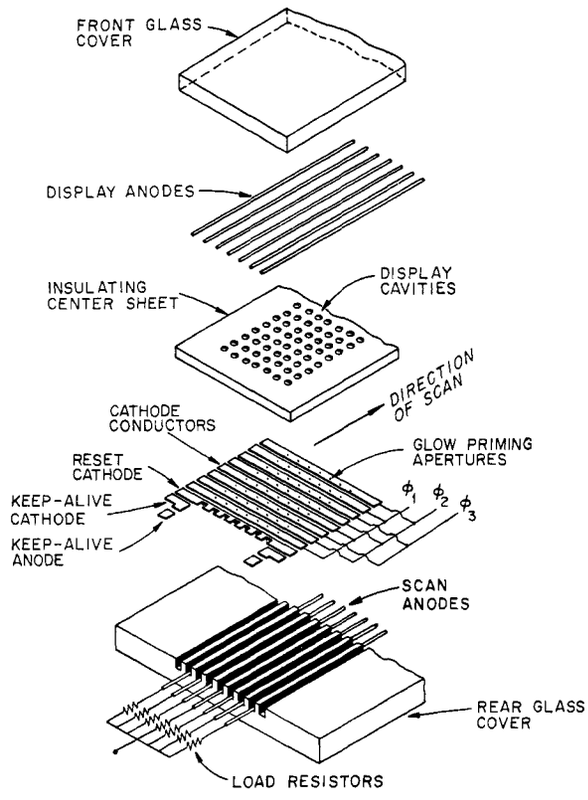

Fig. 1. Exploded view of the Burroughs Self-Scan Panel. A line of discharges struck between a single cathode and the scan anodes is stepped by connecting to a common bus bar every third cathode and driving the cathodes with a three-phase clock. The scanning discharge is confined to the lower portion of the device and serves to prime the display cavities by the diffusion of metastable atoms through a small aperture in the cathode. Information is displayed along a line defined by a given cathode conductor by striking a discharge in the display cell. By virtue of the priming action, the voltage necessary for this is less than the full striking voltage. A pulse applied to the reset cathode initiates a new scan sequence. The keep-alive anode and cathode are used to prevent time jitter in the scanning operation.

The need for color has been widely appreciated and several solutions have been advanced, all based on the photo-excitation of phosphors by the UV emitted from the gas discharge. (It is recognized [7] that the visible luminous output from discharges themselves using gases other than neon is not high enough to warrant consideration of such an approach.) Forman [7], using a Burroughs Self-Scan panel, has obtained green emission by coating the display cavity walls with a manganese-doped zinc orthosilicate phosphor. The excitation of the phosphor is postulated to result from the UV generated in the negative glow of Ne–Xe mixtures. Forman also points out that emission from the positive column and anode glow can also excite the phosphors. Van Houten, Jackson, and

Weston [3] have reported the use of the UV emission from mercury in the positive column to excite phosphors coated on the display cavity walls. Mercury is usually present in dc gas discharge panels to inhibit sputtering of the cathode [8], but under normal operating conditions its vapor pressure is too low (about 0.003 torr at 30°C) to give appreciable UV emission. A luminous efficiency of 1 lm/W was obtained [3], however, by operating the panel between 60° and 70°C, where the mercury partial pressure is in the range between 0.025 and 0.05 torr.

There are difficulties with both of the preceding solutions. From the data presented in Forman's paper [7], it appears that the luminous output efficiency at high current levels is very much lower than for neon alone [9]. The approach based on operating the panel at an elevated temperature seems impractical. Although the high partial pressure of mercury at the elevated operating temperature may in fact prolong the life of the device, this advantage is probably offset by an increased warm-up time and by higher power requirements. There is a further difficulty common to both solutions when a full-color display is desired: since a separate display cell is needed for each color, the cells must be made sufficiently small and closely spaced to overcome the acuity of the human eye [10]. Such requirements lead to problems in panel fabrication.

The approach to generating color which we propose here is based on the low-energy electron (LEE) excitation of phosphors which have been coated onto anodes. In one possible embodiment of this concept, each display anode of a device such as Burroughs' Self-Scan (see Fig. 1) could be replaced by three parallel anodes (one for each primary color) formed by coating the faceplate with a transparent conducting material coated in turn with a suitable phosphor. A device such as this would require the use of a gas with low luminosity or some light-trapping arrangement between the cathode and display anode.

As we shall see later, the energies of electrons incident on the anode are not expected to exceed 15–20 eV [11]. Thus a phosphor is required which is conducting and which has an adequate efficiency in the anticipated range of energies. There is only one commercially available phosphor, green-emitting ZnO:Zn (P15) [12], which is known to meet these requirements [13]. This phosphor is employed in vacuum fluorescent tubes[1] which operate by drawing electrons from a hot cathode to anodes coated with P15 phosphor. Plate voltages of 10–30 V lead to efficient operation. A display device operating on the principle of the vacuum fluorescent tube in which a helium glow discharge serves as the source of electrons rather than the hot cathode has been constructed by Kazan and Pennebaker [14]. These authors also used P15 as the anode and reported an efficiency of 10 lm/W.

The lack of commercially available low-voltage phosphors other than P15 prevents the implementation of our concept for a full-color display system at this time, and would also seem to eliminate a white monochrome device. We have discovered, however, that it is possible to construct a device whose output is white and whose color is independent of intensity by combining the green emission from P15 phosphor and the red–orange output of a glow discharge using mostly neon. In this paper we describe the construction and operation of such a display device, as well as experiments on single discharge cells whose results indicate that LEE excitation dominates in the *pd* (pressure×cathode–anode separation) range of interest.

The following section is concerned with the experiments designed to identify the excitation mechanism. Here some of the complexities resulting from the use of a ZnO:Zn phosphor in a gas discharge are discussed. This is followed in Section III by a description of the construction and operating characteristics of a small panel with black-and-white output. In the final section our approach is evaluated and future directions are outlined.

II. Single Cell Experiments

A. Construction and Operation

Experiments were carried out using simple cells such as shown in Figs. 2 and 3. The discharge region was 2 mm long with a diameter of 2.5 mm. The cathodes were made of aluminum foil or nichrome mesh, the latter method enabling one to look through the cell. For the structure shown in Fig. 2, which will be referred to as a type I cell, the anode was formed using a conductive transparent coating of $In_{2-x}Sn_xO_{3-y}$ (indium–tin oxide) [15] sputtered on the glass. Only a portion of the end wall of the cell was coated with indium–tin oxide; the reason for this partial coating will become evident later. The anode in the type of cell shown in Fig. 3 (type II cell) consisted of 0.18-mm thick glass with a 0.5-mm aperture onto which aluminum had been evaporated. This cell had, in addition, a field plate consisting of glass coated with indium–tin oxide. Uncoated phosphors[2] were settled onto the anodes using distilled water for both phosphor slurry and the cushion solution. Typical coating thicknesses were 3 mg/cm². The components were sealed together with Torr-Seal®.

Experiments were carried out with the discharge operated in the abnormal glow regime, and under pulse excitation with a pulsewidth of 100 μs and a duty factor of 1/250. The cell was placed in series with a limiting resistor and a high voltage transistor which was operated as a switch.

B. Results

To determine the excitation mechanism we studied the luminous output from the following structures as a function of gas pressure.

1) A type I cell with the end wall coated over 70 percent of its area with indium–tin oxide (the anode) but with P15 phosphor settled over its entire surface. The conductivity along the phosphor was sufficiently low that one could neglect the current flowing from the region of phosphor deposited on bare glass to the anode.

2) A type I cell with half the end wall coated with indium–tin oxide and having P1 phosphor (Zn_2SiO_4:Mn) deposited on the other half.

3) A type II cell with P15 phosphor on the anode. Since all the gases studied—helium, neon, argon, and xenon—behave in a qualitatively similar manner, only the results on neon will be discussed in detail.

The results obtained with the first of the afore-mentioned structures are the most important. At a neon pressure of about 5 torr, both the conducting region (anode) and the noncon-

[1] For example: Tung-sol Digivac S/G Tubes; General Electric Y-1939 Readout Tubes.

[2] Phosphor particles are usually coated with a thin layer of nonluminescing material to improve their handling properties. While these layers have little effect on the efficiency when the phosphor is excited by electrons having energies of several thousand electron-volts, they would clearly degrade the performance in the present application.

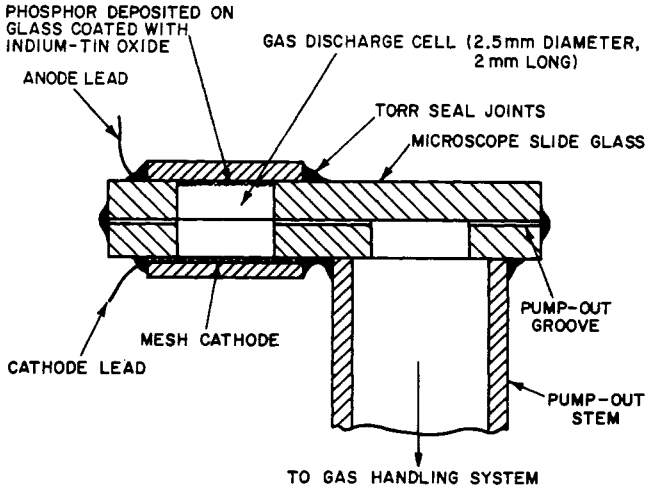

Fig. 2. Cross section of a type I cell—a structure in which the phosphor is back-excited.

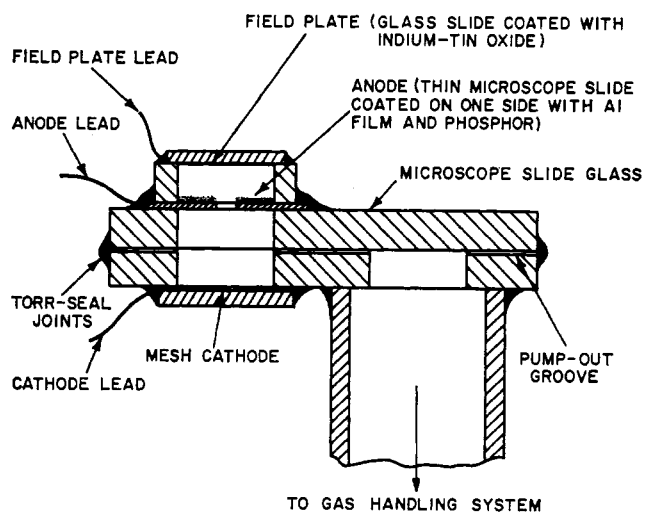

Fig. 3. Cross section of a type II cell—a structure in which the phosphor, deposited on the anode, is front-excited. In addition, a field plate whose potential with respect to the anode may be varied permits modulation of the current reaching the anode.

ducting region of the end wall appear green with some orange content, but the green output from the P15 phosphor is definitely weaker in the anode region. When the pressure is raised to about 15 torr, both regions appear orange, and little difference can be discerned between them. Finally when the pressure exceeds 30 torr, the anode region takes on a white color—the results of the combination of the green phosphor emission and the red–orange of the neon negative glow. The nonconducting region, however, remains orange, and the boundary between the two regions is well defined. This behavior persists up to the highest pressure studied, 130 torr, or $pd = 26$ torr·cm. In the anode region at 31 torr, a peak brightness of 14 000 fL was attained at a current density of 900 mA/cm² and 420 V across the discharge cell. Under these conditions the brightness of the nonconducting region was 6500 fL (orange), with both regions showing a dependence of intensity on current that was essentially linear. Thus for neon approximately half of the luminous output emanating from the anode region may be ascribed to phosphor emission and half to the transmitted negative glow. For helium, the luminous output at 38 torr was 6500 fL at 500 mA/cm² with 600 V across the cell. The luminous efficiency for argon and xenon at high pressure was more than an order of magnitude lower than for neon.

The second device previously described, having half of the end wall coated with P1 phosphor, exhibits green emission from the phosphor at low pressure ($p \leq 5$ torr) only. As the pressure is raised beyond this point, the green emission is reduced and the negative glow dominates for pressures exceeding 15 torr. Argon and xenon were not studied in this cell. It should be noted that to repeat the experiments on the first structure, substituting P1 for P15 is impossible since P1, like most phosphors, is nonconducting.

The experiments on the third structure which are pertinent to this discussion were performed at high pressures, between 25 and 30 torr. If the anode is held positive with respect to the field plate, green emission from the phosphor on the anode is seen. If, however, the field plate is held 20 V positive with respect to the anode, the emission from the phosphor is quenched.

C. Interpretation

A satisfactory model will have to account for the following features of the results on the first structure.

1) At low pressure, the emission from the phosphor in the nonconducting region is stronger than in the anode region.

2) There is virtually no phosphor excitation in either region at medium pressure.

3) At high pressure, there is strong emission from the phosphor in the anode region, but none in the nonconducting region.

The following qualitative model is advanced. At low pressure, the phosphors are photoexcited. Although there are differences between the emission in the two regions of the first structure, they may be accounted for by effects resulting from wall sheaths [16]. (These sheaths can modify the electron concentration near the surface of the semiconducting ZnO:Zn phosphor. Since the excitation, whether by UV or by low-energy electrons, is confined to a region within about 1000 Å of the surface [17], and since the radiative efficiency for the green band of ZnO:Zn has been shown to depend linearly on electron concentration [18], it is clear that wall sheaths may control the radiative efficiency of this phosphor. Furthermore, the wall sheaths at the two regions will differ by virtue of the fact that while electrons are flowing to the anode, there is no net current to the nonconducting portion. It is readily shown that this difference in the wall sheaths can account qualitatively for the appearance of the two regions.)

At medium pressure ($p \approx 15$ torr) there is negligible excitation of the P15 phosphor in either region, and the P1 phosphor in the second structure also does not luminesce. Since P1 may only be photoexcited, these observations suggest that in this pressure region, the intensity of UV radiation reaching the phosphors has been greatly reduced.

The onset of P15 excitation at about 30 torr in the first structure is ascribed to the development of an anode fall [11] in which electrons having energies between 15 and 20 eV are produced. Until the pd product is large enough to allow such a space charge region to be set up [11], electrons reach the anode without sufficient energy to excite the phosphor. The presence of an anode fall implies the presence of an anode glow and raises the question of whether the phosphor is excited by low energy electrons or by the UV produced in the anode glow. This question could be more easily answered if the

photoexcitation spectrum of the phosphor and the spectrum of the radiation from the anode glow were known. While the former could be qualitatively estimated on the basis of [17], measuring the latter is very difficult since the emission lines of interest probably lie in the vacuum UV. Two observations cited earlier are thus used to argue in favor of LEE excitation. The first is that the relative efficiencies with which these discharges excite the phosphor are quite different from those observed for photoluminescent excitation of phosphors by gas discharges. It appears that generally the efficiency increases with the atomic number of the gas [19]. We have found, however, that neon and helium are much more efficient than argon and xenon. Our trend, therefore, is opposite to that observed for photoluminescent excitation. In fact, our efficiencies generally increase with ionization potential in agreement with the model of electrons being produced in the anode fall. The second observation concerns the sharp difference in appearance at high pressure between the P15 phosphor on either side of the boundary between the two regions of the end wall. Excitation by the anode glow would be expected to spill over from the anode region to the nonconducting region. No such spill over was observed when the boundary region was viewed with a microscope having a magnification of 25. In the light of these observations, it is concluded that LEE excitation dominates when the pd product exceeds approximately 6 torr·cm.

III. Experimental Panels

In order to implement as conveniently as possible the concept of a black-and-white display in a matrix form, and under more realistic driving conditions than those employed in the single cell experiments, a Burroughs Self-Scan panel has been modified to incorporate P15 phosphor on transparent anodes. This panel consisted of an array of 7×110 cells, each 1 mm in diameter on 1.5-mm centers. An exploded view of the modified structure is shown in Fig. 4. Indium–tin oxide stripes were defined on the faceplate and P15 phosphor was settled in the same manner as used for single cells. In order to facilitate comparison between operation with and without phosphor, a control region (about a third of the panel) was left uncoated. The components were assembled with Torr-Seal, and the panel was pumped out and filled with 95 torr of neon ($pd \simeq 9.5$ torr·cm) in one instance and with neon at 95 torr and argon at 0.5 torr in another.

To establish the scanning function, 160 V was applied to the scan anodes through 160-kΩ resistors and the cathodes were switched between −180 and −80 V, representing respectively the "on" and "off" states. The clock frequency for the three-phase cathode drivers and the reset pulse for the reset cathode were adjusted so that each row was active for 125 μs with a duty factor of 1/100. The intensity of the display cells was controlled by means of p-n-p transistors whose collectors were connected to individual anodes and whose emitters were grounded.

Uniform white emission was observed over the entire area where phosphor had been settled. (A UV chromaticity diagram is shown in Fig. 5 with the coordinates for P15 and neon glow indicated.) The unfiltered output color thus lies on the straight line which connects these points [20, p. 83] and is seen to pass through the white region [20, p. 123]. The color was independent of intensity, which in turn was linearly dependent on current density. The peak cell brightness was 3000 fL for the white display and 7500 fL for the neon glow

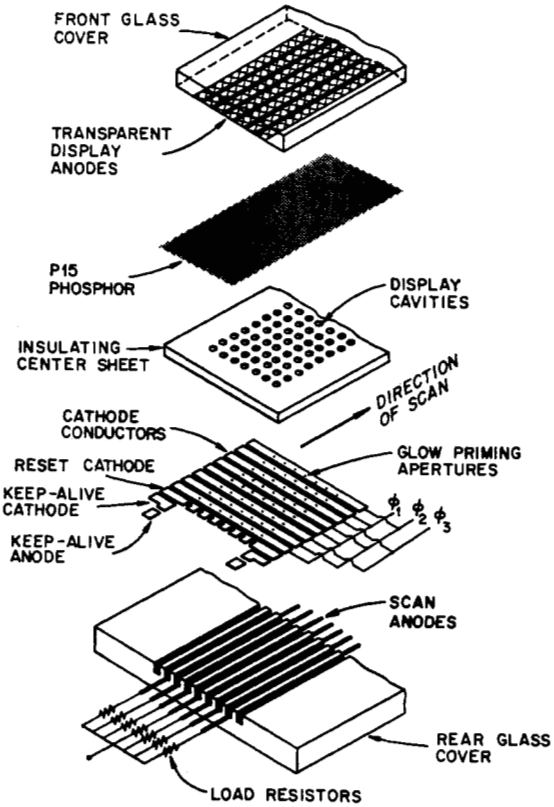

Fig. 4. Exploded view of the panel used in our experiments. The faceplate and anode wires of the device shown in Fig. 1 are replaced by a faceplate with transparent thin-film anodes, coated with an appropriate thickness of P15 phosphor.

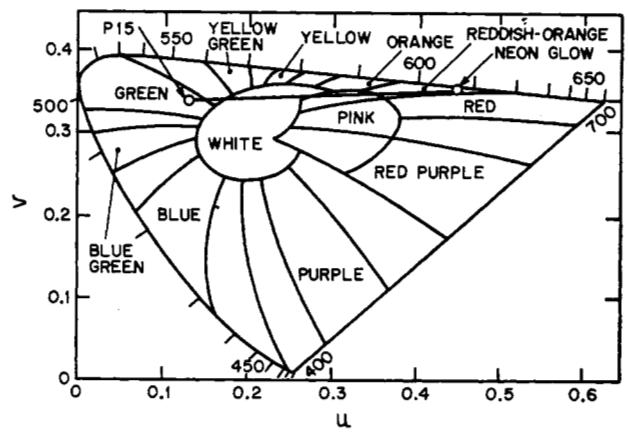

Fig. 5. A UV chromaticity diagram indicating the coordinates for P15 and neon glow. Combinations of these two colors will lie along the straight line joining the two points. It is seen that the line passes through "white." (Based on [22].)

in the control region at a display cell current density of 0.33 A/cm². The addition of argon did not essentially change these results. With the deposition procedure used, it was not possible to restrict the phosphor to the display anode stripes. Since the phosphor was semiconducting, it gave rise to sufficient conductivity between the display anodes to prevent totally independent control of each anode. This drawback was overcome through the use of electrophoretically deposited phosphors [21]. To date, however, the brightness using phosphors deposited in this manner is not as high as that resulting from a simple settling procedure.

IV. Discussion

The results of the single cell experiments have pointed the way to a means for obtaining a white display, and the approach has been demonstrated in a matrix form using a structure based on a Burroughs Self-Scan panel. LEE excitation of a ZnO:Zn phosphor has been shown to lead to a brightness considerably higher than that previously attained with the use of UV-excited phosphors. It must be kept in mind also that in our panels the light is attenuated by at least a factor of 5 by passage through the phosphor layer.[3] Generation of color by means of LEE excitation of phosphors offers three other important advantages over previous approaches.

1) The intensity of emission from the phosphor is proportional to the current density; no saturation effects have been observed.

2) Three independent display anodes may pass through a single display cavity in a full-color system.

3) LEE excitation offers the possibility of situating the phosphor so that it is not exposed directly to the cathode. (A type II cell discussed in Section II is an example of this arrangement.) Apart from shielding the phosphor from sputtering, such an arrangement should allow the full phosphor output to be realized as the light would not have to pass through the phosphor layer.

Our system, while possessing definite advantages over many of those previously described, still suffers from a lack of a sufficiently high peak brightness. It is not clear how the luminous output from the phosphor can be increased to be considerably higher than that from the negative glow alone. This is a most important point since the latter does not yield an output sufficiently high to be useful in video display systems with significantly more than 200 scanning lines under line-at-a-time operation [3]. A second drawback of our approach is that implementation of a full-color display will have to await the development of low-voltage phosphors emitting colors other than green.

Apart from these drawbacks, the following points are to be noted. Although it is recognized that the introduction of mercury as an antisputtering agent [8] is necessary to prolong the life of this type of device, none has been used in our panel. The question must be raised, therefore, as to its possible effects in our system since any low-voltage phosphor is very sensitive to any impurities on its surface. In this connection it is interesting to note Forman's finding [7] that his test panels have shown less than 10-percent degradation of the green output after a year's operation. He conjectures also that it is the xenon lines at about 1300 and 1470 Å which are chiefly responsible for the excitation of his Zn_2SiO_4:Mn phosphor. Since radiation of this wavelength is likely to be absorbed within 100 Å of the surface [17], the emission is also very surface sensitive [7]. Since mercury appears not to affect adversely the performance of Forman's panels, there is reason to believe that there are unlikely to be mercury deposits on the phosphor which would degrade its performance. On the other hand, it is possible that the anode fall may be affected by the presence of mercury. Generally, the anode fall is limited to less than the ionization potential of the most easily ionized gas present. At elevated temperatures, mercury could thus lower the anode fall and consequently reduce the luminescence efficiency.[4]

[3] The attenuation factor was determined by comparing the orange output at 15-torr Ne of two type I cells, one having the anode coated with phosphor and the other with the anode uncoated.

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[4] We are grateful to G. E. Holz for bringing this problem to our attention.