R. M. Schaffert

Charge Transport Mechanisms in the Transfer of Latent Electrostatic Images to Dielectric Surfaces

Abstract: The transfer of electrostatic charge patterns from one surface to another requires movement of electrical charges across very small air gaps. Gaseous electronics alone is not sufficient to account for charge transport across extremely small gaps. The concept of field emission is introduced as a supplementary mechanism of charge transport and as a source of primary electrons.

Introduction

In xerography the latent images are formed on a photoconductive insulating layer as electrostatic charge patterns. When the photoconductive layer is amorphous selenium, the conventional procedure is to develop the electrostatic image directly on the selenium surface with a fine powder and then transfer the powder images to paper, or some other sheet material.[1] However, it is known that these charge patterns, or latent images, can be transferred to, or reproduced on, dielectric surfaces, such as Mylar*, polyethylene, etc., prior to development.

The transfer of electrostatic images is not a new subject. The process was discovered by L. E. Walkup,† a former associate of the author, at Battelle Memorial Institute. Apparently, Walkup has not widely published the experimental results except in patent literature,[2] and the charge transfer processes seem to have remained more or less dormant so far as useful applications are concerned. However, the technical implications and potential advantages of the charge transfer concept become readily apparent when we examine the procedure of conventional xerography. The first and most obvious benefit would be elimination of plate and drum cleaning devices, and consequent improvement in plate and drum life and maintenance. If the latent electrostatic image is transferred or formed on a stable unsensitized medium, such as plastic film, it can be developed at a station removed from the immediate vicinity of the selenium surface. Developing could be performed under full illumination, and, if desirable, under continuous visual inspection. Also, "heat development" of electrostatic charge patterns on thermoplastic resins,[3,4] has generated renewed interest in charge transfer as a means of producing images on plastic film.

The charge transport phenomena involved in the transfer of latent electrostatic images have been the subject of recent investigations by the author. The object of this paper is to show that the ionic conduction of gaseous discharge alone is not sufficient to account for charge transfer across extremely small air gaps. It is proposed that field emission is the primary factor in initiating charge transfer under these conditions.

Physics of electrostatic image transfer

Electrostatic image transfer processes can be divided into two classes: (1) techniques wherein the electrostatic image is first formed on a surface, such as a xerographic plate, or other media, and subsequently transferred to a dielectric surface; and (2) techniques wherein the electrostatic image is formed while the dielectric film is in virtual contact with an electrophotographic plate.

Both classes have one thing in common: the application of an electrical field, in a thin air gap, to produce a field intensification sufficient to cause charge transfer in the areas corresponding to the electrostatic image. In all electrostatic image transfer processes, two surfaces must be brought into virtual contact and subsequently separated. One surface, of course, is the dielectric to which the electrostatic image is transferred; the other is the image-bearing or image-forming surface.

---

* Trademark, E. I. du Pont de Nemours and Company.

† Walkup's discovery was made while engaged on a project sponsored by the Xerox Corp., Rochester, N.Y.

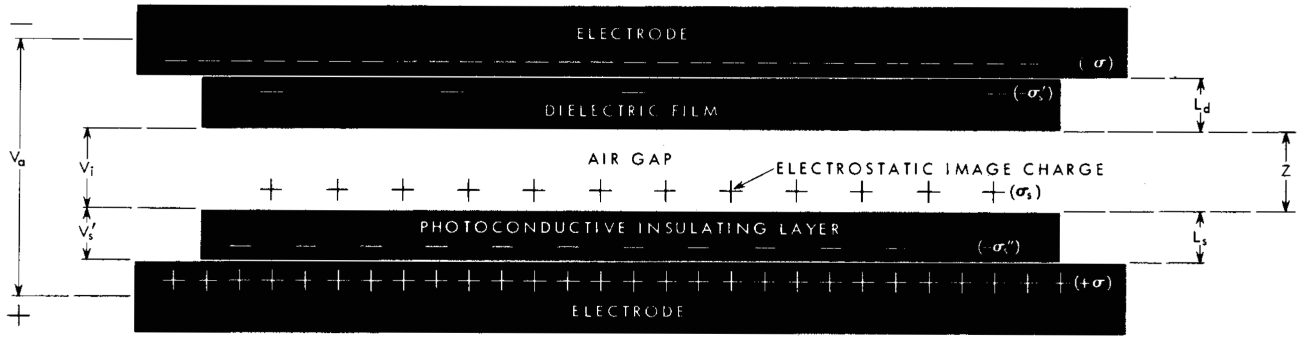


Figure 1 **Essential elements in electrostatic image transfer.**

The essential elements in electrostatic image transfer are illustrated in Fig. 1. When the dielectric film and electrophotographic plate are brought together, the gas layer between them decreases from some relatively large thickness to a very thin film as the surfaces come into virtual contact. When these surfaces are subsequently separated, of course, the gas layer becomes progressively larger. The gas film thickness at virtual contact will depend upon the degree of surface smoothness. Surfaces prepared by lapping and polishing provide gaps of approximately 1 micron when placed in virtual contact,[5] optically polished surfaces provide gaps of about 0.25 micron.[6]

In view of the foregoing, it becomes apparent that transfer of electrostatic images to a dielectric film requires the movement of electrical charges through a gas film even when the surfaces are in virtual contact. There is no *a priori* evidence from which we can determine whether transfer takes place at virtual contact or during separation of the surfaces. Therefore, we shall consider the phenomena and conditions whereby electrical charges can be transported through gaseous media across very small gaps, in the range of 1 to 50 microns.

Gaseous discharge has been previously proposed to explain charge transport in the transfer of electrostatic images.[7] The mechanism of charge transfer can be explained on the basis of gaseous discharge phenomena alone when the air gap is relatively large (i.e., greater than about 8 microns).

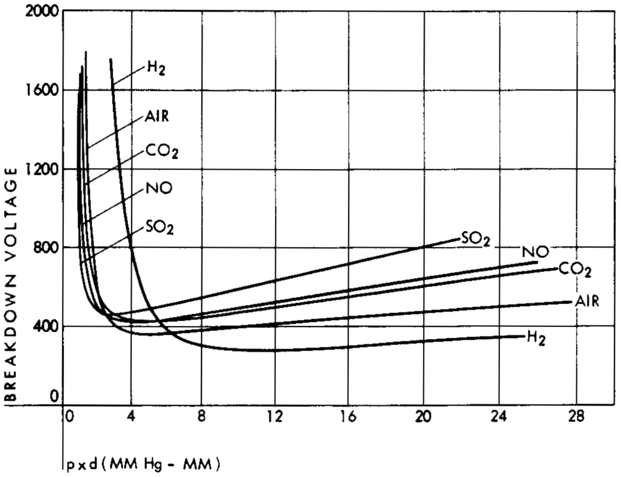
Paschen's law for the breakdown of a gas in an electric field states that breakdown voltage is a linear function of gas pressure p times distance d between electrodes. This law holds for values of $p \times d$ greater than about 5 mm Hg-mm when the gas is air at room temperature. Below this value the breakdown curve takes a sharp upturn (see Fig. 2). It will be noted that the minimum breakdown voltage for air is about 360 volts; below this voltage gaseous breakdown will not occur, no matter what the pressure or distance between electrodes. However, for very short air gaps, conduction through the air film could conceivably take place by field emission[6] at less than 360 volts.

Figure 3 shows a reconstruction of the Paschen curve for air as obtained from the data in Fig. 2 with the pressure constant at 760 mm Hg. Breakdown voltage is plotted as a function of gap width. Now, if we compute the voltage across the air gap (V_i, Fig. 1) as a function of gap width, we can plot the results on the same graph as the Paschen curve and determine the gap width at which gaseous discharge will take place. This will also determine the maximum gap width or surface separation at which the electrostatic image will be transferred to the dielectric surface.

If the photoconductive layer of Fig. 1 is initially charged to a potential V_s, and subsequently a voltage V_a is applied across the two electrodes, the voltage V_i across the air gap can be determined in the following manner:

Let the charge density due to the applied voltage V_a at the interface of the top electrode and the dielectric film be $-\sigma$. Then the charge density at the interface of the bottom electrode and the photoconductive layer due to V_a will be $+\sigma$. The image charge, assumed to be of uniform surface density, σ_s will induce a negative charge at the top electrode of density $-\sigma'_s$ and at

Figure 2 **Paschen curves for several gases.**
M. Knoll, F. Ollendorf and R. Rompe.[8]



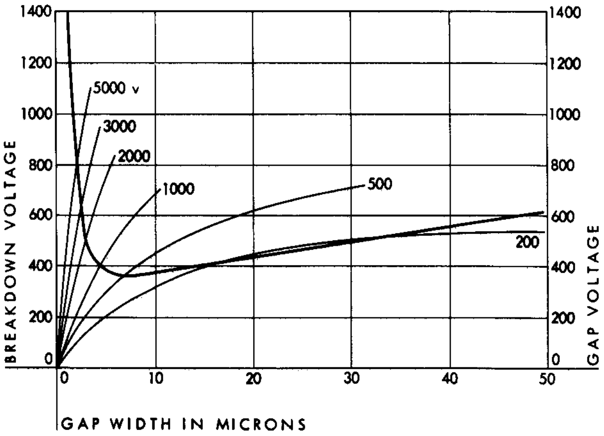


Figure 3 **Theoretical characteristics for electrostatic image transfer by gaseous discharge, using one set of conditions.** *Heavy line: Paschen breakdown curve for air at 760 mm Hg. Light lines: gap voltage vs gap width at different applied voltages for* $L_s = L_d = 25$ *microns,* $K_s = 6.3$, $K_d = 3.0$, $V_s = 500$ *v.*

the bottom electrode of density $-\sigma''_s$, such that $\sigma_s = \sigma'_s + \sigma''_s$.

The total charge density at the top electrode, due to V_a and the image charge, is $-(\sigma + \sigma'_s)$, and at the bottom electrode is $\sigma - \sigma''_s$.

Neglecting edge effects, we can write

$$V_d = \frac{\sigma + \sigma'_s}{K_d \varepsilon_0} L_d \,, \tag{1}$$

$$V_i = \frac{\sigma + \sigma'_s}{\varepsilon_0} z \,, \tag{2}$$

$$V'_s = \frac{\sigma - \sigma''_s}{K_s \varepsilon_0} L_s \,, \tag{3}$$

where V_d, V_i, and V'_s are the voltages across the dielectric layer, the air gap and the photoconductive layer, respectively; L_d, z, and L_s are the respective thicknesses of these layers (see Fig. 1); K_d and K_s are the dielectric constants of the dielectric and photoconductive layers, and ε_0 is the permittivity of free space.

Taking into account that $\sigma_s = \sigma'_s + \sigma''_s$, and $V_s = \sigma_s L_s / K_s \varepsilon_0$, and substituting Eq. (2) in Eqs. (1) and (3), we obtain

$$V_d = V_i L_d / K_d z \tag{4}$$

$$V'_s = (V_i L_s / K_s z) - V_s \,. \tag{5}$$

Inspection of Fig. 1 shows that

$$V_d + V_i + V'_s = V_a \,. \tag{6}$$

Substituting Eqs. (4) and (5) in Eq. (6), we obtain

$$V_i[(L_d/K_d z) + 1 + (L_s/K_s z)] = V_a + V_s \,. \tag{7}$$

Solving for V_i in Eq. (7), we obtain

$$V_i = \frac{(V_a + V_s) z}{(L_s/K_s) + (L_d/K_d) + z} \,. \tag{8}$$

Using Eq. (8), a series of curves were plotted in Fig. 3 with V_a as a parameter, taking $V_s = 500$ volts, $L_s = L_d = 25$ microns, $K_s = 6.3$ and $K_d = 3$.

Note that very high voltages would be required to transfer electrical charges by gaseous discharge when the air gap is only a few microns if the left-hand portion of the Paschen curve is correctly represented in Fig. 3. For example, an applied voltage of more than 5000 volts would be required for transfer at 2 microns under the conditions given. Electrical fields in the air gap would reach very high values ($\sim 10^6$ v/cm) on the left hand side of the Paschen minimum. Fields of this order of magnitude are in the range where field emission of electrons might be expected.

In view of these considerations we shall examine the mechanism of gaseous discharge in order to determine the limitations imposed by very small air gaps.

Mechanism of charge transfer by gaseous discharge

A tremendous amount of research has been done on gaseous electronics since the early work of J. S. Townsend at the turn of the century. Thus, there is a large amount of data available on the subject.[9]

The determining factors for the conduction of electricity through gases are : (1) pressure, (2) length of path through the gas, (3) magnitude of the electric field over the gas path, (4) energy attained by free electrons in the gas, (5) mean free path for ionization by electrons in the gas, and (6) number of free electrons initially present in the gas. (For extremely short paths and high fields, additional electrons may be supplied by field emission.)

When the path through the gas is short, conduction is due primarily to electrons and positive ions.[10] Conduction is initiated first by free electrons in the gas. These are accelerated by the field-producing positive ions and more electrons by impact with gas molecules, resulting in the so-called Townsend electron multiplication or avalanche.

In the transfer of electrostatic images we shall be dealing primarily with short paths, in the range of about 1 to 50 microns. Therefore, our concern will be mainly with the Townsend type of conduction, and the source of free electrons in the gas.

Since the Townsend electron multiplication progresses exponentially with the electron path length, it is important to consider the limitations imposed by small gaps. The first step is to determine the relationship between the electric current through a gas and gap width.

• *Variation of current with gap width for constant field*

If an electron produces α new electrons and positive

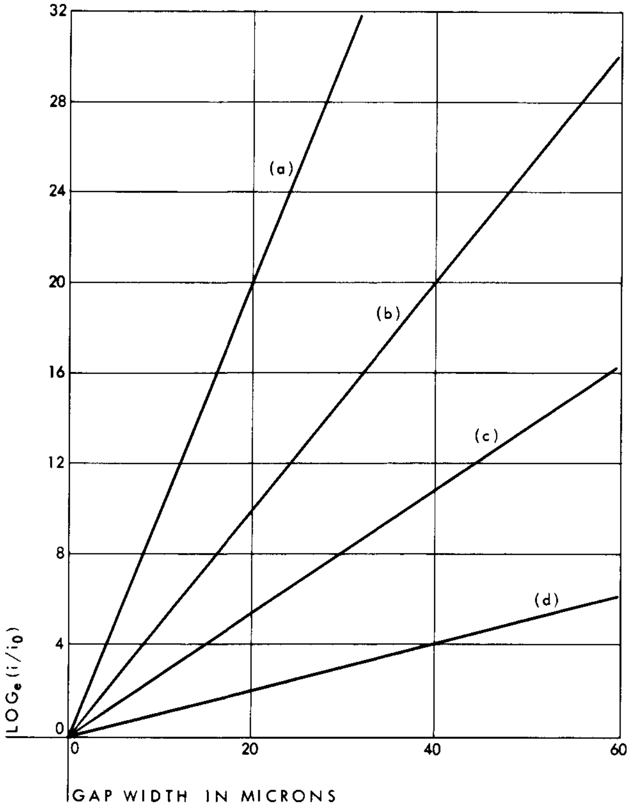


Figure 4 **Increase of current ratio as function of gap width for four different values of field strength.**
a) $\alpha = 10,000$, $E = 707,000$ *v/cm; b)* $\alpha = 5,000$, $E = 364,800$ *v/cm; c)* $\alpha = 2,700$, $E = 200,000$ *v/cm; d)* $\alpha = 1,000$, $E = 98,800$ *v/cm. (Air at 760 mm Hg.)*

ions in traveling 1 cm through the gas in the direction of the field, the increase in ions, dn, caused by n electrons in traveling a distance dx, is given by,

$$dn = \alpha n\, dx\ . \tag{9}$$

Integrating this between $n = n_0$ at $x = 0$, and $n = n$ at $x = x$, we get,

$$n/n_0 = e^{\alpha x} = i/i_0\ . \tag{10}$$

Since the current i through the gas is proportional to n, $n/n_0 = i/i_0$, where i_0 is the initial current due to the n_0 free electrons initially present in the gas. We then have

$$\log_e i/i_0 = \alpha x\ . \tag{11}$$

This relationship, originally developed by Townsend, holds true when the field is independent of x, through a rather wide range of gap widths. In Eq. (11), α is the well-known first Townsend coefficient.* It is assumed that the distance x is equal to the gap width. Using Eq. (11), a number of plots of $\log_e i/i_0$ were computed for several different field strengths. These are shown in Fig. 4. The current ratios were computed for air at 760 mm Hg, using values for α taken from Fig. 5 and other sources. It will be noted that increase in current for small gaps, e.g., for gaps of less than 5 microns, is not great. Thus the current multiplication for these small gaps may be only a few orders of magnitude even at very high fields.

- *Variation of current with gap width for constant voltage*

When the voltage is held constant while the surfaces are being separated, the field will decrease as the gap width increases. The relationship between the current through the gas and the gap width under these conditions must take into account the variation of α with field strength.

The nature of this variation is shown in Fig. 5. The shape of the curve, α/p vs E/p, is such that the empirical equation

$$\alpha/p = Ae^{-Bp/E} \tag{12}$$

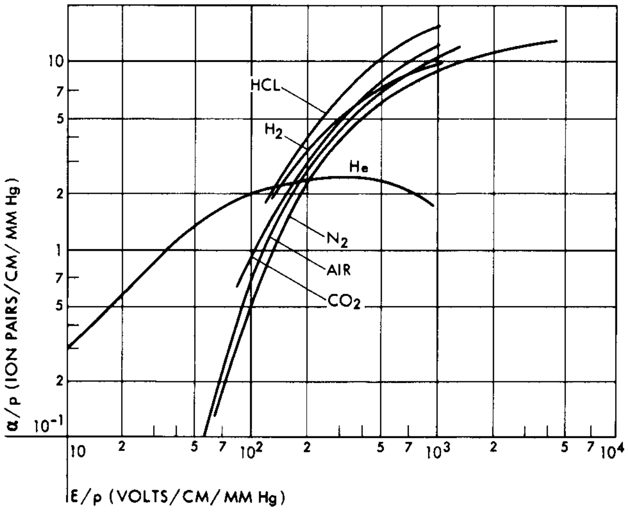
can be fitted over at least a sizeable range of the curve[13] by proper selection of the constants A and B. In Eq. (12), p is the pressure in mm Hg, and E is the field strength over the gas path.

Since we are interested primarily in short paths and relatively high field strengths, Eq. (12) was fitted to the upper portion of the curve for air in Fig. 5. The values for the constants were found to be, $A = 15.6$ and $B = 400$. The results of this fit are shown in Fig. 6.

Substituting α from Eq. (12) in Eq. (9), we get

$$dn/n = Ape^{-Bp/E}\, dx\ . \tag{13}$$

Figure 5 **First Townsend ionization coefficients vs field strength for several gases.**
A. von Engel and M. Steenbeck.[12]



---

* For high fields, Eq. (11) departs from linearity at increased values of x due to secondary effects (the second Townsend coefficient).[11] The effect is negligible at very small gaps.

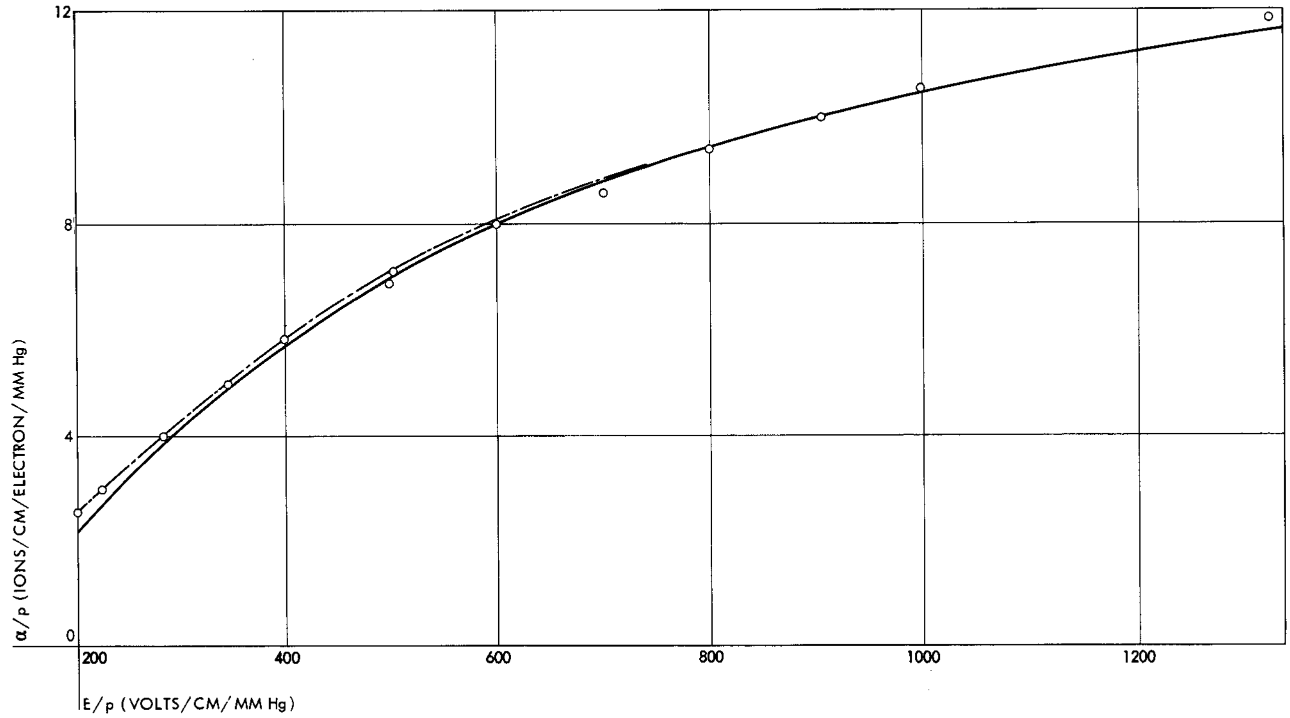


Figure 6 **α/p vs E/p for air.** ○*: values taken from Fig. 5 and L. B. Loeb.*[14] *Solid line:* $\alpha/p = 15.6\, e^{-400/E}$.

Since the potential drop across the gas path is $V = Ex$, Eq. (13) becomes

$$dn/n = Ape^{-Bpx/V}\, dx\,. \qquad (14)$$

Integrating from n_0 to n, and 0 to x, we obtain

$$\log_e n/n_0 = \log_e i/i_0 = (AV/B)(1 - e^{-Bpx/V})\,. \qquad (15)$$

With this equation we can determine the ratio of i/i_0 for various voltages and gap widths since A, B, and p are known.

Curves of $\log_e i/i_0$ vs x for voltages from 100 v to 4000 v are shown in Fig. 7. For very small gaps (up to about 3 microns) $\log_e(i/i_0)$ is nearly independent of voltage. These values correspond to the high-field portion of the curve in Fig. 6, the field strengths being in the range of 10^6 to 10^7 volts/cm. It will be noted that α/p tends toward a constant value at high values of E/p. Also for these small gaps, current multiplication is small, e.g., at 2.5 microns the current is increased only by a factor of about 15, i.e., $\log_e i/i_0 = 2.7$. This is not surprising since the gap width of 2.5 microns is scarcely an order of magnitude greater than the electron mean free path in air at atmospheric pressure.

- *Magnitude of currents required to transfer electrostatic images*

When an electrophotographic plate or a dielectric film mounted on a conductive substrate is electrically charged to a potential V by an external source (e.g., corona emission), the surface charge density σ is given by

$$\sigma = K\varepsilon_0 V/L\,, \qquad (16)$$

where L is the thickness of the dielectric films, K is the dielectric constant, and ε_0 is the permittivity of free space.

Figure 8 shows surface charge density as a function of the voltage V as obtained with Eq. (16) with $L = 25$ microns. These values were computed for three different dielectric constants, $K = 2.5$, $K = 3$, and $K = 6.3$. The first two are representative of some of the transparent resins; the third for amorphous selenium.

The current required to transfer a specified amount of charge in a limited period of time can be determined from data of the type given in Fig. 8. For example, if we want to establish a 300 volt image charge on a dielectric film with a dielectric constant of 3.0, and a thickness of 25 microns, 3.2×10^{-1} coulombs per cm^2 must be transferred. If we assume a transfer time of 0.001 sec for the charge transfer, the required current density for the case above would be

$$i = 3.2 \times 10^{-8}/0.001 = 32\mu\text{a}/\text{cm}^2\,. \qquad (17)$$

With an air gap of 2.5 microns, $i/i_0 = 15$ (see Fig. 7), and therefore,

$$i_0 \simeq 2.13\mu\text{a}/\text{cm}^2\,. \qquad (18)$$

With an air gap of 1.0 micron, $i/i_0 \simeq 3$, and

$$i_0 \simeq 10.67\mu\text{a}/\text{cm}^2\,. \qquad (19)$$

These initial currents are many orders of magnitude greater than would be expected from electrons initially present in the gas film, even with the aid of a strong ionizing source, such as ultraviolet radiation. It is evident, therefore, that such large initial currents must depend upon field emission of electrons from the surfaces to supply the necessary amount of free electrons.

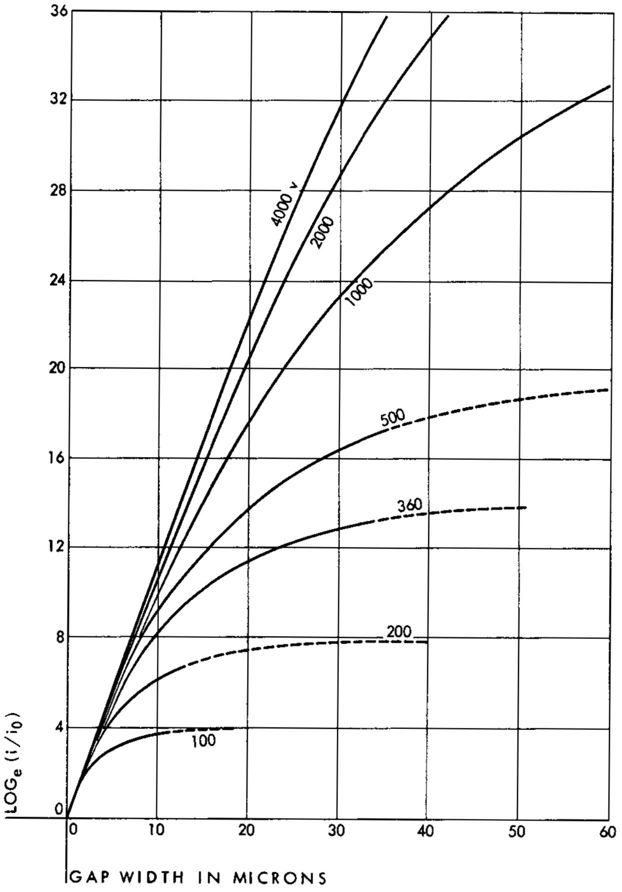
A similar consideration of the right-hand side of the Paschen minimum will show that much smaller initial currents are required to account for transfer of the same amount of charge in the same time period (i.e., 3.2×10^{-8} coulombs per cm^2 in one millisecond). At the Paschen minimum (360 v and 8 microns), $i_0 = 2.67 \times 10^{-12}$ amps/cm.

The time of 1 millisecond is used merely for comparison, but actual transit times under discharge conditions could be much less.

Charge transfer across small air gaps

The right-hand portion of the Paschen curves, showing $p \times d$ proportional to the breakdown voltage, has been studied extensively. The results are well known, and predictions as to the behavior of a particular gas within the range of $p \times d$ greater than the Paschen minimum can be made accurately and reliably. The steep-rising portion to the left of the Paschen minimum, however, is comparatively rare because of the tendency of discharges in this range of $p \times d$ to seek longer paths between electrodes when the applied field is greater than that indicated by the slope of the right-hand portion of the Paschen curve.[15] The left-hand part of the curve, as shown in Fig. 3, can be observed at low pressures where the gap distance is relatively large. However, at atmospheric pressure, where the gap on the left-hand side of the Paschen minimum (for air) is less than 8 microns, no steep rising curve has been observed. The high fields in small gaps apparently initiate field emission currents which predominate over any currents generated by the Townsend avalanche mechanism.[16]

Figure 7 **Increase of current ratio as function of gap width for different voltages.**
(Air at 760 mm Hg.)



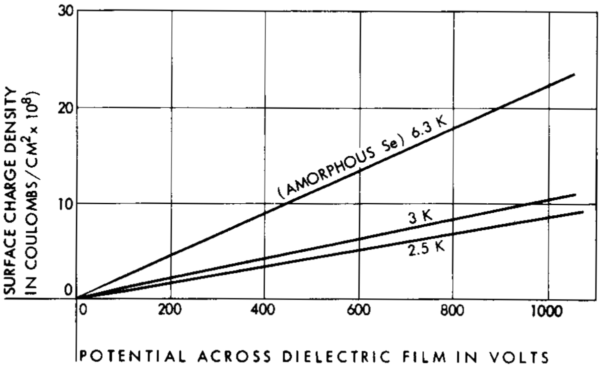


Figure 8 **Surface charge density vs voltage for 3 dielectric films.**
K = dielectric constant. Film thickness = 25 microns.

Figure 9 illustrates the type of data obtained for the left-hand side of the Paschen minimum when the path through the gas is limited by very small gap widths. These curves are characterized by a plateau extending to the left of the Paschen minimum and a steep line running to the origin. It will be noted that the slope of this line is independent of the type of gas. The line to the right of the Paschen minimum is the beginning of the normal Paschen breakdown curve. The left-hand portion of Fig. 3, therefore, represents a hypothetical rather than a real situation at atmospheric pressure.

A new curve, utilizing the data given in Fig. 9, has been constructed (Fig. 10). The field emission end of the curve should be regarded as an approximation, since the data used were obtained from discharge characteristics between platinum electrodes. In the transfer of electrostatic images, charges are transported between two surfaces, one of which is a dielectric (e.g., a thermoplastic resin film), the other usually a high-resistance photoconductor, such as amorphous selenium. No data were found from which the critical field emission from such surfaces could be determined.

The Fowler–Nordheim equation for field emission currents from a cold surface is usually given in the form,[18]

$$i = 1.55 \times 10^{-6}(E^2/\phi) \times \exp[(-6.8 \times 10^7 \times \phi^{3/2}/E)]f(y)\,, \qquad (20)$$

where i is the current density in amps/cm^2, E is the field strength in volts/cm, ϕ is the work function in electron volts, and $f(y)$ is a correction factor involving the image force of the field and the work function. Values for $f(y)$ are obtainable from tables.[19]

This equation is quite sensitive to the value of ϕ. Currents of the order of the value given in Eqs. (10) and (11) require work functions in the range of 1.0 to 1.1 for a field of 2.0×10^6 volts/cm. Such values may not be out of line for the surfaces under consideration here since we are dealing with surfaces which might be classified as "dirty, gassy" surfaces for purposes of electron emission. These surfaces are exposed to air and often contain microscopic irregularities as well as a certain amount of atmospheric dust. Thus, localized fields may be much higher than the overall field computed from the applied voltage and gap width. Detectable field emission currents have been observed with fields as low as 4×10^4 volts/cm for gassy, irregular surfaces.[20]

The concept of field emission at very small gap widths has a marked effect upon conditions for charge transfer on the left-hand side of the Paschen minimum. If we assume that Fig. 10 is a true representation of the breakdown characteristics in air at atmospheric pressure, charge transfer can take place at extremely small gap widths. To illustrate this, the gap voltage vs gap width curves of Fig. 3 have been inserted in Fig. 10. With field emission taken into account, charge transfer should take place with the surfaces in virtual contact for applied voltages of 2000 v or greater, when the critical field is 2.0×10^6 volts/cm and under conditions as stated previously. With a critical field of 1.0×10^6 volts/cm, transfer should take place during contact at applied voltages of 1000 volts or greater.

Experiments designed to test the hypothesis presented in this paper have been initiated.

Summary and conclusions

1) The transfer of charge from an electrophotographic plate to a dielectric surface is considered from the standpoint of gaseous discharge phenomena and field emission.

2) A modified Paschen curve, incorporating the field emission effect, has been constructed and utilized to demonstrate theoretical feasibility of electrostatic image transfer at extremely small air gaps.

3) Gaseous discharge currents across extremely small air gaps at atmospheric pressure are shown to be much too small to provide electrostatic image transfer in a reasonable period of time.

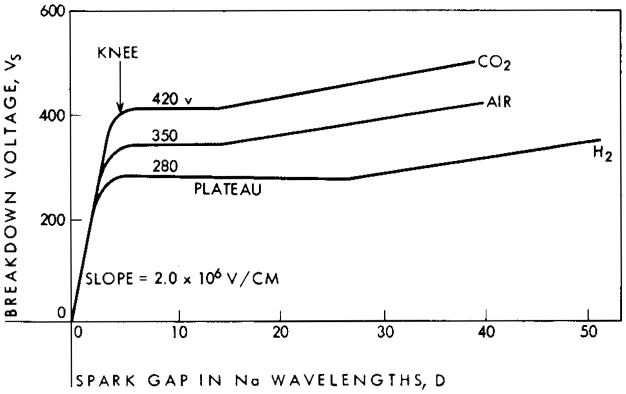


Figure 9 **Striking voltage vs electrode distance for small gaps near the $p \times d$ minimum.** *From Hobbs (1905) in air at normal pressure with platinum electrodes, as cited by H. Ritow.*[17]

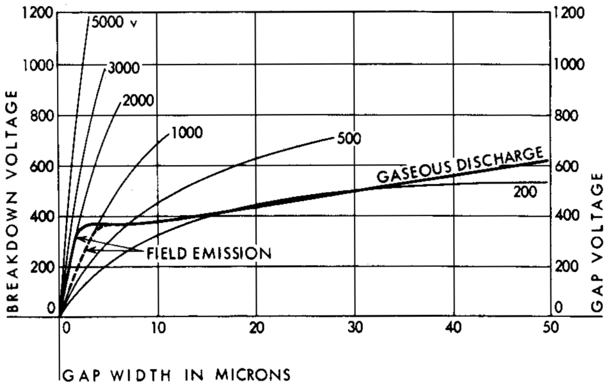


Figure 10 **Characteristics for electrostatic image transfer by field emission and gaseous discharge.** *Heavy line: Paschen curve altered to include field emission at small gaps, with critical field of 2.0×10^6 v/cm. Broken line: critical field of 1.0×10^6 v/cm. Light lines: gap voltage vs gap width, with same conditions as in Fig. 3.*

4) For air gaps greater than the Paschen minimum gap at atmospheric pressure ($\sim 8\mu$), gaseous discharge currents, amplified by Townsend multiplication, are sufficient to account for the rate of charge transport required for electrostatic image transfer.

5) The concept of field emission at extremely small air gaps provides a plausible source for the currents required to transfer electrostatic images when the surfaces are in virtual contact.

References

1. J. H. Dessauer, G. R. Mott and H. Bogonoff, *Photographic Engineering* **6**, 250 (1955).
2. L. E. Walkup, U.S. Pat. 2,825,814, issued Mar. 4, 1958. Also U.S. Pat. 2,833,648, issued May 6, 1958 and U.S. Pat. 2,934,649, issued April 26, 1960.

3. W. E. Glenn, *J. Appl. Phys.* **30**, 1870 (1959).
4. A. M. Thomas, *Brit. J. Appl. Phys.* **2**, 98 (1951).
5. C. Balakrishnan, *Brit. J. Appl. Phys.* **1**, 211 (1950).
6. A. D. Stuckes, *Proc. Inst. Electrical Engineers*, **103B**, 125 (1956).
7. L. E. Walkup, U.S. Pat. 2,937,943, issued May 24, 1960.
8. M. Knoll, F. Ollendorf and R. Rompe, *Gasentladungstabellen, Springer-Verlag OHG*, Berlin, 1935, p. 84. Also *American Institute of Physics Handbook*, McGraw-Hill Book Co., Inc., New York, 1957, p. 5-179.
9. L. B. Loeb, *Basic Processes of Gaseous Electronics*, University of California Press, Berkeley, 1955; also, *Fundamental Processes of Electrical Discharges in Gases*, John Wiley and Sons, Inc., 1939.
10. H. Ritow, *J. Electronics and Control* **7**, 426 (1959).
11. L. B. Loeb, *Basic Processes of Gaseous Electronics*, University of California Press, Berkeley, 1955, p. 751.
12. A. von Engel and M. Steenbeck, *Elektrische Gasentladungen, Springer-Verlag OHG*, Berlin, Vol. 1. p. 106. Also *American Institute of Physics Handbook*, McGraw-Hill Book Co., Inc., New York, 1957, p. 5-168.
13. Loeb, *op. cit.*, pp. 667, 681 and 713.
14. *Ibid.*, pp. 676 and 719.
15. Ritow, *op. cit.*, p. 431.
16. Loeb, *op. cit.*, p. 813.
17. Ritow, *op. cit.*, p. 431.
18. Loeb, *op. cit.*, p. 816
19. R. E. Burgess and H. Kroemer, *Phys. Rev.* **90**, 515 (1953).
20. Loeb, *op. cit.*, p. 817.

Received August 30, 1961