Analysis of Electrostatic Latent Image Blurring Caused by Photoreceptor Surface Treatments*

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The structure of the electrostatic latent image formed by exposure of a corona-charged photoreceptor must be maintained prior to development. To meet this requirement, useful photoreceptors have high dark resistivities. If the photoreceptor surface is conductive, the electrostatic latent image will degrade with time. The time-dependent changes in the structure of an electrostatic latent image are analyzed, using a model with surface resistivity as the only adjustable parameter. The analysis offers a method for determining the surface resistivities of thin polymer films. Surface resistivities are reported for photoreceptors that have been modified by various surface treatments.

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Introduction

Organic photoreceptors comprise thin insulating doped polymeric films on conductive supports.[1] After application of a corona charge, the film is exposed imagewise to create an electrostatic surface image consisting of charged and discharged areas. To obtain acceptable quality in the final image, it is essential for the *electrostatic latent image* to have stable spatial characteristics during the time between exposure and application of toner. Thus photoreceptors must have high volume and surface resistivities.

One method for evaluation of the effects of photoreceptor composition and process conditions on electrostatic image integrity is to determine the time-dependent changes in the image structure. High-resolution surface charge measurements on an organic photoreceptor (IBM Sapphire) have been reported.[2] Successive measurements of charge as a function of position at a fixed time after exposure were carried out, and the edge structure of an exposed region was determined. The edge structure was invariant with time after exposure if the photoreceptor had been wiped with methanol before each measurement. However, if the photoreceptor had not been cleaned it was found that the edge width increased with increasing time delay after exposure because of surface contamination introduced during corona charging. This observation was later quantified[3] and the data described by Ohmic conduction with a resistance of approximately 3×10^{15} Ω. This technique has the advantage of very high spatial resolution but requires specialized equipment.

Degradation of the electrostatic latent image with repeated charge/expose electrical cycling has been observed with an apparatus constructed from a commercial printer equipped with a 300-dpi LED exposure system and a high-resolution electrostatic voltage probe suitably positioned around a photoreceptor drum.[4] Considerable image degradation was observed after 15 h of continuous charge/expose cycling. This result was ascribed to a decrease in the surface resistance of the photoreceptor. The observed changes were analyzed with an equivalent circuit model for the increase in edge width as a function of time due to spreading of the surface charge. This analysis indicated an initial surface resistance of 4.1×10^{15} Ω, which decreased to 3.8×10^{14} Ω at the end of the experiment.

In another report the effects of a thin overcoat layer on a photoreceptor were evaluated.[5] In this case, the overcoat resistivity was determined from the time constant for dark decay of a corona-applied surface voltage. This result was then used with a numerical simulation to calculate the effects on image quality. The conclusion was that image blurring occurred when the surface resistivity was less than 1×10^{15} Ω. This occurred when the overcoat was a 1-μm layer of silicone polymer at 90% RH. Full electrophotographic process exercise (5000 copies) exacerbated the problem, and it was proposed that the mechanism was the transfer of ionic species from the paper to the photoreceptor overcoat.

We have used readily available equipment to examine macroscopic images at relatively long times, and have derived equations to describe the temporal stability of electrostatic latent images. From the physics of the field-induced drift of charge on the surface of a photoreceptor, we have derived the equations describing the temporal characteristics of a *square well* and a *sharp edge* latent image, with sheet resistance as the only adjustable parameter. In this report we describe the electrostatic image measurement and show how to use these equations to quantify the surface resistance of photoreceptors with and without various surface *treatments*.[6]

Experimental

The temporal stability of the electrostatic latent image has been investigated, using a simple charge/expose breadboard. Organic photoreceptor films, approximately 5-cm square, are affixed to a grounded vacuum platen. The position and velocity of the platen are computer controlled. The film sample is corona charged to the desired surface potential in the dark and positioned at a 0.25-cm slit opening for a near-contact exposure. Exposure is effected with a shuttered xenon lamp and monochromator. The electrostatic latent image is read with a Trek Model 344 Electrostatic Voltmeter with a high-resolution probe and the analog

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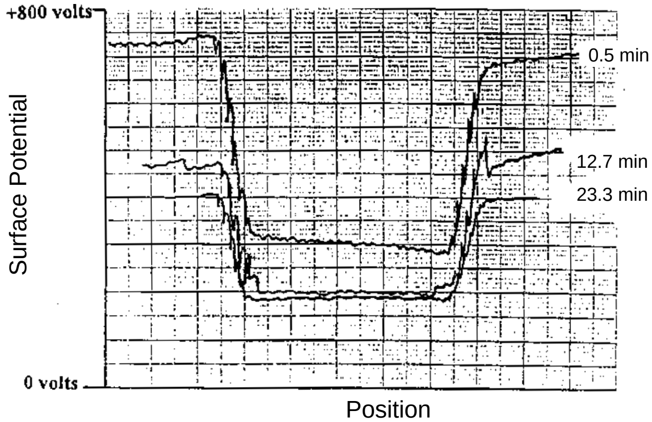

Figure 1. The electrostatic image structure of a positive charging photoreceptor at 0.5-, 12.7-, and 23.3-min delays after exposure through a 0.25-cm slit. The position axis units are 0.0255 cm/major division.

signal is recorded with a Gould TA240 Easy Graf Recorder. The minimum time delay between exposure and recording of the image is approximately 10 s. The charge/expose apparatus is in a dark chamber, which is maintained at ambient (approximately 75°F and 55% RH) or at elevated RH.

Results and Discussion

Figure 1 shows a typical image obtained with a positive charging photoreceptor. The half-height width of the image is approximately 0.25 cm. The initial image shape is affected by several factors. To avoid contact between the photoreceptor and the exposure mask or electrostatic probe, a gap of approximately 0.5 mm is necessary. This gap may introduce exposure flare, and it also limits the resolution of the electrostatic probe. In addition, because of light intensity variations in the exposed area, the ideal *square well* shape is difficult to obtain. Finally, field-dependent dark decay distorts the image, particularly at long delay times after exposure. We have not compensated for these factors in our preliminary work. Nevertheless, it is

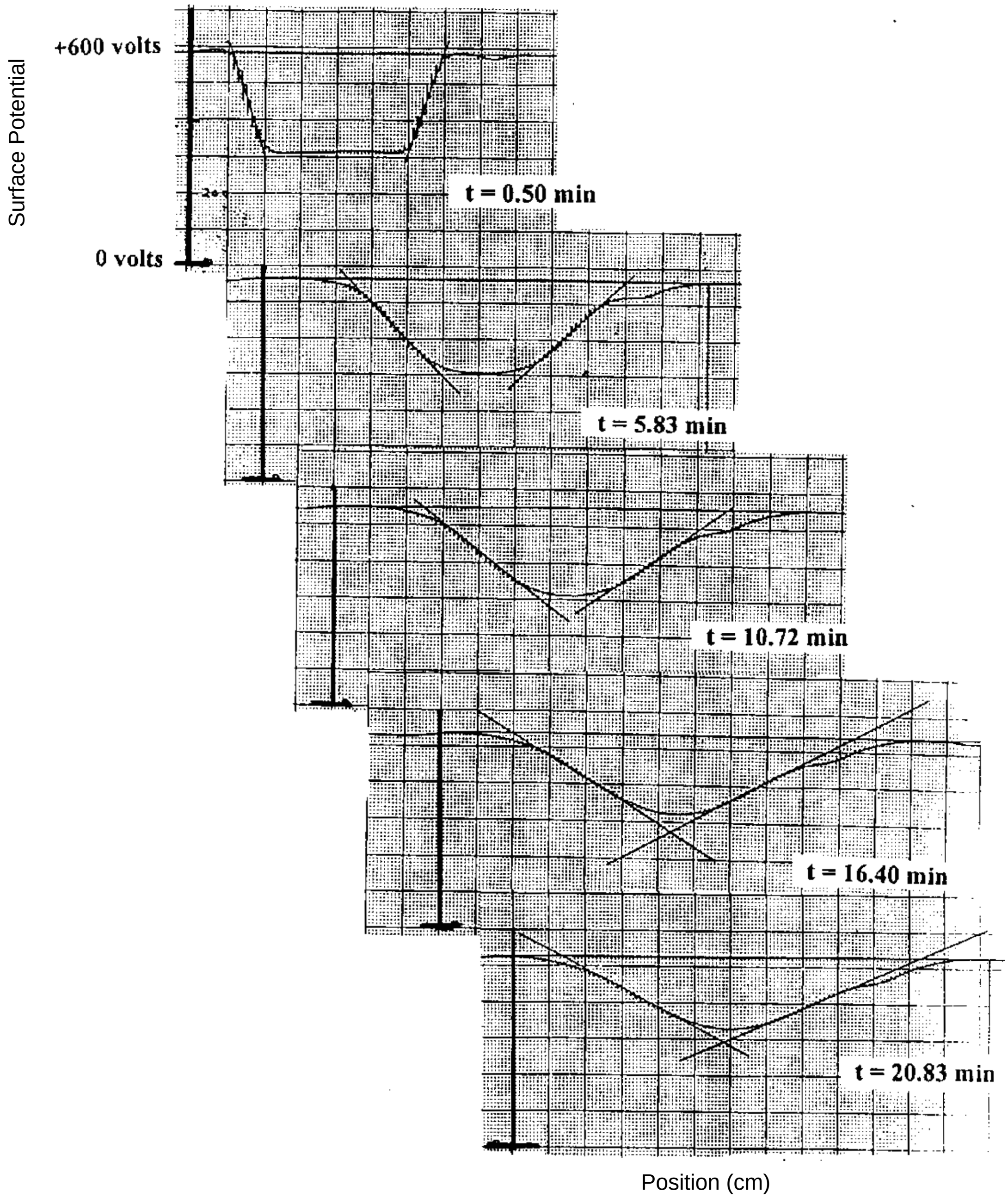

Figure 2. The electrostatic image structure of a positive-charging photoreceptor (22 μm) with a 4-μm sol-gel overcoat[6] at 0.5, 5.83, 10.72, 16.40, and 20.83 min after exposure through a 0.25-cm slit. The position axis units are 0.051 cm/major division.

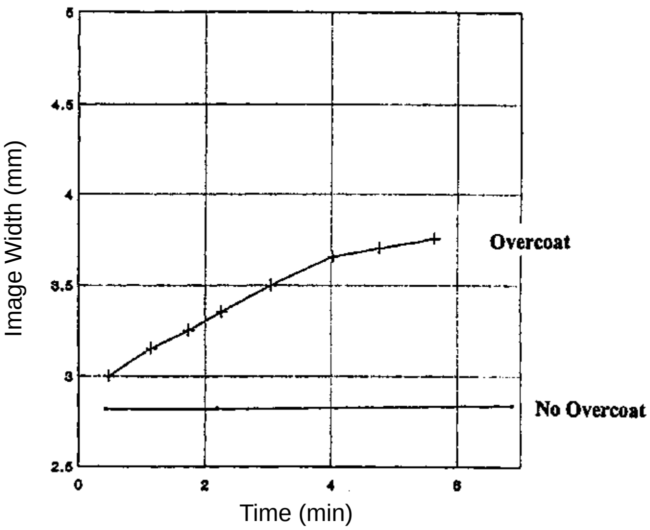

Figure 3. The square well image width as a function of time delay after exposure through a 0.25-cm slit for a nonovercoated and a sol-gel-overcoated[6] positive charging photoreceptor. The image width is defined as the distance, at the surface potential maximum, between the lines drawn tangent to the image edges.

clear that over the time period encompassed by the experiment the square well image shape does not change. Figure 2 shows the images obtained with a positive charging photoreceptor with a 4-μm sol–gel overcoat.[7] In this case, substantial spreading of the image happens during the course of the experiment.

Qualitative evaluation of the time-dependent changes in the image shape was carried out by measuring the width of the square well at the surface potential maximum as the distance between the tangents drawn to the exposed edges, as shown. Figure 3 shows the change in width as a function of time for the nonovercoated and sol–gel overcoated photoreceptors. To illustrate the effect of chemical treatment, we sprayed the surface of a photoreceptor with a commercially available glass cleaner. The results in Fig. 4 show that this treatment caused considerable image degradation. However, after a water rinse of the photoreceptor surface, the image structural integrity was restored.

These results demonstrate that a photoreceptor with a conductive surface, caused by chemical treatment or by application of a polymeric overcoat, will exhibit image degradation with time after image formation and that these changes are readily measured, using commercially available instrumentation.

For quantitative analysis of the change in electrostatic image shape with time, in terms of surface resistance, we have utilized a model that has seen previous application. The equation

$$\frac{\partial V}{\partial t} = \frac{1}{R_{sq}C}\frac{\partial^2 V}{\partial x^2} \tag{1}$$

describes the 1-D time-dependent change in voltage (V) because of field-induced drift of surface charge on a dielectric sheet in terms of the surface resistance (R_{sq}) and capacitance per unit area ($C = \kappa\varepsilon_0/l$), where l is the photoreceptor thickness and the other symbols have their usual meanings. Assumptions implicit in the use of this model are that the distance over which the surface charge density varies is significantly larger than the photoreceptor thickness, so that the surface charge density and voltage are related through geometric capacitance, and that the surface resistance is constant.

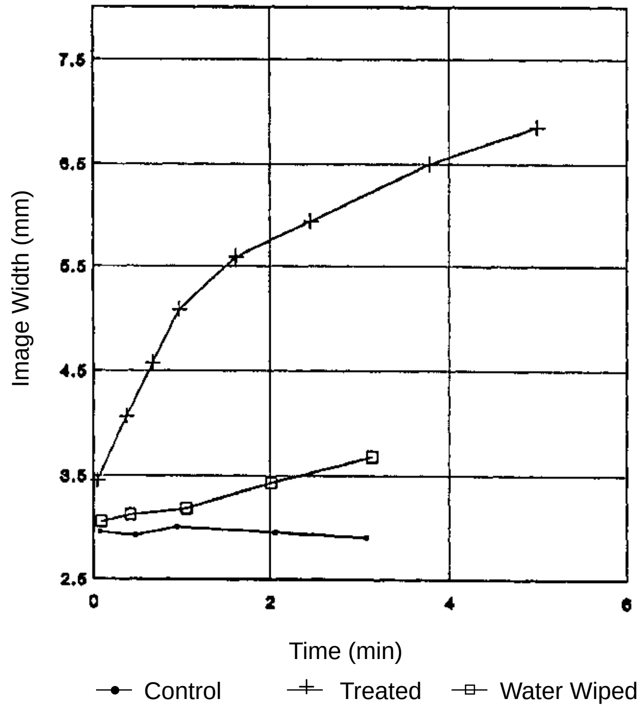

Figure 4. The square well image width, as a function of delay after exposure through a 0.25-cm slit, for a positive charging photoreceptor before and after spraying the surface with a commercially available glass cleaner. The treated photoreceptor is returned to the original state by rinsing the surface with water.

Essentially the same approach has been used to describe Ohmic conduction on a glass plate[8] and lateral conduction in paper,[9] as well as to describe the degradation of the electrostatic latent image on an organic photoreceptor.[4]

Because our exposure is through a slit, we have integrated Eq. 1 for an initial square well latent image profile with the image centered about $x = 0$ and a width of $2a$. The equation

$$V(x,t) = V_0 - \tfrac{1}{2}\Delta V_0\left[\operatorname{erf}\left(\frac{a+x}{\sqrt{\frac{4t}{R_{sq}C}}}\right) + \operatorname{erf}\left(\frac{a-x}{\sqrt{\frac{4t}{R_{sq}C}}}\right)\right] \tag{2}$$

is the result, with the symbols as defined previously; in addition, V_0 is the initial surface potential and $\Delta V_0 = V_0 - V_{\exp}$, where $V_{\exp}$ is the surface potential in the exposed area. This model can be used to determine the temporal characteristics of a square-well image on a photoreceptor of a given capacitance as a function of the surface resistance. Figure 5 shows the calculated results for a square-well image with a 40-μm width on a photoreceptor of 20-μm thickness and an assumed dielectric constant of 3.0. These results clearly demonstrate the necessity of a nonconductive photoreceptor surface if electrostatic latent image integrity is to be maintained in an electrophotographic process when the time between exposure and image development is typically on the order of 1 s.

The experimentally determined images can be analyzed to obtain R_{sq} from the model, using several techniques. An experimental image, at a given time delay, or the experimental change in voltage as a function of time at any

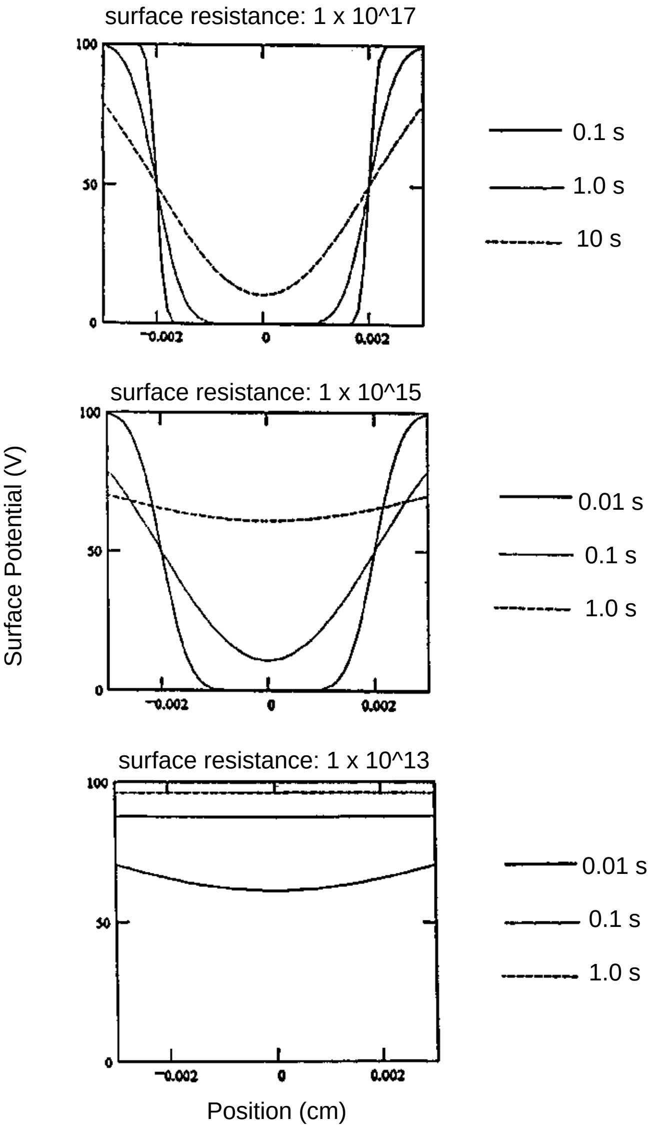

Figure 5. Calculated 40-μm square-well image shapes on a 20-μm photoreceptor as a function of time after exposure for surface resistances of 1×10^{17}, 1×10^{15}, and 1×10^{13} Ω.

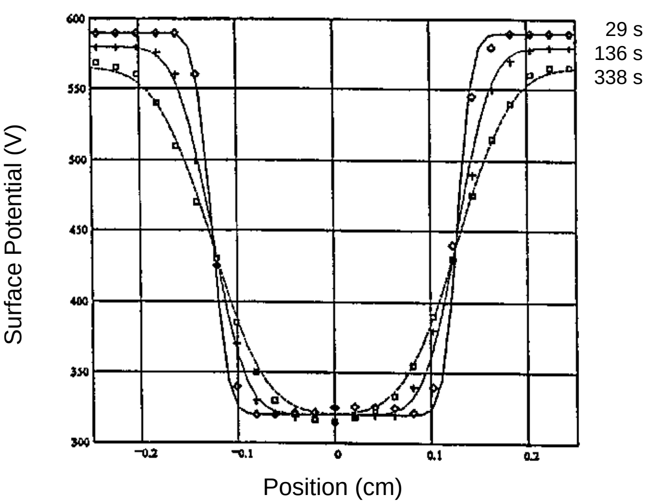

Figure 6. Experimental data (symbols) and image shapes calculated with Eq. 2 (curves) for a sol–gel-overcoated photoreceptor at 29, 136, and 338 s after exposure. The best "eyeball fit" to these data is with a surface resistance of 3.0×10^{15} Ω.

position can be fit to the model. Figure 6 shows the experimental changes in electrostatic image shape for a sol–gel-overcoated photoreceptor at three time delays after formation and the best "eyeball fit" of these data to Eq. 2 with a surface resistance of 3×10^{15} Ω.

A more convenient method of data analysis is to follow the time-dependent changes in the slope of the tangent line drawn at the original edge position. The equation describing the time-dependent changes in the edge slope is obtained by differentiating Eq. 2:

$$\left(\frac{d\ V}{d\ x}\right)_{x=a} = \frac{\Delta V_0}{\sqrt{\dfrac{4\pi t}{R_{sq}C}}}\left[1-\exp\left[-\left(\frac{2a}{\sqrt{\dfrac{4t}{R_{sq}C}}}\right)^2\right]\right]. \tag{3}$$

This equation shows that the slope will vary linearly with $t^{-1/2}$, with an exponential "correction" at relatively long times because of "communication" between the two square-well edges as the image collapses. Figure 7 shows a plot of the edge slope versus $t^{-1/2}$ for a sol–gel-overcoated photoreceptor. Experimentally, image edge slope analysis at both short and long times after exposure is problematic. At short times the image is distorted because of exposure flare and limited voltmeter resolution. At long times the image is distorted because dark decay of the surface potential is greater in the unexposed areas than in the exposed areas. Also, completely uniform exposures are difficult to obtain. A convenient technique is to average the slopes from both edges of the image, plot them as a function of $t^{-1/2}$, and then superimpose plots of Eq. 3 for various values of R_{sq}. Data shown in Fig. 7 include data from the images of Fig. 6. A good "eyeball fit" of the experimental data to Eq. 3 is with a surface resistance of 2.0×10^{15} Ω. The surface resistance fitting parameter differs in Figs. 6 and 7 because the former contains a limited data set and includes the early time image, which is distorted as described previously.

Another method is to measure the change in square-well depth as a function of time. The equation describing this is obtained from Eq. 2 with $x = 0$ as

$$V(0,t) = V_0 - \Delta V_0 \operatorname{erf}\left(\frac{a}{\sqrt{\dfrac{4t}{R_{sq}C}}}\right). \tag{4}$$

Figure 8 shows the time dependence of the surface potential at the minimum of a 0.25-cm square-well exposure on a 20-μm photoreceptor with different surface resistances. The minimum voltage is readily measured, so with an appropriate choice for the initial square well image width and a convenient measurement time period, it is possible to study photoreceptors having a wide range of surface resistances.

The equations governing the temporal changes in shape of a square-well image are complex because of interactions between the two image edges as the image spreads. The equations governing the temporal characteristics of a sharp-edge exposure are simpler. The time dependence of the spreading of a sharp-edge image is given by

$$V(x,t) = V_0 - \tfrac{1}{2}\Delta V_0\left[1+\operatorname{erf}\left(\frac{a-x}{\sqrt{\dfrac{4t}{R_{sq}C}}}\right)\right]. \tag{5}$$

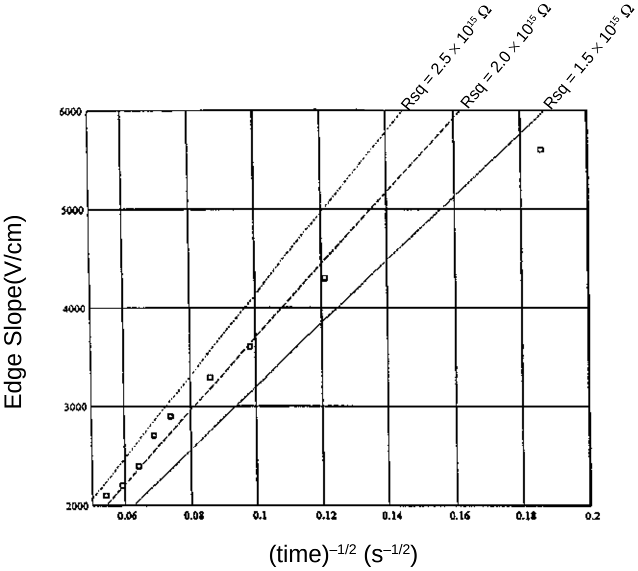

Figure 7. The image edge slopes (symbols) for a sol–gel-overcoated photoreceptor as a function of time (s) after exposure. The lines are calculated from Eq. 3, using the surface resistance values indicated. The best "eyeball fit" is with a surface resistance of $3.0 \times 10^{15}\,\Omega$.

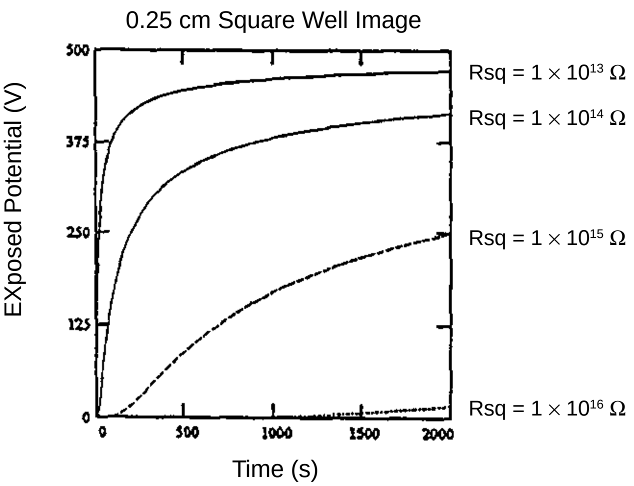

Figure 8. The surface potential at the exposed minimum of a 0.25-cm square-well image as a function of time after exposure for varied surface resistances calculated from Eq. 4.

In this case the slope of the image edge tangent at the original edge position (a in Eq. 2) becomes

$$\left(\frac{dV}{dx}\right)_{x=a} = \frac{\Delta V_0}{\sqrt{\dfrac{4\pi t}{R_{sq}C}}}. \qquad (6)$$

Thus for the sharp-edge exposure case the change in edge slope is a linear function of $t^{-1/2}$ rather than the complex expression of Eq. 3. In future work we will describe the use of the sharp-edge model to characterize photoreceptor surface conductivity.

We have carried out many analyses of surface-treated and surface-overcoated photoreceptors, using the edge slope method described by Eq. 3 and shown in Fig. 7. Table I shows some representative results. A typical untreated photoreceptor at approximately 55% RH has a surface resistance that is too high to measure accurately. The primary difficulty is the field-dependent dark decay that occurs over the many hours required to see measurable changes in the image shape. However, at slightly elevated humidity, there is approximately an order of magnitude decrease in surface resistance. We ascribe this difference to a higher concentration and/or mobility of corona-deposited ions on the photoreceptor surface. A further decrease in surface resistance is observed after a 5-min exposure to corona (grounded grid). Spraying the surface of the photoreceptor with a commercially available glass cleaner dramatically reduces the surface resistance, as described previously.

TABLE I. Surface Resistances of Photoreceptors Determined Using Eq. 3 and the Square Well Image Edge Slope Analysis.

Photoreceptor Description (Treatment)	Surface Resistance (Ω)*
Untreated (55% RH)	$>10^{18}$
Untreated (65% RH)	2.5×10^{17}
Corona exposure (5 min, 55% RH)	1.0×10^{16}
Corona exposure (5 min, 65% RH)	2.5×10^{14}
Sol–gel overcoated	2.0×10^{15}
Glass cleaner treated	5.0×10^{12}

*Surface resistances are determined from the best "eyeball fit" of the model to the average of the two edge slopes at each time delay after exposure.

Conclusions

We have investigated the effects of corona treatment, chemical treatment, and a polymeric sol–gel overcoat on the temporal stability of a square-well electrostatic image on an electrophotographic photoreceptor. The effects of RH have also been studied. We have derived equations describing the time-dependent evolution of a sharp-edge or a square-well image on an electrophotographic photoreceptor as a function of surface resistance as the only adjustable parameter, and we have described several techniques for quantitative extraction of surface resistance from the experimental data. Compared with the nonovercoated photoreceptor, the sol–gel-overcoated photoreceptor has a low surface resistance. Extended exposure to corona gases, particularly at high RH, results in substantial decreases in surface resistance. The effects of surface resistance changes on the temporal characteristics of digital electrostatic latent images may be readily calculated, using the appropriate function to describe the image shape as an initial condition for the integration of the equation describing the field-induced drift of surface charge. We have demonstrated such an analysis, using a square-well image of 40-μm width. In addition, the techniques and theory described can be used to determine the resistance of thin polymeric overcoat materials applied to a photoreceptor surface. In this case, a sharp-edge exposure may simplify the analysis.

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