# Dynamic Electronic Circuit Model for an Emerging, High Quality Liquid Electrophotographic Process

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## Abstract

An accurate analog electronic circuit model of a high quality liquid electrophotographic process is presented. The critical static and dynamic electrical material characteristics were measured experimentally, and programmed into the dynamic model. The process is then "run on the computer," revealing important and subtle process characteristics and parameters which are otherwise not measurable. The process model is refined through iterative cross-checking with the physical process so that all of the experimentally measurable electrical parameters are in agreement with the analog circuit model parameters. The power of such an accurate dynamic model lies in its ability to investigate on the computer, rather than in custom hardware, with reasonable confidence: 1. different experimental arrangements, varying considerably from the initial physical embodiment, 2. dramatically different speed regimes, for future embodiments, 3. various internal dynamic voltages, currents and fields, within development "nips," photoreceptor layers, etc., which are inaccessible to normal, experimental "observation," and 4. possible future problem areas, along with various alternatives.

For example, the process model was used to investigate accurately, a new high speed design for more than a year before the experimental hardware was available, providing important design changes before the hardware was "off the drawing board."

## Introduction

The high quality liquid electrophotographic process modelled herein, and designed as a computer color printer, is shown

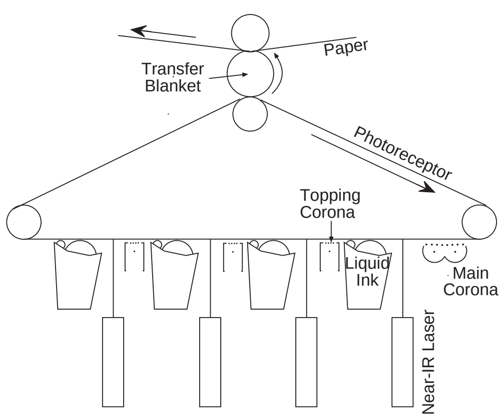


*Figure 1. Diagram of Printing Process*

schematically in Figure 1. The photoreceptor is charged, exposed to a scanning laser, and developed with a liquid ink which is substantially "film-formed" after the development station. It is rapidly and sequentially recharged, exposed, and developed with at least 3 more color liquid ink stations before the film-formed and dried composite color image is transferred *en masse* to an intermediate transfer blanket, from which the image is again transferred to the final paper or transparency receptor. The liquid inks are designed to transmit the near-IR laser radiation. While the quality obtainable with this one-pass single transfer process is truly remarkable, the subject of this paper focuses on the process physics, and in particular, on dynamic electronic circuit modelling of the rapid, multiple, charge, exposure and development cycles involved.

## Modelling

In Figure 2, the organic photoreceptor, OPR, comprises four layers: a conductive substrate, a photoconductive layer, a barrier layer, and a release layer. These layers can be modelled

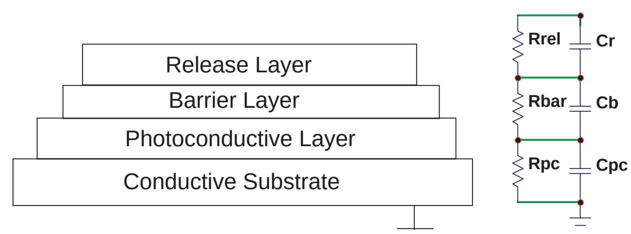


*Figure 2. Photoreceptor*

electronically, in the simplest approximation, as a "stack" of capacitors in series, each with its own characteristic parallel resistance. The parallel resistance for the photoconductive layer, $R_{pc}$, changes its resistance value at the proper times to represent its dark resistance, light resistance, persistent resistance, field-dependant leakage, etc. The parallel resistance of the barrier and release layers are not responsive to the laser radiation, but will have other specially-modelled electrical dependencies as will be shown.

Figure 3 is a highly-simplified (for clarity) electronic schematic diagram representing the charge, exposure, and development circuit elements for one color plane. The switches are time-controlled, representing the timing of the process steps. The general circuit functions of corona charging, laser exposure, and liquid ink development are identified on the diagram. Figure 4 shows the transient potentials resulting for the

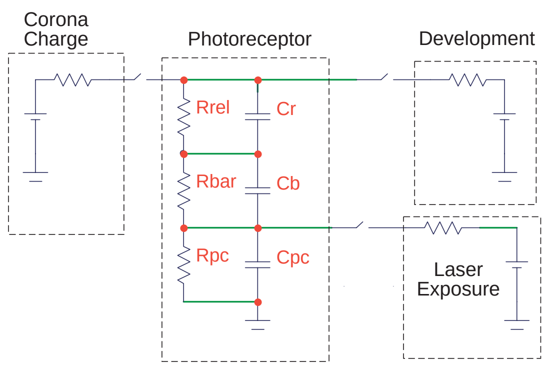


*Figure 3. Highly Simplified Circuit*

first color-plane from the viewpoint of one tiny area of photoreceptor traversing the first charging, exposing and developing stations. In this example, the photoreceptor is corona charged to 600 volts. A simple voltage supply and RC charging circuit are depicted for simplicity, but the actual position

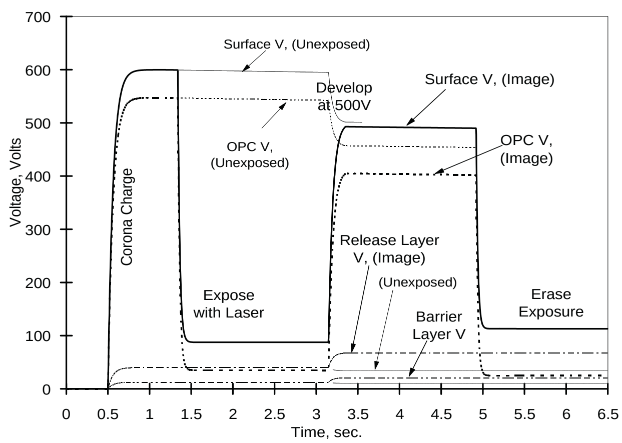


*Figure 4. Transient Potentials for One Color Plane, (Image Area and Unexposed Area)*

dependent and electric field dependent conductance profiles of the corona source, discussed in the previous companion paper[1], are programmed into a time-dependant "user file" to generate an accurately-modelled transient voltage. While the photoreceptor surface potential after charging can be measured directly, the dynamic potentials during charging cannot, and the individual layer potentials are inaccessible experimentally. The dynamic model provides all these calculated transients which are very valuable as will be seen. As is typical for laser printers, discharged area development is employed. A development bias potential of 500 volts is applied to the liquid ink development roll, below the unexposed background potential, but above the exposed area residual potential. The development current "plates" ink (toner) as it "recharges" the photoreceptor to the developer bias potential, assuming the development proceeds to "completion," as was discussed in the previous, companion paper. In unexposed background areas, liquid ink counter ions "plate" onto the surface, reducing the potential to the development bias value, 500 volts. Since the counter ions are not colored, they are not apparent in the image. Notice the significantly different layer voltages depending upon whether the area was exposed (image area), or unexposed. More will be said about this later.

Figure 5 shows the transient potentials for one complete print of 4 color planes. Notice that the charge "stored" on the barrier and release layers keeps rising since these layers are quite insulating, and they are not light (radiation) responsive.

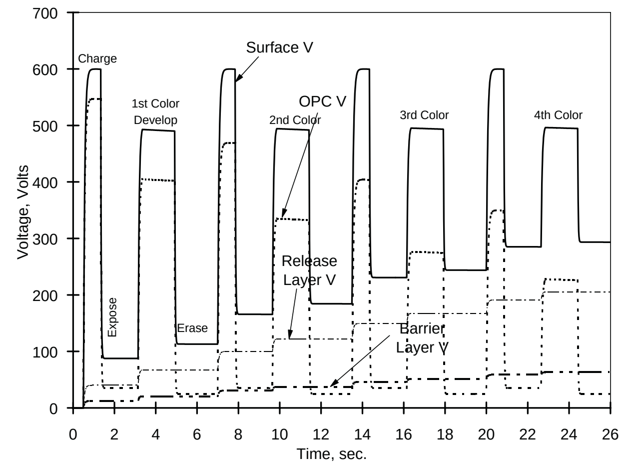


*Figure 5. One Print, Four Color Planes*

If one continues, say, 4 prints (16 color planes) under these conditions, as shown in Figure 6, the barrier and release layers would continue to charge, progressively "stealing" all the voltage at the expense of the photoconductive layer. However,

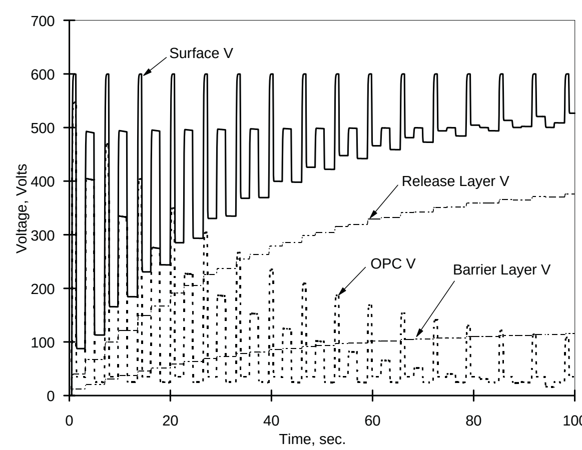


*Figure 6. Four Prints (16 Color Planes), Insulating Barrier and Release*

this does not happen experimentally, as evidenced by the surface potential measurements one can make, and this demonstrates the critical importance of always comparing modelling assumptions and results with known measurements and performance to keep the model accurate and useful. In this case, the discrepancy lies in using a fixed parallel resistance for the insulating barrier and release layers. As one can see from Figure 6, the potentials across these insulating layers would rise to many hundreds of volts. But these layers are very thin, only a fraction of micrometer, and could never sustain such high electric fields, so we have to measure their field-dependant leakage characteristics, and include them in the model. Fortunately, these layers do not break down abruptly and destructively, but exhibit a relatively "smooth" increase in electrical conductance with increasing fields. Therefore, the potentials across these layers never rise above certain amounts, depending upon the particular dynamic conditions. When these field-dependant resistances are included in the model, the experimentally-measurable voltages agree very well with the model-calculated values, giving one confidence in the accuracy of the model.

After the first color plane is developed, a "topping corona" recharges the photoreceptor from 500 to 600 volts in preparation for the next color plane.

Figure 7 is the electronic circuit model of the complete process with 4 coronas (one main, and 3 topping coronas), 4 near-IR lasers and 4 color ink development stations. An erase illumination source is added to "reset" the photoreceptor before subsequent prints. The circuit "macro" boxes adjacent the barrier and release layer capacitances, $C_b$ and $C_r$ respectively, in Figure 7, are the field dependent leakage resistances matching the experimentally-measured characteristics for the layers

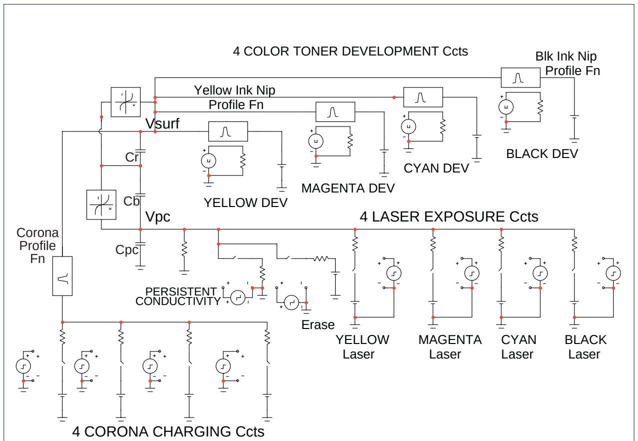


*Figure 7. Four Color Circuit Model*

The liquid ink conductance profiles, both position dependant and electric field dependant, reported in the previous companion paper, are converted into time and field dependant "user files," and are included in the present model. Since there is a known relationship between the deposited toner mass per unit area and the development current integral per unit area (experimentally measured), one can even know the deposited toner mass and the optical density for each color plane.

As an example of the usefulness of the model, it was developed as a research tool on an earlier hardware embodiment utilizing a photoreceptor drum making 4 turns as the different color development stations were sequentially indexed into position. A complete print took about 26 seconds, and the transient voltages for this embodiment are shown in Figure 8.

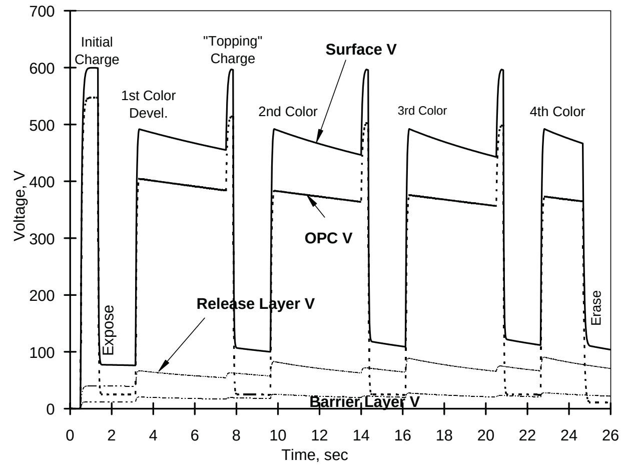


*Figure 8. Transients for Four-Turn Drum Machine*

It was then decided to develop a one-turn, in-line embodiment which would produce one print in only about 6 seconds. While it took over one year to build the actual hardware embodiment, it was "up and running" on the computer within a day or two.

Furthermore, the model prompted several important design changes before the new embodiment was "off the drawing board." When the hardware was finally finished, the accuracy of the model in the new, faster regime was confirmed.

Figure 9 shows the higher speed print transient. Notice the buildup of the potential across the barrier and release layers, and the increasing decay rate as the electric field increases on them. It is readily apparent that the voltage buildup on the barrier and release layers is a significantly larger fraction of the photoreceptor voltage in the higher speed case, despite the field dependent leakage. Since the developed toner mass is proportional to the "development vector voltage" (the development bias voltage minus the residual voltage on the photoreceptor prior to development), clearly the developed toner mass is "history-dependant." That is, the last color plane's de-

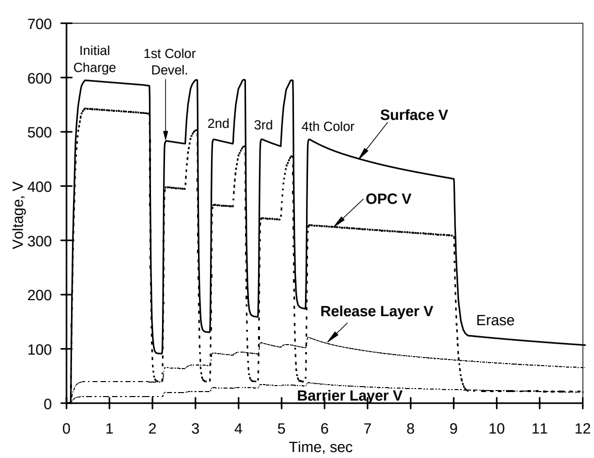


*Figure 9. Higher Speed, Single Turn, In-Line*

velopment current integral will depend upon the amount of voltage stored on the barrier and release layers (a significant component of the photoreceptor's residual potential), which depends upon the immediate history of the unit area in question -- whether the preceding color planes were image areas or background areas. This effect is aggravated by the higher speed. To ameliorate this effect, from the model, one can suggest incorporating a weakly-conductive material into the barrier and release layers to increase the leakage rate without adversely affecting the transverse resolution. A material time constant of about 1/3 second would correspond to a bulk resistivity of about $10^{12}$ ohm-cm. If one were to incorporate this into the two layers, the transient potentials that would result for one print cycle (4 color planes) is shown in Figure 10.

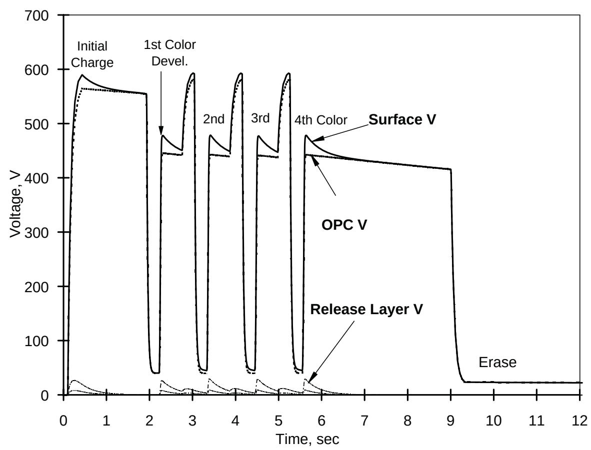


*Figure 10. Weakly-Conductive Material Added to the Barrier and Release Layers ($\rho = 1x10^{12}$ ohm-cm)*

Clearly, this is a significant improvement compared to Figure 9 relative to the cumulative potential stored on the barrier and release layers (and consequently "stolen" from the photoconductive layer). However, it's far easier to achieve the $10^{12}$ ohm-cm bulk resistivity in the computer model than it is to achieve it experimentally in real materials without compromising other properties.

One could also increase the thickness of the photoconductive layer relative to the constant-thickness barrier and release layers, so that the fractional voltage on the barrier and release layers diminishes. This is modelled in Figure 11, where the photoconductive layer thickness is about doubled, while keeping the barrier and release layer thicknesses constant. The charge density on the photoreceptor is maintained constant by increasing the voltage to which the photoreceptor is charged and the development bias, an approximate requirement for equivalent developed toner mass on the thicker, lower capacity photoreceptor. This results in an improvement relative to Figure 9, but at the expense of higher voltages.

All the various permutations and combinations of the 4 color planes have been run (all color planes exposed, only

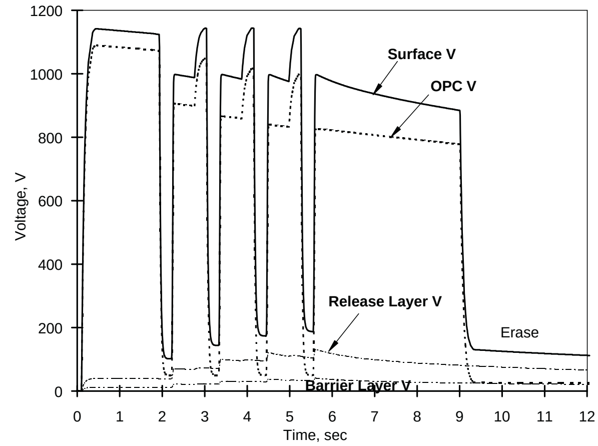


*Figure 11. Double-Thickness Photoconductive Layer*

magenta exposed, etc.).

Time and space does not permit explanation of some of the subtler items, such as the "persistent conductivity" components. Also, much-refined "internal" elements can be included within the photoconductive layer to model trapping effects, charge-injection, field-dependence, space charge, etc., as well as between layers and surfaces.

Much more complex models can also be developed for the ink layers as well, to represent toner-on-toner, space charge, charge "trickle-down" within and between layers, charge reversal as earlier image areas become background areas in subsequent color planes, etc.

It is a simple task to model much higher speeds, photoreceptors with different characteristics, etc.

## Conclusion

A powerful, dynamic, analog electronic circuit model has been developed and used effectively for an emerging high quality liquid electrophotographic process. It has been used not only for additional knowledge and understanding, but for "real world" design and experimentation

## References

1. Arthur R. Kotz and David A. Ender, Paper I-059, NIP 14, (1998).

## Biography

Arthur Kotz received his BS in Physics from The University of Minnesota, and MS and Ph.D. in Physics from The University of Wisconsin, Madison. He joined 3M in 1955, has 43 years experience in the area of electrophotography, toner systems and electronic printers, and has a number of patents and publications in the field. He retired as a Corporate Scientist from 3M in 1996 and is now an independent consultant in the area of electrophotography, liquid and dry, high speed electronic imaging, and physics in general. He is a member of the APS and IS&T.

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