

# **Variability of Electroluminescent Displays**

By

C. Michael Shedd & Nathan Ostrout

Graphic Communication Department

College of Liberal Arts

California Polytechnic State University

2011

## **APPROVAL PAGE**

TITLE: Variability of electroluminescent Displays

AUTHOR: C. Michael Shedd & Nathan Ostrout

DATE SUBMITTED: June 2011

Professor Xiaoying Rong, Senior Project Advisor \_\_\_\_\_

## **Acknowledgements**

The completion of this senior project was made possible through the generous donations of time, energy and financial resources. A special thank you to the California Polytechnic State University Graphic Communication faculty who prepared us over the past three years to apply the knowledge and skills we have learned through our education towards the testing and writing of these five chapters.

To Professor Xiaoying Rong who spent countless hours guiding us through this project, helping us grow as students and insuring we smiled every step of the way. To Professor Nancy Cullins who encouraged us in the early phases of this project and lent us her extensive understanding of the graphic communication industry, particularly screen printing. We would like to extend a special thank you to the Graphic Communication Department at Cal Poly and to Gwent Group for donating equipment and supplies for all of the testing. Last, but not least, thank you to my senior project partner and friend for making this process an enjoyable experience.

## Table of Contents

Chapter I — Introduction.....	5
Chapter II — Literature Review.....	7
Chapter III — Research Methods and Procedures.....	12
Chapter IV — Results.....	17
Chapter V — Conclusions.....	36
Appendices.....	40
Appendix A — Benchmark Test Table.....	40
Appendix B — Benchmark Test “Cal Poly” Wordmark.....	41
Appendix C — Comprehensive Test “CP” Workmark.....	42

## Chapter 1—Introduction

Consumer product companies are demanding new and innovative print solutions to increase sales and compete with the vast amount of advertisements pleading for the attention of consumers. Electroluminescent (EL) printing is one solution to this growing demand for more effective marketing collateral. Electroluminescent displays create a kinetic visual element by lighting up. These displays are useful in such instances where brightness, high contrast and a wide angle of view are required. Electroluminescent printing combines the features of both traditional graphic printing and EL inks for the production of commercial prints, products, and packaging that illuminate (Hart, 2010).

EL displays, by a large part, are produced by screen printing several layers of functional inks. While screen printing has traditionally been used for graphic imaging processes, awareness of the process' functional printing uses has introduced it to the EL printing segment. Screen printing, currently the optimal print choice for EL displays, have many variables, which arise from the nature of this process, both which promote and inhibit the performance of functional ink layers. The effects that these variables have on printing EL displays will need to be analyzed to make constructive improvements for all applications.

This study asks: how does the screen printing variables affect efficiency of electroluminescent displays? Based on previous studies and research, traditional screen printing methods are adequate for obtaining desired results for different functional layers in electroluminescent displays . Squeegee pressure, printing speed, emulsion thickness, and screen mesh count are all variables that are involved in screen printing and need to be quantified in order to determine optimal operational conditions. Furthermore, printed functional ink film variables need to be examined for their effect on the display. These variables include surface uniformity, thickness, and printing processes (e.g. wet over wet method or wet ink on dry method). In order to understand optimal printing characteristics for efficient current

conduction and illumination of a display, this study attempted to control human errors during operation that might lead to additional printing related variables. As a result, an automated screen printer was used. The enhancements of the screen printing processes were key for printing fine detail work and in the end aided to the success of printing electroluminescent displays.

The purpose of this study was to optimize the screen printing process pertaining to the printing of electroluminescent displays. Printed electronics is a fairly new concept in the graphic communication industry and to date has only been employed by a limited number of professionals. Therefore, this research study was conducted to identify optimal processes for screen printing electroluminescent displays. The research was intended to help understand how printed electronics could be printed with conventional screen printing.

## Chapter 2 —Literature Review

There are two main categories of emitted light, consisting of incandescence and luminescence. Incandescent light is produced by an electric current, which passes through a filament, the transmission of which generates heat and in turn emits light. Luminescence is thereafter defined as any radiant energy that is not generated by a change in temperature and encompasses electroluminescent, and is the focus of this study (Hart, 2010).

Electroluminescent displays require a minimal amount of energy compared to other forms of light. These displays which are composed of a series of functional layers, undergo several steps in order to generate light. Electrons are tunneled from an electronic state at the phosphor interface until they are ultimately accelerated to high levels by fields in the phosphor. These highly energized electrons then activate the luminescent region of the phosphor. Once this region returns to a ground state it emits the basic unit of light, a photon (Hart, 2010).

A record of the electroluminescent phenomenon dates back to the early 1900s. Henry J. Round conducted the first recorded study of electroluminescent in 1907. Round, an American scientist who at the time was analyzing radio waves, observed a discharge of various hues of light while transmitting a current through silicon carbide (SiC). However, research on the technology remained relatively quiet until in 1923, a Russian experimenter by the name of Oleg Lossev made a similar observation to that of Round while also conducting fieldwork on radio waves. Lossev would later make a significant contribution to the field of electroluminescent by publishing detailed documentation on his findings in 1940. Concurrently as Lossev was performing his research, French engineer Georges Destriau discovered that zinc sulphide (ZnS) was capable of emitting light under conduction. In 1959, the Westinghouse Company produced the first zinc sulphide electroluminescent panel in America as part of their research and development and would eventually lay the foundation for commercial production

of electroluminescent displays. Today, electroluminescent displays have found a market in commercial prints, products, and packaging and are primarily produced by methods of screen printing (Peaker, 1970).

For many years, only those who were exceptionally skilled at screen printing could print superior results for electroluminescent displays. However, R. J. Horwood (1974), screen printing researcher focused in ink film thickness, explains, “in recent years, a more scientific approach to the age-old craft of screen printing has resulted in the evolution of complex precision-built printing machines for use in the electronics micro-circuit industry” (p.129). As print technology keeps growing, the call for specialized print processes does as well. As a result, due to screen printing’s capabilities, the process appears to be the most optimal form of production for printed electronics (Horwood, 1974).

Screen printing is a process by which ink is pushed through a polyester screen stencil and onto a substrate (Hensen, 2007). The image (C in Figure 1) is printed onto a transparency, which is used to image a polyester screen, mounted into a frame (D in Figure 1) and coated with a photosensitive emulsion layer. The transparency is secured on the screen and then exposed with ultraviolet light to cure the emulsion. The uncured portion of is then removed by water, leaving openings in the screen for printing. Screen printing ink (A in Figure 1) is then placed onto the screen and a squeegee (B in Figure 1) is used to force the ink through the stencil. There are certain types of squeegees that can be used, each having a unique affect on how the ink is transferred through the stencil. The image can be printed onto numerous types of substrates (E in Figure 1) including paper, fabrics plastics, and metals (Hensen, 2007).

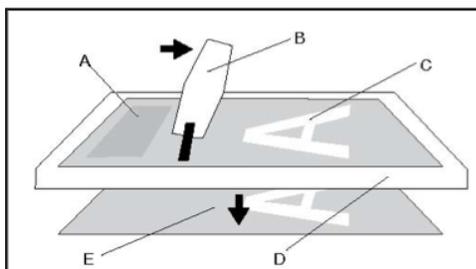


Figure 1: the screen printing process

Traditional screen printing techniques do not require extremely tight process controls over each variable of the printing process. However, the printing of functional inks need careful monitoring to ensure accurate print results. Printed electronics depend on specific characteristic values to function, which influence resistivity (Horwood, 1974). Therefore, it is important to maintain control during the printing process to ensure electroluminescent displays function effectively.

It is also important to understand the qualities of screen printing inks and how they are comparable to that of electroluminescent inks. The important aspect of screen printing inks is the their viscosity, and how ink's resistance to flow plays a part in the screen printing process. Horwood explained that screen printing inks, "exhibit a kind of quality that when at rest are extremely viscous but flow quite readily under moderate shearing stress, a force that is applied parallel or tangential to the face of the material, which are termed pseudo-plastic" (Horwood, 1974). The purpose of such qualities is to ensure that the inks do not flow after they are printed so that the image does not acquire any dot gain (Horwood, 1974). Screen printing inks have a high viscosity making them very rigid and able to hold their form.

The pillar theory presented by Horwood (1974) gives a detailed formula of certain elements of the screen printing process to calculate accurate ink film thicknesses. The key elements revolve around the screen where mesh count ( $T$ ), thread diameter ( $d$ ), and emulsion thickness ( $e$ ) all play a part in the calculation of the ink film thickness (Horwood, 1974,). First, the mesh thickness is determined by doubling the thread diameter ( $2d$ ). Screen thickness can then be determined by adding the mesh thickness and the emulsion thickness ( $2d+e$ ) (Horwood, 1974). Horwood (1974) also made note of another variable where he stated, "the warp lines have larger amplitudes ( $a$ ) than the weft lines resulting in an overall mesh thickness ( $a+d$ ). Warp and weft describes the characteristics of a weave in fabric, usually weft is the threads running left to right and warp running up and down (Mahon, 2007). Thus, the

variation of mesh thickness is due to the warp and weft characteristics of the mesh weave. The pillars of ink are printed through the mesh weave resulting in pillars of ink being deposited onto the substrate. It is also known that, “there are  $T_2$  such pillars in a unit square of area,” therefore the total ink volume per unit area can be calculated by the formula:  $v = [(1/T) - d]^2 (ad+e) T_2$  (Horwood, 1974).

After the ink has been deposited there can be some lateral flow by gravitational stress (Horwood, 1974). However, Horwood (1974) discusses how, “pillars are usually close enough that the pillars merge by surface tension once they are printed resulting in a continuous print thickness ( $t$ ).” Surface tension is the intermolecular force that attracts like molecules at the surface of a liquid (Escobedo and Mansoori, 1996). Therefore, the similar pillars of ink would merge by the attraction force the ink molecules have. Horwood also stated that the possible losses in the pillar merging process such as; surface uniformity, line sharpness, and presence of pinholes are minute enough to be ignored in the calculation process and therefore  $t = v = [(1/T) - d]^2 (ad+e) T_2$  (Horwood, 1974). The examination of this formula is important because of the relationship between functionality of electric materials and the ink film thicknesses. Research has shown that the conductivity of ink layers depends heavily upon the ink film thickness and it is therefore important to understand the variables related to ink film thickness. Horwood (1974) concludes that this formula can accurately predict ink film thicknesses within ten percent as long as the printing conditions are held constant.

There are a few other variables of the printing process that could affect ink film thickness. Horwood (1974) found that the traverse speed of the squeegee directly affects the ink film thickness. Studies showed that the faster that the squeegee traverses, the thicker the ink film thickness will be (Horwood, 1974). In addition to the squeegee speed, the durometer (hardness) of the squeegee also plays a role in ink film thickness. Softer squeegees lay down more ink (Horwood, 1974). In addition, screen tension exerts force upward against the squeegee affecting the “snap off,” which is the distance

between the substrate and the screen (Horwood, 1974). Greater distance between substrate and screen reduces the likelihood of the screen causing ink pick up and thus inadvertently leading to uneven ink film thickness. Screen tension loss occurs over time through the use of the screen. Horwood found that as long as the screen is no less than 50 percent of its original tension, it will produce adequate quality prints (1974).

This project was performed to understand how screen printing variables affect electroluminescent displays. The knowledge of screen printing inks and electroluminescent displays gathered and presented in this chapter were used to design the experimental testing.

## Chapter 3—Research Methods and Procedures

The scientific method is used when experimentation is needed to answer questions correlating with cause and effect relationships of the experiment. This is done by first identifying and defining the problem that is needed to be resolved. The observer then forms a hypothesis to what the cause of the problem is, in order to prepare for the next step. Experiments are then conducted to collect, organize, and analyze data to further understand the experiment. The observer then forms a conclusion based on the analyzed data. Testing is repeated to ensure the accuracy of the experiment. The scientific method was used in this experiment to reach conclusions (Science Buddies, 2011).

### Benchmark Test

Benchmark analysis was conducted in the labs at the Graphic Communication Department at California Polytechnic State University. The purpose of the benchmark test was to predetermine the influence of printing speed on surface uniformity and the conductivity of conductive inks in order to narrow down the variables for the comprehensive test by using one printing speed (220 millimeters per minute or 440 millimeters per minute).

To determine the variability of electroluminescent displays, a series of twelve benchmark tests were conducted (see Appendix A). A monotone “Cal Poly” wordmark, a text only logo, was selected and prepared in Adobe Illustrator Creative Suite 5 (see Appendix B). Two types of inks were tested: silver and dielectric. The layers were output, on an Epson Stylus Pro 7880. Each layer was printed on a separate sheet of polyester transparency for screen exposure.

Polyester screens with a different mesh count were selected: 156 threads per inch (tpi) and 305 threads per inch (tpi). A sheet of Ulano capillary emulsion film with 30 microns of thickness was then applied to each. After the emulsions were applied, the screens were kept at room temperature and in a light-less storage cabinet while they dried.

Screen exposure and preparation was performed in house at the Cal Poly Graphic Communication Department. The positive Cal Poly graphic transparency film was exposed at 40 LTU (light units) with a NuArc 3140 exposure unit. After exposure, the silver and dielectric screens were washed and dried.

Once all preparations of the screens were made, a close examination was performed to check for pinholes and other defects that might cause issues to the finished product. Each screen was then mounted into the ATMA Electric Screen Printer for printing. The press was then prepared for printing by clamping in the squeegee and flood bar and placing ink onto the screen.

A silver ink provided by Gwent Group was printed through a 156 tpi mesh and a 305 tpi mesh at speeds of 220 millimeters per minute and 440 millimeters per minute to create four silver benchmark samples. All four samples were then sent through a M&R Economax II conveyor drier for 60 seconds at 925 degrees Fahrenheit.

Gwent Group dielectric ink was printed following the same procedures as the silver ink. Dielectric ink was printed with two passes to buildup the ink film thickness in order to obtain greater insulation properties. Two experiments were done to understand how printing processes affect ink film qualities: wet over wet method and wet over dry method.

The wet over wet layer was printed with two consecutive passes of dielectric ink, one on top the other without drying in between passes. Printing was performed with a 156 tpi mesh and a 305 tpi mesh at speeds of 220 millimeters per minute and 440 millimeters per minute to create four silver benchmark samples. All four samples were then sent through the conveyor drier for 60 seconds at 925 degrees Fahrenheit.

The dielectric ink was also printed with the wet over dry method. The first pass was printed and dried through a conveyor for 60 seconds at 925 degrees Fahrenheit, and then a second pass was laid on

top of the previously dried ink film. Four samples were printed wet over dry similar to the wet over wet printing process. After printing, the samples were analyzed to verify which variables of printing could produce efficient lighting.

A Keyence LK-682 laser displacement sensor was used to measure thickness and height variation (roughness) for each sample. Resistivity of each sample was also analyzed. Resistivity is defined as “the fundamental parameter of the material that describes how easily the material can transmit an electrical current. High values of resistivity imply that the material is very resistant to the flow of electricity. Low values of resistivity imply that the material transmits electrical current very easily” (Exploration Geophysics, 2002). In order to test the electrical resistance of each sample a Fluke 115 ohmmeter was used. Each sample was tested using the mentioned devices and the results were recorded in a chart for comparison of the variables.

Once all the samples were tested and measured, the results were then used to infer an optimum combination of print variables that would allow for efficient current conduction and illumination of EL displays.

## Comprehensive Test

The comprehensive test was conducted in the labs at the Graphic Communication Department at California Polytechnic State University. The purpose of the comprehensive testing was to optimize the screen printing process pertaining to the printing of electroluminescent displays. Displays were analyzed in order to determine how printing variables affect luminance.

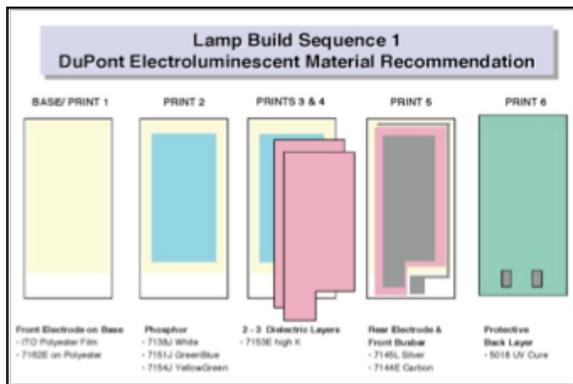


Figure 2: Display build sequence (DuPont, 2000)

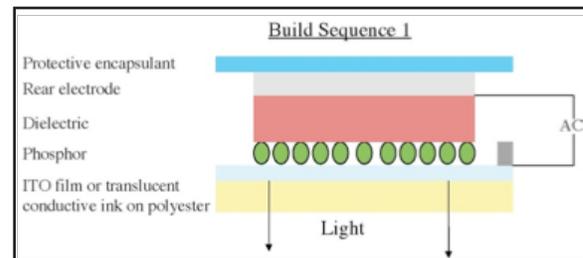


Figure 3: Display build sequence cross section view (DuPont, 2000)

An EL display is constructed by consecutively printing phosphor, dielectric and silver ink layers on top of a conductive transparent ITO film (see Figure 2 and Figure 3). An electroluminescent display illuminates when an alternating current between positive and negative is transferred to the phosphor layer, which is sandwiched between the two conductive materials: ITO and silver. The dielectric layer acts as an electrical insulator between the two opposing charges.

A “CP” wordmark was selected and prepared in Adobe Illustrator 5 in order to construct a functional EL device (see Appendix C). The design was printed for 16 different samples (see Appendix A) with a constant squeegee speed of 220 millimeters per minute. Each of the three layers: phosphor, dielectric, and silver were printed in sequence on an ITO spattered transparency. Mesh count was kept constant for each layer of an EL display in order to reduce the number of variables per test. The phosphor layer was printed as a 100%, 75%, 50% and 25% halftone dot using Gwent Group green phosphor ink.

After printing, the samples were analyzed to verify which print variables could produce the brightest lighting. Additionally, four registration marks were added half an inch from all adjacent sides for accuracy in aligning ink layers.

Ink film thickness was measured using a laser displacement sensor. Data was recorded for later print variable comparison for current conduction and illumination.

## Chapter 4—Results

### Benchmark Test

Silver and dielectric inks were printed on 12 micron polyester transparencies to analyze electroluminescent print variables.

#### ***Ink Film Thickness***

Ink film thickness for the silver and dielectric layers were estimated with a Keyence LK-682 laser displacement sensor. The sensor measured relative ink film height in order to infer ink film thickness for the silver and dielectric layers. Ten ink film thickness measurements were conducted on each test sample (156 tpi mesh printed at 440 mm/min, 305 tpi mesh printed at 440 mm/min, 156 tpi mesh printed at 220 mm/min and 305 tpi mesh printed at 220 mm/min) at random locations. Readings for each sample were then averaged. Findings demonstrate that the combination between speed and tpi mesh have an impact on ink lay down.

#### **Silver Ink**

Silver Ink Film Thickness ( $\mu\text{m}$ )		
	156 tpi	305 tpi
220 mm/min	17.9 $\mu\text{m}$	9.5 $\mu\text{m}$
440 mm/min	22 $\mu\text{m}$	12.6 $\mu\text{m}$

Table 1: Silver ink film thickness across speed and mesh count variables

Silver ink film thickness was important to this study because an EL display luminance value relies on a sufficient amount of silver conductor for a current to flow throughout the display. In summarizing Table 1, a greater print speed in conjunction with a lower tpi mesh produced a greater silver ink film thickness. Printing with a 156 tpi mesh at 440 millimeters per minute produced a greater ink film thickness than at 220 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 440 millimeters per minute produced a greater ink film thickness than at 220 millimeters per minute.

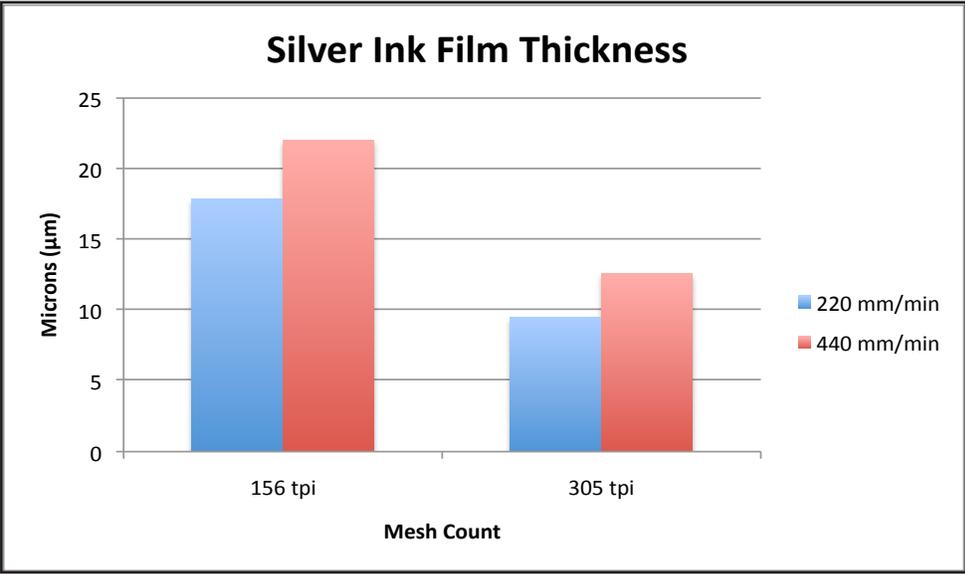


Figure 4: Silver ink film thickness across speed and mesh count variables

Figure 4 illustrates that a lower tpi mesh produced a greater silver ink film thickness. In keeping the print speed constant, at 440 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh. Comparatively, while keeping the print speed constant at 220 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh.

Considering all ink film thickness variables tested, printing with a tpi mesh of 156 at 440 millimeters per minute produced the greatest ink film thickness.

<b>Standard Deviation of Silver Ink Film Thickness</b>		
	<b>156 tpi</b>	<b>305 tpi</b>
<b>220 mm/min</b>	0.0029	0.019
<b>440 mm/min</b>	0.0325	0.0226

Table 2: Silver ink film thickness standard deviation across speed and mesh count variables

The standard deviations of silver ink film thickness were used to understand the surface uniformity of the ink film. Surface uniformity was important to this study because an uneven surface or pinholing can hinder the efficiency of a current flowing throughout a display. In summarizing Table

2, a slower print speed in conjunction with a lower tpi mesh produced a smoother ink film surface compared to other printing variable combinations. Printing with 156 tpi mesh at 220 millimeters per minute produced a slightly smaller variance in ink film thickness than 440 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 220 millimeters per minute produced a slightly smaller variance in thickness than 440 millimeters per minute.

Upon analysis of Figure 5, one can identify that a higher tpi mesh produced a smoother silver ink film surface. In keeping the print speed constant, at 440 millimeters per minute, a 305 tpi mesh produced a slightly smaller variance in ink film thickness than a 156 tpi mesh. Contrarily, while keeping the print speed constant at 220 millimeters per minute, a 156 tpi mesh produced a smaller variance in ink film thickness than a 305 tpi mesh.

Considering all surface uniformity variables tested, printing at 220 millimeters per minute produced a smoother silver ink film surface than 440 millimeters per minute when the tpi mesh was kept constant for comparison.

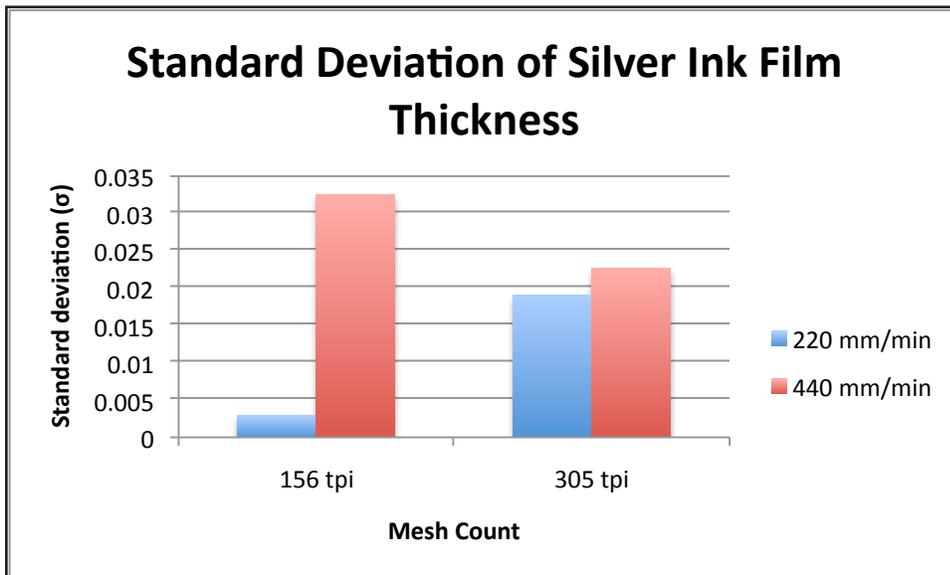


Figure 5: Silver ink film thickness standard deviation across speed and mesh count variables

## Dielectric Ink

The dielectric ink layer was printed with two passes in order to produce a greater ink film thickness, thus creating a better insulator between the phosphor and silver layers. The test sample results provided in Table 3 were printed with the wet over wet method. Wet over wet method is defined as: two dielectric ink passes printed consecutively onto polyester transparencies without being dried in between passes.

<b>Dielectric Ink Film Thickness (<math>\mu\text{m}</math>)</b>		
<b>wet over wet</b>	<b>156 tpi</b>	<b>305 tpi</b>
<b>220 mm/min</b>	19.48 $\mu\text{m}$	13.16 $\mu\text{m}$
<b>440 mm/min</b>	19.96 $\mu\text{m}$	15.13 $\mu\text{m}$

Table 3: Dielectric ink film thickness across speed and mesh count variables while printing wet over wet method

Dielectric ink film thickness was important to this study because EL display functionality relies on this layer providing a sufficient insulator between the alternating positive and negative currents flowing throughout an illuminated display. Too thick or too thin a dielectric layer can hinder a display's luminance value. In summarizing Table 3, a greater print speed in conjunction with a lower tpi mesh produced a greater dielectric ink film thickness. Printing with a 156 tpi mesh at 440 millimeters per minute produced a slightly greater ink film thickness than 220 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 440 millimeters per minute produced a greater thickness than 220 millimeters per minute.

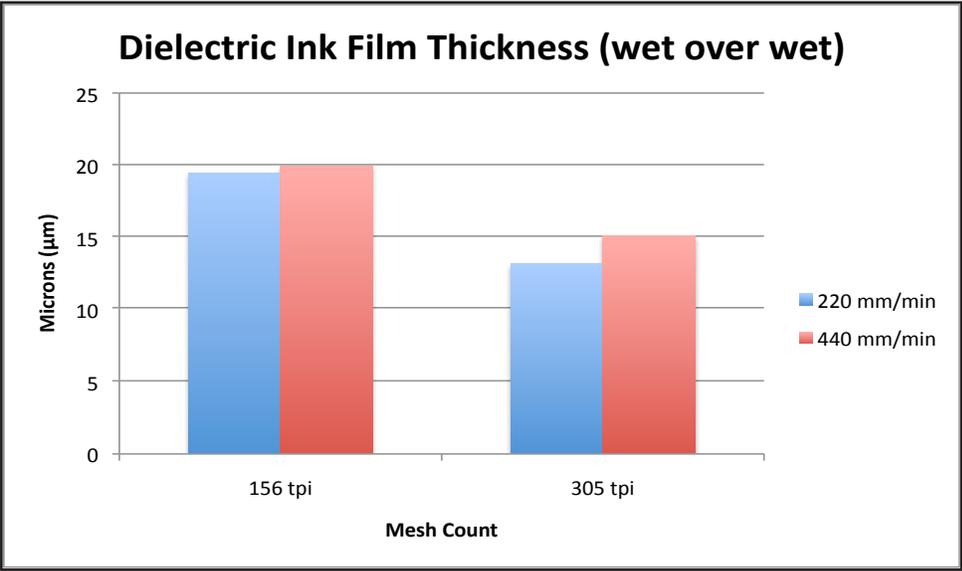


Figure 6: Dielectric ink film thickness across speed and mesh count variables while printing wet over wet method

Figure 6 illustrates that a lower tpi mesh produced a greater dielectric ink film lay down. In keeping the print speed constant, at 440 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh. Comparatively, while keeping the print speed constant, at 220 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 mesh count.

The test sample results provided in Table 4 were printed with the wet over dry method with the same variables as the wet over wet method. Wet over dry method is defined as: one dielectric ink pass being printed and allowed to dry prior to a second pass of the dielectric ink.

Dielectric Ink Film Thickness (µm)		
wet over dry	156 tpi	305 tpi
220 mm/min	23.84 µm	13.7 µm
440 mm/min	24.71 µm	17.2 µm

Table 4: Dielectric ink film thickness across speed and mesh count variables while printing wet over dry method

In summarizing Table 4, a greater print speed in conjunction with a lower tpi mesh produced a greater dielectric ink film thickness. Printing with a 156 tpi mesh at 440 millimeters per minute produced

a slightly greater ink film thickness than 220 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 440 millimeters per minute produced a greater thickness than 220 millimeters per minute.

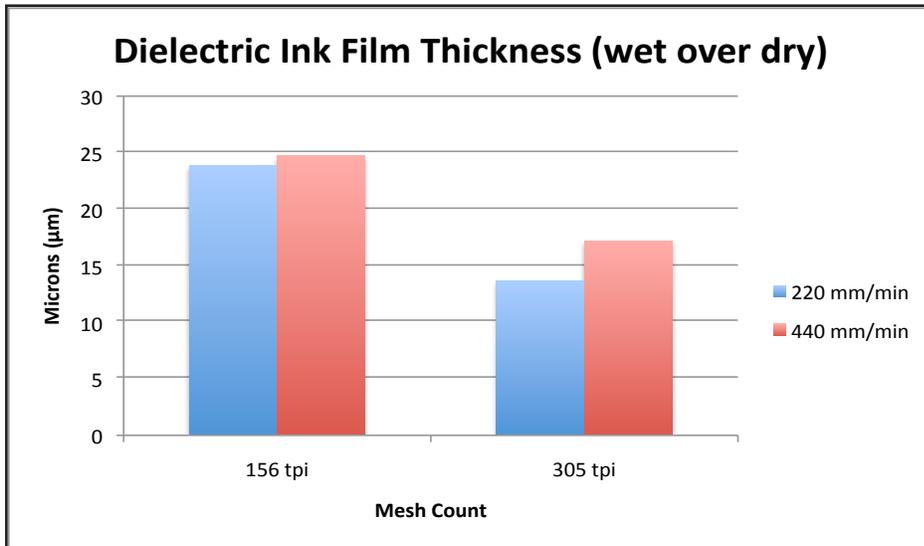


Figure 7: Dielectric ink film thickness across speed and mesh count variables while printing wet over dry method

One can infer from Figure 7 that a lower tpi mesh produced a greater dielectric ink film lay down. In keeping the print speed constant, at 440 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh. Comparatively, while keeping the print speed constant, at 220 millimeters per minute, a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh.

<b>Standard Deviation of Dielectric Ink Film Thickness</b>		
<b>wet over wet</b>	<b>156 tpi</b>	<b>305 tpi</b>
<b>220 mm/min</b>	0.00361	0.00209
<b>440 mm/min</b>	0.0033	0.00236

Table 5: Dielectric ink film thickness standard deviation across speed and mesh count variables

In summarizing Table 5, a slower print speed in conjunction with a higher tpi mesh produced a smoother dielectric ink film surface. Printing with a 305 tpi mesh at 220 millimeters per minute produced a slightly smaller variance in ink film thickness than 440 millimeters per minute. Contrarily, printing with a 156 tpi mesh at 220 millimeters per minute produced a slightly greater variance in

thickness than 440 millimeters per minute.

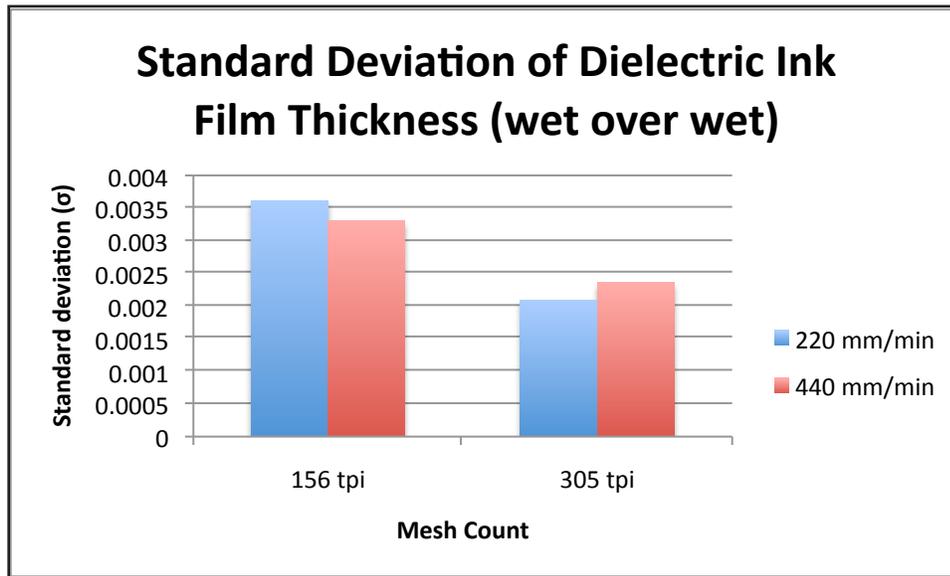


Figure 8: Dielectric ink film thickness standard deviation across speed and mesh count variables

Upon analysis of Figure 8, one can identify that a lower tpi mesh produced a smoother dielectric ink film surface. In keeping the print speed constant, at 440 millimeters per minute, a 305 tpi mesh produced a slightly smaller variance in ink film thickness than a 156 tpi mesh. Comparatively, while keeping the print speed constant at 220 millimeters per minute, a 305 tpi mesh produced a slightly smaller variance in ink film thickness than a 156 tpi mesh.

Uneven ink film surface can cause pin holing in the surface of the dielectric layer, therefore increasing the likelihood of current shorting, and thus a defective display. One can infer from Table 5 that printing at 220 millimeters per minute produced a smoother dielectric ink film surface when mesh count was kept constant. However, Figure 8 shows a tpi mesh of 156 had a smoother ink film surface when printing at 440 millimeters per minute. This discrepancy is possibly due to inaccurate test readings, but further analysis is needed to determine the root cause.

Standard Deviation of Dielectric Ink Film Thickness		
wet on dry	156 tpi	305 tpi
220 mm/min	0.0029	0.0025
440 mm/min	0.0031	0.0027

Table 6: Dielectric ink film thickness standard deviation across speed and mesh count variables

In summarizing Table 6, a slower print speed in conjunction with a higher tpi mesh produced a smoother dielectric ink film surface. Printing with a 156 tpi mesh at 220 millimeters per minute produced a slightly smaller variance in dielectric ink film thickness than 440 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 220 millimeters per minute produced a slightly smaller variance in thickness than 440 millimeters per minute.

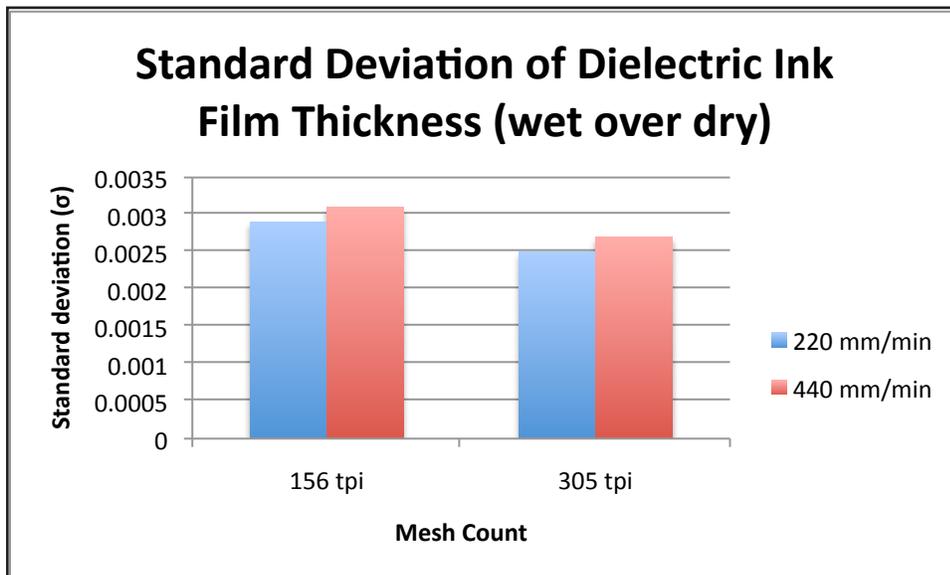


Figure 9: Dielectric ink film thickness standard deviation across speed and mesh count variables

Figure 9 illustrates that a lower tpi mesh produced a smoother thicker dielectric ink film surface. In keeping the print speed constant, at 440 millimeters per minute, a 305 tpi mesh produced a slightly smaller variance in ink film thickness than a 156 tpi mesh. Comparatively, while keeping the print speed constant at 220 millimeters per minute, a 305 tpi mesh produced a slightly smaller variance in ink film

thickness than a 156 tpi mesh.

One can infer from Table 6 that printing at 220 millimeters per minute produced a smoother dielectric ink film surface when mesh count was kept constant. After comparison of Table 2, 5 and 6 one can identify that printing at 220 millimeters per minute produced a smoother ink film surface for both silver and dielectric ink layers.

After analyzing all the data collected for both dielectric printing methods, one can conclude that printing with the wet over dry method produced a thicker ink film thickness and in general led to slightly more ink surface uniformity than the wet over wet method. Both printing methods produced greater ink film thickness for a tpi mesh of 305 versus a tpi mesh of 156. Furthermore, for both printing methods, printing at 440 millimeters per minute produced a greater ink film thickness than printing at 220 millimeters per minute.

### **Ink Resistivity**

Ink resistivity for the silver layer was estimated with a Fluke 115 Ohmmeter. Ten resistivity measurements were conducted for each test sample (156 tpi mesh printed at 440 mm/min, 305 tpi mesh printed at 440 mm/min, 156 tpi mesh printed at 220 mm/min and 305 tpi mesh printed at 220 mm/min) at randomized location over one inch distances with silver printed over polyester transparencies. Readings for each sample were then averaged. One can observe that the relationship between mesh count and speed led to a difference in ink film resistivity.

<b>Silver Ink Film Resistivity (<math>\Omega</math>)</b>		
	<b>156 tpi</b>	<b>305 tpi</b>
<b>220 mm/min</b>	13.2 $\Omega$	6.5 $\Omega$
<b>440 mm/min</b>	3.7 $\Omega$	3.07 $\Omega$

Table 7: Silver ink film resistivity across speed and mesh count variables

In summarizing Table 7, a higher tpi mesh produced a lower ohm reading. Printing with a 156 tpi

mesh at 440 millimeters per minute produced a smaller ohm reading than at 220 millimeters per minute. Comparatively, printing with a 305 tpi mesh at 440 millimeters per minute speed produced a smaller ohm reading than printing at 220 millimeters per minute.

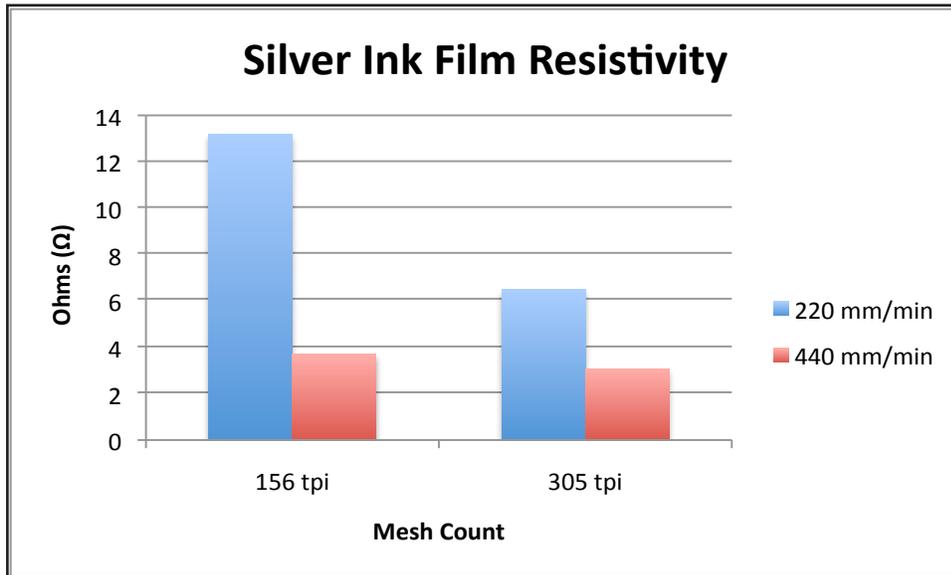


Figure 10: Silver ink film resistivity across speed and mesh count variables

One can infer from Figure 10 that a higher tpi mesh produced a lower resistivity. In keeping the print speed constant, at 440 millimeters per minute, a 305 tpi mesh produced a smaller ohm reading than a 156 tpi mesh. Comparatively, while keeping the print speed constant, at 220 millimeters per minute, a 305 tpi mesh produced a smaller ohm reading than a 156 tpi mesh.

Considering all ink film resistivity variables tested, printing at 440 millimeters per minute resulted in a better conductor for the silver ink film layer than 220 millimeters per minute.

In conclusion, the benchmark test was designed to draw some general inferences in order to narrow down the testing variables for the comprehensive test. Based on benchmark findings, although printing at 440 millimeters per minute produced a silver layer which was less resistive to current flow than 220 millimeters per minute, printing at 220 millimeters per minute produced a thinner and more uniform dielectric layer than 440 millimeters per minute. Based on prior research, these dielectric layer

qualities were believed to have a greater impact on EL display luminance value than the silver layer qualities. As a result, printing at 220 millimeters per minute was chosen as a constant print speed for the comprehensive test.

## Comprehensive Test

Phosphor, dielectric and silver inks, respectively, were printed on 17 micron ITO spattered polyester transparencies to analyze electroluminescent print variables.

### **Ink Film Thickness**

Ink film thickness for the silver and dielectric layers were estimated with a laser displacement sensor. Ten measurements were conducted on each test sample (the silver ink layer was printed at a constant speed of 220 mm/min for 156 tpi mesh and 305 tpi mesh, the dielectric ink layer was printed at a constant speed of 220mm/min for 156 tpi mesh as wet over wet and wet over dry, and 305 tpi mesh as wet over wet and wet over dry) at random locations. Readings for each sample were then averaged.

### **Silver Ink**

<b>Silver Ink Film Thickness (<math>\mu\text{m}</math>)</b>	
<b>156 tpi</b>	19.2 $\mu\text{m}$
<b>305 tpi</b>	11.2 $\mu\text{m}$

Table 8: Silver ink film thickness across mesh count

The silver ink film thickness measurements from the comprehensive test were consistent with the findings from the benchmark test. In summarizing Table 8 and Figure 11, printing with a constant speed at 220 millimeters per minute with a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh.

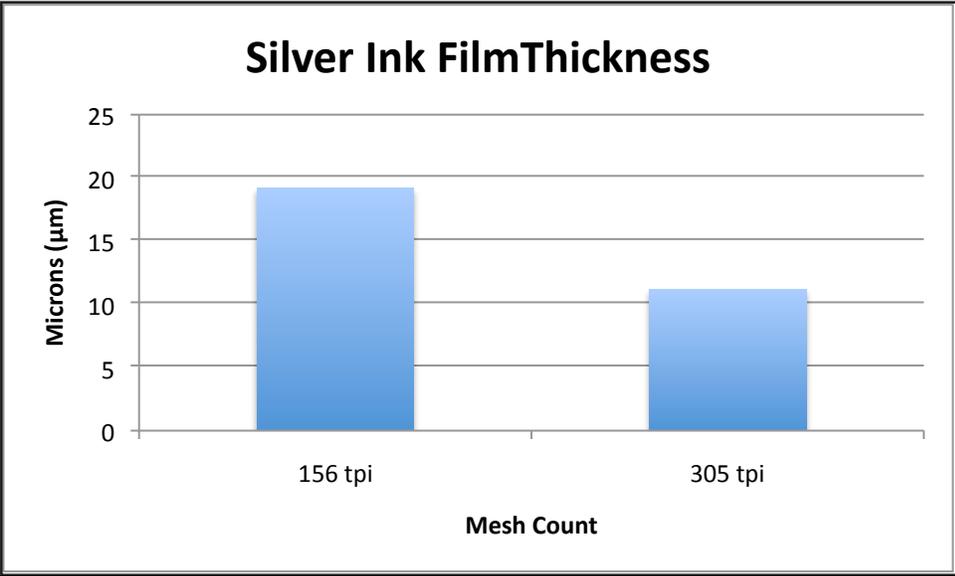


Figure 11: Silver ink film thickness across mesh count

**Dielectric Ink**

Dielectric Ink Film Thickness (μm)		
	156 tpi	305 tpi
wet on wet	12.2 μm	9.2 μm
wet on dry	18.5 μm	13.8 μm

Table 9: Dielectric ink film thickness across mesh count and printing process

In summarizing Table 9, two layers of dielectric ink, printed by the wet over dry method at a constant speed of 220 millimeters per minute with a 156 tpi mesh produced a greater ink film thickness than the one printed with the wet over wet method. Comparatively, printing with a constant speed at 220 millimeters per minute with a 305 tpi mesh with the wet over dry method produced a greater ink film thickness than the one printed with the wet over wet method.

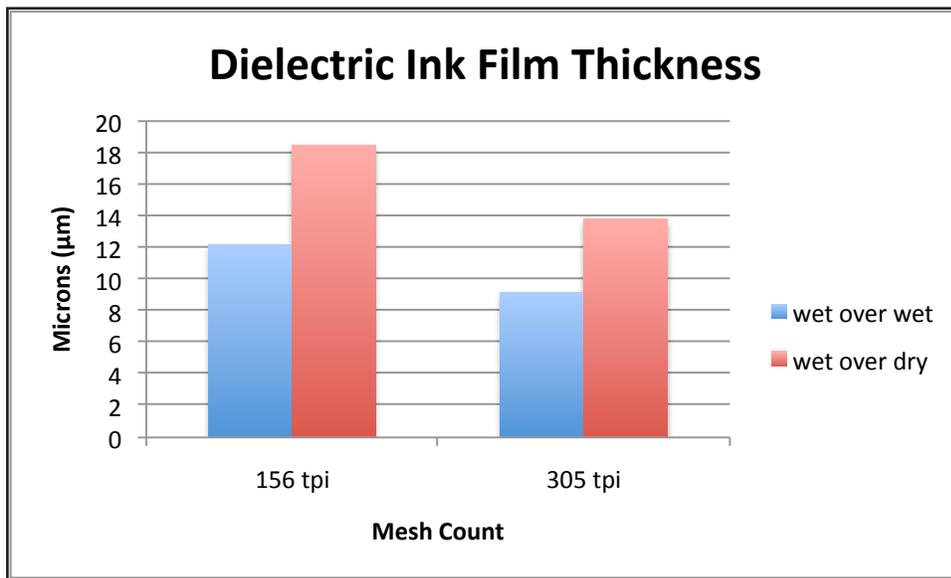


Figure 12: Dielectric ink film thickness across mesh count and printing process

Figure 12 illustrates that in keeping the print technique constant, with the wet over wet method, printing with a constant speed of 220 millimeters per minute and a 156 tpi mesh produced a greater dielectric ink film thickness than a 305 tpi mesh. Comparatively, printing with the wet over dry method while keeping the print speed constant at 220 millimeters per minute and with a 156 tpi mesh produced a greater ink film thickness than a 305 tpi mesh.

### **Resistivity**

Ink resistivity for the silver layer was estimated with an ohmmeter. Ten resistivity measurements were conducted for each test sample (silver ink layer was printed at a constant speed of 220 mm/min for 156 tpi mesh and 305 tpi mesh on top of dielectric ink printed as wet over wet method and wet over dry method) at random locations over one inch distances. Readings for each sample were then averaged. One can observe that the combination of mesh count and printing method variables led to differences in ink film resistivity.

Silver Ink Film Resistivity (Ink Film Thickness ( $\Omega$ ))					
Wet Over Wet	Silver Over ITO	Over Dielectric	Wet Over Dry	Silver Over ITO	Over Dielectric
156 tpi	10.09 $\Omega$	0.84 $\Omega$	156 tpi	6.21 $\Omega$	0.95 $\Omega$
305 tpi	15.05 $\Omega$	1.61 $\Omega$	305 tpi	78 $\Omega$	3.07 $\Omega$

Table 10: Silver ink film resistivity across mesh count and printing process

### Silver Ink Over ITO

Upon analysis of Table 10, one can identify that the silver layer printed over the ITO transparency with a 156 tpi mesh had a higher ohm reading with the wet over wet method versus the wet over dry method. Contrarily, silver printed over the ITO transparency with a 305 tpi mesh had a higher ohm reading with the wet over dry method versus the wet over wet method.

One can infer from Table 10 that in keeping the print technique constant, the wet over dry method, printing with a constant speed of 156 tpi mesh produced a lower ohm reading than a 305 tpi mesh. Comparatively, printing with the wet over wet method, a 156 tpi mesh produced a lower ohm reading than a 305 tpi mesh.

### Silver Ink Over Dielectric Ink

Both Figure 13 and Figure 14 illustrate that printing with a 156 tpi mesh produced a lower ohm reading with the wet over wet method versus the wet over dry method. Comparatively, printing with a 305 tpi mesh produced a lower ohm reading with the wet over wet method versus the wet over dry method.

Upon analysis of Figure 13 and Figure 14, one can identify that in keeping the print technique constant, with the wet over dry method, printing with a constant speed of 156 tpi mesh produced a lower ohm reading than a 305 tpi mesh. Comparatively, printing with the wet over wet method, a 156 tpi mesh produced a lower ohm reading than a 305 tpi mesh.

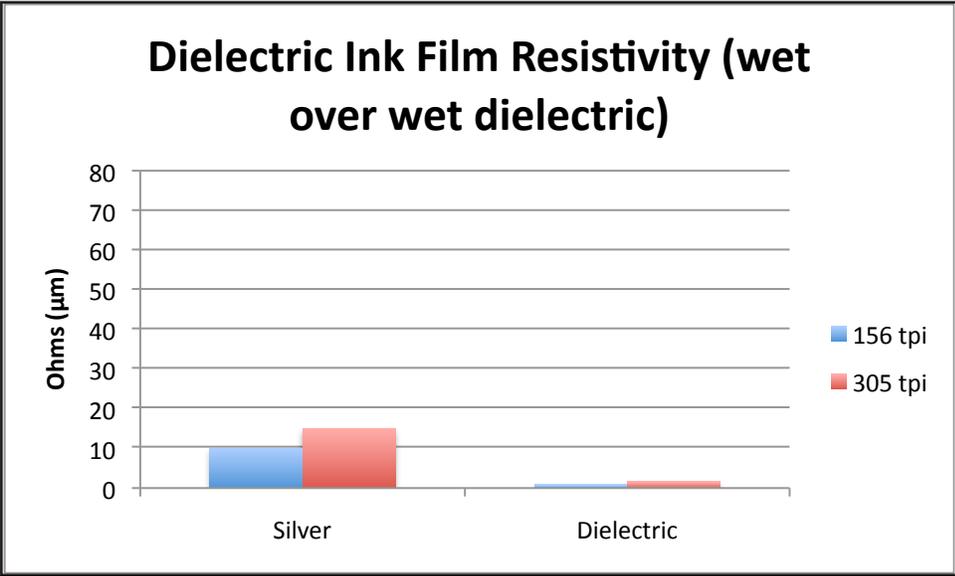


Figure 13: Silver ink film resistivity across mesh count for wet over wet method

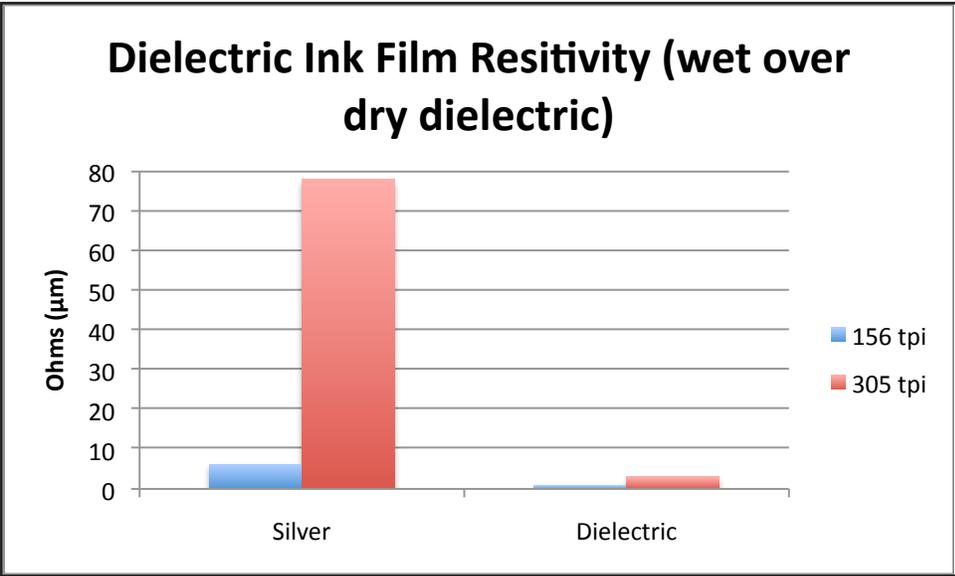


Figure 14: Silver ink film resistivity across mesh count for wet over dry method

## Luminance

<b>Luminance of Halftone</b>					
<b>wet over wet</b>	<b>156 tpi</b>	<b>305 tpi</b>	<b>wet over dry</b>	<b>156 tpi</b>	<b>305 tpi</b>
<b>100%</b>	120.86	125.62	<b>100%</b>	111.46	111.44
<b>75%</b>	Defective	Defective	<b>75%</b>	100.26	92.46
<b>50%</b>	78.34	94.38	<b>50%</b>	69.18	71.42
<b>25%</b>	60.24	71.62	<b>25%</b>	54.32	56

Table 11: Luminance for each halftone across mesh count and printing process

Upon analysis of Table 11, one can identify that printing a 100% solid phosphor dot and a dielectric layer printed with the wet over wet method, produced a brighter luminance value for 305 tpi mesh versus a 156 tpi mesh. Comparatively, printing a 100% solid phosphor dot and a dielectric layer printed with the wet over dry method, produced a brighter luminance value for 305 tpi mesh versus a 156 tpi mesh.

Table 11 demonstrates that printing a 100% solid phosphor dot and a dielectric layer with a 156 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method. Comparatively, printing with a 305 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method.

Upon analysis of Table 11, one can identify that printing a 75% halftone phosphor dot and a dielectric layer printed with the wet over dry method, produced a brighter luminance value for a 156 tpi mesh versus a 305 tpi mesh. The results for a 75% halftone phosphor dot was contrary to all other halftone phosphor luminance's, where a 156 tpi mesh had a brighter value than 305 tpi mesh. Due to printing error, the 75% halftone phosphor dot printed with the wet over wet method was defective.

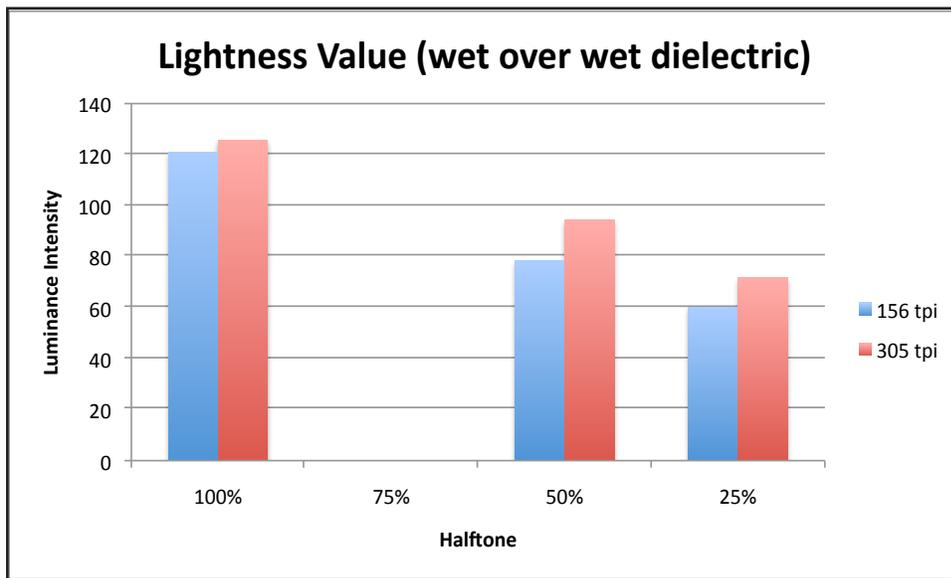


Figure 15: Luminance for each halftone across mesh count for wet over wet dielectric

Upon analysis of Table 11 and Figure 15, one can identify that printing a 50% halftone phosphor dot and a dielectric layer printed with the wet over wet method, produced a brighter luminance value for a 305 tpi mesh versus a 156 tpi mesh. Comparatively, while referring to Figure 16, one can observe that printing the dielectric layer with the wet over dry method, produced a brighter luminance value for a 305 tpi mesh versus a 156 tpi mesh.

One can infer from Table 11 that printing a 50% halftone phosphor dot and a dielectric layer with 156 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method. Comparatively, printing with a 305 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method.

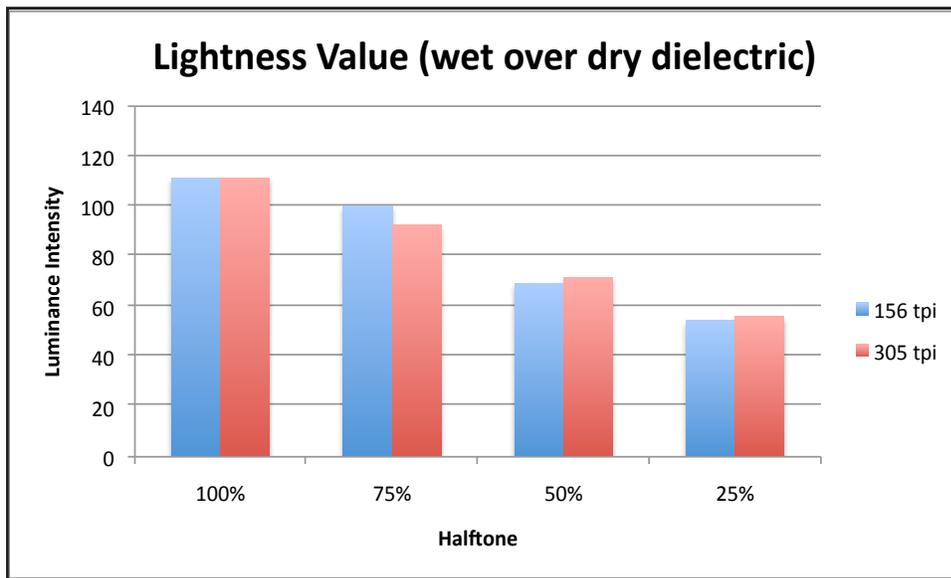


Figure 16: Luminance for each halftone across mesh count for wet over dry dielectric

Both Table 11 and Figure 15, demonstrate that printing a 25% halftone phosphor dot and a dielectric layer printed with the wet over wet method, produced a brighter luminance value for a 305 tpi mesh versus a 156 tpi mesh. Comparatively, while referring to Figure 16, one can observe that printing the dielectric layer with the wet over dry method, produced a brighter luminance value for a 305 tpi mesh versus a 156 tpi mesh.

Upon analysis of Table 11, one can identify that printing a 25% halftone phosphor dot and a dielectric layer with a 156 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method. Comparatively, printing with a 305 tpi mesh produced a brighter luminance value for the wet over wet method versus the wet over dry method.

In summarizing the above results, as the halftone phosphor dot percent increased so did the luminance value incrementally for both dielectric printing methods and tpi mesh count.

After analyzing Table 10, one can infer that printing with a 156 tpi mesh produced lower ohm readings than a 305 tpi mesh. However, when compared with the luminance values of Table 11, printing

with a 156 tpi mesh produced, in a majority of the samples, a lower luminance value than a 305 tpi mesh. This is contrary to the assumption that a lower ohm reading should produce a brighter display. One possible explanation for this discrepancy is that for these test samples, the dielectric layer's characteristics may have had a greater impact on luminance value than the silver layer's characteristics.

After analysis of the comprehensive test data, one can conclude that further tests are needed to determine the contribution that each variable makes on the luminance of electroluminescent displays.

## Chapter 5—Conclusions

Analysis of the comprehensive and benchmark tests revealed that screen printing variables do in fact affect the luminance value of electroluminescent displays. Printing speed, threads per inch mesh, printing processes such as the wet over wet method and the wet over dry method, and the halftone screening of phosphor should be considered when producing EL displays. These printing variables, as the data presented in chapter 4 supports, influence the conductivity of EL displays and their resulting luminance value.

Testing revealed that a threads per inch mesh of 305 printed with the wet over wet method and at a 100% phosphor dot produced the brightest value of luminance across all findings. This finding is supported by data demonstrating that printing with a tpi mesh of 305 with the wet over wet method produced a lower ohm reading than with a tpi mesh of 156. However, a tpi mesh of 156 was found to have a lower resistivity reading for the silver over ITO than a tpi mesh of 305. These two contrasting results allude to the assumption that testing procedures constrained luminance values of the EL displays by limiting the variability in relation to speed and threads per inch between layers. Rather, more efficient EL displays might result from combining a dielectric layer printed with a tpi mesh of 305 with the wet over wet method and a silver ink layer printed with a 156 tpi mesh.

The intent of this research project was to provide suggestions for, a still not widely documented area of electronic printing. Data collected does provide a new understanding for the affects of print variables on EL displays. However, further testing is still required for more conclusive findings. Proposed future research should include a more extensive degree of variability between ink layers by combining different mesh counts and print speeds. By examining the influence of display layer variability in more depth, functional printers can further improve the printing process of EL displays.

## Works Cited

- Escobedo, J., Mansoori, A. G. (1996). Surface Tension Prediction for Pure Fluids. *AIChE Journal*, 42, 5, 2.
- Exploration Geophysics (2002). DC Resistivity Notes  
<http://galitzin.mines.edu/INTROGP/MISC/resnotes.pdf>
- Dr. Rong, X. (2010) Characterize Screen Printing Parameters for Electroluminescent Inks. California Polytechnic State University. 1-10.
- DuPont. (2000). Processing Guide For DuPont Luxprint® Electroluminescent Inks. DuPont Microcircuit Materials. 1-12.
- Hart, J. A., Lenway, S. A., Murtha, T. (1999). A History of Electroluminescent Displays, 1-14.
- Hensen, S. (2007). A Guide to Screen Printing As a Supremely Accessible Art Form. 1-6.
- Horwood, R. J. (1974). Towards a Better Understanding of Screen Print Thickness Control. *Electrocomponent Science and Technology*, 1, 129-136.
- Mahon, J. (2007). Weft, Warp & Weave: Understanding the mystery of fabric structure. *SQE Professional*, 38-39.
- Peaker, A. R. (1970). Electroluminescent and its Applications. *Electronics & Power*, 329.
- Science Buddies (2011). Steps of the Scientific Method.  
[http://www.sciencebuddies.org/sciencefairprojects/project\\_scientific\\_method.shtml](http://www.sciencebuddies.org/sciencefairprojects/project_scientific_method.shtml)

## Appendix A

### Benchmark Test Table

<b>Silver</b>		
Sample 1	156 mesh count / 220 millimeters per minutes	
Sample 2	305 mesh count / 440 millimeters per minutes	
Sample 3	156 mesh count / 440 millimeters per minutes	
Sample 4	305 mesh count / 220 millimeters per minutes	
<b>Dielectric</b>		
Sample 5	156 mesh count / 220 millimeters per minutes	wet over wet
Sample 6	305 mesh count / 440 millimeters per minutes	wet over wet
Sample 7	156 mesh count / 440 millimeters per minutes	wet over wet
Sample 8	305 mesh count / 220 millimeters per minutes	wet over wet
Sample 9	156 mesh count / 220 millimeters per minutes	wet over dry
Sample 10	305 mesh count / 440 millimeters per minutes	wet over dry
Sample 11	156 mesh count / 440 millimeters per minutes	wet over dry
Sample 12	305 mesh count / 220 millimeters per minutes	wet over dry

### Comprehensive Test Table

<b>EL Displays</b>				
Sample 1	100%	156 mesh count	220 millimeters per minute	wet over wet
Sample 2	100%	305 mesh count	220 millimeters per minute	wet over wet
Sample 3	100%	156 mesh count	220 millimeters per minute	wet over dry
Sample 4	100%	305 mesh count	220 millimeters per minute	wet over dry
Sample 5	75%	156 mesh count	220 millimeters per minute	wet over wet
Sample 6	75%	305 mesh count	220 millimeters per minute	wet over wet
Sample 7	75%	156 mesh count	220 millimeters per minute	wet over dry
Sample 8	75%	305 mesh count	220 millimeters per minute	wet over dry
Sample 9	50%	156 mesh count	220 millimeters per minute	wet over wet
Sample 10	50%	305 mesh count	220 millimeters per minute	wet over wet
Sample 11	50%	156 mesh count	220 millimeters per minute	wet over dry
Sample 12	50%	305 mesh count	220 millimeters per minute	wet over dry
Sample 13	25%	156 mesh count	220 millimeters per minute	wet over wet
Sample 14	25%	305 mesh count	220 millimeters per minute	wet over wet
Sample 15	25%	156 mesh count	220 millimeters per minute	wet over dry
Sample 16	25%	305 mesh count	220 millimeters per minute	wet over dry

## Appendix B

### Benchmark Test “Cal Poly” Wordmark

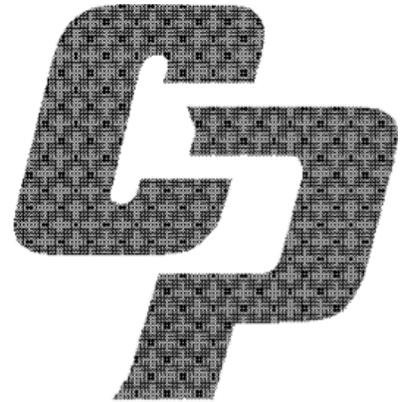


# Appendix C

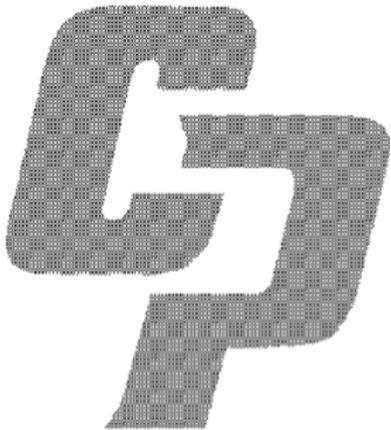
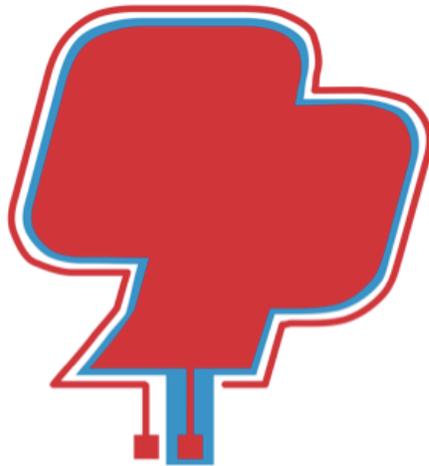
## Comprehensive Test “CP” Wordmark



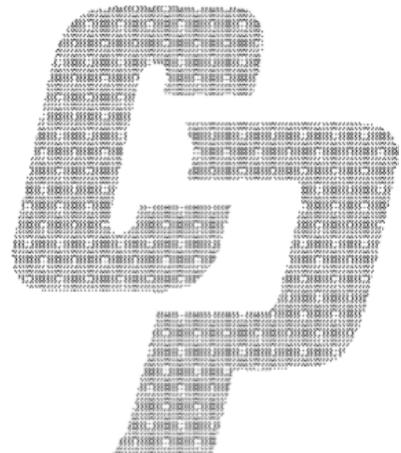
100W



75W 



50W 



25W 