ABSTRACT

Title of Thesis: INVESTIGATION OF PDA LCD SCREEN FAILURES UNDER HUMIDITY CYCLING AND BENDING LOADS

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Liquid crystal displays are commonly used in various applications and subjected to numerous environmental and handling conditions that can especially affect the performance and life of these devices. In addition to humidity and temperature exposure, cyclic loadings and handling conditions (bending, repetitive shock, and drop loading) have been shown to cause failures in LCDs. Due to the large number of variable failure modes and use conditions, the question arises: how long can a LCD survive before a failure occurs? Characterizing these failures, along with providing information and techniques to help assess the life expectancy of an LCD are addressed here.

The effects of cyclic humidity exposure and biaxial bending were studied. The resulting failures were analyzed and compared to previous studies to determine common failure modes and relationships that would be useful in providing a rapid product life assessment. Conclusions were made concerning appropriate methodology and testing that can be consistently and efficiently be used to assess LCD assemblies, thus saving time and money in the manufacturing process.

INVESTIGATION OF PDA LCD SCREEN FAILURES UNDER HUMIDITY CYCLING AND BENDING LOADS

By

Morrigan Lynn Johnson

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Liquid crystal displays (LCDs) are used through out the world in various different applications. Portable electronic devices such as iPods®, cellular phones, and personal digital assistants all rely on LCD technology. LCD failure can occur for several reasons. One reason of failure is the effect of environmental conditions on the LCD assembly. Environmental conditions include both the effects of temperature and humidity, and cyclic loading. Another reason of failure is the effects of handling conditions on the LCD. Handling can include bending, repetitive shock, and drop loading conditions. Common failures seen in LCDs are a decrease in screen contrast, non-functioning pixels or display, and broken glass within the assembly. Due to the large number of LCDs used in portable electronic devices a critical question can arise: How long can a LCD survive before a failure occurs? Characterizing these failures along with providing information and techniques to help assess the life expectancy of an LCD is an important issue that needs to be addresses.

1.1 Background

Two major types of LCDs exist; the older passive matrix LCD and the newer, more commonly used active matrix LCD (AMLCD). The active matrix LCD employs several variations of liquid crystal technology and materials to allow LCDs to have a range of capabilities.

The basic structure and corresponding materials of an AMLCD are shown below, in Figure 1.1.

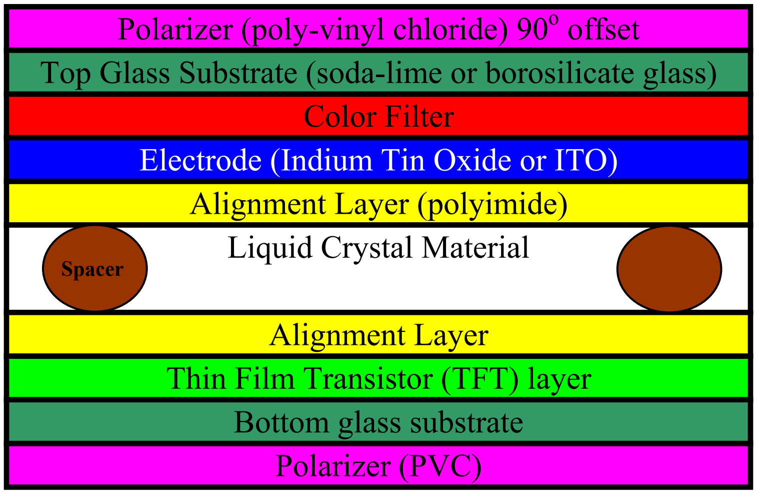
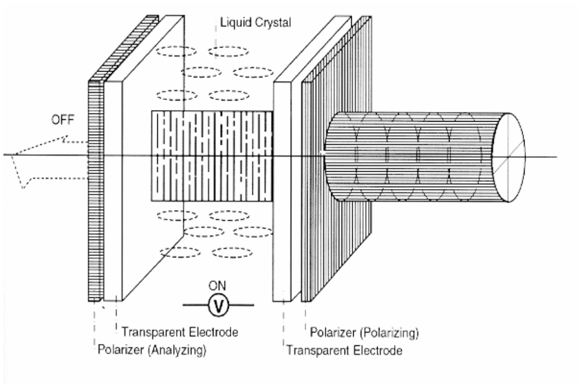
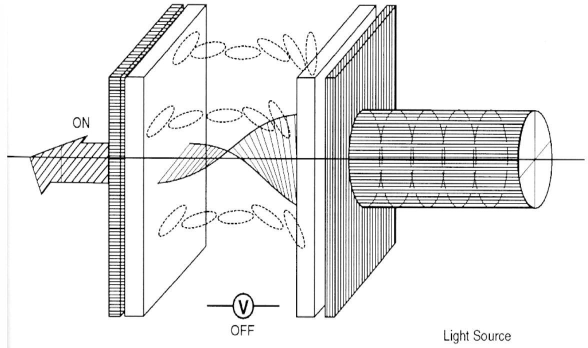


Figure 1.1 Active matrix liquid crystal display structure. [2]

Liquid crystal molecules are naturally in a twisted orientation, similar to a helix-type structure. When current passes through the molecules, they untwist and align with the direction of the electric field, with help of the alignment layers in the screen's structure. When no external voltage is applied to the screen, light passes through one polarizer, twists along the helix structure of the liquid crystal material, and then passes through the second polarizer. When an external voltage is applied to the screen, light passes through the first polarizer, then through the aligned liquid crystal material remaining in the polarized direction, and then the polarized light is completely blocked by the second polarizer. When light is blocked from passes through the screen structure, the screen appears black. Figure 1.2 shows the effect of applied voltage on light transmission through the LCD screen.





Applied voltage, light is completely blocked by perpendicular polarizers

No applied voltage, light passes through polarizers, by the twisting action of LC material

Figure 1.2 Effects of applied voltage on a LCD screen [5]

To protective the LCD assembly a sealant is applied to the outside of the layered structure to prevent liquid crystal material leakage and to prevent moisture penetration. Then a protective film is applied to the surface, over the polarizing films. The protective film is used to prevent depolarization of the polarizing layers due to UV ray and humidity exposure [2]. Unfortunately the seal is not 100% effective and over time LC leakage and moisture degradation could pose a reliability problem.

LCDs are made up of a grid of electrodes in rows and columns; the intersection of each l electrode marks the location of a pixel. To control a particular pixel cell, a row is switched on and a charge is sent down the appropriate column. The transistor at that pixel cell location receives the charge and is able to hold the charge for a specified amount of time. By controlling the amount of voltage supplied to the transistor, the amount of light passes though a pixel cell can be controlled to create a grey scale. Commonly displays offer 256 levels of brightness, or intensity. A decrease in intensity can be considered a failure. Figure 1.3 shows the controlling transistors and electrodes on the inside of the glass layer of an LCD.

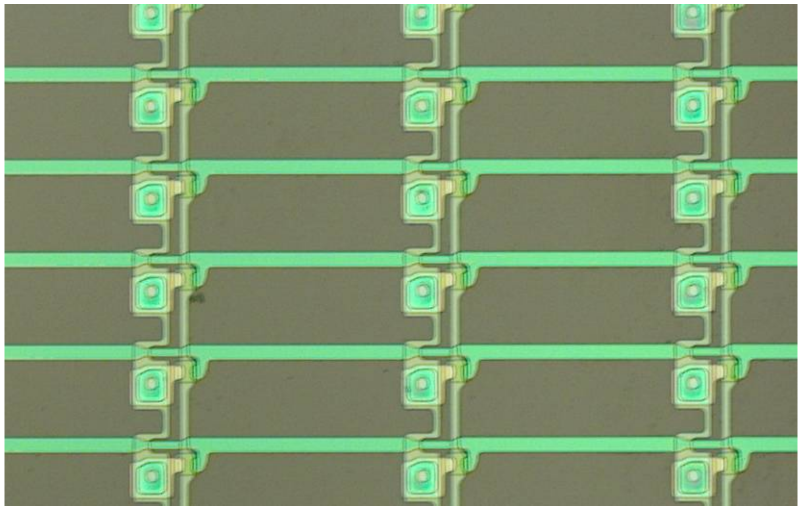


Figure 1.3 Electrodes and transistors on the inside of the glass layer—200x magnification

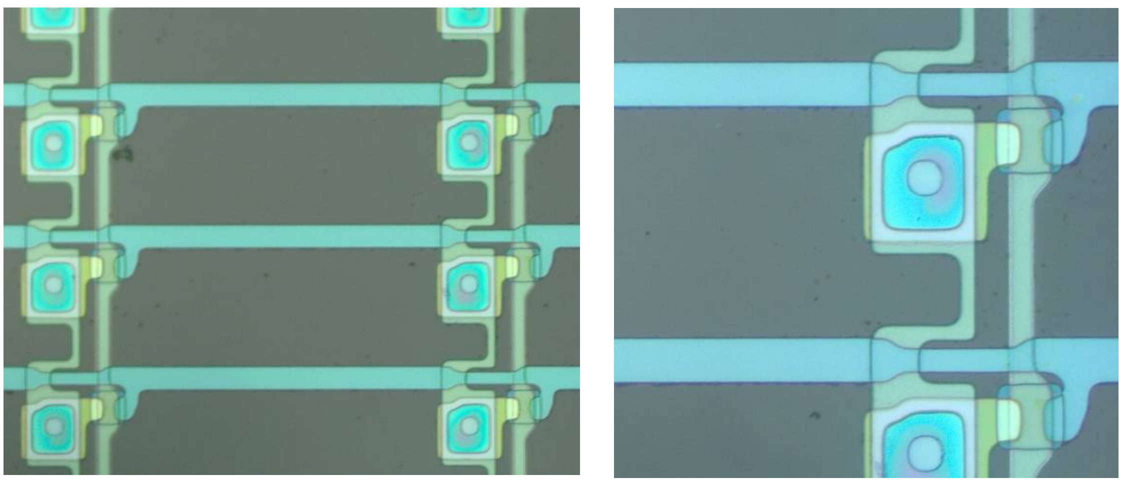


Figure 1.4 Electrodes and transistors—500x and 1000x magnification, respectively.

If the LCD displays color, then each pixel cell contains three color pixels (Red, Green, and Blue). Since each color has 256 shades, there a possible 16.8 million colors in typical LCD. In small portable electronic devices, such as a cellular phone, a 260 x 240 pixel screen has 187,200 pixels and transistors controlling the display. Having a few non-functioning pixels throughout any LCD is very plausible and still considered a pixel failure.

1.2 Motivation

Over the last ten years LCDs have become a staple in everyday electronics, cell phones, personal digital assistants, and computers all rely on LCDs; LCDs are becoming smaller, faster, and clearer as each day passes. Cell phones with a 2 inch screen are expected to display high definition videos with crystal clear, microscopic pixels while being able to handle severe environmental and handling conditions. These devices are repeatability subjected to severe environmental conditions, a cell phone inside a car on a hot day can reach temperatures above 120F, then the device is moved to room temperature, controlled environment and expected to function properly. But, with the increased use expectations of LCDs, the life expectancy and reliability has become a second to short-term performance. Manufacturers design small portable devices to last six months to a year, hoping the next, upgraded model will be available to replace any non-functioning, current devices.

Generally this manufacturing plan works, customers experiencing functionality problems are given a new module or the next model to cover-up reliability issues instead of fixing the problem. But, occasionally so many failures are seen replacements or repairs can not keep up with the rate of returns. Customers are left waiting weeks with no device and become unforgiving with manufacturers' efforts to fix a problem. Apple Computer, Inc is currently involved in a class-action lawsuit for reliability problems associated with iPod Nano in case No. C-05-04244 RS James M. Wimmer, individually and on behalf of all others similarly situated, v. Apple Computer, Inc. In an attempt to flood the market with their tiny device before their competitors, Apple overlooked reliability issues that will end up costing millions of dollars to repair, along with customers.

Currently research exists on LCDs and the associated materials used in construction. But, with the rapidly decreasing size of LCDs, what new reliability problems will be encountered? Smaller and smaller devices are expected to withstand the same handling conditions as their larger, more durable counterparts do. The failure mechanisms of LCD modules for portable electronic devices need to be examined. Information and techniques need to be gathered to help in assessing the life expectancy of these LCD modules under use, handling, and environmental condition.

1.3 Objective

The objective of this thesis is to identify failure mechanisms of liquid crystal screens in portable electronic equipment during use in high humidity environments and handling (bending, repetitive shock, and drop loading conditions); and to provide information and techniques to help assess the life expectancy of LCD modules. To complete this objective, several issues must be considered. First, it is important to determine and gather information concerning existing known failure modes. Both environmental and handling conditions will need to be explored, since both conditions will be examined during testing. Then, based upon the specifications of the LCD test screens, test criteria will be determined. Both temperature/humidity and handling conditions will need to be determined. After completion of experimental testing, results will be compared to those of found in published literature. The scope of this thesis is to develop a knowledge base for assessing LCDs that would be potentially subjected to handling conditions. This thesis is limited to examining only portable electronic devices, testing will only be completed using samples from one manufacturer. Further research could potentially use the results from this thesis to assist in assessing life in other devices containing LCDs.

2.0 EXISTING FAILURE MODES OF LCDS

The failure modes of LCDs are needed to assist in determining the life expectancy of portable electronic equipment. Portable electronic devices containing LCDs are subjected to a variety of conditions on an everyday basis; conditions that can lead to failure of the LCD module. By determining the components most susceptible to failure, information and techniques can be gathered to help assess the life of LCD modules. Previous research has been conducted studying the effects of many different environmental and loading conditions on LCDs.

2.1 Environmental Effects

In general, consumers have high expectations for electronic equipment, LCDs are required to use more advanced packaging technologies to increase resolutions and color quality of the display. To increase the overall quality of an LCD, the number of pixels, thus the number of I/O interconnects, have to be increased [7][8]. These sensitive devices are sometimes subjected to extreme environmental conditions and are still expected to function properly.

2.1.1 Anisotropic Conductive Adhesives

Environmental conditions have been shown to degrade the contact achieved when using anisotropic conductive adhesives (ACA) in LCD assemblies. Typically an anisotropic conductive adhesive is used to achieve electrical contact between the Indium Tin Oxide (ITO) electrodes and the integrated circuit. Chip-on-glass (COG) or chip-on-flex (COF) assemblies are widely used in LCD technologies. COG is preferred in small area LCDs, such as cellular phones, where the IC is connected directly to the glass and ITO layer. While, the COF assemblies are used in larger LCDs, where the IC is connected to a flexible substrate and the substrate is then connected to the ITO electrodes [9].

The conductive adhesive, either in paste or film form, contains dispersed conductive particles, usually gold, sliver, or nickel, within an epoxy-type material. The conductive particles within the epoxy are compressed together during assembly, resulting in an electrical connection between the two surfaces being adhered. A residual compressive stress is achieved during the adhesive's curing process. The result is a strong interconnection between the two surfaces, the ITO and the IC, without the need for any conventional wiring [10] [11].

2.1.2 Humidity Effects

Many different types of failures have been observed in the interconnections using conductive adhesives, humidity testing, along with elevated temperature testing, have been conducted to evaluate the reliability of the interconnection in question.

A constant humidity test was run at 85C/85% RH for 500 hours, testing LCD modules containing either COG and COF assemblies and either a thermoset paste or a thermoplastic film adhesive. The COG assemblies with adhesive paste had a slight resistance increase while the film adhesives had a dramatic resistance increase, reaching at least 400% of the initial value. Delamination at the adhesive/glass interface was also observed. The resistance increase is due to moisture penetration at the film adhesive-glass interface eventually leading to delamination. In the COF assemblies, humidity testing also resulted in higher resistance values. The cause of the increased resistance, in this case, is from either swelling of the adhesive in the z-direction (due to moisture absorption) or an oxidation effect [10] [12]. Swelling in the z-direction diminishes the compressive stresses resulting in an increased resistance and possibly a complete loss of electrical contact [9].

During a COG bonding test, warping of the assembly was observed due to CTE mismatch. After the ACF (anisotropic conductive film) is cured (180-200C) and cooled to room temperature, the IC shrinks more than the glass causing some delamination at the corner joints, but no resistance increase. When a humidity test (80C/90%RH) was conducted, a severe increase in contact resistance at the corner joints was observed due to the increased delamination seen at these joints. The absorption of moisture by the ACF causes adhesion weakening and results in delamination to release the residual stresses created from the bonding process [13] [19].

Another high humidity test (85C/85%RH) resulted in a 20% drop in shear strength, with clear appearance of voids and delamination. Water was also found between the ACF and the glass, again indicating that water absorption causes strength degradation [13]. Many times in COG assemblies, the existence of moisture in the joint can accelerate the corrosion of the ITO trace [13]. Under the same testing conditions, the peel strength was also shown to decrease, sometimes as much as a 62% decrease after humidity exposure.

2.1.3 Failure Mechanisms – Humidity

Almost all of the high humidity tests resulted in an increase in electrical resistance. A previously observed failure mode in the particle LCD modules tested was screen flickering, no display, or low display contrast. Again, this is due to an increased resistance in the ACF bonds, probably due to humidity exposure, as commonly seen in LCDs.

Humidity causes hygroscopic expansion of the adhesive and weakens the adhesive/contact pad adhesion, resulting in an increase in the conduction gap and thus resistance [13]. An increase in resistance could potentially affect the appearance of an LCD. Another reason for the increased electrical resistance is oxidation of the metallic particles in the adhesive. Oxide formation has been observed at the interface between the conductive particles and the ITO pad. The oxide can degrade the electrical contact resulting in an increased electrical resistance [7] [13] [14] [15] [18].

Another failure mechanism resulting from humidity exposure is delamination. Warping during the curing process can cause delamination at the corners of a chip when adhered directly to glass. When the warped assembly is subjected to a humid environment, further delamination can occurs due to swelling, causing large electrical resistances [13]. The presents of moisture at the adhesion interface can degrade the adhesion properties. Degradation of the adhesion can cause decreased peel strength and further delamination between the two materials [7]. Humidity exposure has also been shown to cause depolarization of the polarizer leading to the deterioration of the display quality [2]. In regards to high temperature exposure, CTE (coefficient of thermal expansion) mismatch, between the glass and deposited film materials, has also been shown to generate stresses on the surface of glass, leading to cracking [20].

Humidity exposure has been shown to cause failures in LCDs. Flickering, no display, or low display contrast are failures seen from humidity exposure. Moisture causes an increase in resistance within the ACF bonds leading to failure of the LCD.

Humidity cycling testing should result in the same failures seen in previous research, but should accelerate the observed failures compared to previous constant high humidity / temperature exposure.

2.2 Mechanical Strength

Determining the mechanical strength of glass can be difficult due to the brittle properties of the material. Mounting the specimens is too difficult for tension tests. Fixtures designed for ductile materials rely on plastic deformation of the specimen ends and generally causes fracture before any measurable deformation. Any fixture that relies on dog-bone grips requires perfect alignment, which may be too difficult to achieve. Therefore, to determine the mechanical strength of a brittle material, such as glass, bend testing was chosen [16].

The origin of glass/LCD damage has been shown to be a result of LCD manufacturing and not a result of the glass manufacturing process. Many opportunities exist to generate damage, impact, friction, and indentations during LCD processes can all produce damage. Since handling conditions are potentially a cause of failure, great care will be taken when handling specimens to reduce to chance of minor abrasions that could result in decreased failure strength [20]. Results from bending tests should be analyzed using Weibull statistics. [16].

2.2.1 Flaw Effects

Brittle material fracture, like that of glass, is dependent on the probability of having a flaw in the area of testing for example, the supported area in a bend test setup. In glass the flaw considered to be the “weakest link” is situated on the surface of the specimen and respond to tensile stress [16]. For this reason, bend testing is an ideal method of characterizing the strength of glass [16]. Glass edge flaws can also affect the mechanical strength. Generally edge flaws cause failure when the LCD assembly is subjected to fast heating and cooling rates, commonly seen during the LCD manufacturing process [20]. Since all LCD specimens appear to be free of cracks and obvious flaws and have survived the LCD manufacturing process, edge effects will not be studied in this thesis.

2.2.2 Bending of Glass and LCDs

In two studies supported by Corning Display Technologies, a leading supplier of glass substrates used to produce AMLCDs, the strength of both the top glass layer and the assembled LCD, under static loading, were tested. Results have shown a high dependency on surface quality and independency of structure thickness, allowing for comparison between different panel sizes [6] [17].

2.2.2.1 Glass Panel Strength

The mechanical reliability of an LCD has been found to have a direct bearing on the strength of the glass panel. Optimizing the surface quality of the glass panel by minimizing flaws can ensure sufficient strength to prevent failure.

The biaxial strength of both 0.7 mm and 1.1 mm thick glass, approximately 50mm square, was measured while supported on a concentric ring fixture. The loading rate used caused failures to occur in approximately 30 seconds. The failure loads measured were generally higher in 1.1 mm glass than those of the 0.7 mm glass, however when loads were converted to failure stress, using a Finite Element model, the stress values were found to be near identical. The specimens tested were “as-received” from the manufacturer and then abraded to determine the effect of surface flaws.

The results of these two tests found the strength between the two thicknesses to be almost identical. The characteristic life of “as-received” and abraded glass was found to be approximately 430MPa and 230MPa, respectively [6].

2.2.2.2 AMLCD Panel Strength

The mechanical strength of AMLCD panels were tested, the panel’s corners were supported during static loading with contact at the center of the panel. The strength of 17” and 23” square panels were tested

The results from this study found the characteristic life of the 17” and 23” panels to be 250MPa and 247MPa, respectively [17]. The LCD panels tested were in “as-received” condition.

2.2.3 Failure Stress Comparison

Comparing the characteristic life of the “as-received” glass layer and the LCD panels yielded a difference of almost 200MPa. But, the LCD panels were significantly larger then the glass samples, increasing the probability of finding a flaw during testing, resulting in a lower strength. Comparing the abraded glass layer to the LCD assembly yielded a similar characteristic life value, ~240 MPa, but due to the much larger LCD assembly size, this comparison is weakly supported by literature. The bend tests to be completed in this study will be compared back to the Corning data to determine if the tested failure stress on the top layer glass can be related to the failure stress of the entire LCD assembly.

3.0 CHARACTERIZING COLOR VARIATIONS IN LIQUID CRYSTAL SCREENS

The appearance of LCDs change due to aging that can result in appearance variations. Aging can be caused by different factors, including temperature, humidity, or length of operation. Determining the changes that occur in the LC screen's appearance can be a difficult task because appearance can be effected by many different factors. This study develops a method of measuring the appearance change or contrast change of an LCD using both digital photographs and Adobe® Photoshop®.

The most obvious and identifiable change in a screen's appearance is a malfunctioning pixel of group of pixels. When an LCD is operational, a non-functioning pixel or group of pixels will appear black. This type of failure is very easy to identify and pinpoint, visual inspection of a magnified photograph is usually sufficient to identify the failure site. Unfortunately screen degradation caused by a decrease in color intensity or contrast within a pixel or group of pixels is much more difficult to determine, especially if the change is relatively small. A method of quantifying these contrast or intensity changes is determined in this thesis.

As cited in the operational specifications from the manufacturer, the previously observed failures of the test LCD module were flickering of the display, no display, or a decreased contrast of the display. Also cited were failures, previously seen, that had been caused by an increased resistance in the ACF bonds. Previous research has discussed the potential effects of ACF bonds and increased resistance on the display quality of an LCD.

3.1 Photo Documentation Process

To determine a method of identifying degradation in a screen, all 60 of the operational test screen were first photo documented in their original state before being subjected to any testing that could potentially change any aspect of the screen's appearance. All photos were shot with a Canon EOS D30 digital camera using the large/fine detail JPEG format. This file format and camera allows for a 2160 x 1440 pixel picture (3.1 mega pixels) and has 8 data bits that allow for 256 different intensity levels per color (red, green, and blue). File size limitations preventing the use of the RAW image format even though it allows for the highest number of intensity levels. The camera was mounted on a tripod and a remote control was used to take each photograph to remove human interaction with the photographing process.

Each screen was marked for identification purposes and connected to the test module. The test module consists of a cell phone structure that allows for interchangeable screens. When a screen is connected to the test module, it can be powered on to display a preset color pattern. The test pattern used for this section of the study displays all three colors (RGB) on a white background. Each screen was photographed while displaying the test pattern. An example photograph of a test screen displaying the test pattern is seen in Figure 3.1.

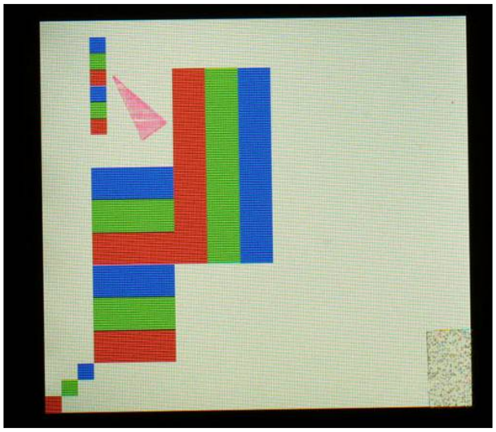


Figure 3.1 Test pattern displayed

The pink triangle and grey rectangle in the lower right hand corner are both due to small pieces of tape placed on the screen by the manufacturer.

3.1.1 Camera Settings and Photographs

Every test screen was photographed, while displaying the test pattern, using the same camera settings and magnification to ensure uniformity between pictures. A general overview photograph, seen in Figure 3.1, was shot inside a dark room with no light source other than that of the LCD. The f number was set to the maximum, 16, and high image resolution was selected. This camera set up allows for 2160 x 1440 photograph pixels, for approximately 3.1 mega pixels total. The test screen has 780 x 720 color pixels (approximately 561,600 pixels). The difference between photograph pixels and screen color pixels only allows for about 5 photograph pixels per screen color pixel. The clarity of the overview photograph was too blurry to see the individual LC screen's color pixels.

Each screen was also photographed a second time at a higher magnification, a 1 to 1 magnification ratio between the photograph image and the actual object was used, seen in Figure 3.2. Only a portion of the screen is seen in each photograph, one corner. The documentation of the test screens at this magnification required the use of a Canon MP-E 65mm macro lens capable of up to a 5 to 1 magnification ratio. The same camera set up was used as before for the overview photographs. The increased magnification allowed for more photograph pixels per screen pixel, producing a more defined picture. Using Adobe® Photoshop® to zoom in, individual screen pixels can be seen, but the pixels are relatively blurry, as seen in Figure 3.3

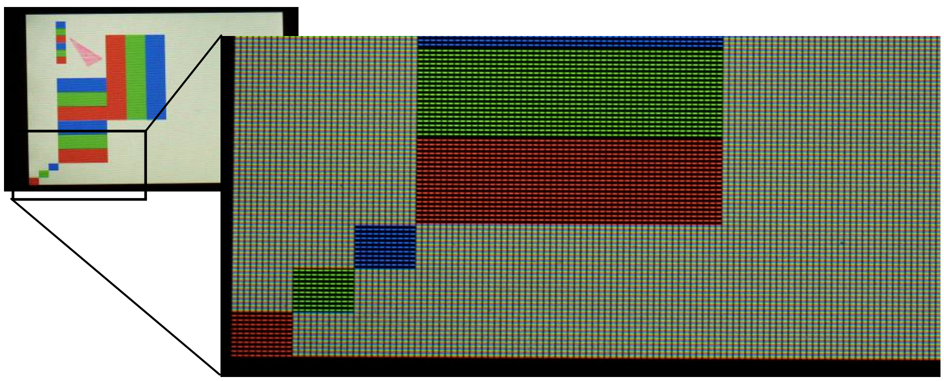


Figure 3.2 Screen photograph using the 1:1 magnification ratio as compared to the overview photograph

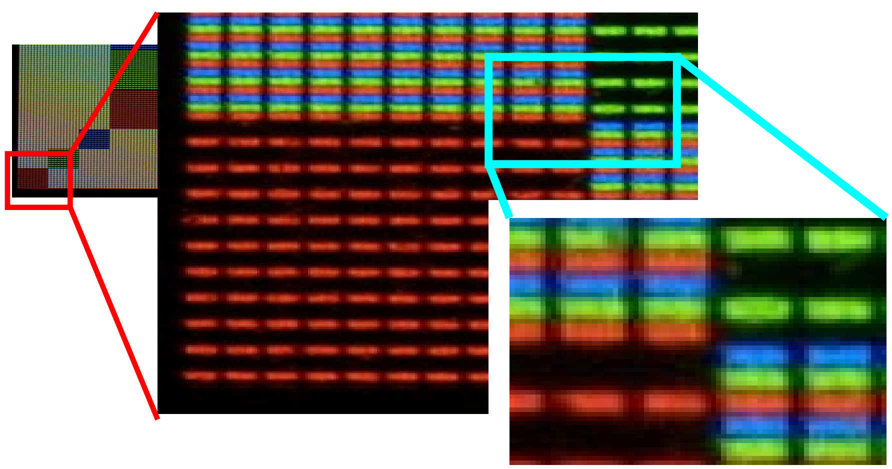


Figure 3.3 Pixels viewable using Adobe® Photoshop ®--photograph at a 1:1 magnification ratio

A third photograph was taken at a higher magnification, 4 to 1 magnification ratio between the photograph image and the actual object was used. This photograph yielded a relatively clear picture of individual screen pixels when viewed up close, seen in Figure 3.4

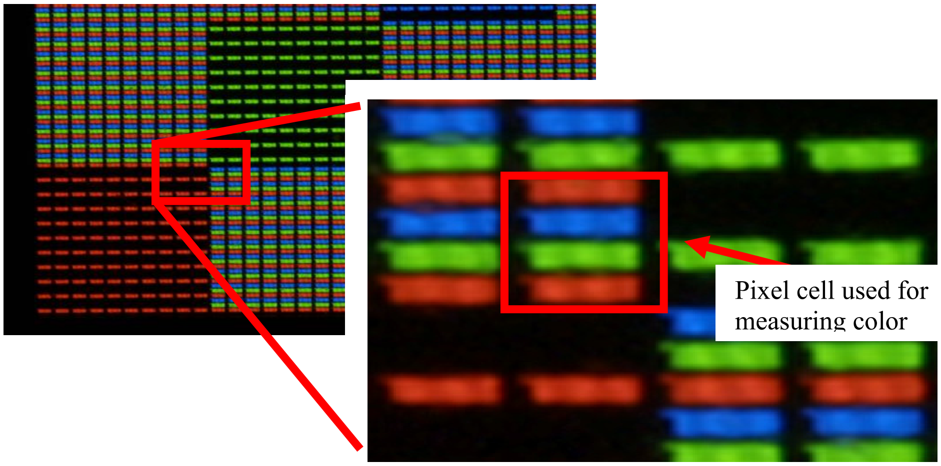


Figure 3.4 Clear pixels viewable using Adobe® Photoshop ®- photograph at a 4:1 magnification ratio

The 4 to 1 magnification ratio photographs allow for almost 1600 photograph pixels per color pixel needed to complete a color intensity analysis. All 60 test screen were photographed using the above mentioned process and a color analysis test was completed The color analysis of the pixel cell location, cited in Figure 3.4, was used to determine if a change in contrast or color intensity is measurable.

3.1.2 Color Intensity Analysis with Adobe® Photoshop®

A method for measuring the color intensity within a LC screen color pixel was established by using the Eyedropper tool in Adobe® Photoshop®. The Eyedropper tool measures the intensity of the red, green, and blue colors on a scale of 0 to 256, a measurement of zero would be no color present and a measurement of 256 would be the most intense color possible. The Eyedropper® tool can be found in the Tools window, and used by simply moving the Eyedropper cursor over an area of a picture. The resulting color intensity measurements can be viewed in the Info window of Photoshop®, any single location will have a three different color intensity measurements, one for each red, green, and blue.

When measuring the RGB color intensities of a liquid crystal screen pixel cell from a digital photograph, two different measurements can be taken. Intensity measurements can be taken of an individual photograph pixel within a screen color pixel or the measurement can be an average of a 5 by 5 square of photograph pixels. For the purpose of characterizing LCD screens' intensities, only the average color measurements are used for color analysis to help to better characterize the color data.

3.2 Liquid Crystal Screen Analysis

A total of 60 functioning LC screens are available for color analysis, each screen is labeled A through HHH for identification purposes and also photographed for overall general identification purposes. The entire screen is viewable in these identification photographs. The photographs identify nonfunctioning pixels and black spots but are not used for any in-depth analysis.

All screens were also photographed at a 1:1 magnification ratio for general characterization of the screen. Black spots can be seen more clearly then before and the spot can be identified with a group of pixels, a single LC pixel cell, or a single color pixel. The general view photographs did not contain enough detail to identify the precise location of any black spots or malfunctioning screen areas. The 1:1 magnified photographs were adequate for identifying non-working pixels, but contained too few photograph pixels per screen pixel, for accurate color intensity measurements.

3.2.1 Measurement Variation: Photograph Variation within the same Pixel of a Single LC Screen

A single pixel cell was selected from one LC test screen (screen C). This pixel cell was photographed multiple times at a 4:1 magnification ratio. The purpose of analyzing the color intensity of a single pixel within a single LC screen is to determine if any variations occur between photographs taken of the same object, i.e. photographic variation. Theoretically there should be no variation from photograph to photograph since it is assumed the LCD screen does not degrade in such a short time. In reality there is a variation due to natural uncertainties in the measurement process. This test is quantifying the measurement variability. To eliminate as much variation from photograph to photograph the same camera setup and settings were used for all the photographs taken. The same pixel cell was analyzed from each photograph, so the same photograph area was always analyzed, minimizing as much variation as possible between photographs due to potential camera imaging issues.

The camera settings were modified to allow for a properly exposed picture at the higher magnification. The exposure time was increased from one second to four seconds to compensate for the closeness of the lens to the LCD screen, which reduced the amount of light seen by the camera. At the higher magnification each color pixel of the screen has about 1600 photograph pixels where as the lower magnification has only about 100 photograph pixels. 27 different photographs of the same LC screen pixel cell were analyzed using the 5x5 average photograph pixel color intensity. Since the overall number of photograph pixels within a LC screen color pixel increased by a factor of 16, little color intensity variation should be seen when the pixels are analyzed for color intensity. The analysis results are displayed in Figure 3.5.

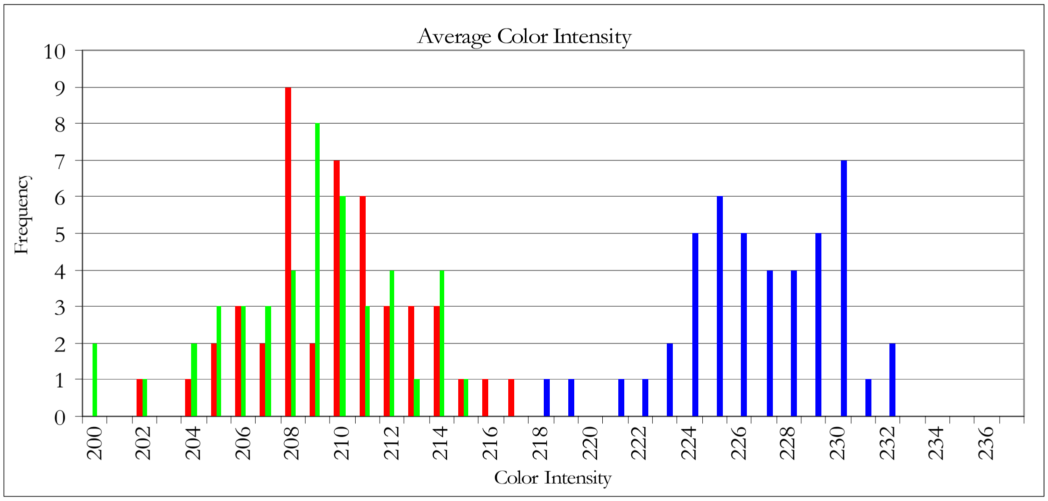


Figure 3.5 Color intensity variation of a LC screen pixel at the same single location, between photographs

From the histogram, the red and green colors have very close intensity values and variation spreads, while the blue color has much more intense colors but a similar variation spread. All three colors appear to follow a normal distribution. The calculated mean and standard deviation for each color's measurements are seen in Table 3.1

Table 3.1 Statistical analysis of the intensity measurements taken from photograph variation analysis

		5x5 Average Intensity		
		Red	Green	Blue
4:1 Magnification	Mean	209.8	208.7	226.6
	Standard Deviation	3.2	3.6	3.2

The standard deviations for each of the three color intensities is small compared to the overall color intensity scale of 256. The photographic variation of the same location on a single object is very small; the most variation was 16 units, or 6.25%. Thus, it should be possible to use digital photographs to characterize screen pixel color intensities without having photographic variation distortion.

3.2.2 Measurement Variation: Pixel Color Variation within a Single Photograph of a Single LC Screen

A single LC test screen, was photographed at a 4 to 1 magnification ratio while running the test pattern and using the same camera settings as the previous test. The photograph from this test will be used to analyze the variation within a single photograph of a single screen. This test is used to quantify any color variations that occur between different pixels within a single LC screen at any given time. Again, a 5x5 photograph pixel average measurement was used to analysis the color variations within randomly selected pixels of the LC screen. To minimize the effects of potential imaging variations across the camera imaging sensor, the randomly selected screen pixel cells are all located near the area of interest from the previous test. The histogram seen in Figure 3.6 shows the different colors' intensity variation within 15 random pixel cells.

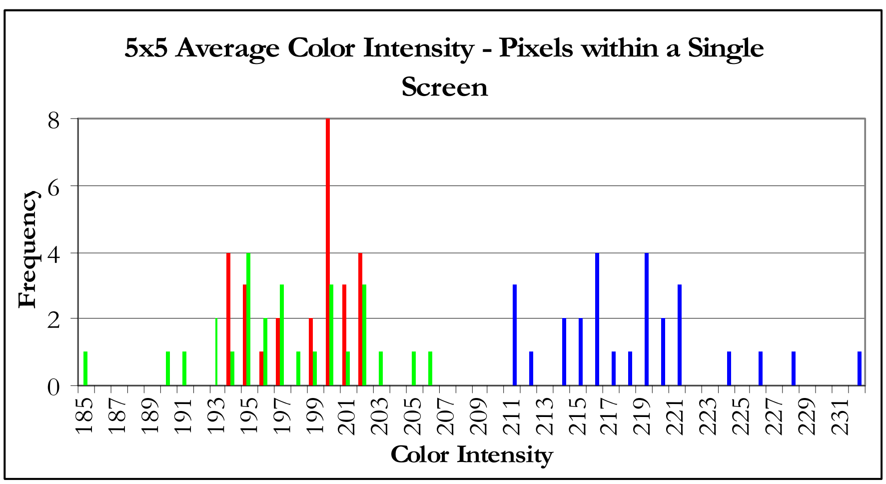


Figure 3.6 Pixel to pixel variation within a single photograph of a single LC screen

From Figure 3.6 only a small variation in color intensity is seen in each color of the screen's pixel cell. The red color pixels have the least variation with a range of only 8 intensity units out of a total 256 (~3%) and green pixels have the greatest amount of color intensity spread, 21 units. On a color intensity scale of 256 units, a measurable color intensity spread of 21 units, approximately 8%, is relatively small. The color intensity data follows a normal distribution for each color of the screen's pixel cell. The calculated color intensity means and standard deviations are displayed in Table 3.2.

Table 3.2 Statistical analysis of the intensity measurements taken from pixel variation analysis

	5x5 Average Intensity		
	Red	Green	Blue
Mean	198.5	197.3	218.2
Standard Deviation (σ)	2.9	4.8	5.1

The calculated mean and standard deviation for each color yields a very small standard deviation of approximately 3-5 intensity units, or less than 2% of the measurable intensity scale. Since the data appears to follow a normal distribution, 99% of the screen pixels tested will have a color intensity measurement within the mean +/- 3 standard deviations. For the red color intensity measurements, 99% of color intensity measurements taken will measure between 190 and 207 intensity units; green and blue colors will have a slightly larger spread but still relatively small compared to the overall intensity scale.

The color intensity variations within a single LC screen is relatively small, σ =3-5 intensity units (1-2%), compared to the measuring scale. Within a single photograph of a single LC test screen, the color intensity variation is small and quantifiable. If aging were to occur on a LC test screen any changes in the color intensity of a screen's color pixel would be measurable knowing both the effects on intensity variation due to the variation within a photograph and the variation within a single test screen.

3.2.3 Measurement Variation: Variation between different LC Screen—Single Pixel Location

All 60 functioning LC screens were photographed at a 4:1 magnification ratio while the test pattern was displayed. These photographs are used to analyze the color intensity variation between different screens. The color intensity for each screen was measured at the same location, i.e. the same physical pixel cell location. The purpose of this test is to determine the variation in color between LC test screens. Since small variations have already been identified between screen pixels within a single screen, and small variations have been quantified due to the measurement process, any variation seen in this study should be a combination of the two previous test's color intensity variation. Theoretically the standard deviation of the color intensity variation between screens should be the square root of the sum of the squares of the standard deviations from the previous two colors analyzes.

To get an overview of the LC screens' color intensity, a 5x5 photograph pixel average measurement was used to analyze all 60 of the LC test screens. The histograms for each individual colors are shown in Figure 3.7 through Figure 3.9.

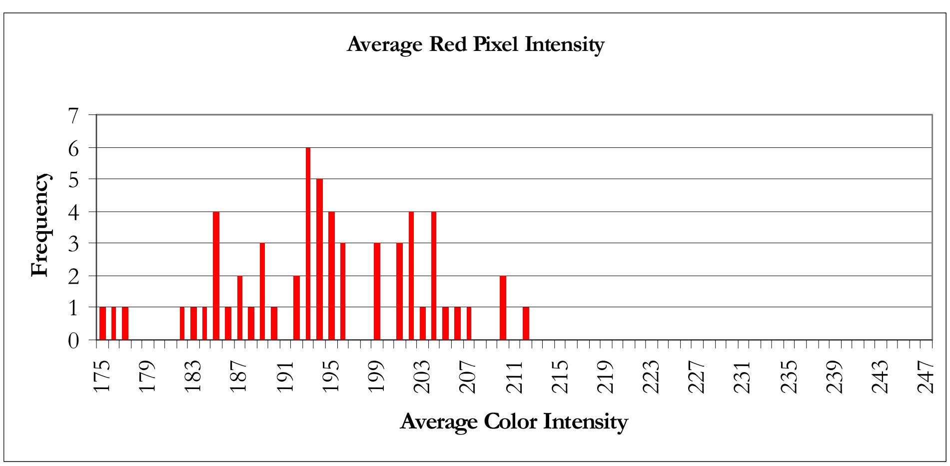


Figure 3.7 Variation of Red Color Intensity

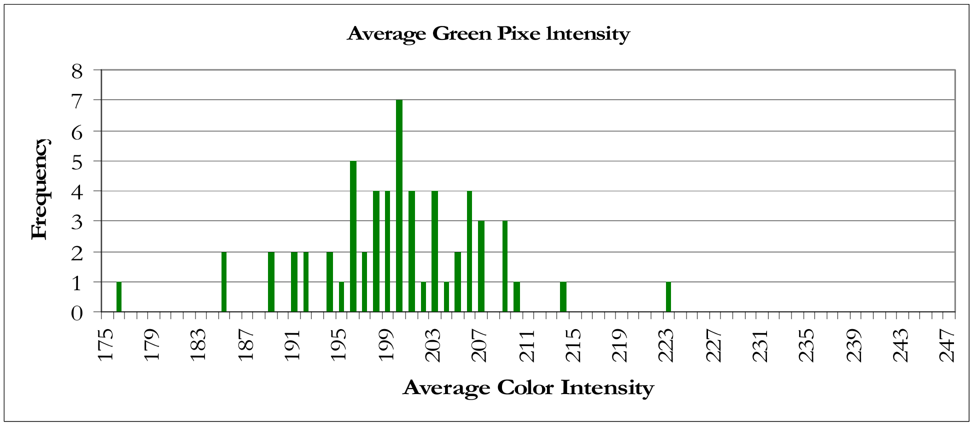


Figure 3.8 Variation of Green Color Intensity

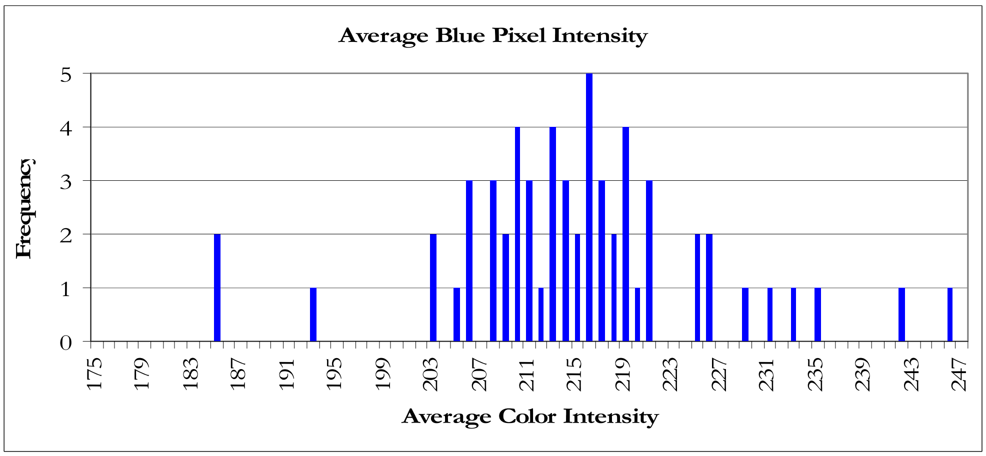


Figure 3.9 Variation of Blue Color Intensity

The LC screen's color pixel intensity measurements follow a normal distribution just as the intensity measurements from the previous tests did. Again, the blue color pixel intensities have the highest measurements overall, with the majority of the screen intensity measurements between 200 and 225, while as red is the least intense with a range of about 175 to 210 intensity units. Calculating the mean and standard deviation yields a more general view of the data seen in Table 3.3

Table 3.3 Statistical analysis color intensity measurements—comparing screens

	5x5 Average Pixel Value		
	Red	Green	Blue
Mean	194.5	199.8	214.9
Standard Deviation, σ	8.6	7.6	11

3.2.4 Comparison of the three Color Analyses Tests: Theoretical vs. Analytical Results

The calculated standard deviations for the variations within different LC screens yield larger values then the previous two tests. Theoretically, the standard deviation for each color of screen to screen variation, seen in this test, is a related to the standard deviations from the previous two tests, photograph variation (test 1) and pixel variation within a single screen (test 2). The estimated standard deviation for test 3 is $\sigma_{total} = \sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_1 and σ_2 correspond to test 1 and test 2, respectively. Calculating the weighted average of the means (due to different sample sizes) and the combined standard deviation for each color yields the following

Table 3.4 Theoretical vs. Calculated statistical averages

	Test 3 Theoretical	Test 3 Actual	Test 1	Test 2
Average Mean	205.8	194.5	209.8	198.5
Average σ	4.3	8.6	3.2	2.9
	Green			
Average Mean	204.6	199.8	208.7	197.3
Average σ	6.0	7.6	3.6	4.8
	Blue			
Average Mean	223.6	214.9	226.6	218.2
Average σ	6.0	11.0	3.2	5.1

Comparing the test 3 actual measurements (same pixel location but different screens) and the theoretical values using the data from the two previous tests, the theoretical values all have a slightly more intense or higher mean value and a smaller standard deviation. The varying sample sizes may account for some of the differences between the theoretical values and the actual values. The first two tests have smaller sample sizes then the final test; collecting more data from the first two tests may result in theoretical values that more closely match the actual measurements.

Comparing the statistical data from test 3 (variation between screens) to test 1 (variation in photographs of the same pixel within a single screen), the mean values for each color are very similar, but the spread of the data in test 3 is larger than in test 1. Since both tests, 1 and 3, measured the color intensity in the exact same screen pixel cell location, these two tests are a better comparison than comparing measurements taken from different locations within a single screen.

From the actual measurements taken in test 3, the ranges of the color intensity measurements are still small. The largest range is seen in the blue color pixels with a standard deviation of 11.0 intensity units. From the histogram of the blue intensity values there are two measurements that are much lower then the other 58 measurements; these two outliers are affecting the statistical analysis of the blue intensity measurements. The same applies for the red and green pixel colors; a few outliers are increasing the value of the standard deviations.

3.4 Conclusion

Three different color intensity analyses were performed on the test LC screens. The variation between photographs of the same pixel of a single LCD screen, the variation between different LC screens when viewing a single pixel location, and the variation in pixels within a single photograph of a single LC screen were all analyzed.

From the analysis the variations between the different LC test screens was found to be comparable to the variations studied in the first two tests. It was concluded that a change in a LCD's contrast (or color intensity) is measurable and predictable.

4.0 CHARACTERIZING THE EFFECTS OF HUMIDITY ON FAILURES

Exposing electronics to high humidity, generally associated with operational environment, can potentially cause any number of adverse side effects. Since portable electronics, such as cellular phones, are used all over the world, these devices can be subjected to an array of environments. Temperature extremes in the United States have been recently recorded as high as 57 C (recorded 29 May 2000 in Greenland Ranch, California) and as low as -51C (recorded 2 February 1996) Tower, Minnesota) [1]; while relative humidity can range from almost 0% (desert climate) to 100% (tropical rainy climate). To help assess the life of LCDs, the effects of humidity should be analyzed to determine potential failure sites.

The operational specifications of the test LCDs are -10 – 60C and 5% - 95% relative humidity. Since recent recorded extreme temperatures are close to or beyond the operational specifications of the test screen, it would be reasonable to assume that an LCD (potentially used in a cellular phone) could be used in environments very close to the limits of operation. The possibility of seeing failures in the LCD are likely to occur when the device is being pushed to it limits.

One objective of this thesis is to determine the effects of humidity cycling on an LCD screen. Previous research has indicated that a decrease in screen contrast can occur when a LCD is exposed to humidity. For the experiment, humidity cycling was chosen over constant high humidity because physics of failure indicates that cycling will accelerate failures versus constant high exposure. Also, in extremely humid environments it is common for people to travel between high humidity outdoors environments and air-conditioned, controlled indoor environments having relatively low humidity. Determining the appropriate cycle time will be dependent upon maximizing the moisture absorbed in the LCD while minimizing the time required.

4.1 Test Setup

The appropriate humidity cycle time had to be established to use as the testing cycling for the experiment. This involves determining the maximum amount of moisture that a LCD screen is capable of absorbing. The time it takes the LCD to absorb the moisture and dry out must be considered along with the capabilities of the humidity chamber that will be used for testing.

4.1.1 Determining the LCD Weight Profile

A non-functioning LCD screen was placed in a desiccant jar with Drierdite™ (Anhydrous Calcium Sulfate); air was vacuumed out of the jar, with the use of an air pump, removing a majority of the moisture from the desiccant jar. The sample was allowed to dry until the sample weight no longer decreased, approximately 85 hours. The LCD screen was removed every two hours to be immediately weighted on an electronic scale to track the weight change of the sample as the moisture was removed. The sample was exposed to room temperature and humidity for approximately 30 seconds during each weight measurement. The average room conditions were 28.5C and 28%RH, measurements utilized a thermo hygrometer and digital sling psychrometer. Once the weight change stabilized and the sample was considered dry, it was removed from the desiccant jar. The weight profile in Figure 4.1 shows the weight change due to drying.

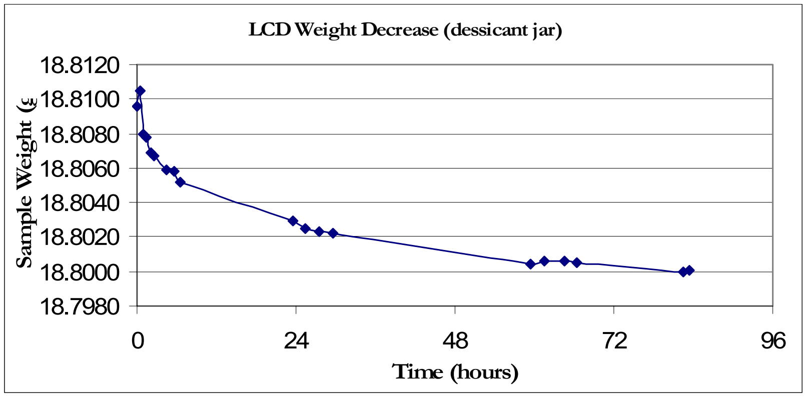


Figure 4.1 LCD weight change due to desiccant jar drying

The initial drying test d demonstrated the ability to measure the weight change that can occur within an LCD due to moisture increases or decreases. A baseline weight for an LCD screen can also be obtained through drying the test screen in a desiccant jar or other type of drying device.

Once the LCD test screen was dry, a saturated weight needed to be determined. This was accomplished by placing the dry screen into a humidity chamber set at a constant 50^{C}/50% RH; initial testing had equipment limitations that prevented the use of a higher humidity. The sample was removed every two hours and weighted to track weight gain, as shown in Figure 4.2. Weight measurements were taken until the sample reached a constant weight, completely saturated.

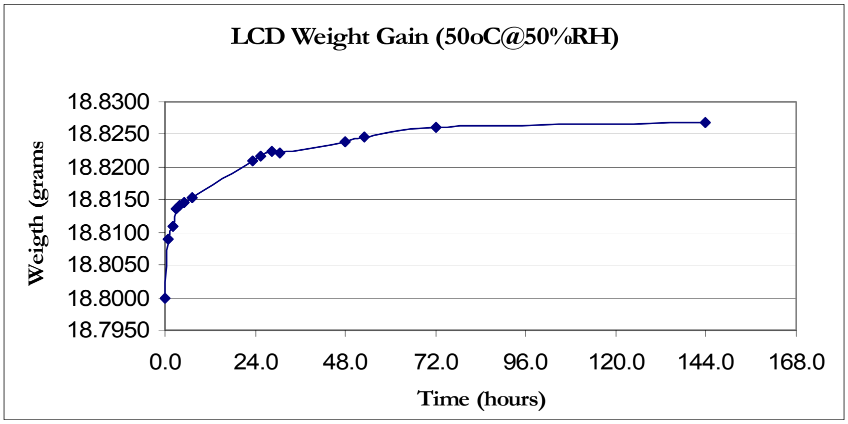


Figure 4.2 LCD screen moisture uptake, exposed to a constant 50^{C} / 50%RH

From both tests, drying and moisture uptake, a weight change curve was established for the LCD screen. The minimum weight was recorded at 18.800g and the saturated weight was recorded at 18.827g, a weight change of 0.142% was observed. The total time to achieve a completely dry or saturated sample took approximately 200 hours.

From these two weight tests it was observed that the LCD screen would absorb and dry out a measurable amount of moisture. Since time has to be minimized for humidity cycling testing, a more reasonable cycle time had to be established. The humidity cycle chosen will have to demonstrate a repeatable weight profile, or change, for the cycling to be consistent.

4.1.2 Repeatability of LCD Screen Weight Change—Humidity Chamber Cycling

Minimizing the humidity cycle time will depend on the repeatability of the LCD test screen weight change and the capabilities of the humidity chamber. The chamber chosen for testing was an ESPEC humidity chamber model PRA-3AP. Working within the operational specifications of the LCD screen a 48 hour humidity cycle was run to determine if a repeatable weight change could be achieved while shortening the cycle time, i.e. not allowing the sample to completely dry or become completely saturated.

Temperature was held at a constant 60C, the humidity was held at a constant 95% RH for 24 hours followed by a constant 5% RH for another 24 hours. Again the screen was removed for weighing, and the weight change was monitored over the 48 hour cycle period. The resulting weight profile is shown in Figure 4.3.

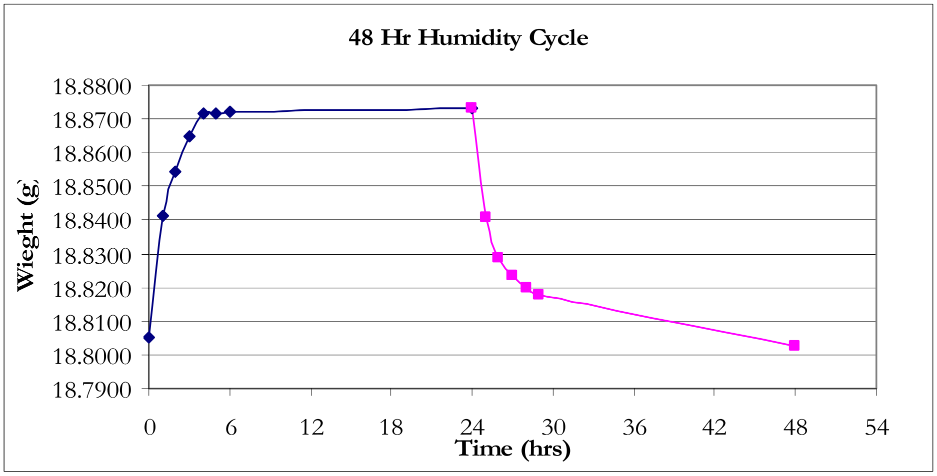


Figure 4.3 LCD Screen Weight Profile: 48 Hour Humidity Cycle

From the 48 hour humidity cycle test it was apparent that a majority of the weight uptake and decrease occurs in the first four hours of each stage of the cycle. Using this knowledge, an eight hour humidity cycle was chosen; see Figure 4.4. This cycle minimizes the time required for testing while maximizing the amount of moisture absorbed by the LCD screen. Allowing the screen to become moisture saturated should facilitate failures more quickly then if the LCD screen did not become moisture saturated.

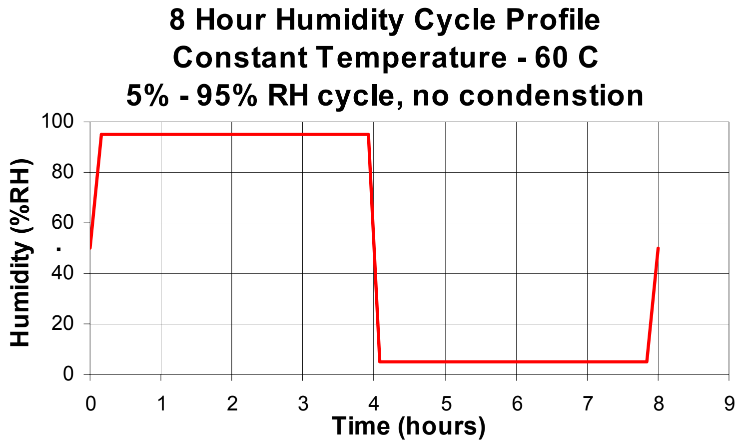


Figure 4.4 Chosen Humidity Cycle: 8 Hours

The eight hour humidity chamber cycle consisted of holding temperature at a constant 60C, while cycling humidity, four hours at high humidity (95%) and then four hours at a low humidity (5%). At these conditions no condensation was observed within the chamber. The rate of change of humidity within the chamber is not exactly known, and depended on the surrounding room conditions, but the complete humidity change (95% to 5% or 5% to 95%) takes approximately 15 minutes.

Much like the 48 hour cycle, the eight hour cycle yielded very repeatable weight changes, seen in Figure 4.5

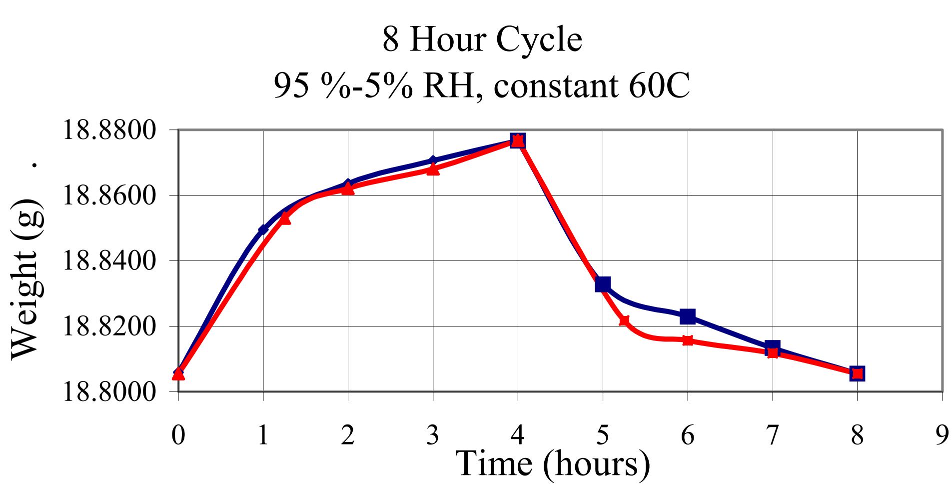


Figure 4.5 Two Weight Profile Tests: Eight Hour Humidity Cycles.

The average weight change seen between the two test cycles in Figure 4.5, was 78.8mg, yielding a change of about 0.42%. Almost identical weight profiles prove that an eight hour humidity cycle will yield repeatable results while allowing for 3 humidity cycles per day.

4.2 Humidity Cycling Results

Initially all test LCD screens were in proper working order with no non-functioning pixels. All test screens were connected to the test module and photo-documented before any testing occurred. These photographs, along with the knowledge gained from the intensity analysis, will be used as a baseline for comparison later on. During humidity cycle testing, appearance changes can be determined by comparing the test screen back to the original pre-test photograph.

Humidity cycling was initiated with two test screens as a test of the humidity cycle. After every five humidity cycles each test screen was removed from the humidity chamber and photographed. Three types of photographs were taken of each test screen displaying a multi-color test pattern and a black test pattern. Failures were seen immediately, after only the first five humidity cycles. When a functioning LCD is connected to the test module and the black color pattern is displayed, all pixels are black except for the white pixels used to display the word “black” on the screen, see Figure 4.6.

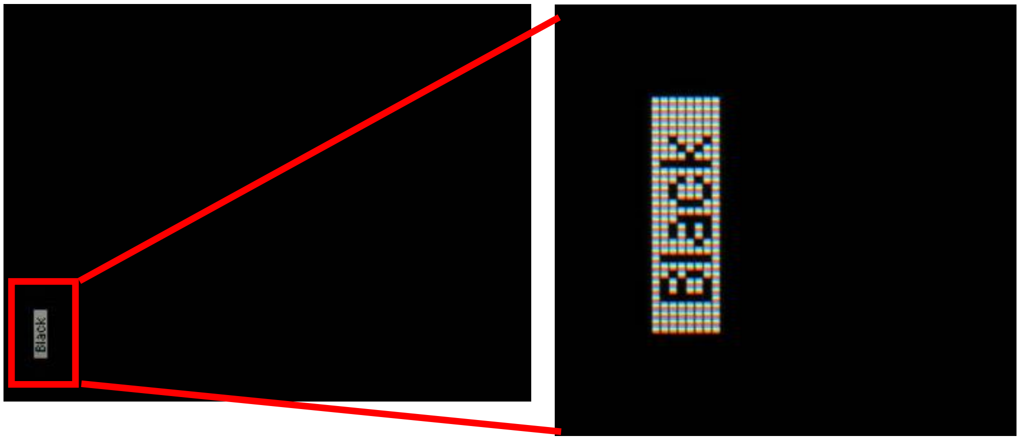


Figure 4.6 Black color pattern display – original untested LCD

4.2.1 Pixel Degradation

After only five humidity cycles, non-extinguished pixels (or failed pixels) were noticeable around the perimeter of the test screens when viewing a black color pattern on the screen. The non-extinguished pixels appear as a thin white line around the screen's edge, seen in Figure 4.7; arrows identify failed pixels.

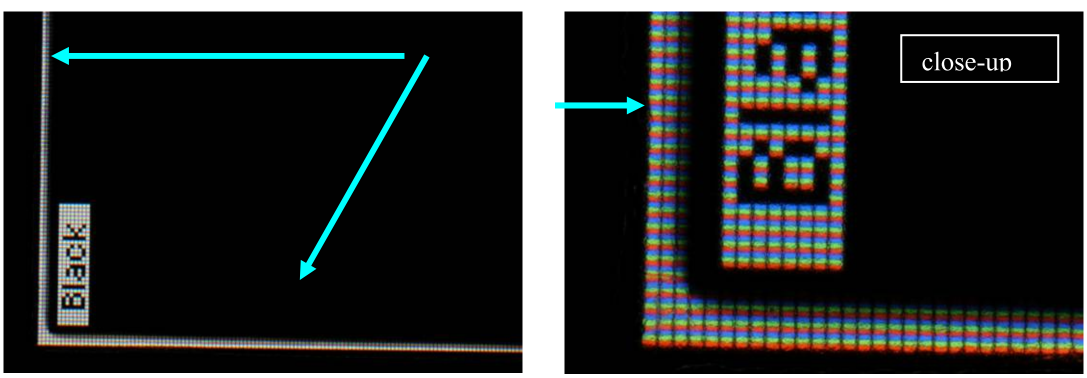


Figure 4.7 Pixel failures screen after 15 humidity cycles.

Using Adobe® Photoshop® to view the photograph close-up, individual color pixels can be seen. The white perimeter, of this particular screen, contains approximately three rows of pixel cells no longer extinguished. Two possible causes for this type of failure are either the polarizing film has become damaged or the liquid crystal material is not aligning properly.

Since failures started occurring almost immediately after testing began, an additional larger group of LCD screens were added to the humidity chamber for testing. Of the 13 screens subjected to humidity cycling only four screens displayed pixel degradation after the first five humidity cycles.

4.2.2 Polarization Delamination

The pixel failures observed in the test screens all appear to be the same type of failure. As humidity cycling continued on the test screens, the failures on a few of the screens became more prevalent. The perimeter of the non-functioning pixel rows became wider as cycling continued. After 45 humidity cycles, test screen C, displayed approximately 21 nonfunctioning pixels around the perimeter of the screen, as seen in Figure 4.8.

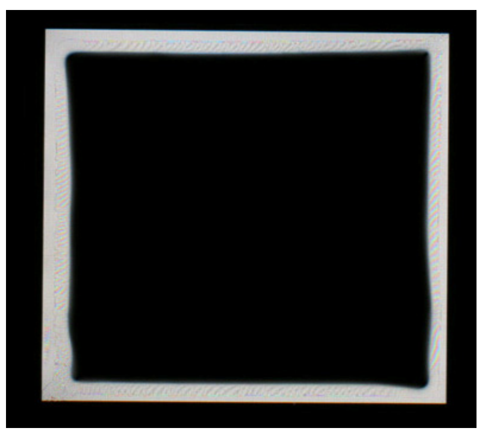


Figure 4.8 Test screen C, 45 humidity cycles

The relatively large area of failure on this particular screen yielded an observable failure mode, shown in Figure 4.9.

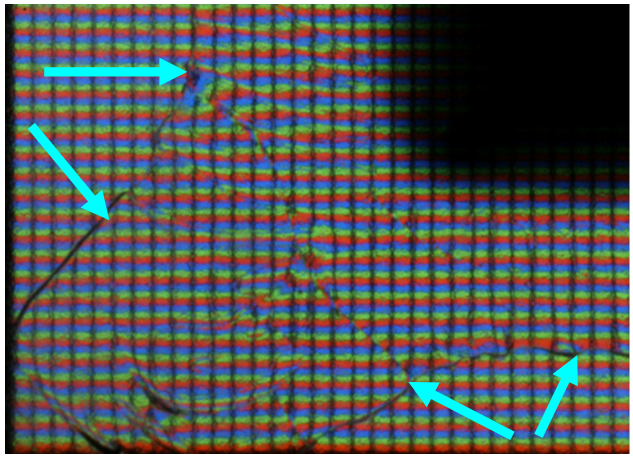


Figure 4.9 Test screen C, 45 humidity cycles

The arrows identify the wrinkled edge of the polarizing film, the top layer of the screen assembly, while the test screen stills displays the appropriate test pattern. In an attempt to remove to the polarizing film from the test screen, the film ripped. Only the edge of the polarizing film has delaminated from the screen, the remaining center portion of the polarizer is strongly adhered to the screen, with no signs of delamination.

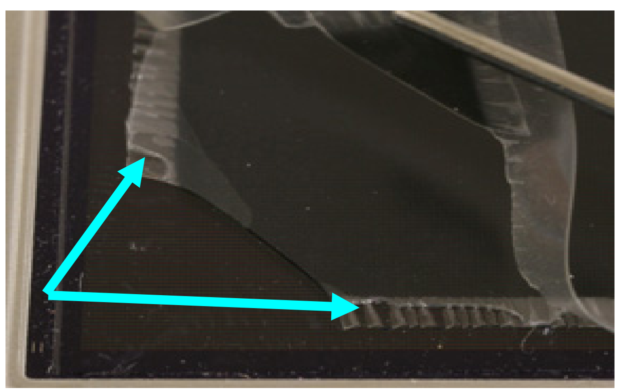
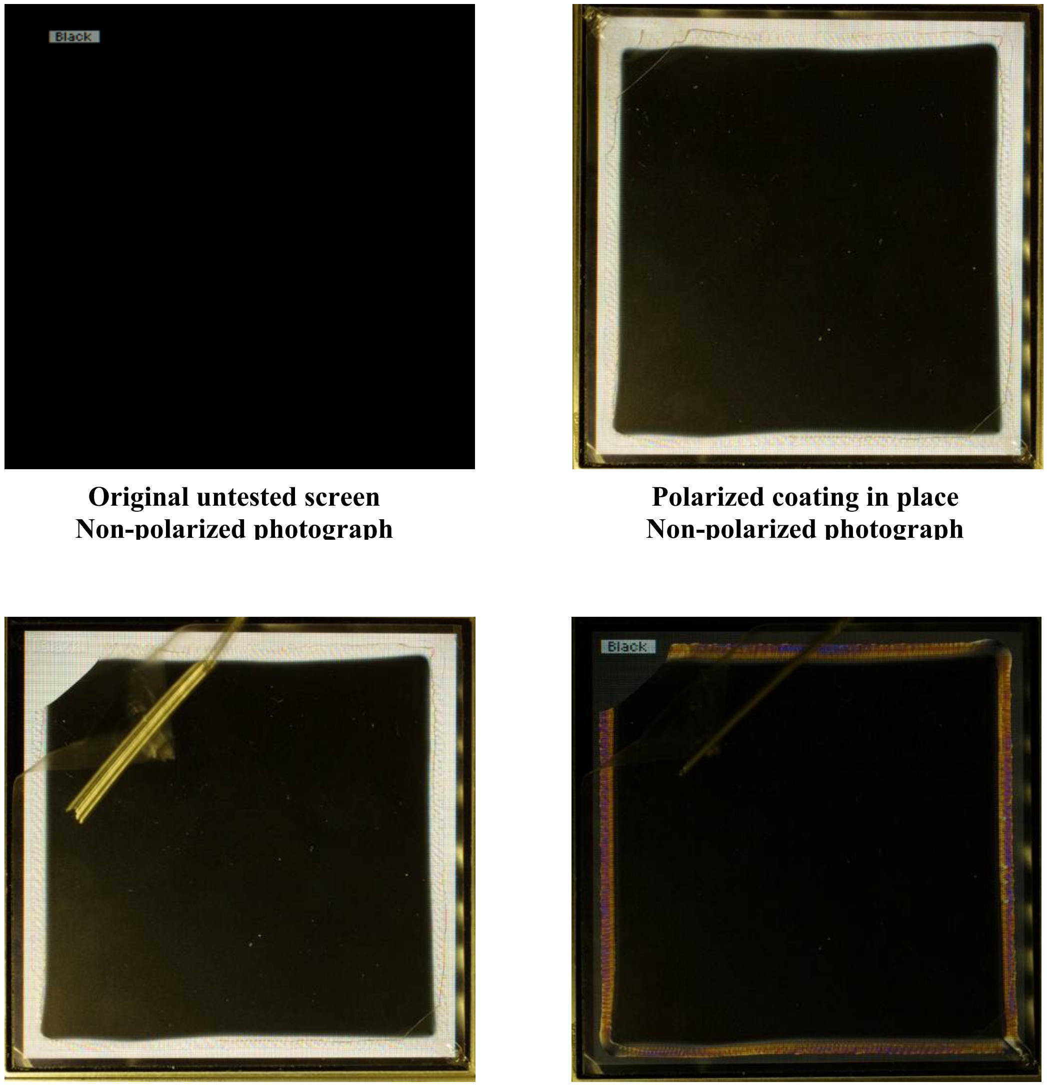


Figure 4.10 Test screen C—ripped polarizing film

Figure 4.10 displays the delaminated and adhered portions of the polarizing film. The humidity cycling has had an adverse effect on the adhesive used between the top layer of glass and the polarizing film, but only along the edge of polarizing film. The proposed, expected failure mode seen in previous research was an increased resistance of the anisotropic conductive adhesive film leading to display and/or contrast degradation. The only observed failure from testing was degradation of t he polarizing film, with the possibility of degradation of the liquid crystal properties. No display or contrast changes were observed as a result of humidity exposure.

To determine if any degradation of the liquid crystal material had occurred, a series of photographs were shot using a polarizer attached to the camera lens, seen in Figure 4.11.



Original untested screen
Non-polarized photograph

Polarized coating in place
Non-polarized photograph

Polarized coating peeled back
Non-polarized photograph

Polarized coating peeled back
Polarized photograph

Figure 4.11 Photograph sequence—polarized picture

The original untested screen is shown as the top left-hand photograph; all pixels are extinguished except for the word "Black" in the corner of the display. After almost 50 humidity cycles a perimeter of non-extinguished pixels have developed and the word "Black" is no longer visible on the display, shown in the upper right-hand photograph. Peeling back the polarizing film revealed even more non-extinguished pixels in the lower left-hand photograph. The final photograph, in the lower right-hand corner of the sequence, was taken with a polarizer attached to the camera's lens while the polarizing film on the display was peeled back. The subsequent photograph revealed that all of the pixels are functional and displaying the appropriate pattern. The discoloration around the perimeter of the last photograph is due to the interaction between the wrinkled polarizing film on the LCD and the polarizer attached to the camera lens.

The use of the polarizing lens attached to the camera demonstrated the non-extinguished pixels were the direct result of the delaminating polarizing film on the LCD screen. In general, of the test screens displaying polarizing film delamination, the amount of delamination increases as the exposure time to humidity also increases.

4.2.3 Rate of the Polarization Failure

As humidity cycling continued, it was observed that the LCD test screens had a variation in the number of the failed or non-extinguished pixels. Some of the test screens had no observable pixel failures while other had relatively large portions of the screen displaying delamination.

During the humidity cycle testing it was observed that if an LCD screen developed any non-extinguished pixels they would be observed within the first 20 humidity cycles. The number of non-extinguished pixels per LCD screen is shown in Figure 4.12

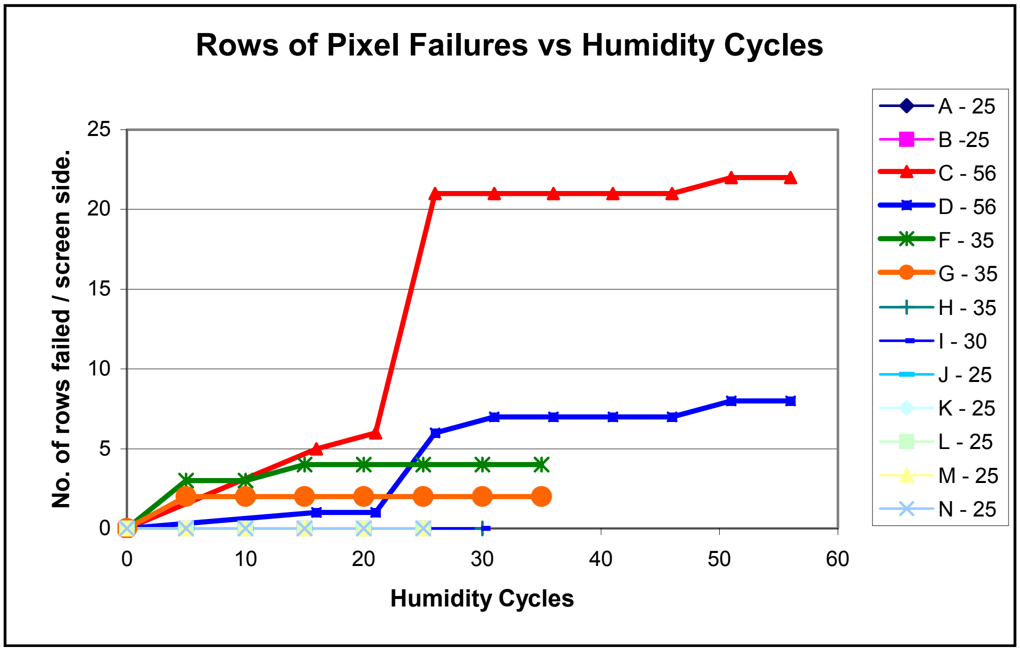


Figure 4.12 Rate of Polarization Failure—8 Hour Humidity Cycle

As the number of the humidity cycles increased the number of non-extinguished pixels also increases. But only 4 of the 13 screens (screens C, D, F, and G) showed any pixels failures after 25 humidity cycles and of those 4 screens the number of failed pixels has begun to level off without a continuous increase in the number of failures. To attempt to increase the number of failures observed, a time compression was applied to the experimental humidity cycle.

Initially an 8 hour humidity cycle was used for the humidity cycle testing, but to accelerate pixel failures a 4 hour humidity cycle was chosen. The humidity range and temperature remained unchanged but cycle time changed to 2 hours at 95% RH followed by 2 hours at 5% RH. The compressed humidity cycle can be seen in Figure 4.13 as compared to the original cycle time chosen at the start of the experiment.

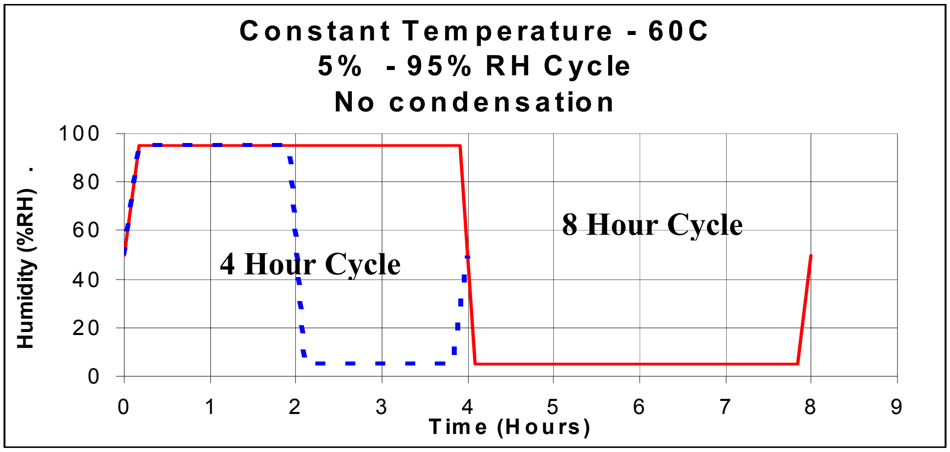


Figure 4.13 Humidity Cycle—Time Compression

The time compressed humidity cycle was applied to all further testing. Initially the time compression had no effect on the rate of the failures but as testing continued a few more failures were observed. The change in failures can be seen in Figure 4.14

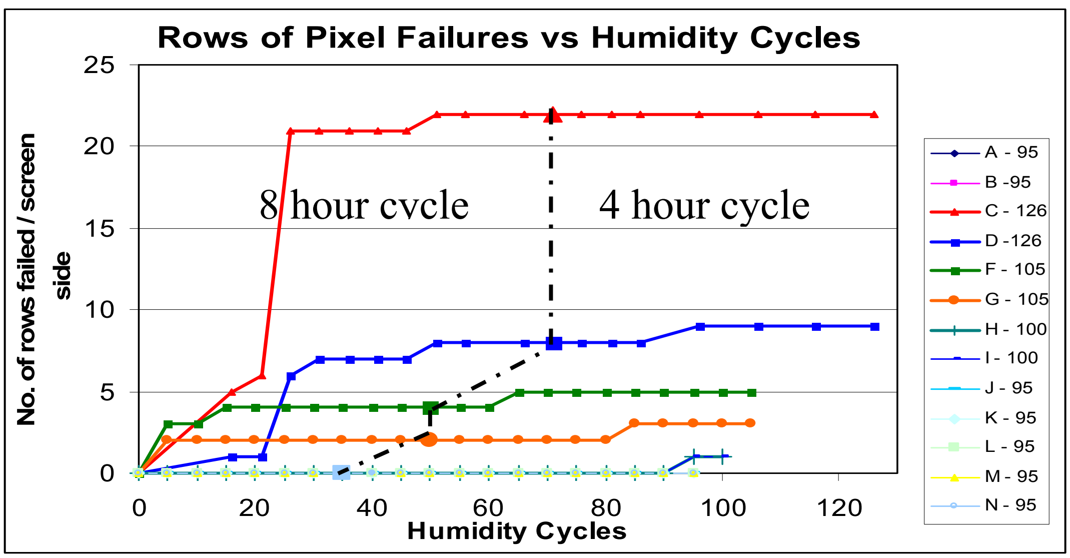


Figure 4.14 Rate of Polarization Failure—after application of time compression

The increase in pixel failures does not appear to be linked to the time compression applied to the humidity cycle time. The dashed line through the graph in Figure 4.14 identifies where the cycle time change occurred for each LCD test screen. The same four test screens that previously had non-extinguished pixel rows (screens C, D, F, and G) remained the only four screens displaying failures, except for the addition of screen I.

After 95 humidity cycles, screen I had one observable non-extinguished pixel row. Of the initial four screens displaying non-extinguished pixels only three gained an additional row of non-extinguished pixels after exposure to the accelerated humidity cycles.

4.3 Conclusions

When exposing LCD screens to a high humidity environment the anticipated failures are a decrease in display contrast, and non-functioning or intermittent pixels as shown from previous research. Non-functioning or intermittent pixels would be observable when the test screens were removed from the humidity chamber for display testing and documentation. A change in contrast would also be observed using the methodology developed in Chapter 3.0. Analyzing the intensity levels of the LCD test screen's pixels would identify a contrast change that would be a result of exposure to a high humidity environment.

After exposing the LCD test screens to the chosen high humidity test cycles none of the expected failures were observed. The previously discussed method of measuring the color intensity (or contrast) of a pixel or group of pixels (in chapter 3) was used to monitor the contrast of the LCD test screens during humidity testing. No contrast change was observed in any of the LCD test screens.

The LCD test screens did display pixel row failures as discussed in this chapter. Generally pixel failures developed after exposure to only five humidity cycles, 40 hours of exposure, with the occasional additional pixel row failure scattered throughout the testing. From the onset of humidity cycle testing either test screens immediately developed failures or they did not, the only exception being a single test screen that developed one pixel row failure after exposure to 90 humidity cycles. The cause of failure is probably due to poor adhesion between the polarizing film and the top glass layer, since the failures seen from humidity cycling were only polarization film degradation, and not contrast degradation. A poor adhesion would allow moisture to ingress between the two layers and cause delamination due to adhesive volume expansion caused by moisture. The adhesive used to attach the polarizing film to the glass should be considered and further analysis in needed to determine if it is the cause of the display failures observed in humidity testing.

5.0 CHARACTERIZING MECHANICAL STRENGTH

LCDs are subjected to various loading conditions through out the duration of there life. Everyday use can stress the layered screen structure. Placing a portable electronic device in one's pocket, for example, can potentially cause the screen to bend and become damaged if other items (such as pens, coins, and keys) come in contact with the screen. Figure 5.1 shows an example of a cracked LCD screen in a portable electronic device, the Apple Nano®.

Figure 5.1 Mechanical failure—cracked top glass layer of LCD screen [4]

An accidental drop can cause an impact significant enough to fracture the glass in the screen (seen in Figure 5.1) and prevent any functionality of the device [3]. Due to the almost unlimited conditions that LCDs are exposed to, the mechanical strength characterization will be limited to the chosen test plan, but further testing and analysis would be extremely useful in further assessing the life expectancy of LCDs.

One objective of this thesis is to characterize the mechanical strength of the LCD assembly in comparison to a single layer of glass used in the same LCD assembly. A mechanical bend test will be used to characterize and compare the strength of the assembly and the top glass layer because of the results seen in previous testing [16].

Both, functional and non-functional screens and assemblies will be considered for testing. Also, due to the rate sensitivity of glass, different loading rates will be considered.

5.1 Experimental Setup

To determine the mechanical strength of the LCD test screen assembly a mechanical bend test was chosen [16]. Using a screw-driven, displacement rate controlled machine, both the applied force and displacement rate will be monitored and recorded. The breaking force, along with a finite element model will be used to determine the stress seen at failure. The relationship between the critical strength of the LCD assembly and the critical strength of the top layer of glass will be compared and analyzed. The strength relationship between the entire assembly and the top layer of glass can be used to help assess life of the entire LCD module.

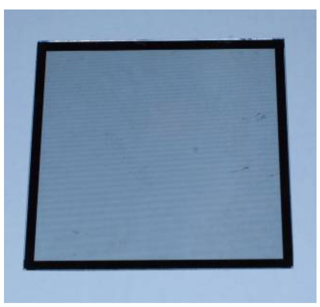
5.1.1 Test Specimens

Two different test specimens will be tested, a LCD assembly and the top glass layer from the LCD assembly. The LCD assembly consisted of the entire LCD structure (as described in Figure 1.1); the plastic frame/housing was removed, along with the controlling circuit assembly, making the screen assembly inoperable. The protective polymer coating covering the glass layer of the screen was also removed; this was accomplished by peeling the polymer layer off with a razor blade. Even though the removal was done with extreme care, slight abrasions or scratches could have resulted. Figure 5.2 shows the LCD assembly as tested.

Assembly dimensions:
length – 49.2 mm
width – 46.8 mm
overall thickness – 1.0mm

Figure 5.2 Test specimen – LCD assembly

The top layer of glass was the second test specimen. This specimen came from a slightly smaller LCD test. The glass layer was separated from the assembly by soaking the assembly in 90% fuming nitric acid, this method prevented any cracks or abrasions on the surface of the glass. Figure 5.3 displays the glass specimen as tested; the dark perimeter around the glass is pigmentation and was not removed by the nitric acid.



Assembly dimensions:
length – 43.7 mm
width – 41.3 mm
overall thickness – 0.25 mm

Figure 5.3 Test specimen – Top glass layer

5.1.2 Test Fixture

The LCD test specimens were both tested on the same fixture to ensure uniformity of results. A load was then applied to the center of the support structure; the force applied to the specimen was recorded. A diagram of the test fixture is shown in Figure 5.4

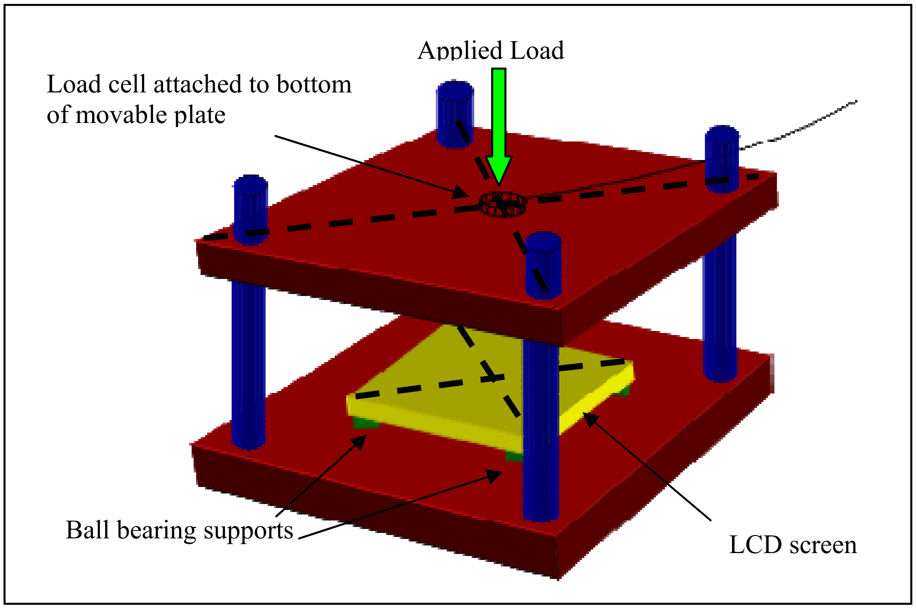


Figure 5.4 Mechanical bend test fixture

The corners of the LCD test specimen are supported on four equally spaced steel, ¼ inch diameter bearings. The spacing of the supports allows for a test area of 31.75 x 31.75mm, well within both test specimens. A round contact was chosen to minimize the damage caused by the supports. A load cell was attached to the underside of the top movable plate; the plate is then lowered onto the test specimen, putting the load cell in contact with the test specimen. The load cell contact point also has a ¼ inch diameter, making all contact points between the test fixture and the test specimen exactly the same.

5.1.3 Experimental Setup

The mechanical strength experiments were tested on an Instron® universal testing machine. This machine allowed a force to be applied by controlling the rate (~mm/min) at which it is applied. The test fixture was placed into the machine; essentially the load cell (Omega® LCKD5 / LCKD 50) was pressed down onto the surface of the specimen, until the specimen broke. Both the applied force and the rate at which the force was being applied were recorded. The use of a data acquisition system and BAM (bridge amplifier and meter) were used to record testing results. All LCD specimens were tested with this setup.

5.2 Test Results – Mechanical Strength

Both specimens were test according to the setup previously explained. The loading rate was varied over two order-of-magnitudes (0.5 to 50 mm/minute) throughout the experiment to determine if the mechanical strength of the screen or the glass layer was rate dependent. First, the LCD assemblies were broken, 21 samples were available for this experiment. The results of the strength test for the LCD assembly are shown in Table 5.1

Table 5.1 LCD Assembly Strength Results

LCD Assembly Results						
Screen #	Loading Rate (mm/minute)	Breaking Force (Newton)		Screen #	Loading Rate (mm/minute)	Breaking Force (Newton)
1	50	55.70		14	5	88.71
2	50	66.58		15	5	76.84
3	50	102.82		16	5	85.36
4	50	50.46		17	5	62.13
5	50	102.19		7	1	55.34
6	50	91.54		8	1	90.23
9	50	91.90		18	0.5	56.80
10	50	85.37		19	0.5	52.68
11	50	96.12		20	0.5	83.95
12	50	94.86		21	0.5	40.44
13	50	91.54				

The LCD assemblies were tested at four different loading rates, 50, 5, 1, and 0.5 mm/min; due to the limitations of the equipment other loading rates were not tested. From the LCD assembly tests, it appears that the breaking load is not dependent on the loading rate. The top glass plates were tested at two loading rates with an order of magnitude difference. The top glass plate was tested at 50 and 5 mm/min loading rates, the results are shown in Table 5.2.

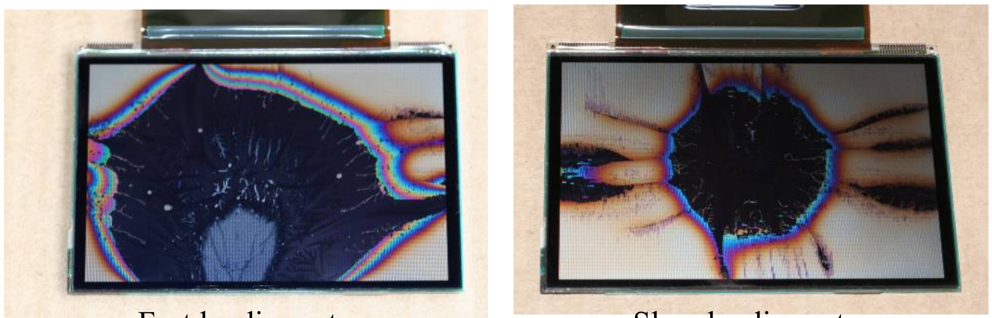
Table 5.2 Top Glass Layer Strength Results

Top Glass Layer Results						
Screen #	Loading Rate (mm/min)	Breaking Force (Newton)		Screen #	Loading Rate (mm/min)	Breaking Force (Newton)
5	5	21.682		9	50	18.762
10	5	18.670		13	50	21.400
11	5	20.830		14	50	22.241
12	5	20.120		15	50	20.436
1	50	19.176		16	50	18.897
2	50	21.174		17	50	22.546
3	50	18.561		18	50	20.366
4	50	18.285		19	50	15.921
6	50	20.447		20	50	20.783
7	50	20.327		21	50	20.213
8	50	20.341		22	50	19.629

Again, a small difference exists between the average breaking forces for the two difference loading rates. The 50 mm/min loading rate tests have an average breaking force of 19.97 N, while the 5 mm/min load rate tests have an average force of 20.33 N, only about a 0.3 N difference. From the strength tests, it appears the LCD assemblies and the top glass layer is not rate sensitive, little difference is seen in the force required to break the glass. However, the size and location of flaws can affect glass strength [16] and is the probable cause of the range seen during testing of the force required to break the assemblies and the glass layers.

From the strength tests performed on the LCD assemblies and top glass layers it was found that the breaking load was not dependent on loading rate. But, the observed failure mechanism was load rate dependent.

The LCD assemblies were photographed after testing to show the breaking pattern of the top layer of glass in the assembly. The two photographs shown in Figure 5.5 are failed LCD assemblies, tested at two different loading rates.



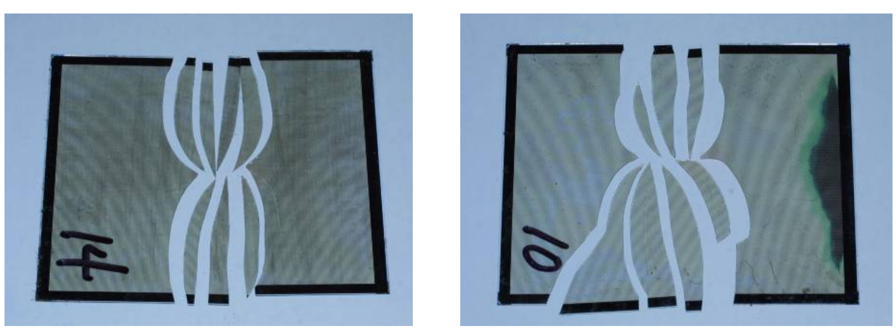
Fast loading rate
50 mm/min

Slow loading rate
5 mm/min

Figure 5.5 Observed failures – LCD Assemblies

In Figure 5.5, the left screen assembly broken at a fast loading rate (50 mm/min) and appeared to be crushed without cracks strictly focused at the contact point. Whereas the assembly on the right was broken at a slower loading rate (5 mm/min), the cracks are focused around the load contact point and then radiate outward in a symmetric manner. The array of colors seen in Figure 5.5 are due to the interaction of the LC material and the camera flash.

The top glass layers were also photo-documented after testing. The failed glass layers, tested at different rates, are shown in Figure 5.6.



Fast loading rate
50 mm/min

Slow loading rate
5 mm/min

Figure 5.6 Observed failures – Top Glass Layer

The glass layer on the left in Figure 5.6 failed during a fast loading rate test. The cracks are symmetrical and uniform, radiating from the center load contact point. While the glass layer on the right tested at a slower loading rate, has less uniform and symmetrical cracks radiating out from the center load contact point. The decrease in uniformity of the cracks can be associated to the effect of surface flaws on crack propagation.

Strength tests performed at slower loading rates results in similar failure loads as those performed at faster loading rates. The rate dependency is observed in the physical failure mechanism of each test specimen and the not the breaking load. The symmetry of the breaking pattern of the glass in both the LCD assemblies and the glass layer depended on the loading rate used during testing.

5.3 Critical Strength – Finite Element Model

To compare the strength of the LCD assemblies to the top layer of glass, the critical stress seen at failure had to be determined from the breaking force values. A finite element analysis was conducted to determine the critical stresses and the results were compared to literature to determine the validity of those results. Finite element models of both the LCD assembly and the glass layer were created to determine the stress values associated with the loading values. The finite element assumed the glass material to be soda-lime; the material properties used are young’s modulus of 70GPa and a Poisson’s ration of 0.23. Altair® HyperMesh® was used to create the model and the finite element mesh, a SOLID95 element was used. A mesh convergence study was completed to ensure an adequate mesh for the model dimensions and the applied load. The finite element analysis was solved using ANSYS®.

The finite element analysis yielded similar stress pattern results to those seen in testing. The figure below, Figure 5.7, displays the bottom-view of the glass plate specimen with a load applied to the center of the screen.

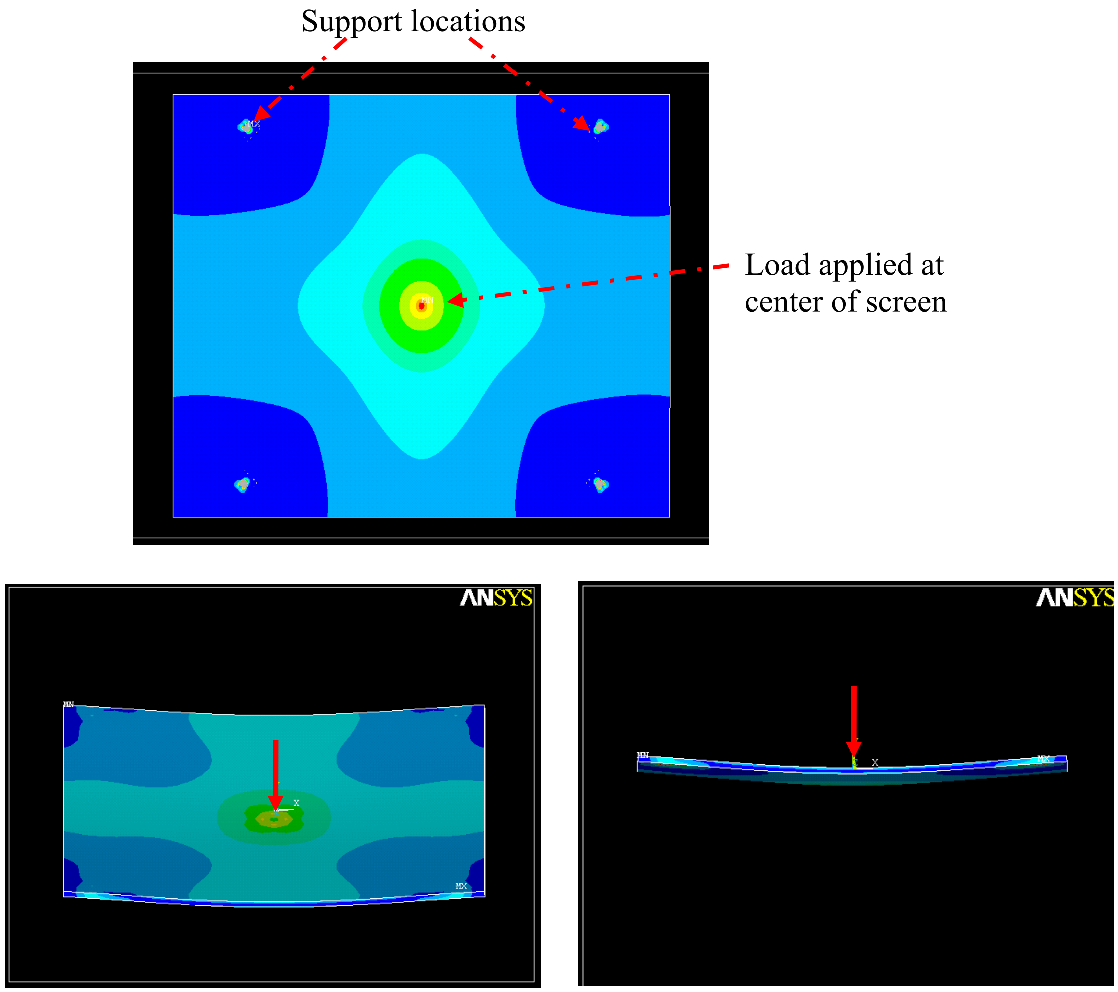


Figure 5.7 Finite Element Analysis – Top glass layer, solid red arrow identifies loading location

The corner supports are identified with arrows along with the location of the applied load. Comparing Figure 5.7 to the photographs of the actual broken specimens in Figure 5.5 and Figure 5.6, the concentrated stress in the center of the screen with cracks radiating outward would be the expected failure mechanism from the finite element analysis.

The critical stresses determined from the FEA of both the LCD assembly and top glass layer specimens are shown below in Figure 5.8 and in Table A.1 and Table A.2 of APPENDIX A.

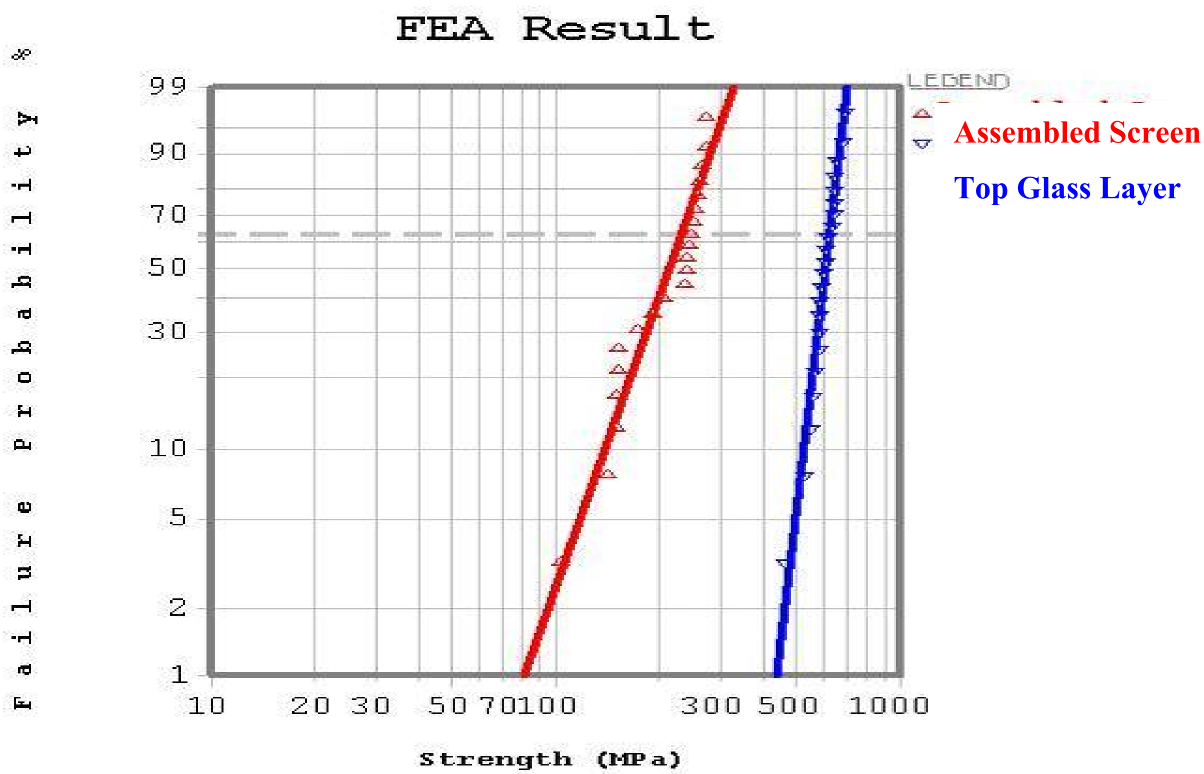


Figure 5.8 Strength results for assembled LCD and glass layer

From the two sets of data it is apparent that the critical stress values determined for the LCD assembly are less than those determined for the glass layer. The method of disassembly accounts for the dramatic difference in strength between the two structures. The LCD assemblies had a protective polymer coating that was removed before testing. The razor blade used in the removal technique most likely created cracks and abrasions on the surface of the glass causing lower strength values, while the glass layers were disassembled with the use of acid, leaving no surface blemishes.

Mathematically calculating the critical stress values at the center of the structures from the applied loads is extremely difficult. Instead, to validate the FEA, the critical stress values were compared to previous research where similar structures and loading conditions were applied. The maximum principal stress as determined from the FE model can be related to the breaking load and stressed area for both the screen assembly and the top glass layer, seen in Table 5.3

Table 5.3 Relationship between max principal stress and breaking load

Specimen	Relationship, σ = P/A
Screen Assembly	σ = 2.7*(breaking load / stressed area)
Top Glass Layer	σ = 30.2*(breaking load / stressed area)

In the cases of the assembly and the glass layer, the stresses area is the supported area during the mechanical bend tests, 31.75 x 31.75 mm, breaking load is in Newtons. An order of magnitude difference in the maximum principal stress is observed between the assembly and top glass layer specimens.

5.4 Critical Stress Comparison – FEA vs. Published Data

In a study supported by Corning Display Technologies [6], the mechanical reliability of the glass panel (top glass layer) was studied along with its' direct impact on the LCD module reliability, under static loading. The LCD glass was supported by a ring, instead of on four points and two different glass thicknesses were tested. Even though the Corning test fixture was different, the edges of the glass were freely supported allowing for a range of motion during bend testing. According to Corning the thickness of the glass does not affect the strength, so their strength values should compare to the strength calculated from the FEA without the concern of thickness differences. In the

Corning study both the biaxial strength of "as-received" glass and "abraded" glass were measured.

The critical stress values from the FEA model were compared to the critical stresses seen in the study by Corning Display Technologies [6]. The top glass layer data was compared to that of the "as-received" glass data from Corning and the LCD assembly data was compared to the abraded glass data from Corning.

The top glass (or cover glass) was plotted using a Weibull distribution. The comparison of the data with Corning data can be seen in Figure 5.9.

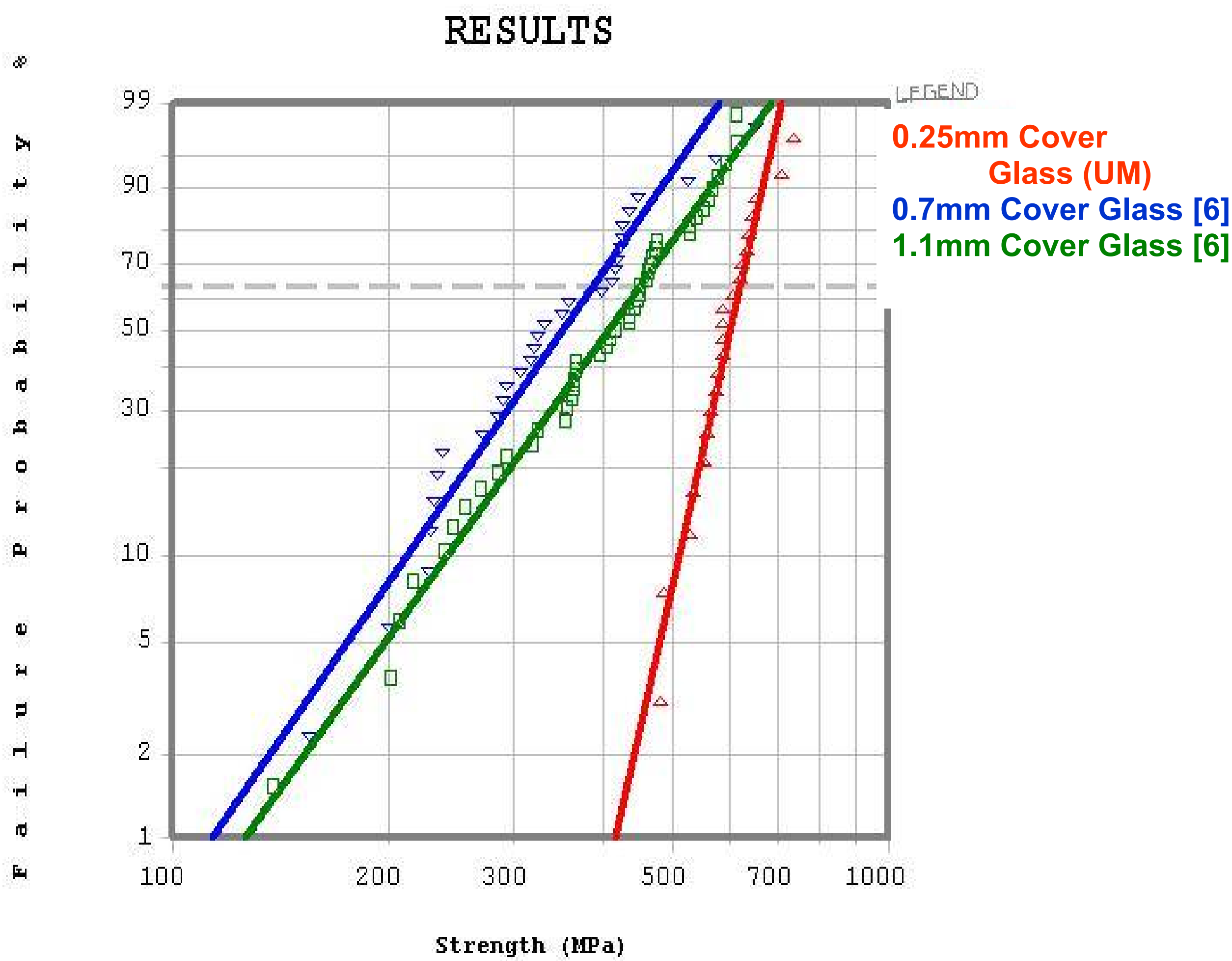


Figure 5.9 Corning Strength Analysis – Cover Glass [6]

The experimental data exhibits a higher characteristic failure stress and steeper Weibull slope, 618MPa and 11, respectively. The characteristic life for the 0.7mm and 1.1mm Corning data was 385MPa and 450MPa, respectively. The difference between the experimental data and the Corning data Weibull slopes is not surprising and due to the difference in “stressed” area. The experimental data has a much steeper slope than the Corning data because the experimental results stressed a relatively small area compared to the Corning experiment. The Corning data tested a larger area of glass compared to the experimental data, making the probability of finding a surface flaw more likely.

The experimental data from the LCD assemblies was compared to the abraded glass from Corning, to determine if the LCD assemblies displayed similar strength to that of glass. The comparison was made to the abraded glass because of the disassembly process used on the LCDs and the increased probability of having surface flaws. These results were also plotted using a Weibull distribution seen in Figure 5.10

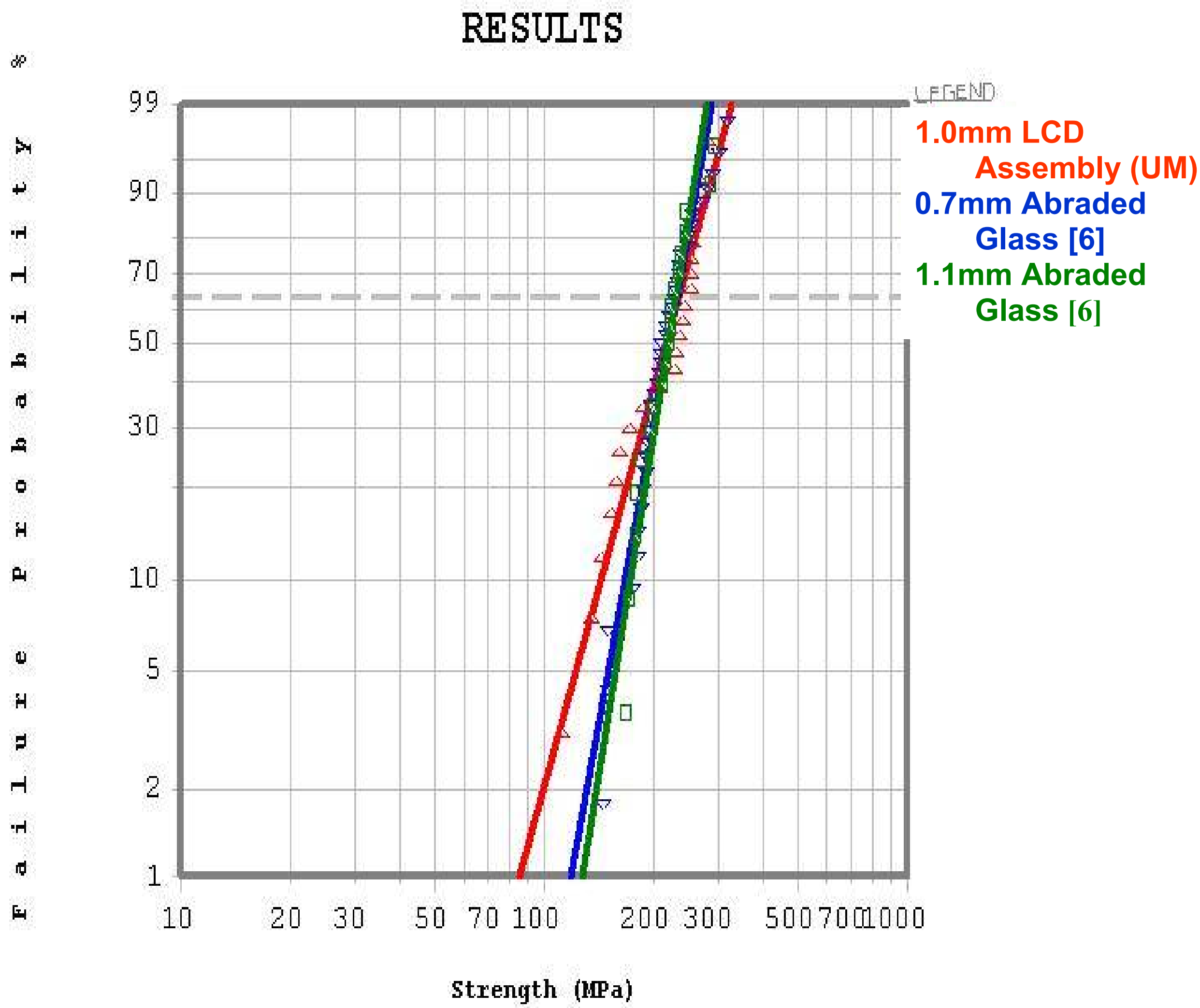


Figure 5.10 Corning Strength Analysis – Abraded Glass [6]

The assembly – abraded glass comparison yielded much closer results then the top glass comparison. The characteristic failure stresses are almost identical between all three data sets, ranging from 230 to 234 MPa. The difference is seen in the Weibull slope. The LCD assemblies have a slope of 4.5 while the 0.7mm and 1.1mm abraded glass have slopes of 6.8 and 6.6, respectively. The difference in slope is due to the disassembly technique used on the LCD assembly to remove the protective coating. The removal technique results in a high probability of larger, deeper surface flaws then those seen in the abraded glass, resulting in a larger range of failure stresses. The controlled abrading technique used by Corning involved dropping characterized sand from a specific height onto the surface of the glass [6]. Whereas the razor blade technique was not as controlled and can result in varied surface flaws.

5.5 Conclusion

From the experiments presented in this chapter it is possible to determine the strength of an LCD assembly or glass panel using a mechanical bend test due to the dependency of surface flaws on the glass strength. The thickness of the glass panel or the LCD assembly does not appear to interact with the strength of the material. Even though many different factors can affect glass strength, surface flaws appear to be one of the greatest influencers.

The comparison between the experimental data and the data collected from the Corning study yielded very useful results. When the strength results of the LCD assemblies were compared to the Corning abraded glass data a useful relationship was found. The result of all three studies, seen in Figure 5.10 show almost identical failure stresses. The slight variations, especially in the slope difference, are due to varying test size and tested area size. From this study, the strength of a LCD assembly specimen can be estimated from the strength of an abraded LCD glass layer.

6.0 CONCLUSION

The purpose of this LCD study was to determine techniques and information that can be used to help assess life in LCDs. Three different aspects of LCDs were studied, measurability of color intensity, the effects of environmental conditions, and assessing the strength of the LCD assembly. All three aspects were successful, but can still benefit from more research.

Since screen degradation, in the form of a contrast change, is a common failure seen in LCDs exposed to humidity, a method of measuring the change had to be determined. Contrast changes can be a result of a resistance change, but since the LCD modules had to be kept intact, monitoring resistance was not an option. Another method had to be determined. The methodology developed in this study used digital photography to characterize screen contrast.

Three different color intensity analyses were performed on the LCD test specimens to determine if a change in color intensity or contrast was measurable. The intensity analyses included:

- Variation between photographs of the same pixel of a single LCD screen
- Variation between different LC screens when viewing a single pixel location
- Variation in pixels within a single photograph of a single LC screen

With the use of digital photography and Adobe® Photoshop® the contrast of the LCD pixels was found to be measurable. The variations found in this study were small but quantifiable.

From the results of this analysis, it was determined that the contrast can be measured using the characterization described. The methodology developed in this thesis can be used to determine if a screen has had a decrease in contrast.

The second objective of this thesis was to determine the effects of humidity on LCD modules for the purposes of using the information for life assessing. Previous research has shown high humidity environments can potentially cause multiple different failures. Characterizing the effects of humidity of LCD modules will help provide information used to assess the life of LCDs.

Functional LCD modules were subjected to constant high temperature humidity cycling, resulting in maximum moisture absorption while minimizing cycle time. Periodically, the LCDs were monitored for both pixel failures and contrast degradation. Prior research suggests that contrast degradation should be a common failure associated with humidity exposure.

From the conducted experiment no contrast degradation was observed. Instead, the observed failure was degradation of the polarizing film. Some test LCDs experienced polarization failures after exposure to as little as five humidity cycles. The test specimens either displayed failures immediately or displayed no failures. 30% of the screens displayed polarization delamination after only five humidity cycles; overall only 38% of the test screens displayed any polarizer delamination. Even though previous research suggests a contrast change would be the expected failure mode, the polarizing film delaminated from the glass well before any contrast changes were observed. Even though the LCDs were functioning as expected, the polarizing film was no longer appropriately polarizing the light passing through the screen. The result was nonviewable functional pixels. Poor adhesion of the polarizing film to the glass would allow moisture ingress between the two layers and could cause the delamination.

The adhesion failures could be a result of manufacturing, contamination, or material selection. Further investigations should focus on the root cause of the polarizing failures and then begin assessing the effects of humidity on the contrast of an LCD. Once the polarizing film has been addressed, then proving life assessment techniques of the LCD can be concentrated on.

The final objective of this thesis was to assess the mechanical strength of the LCDs to prove information that could be to assess the overall life of the LCD. Mechanical bend test were performed to determine the biaxial strength of the LCD specimens, both the top glass and the entire LCD assembly. Proving a relationship between the glass layer and the LCD would be helpful towards developing techniques to assess life.

Mechanical bend tests were performed on the top glass layer and the LCD assembly, keeping the setup and supported area the same with all tests. Various loading rates were applied and the results analyzed. From the experiment loading rate was found to have a negligible effect on the strength of the glass layer and only a slight variation was seen on the LCD assemblies. The top glass exhibited a strength of at least twice that of the LCD assembly. No comparison was found between the two specimen types but when the experimental results were compared to those results in literature a relationship was identified.

A study supported Corning tested the strength of LCD glass, both "as-received" and abraded. The abraded glass results were almost identical to the LCD assembly results, as seen in Figure 5.10.

Further testing is needed to determine the extent of the relationship. Currently the strength of a 1.0mm thick LCD assembly is equivalent to the strength of 1.1mm or 0.7mm LCD glass. Further investigations should analysis different thicknesses of both LCDs and glass to determine the full range of the relationship. The strength comparison between abraded glass and LCD assemblies could prove to be very helpful in developing techniques to assess the life of an LCD.

The three objectives of this thesis were analyzed. A methodology was developed to determine if a color intensity or contrast change was observable and measurable. The result, yes, a contrast change is measurable with the technique proved in this paper. The effects of humidity on a LCD were analyzed. Even though the generally common failure (decrease in contrast) was never observed another less common failure mode was identified. And, finally the biaxial strength of an LCD was studied and a relationship between the top glass and the assembly structure was recognized.

Further research is needed to determine the effects of humidity exposure and to develop the relationship between the top glass and the LCD assembly. The knowledge base developed in this thesis does provide some information and techniques that could prove to be very helpful in assessing the life of a LCD.

APPENDIX A
STRENGTH EXPERIMENT RESULTS

Table A.1 Strength of LCD Assembly Samples

LCD Assembly Strength Results								
Screen #	Loading Rate (mm/minute)	Breaking Force (N)	Critical Stress (MPa)		Screen #	Loading Rate (mm/minute)	Breaking Force (N)	Critical Stress (MPa)
1	50	55.70	152.63		14	5	88.71	242.83
2	50	66.58	182.27		15	5	76.84	210.34
3	50	102.82	281.47		16	5	85.36	233.66
4	50	50.46	138.13		17	5	62.13	170.09
5	50	102.19	279.75		7	1	55.34	151.48
6	50	91.54	250.60		8	1	90.23	247.00
9	50	91.90	251.57		18	0.5	56.80	155.48
10	50	85.37	233.70		19	0.5	52.68	144.21
11	50	96.12	263.13		20	0.5	83.95	229.80
12	50	94.86	259.68		21	0.5	40.44	110.70
13	50	91.54	250.59					

Table A.2 Strength of Glass Layer Samples

Glass Strength Results								
Screen #	Loading Rate (mm/minute)	Breaking Force (N)	Critical Stress (MPa)		Screen #	Loading Rate (mm/minute)	Breaking Force (N)	Critical Stress (MPa)
5	5	21.682	650.5		9	50	18.762	562.9
10	5	18.670	560.1		13	50	21.400	642.0
11	5	20.830	634.9		14	50	22.241	667.2
12	5	20.120	603.6		15	50	20.436	613.1
1	50	19.176	575.3		16	50	18.897	566.9
2	50	21.174	635.2		17	50	22.546	676.4
3	50	18.561	556.8		18	50	20.366	611.0
4	50	18.285	548.6		19	50	15.921	477.6
6	50	20.447	613.4		20	50	20.783	623.5
7	50	20.327	609.8		21	50	20.213	606.4
8	50	20.341	610.2		22	50	19.629	588.9

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