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Photometric Measurement of Aydin Controls 8980 CRTs

John Boreczky
Paul Green

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16. Abstract

This report describes measurements taken for three Aydin Controls 19-inch color CRTs. Measurements of uniformity (center and four corners for 6 colors), color (32 combinations in the center), and reflectance (at four angles) were made using a Photo Research PR-1980A photometer, with each measurement taken on two of the three units.

The display units were reasonably uniform although corner luminances were always below those measured in the center, with worst case values being 76% and 65% for the two displays. Colors were fairly consistent between displays, and there were no differences due to location (other than the luminance differences just mentioned). The settings for white had a slight bluish tint to them. Reflectance, was 98% for the polished glass face vs. 33% for the non-glare coated display (both measured at 0 degrees incidence). These measurements suggest the displays examined are adequate for control room use.

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TABLE OF CONTENTS

INTRODUCTION

Dow Chemical is developing a new CRT-based system for chemical process control (Mod 6) to replace the existing system (the "cans," Mod 5). The system is to be fielded on a world-wide basis.

Considerable effort is being expended to make the user interface to the system (the controls and displays the operators interact with) easy to use. By improving operator control over chemical processes, the operators will be better able to make use of the available resources, input materials, fuel, etc., and to maximize the quality and quantity of the output, and hence plant profitability. Further, when alarms occur, the operators will be able to identify the cause and correct it more quickly.

A part of this effort involves verifying that the displays Dow will be producing meet accepted national and international human factors engineering standards (e.g., Human Factors Society, 1988). The research reported here describes several tests conducted for that purpose.

Brief Introduction to Color Measurement

This section is not intended to explain in detail the science of color measurement but rather to provide a rationale for the test plan. Readers interested in further details of color measurement and color discrimination should consult Billmeyer and Saltzman (1981) or Silverstein and Merrifield (1985). The $\Delta E(Yu'v')$ formula is from the ANSI standard (Human Factors Society, 1988), while discussion of gamma correction is from Silverstein and Merrifield.

The color of a light source is not defined in terms of the physical properties of that light, but rather on the subjective perception of a human observer. Therefore, most color measurement systems quantitatively define the response of the average human eye to a light source. For this reason it is important to remember that although measurements can be made to arbitrary levels of precision, values beyond 1 or 2 decimal places usually have no practical significance.

The most common way to describe the light produced by a CRT is in terms of luminance, expressed in candela/meter^2 (cd/m^2), and chromaticity (color), expressed in the x and y coordinates of the 1931 Commission Internationale de l'Eclairage (CIE) chromaticity system.

The luminance of a light source is determined by measuring the amount of light that passes through a filter that approximates the response of the human eye to light at various wavelengths. There are two such response characteristics, called "photopic" and "scotopic." The former applies to daytime viewing conditions, the latter to nighttime. The CIE defined three ideal colored lights (primaries) which, when combined in various proportions, can match any color of light (as determined by a human observer). The CIE chromaticity, a unique color identifier, is determined by measuring the proportions (tristimulus values) of the primaries needed to reproduce a given light source. The three ideal primaries, $\bar{x}$, $\bar{y}$, $\bar{z}$, are intended to correspond to red, green, and blue, respectively. In order to simplify calculations, the tristimulus value Y is defined to be equal to the luminance, and therefore can be measured with a photopic filter. The tristimulus values X and Z are measured with other filters. The CIE chromaticity coordinates of the light source are easily computed from X, Y, and Z

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = \frac{Z}{X + Y + Z}$$

Normally only x and y are specified since z = 1-(x+y). The appearance of a color (chromaticity and luminance) is fully specified by the values of x, y, and Y. Colors are often plotted on chromaticity diagrams using the x and y coordinates.

Although the CIE x,y coordinates can be used to tell whether or not two colors appear the same, they cannot be used to measure the discriminability of colors, since it is easier to perceive color differences in some areas of the CIE x,y chromaticity diagram than others. One attempt to correct this problem is the 1976 CIE u',v' Uniform-Chromaticity-Scale (UCS) diagram. The u' and v' coordinates are computed from the CIE x,y coordinates as follows:

$$u' = \frac{4x}{-2x + 12y + 3} \qquad v' = \frac{9y}{-2x + 12y + 3}$$

The advantage of this system is that pairs of colors that are equidistant in u',v' space are equally distinguishable.

There are two formulas commonly used to estimate the discriminability of color pairs based on the CIE UCS diagram. The ΔE(L*u*v*) formula is used to estimate absolute color discriminability. The ΔE(Yu'v') formula is used to assess the legibility of colored characters on a colored background, which is more suitable for this work. The ΔE(Yu'v') formula is as follows:

$$\Delta E \text{ units (CIE Yu'v')} = \sqrt{(155\Delta Y/Y_M)^2 + (367\Delta u')^2 + (167\Delta v')^2}$$

where:
- Y_M = maximum luminance of text or background in cd/m^2
- ΔY = difference in luminance between text and background
- $\Delta u'$ = difference between u' coordinates of text and background
- $\Delta v'$ = difference between v' coordinates of text and background

Unfortunately, CRT colors are not selected by CIE coordinates but by RGB values. The RGB values for a given display pixel determine the intensity of the electron guns (drive voltage) which stimulate the red, green, and blue phosphors for that pixel. The first problem with this arrangement is that the same drive voltage produces different luminances for the three primary colors. At a given drive voltage, green is brighter than red, which is brighter than blue. The second problem is that the drive voltage vs. luminance curves (plotted on a log-log scale) have different slopes for the three primaries. Thus a white pixel will begin to look bluish as the drive voltages are proportionally reduced. Gamma correction is the technique of using photometric and electrical measurements to transform the drive voltage/luminance equations into linear functions for a specific display. Using gamma correction, it is possible to convert the RGB drive voltages into CIE x,y coordinates. This technique is beyond the scope of this study. Readers interested in further details should consult the references listed at the beginning of this section.

TEST PLAN

Test Equipment and Materials

The displays measured were three Aydin Controls model 8980 19-inch diagonal color CRTs, serial numbers ENG-2053, 2055 and 2058, unit number ID 8865. Displays 2053 and 2058 had a standard polished glass face. Display 2055 had a non-glare coating. All displays were mounted on adjustable stands. These displays were connected to an IBM AT with a Quantum Data video generator board, model ACF-400. Screen images were generated by the Fox program supplied with the video generator. A crosshair image was used for aiming the photometer at the center of the display, whereas all measurements were taken with the display filled with a solid color.

Display luminance was measured using a Photo Research model 1980A digital spot photometer (Photo Research, 1984), which has an adjustable field of view. The photometer was mounted on a tripod. For collecting the reference reflectance levels a 98% reflecting surface provided with the photometer was used.

Readings from the photometer were keyed into an Excel spreadsheet (MicroSoft, 1986) running on a Macintosh SE computer. Included in the spreadsheet were functions to compute CIE x,y coordinates from the various photometer readings.

For measurements of reflectance, a Kodak model 650H 35mm slide projector was used as the light source. An aluminum plate with a small hole was inserted into the slide mechanism to provide a narrow beam of light.

Test Activities and Their Sequence

The displays examined were in the display evaluation room (#180) of Building 424 used by the Global Process Control Group at the Dow facility in Midland, MI. The windows in the doors to the room, the only sources of external illumination, were covered with cardboard. Measurements were taken with the room lights out. The only illumination remaining was light from the test display, and stray light from the controlling AT, the Mac used to record the data, and from the photometer display. All sources were aimed away from the photometer to minimize the extent to which stray light would influence the readings. The contrast and brightness of the displays were set to a comfortable viewing level by Dow personnel with the room lighting on. Each test display was degaussed after being turned on and also before being measured.

Each photometer measurement is made by taking a reading through each of 4 separate filters. The photopic filter is used to measure the luminance in cd/m^2 and also provides the green tristimulus value Y, while the blue filter provides the blue tristimulus value Z. The red filter provides the larger peak of the red tristimulus curve, and the x_b filter provides the smaller peak of the red tristimulus curve, which are added together to compute the red tristimulus value X.

Since the filters used to make the photometer measurements do not provide a perfect representation of the CIE tristimulus values for all luminance and illumination conditions, it is necessary to calculate calibration constants using a source of known

CIE x,y coordinates under similar conditions. An IBM Monochrome Display was used as the known source. The P39 phosphor used in this display has CIE coordinates of x = .223 and y = .698 (Cakir, Hart, and Stewart, 1980). The calibration constants were determined to be C1 = 1.00002 and C2 = 1.325326. Thus, the formulas used to compute the CIE x,y coordinates from the photometer readings are as follows:

$$x = \frac{(X+X_b)*C1}{(X+X_b)*C1 + Y + Z*C2} \qquad y = \frac{Y}{(X+X_b)*C1 + Y + Z*C2}$$

where:

X is the photometer reading taken through the red filter
X_b is the photometer reading taken through the x_b filter
Y is the photometer reading taken through the photopic filter
Z is the photometer reading taken through the blue filter
C1 = 1.00002
C2 = 1.325326

Six sets of measurements were taken, two concerning screen uniformity, two concerning colors, and two concerning reflectance. (See Table 1.) The purpose of the uniformity tests was to determine if the corners and center of the display had similar luminance and chromaticity values, since decisions about contrast adequacy could depend upon where on the screen the information was presented. The purpose of the colors test was to determine the CIE coordinates for the colors currently selected for the user interface. The reflectance data will be used to assess the effect of glare and provide a basis for examining at a later time the effects of alternative control room illumination levels on display legibility.

Table 1. Description of tests conducted on various displays.

Test	Display
Uniformity 1	ENG 2053 - Display 1
Colors 1	ENG 2053 - Display 1
Reflectance 1	ENG 2058 - Display 2
Uniformity 2	ENG 2058 - Display 2
Colors 2	ENG 2058 - Display 2
Reflectance 2	ENG 2055 - Display 3

In the uniformity tests measurements were taken with the field of view set at 20 minutes of arc with the photometer 54 inches from the display. (Thus the on screen size of the target circle was .31 inches.) Measurements were taken in the center of the screen and the four corners, about 1 inch from the screen edge along the diagonal in the following order--center, upper left, upper right, lower right, lower left. Six colors were examined--dark grey (grey #4, pen 104), medium grey (grey #8, pen 108), light grey (grey #12, pen 112), pure red (pen 1), pure green (pen 2), and pure blue (pen 4). These colors were chosen to determine if the output of one or more of the electron guns fell off in the corners of the display.

The initial set of measurements was taken after the display had warmed up for 30 minutes. After an additional 15 minutes, the first few measurements were re-taken (center location) and it was found the values had increased by 50%. A new measurement was taken every minute until the reading began to stabilize about 20 minutes later. To avoid warmup problems, all of the displays to be used that day were then turned on and allowed to warm up. Because the other displays were not used until several hours later, warmup time for them should have been adequate and changes due to warmup were not checked.

In the color tests, the photometer was aimed at the center of the display with a 20 minutes of arc field of view from a distance of 54 inches. Colors measured include pens 100-115 (colors 1-16, black through white), 116 (gold), 117 (dark green), 118 (green), 119 (yellow), 120 (orange), 121 (red), 122 (magenta), 123 (violet), 124 (lavender), 125 (pink), 126 (light pink), 127 (light blue), 128 (blue), 129 (brown), 130 (cyan), and 131 (dark blue). Measurements were only taken in the center of the display and CIE coordinates (computed by the spreadsheet) were checked to make sure the color shown and x, y values agreed. The RGB gun values corresponding to each pen number are shown in Appendix A.

For the reflectance measurements, the photometer was placed 47-1/2 inches from the display with the field of view set at 6 minutes of arc and a number 4 neutral density filter was used to keep the values from going off scale. This cuts the amount of light reaching the photometer by a factor of 10,000. Measurements were taken at zero degrees (reference) and with the photometer 15°, 30°, and 45° to the right of the normal to the screen center. The projector was placed 32-1/2 inches from the display. As the display was rotated, the projector was moved so that the incident light was always perpendicular to the center of the display. (See Olson and Bender, 1986 for related research.)

RESULTS AND DISCUSSION

The raw data appears in Appendices B, C, and D. The Photopic Filter value for each measurement is the luminance. All values are in candelas per square meter. There were no missing data. In several cases (described earlier) measurements were repeated to get rid of misleading information resulting from warmup lags. Those original data were discarded.

The long time period needed for display warmup was one of the more dramatic surprises of the measurement procedure. More than an hour elapsed from the time Display 1 was turned on until the readings stabilized enough so that uniformity measurements could be taken. There was even a substantial (10-25%) difference between the uniformity measurements and the color measurements taken an hour later. Since the displays have less than half of their maximum luminance when they are first turned on, it is necessary to let them warm up for 2 hours before use if they are allowed to cool off.

The Excel spreadsheet running on the Macintosh computer was very useful for providing real-time quality control of the data. The built in x,y computations were quite helpful in spotting erroneous entries (either due to misreading the display or typos). Erroneous entries appeared either as values that were not physically achievable (not in the CIE space) or mismatches between color appearance and the associated color name at coordinates identified (for example, a pen color that looked green but whose coordinates corresponded to pink). To some extent, these on-the-spot calculations also helped spot the warmup shift and the absence of the color uniformity variations.

Uniformity

The uniformity measurements uncovered substantial differences in the luminances of various portions of the screens. Such variations are common in contemporary displays. (See Linzmayer and the MacUser Labs staff, 1989; Mello, 1989; Eckhardt, 1990a,b.) The variations found are not obvious at first glance to the eye though they were easily measured using the digital photometer. The uniformity data appears in Appendix B.

The uniformity data for display 1 (ENG 2053) show that the luminance of the corners, but especially the lower left corner is consistently less (76% to 95%) than the center of the display. This occurs because the measurements are taken perpendicular to the display but the path of the electron beam is linear between the electron gun and each point on the tube surface (hence, measurements of the corner are at an angle to the light path). The effect is more pronounced at the lower luminance grey levels. The pure color data indicates that the three primary guns have similar uniformity patterns. (This data also highlights the need for gamma correction in order to compare the output of the three guns.) The CIE x,y coordinates of these colors are very uniform, which means that although colors may vary in luminance in different areas of the display, the chromaticity does not change.

The upper left corner of display 2 (ENG 2058) is the dimmest, providing 65% to 92% of the luminance of the center of the display. Again, the effect is greater at lower luminances. However, the blue gun produces the least luminance in the lower right corner, where the red and green guns have their highest values. This produces a larger variation in the CIE x,y coordinates of the gray levels than on display 1. There is also more variation in CIE coordinates within each gun. This means that not only will colors vary in luminance on this display, but that colors will appear more yellow in the lower right corner of the display.

Color

The color data for displays 1 and 2 appear in Appendix C. There is very little difference in color between the two displays, although the grays of display 2 are slightly more blue at higher luminance levels. Differences in color are particularly small when one of the colors was above 35 cd/m2, which is recommended by the ANIS standard. On both displays, white (and the grays) has a light blue tint. This is normal for most color displays (Eckhardt, 1990a), and is due to the color of the phosphor used.

With regard to design requirements, the ANSI Standard (Human Factors Society, 1988) requires that color combinations have a ΔE of 100 or more, a requirement met by numerous color combinations here.

Reflectance

The reflectance data is straightforward. (See Appendix D.) Display 2, with a polished glass face, had a sharp drop in luminous reflectance as the observer moves off-center, with the straight-on luminance being even greater than that of the 98% reflecting reference surface. These properties would produce a large amount of glare, as the reflections of light sources in the room would wash out the output of the display. There was some chromaticity difference between the angular measurements, but not a great deal.

Display 3, with a non-glare coating, showed less variation in luminous reflectance due to angle than display 2. This is accomplished by reducing the reflectance from all angles substantially. Even the 0° measurement is less than 33% as luminous as the reference surface. This should be sufficient to keep glare to an acceptable level under normal lighting conditions.

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APPENDIX A - RGB-PEN COMBINATIONS

Pen #	Color	Red	Green	Blue
0	black	0	0	0
1	red gun	255	0	0
2	green gun	0	255	0
3	yellow	255	255	0
4	blue gun	0	0	255
5	magenta	255	0	255
6	cyan	0	255	255
7	white	255	255	255
100	black	0	0	0
101	gray 1	17	17	17
102	gray 2	34	34	34
103	gray 3	51	51	51
104	gray 4	68	68	68
105	gray 5	85	85	85
106	gray 6	102	102	102
107	gray 7	119	119	119
108	gray 8	136	136	136
109	gray 9	153	153	153
110	gray 10	170	170	170
111	gray 11	187	187	187
112	gray 12	204	204	204
113	gray 13	221	221	221
114	gray 14	238	238	238
115	white	255	255	255
116	gold	204	153	0
117	dark green	0	119	0
118	green	0	170	0
119	yellow	255	255	0
120	orange	255	102	51
121	red	238	0	0
122	magenta	255	0	102
123	violet	102	0	102
124	lavender	255	51	255
125	pink	255	153	255
126	light pink	255	204	255
127	light blue	204	255	255
128	blue	0	204	255
129	brown	68	0	0
130	cyan	0	153	204
131	dark blue	0	51	255

APPENDIX B - RAW UNIFORMITY DATA

Uniformity Data Set 1

Uniformity	CON1=	1.00002	CON2=	1.32533	
Display 1	Center	Top Left	Top Right	Low Right	Low Left
Dark Gray	GREY#4,No Lights,pen 104,20 mins arc, corners 1 inch in at 54 inches, brightness on max				
Photopic Filter	3.930	3.850	3.840	4.040	2.980
Red Filter	2.710	2.580	2.650	2.760	2.010
Blue Filter	5.300	5.250	4.980	5.230	4.020
Xb Filter	0.910	0.902	0.851	0.890	0.690
L	3.930	3.850	3.840	4.040	2.980
x	0.248	0.244	0.251	0.250	0.245
y	0.270	0.269	0.275	0.276	0.271
Medium Gray	grey#8, pen 108,20 mins of arc, etc				
Photopic Filter	23.100	19.900	21.300	22.000	17.900
Red Filter	16.100	13.550	14.830	15.200	12.150
Blue Filter	30.000	25.900	27.300	28.000	23.300
Xb Filter	5.120	4.400	4.630	4.780	3.950
L	23.100	19.900	21.300	22.000	17.900
x	0.252	0.249	0.253	0.253	0.248
y	0.275	0.276	0.277	0.278	0.276
Light Gray	grey #12,pen112				
Photopic Filter	48.000	45.500	50.400	49.600	45.500
Red Filter	36.000	32.100	37.700	36.900	32.300
Blue Filter	61.400	59.100	63.600	63.100	58.000
Xb Filter	11.050	10.420	11.500	11.430	10.170
L	48.000	45.500	50.400	49.600	45.500
x	0.267	0.256	0.268	0.266	0.258
y	0.272	0.274	0.274	0.273	0.276
Pure Red					
Photopic Filter	16.670	14.670	16.100	15.500	13.730
Red Filter	29.100	25.600	28.000	27.000	23.900
Blue Filter	1.487	1.343	1.389	1.416	1.288
Xb Filter	0.212	0.191	0.197	0.202	0.185
L	16.670	14.670	16.100	15.500	13.730
x	0.611	0.611	0.611	0.610	0.609
y	0.348	0.347	0.349	0.348	0.347
Pure Green					
Photopic Filter	57.500	52.100	53.400	53.000	49.800
Red Filter	32.300	29.400	30.400	30.100	27.900
Blue Filter	10.500	9.800	9.890	9.800	9.280
Xb Filter	0.970	0.921	0.914	0.901	0.875
L	57.500	52.100	53.400	53.000	49.800
x	0.318	0.318	0.320	0.320	0.317
y	0.549	0.546	0.546	0.546	0.548

Pure Blue

Photopic Filter	9.470	8.760	8.910	8.940	8.020
Red Filter	1.380	1.251	1.268	1.260	1.190
Blue Filter	88.300	82.500	83.700	83.600	76.200
Xb Filter	18.600	17.100	17.400	17.400	15.500
L	9.470	8.760	8.910	8.940	8.020
x	0.136	0.134	0.135	0.135	0.133
y	0.065	0.064	0.064	0.065	0.064

Uniformity Data Set 2

Uniformity	CON1=	1.00002	CON2=	1.32533	
Display 2	Center	Top Left	Top Right	Low Right	Low Left
Dark Gray,pen 104					
Photopic Filter	4.260	2.750	3.960	4.440	3.390
Red Filter	3.240	2.040	3.000	3.400	2.490
Blue Filter	5.660	3.500	4.920	5.350	4.560
Xb Filter	0.975	0.603	0.865	0.911	0.780
L	4.260	2.750	3.960	4.440	3.390
x	0.264	0.263	0.269	0.272	0.257
y	0.267	0.274	0.276	0.280	0.267
Medium Gray,pen 108					
Photopic Filter	20.600	15.600	20.600	20.600	16.700
Red Filter	15.200	11.250	15.100	15.400	12.020
Blue Filter	30.700	22.000	29.400	28.000	24.400
Xb Filter	5.260	3.750	5.030	4.780	4.160
L	20.600	15.600	20.600	20.600	16.700
x	0.250	0.251	0.253	0.259	0.248
y	0.252	0.261	0.258	0.264	0.256
Light Gray,pen 112					
Photopic Filter	48.800	44.000	49.200	45.700	41.400
Red Filter	37.400	32.200	37.300	34.300	30.100
Blue Filter	69.500	60.200	68.600	62.700	58.800
Xb Filter	12.910	10.500	12.730	11.210	10.270
L	48.800	44.000	49.200	45.700	41.400
x	0.263	0.256	0.263	0.261	0.253
y	0.255	0.264	0.259	0.262	0.259
Pure Red,pen 1					
Photopic Filter	16.500	11.400	16.110	16.900	12.950
Red Filter	28.100	19.530	28.100	29.400	22.500
Blue Filter	1.348	1.445	1.606	1.487	1.416
Xb Filter	0.190	0.220	0.237	0.210	0.210
L	16.500	11.400	16.110	16.900	12.950
x	0.607	0.597	0.608	0.611	0.605
y	0.354	0.345	0.346	0.349	0.345
Pure Green,pen 2					
Photopic Filter	47.300	38.700	48.900	50.000	43.300
Red Filter	26.000	20.000	27.200	27.800	22.900
Blue Filter	8.460	6.990	8.610	9.210	7.490
Xb Filter	0.788	0.695	0.778	0.879	0.705
L	47.300	38.700	48.900	50.000	43.300
x	0.314	0.301	0.317	0.316	0.307
y	0.555	0.564	0.554	0.550	0.564

Pure Blue,pen 4

Photopic Filter	9.400	8.670	9.330	8.320	8.910
Red Filter	1.346	1.396	1.389	1.288	1.296
Blue Filter	86.100	80.000	85.600	79.000	83.300
Xb Filter	18.000	16.300	17.800	16.100	17.200
L	9.400	8.670	9.330	8.320	8.910
x	0.135	0.134	0.135	0.133	0.134
y	0.066	0.065	0.066	0.064	0.065

APPENDIX C - RAW COLOR DATA

Color Data Set 1

Colors CON1=1.00002
Display 1 CON2=1.32533
6

Color1,pen 100,black

Photopic Filter	0.0134
Red Filter	0.0100
Blue Filter	0.0290
Xb Filter	0.0051
L	0.0134
x	0.0000
y	1.0000

Color2,pen 101

Photopic Filter	0.1910
Red Filter	0.1330
Blue Filter	0.3280
Xb Filter	0.0575
L	0.1910
x	0.0000
y	1.0000

Color3,pen 102

Photopic Filter	0.9320
Red Filter	0.6430
Blue Filter	1.4100
Xb Filter	0.2440
L	0.9320
x	0.0000
y	1.0000

Color4

Photopic Filter	2.4700
Red Filter	1.7000
Blue Filter	3.5300
Xb Filter	0.6060
L	2.4700
x	0.0000
y	1.0000

Color5,pen 104

Photopic Filter	4.9500
Red Filter	3.4400
Blue Filter	6.8000
Xb Filter	1.1600
L	4.9500
x	0.0000
y	1.0000

Color6pen 105

Photopic Filter	8.3300
Red Filter	5.7900
Blue Filter	11.2800
Xb Filter	1.9400
L	8.3300
x	0.2493
y	0.2686

Color7,pen 106

Photopic Filter	12.7300
Red Filter	8.8700
Blue Filter	19.9900
Xb Filter	2.9100
L	12.7300
x	0.2310
y	0.2496

Color8,pen 107

Photopic Filter	18.0600
Red Filter	12.5900
Blue Filter	23.9000
Xb Filter	4.0700
L	18.0600
x	0.2509
y	0.2720

Color9,pen 108

Photopic Filter	24.5000
Red Filter	17.2000
Blue Filter	31.9000
Xb Filter	5.4300
L	24.5000
x	0.2531
y	0.2740

Color10pen 109

Photopic Filter	31.7000
Red Filter	22.3000
Blue Filter	40.9000
Xb Filter	6.9800
L	31.7000
x	0.2542
y	0.2752

Color11,pen 110

Photopic Filter	39.8000
Red Filter	28.1000
Blue Filter	50.9000
Xb Filter	8.7100
L	39.8000
x	0.2555
y	0.2763

Color12,pen 111

Photopic Filter	47.0000
Red Filter	34.5000
Blue Filter	60.0000
Xb Filter	10.5800
L	47.0000
x	0.2627
y	0.2739

Color13,pen 112

Photopic Filter	53.9000
Red Filter	41.5000
Blue Filter	68.1000
Xb Filter	12.6300
L	53.9000
x	0.2730
y	0.2718

Color14,pen 113

Photopic Filter	61.3000
Red Filter	48.6000
Blue Filter	77.0000
Xb Filter	14.7100
L	61.3000
x	0.2793
y	0.2704

Color15,pen 114

Photopic Filter	67.2000
Red Filter	54.6000
Blue Filter	84.3000
Xb Filter	16.6000
L	67.2000
x	0.2847
y	0.2687

Color16,pen 115	
Photopic Filter	68.4000
Red Filter	55.5000
Blue Filter	84.7000
Xb Filter	16.7000
L	68.4000
x	0.2855
y	0.2705

Color17,pen 116,gold	
Photopic Filter	32.4000
Red Filter	30.1000
Blue Filter	4.5000
Xb Filter	0.4630
L	32.4000
x	0.4434
y	0.4701

Color18,pen 117,darkGreen	
Photopic Filter	12.5300
Red Filter	6.5700
Blue Filter	2.0500
Xb Filter	0.1890
L	12.5300
x	0.3071
y	0.5694

Color19,pen 118,green	
Photopic Filter	28.5000
Red Filter	14.7900
Blue Filter	4.6800
Xb Filter	0.4290
L	28.5000
x	0.3049
y	0.5709

Color20,pen 119,yellow	
Photopic Filter	70.5000
Red Filter	63.4000
Blue Filter	14.3000
Xb Filter	1.1910
L	70.5000
x	0.4193
y	0.4577

C21,pen120,orange	
Photopic Filter	26.1000
Red Filter	34.8000
Blue Filter	5.8200
Xb Filter	0.8380
L	26.1000
x	0.5131
y	0.3758

Color22,pen 121,red	
Photopic Filter	14.8600
Red Filter	26.2000
Blue Filter	1.3200
Xb Filter	0.1890
L	14.8600
x	0.6137
y	0.3456

C23,pen122,magenta	
Photopic Filter	18.6000
Red Filter	30.4000
Blue Filter	16.4000
Xb Filter	2.8800
L	18.6000
x	0.4521
y	0.2527

C24,pen 123,violet	
Photopic Filter	3.5700
Red Filter	4.0300
Blue Filter	15.5300
Xb Filter	2.7800
L	3.5700
x	0.2199
y	0.1153

C25,pen124,lavender	
Photopic Filter	28.9000
Red Filter	33.2000
Blue Filter	89.8000
Xb Filter	18.8000
L	28.9000
x	0.2601
y	0.1446

Color26,pen 125,pink	
Photopic Filter	47.0000
Red Filter	42.6000
Blue Filter	90.7000
Xb Filter	18.8000
L	47.0000
x	0.2686
y	0.2056

C27,pen126,lightPink	
Photopic Filter	59.7000
Red Filter	51.2000
Blue Filter	91.2000
Xb Filter	18.7000
L	59.7000
x	0.2791
y	0.2384

C28,pen127,lightBlue	
Photopic Filter	69.2000
Red Filter	50.3000
Blue Filter	91.9000
Xb Filter	18.6000
L	69.2000
x	0.2651
y	0.2663

Color29,pen 128,blue	
Photopic Filter	46.3000
Red Filter	22.0000
Blue Filter	90.8000
Xb Filter	18.7000
L	46.3000
x	0.1963
y	0.2233

C30,pen129,brown	
Photopic Filter	0.7850
Red Filter	1.3800
Blue Filter	0.0945
Xb Filter	0.0145
L	0.7850
x	0.6051
y	0.3406

125 doesnt
look
pink
126 is very
light

Color31,pen 130,cyan

Photopic Filter	28.3000
Red Filter	12.4400
Blue Filter	65.5000
Xb Filter	12.2400
L	28.3000
x	0.1766
y	0.2024

Color32,pen 131, dark blue

Photopic Filter	11.2200
Red Filter	2.2700
Blue Filter	88.6000
Xb Filter	18.6000
L	11.2200
x	0.1396
y	0.0750

Color Data Set 2

Colors CON1=1.00002
Display 2 CON2=1.32532
6

Color1 Pen 100, black		**C6,pen105,grey 5**		**Color11,pen 110**	
Photopic Filter	0.0266	Photopic Filter	7.5500	Photopic Filter	35.4000
Red Filter	0.0241	Red Filter	5.6800	Red Filter	26.1000
Blue Filter	0.0146	Blue Filter	10.3900	Blue Filter	52.1000
Xb Filter	0.0028	Xb Filter	1.7800	Xb Filter	8.9700
L	0.0266	L	7.5500	L	35.4000
x	0.3693	x	0.2592	x	0.2514
y	0.3651	y	0.2623	y	0.2537
Color2,pen101		**Color7,pen 106**		**Color12,pen 111**	
Photopic Filter	0.2500	Photopic Filter	11.3700	Photopic Filter	43.4000
Red Filter	0.2070	Red Filter	8.5000	Red Filter	32.1000
Blue Filter	0.1920	Blue Filter	16.1400	Blue Filter	62.2000
Xb Filter	0.0320	Xb Filter	2.7800	Xb Filter	11.0000
L	0.2500	L	11.3700	L	43.4000
x	0.3215	x	0.2561	x	0.2551
y	0.3363	y	0.2582	y	0.2569
Color3,pen 102		**Color8,pen 107**		**Color13,pen 112**	
Photopic Filter	0.9780	Photopic Filter	16.0100	Photopic Filter	50.0000
Red Filter	0.7730	Red Filter	11.8800	Red Filter	38.6000
Blue Filter	1.0330	Blue Filter	23.3000	Blue Filter	70.7000
Xb Filter	0.1780	Xb Filter	3.9600	Xb Filter	13.2200
L	0.9780	L	16.0100	L	50.0000
x	0.2884	x	0.2525	x	0.2650
y	0.2965	y	0.2552	y	0.2557
Color4,pen 103, grey 3		**Color9,pen 108**		**Color14,pen 113**	
Photopic Filter	2.3900	Photopic Filter	21.7000	Photopic Filter	56.8000
Red Filter	1.8400	Red Filter	16.0000	Red Filter	45.6000
Blue Filter	2.8900	Blue Filter	31.5000	Blue Filter	80.0000
Xb Filter	0.4970	Xb Filter	5.4000	Xb Filter	15.5000
L	2.3900	L	21.7000	L	56.8000
x	0.2731	x	0.2522	x	0.2729
y	0.2793	y	0.2558	y	0.2537
Color5,pen 104,grey 4		**Color10,pen 109**		**Color15,pen 114**	
Photopic Filter	4.5800	Photopic Filter	28.1000	Photopic Filter	63.7000
Red Filter	3.4800	Red Filter	20.7000	Red Filter	52.6000
Blue Filter	6.0200	Blue Filter	41.2000	Blue Filter	88.8000
Xb Filter	1.0290	Xb Filter	7.0800	Xb Filter	17.9000
L	4.5800	L	28.1000	L	63.7000
x	0.2642	x	0.2514	x	0.2799
y	0.2683	y	0.2543	y	0.2529

Color16,pen 115	
Photopic Filter	70.0000
Red Filter	59.3000
Blue Filter	96.4000
Xb Filter	19.8000
L	70.0000
x	0.2857
y	0.2528
Color17,pen 116,gold	
Photopic Filter	28.1000
Red Filter	27.9000
Blue Filter	3.7800
Xb Filter	0.3970
L	28.1000
x	0.4608
y	0.4576
Color18,pen117,dark green	
Photopic Filter	10.1100
Red Filter	5.3300
Blue Filter	1.6700
Xb Filter	0.1566
L	10.1100
x	0.3081
y	0.5677
Color19,pen 118, green	
Photopic Filter	23.2000
Red Filter	12.0600
Blue Filter	3.8500
Xb Filter	0.3600
L	23.2000
x	0.3050
y	0.5697
Color20,pen 119,yellow	
Photopic Filter	65.9000
Red Filter	61.0000
Blue Filter	11.0900
Xb Filter	1.1110
L	65.9000
x	0.4352
y	0.4618

C21,pen120,orange	
Photopic Filter	25.2000
Red Filter	34.9000
Blue Filter	5.0300
Xb Filter	0.7440
L	25.2000
x	0.5280
y	0.3733
Color22,pen 121,red	
Photopic Filter	15.3000
Red Filter	26.7000
Blue Filter	1.2730
Xb Filter	0.1800
L	15.3000
x	0.6128
y	0.3488
C23,pen122,magenta	
Photopic Filter	19.0000
Red Filter	31.1000
Blue Filter	15.8000
Xb Filter	2.7600
L	19.0000
x	0.4588
y	0.2575
C24,pen123,violet	
Photopic Filter	3.5600
Red Filter	4.2200
Blue Filter	14.5600
Xb Filter	2.6100
L	3.5600
x	0.2301
y	0.1199
C25,pen124,lavender	
Photopic Filter	30.3000
Red Filter	33.9000
Blue Filter	96.5000
Xb Filter	20.6000
L	30.3000
x	0.2562
y	0.1425

Color26,pen125,pink	
Photopic Filter	45.0000
Red Filter	41.3000
Blue Filter	94.4000
Xb Filter	19.8000
L	45.0000
x	0.2643
y	0.1946
C27,pen126,lightPink	
Photopic Filter	56.1000
Red Filter	49.2000
Blue Filter	94.8000
Xb Filter	19.7000
L	56.1000
x	0.2749
y	0.2238
C28,pen127,lightBlue	
Photopic Filter	65.7000
Red Filter	48.3000
Blue Filter	96.0000
Xb Filter	19.8000
L	65.7000
x	0.2609
y	0.2517
Color29,pen128,blue	
Photopic Filter	42.6000
Red Filter	18.8000
Blue Filter	93.4000
Xb Filter	19.5000
L	42.6000
x	0.1871
y	0.2081
C30,pen129,brown	
Photopic Filter	0.9150
Red Filter	1.6080
Blue Filter	0.0845
Xb Filter	0.0128
L	0.9150
x	0.6121
y	0.3456

Color31,pen 130, cyan	
Photopic Filter	24.6000
Red Filter	10.3300
Blue Filter	68.2000
Xb Filter	12.7800
L	24.6000
x	0.1673
y	0.1781
Color32,pen 131, blue	
Photopic Filter	11.8000
Red Filter	2.2400
Blue Filter	94.1000
Xb Filter	19.9000
L	11.8000
x	0.1396
y	0.0744

APPENDIX D - RAW REFLECTANCE DATA

Reflectance Data Set 1

Reflectance	CON1=	1.00002	CON2=	1.32533	6 minutes
Display 2	Center	15° Left	30° Left	45° Left	Reference
Using ND4 filter					
Photopic Filter	5570	800	600	500	4560
Red Filter	5030	710	530	450	3820
Blue Filter	2600	440	320	270	2120
Xb Filter	420	90	80	75	360
L	5570	800	600	500	4560
x	0.377	0.366	0.373	0.380	0.362
y	0.385	0.366	0.367	0.362	0.395

** Reference is straight on off of white source

Reflectance Data Set 2

Reflectance	CON1=	1.00002	CON2=	1.32533	
Display 3,ENG 2055	Center	15° Left	30° Left	45° Left	reference
Use ND4 Filter and 6 minute					
Photopic Filter	2100	1550	1200	1080	6420
Red Filter	1860	1370	1060	950	5850
Blue Filter	1240	890	670	610	3330
Xb Filter	220	180	140	120	560
L	2100	1550	1200	1080	6420
x	0.357	0.362	0.365	0.362	0.372
y	0.361	0.362	0.365	0.365	0.372

** reference 98% reflectance