NBSIR 86-3403

Final Evaluation of a Color Calibrator for a Radar Remote Weather Display System

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

This report is the final report on the development and field testing of an inexpensive color calibrator for the standardization of the Weather Intensity Level (WIL) colors used in the FAA's Radar Remote Weather Display System or RRWDS. The report covers the field validation of the color calibrator and, as an end product, the construction of a tentative look-up table that identifies whether the six WIL colors are within acceptable limits. The look-up table is tentative due to the small (5) number of field sites visited. The development of a color lookup table finalizes the validation of the color calibrator as a useful tool for calibrating the WIL colors used in RRWDS. Moreover, the color calibrator can be used to calibrate the colors of other tricolor display systems, provided an appropriate lookup table is developed.

In addition, this report includes a general review of significant literature on color-coding, since RRWDS color codes weather information. The report presents first-of-its-kind objective data on the effects of ambient room lighting on colors used in a self-luminous display. The effects were chromaticity shifts due to the presence of veiling reflections or glare from the face of the CRT console. This report may, accordingly, have significant impact on the design of building environments where color-coded CRT's are to be used.

Keywords:

building lighting environments; cathode ray tube (CRT); chromaticity shifts; color calibrator; color coding; room illuminant reflections; self-luminous displays; specular glare from CRT's; veiling luminances; video display terminals (VDT)

FOREWORD

This report is the final report of the FAA/NBS Agreement No. DTFA01-83-Y-20592, including the agreements attached thereto. This report is a continuation of material discussed in report NBSIR 84-2924: Color Calibrator for RRWDS Radar Remote Weather Display System prepared by J. L. Heldenbrand and L. G. Porter for the FAA, U.S. Department of Transportation [9]. NBSIR 84-2924 proved the feasibility of an inexpensive color calibrator under laboratory conditions only. The present report summarizes research conducted from January 1, 1985 to October 30, 1985 to verify that the color calibrator - with lookup table - can calibrate the WIL colors of the RRWDS as originally envisioned. In addition, this report represents some original information on the effect of a building's lighting environment on colors used in a CRT display.

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DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this report to specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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1. INTRODUCTION

1.1 BACKGROUND

The Federal Aviation Administration (FAA) commissioned the National Bureau of Standards (NBS) to develop, test, and field evaluate an inexpensive ($100.00) color calibrator for its Radar Remote Weather Display System (RRWDS). An RRWDS receives radar echoes from moisture in the air (i.e., in liquid or solid forms such as mist, rain, snow, sleet, etc.), processes the echoes into six Weather Intensity Levels (WIL's), and displays the resulting weather patterns on a tri-color (red, green, blue or RGB or P22 phosphors) CRT display console. The six WIL's represent increasing amounts of air moisture. Starting from the least amount of air moisture, the colors used are described as: (1) light green, (2) dark green, (3) yellow, (4) tan/gold, (5) light red, and (6) dark red. This assignment of weather information to colors is called color coding. U.S. Weather Service meteorologists use this color-coded information as one source in making their local area weather forecasts.

A first report (see reference No. 9) was prepared for the FAA to document the design, development, and laboratory testing required to produce an inexpensive color calibrator for RRWDS. The recommended color calibrator consists of three silicon photodiodes, each with an R, G, or B encapsulated narrow-band Wratten filter, and an AC-DC power supply. To keep costs down, the output of the color measuring head was designed to be used with most digital volt-meters (DVM's) currently available. The sensitivity of the color calibrator plus DVM was at least equivalent to one test digital level (TDL) as entered into the RRWDS display console keyboard using special erasable, programmable read only memory (EPROM) chips or integrated circuits (IC). Each of the RGB colors can be changed over 16 TDL's, i.e. TDL=00 to 15, for a total of 4096 color combinations. Since the spectra of the RGB phosphors are nominally the same for all RRWDSs' CRTs, it is possible for the color calibrator to provide the basis for a true CRT colorimeter employing a microprocessor and using appropriate matrix algebra algorithms. However, using such a colorimeter with any other CRT requires that the spectral power distribution (SPD) of the CRT's phosphor be known and entered-in in advance of any measurement.

The present report documents the results of the field-testing phase of this project as well as a laboratory study of the effects of different building lighting environments on WIL chromaticities as measured by a rapid-scan spectroradiometer. The basic reasons for this continuation study were to: (1) develop an RGB look-up table of the acceptable range of color calibrator outputs for each WIL; (2) assess ease of use and accuracy of color adjustments by field technicians; and (3) assess the effect of various building lighting environments on color discriminability under real-time field use of RRWDS. Although only a limited number of field sites were visited of the

30 field sites proposed, the obtained intersite differences clearly highlight the need for more data on such differences as well as on the effects of different lighting environments on color discriminability. The last part of this report contains data on a substantive, first of its kind, laboratory study of the effect of various room illuminants on WIL chromaticities. The effect investigated was the determination of the net result of superimposing room illuminant reflections from the CRT display on each of the WIL colors. Logically, both the luminance and spectral composition of these reflections should simply add to the luminance and spectral composition of the WILs to produce some net effect. That this is not necessarily true will be discussed later.

1.2 LITERATURE REVIEW - COLOR CODING

1.2.1 Review by Christ

The most recent and most substantive review of the use of color as a coding medium was performed by Christ [3]. Color coding has been used primarily for two kinds of tasks: search and identification. A search task consists simply of searching, locating and counting categories of items known in advance. An identification task consists of finding a given target/location and identifying its category when the category is not known in advance. Christ concluded that color coding, either redundant[1] or non-redundant, for search tasks is the most effective form of coding, e.g. reducing search time by up to 70%. Christ also concluded that nonredundant color coding is superior to size, brightness, and shape coding for identification tasks although it is inferior to alphanumeric coding. The use of redundant color coding for identification tasks remains questionable due to a scarcity of relevant experiments.

On the other hand, the presence of irrelevant color may adversely affect or interfere with the processing of the achromatic attributes of a multidimensional display. Smith and Thomas [15] found that the presence of irrelevant color decreased counting speed for geometric shapes whereas Egeth and Pachella [4] found that it reduced the accuracy of shape and size identification. When a color code has been applied systematically but not made known, performance on a color-coded display is impaired relative to that on a monochromatic display [5]. This interference effect increases as the number of colors in the display is increased. The reason(s) for the interference effect of irrelevant color is unknown, although the human visual system appears to assign color high priority in viewing a global visual scene.

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[1] Redundant coding refers to the use of two (or more) coding techniques, e.g. a deck of cards uses color, form, numeric, and positional (one-eyed jack) coding. Redundant coding lets the same deck of cards to be used in a variety of card games.

The interference effect of irrelevant color may be due to different visual system mechanisms for processing color than for processing achromatic target attributes. A color-detection/letter-recall study by Gummerman [8] suggested that letters are processed serially, left to right or top to bottom, whereas color is processed in parallel by operating over the entire display simultaneously. Further support of different visual mechanisms for shape and color-processing was reported by Williams [19] who found evidence that search can be guided extrafoveally on the basis of color but not of shape. The global nature of color processing was supported by Luria and Strauss [13] who found that fewer fixations are needed to locate a color-coded target than a shape-coded one. Although large multivariate experiments are extremely difficult to accomplish, the findings cited above suggest that color processing and shape processing may be performed by different visual system mechanisms. Whether or not color is always processed in parallel and shape is always processed serially is a point of conjecture contingent on the type of experiment performed. Independently of the type of processing involved, color coding is still beneficial in many multi-task situations.

1.2.2 Post-Christ Review

A post-Christ literature search found only four studies [11,14,16,17] that used a multi-task paradigm instead of the usual single-task paradigm. These four studies investigated redundant color-coding for search tasks. Color-coding seemed to have a slight advantage over other forms of coding, although this effect was not clear-cut. In three of these studies [11,14,17], a significant improvement in performance of the non-color-coded task was found, whereas in two of these studies [11,14], a significant improvement on the color-coded task was also found. The fourth study [16] found no advantage of color-coding for non-color-coded tasks. With increasing use of color CRT's aboard aircraft and other military weapons systems, these studies indicate an increasing need for multi-task studies employing both search and identification task paradigms.

The review of the post-Christ literature found no studies using color coding on dynamic (unfixed) or cluttered displays such as the RRWDS. A single study using a fixed-format, redundant color-coding for airborne CRT displays was performed by Luder and Barber [12]. They found that: "the availability of redundant color coding on the secondary task resulted in a global improvement in tracking performance (primary task) that applied at all times, even when subjects were not attending to the systems-management display. With regard to the response-time data for the color-coded display, redundant color coding improved search performance, but there was no benefit for performance on the identification task."

Another type of fixed-format task is the static system maps often used in process control systems (e.g. nuclear power plants, oil/gas refineries, gas transmission control operations). Dynamic system information, depicting the state of the system, occurs at specific map locations. For such identification tasks, the operator is position-cued as to where to look (given a particular status of the display) for cues for appropriate further responses. In some systems additional visual cues (flashing lights) and auditory cues (gongs) are used to reduce an operator's "alert", "search", "identify", and "take appropriate action" times for high criticality conditions.

1.3 REVIEW SUMMARY

In summary, the behavioral research data indicate that color-coding is very effective in reducing search time but much less so in reducing identification time. The research data also indicate that as the number of colors in the code increases, the various response times increase accordingly. If the number of colors becomes too large (the critical number remains undetermined and appears to be task dependent), the color codes may become irrelevant and result in a serious decrement in human performance. With the increasing use of color CRT's to display vital cockpit information, already on the Boeing 757 and 767 and airbus A310 and with 7-9 color CRT's proposed for certain military aircraft, careful attention must be paid to the number and kind of colors selected to insure aircraft safety.

The literature clearly indicated a critical need for more data about systems which incorporate self-luminous CRT displays. The International Standards Organization (ISO) has set up a special committee to develop standards for various visual attributes of CRT's, including some aspects of color, e.g. figure/background relationships. Undoubtedly, these standards will be useful but will not address the need for more information (data) on chromaticity maintenance of self-luminous displays. These data are needed for total systems (including the CRT) that use color-coding techniques, i.e. where various colors represent specific information content in contrast to, say, TV's where color is not only symbolic but aesthetically pleasing. Some of the general problems of color-coded self-luminous displays that might be addressed are:

1. Chromaticity changes and/or loss of color contrasts as a function of system aging and/or maintenance/replacement of parts.

2. Impact of the building lighting environment on color and color contrasts.

3. Enhancement of color contrasts for the mildly color defective, e.g. the anomalous observer.

4. Optimization of the number of colors used in color-coded CRT displays to achieve clearly detectable color contrasts.

The above list of problems covering color-coded CRT-type displays is meant as an introduction to the body of this report. It is not an exhaustive listing of the many problems associated with CRT-generated displays in general. For an interested reader, reference #1 is suggested as an overview.

2.0 BACKGROUND FOR RRWDS EVALUATION

2.1 WEATHER INTENSITY LEVELS (WIL'S) CHROMATICITIES

The first step in the evaluation of the RRWDS was to determine specifications established for the chromaticities used to indicate different weather intensity levels. A review of the documentation for contract DOT-FA79WA1-097 did not find any official FAA chromaticity specifications that applied to the WIL's for RRWDS. The first NBS color code proposal [10], however, contained chromaticity coordinates and suggested relevant luminances for the 6 WIL's (see Table 1 and Figure 1). The six chromaticities were chosen to lie on the edge of the triangle formed by the RCA RGB P22 phosphor chromaticities. These colors were chosen on the triangle edges to obtain maximum saturation. The relative luminances were chosen to achieve maximum available light/dark contrast ratios. The six WIL colors recommended would allow people with moderate red-green color deficiencies (protanomalous or deuteranomalous) to discriminate on the basis of color and/or light/dark contrasts.

The next NBS color code proposal for RRWDS was contained in a letter report on May 8, 1981 by Robert A. Glass [6] (see Table 2). The proposed chromaticities were based on a summary of spectroradiometer measurements taken at the RRWDS system manufacturer's premises. By this time a decision had been made to use three colors; namely red, yellow, and green with high/low luminances to provide the six WIL's. Further, in the NBS letter report, the brighter WIL was the more intense weather condition. Later, the National Weather Service recommended that the darker color should represent the more intense weather because of experience with black-white displays where the darker levels represented more extreme conditions.

2.2 WIL LUMINANCES

Except for the first NBS proposal, no other specification for the luminances of the six WIL's was found. The rationale for specifying the luminances of the WIL's is to insure optimum light/dark contrast ratios. There are, in fact, two light/dark contrast ratios involved, namely: (a) the contrast between the light and dark color for a single hue, e.g. light versus dark green; and (b) the contrast ratio between a dark color and the display's background. To illustrate, a more intense weather condition (e.g. the dark green of WIL #2) may be embedded in a large area of less intense weather (e.g. the light green of WIL #1). Depending on the ambient lighting system as well as the luminance of WIL #1, the actually more intense WIL #2 cells may be misinterpreted as dark background. This is due to a visual effect known as "simultaneous contrast", in which a bright area makes a dark area appear even darker. Recourse to the display console's menu, which permits any combination of WIL's to be displayed, is a built-in solution to this problem, i.e. a single dark WIL can be displayed individually from the dynamic weather display.

Table 1. NBS's original proposed color code for use in color weather radar (August 14, 1980).

Level	Color Name	Chromaticity[1] Coordinates x	y	Munsell Hue	Relative Luminance %	Equivalent Munsell Value
6	Red	.575	.315	5R	100	10
5	(Orange) Brown	.530	.425	5YR	30	6
4	Yellow	.490	.460	2.5Y	80	9
3	(Yellow-green) Olive	.435	.505	10Y	30	6
2	Green	.270	.390	5G	60	8
1	Blue	.195	.190	5PB	30	6

[1] The chromaticities of all six colors were chosen to lie on the edge of the triangle formed by the RCA phosphor chromaticites. These colors were chosen on the triangle edges to obtain maximum saturation. We have not attached tolerances, and these exact coordinates may not be achievable. However, these coordinates should be viewed as target coordinates. The manufacturer should try to get as far out from the white point towards the chromaticites as possible, to maximize the color saturation.

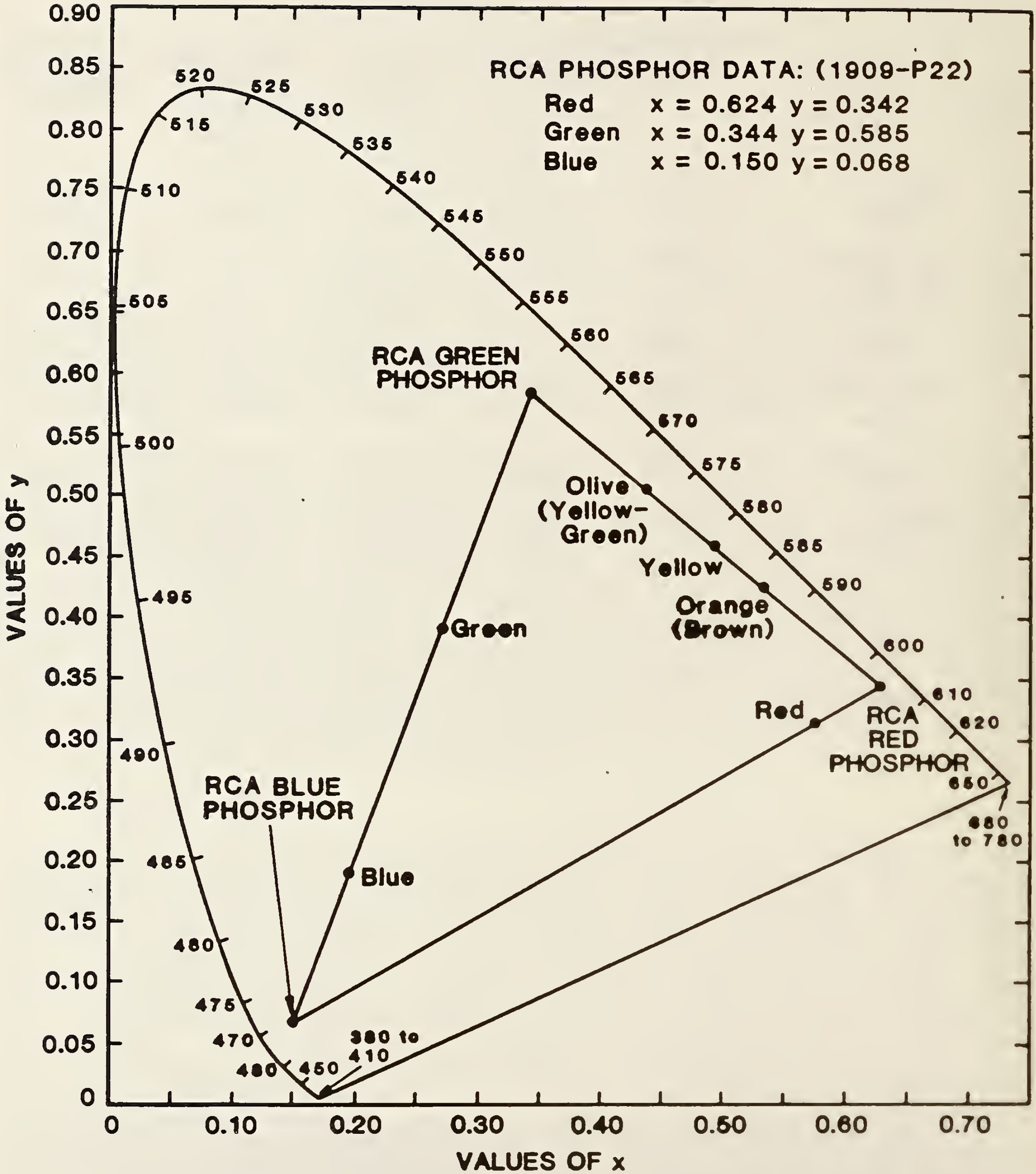

Figure 1 TARGET CHROMATICITY COORDINATES FOR COLOR WEATHER RADAR

Table 2. Summary measurements taken at Electrodynamics (April 15, 1981), representing NBS's final proposed chromaticities for the WIL's.

Intensity Number	Color Name	Average Chromaticity Coordinates
6	RED	x = .6656 y = .3340
5	*DARK RED	x = .6812 y = .3186
4	YELLOW	x = .4021 y = .5292
3	*TAN/GOLD	x = .4064 y = .5538
2	GREEN	x = .3454 y = .5793
1	*DARK GREEN	x = .3553 y = .5885

* These NBS color pairs for light and dark were reversed at the request of the NWS of NOAA (DOC) per letter request of May 16, 1981.

2.3 SUGGESTED WIL CHROMATICITY CHANGES

The chromaticities of the current 6 WIL's, when plotted on a CIE chromaticity diagram, lie almost in a straight line (see Figure 1 or Figures 12-20). This line is very close to the line of maximum RG color confusion. NBS has suggested that a new set of chromaticities could be developed which would allow people with minor RG color deficiencies to make appropriate discriminations among the 6 WIL's. The changes are relatively small but appear to be effective. People with normal color vision will still see high contrasts between pairs of the proposed new chromaticities although some may aesthetically prefer the original six chromaticities. On the other hand, people with slight color deficiencies should be able to discriminate between all six WIL's using the proposed new set of chromaticities. These people would generally pass the usual color-blindness tests. It would take somewhat more sophisticated color testing techniques to determine their true color deficiencies.

The effect of making slight color changes in some of the recommended WIL's may allow more people to use RRWDS and avoid possible discrimination against hiring new people who may have only minor color defects. Two possible retrofits to the RRWDS are available: (1) change the firmware color table in the EPROM's on the display CPU/interface circuit card assembly (i.e. CCA N3NBA1) or (2) replace the same EPROM's with color test EPROM's. These color test EPROM's permit entry through the console keyboard to the WIL color and background RAMs. The programs written into the EPROM's allow each color gun to be changed by 16 test digital levels (TDL). Although this latter procedure would allow individual color-deficients to personally minimize WIL color confusions, the need to check and/or change the chromaticities every shift may be irritating and/or unacceptable to some meteorologists.

2.4 WIL VARIABILITIES

In NBSIR 84-2924 the variability of both luminance and chromaticity for a single RRWDS was stressed. Some sources of variability were: (a) warm-up effect; (b) system drift; (c) change in the power supplies (e.g. replacing a new tripler and high voltage junction box); and (d) a hysteresis effect. The latter effect was seen when the TDL's were plotted as a function of mV DC (the output of the color calibrator) for an ascending series (00-15) and for a descending series (15-00). This effect was measured for each of the RGB primary colors. Variability in both chromaticity and luminance was also observed in the data taken for the present report.

3.0 FIELD TEST OF COLOR CALIBRATOR FOR RRWDS

The original purpose for the development of the color calibrator was to produce a cheap device ($100.00) that would objectively discriminate the six WIL colors. NBSIR 84-2924 provided supporting data which verified that the color calibrator can detect minor changes in the chromaticities of the WIL's. If a technician receives a call that one or more of the WIL's do not look right, he/she could try tweaking the grid controls (especially the G-2s) to obtain the best WIL color. If the technician were using the color calibrator, he/she would obtain the color wedges from a digitizer. Using available console menus, each WIL can be centered one at a time. The technician would check each RGB channel to see if the color calibrator readout was within the limits specified in the look-up table. If by tweaking the G-2s, the WIL colors are brought within those set in the look-up table, then the system is within specifications.

3.1 FIELD OBSERVATIONS

Casual observation of a few field RRWDS indicated that some WIL colors did not appear to have the same chromaticities as the test system at NBS. To check for correct adjustment of the processor, the processor input signal to the control console was monitored for each RGB channel. An oscilloscope was attached to J3, J4, or J5 on the back of the console (using Tee BNC connectors). Using the vertical bars from the processor's Built In Test Equipment (BITE), the contribution of each primary color to each WIL color could be measured by means of the oscilloscope. If the oscilloscope was connected to J3, then the display showed the amount of red present in each of the vertical bars (white, black, plus the 6 WILS), in a form similar to an eight item histogram. According to site acceptance specifications, the voltage reading on the oscilloscope should be 3.2 mVDC for those bars having the maximum level (TDL=15) for the color channel being monitored. Under field conditions, a voltage range of 3.0-3.6 mVDC was found for some RGB channels. The RGB video amplifiers on the video color generator board in the processor were adjusted to meet site acceptance specifications before the field color calibrator tests were conducted. Further, at some sites the brightness control did not "track" accurately, i.e. at high brightness settings the alphanumerics on a live display tended to "bloom" or become blurred rather than simply become brighter.

3.2 TRI-COLOR SYSTEM EFFECTS

It has been established by the television tube industry (i.e. Joint Electron Device Engineering Council or JEDEC, see Publication No. 16-C, 1975) that each phosphor has its own unique spectral power distribution (SPD). Usually variations across different batches are very small. However, when phosphors are selected for a tri-color system, the basic primaries (RGB) may show slight changes in the phosphor chromaticities. In the NBSIR 84-2924, it was noted that decreasing the TDL of a single RGB cathode of the RRWDS's CRT resulted in changes in chromaticity as the TDL was adjusted to a low level. On the other hand, if a similar CRT is placed in a test jig, then decreasing the current to a single cathode does not result in chromaticity shifts for any of the RGB primary colors. The distinction is that in RRWDS some current is always applied to the RGB cathodes whereas in a test jig current can be applied to a single RGB cathode only. This differential effect may be interpreted as a system's effect.

3.3 GRID #2 VOLTAGES

Table 3 presents the DC voltage readings taken at test points TP4, TP5, and TP6 for each of the sites visited. The test points are located on the dynamic focus/screen balance Circuit Card Assembly (CCA N3NC1) in the CRT console. At each site visited, the local technician was asked to check that the system was operating "normally". By normal, it was meant that: 1) the CRT's background was barely visible as a neutral gray; and, 2) the WIL color wedges obtained from a digitizer were visually "acceptable". At this point, the display CPU/Interface CCA (N3NB3A1) was removed and replaced by the CCA containing the color test EPROM's.

With the Brightness Control set to maximum and the contrast control to a minimum, a white (R=15, G=15, and B=13) target area was keyed in to determine the CRT's specification luminance (i.e. 77 fL as specified by RCA). Only two systems (NBS and Teterboro) could achieve this luminance level. For the two Leesburg consoles the target area would "snap in/out", thereby indicating trouble with the triplers and/or high voltage junction block. Thus, the Leesburg CRT console tests were made at a lower Brightness Control setting. Theoretically, running the system at lower luminance levels should not seriously affect the chromaticities of the WIL colors.

A question may arise as to why NBS preferred to use the color test EPROM's in the field tests. The answer is: a.) ease of use; b.) the ability to fill the whole target area with a single color; and c.) the ability to change a WIL color component one or two TDL's. Previous laboratory testing had shown no significant chromaticity differences between: a.) the vertical bars from the processor's BITE; b.) the WIL wedges from a digitizer's BITE; or c.) the WIL's produced by using the color test EPROM's. Therefore, a major reason for using the color test EPROM's was to determine if the color calibrator would still detect a one TDL change in any of the RGB color components over all six WIL colors. The results of this test were positive except when an RGB component was 2 TDL's or less as in WIL #2 (R=01, G=06, B=02). As cited in NBSIR 84-2924, low TDL's can not be detected by the spectroradiometer.

Table 3. VDC Readings of Grid #2 Voltages for Each RGB Channel

	RED TP4	GREEN TP5	BLUE TP6
NBS	394	460	395
Leesburg #1	319	471	404
Leesburg #2	543	393	542
A. Godfrey	343	501	328
Leesburg #3	475	485	403
Teterboro	392	323	321
Mean	411.0	438.8	398.8
Standard Deviation	83.97	67.82	79.54

3.4 WIL CHROMATICITIES

Table 4 presents the six WIL chromaticities, measured by the spectroradiometer, in CIE (x,y) coordinates, for each of the field sites visited. The data in Table 4 allow some interesting comparisons to be made. First, the standard deviation (S.D.) data indicate fairly large (and visually detectable) inter-site differences for five of the six WIL's. The smallest S.D. is for WIL #5 (red). WIL #5 is the only WIL composed of a single primary (R) color. This suggests that, although the RGB phosphors may vary slightly between different CRT's, there is a larger variation in the mixing of RGB primaries which occurs in the electronics of the RRWDS - a so-called systems effect. This effect appears to be supported by the smaller differences in chromaticity between the two Leesburg RRWDS. Re-examination of Table 3 indicates that these smaller WIL color differences were probably obtained by changes in the G-2 DC voltages. Since the two consoles are side-by-side, the maintenance technician can adjust one system and then use it to aid in adjusting the second system. If this is true, then using a standard color measuring device, i.e. the color calibrator, may prove to be useful in maintaining color constancy across all RRWDS's.

Comparison of the WIL color data for the two NBS measurements indicates that the WIL colors change over time for a given system (approximately 2 years for the NBS RRWDS). This change over time may be due to a number of factors, e.g. erosion of the electrodes, warping of the color shadow mask, replacement of the triplers/high-voltage junction block, or other changes. However, if the WIL colors are too different from their desired colors, new CCA's or the CRT may have to be replaced before the colors can be adjusted to the color look-up table values.

3.5 FIELD TEST PROCEDURE AND RESULTS

The initial procedure used to obtain the data to develop a color calibrator look-up table consumed a great deal of time. The first step was to obtain the WIL color wedges from a digitizer. Each WIL wedge was then displayed independently and spectroradiometric data recorded. The second step was to switch to the color test EPROM's and repeat step one. The two sets of data were then scanned for major discrepancies. As expected, no significant differences were found. The third step was to record the DC voltages for each RGB component of each WIL using the color calibrator. These data formed the basis for the look-up table and are presented in Tables 5-8. The fourth step involved incrementing/decrementing each RGB component of a WIL by one TDL. The data obtained during this step were compared to the data from step 3. The results from this comparison were consistent with laboratory findings - the color calibrator can detect a one TDL

Table 4. WIL chromaticities as a function of field sites.

WIL#		NBS LAB	Leesburg #1	Leesburg #2	Arthur Godfrey	Teterboro	Initial NBS Lab	Mean	Standard Deviation
1	x	.3605	.3426	.3426	.3481	.4198	.3572	.3618	.0294
	y	.5333	.5854	.5774	.5787	.5186	.5723	.5609	.0278
2	x	.2941	.3482	.3469	.3507	.3466	.3406	.3378	.0217
	y	.4399	.5625	.5774	.5692	.6156	.5958	.5601	.0620
3	x	.4224	.3879	.3970	.4073	.5012	.4226	.4231	.0407
	y	.5050	.5476	.5274	.5251	.4443	.5124	.5103	.0355
4	x	.4771	.3573	.4242	.3984	.5034	.4855	.4410	.0571
	y	.4600	.5691	.5074	.5287	.4434	.4566	.4942	.0493
5	x	.6079	.5962	.6090	.5915	.6138	.6174	.6060	.0101
	y	.3382	.3501	.3419	.3481	.3440	.3389	.3435	.0048
6	x	.6012	.6105	.5793	.5397	.6137	.6184	.5938	.0299
	y	.3379	.3471	.3618	.3717	.3432	.3396	.3502	.0136

change in any of the RGB components of a WIL (except when TDL's of two or less). As a result, step one was deleted and step 4 was reduced to several checks using the color test EPROM's.

For the remainder of the tests, spectroradiometric data were always taken first to determine if stray fluorescent light was detectable. (Fluorescent light has characteristic peaks at 404, 436, 546, and 578 nanometers). Since this characteristic fluorescent signature was noted at all field sites, a canopy with black sides was used thereafter. In addition, a black cardboard tube was used as a light conduit between the CRT's protective screen and the spectroradiometer lens. Color calibrator data were obtained with the face of the color calibrator directly against the protective screen.

Table 5 presents data, in DC voltage form, from the main console used at Leesburg. In order to reduce congestion at its original use position, this console was moved to the basement. The console was connected to the processor with 10 ft. of coaxial cable and readjusted to yield EPROM-produced chromaticities closer to those of the NBS lab console. Comparison of the relative luminances of the RGB primaries when using the EPROM's vs the digitizer's wedges indicated that the wedges had the higher relative luminances, e.g. WIL #3 had almost twice the voltage readout for the wedges than for the EPROM's. During rather extensive laboratory testing, when all system controls were kept constant, the wedges generally yielded lower relative luminances than the EPROM's, although both sets of luminances varied over time.

The higher relative luminances for the digitizer's wedges used for the Leesburg #1 console may be partially due to the console's close proximity to the processor. However, the RRWDS manufacturer claims there should be no "significant" voltage drop in the coaxial cable up to a distance of 200 feet. NBS laboratory tests suggested there is a voltage drop of 0.1 to 0.2 mVDC per 100 feet of coiled coaxial cable. Additionally, "noise" may be induced by the electromagnetic fields surrounding such computer peripherals as magnetic disks. Other NBS laboratory tests revealed small luminance differences in the WIL wedges obtained from different digitizers although the WIL wedges never produced higher luminances than the WIL luminances obtained using the EPROM's. On the other hand, the proportions of the RGB components are in the right direction. For example, WIL #3 is generated by using 15 TDL's of red and green and no blue (i.e. R=15, G=15, B=00). Therefore, the color calibrator readout should be near some maximum value for both R and G. Wil #5, which is a pure red (R=15, G=00, B=00), is a good indicator of the variability seen across all five field sites. Since the blue components of WIL's 1 & 2 contain TDLs of only 2 units, which are not detectable by the human eye, differences in the color calibrator readouts for the blue phosphor across the five field sites appear to be random in nature.

Table 5. Color calibrator DC voltage readings as a function of field site - Leesburg #1

Leesburg #1 EPROM's	Color Calibrator DC Voltage Readings in Millivolts			Digitizer Wedges			
WIL No.	Red	Green	Blue	WIL No.	Red	Green	Blue
1	.060	.186	.008	1	.091	.292	.011
2	.014	.028	.001	2	.017	.040	.002
3	.276	.270	.012	3	.511	.472	.021
4	.039	.072	.003	4	.070	.106	.004
5	.197	.003	.003	5	.360	.008	.005
6	.006	.003	.000	6	.013	.003	.000
Dark current of C.C.*	.002	-.005	.000				
G-2 voltage	543	393	542				

* Color Calibrator

Table 6 presents color calibrator data from the backup console in the Leesburg Air Traffic Control (Leesburg #2) room which was functioning properly at the time. The RRWDS of Leesburg #3, actually Arthur Godfrey airport, had just been installed but not checked out. With the overhead fluorescent lights off, the maximum luminance of a white target circle was 24.25 FL or approximately one-third the site acceptance specification value of 77 FL. With all fluorescent lights on, the dark WIL's were barely detectable. Leesburg #3 appeared to represent an unadjusted console, perhaps because of its recent installation.

Table 7 presents a second set of color calibrator data from Leesburg #2 as well as from Teterboro, N.J. Approximately three months elapsed between the data for Leesburg #2 presented in Table 6 and in Table 7. Local Leesburg maintenance people thought the differences in color calibrator voltage readouts were due to a need for new triplers. On the other hand, the Teterboro system had recently installed new triplers and high voltage junction block. Visual inspection of the Teterboro WIL's suggested that they were green-deficient. Spectroradiometric and color calibrator data support the green deficiency visual observation. Since local maintenance personnel were not available, no changes in the G-2's were made. The Teterboro data, however, strongly suggest the need for an objective measuring device to bring each RRWDS more in line with chromaticity standards for each WIL.

Table 8 presents a tentative look-up table for using the color calibrator. Examination of this table illustrates some obvious problems. First, the small size (N=6) of the sample of sites on which the values in the table are based is grossly inadequate to obtain a stable distribution of WIL chromaticities. A single misaligned system, e.g. Teterboro, will greatly distort both mean and standard deviation values. Comparison of the Leesburg versus the Teterboro data indicates, that in the absence of some objective color measuring device, such as the color calibrator, individual technicians vary greatly in obtaining the "standard" WIL colors. Some technicians may add too much blue or others too much red or green. To reduce inter-system variances in the WIL chromaticities, a twofold approach may be required. First, by sampling a large number of RRWDS (e.g. N > 30), a better distribution of WIL chromaticities could be obtained to set "standards" for the WIL chromaticities. Second, the color calibrator should be used to adjust the WIL chromaticities, thereby eliminating "eyeballing" differences. These procedures may not eliminate inter-system differences but will tend to reduce them to a less noticeable level.

Examination of the B component in Table 8 indicates that the blue-filtered photodiode apparently was responding to green wavelengths. For example, the maximum response of the B photodiode was to WIL #3 (G=15), then WIL #1 (G=12) and WIL #4 (G=8). This suggested problems in assuring the proper sensitivity setting for the B photodiode. The color calibrator

Table 6. Color calibrator DC voltage readings as a function of field site - Leesburg #2 and #3

Leesburg #2	Color Calibrator DC Voltage Readings in Millivolts			Leesburg #3	Color Calibrator DC Voltage Readings in Millivolts		
EPROM's				EPROM's			
WIL No.	Red	Green	Blue	WIL No.	Red	Green	Blue
1	.122	.313	.028	1	.063	.160	.008
2	.055	.085	.015	2	.018	.046	.003
3	.546	.477	.034	3	.278	.207	.013
4	.177	.144	.018	4	.093	.081	.005
5	.381	.026	.017	5	.201	.007	.004
6	.068	.006	.002	6	.047	.002	.001

Table 7. Color calibrator DC voltages readings as a function of field site - Leesburg #2 and Teterboro, N.J.

Leesburg #2[1]	Color Calibrator DC Voltage Readings in Millivolts			Teterboro, NJ	Color Calibrator DC Voltage Readings in Millivolts		
EPROM's WIL No.	Red	Green	Blue	EPROM's WIL No.	Red	Green	Blue
1	.084	.250	.017	1	.163	.103	.007
2	.024	.068	.003	2	.012	.031	.001
3	.440	.460	.027	3	.548	.126	.013
4	.180	.121	.008	4	.460	.103	.011
5	.275	.011	.006	5	.513	.017	.008
6	.099	.006	.002	6	.393	.014	.006

1 Data are from a second trip taken 3 months later.

Table 8. Tentative look-up table for the WIL's using the color calibrator.

WIL No.		Red	Green	Blue
1	U.L.[2]	.142	.283	.023
	Mean	.098	.202	.014
	L.L	.054	.121	.005
2	U.L.	.042	.076	.010
	Mean	.025	.052	.005
	L.L.	.007	.027	.000
3	U.L.	.553	.463	.030
	Mean	.418	.308	.020
	L.L.	.282	.153	.010
4	U.L.	.352	.134	.015
	Mean	.190	.104	.009
	L.L.	.028	.075	.003
5	U.L.	.448	.022	.013
	Mean	.313	.013	.009
	L.L.	.179	.004	.002
6	U.L.	.277	.011	.004
	Mean	.123	.006	.002
	L.L.	.000	.002	.000

[2] The Upper and Lower Limits (U.L. and L.L.) represent 1.0 standard deviation, i.e. the middle 68.26% of a normal distribution.

head was redesigned to place adjustable sensitivity potentiometers in the head for each photodiode. The result is a cleaner engineering design which also allows the dark current and sensitivity both to be pre-set at the factory. This new design was not thoroughly tested but was easier to use even though the head was considerably larger. Further minor refinements could be made but should probably be performed by the eventual manufacturer.

One of the early questions concerning the RRWDS was: do the WIL's shift in chromaticity and luminance and, if so, over what time frame? The previous NBS report discussed some of these problems. However, for the laboratory study, weekly minor adjustments were often required to keep the WIL chromaticities within approximately one standard deviation of initial values. Field data is scanty but suggest that checks should be made at least monthly. The color calibrator data should be recorded by local personnel for possible use in detecting and correcting problems. Drops in luminance, for example, were generally a precursor of future problems in the high voltage power supply (e.g. tripler or HV junction block). Adjustment of the Green G-2 appeared to be critical in maintaining a neutral gray background, whereas the Blue G-2 was not very critical, except in adjusting a white circle for an equivalent temperature of 9300^{o}K (RCA specification). RGB phosphor dots were examined, using 10X magnification to check for misregistration and required adjustments to the CRT yoke and RGB control magnets. Although the status of the color shadow mask could also be checked for demagnetization and possible local warping, these latter tests and checks require laboratory equipment. They are given here as an indication that the variability of the WIL chromaticities and luminances can be kept to a minimum.

During laboratory testing, one of the problems investigated was whether the source of inter-system variability could be determined. Discussion with the CRT manufacturer indicated that their quality control program was designed to minimize variability between CRT's. Similar discussions with TV manufacturers indicated that their quality control programs permit somewhat more variability in RGB chromaticities. Manufacturers of special military systems indicated they had more of a problem in minimizing variability for color-coded display systems.

The conclusion drawn from these discussions is the more complex the system, the more the information content of the colors, and the more controls to be set, the greater the difficulty of maintaining inter-system constancy.

3.6 <u>WIL CHROMATICITY CHANGES OVER TIME</u>

Although not part of the laboratory testing of RRWDS, data were obtained on the chromaticities of the RGB primaries and the WIL's over approximately 6 months when no major system changes were made. The CIE plots for each of the RGB primaries displayed tightly packed measurements. On the other hand, the CIE plots of the WIL's suggested there was a slow, long term trend towards the center of the color gamut, i.e. toward white.

Since the above data confirmed the usual presumption that the color of radiation from each phosphor is stable, the above trend in the WILs must arise somewhere in the color mixing electronic circuitry. This trend raises some questions about the long-term stability of the 16 reference colors to be used in NEXRAD, depending on how the reference colors are produced. For example, if highly-stable impregnated glass filters, backlighted by halogen bulbs to produce more blue, are used, then the long-term stability problem would be greatly reduced. On the other hand, if the reference colors are produced through electronic mixing, there may be a problem with adjacent colors losing color contrast through desaturation (whitening), depending on the electronics used in NEXRAD. Detection of such changes by the color calibrator may be difficult without the development of a color look-up table based on a large number of NEXRAD systems. Since the sensitivity of the detector head would remain the same, the advantage of the suggested CRT colorimeter is that it would provide a readout in the well known CIE (x,y) color system.

4.0 ROOM ILLUMINATION EFFECTS

The final stage of the RRWDS evaluation was a laboratory assessment of the effects of room illumination. Three major types of effects from room illuminations have been observed: chromaticity shifts, luminance variations, and bright reflections from the protective glass screen of the RRWDS CRT display console.

CRT workers have frequently complained of eyestrain and fatigue from working with video display terminals or VDT's. To date, the source of eyestrain and fatigue has not been firmly established, although experiments have ranged from using pebbled CRT face surfaces (i.e. to reduce reflections) to studies of self- versus machine-pacing. The present study was designed to determine if reflections from room illuminants produce chromaticity shifts in the WIL's used in RRWDS. If chromaticity shifts did occur, they would be expected to be towards the spectral power distribution of the room illuminant. If the room illuminant was a white light source, then all the WIL colors would shift towards white, i.e. the WIL's would become more desaturated and color contrasts would be reduced. The result would be to make the discrimination of the WIL colors more difficult. The term screen reflections is used hereafter to define the total of the five reflecting surfaces involved, namely: (1) the front and back surfaces of the protective screen, (2) the front and back surfaces of the CRT glass tube, and (3) the phosphor layer itself.

4.1 LABORATORY OBSERVATIONS ON ROOM ILLUMINANT REFLECTIONS

One effect noted early in the laboratory work was the large amount of specular reflections or glare from the overhead lights reflecting from the protective screen. Due to the 18° backward tilt of the CRT, these reflections appeared greatest when a person was sitting at the console such that the plane of the protective screen was perpendicular to the typical line of vision. Bright, diffuse overhead lighting produced the most specular reflections or glare; with side lighting and reflections from other surfaces having a somewhat lesser effect. In the laboratory, illumination coming from behind the seated operator also produced severe specular reflections while direct illuminance to the face of the operator produced strong veiling glare. Both conditions should be avoided. Placement of the RRWDS console, therefore, should be made only after consideration of the various illumination sources, e.g. overhead lights, windows, and even desk lamps.

4.2 LABORATORY ILLUMINATION LEVEL EFFECTS

With an illumination of 100 fc from a fluorescent light source, as measured at the face of the protective screen, the spectral power distribution (SPD) of the WIL's was dominated by the SPD of the illuminant. With an illumination level of approximately 1 fc, the SPD of the WIL's did not show the four spectral peaks associated with the laboratory's fluorescent lighting system. Evidence of similar reflections at high illuminance was also detected at all field sites visited.

4.3 ILLUMINANT REFLECTIONS IN THE FIELD

The role of RRWDS in the forecasts of meteorologists appears to be useful, especially for monitoring moving storm systems. The meteorologists have a multiplicity of data sources for making weather predictions. When questioned, these meteorologists indicated that they were generally not affected by the screen reflections present. On the other hand, at some flight services facilities a private pilot could misinterpret certain weather conditions along his intended flight path due to the obscuring of reflections from an RRWDS's display.

4.4 ANALYSIS OF COLOR SHIFTS

4.4.1 Background Studies

As cited earlier, no studies were found in the literature that investigated the impact of building lighting environments in producing specular reflections or chromaticity shifts, on dynamic, multi-color (i.e. color-coded) visual display systems as a function of the type of ambient lighting available. A considerable amount of research has been performed on various ergonomic parameters of video display terminals (VDT's), e.g. see textbook references [2] and [7]. Some of the research cited is of unknown validity and has been seriously questioned [1], as have the differences between the various European national standards for VDT's. Unfortunately, obtaining a consensus on optimum values for the many parameters of coded self-luminous displays (e.g. via International Standards Organization standards) may be long and time-consuming. Among the more difficult parameters to be resolved are: (a) optimum number of colors to be used in color codes; (b) optimum chromaticities and brightnesses to allow for minor color deficiencies; and (c) the impact of various lighting systems and their optimum lighting geometries.

Subjective responses and logic suggests that darker colors should appear more "washed-out" or become more desaturated (loss of chroma) than brighter colors in the presence of screen reflections. For dark colors, the ambient light added by the room illumination represents a much higher percentage dilution of the emitted phosphor light than is true for bright colors. Also, no experimental evidence was found in the literature concerning an optimum ratio of various self-luminous bright colors to various dark colors, e.g. bright green vs dark green. Similarly, there was no evidence on the optimum ratios between these colors and a neutral gray, slightly luminous background. In a "real-time" weather display, the amount and distribution of the weather display's background (no weather condition) varies continuously as a function of each radar sweep. Thus, under some weather conditions a dark color may become confused with or become indistinguishable from the background. However, when the WIL color wedges (i.e. from a digitizer's Test #10) were used, each of the three dark WIL wedges appeared quite bright in contrast to the background in a darkened room. Filling the remainder of the screen with the (three) bright wedges, however, changed subjective contrast ratios so dark colors appeared dark and desaturated. Since no physical changes were involved, the apparent change must occur in the human visual system.

4.4.2 Effect of Room Illuminants on WIL Chromaticities

4.4.2.1 Laboratory Description and Procedure

The experiment on the effects of various room illuminants on WIL chromaticities was conducted in the NBS Illumination Color Laboratory with the plane of the CRT console's screen aligned along the room's long axis. A Spectra (Model PR 702AM) rapid scan spectroradiometer (SR) was used to make luminance and chromaticity measurements. The NBS Illumination Color Laboratory permits such variations as: (a) diffuse vs direct lighting; (b) changing three of the walls for reflectivity and/or color; and (c) a selection of various illuminants. Some control of the brightness level of the illuminants can be accomplished by using shutters, or disconnecting some lamps to obtain a given illuminance. Although it was desirable to equalize maximum and minimum illuminance levels across all illuminants (at the face of the CRT display), this could only be approximated.

Three illuminance levels were used in the room illuminant reflections study, namely: (a) dark or no light; (b) minimum; and (c) maximum illuminance (see Table 9). Each WIL was presented serially (1 through 6) by keyboard entry of the appropriate digital code. Thus, each WIL completely filled the circular weather target area (14.7 in. diameter). This approach eliminates interacting color relationships found in dynamic or unfixed, color-coded self-luminous displays. In order to evaluate the figures presented in this section, a number of factors must be taken into consideration: (1) a full screen display of a WIL has significantly higher luminance than a small area of the same WIL isolated from a regular weather display; and (2) the human visual response system is a non-linear system and maintains some color constancy. [However, color constancy is not operative under all possible conditions. Color constancy may be demonstrated by looking at a color sample under two different illuminants having different SPD's. For some pairs of illuminants, the sample will be seen as having very nearly the same color under the two illuminants, even though the spectrum of light reflected from the sample may be quite different in the two cases;] (3) the chromaticities of the three primaries (RGB) change at low TDLs; and (4) finally, as an extension of (1) above, a large static display appears to produce reduced screen reflections relative to a dynamic display (under the same lighting conditions) because, in the latter situation one is

Table 9. Illuminance Values for Laboratory Evaluation

Illumination Type	Illuminance
Dark Room	0
LPS Low (minimum)	41 fc
LPS High (maximum)	86 fc
HPS High (maximum)	76 fc
HPS Low (minimum)	1 fc
Cool White Fluorescent	10 fc
Color Classer Fluorescent	14 fc
Incandescent (minimum)	3 fc
Clear Mercury (minimum)	4 fc
Metal Halide (minimum)	8 fc

looking for fine details associated with rather small weather cells. Specular reflections tend to have more visual effect on fine details than on gross images.

A preliminary study was conducted in the NBS laboratory to determine the conditions most representative of the building lighting environments observed at FAA field sites. The results of this preliminary study suggested that: (a) diffuse overhead lighting (obtained by using two separate plastic diffusing panels); and (b) neutral gray walls of low reflectivity would best simulate field site lighting environments. Since illuminance could not be precisely controlled, a Weston foot-candle meter (Model 614-60) was placed at the center of the CRT face to measure the actual illuminance at the start of each set of data measurements.

4.4.2.2 Tabulated Results

Table 10 presents, in summary form, the results of many measurements of the WIL chromaticities and luminances taken under the different room illuminants (currently) available in the NBS lighting laboratory. For many readers, it may be difficult to translate or visualize the various shifts in WIL chromaticities from the numerical data presented in Table 10. To assist the reader in visualizing these shifts in WIL chromaticities, as they occur under different room illuminants, the next section presents computerized graphics, based on Table 10. The computerized graphics are presented in two forms, namely: (1) CIELAB plots and (2) the more familiar CIE chromaticity diagrams.

The human visual system responds to the total radiation, regardless of its original source, reaching the eye from every area of a visual scene. In this RRWDS experiment, the total luminance of the circular area (14.7 in diameter) emitting a particular WIL color may be analyzed into three components, namely: (1) the emitted CRT display luminances; (2) the luminances resulting from the reflection(s) of the ambient light from the CRT display; and (3) the luminance resulting from the scattering within the eye of light entering the eye from the room illuminant. Component number 2 above presents a very complex problem because of the five reflecting surfaces cited earlier. For each of the four glass surfaces there is approximately a four percent loss in the reflectance of the light energy. The effect of the ambient light striking the phosphor layer presents a separate problem, to be discussed later.

When a room illuminant is a very bright light source, then the room illuminant's contribution to the total luminance measured becomes proportionally very large. This results in the CRT colors being driven towards the color of the room illuminant, i.e. in the case of a white light all the CRT colors are driven towards the white of the room illuminant which is to say the CRT colors become more desaturated. As the intensity of the light source is reduced, the light source's contribution to total

Table 10. Measured and calculated chromaticity and luminance values for the 6 WILs and White under dark room and under selected light sources. Values measured under peak operational conditions are given for the dark condition, followed by calculated values for different sources, followed by both measured and calculated values (non-peak) under different light sources.

SOURCE	ROOM[1] ILLUM	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	WIL#1	WIL#2	WIL#3	WIL#4	WIL#5	WIL#6
				LUMINANCES AND CHROMATICITIES						
PEAK, MEASURED										
DARK	DARK	fL		80.00	69.30	23.80	118.00	52.10	12.40	4.78
		x		0.3316	0.3527	0.3456	0.3725	0.3971	0.5844	0.5794
		y		0.3790	0.5524	0.5602	0.5472	0.5298	0.3605	0.3600
NON-PEAK, MEASURED										
DARK	DARK	fL		27.14	12.90	0.28	35.64	6.14	3.90	2.20
		x		0.3075	0.3757	0.3412	0.4161	0.5240	0.6159	0.6194
		y		0.3507	0.5576	0.6051	0.5200	0.4230	0.3399	0.3412
LPS - LOW[3] PEAK, CALCULATED		fL	4.74	84.74	74.04	28.54	122.74	56.84	17.14	9.52
		x	0.5707	0.3435	0.3704	0.3921	0.3822	0.4146	0.5811	0.5754
		y	0.4287	0.3815	0.5424	0.5330	0.5414	0.5196	0.3771	0.3912
CIELAB COORDINATES		L*		100.0000	94.8964	64.7074	115.2474	85.5422	52.0924	39.9724
		a*		0.0000	-42.1081	-22.6823	-44.1014	-17.2665	57.5600	42.8770
		b*		0.0000	75.2267	58.4830	94.8961	77.0382	54.4849	49.1434
LPS - HIGH PEAK, CALCULATED		fL	27.98	107.98	97.28	51.78	145.98	80.08	40.38	32.76
		x	0.5669	0.3872	0.4261	0.4797	0.4177	0.4649	0.5729	0.5690
		y	0.4281	0.3906	0.5098	0.4801	0.5195	0.4892	0.4048	0.4166
CIELAB COORDINATES		L*		100.0000	96.0344	74.7955	112.2650	88.9989	67.5729	61.9456
		a*		0.0000	-26.7222	1.0194	-37.2705	-6.3317	45.3981	37.8745
		b*		0.0000	76.3627	73.9276	89.1796	81.7383	77.9419	81.5667

Table 10. (Continued)

SOURCE	ROOM[1] ILLUM	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	LUMINANCES AND CHROMATICITIES WIL01	WIL02	WIL03	WIL04	WIL05	WIL06
LPS - LOW NON-PEAK, MEASU	41 fc	fL		32.89	20.58	9.31	34.81	14.49	12.79	11.24
		x		0.3799	0.4729	0.5628	0.4590	0.5534	0.5845	0.5802
		y		0.3788	0.4915	0.4329	0.4954	0.4259	0.3977	0.4072
LPS - LOW NON-PEAK, CALCULATED		fL		31.88	17.64	5.02	40.38	10.88	8.64	6.94
		x		0.3404	0.4388	0.5615	0.4376	0.5442	0.5937	0.5886
		y		0.3605	0.5159	0.4358	0.5073	0.4255	0.3835	0.3965
CIELAB COORDINATES		L*			79.2324	46.6402	109.5087	65.0640	59.0596	53.7879
		a*			-14.0884	29.4576	-16.1043	37.1790	57.9492	48.9731
		b*			86.5220	78.5609	106.5252	78.0887	75.6693	77.4354
LPS - HIGH NON-PEAK, MEASURED	86 fc	fL		60.52	38.44	28.10	48.94	32.55	31.97	30.34
		x		0.3946	0.5241	0.5661	0.5151	0.5649	0.5746	0.5719
		y		0.3335	0.4541	0.4275	0.4511	0.4230	0.4162	0.4210
NON-PEAK, CALCULATED		fL		55.12	28.16	28.26	63.62	34.12	31.88	30.18
		x		0.4263	0.5653	0.5653	0.4897	0.5591	0.5742	0.5716
		y		0.3861	0.4293	0.4293	0.4751	0.4272	0.4149	0.4203
CIELAB COORDINATES		L*			89.0006	76.8422	105.6801	82.8609	80.6453	78.9010
		a*			2.0463	24.2143	-11.8701	24.8848	32.5938	29.4624
		b*			98.6770	112.8879	97.7635	101.5231	103.7157	107.8381
HPS - LOW[4] PEAK, CALCULATED		fL	12.80	92.80	82.10	36.60	130.80	64.90	25.20	17.58
		x	0.5241	0.3556	0.3858	0.4196	0.3911	0.4268	0.5563	0.5410
		y	0.4257	0.3848	0.5279	0.5045	0.5323	0.5054	0.3909	0.4056
CIELAB COORDINATES		L*		100.0000	95.3584	69.0685	114.0602	86.9651	59.1177	50.6216
		a*		0.0000	-36.0944	-12.6437	-41.2794	-13.1196	50.1180	37.3857
		b*		0.0000	72.3116	57.6946	90.2445	73.9356	53.7360	48.2397

Table 10. (Continued)

SOURCE	ROOM ILLUM[1]	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	WIL01	WIL02	WIL03	WIL04	WIL05	WIL06
					LUMINANCES AND CHROMATICITIES					
HPS - HIGH PEAK, CALCULATED		fL	0.9293	80.93	70.23	24.73	118.93	53.03	13.33	5.71
		x	0.5104	0.3335	0.3555	0.3539	0.3739	0.3996	0.5799	0.5694
		y	0.4134	0.3794	0.5500	0.5528	0.5458	0.5272	0.3637	0.3677
CIELAB COORDINATES		L*		100.0000	94.6442	62.1316	115.8820	84.7538	47.5856	31.9311
		a*		0.0000	-46.4588	-33.7882	-45.3367	-20.9235	60.1494	42.9099
		b*		0.0000	74.3646	53.0256	95.6936	75.0253	45.0068	32.3151
HPS - HIGH NON-PEAK, MEASU	76 fc	fL		36.01	25.14	13.07	39.03	18.02	16.36	14.74
		x		0.3311	0.4633	0.5213	0.4605	0.5265	0.5480	0.5400
		y		0.2864	0.4789	0.4298	0.4795	0.4222	0.4029	0.4116
HPS - HIGH NON-PEAK, CALCULATED		fL		39.94	25.70	13.08	48.44	18.94	16.70	15.00
		x		0.3681	0.4596	0.5213	0.4490	0.5241	0.5494	0.5409
		y		0.3717	0.4831	0.4298	0.4912	0.4248	0.4020	0.4108
CIELAB COORDINATES		L*			84.1459	63.9573	107.7058	74.4583	70.7364	67.6961
		a*			-5.7413	24.4908	-14.0615	29.6153	42.3725	35.9465
		b*			77.0780	61.8572	94.2908	69.2508	66.3007	64.6897
HPS - LOW NON-PEAK, MEASURED	1 fc	fL		37.24	10.25	0.37	19.43	4.39	5.30	3.12
		x		0.2679	0.3868	0.4796	0.4312	0.5591	0.6121	0.6093
		y		0.2866	0.5333	0.4937	0.5034	0.3880	0.3439	0.3394
NON-PEAK, CALCULATED		fL		28.07	13.83	1.21	36.57	7.07	4.83	3.13
		x		0.3132	0.3876	0.4815	0.4191	0.5222	0.5986	0.5912
		y		0.3525	0.5448	0.4461	0.5166	0.4217	0.3519	0.3599
CIELAB COORDINATES		L*			75.6180	24.6650	110.6931	57.2553	48.5037	39.8411
		a*			-28.2155	11.7326	-16.3452	36.9173	67.1675	54.7218
		b*			77.7974	31.0521	107.4391	60.6753	52.3696	45.8967

Table 10. (Continued)

SOURCE	ROOM[1] ILLUM	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	WIL01	WIL02	WIL03	WIL04	WIL05	WIL06
				LUMINANCES AND CHROMATICITIES						
FLUOR CW[5]		fL	3.875	83.88	73.18	27.68	121.88	55.98	16.28	8.66
PEAK, CALCULATED		x	0.3880	0.3337	0.3547	0.3520	0.3728	0.3956	0.5394	0.4952
		y	0.3993	0.3799	0.5414	0.5303	0.5408	0.5181	0.3690	0.3766
CIELAB COORDINATES		L*		100.0000	94.8412	64.1573	115.3869	85.3706	51.1564	38.4088
		a*		0.0000	-44.5201	-30.8114	-43.9659	-19.9570	53.5438	33.7500
		b*		0.0000	69.9746	46.2550	91.5011	69.0891	35.8503	21.8376
FLUOR CW	10 fc	fL		38.10	13.15	3.96	29.31	8.59	7.69	5.91
NON-PEAK, MEASURED		x		0.2989	0.3815	0.3793	0.4216	0.4757	0.5078	0.4711
		y		0.2973	0.4938	0.4047	0.4885	0.3981	0.3671	0.3764
FLUOR CW		fL		31.02	16.78	4.16	39.52	10.02	7.77	6.08
NON-PEAK, CALCULATED		x		0.3156	0.3770	0.3782	0.4116	0.4663	0.5078	0.4756
		y		0.3561	0.5108	0.4087	0.5050	0.4135	0.3671	0.3761
CIELAB COORDINATES		L*			78.5123	43.3551	109.7539	63.5825	57.1327	51.3747
		a*			-24.1078	3.7334	-14.9075	28.6953	50.4217	36.5487
		b*			61.9298	17.7036	94.6211	43.8223	35.5985	28.6430
FLUOR CC[6]		fL	4.784	84.78	74.08	28.58	122.78	56.88	17.18	9.56
PEAK, CALCULATED		x	0.2993	0.3296	0.3475	0.3344	0.3682	0.3852	0.5035	0.4376
		y	0.3513	0.3773	0.5327	0.5095	0.5356	0.5081	0.3579	0.3556
CIELAB COORDINATES		L*		100.0000	94.8991	64.7348	115.2403	85.5508	52.1388	40.0488
		a*		0.0000	-44.3635	-31.6544	-43.4464	-20.2072	50.5612	29.2223
		b*		0.0000	64.6993	37.0978	87.3396	61.8637	24.3265	8.8782
FLUOR CC	14 fc	fL		42.69	15.75	4.93	30.94	9.82	8.93	6.99
NON-PEAK, MEASURED		x		0.3132	0.3490	0.3004	0.4048	0.4184	0.4456	0.3974
		y		0.3090	0.4676	0.3561	0.4701	0.3726	0.3461	0.3480
FLUOR CC		fL		31.92	17.68	5.06	40.42	10.92	8.68	6.99
OR CALCULATED		x		0.3063	0.3474	0.3007	0.3967	0.4152	0.4440	0.4022
		y		0.3508	0.4812	0.3596	0.4920	0.3883	0.3461	0.3481
CIELAB COORDINATES		L*			79.2677	46.7938	109.4966	65.1358	59.1523	53.9029
		a*			-25.2053	-3.8837	-14.1575	24.4575	44.3405	29.5160
		b*			46.9244	1.2363	83.5684	27.5730	19.0638	11.8087

Table 10. (Continued)

SOURCE	ROOM[1] ILLUM	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	WILØ1	WILØ2	WILØ3	WILØ4	WILØ5	WILØ6
					LUMINANCES AND CHROMATICITIES					
TUNGSTEN PEAK, CALCULATED		fL	5.572	85.57	74.87	29.37	123.57	57.67	17.97	10.35
		x	0.4636	0.3393	0.3632	0.3734	0.3777	0.4049	0.5511	0.5219
		y	0.4259	0.3817	0.5405	0.5286	0.5403	0.5176	0.3785	0.3927
CIELAB COORDINATES		L*		100.0000	94.9483	65.2192	115.1155	85.7035	52.9519	41.3705
		a*		0.0000	-42.5702	-25.8103	-43.4664	-18.2696	53.1423	35.4878
		b*		0.0000	71.7538	51.3720	92.1699	71.9790	43.5558	32.8848
TUNGSTEN NON-PEAK, MEASURED	3 fc	fL		40.09	16.82	5.81	32.19	10.85	9.52	8.18
		x		0.3123	0.4170	0.4600	0.4433	0.5740	0.5366	0.5232
		y		0.3110	0.4994	0.4304	0.4851	0.4084	0.3849	0.3939
TUNGSTEN NON-PEAK, CALCULATED		fL		32.71	18.47	5.85	41.21	11.71	9.47	7.77
		x		0.3301	0.4075	0.4594	0.4237	0.4954	0.5347	0.5151
		y		0.3616	0.5100	0.4320	0.5049	0.4244	0.3857	0.3979
CIELAB COORDINATES		L*			79.8798	49.3618	109.2844	66.3694	60.7344	55.8517
		a*			-17.9725	14.7054	-14.9428	30.3192	49.4207	38.2314
		b*			70.3206	37.7032	97.3533	56.0554	49.8802	45.1797
MERCURY (CLEAR) PEAK, CALCULATED		fL	5.065	85.07	74.37	28.87	123.07	57.17	17.47	9.85
		x	0.3548	0.3328	0.3529	0.3476	0.3716	0.3927	0.5268	0.4751
		y	0.4397	0.3821	0.5429	0.5345	0.5417	0.5204	0.3804	0.3970
CIELAB COORDINATES		L*		100.0000	94.9168	64.9093	115.1956	85.6056	52.4327	40.5301
		a*		0.0000	-44.4280	-32.3593	-43.2567	-20.4285	49.3301	27.2199
		b*		0.0000	69.6047	46.5508	90.8126	68.7764	36.6864	23.7918
MERCURY (CLEAR) NON-PEAK, MEASURED	4 fc	fL		54.96	23.38	5.33	37.92	10.69	8.94	7.05
		x		0.3195	0.3665	0.3539	0.4133	0.4545	0.4857	0.4448
		y		0.3486	0.5308	0.4458	0.5030	0.4252	0.3909	0.4055
MERCURY (CLEAR) NON-PEAK, CALCULATED		fL		32.21	17.97	5.35	40.71	11.21	8.96	7.27
		x		0.3136	0.3688	0.3543	0.4073	0.4491	0.4850	0.4498
		y		0.3622	0.5184	0.4461	0.5084	0.4304	0.3899	0.4043
CIELAB COORDINATES		L*			79.4903	47.7479	109.4198	65.5870	59.7330	54.6212
		a*			-26.1039	-7.7979	-13.8367	22.5821	41.9110	26.5278
		b*			61.8661	22.6674	92.9762	45.1777	37.8271	31.8134

Table 10. (Continued)

SOURCE	ROOM[1] ILLUM	VALUES	SCREEN REFLECTIONS,[2] WITH NO SIGNAL	WHITE	WIL01	WIL02	WIL03	WIL04	WIL05	WIL06
					LUMINANCES AND CHROMATICITIES					
METAL HALIDE PEAK, CALCULATED		fL	3.099	83.10	72.40	26.90	121.10	55.20	15.50	7.88
		x	0.3976	0.3338	0.3552	0.3532	0.3733	0.3971	0.5517	0.5148
		y	0.4238	0.3805	0.5453	0.5402	0.5432	0.5225	0.3716	0.3827
CIELAB COORDINATES		L*		100.0000	94.7908	63.6474	115.5143	85.2130	50.2767	36.8952
		a*		0.0000	-45.1344	-32.0309	-44.2859	-20.3580	54.7497	34.9289
		b*		0.0000	71.8117	49.3607	93.0909	71.6171	39.9526	25.5159
METAL HALIDE NON-PEAK, MEASURED	8 fc	fL		42.63	15.81	3.76	36.73	9.43	7.32	5.96
		x		0.3042	0.3896	0.3910	0.4217	0.4643	0.5157	0.4966
		y		0.3146	0.5109	0.4267	0.4975	0.4263	0.3716	0.3825
METAL HALIDE NON-PEAK, CALCULATED		fL		30.24	16.00	3.38	38.74	9.24	7.00	5.30
		x		0.3153	0.3810	0.3942	0.4143	0.4817	0.5309	0.5016
		y		0.3570	0.5255	0.4346	0.5107	0.4233	0.3726	0.3851
CIELAB COORDINATES		L*			77.8209	39.8725	109.9848	62.1287	55.2118	48.9214
		a*			-25.7381	2.1672	-15.1513	29.6972	53.0703	38.7040
		b*			68.1177	23.6744	99.3199	50.4490	42.2379	35.3201

[1] Room Illuminance as measured by a Weston foot-candle meter (Model 614-60) placed at the center of the protective CRT screen.

[2] Screen reflections with no power to CRT console as measured by a Photo Research spectroradiometer (Model PR 702 AM).

[3] Low Pressure Sodium

[4] High Pressure Sodium

[5] Cool White

[6] Color Classer

luminance becomes proportionally less, and has less effect on shifting the chromaticities of the WIL's of the CRT display. Obviously, the extreme condition is total darkness where the only luminances available are those of the WIL's themselves. Thus, in this report, the reference conditions are always the WIL's as measured in complete darkness.

Since lighting engineers can eliminate direct light from reaching the human eye, e.g. by employing recessed lighting, this study used two layers of overhead plastic diffusing panels to reduce or eliminate scattered direct light as a component (component #3 above) of the total luminances involved. The walls of the lighting laboratory were a neutral, medium grey having low reflectance in the range of 20-30%. Since the walls are diffuse, extended sources of reflected light which are considerably dimmer then the ceiling, the wall's reflected light was considered relatively insignificant compared to that of the ceiling for the purposes of this study. In addition, the lens shield of the SR is designed to reduce or prevent direct light from entering the lens of the SR during measurement taking. Thus, any shift in WIL chromaticity could be attributed to the room illuminant's reflected light from the CRT console display.

Table 10 contains sets of luminance and chromaticity data labelled "measured" and "calculated". The "measured" data are spectroradiometric measurements taken with the room illuminant(s) ON and the WILs displayed to fill the 14.7 diameter circular radar sweep area. These data are the net result of the CRT display values plus the superimposition of the veiling luminance(s) of the room light. The "calculated" data represent the results of a computerized calculation (discussed later) which utilizes the luminance and chromaticity data of the WILs, as measured under dark room conditions plus the spectroradiometric measurements of the room light reflections, as measured with the CRT console OFF. Theoretically, the measured and calculated data should be in close agreement. That they were not is discussed in the next paragraph.

The measured values presented in Table 10 contain certain anomalies which required further experimentation and evaluation to understand what occurred in the room light ON measurements. Of the two anomalies in the data of Table 10, one had a small effect and the other a much larger one. The small effect usually occurred under maximum luminance conditions. This small anomaly occurred when the measured luminance was slightly larger than the calculated luminance. This increase in luminance was thought to be due to a slight fluorescing of the phosphor layer of the CRT and is discussed in the next section. The second and larger anomaly occurred when the measured luminance (i.e. with the added room light) was less than the luminance of the WIL(s), as measured under dark room conditions. Theoretically this result should not but did occur. The answer appears to lie in the electronics of the RRWDS. As cited in NBSIR 84-2924 there are day-to-day fluctuations in the WIL luminances. However in the present study these larger fluctuations appeared to be caused by variations in the anode voltage due to malfunctioning triplers in the HV sections of the power supplies (PS #1 and #2). The question of concern regarding these anomalies is whether any change in WIL luminance will result in a change in WIL chromaticity. Of particular concern is whether a degraded RRWDS produces changes in WIL chromaticity sufficient to cause errors in interpreting live weather displays.

4.4.2.3 Interpretation of Table 10

The WIL luminances and chromaticities presented in the first row were measured under dark (i.e. no light) conditions during October 1983. These measurements were taken after the RRWDS manufacturer's technical representative (TR) had "peaked" the NBS RRWDS in compliance with FAA's Field Site Acceptance Specifications. Note that White had a luminance of 80 fL whereas the specification requires a minimum luminance for White of 77 fL. In the judgement of the manufacturer's TR, the "peaked" systems WIL colors were approximately similar to those originally agreed upon [6]. During the three day alignment procedure, various boards and parts (i.e. HV function block and PS #1 and #2 triplers) were replaced. The new triplers were improved parts designed to insure long-term reliability of the 30 kv to the CRT anode. Critical system parameters were recorded for maintenance purposes, e.g. critical waveforms were photographed and test point (TP)/potentiometer voltages recorded for various system controls. Thus, the data presented in NBSIR 84-2924 was based on a "peaked" system.

The measured values in Table 10 reflect a "non-peak" system after two years of continuous operation of and experimentation with the RRWDS. The low luminance value of 27 fL for White indicates a drop in anode voltage produced by deteriorating triplers. In order to keep the image from jumping in and out, the Brightness Control was reduced slightly for the room illuminant experiment. Comparison of critical waveforms and some of the test point voltages between the Leesburg systems (#1 and #2) and the NBS RRWDS (at the time of the room illuminant experiment) indicated that all three systems were performing properly except for the tripler problem. This finding suggests that the shifts in WIL chromaticity found in the laboratory, as a function of the room illuminants tested, may be generalized to field RRWDS under equivalent lighting geometries and conditions.

The column labeled "Screen Reflections, with No Signal" refers to the light energy reflected from the screen of the CRT surfaces, (the five areas of reflectance cited earlier), with no power applied to the CRT console. If the screen were a "perfect" or simply a nonselective reflector then the spectral power distribution (SPD) of this reflection should be similar to the SPD of the room illuminant itself. However, based on experimental data, the SPD's of the room illuminant's reflections and the SPD's of the room illuminant measured directly were not exactly the same. The SPD of the room illuminant was measured using a pressed polytetrafluorethylene (PTFE) powder plaque [18] which is a near perfect reflector. The PTFE plaque was attached to a large piece of black felt so it could be placed over the console face and located in the same measurement position used to measure the CRT screen reflections.

4.4.2.4 Fluorescence/Phosphorescence of CRT Display

Since many of the lamps in the NBS lighting laboratory have many hours of use, the SPD's of each room illuminant were checked prior to the study. Under high illumination of some lamps, e.g. metal halide, the measured WIL values under the room illuminant were slightly higher than the calculated values of the WIL, as measured in the dark, plus the reflected light measured with the console power off. The question posed was: "Where did this extra spectral power come from?" This question was answered by the following experiments:

Experiment #1: Four (400 watt) metal halide lamps were energized and warmed up for 15 minutes with the (closeable) shutters wide open. A black felt cloth, with the PTFE plaque attached, was placed over the face of the CRT console. The spectral radiance of the PTFE plaque was measured by the SR, resulting in a SPD plot and/or print-out of the spectral power, from 390 to 730 nanometers (nm) at 2 nm intervals. Five to 15 minutes after the black felt was removed, the same measurement procedure was repeated for the power-off CRT display. Comparison of the two SPD's indicated many small but a few large increases in spectral power over the 2 nm intervals, particularly for the green wavelengths.

Comparison of the total measured luminance with a calculated luminance indicated the measured luminance was slightly larger than the corresponding calculated value. Since the ordinary reflectance of the CRT could not exceed that of the PTFE, the spectral power increases can only be explained by assuming that the CRT's RGB phosphors were fluorescing due to the high intensity of the light energy from the metal halide lamps. At low light intensities of the metal halide lamps, achieved by closing the shutters, this phenomenon did not occur. Experiments in which the black felt was used to control exposure time to the metal halide lamps, indicated that exposure times of ten to fifteen minutes produced the maximum fluorescence of the RGB phosphors.

Experiment #2: This experiment replicated #1 except that after the fifteen minute warm-up, the shutters were closed. With the shutters closed, 2-8 fc of illumination were present due to light leakage around the shutters. SR measurements were taken every five minutes for up to thirty minutes. This latter time interval was a direct function of the initial fifteen minutes exposure time. For exposure times of less than ten minutes, the period of phosphorescence was reduced.

The first five minute SPD plot indicated significant amounts of added spectral energy over the green wavelengths with lesser amounts over the blue and red wavelengths. From visual inspection, the first five minute plot was W shaped. During the next five (at five minute intervals) measurements, the overall added spectral energy or phosphorescence decreased. After the thirty minutes, the black felt, with the PTFE plaque attached, was placed over the console face and another SR measurement taken. Comparison of the PTFE SPD plot against the last test (30 minute) plot indicated the shapes of the two plots were similar. The major difference was less spectral energy in the SPD plot taken from the CRT console display. This loss of spectral energy from the CRT console display may be explained by light losses at the four glass display surfaces, i.e. at lease a 4% loss per each glass surface plus an additional loss at the phosphor layer.

The results of both experiments 1 and 2 indicated that high light intensities produce both fluorescence and phosphorescence of the CRT's RGB phosphors. Low light intensities, e.g. 2-8 fc after the metal halide shutters were closed, were not sufficient to produce either fluorescence or phosphorescence. Further experiments with other room illuminants suggest that fluorescence and phosphorescence were a direct function of the initial light intensity. The length of initial exposure time tended to effect the period of phosphorescence but appeared to be less important than the initial light intensity itself.

Experiment #3: A "black light" fluorescent lamp (F15 T8) was set up vertically with a rectangular piece of aluminum roughly bent to act as a parabolic reflector. Since the "black light" fluorescent tube was only rated at 15 watts, it was desirable to increase the ultra-violet irradiance on the CRT display. The "black light" was not a pure UV source since it produced some light that was visually detectable.

The crude "black light" set-up precluded the measurement of the amount of the fluorescence of the RGB phosphors. As judged visually, the RGB phosphors fluoresced fairly strongly, but not as much as regular fluorescent color samples. In contrast, the PTFE plaque visually appeared almost black when held up against the fluorescing CRT display. The appearance of the PTFE plaque indicated that the amount of light emitted in the visible range by the "black light" source was relatively small.

The duration of the phosphorescent phase, after the crude set-up was removed, was very short, approximately five minutes. This was probably due to the low intensity level of the UV light source. The SPD of the phosphorescence showed maximum spectral power at the blue and red wavelengths of the visible spectrum. The relative proportion of spectral energy in the green wavelengths was considerably less than that found for the metal halide lamps. Thus, the SPD of the phosphorescence produced by the "black light" was roughly U shaped.

Further experimentation with all the room illuminants used in this study indicated they all produced fluorescence and phosphorescence at the maximum illuminance obtainable in the lighting laboratory. At the minimum illuminance, less than 10 fc, none of the room illuminants produced phosphorescence. If any of the room illuminants produced fluorescence, it was below the detection ability of the measurement equipment used. At maximum illuminance, each room illuminant had its own characteristic effect related to its SPD, as measured by the SR using the PTFE plaque as a reference. As one would expect, since the low pressure sodium illuminant has little energy in the short wavelengths, it produced the least amount of fluorescence and phosphorescence whereas UV- and violet rich mercury and metal halide lamps produced the most. These latter results on fluorescence and phosphorescence were in agreement with the Stokes radiation theory wherein a photon of a given wavelength will ordinarily only produce a re-emitted photon of a longer wavelength. There is also an anti-Stokes theory which states that high energy photons (UV) may produce re-emitted photons at shorter wavelengths but the amount is very small.

It should be noted that the NBS lighting laboratory was not designed to equalize the maximum or minimum illuminance across all room illuminants. Since the amount of fluorescence and phosphorescence appears to be a direct function of the intensity of the illumination, the relative rankings of the room illuminants cited in the preceding paragraph should be considered as tentative only. From a knowledge of the SPDs of the room illuminants used in this experiment, the rankings appear appropriate but NBS does not have equal-illuminance data to support the rankings unequivocally.

4.4.2.5 RRWDS Variability

Examination of Table 10 reveals a small number of occasions where the luminance of a WIL, as measured under a room illuminant, is less than the luminance of the same WIL, as measured under dark conditions. This decrease in total luminance is not constant for all WIL's under one illuminant nor is it constant for a single WIL under all room illuminants. The lack of constancy in the measured WIL luminances raises three separate but related issues about the anomalies seen in Figure 10. The first issue concerns the anomaly that some of the WIL luminances, when measured under the room illuminants, were less than when measured under dark conditions. Physically, the superimposition of reflected room light should simply add to the WIL luminance(s) to produce a larger total luminance. If the room light can be considered a constant, then it must be true that the WIL luminance(s), if they had been measured in the dark at the start of each day's measurements, should have been less than the "dark" values given in Table 10. The in-the-dark measurements were taken only at the start of the three month's long experiment. Thus, the answer to this issue lies in the day-to-day variability of the electronics of the RRWDS's display console, and in particular the HV power supplies' tripler. The malfunctioning of the triplers led to unusual and (at the time) unsuspected differences in the total luminance measurements under the various light sources investigated. Following completion of this study, the potting material used in the tripler(s) failed completely with the result that the HV arcs to ground. This failure precluded post-experiment measurements of the WILs, again under the dark room conditions.

The second issue is whether the day-to-day variations in the RRWDS's performance also affected the WIL chromaticities. Theoretical chromaticities were first calculated on the basis of a simple additive model. In the model the light emitted by the WILs, originally measured in the dark, was assumed to combine with the ambient room light reflected from the CRT screen, measured with the CRT off, to produce a total additive chromaticity. These calculations, of course, are not influenced by day-to-day variations in the WIL outputs. When the measured and calculated chromaticities were plotted and compared for the anomalies in Table 10, only small and apparently random differences in chromaticities were found. This finding indicates that changes in WIL luminance (issue one above) did not necessarily result in changes in WIL chromaticity. However, this finding should not be generalized to all malfunctions in the HV section for the CRT display.

The third issue, which involves both luminance and chromaticity, is: Does the reflected room light combine with the emitted WIL light(s) in a simple additive way, as would be expected on the basis of the physics of light, or is there a more complex interactive effect involved? Such an interaction might occur if the glass surfaces of the CRT or the phosphor layer, were not non-selective reflectors; or if the room light excited strong fluorescence in the phosphor layer. Again, comparison of the measured values versus the calculated values for luminance and for chromaticity indicates that the combination of the two light sources, at low levels of the room light, produces net results that are in good agreement with the concept of simple additivity.

At moderate to high levels of this room light, some fluorescence of the phosphor layer does occur as mentioned earlier. Examination of Table 10 and Figure 12-20 indicates that the white target areas luminance and chromaticity was more affected by this fluorescence than the WILs. For example, the measured luminances of the white target were greater than the calculated luminances under high illumination levels for the LPS and HPS room light sources. The chromaticities of the white target were also shifted in unexpected directions as can be seen in Figures 12-20. The basis for the unusual shift in the white target area as compared to the WILs should be investigated further; and especially the role of photon stimulation of the CRT's phosphor layer and the resulting fluorescence.

In summary, the above discussion of some issues raised by apparent anomalies in Table 10 establishes the fact most can be explained by erratic variations in the CRT display. These variations were due to (at the time) unknown malfunctioning of the triplers in the CRT HV power supply(s). Thus, the anomalies are not due to errors in the measurement instrument or in the measurement procedure. The effect of fluorescence by photon stimulation on the chromaticities of CRT colors should be investigated further to explain the remaining anomalies.

4.4.2.6 CIELAB Color Space

CIELAB color space is designed to compare object colors in a uniform color space, based on the relationship of the object colors to some predetermined reference white. The reference white may be any available white, e.g. the white of a piece of paper on which there are colors. Thus, to calculate the effect of the various room illuminants' reflections on the CIELAB coordinates of each WIL, two assumptions had to be made. The first assumption concerns the selection of a reference white. The reference white selected was the White column of Table 10, as measured under dark conditions. Since this reference white had the same RGB digital levels as the white used in the built-in RRWDS geographical maps of a live weather display, it was an appropriate reference white. The other assumption used in the CIELAB equations involved the reflections of the room illuminant from the CRT display, as measured with the power off. For the purposes of the CIELAB calculations, it was assumed that the reflections (plus some fluorescence at high illuminance levels) obtained with the power off would be constant across all WIL's for any given illuminant, and would combine in a simple additive way with the emitted WIL light. In other words, the fluorescence of the RGB phosphors, as stimulated by photon emissions, simply adds to the emitted light of the WIL's, as stimulated by electron emissions, i.e. the two types of emissions do not interact in some strange way. It is similarly assumed that there is no interaction between the reflected room light and electron-driven emissions from the phosphor layer.

The reflection values used in the CIELAB calculations are presented in Table 10 under the heading "Screen Reflections, with No Signal." A special computer program was written to perform the desired calculation of additive light mixtures. This program incorporated two CIELAB subroutines. The program changes the (x,y) values of the reference white, the measured WIL's, and the display screen reflections to their tristimulus values, (i.e. X,Y,Z) in order to make the appropriate calculations. For the reference condition the CIELAB calculations compared the measured WIL color, measured in the dark, to the reference white, measured in the dark. Then to calculate the CIELAB co-ordinates of a WIL plus display screen reflections, the tristimulus values of the display screen reflections, as measured with the CRT off, were added to both the reference white and the WIL, both measured in the dark. In these calculations, as in real life, the display screen reflection tends to shift all colors toward itself in color. In CIELAB the reference white always maps to L*=100, a*=0, and b*=0 as can be seen in Table 10. The final conversion of the tristimulus values (X,Y,Z) back to the x,y coordinate system are presented in Table 10 as "calculated" values. It should be noted that the calculated luminance values are always the sum of the WIL luminances, as measured in the dark, plus the luminance of the display screen due to the room lights, as measured with the CRT console power off.

CIELAB plots of the calculated values along with the measured values were made for all room illuminants. Comparison of the calculated versus the measured values showed no significant chromaticity differences between these two sets of values for any of the room illuminants. These findings may be interpreted in two ways. First, the decreases in total luminance, i.e. where the WIL luminance plus the luminance due to display screen reflections is less than the WIL luminance measured in the dark, is due to a drop in the anode voltage of the RRWDS CRT. More importantly this decrease in total luminance apparently affected all three about equally, an so did not produce a shift in WIL chromaticity. Second, the presence of display screen reflections, due to ambient lighting, did produce significant WIL chromaticity shifts. The amount of WIL chromaticity shifts is a direct function of the intensity of the room illuminant that is being reflected off the display screen face.

The significant findings of this part of the report may be summarized as follows:

(1) The luminance, produced by the ambient lighting systems reflections off the display screen, can and does produce significant shifts in WIL chromaticity. The direction of the WIL chromaticity shifts is dependent on the type of lighting used and the magnitude of the shifts depends on the intensity of the reflections, as measured by the total luminance of the CRT display. Much additional experimental information is required to determine such parameters as: (a) the best lighting source, e.g. LPS versus metal halide, for CRT viewing; (b) the maximum light intensity that will not produce fluorescence or phosphorescence of the RGB layer of the CRT; and (c) the most appropriate lighting geometry for CRT viewing. One recommendation would be to eliminate massive, diffuse overhead lighting in favor of overhead point source lighting to highlight light/dark contrast ratios along with point source lighting (as appropriate) for work station lighting. Although initially this recommendation may require extensive and expensive lighting evaluations, the end result would increase worker efficiency as well as reduce long-term lighting energy costs. The fluorescence and phosphorescence of the phosphor layer of the CRT display presumably may reduce a viewer's ability to discriminate between colors of a color-coded CRT display, but much less than the reflected light. The overall loss of information may be significant under certain lighting conditions, e.g. when a CRT display is located where

relatively strong lighting from an outdoor environment may provide obscuring light such as in some airport control towers or field service units. Potentially there are short term fixes for this problem, e.g. canopies over the CRT display. However, additional experimentation would be required to delineate and/or standardize the best lighting sources and the best lighting geometries required to improve worker efficiency and reduce long-term lighting energy costs.

4.4.3 Comparison of Various Illuminants

Figures 3 through 12 show the effect of illumination from various overhead illuminants on the chromaticities of the six WIL's as measured by the spectroradiometer (SR). The effect on the six WIL's of each illuminant (triangles) is compared against the six WIL chromaticities taken under complete dark conditions (squares). The CIE x,y coordinates obtained by the SR were the data inputs to a CIELAB computer program used to make the plots/figures showing color differences between the dark and illuminated conditions. CIELAB, more formally known as the CIE 1976 L*a*b* color space, is an accepted formula for the amount of color difference perceived between any two colors, and the name also refers to the geometric representation of the color spacing implied by the formula. The idea of a so-called uniform color space is a space in which the distance between the points representing any two colors is proportional to the amount of difference perceived between those colors.

Several realistic features incorporated in the CIELAB space are: (a) recognition of the non-linear relationship between stimulus and response characterizing color vision, as with most other sensory processes; (b) an allowance, of a simple sort, for the chromatic adaptation process that contributes to the maintenance of color constancy; and (c) an adjustment for the fact that if a color of fixed chromaticity is varied only in brightness or lightness, its (perceived) saturation (vividness) decreases as it gets darker.

The L* variable of CIELAB corresponds to lightness or brightness. The chromatic variables are symbolized by a*, the red (positive) -green (negative) dimension, and b*, the yellow (positive) -blue (negative) dimension (see figure 2). Although the L* dimension does not appear in Figures 3-12, the quantities a* and b* are influenced by the luminance of the light, in accordance with (c) of the preceding paragraph. These a*b* diagrams are intended to predict color appearance and color difference, but the quantities plotted are calculated exclusively from the physical spectroradiometric data.

4.4.4 Results

There are several different computer graphics programs to make CIELAB plots according to opponent color theory. Both programs depict the same information. The first program produces diagrams

LPS 41 FC, MODERATE, RRWDS

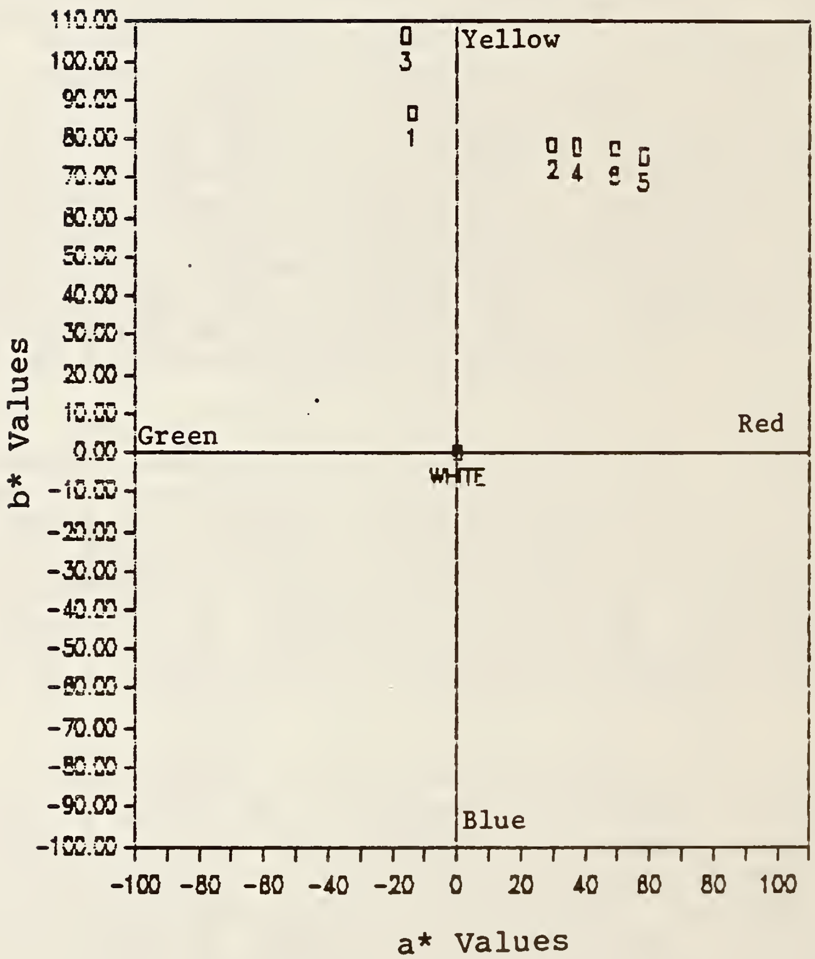

Figure 2. Effect of LPS illuminant on the measured WILs.

wherein white is placed close to the center of the diagram while displaying four nearly equal quadrants. These diagrams point up the opponent-colors structure of a*b* space, even if (as here) some of the quadrants are empty. The resulting diagrams (Figure 2) show major relationships between all colors according to opponent color theory. The second program scales and centers the diagrams so as to encompass just the data points entered; i.e. regardless of whether entire quadrants are eliminated (as they are in Figures 3-11). These diagrams display finer details since they incorporate only the colors of interest. Therefore, these diagrams are useful where colors are nearly alike as for WILs #5 and #6.

Figure 3 shows the effect of illumination from a Low Pressure Sodium (LPS) lamp, at minimum luminance, on the six WIL chromaticities (triangles). The SPD of LPS lamps shows that the bulk of the radiant energy occurs in two very narrow peaks at ("D lines") 589.0 and 589.6 nanometers, i.e. the resonance wavelengths of the electrically excited sodium atom. Examination of Figure 3 shows, that under low LPS illuminance, the WIL's tend to be grouped into two sets of nearby colors, i.e. WIL's (1 and 3) and (2,4,5,6). Within each set, the WIL's appear difficult to distinguish. Under LPS the CIELAB predicted perceived WIL colors should have a strongly yellowish tinge, as indicated by the high b* values for all six WILs. WIL #3 (a bright yellow is shifted very little under the LPS light whereas WIL #2 (a dark green) is shifted the most (it changes quadrants) to become a perceived reddish yellow. WILs #2, #4, #5 and #6 are all shifted to a reddish-yellow in contrast to their color in the dark. This occurs even though the WIL's are self-luminous. In contrast, when LPS light is reflected from almost all colored opaque surfaces, they are visually described as black, tan, or yellow, (except red or orange fluorescent colors). Since LPS has a uniquely low color rendering index of -44, it is used almost solely for outdoor application where high brightness and efficiency are more important than color rendition.

Figure 4 shows the CIELAB predicted perceived colors for the WIL's from a high luminance LPS lighting source. Here the effect of high LPS illuminance is to group the WIL's into two internally indistinguishable groups; one originally having a green component in the dark (1,2,3) and one having a red component (4,5,6). Since the two groups are relatively close together, a deuteranope or protanope (i.e. one who strongly confuses red and green) should see only yellowish shades varying only in brightness level and saturation. Even most normal vision individuals would have trouble distinguishing the six WIL's because of the shift of all the colors toward orange/yellow - the color of the wavelengths characteristic of LPS. It is important to remember that the input data to the CIELAB program was objectively obtained by means of the SR. Although spectroradiometry indicates the presence of trace amounts of power in the blue or short wavelengths of the LPS SPD, this amount is usually insufficient to allow accurate recognition of blue colors. As a result, when

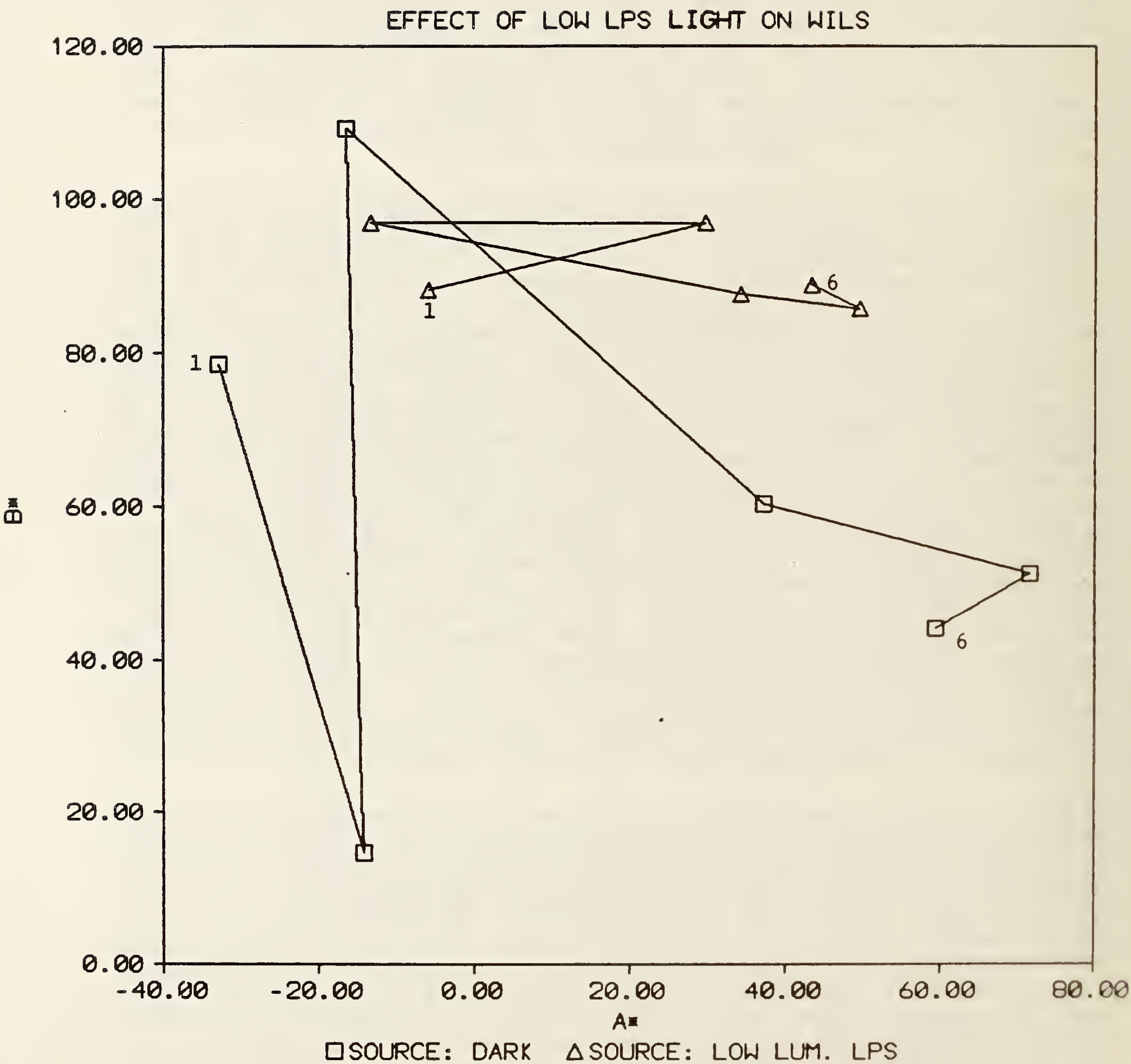

Figure 3. Effect of LPS illuminant (low illuminance of 41 fc) on WIL colors (triangles) as compared with their appearance under dark conditions (squares).

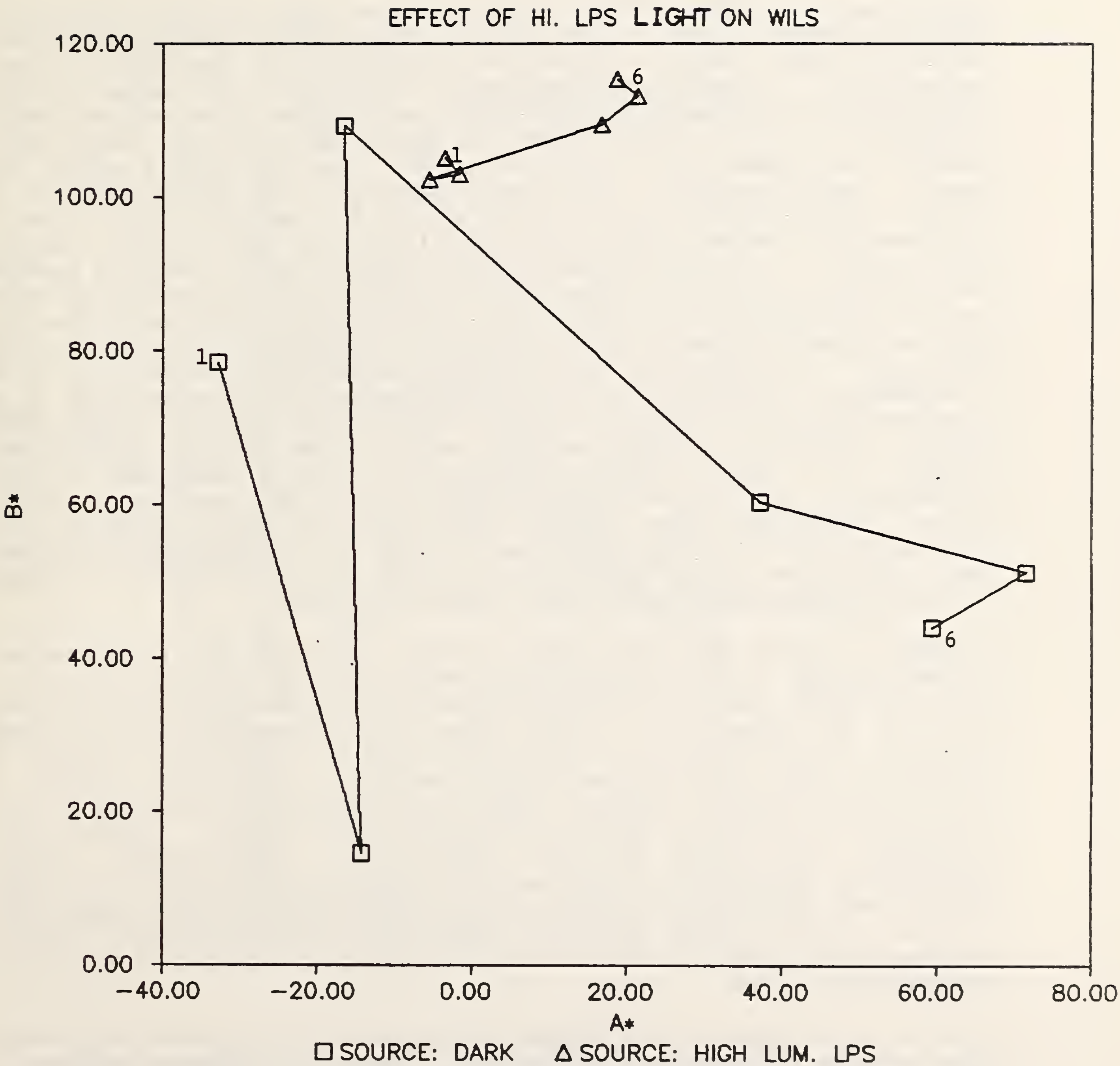

Figure 4. Effect of LPS illuminant (high illuminance of 86 fc) on WIL colors as compared to their appearance under dark conditions.

LPS sources are used occasionally for indoor purposes (e.g. high ceilinged warehouses or heavy manufacturing facilities), they should be interspersed with sufficient metal halide or mercury lamps to provide the extra energy needed in the blue part of the spectrum.

High Pressure Sodium (HPS) lamps are one type of high intensity discharge (HID) lamps - some of the others being metal halide and mercury vapor lamps - that are becoming more frequently used, especially in street lighting. HPS and LPS lamps differ significantly in their construction and in their operation. For example, a 400 watt LPS lamp is approximately four feet long, whereas HPS lamps are less than a foot long and have a screw-in-base. Operationally, a LPS lamp operates most efficiently at a sodium vapor pressure of the order of 0.7 pascal ($5x10^{-3}$ torr) whereas HPS lamps operate most efficiently at 27 kilo pascals (200 torr). To achieve the higher sodium vapor pressure needed for HPS lamps, a small quantity of sodium-mercury amalgam is used so that the mercury vapor acts as a buffer gas to raise the sodium vapor pressure and increase the operating voltage of the HPS lamp. The higher sodium pressure causes the sodium ("D" line frequency) radiation to be self-absorbed and re-radiated as a continuation on both sides of this "D" line frequency. Thus, HPS lamps typically radiate energy across the visible spectrum-except for a "dark" region around the "D" line frequency or 589 nanometers. The golden-white light of the HPS lamp has a better color rendering index (CRI=21) than that of LPS. However, the efficacy of HPS is less than that of LPS - i.e. efficacies of 60-140 lumens per watt, depending on size for HPS whereas LPS has efficacies that may exceed 180 lumens per watt.

Figures 5 and 6 show the effect of low and high HPS illuminance, respectively, on the predicted perceived colors of the six WIL's. Figure 5 shows that the predicted perceived chromaticities of the six WIL's changed very little from the chromaticities measured under a dark (no light) condition. On the other hand, Figure 6 indicates that high levels of HPS induced a significant shift of all six WIL's in the yellow (high b*) direction, resulting in two groupings of WIL's 1 and 3 and WIL's 2,4,5 and 6. Within each grouping, the WIL's will be difficult to distinguish, except possibly by brightness differences. Although brightness (L*) was calculated and used, it was not plotted separately for each WIL. If the L*s had been plotted they would have presented better evidence as to which WIL's could be distinguished by brightness differences alone.

Figure 7 presents the effect of illumination from cool-white fluorescent lamps supplying medium illuminance (approximately 10 fc). Again, although the relationships between the WIL's remains approximately the same as for dark conditions, there is a trend for the reddish WIL's (4,5,6) to lose a significant portion of their redness, i.e. they tend to become desaturated and move towards the white or neutral condition (i.e. where a* and b* = 0). Under the color classer fluorescent illuminant (Figure 8),

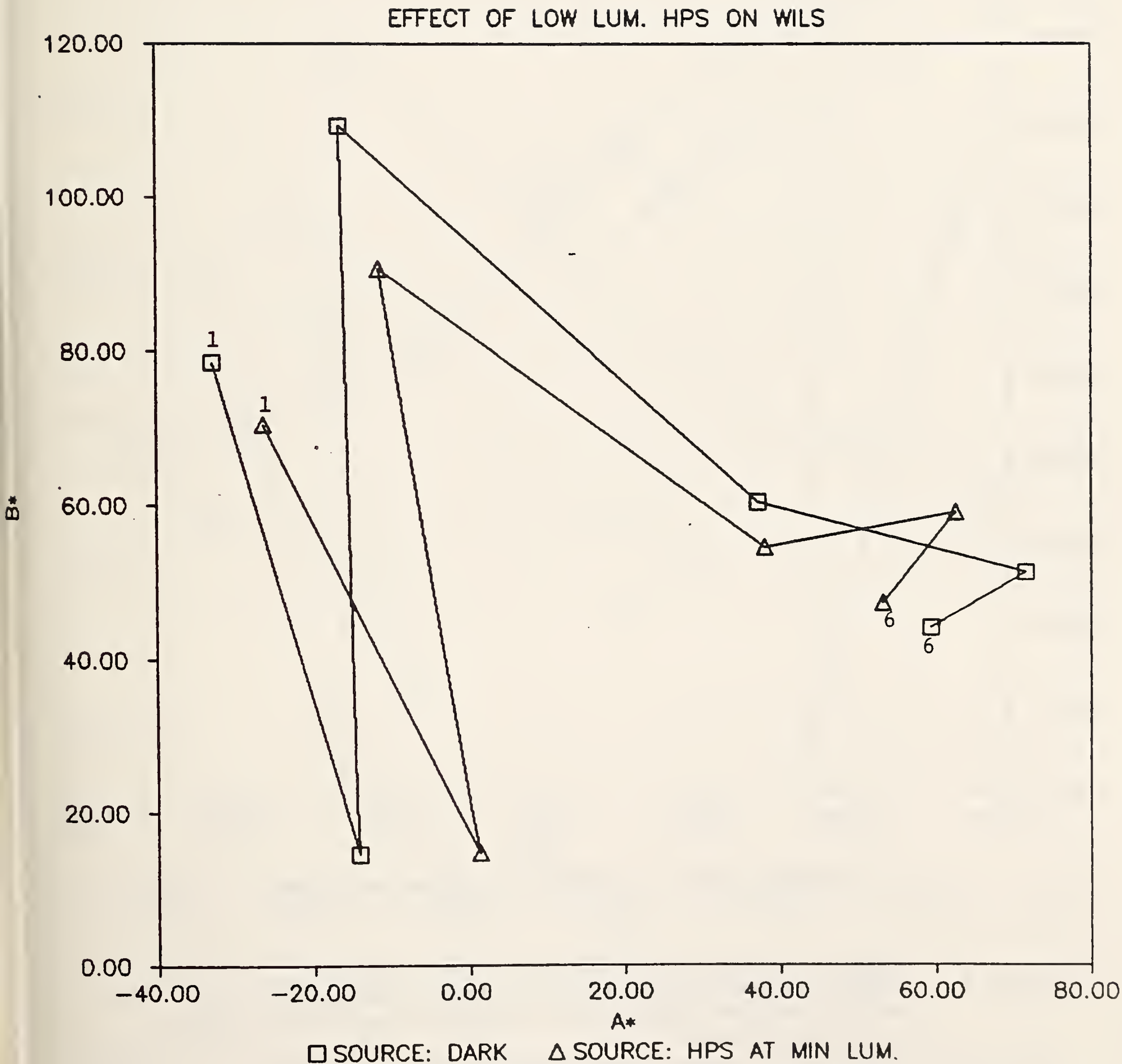

Figure 5. Effect of HPS illuminant (low illuminance of 3 fc) on WIL colors compared to their appearance under dark conditions.

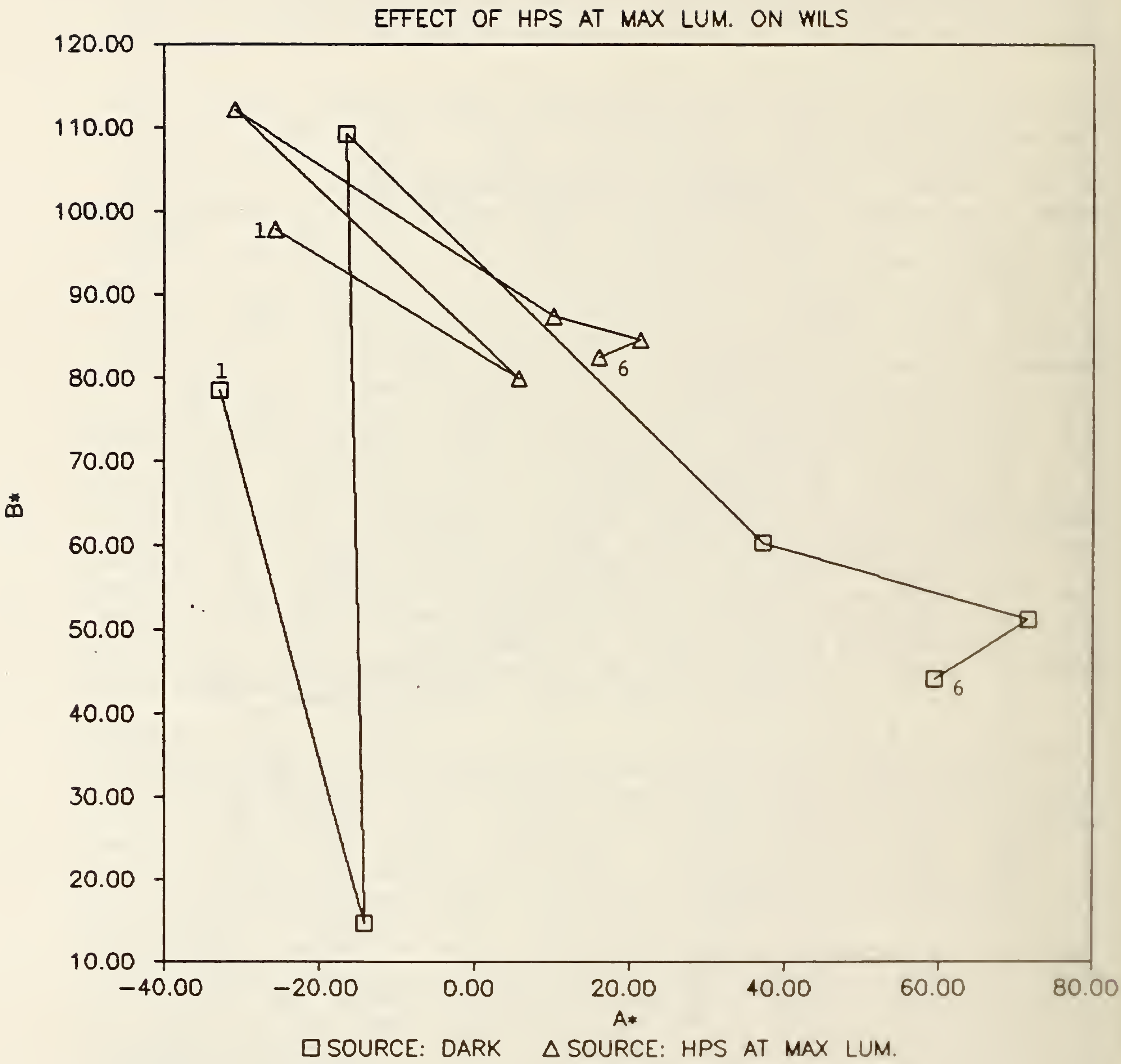

Figure 6. Effect of HPS illuminant (high illuminance of 76 fc) on WIL colors compared to their appearance under dark conditions.

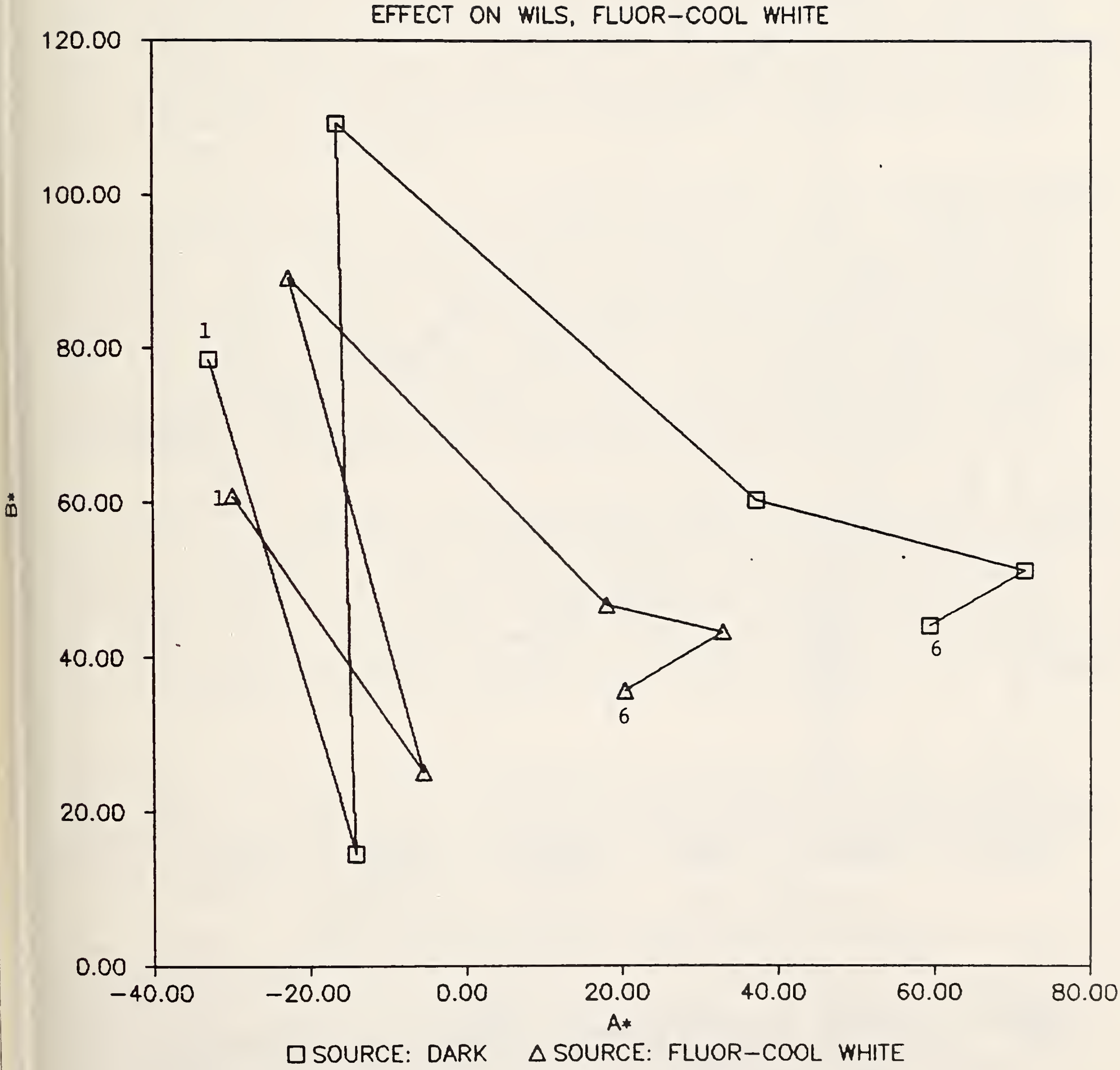

Figure 7. Effect of cool-white fluorescent illuminant (10 fc) on WIL colors as compared to their appearance under dark conditions.

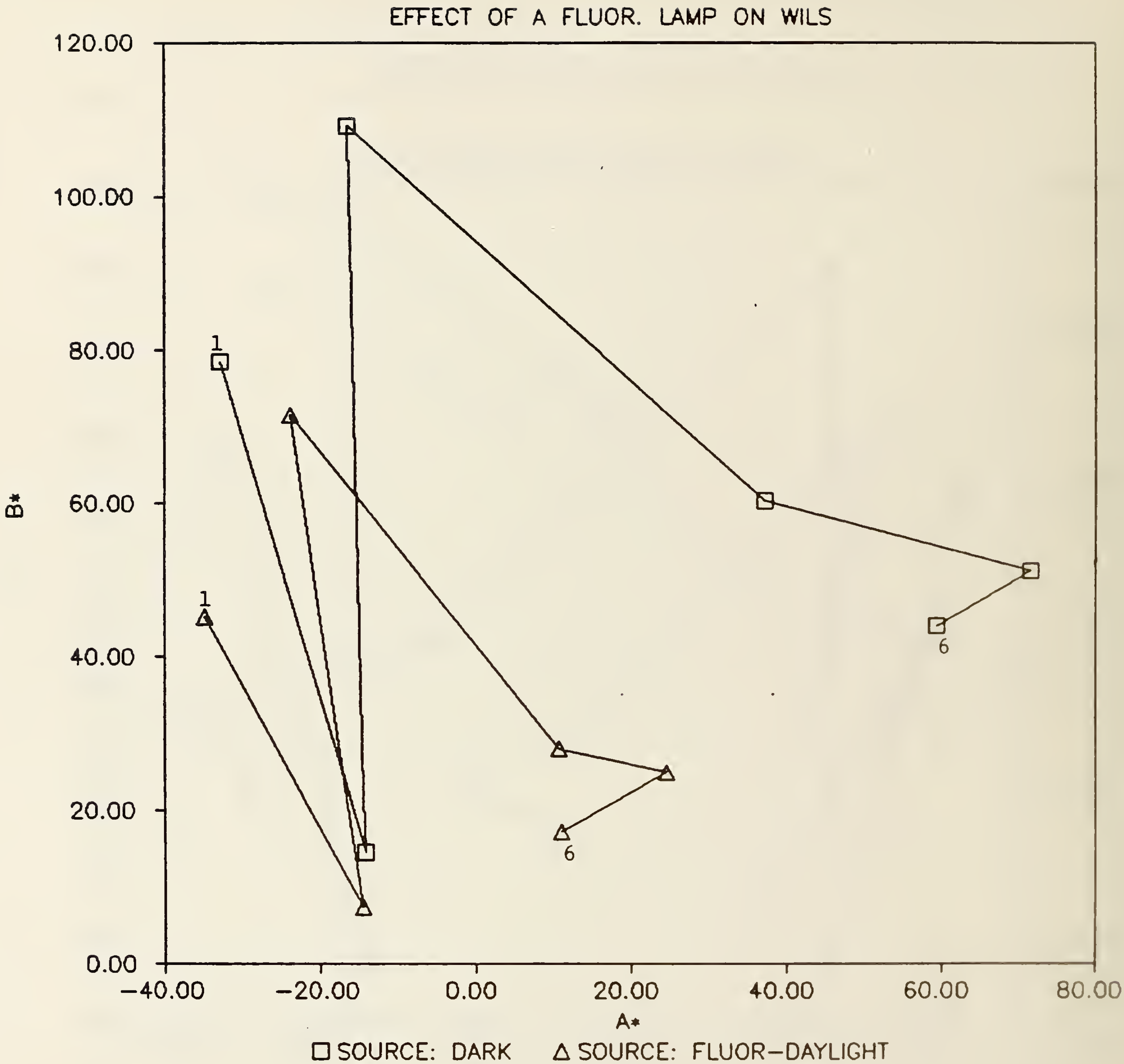

Figure 8. Effect of color-classer fluorescent illuminant (14 fc) on WIL colors compared to their appearance under dark conditions.

the same shift of WIL's 4, 5 and 6 occurs but to a slightly greater extent, i.e. these WIL's tend to shift even further towards the equal energy point thereby losing more of their redness. Since all the field sites visited used fluorescent lamps, these results suggest that cool white fluorescent lamps may be preferable to color classer fluorescent lamps. However, since the amount of chromaticity shift between the dark condition and the two illumination conditions (i.e. from cool-white and color classer fluorescent lamps) were not statistically evaluated for significant differences, the choice for fluorescent lamping may be one of preference which could include other factors than their effect on the RRWDS's.

During field testing of the color calibrator, one advantage of ambient fluorescent lighting overcame the disadvantage of not being able to make certain color calibrator tests in complete darkness. By the judicious use of a black felt canopy over and around the RRWDS display console, spectroradiometric measurements could be taken so the spectroradiometric data could be examined for any trace of spectral power at the four characteristic fluorescent peaks cited earlier. If these peaks were undetectable by the SR, then it was assumed that any residual fluorescent illumination was negligible and the color calibrator tests could be conducted as if the room were in darkness.

The effect of a tungsten (incandescent) illuminant, Figure 9, was a tendency to reduce the brightness contrasts between the six WIL's - (common to the effect produced by most illuminants)- with the greatest effect on WIL #2 or dark green. The red component WIL's 4, 5, and 6 again appeared somewhat desaturated or washed out. As judged by the CIELAB results, illumination from the yellowish white tungsten illuminant tended to drive the self-luminous WIL colors toward the illuminant point i.e. they desaturated all the WIL colors.

Figure 10 (metal halide) and Figure 11 (mercury) show the effects of these two illuminants. Both of these illuminants had more of an effect on WIL's 4, 5, and 6 than did the incandescent illuminant. These colors shifted away from their chromaticities under the dark condition toward the origin, indicating a decrease in the amount of redness.

The results of the CIELAB analysis shows that illumination from different light sources produced different light shifts in the predicted perceived chromaticities of the WIL colors. However, additional research is needed to determine if the color shifts from the white-colored sources differ from one another with statistical significance. Further research is also needed to determine a "best" light source for a building lighting environment where a number of activities take place as well as just viewing the colors of a RRWDS display. According to the CIELAB analysis, the "best" light source was low-level HPS since it produced the least shift in the WIL colors. This is probably not an artifact since the color of HPS light is closer to the

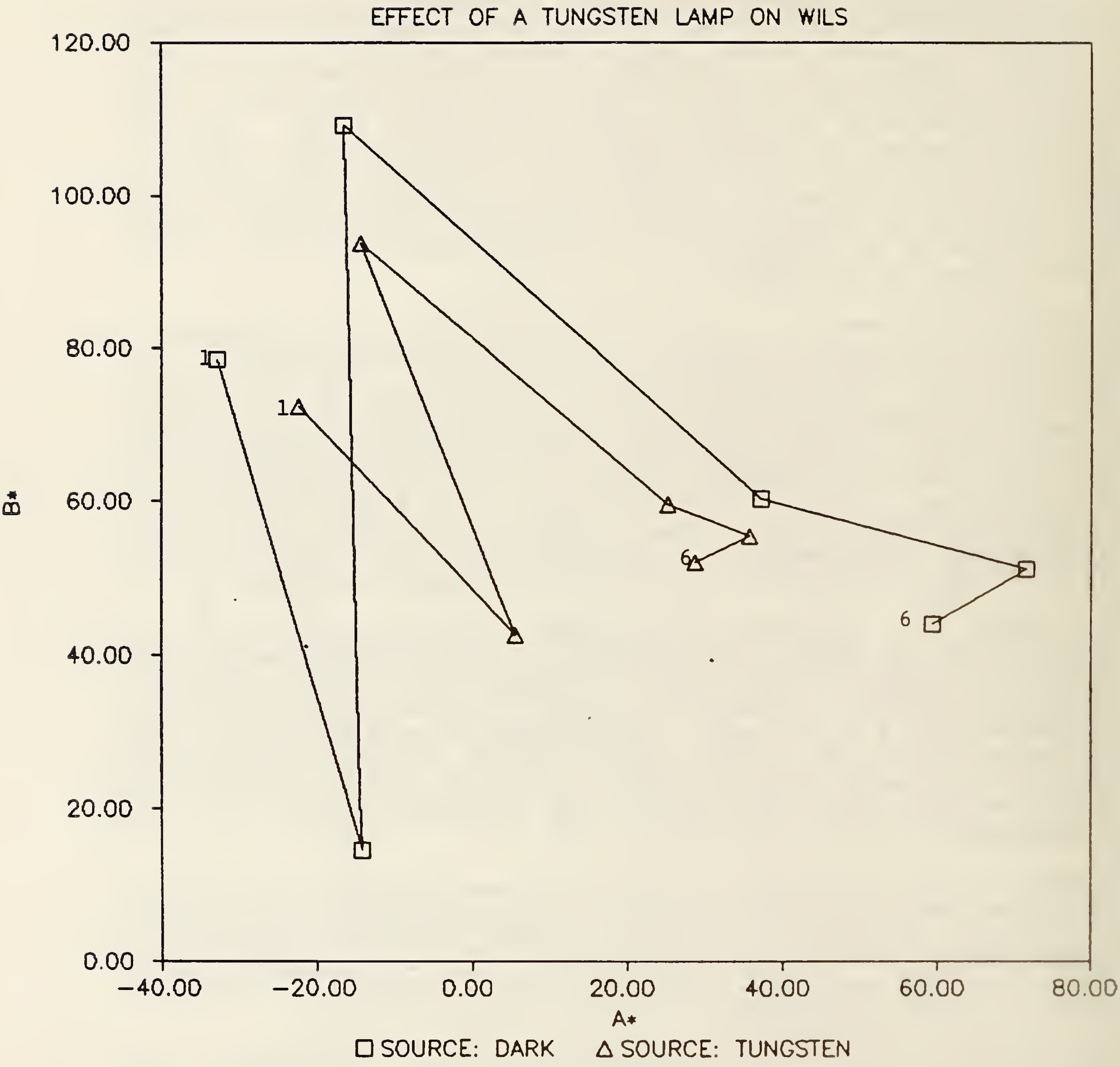

Figure 9. Effect of tungsten illuminant (3 fc) on WIL colors as compared to their appearance under dark conditions.

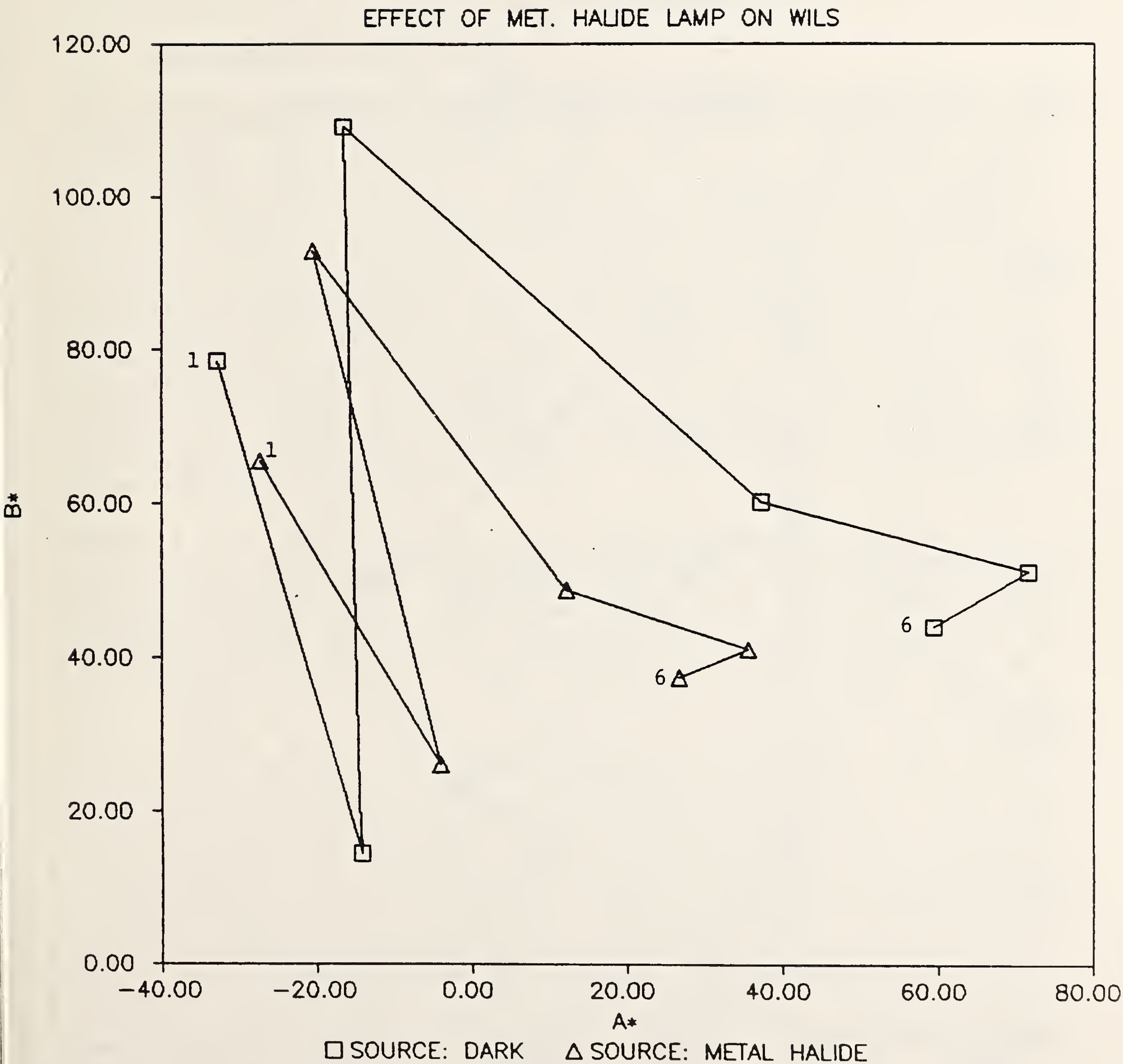

Figure 10. Effect of metal halide illuminant (8 fc) on WIL colors as compared to their appearance under dark conditions.

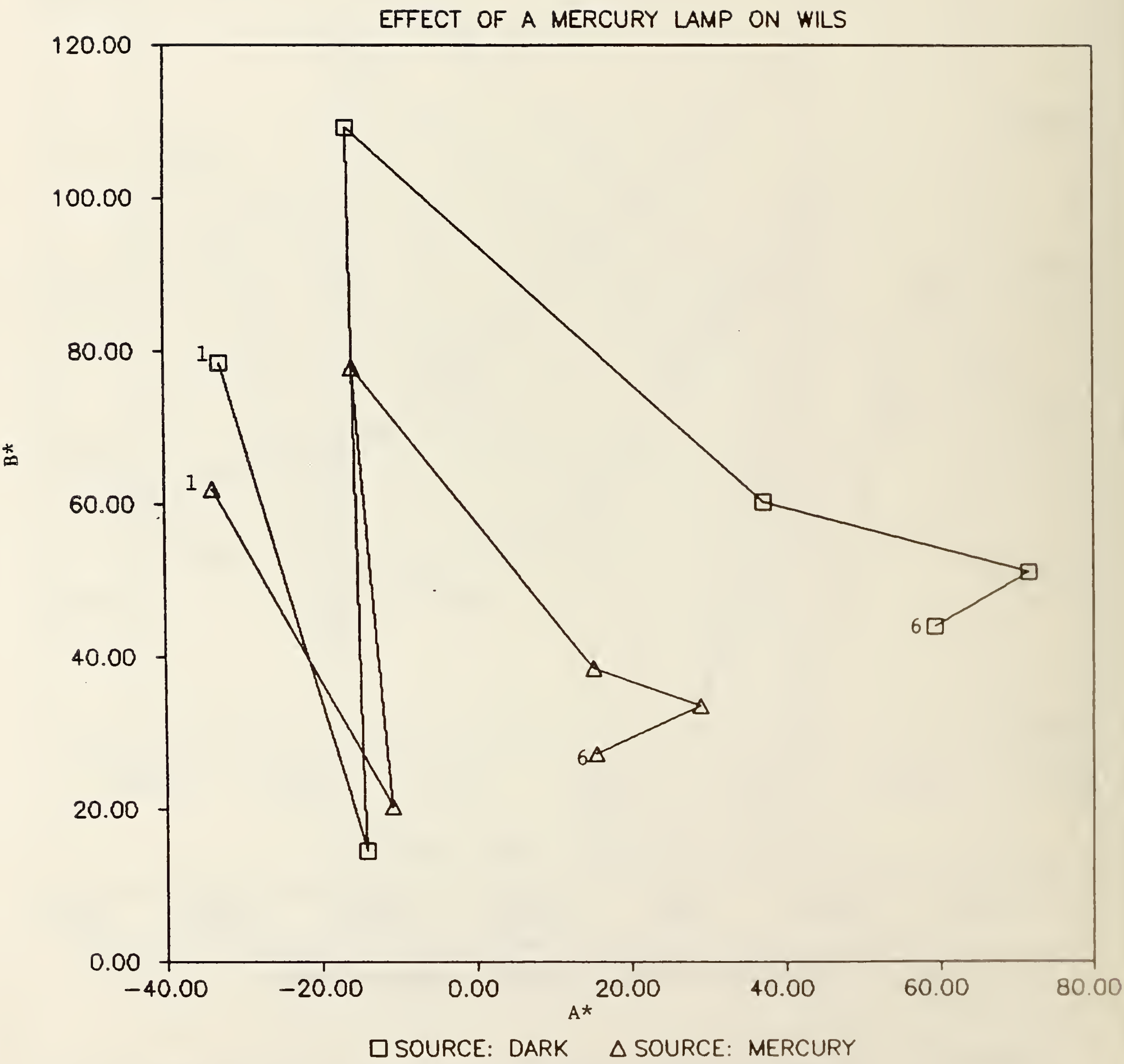

Figure 11. Effect of mercury illuminant (4 fc) on WIL colors as compared to their appearance under dark conditions.

average of the six WIL colors than white is, and hence HPS changes the WIL colors the least when mixed with the WIL colors. In addition, at 1 fc it was much closer to the darkened room condition. For higher levels of illuminance, all sources produce distinct shifts in chromaticity in the RRWDS. However, whether low-level HPS is equally good for other activities and is acceptable by people remains to be determine.

4.5 CIE CHROMATICITY RESULTS

This section presents the basic data obtained by using the SR to measure the SPD's of various light sources. In addition, this instrument also provides other data of interest, and in particular, the CIE x,y chromaticity values. These CIE values were plotted on a standard chromaticity diagram as presented in Figures 12-20. The information presented in these figures is similar to that presented in Figures 3-12 (except for the influence of luminance in the latter), but readers more familiar with the x,y diagram than with the a*,b* diagram may prefer the presentations in Figures 12-20. In these figures, the squares connected by lines represent the WILs measured under dark conditions and is a constant for all room illuminants. The triangles represent the WILs as measured with the various room lights on. The CIE x,y values, recorded with the room lights off, were also used as the input to the CIELAB program discussed in the preceding section.

Readers not familiar with chromaticity diagrams might find it helpful to obtain a full-color poster of the diagram, e.g. as distributed by Photo Research, RCA Solid State Division or Hoffman Engineering. Reference to such a poster will provide guidance about the colors represented at various points in the diagram. The colors represented on the posters are only approximately correct as the saturations are too low toward the outer edges of the region of real colors, i.e. near the horseshoe curve which represents the purity limits of all physically realizable colors. The low saturation is due to the printing inks, which cannot reach theoretical maximum saturations achievable only by monochromatic (single-wavelength) lights from lasers or from white light dispersed into a spectrum by a prism or grating. The curved edge of the horseshoe represents the "spectrum locus", the chromaticities of all pure monochromatic lights. Thus, the blue/violet (shortwave) end of the visible spectrum is at the left end of the curve while the red (longwave) end of the spectrum is at the right. The straight line at the bottom of the horseshoe is the purple boundary, i.e. the loci of purples of maximum saturation obtained by mixing various proportions of red and blue lights. The interior of the closed horseshoe region contains the chromaticities of all colors of lesser saturation, with pure white in the middle. [Note that in Figure 1, page 11, that the gamut of colors that can be produced by a color CRT (i.e. the triangle shown) is limited to less than full saturation by the light emitted by the RRWDS CRT phosphors- a limitation analogous to the poster inks.]

Figure 12 presents the WIL chromaticities as measured under dark conditions (squares) together with their chromaticities as measured with illumination produced by a low level LPS illuminant (i.e. a single 400 watt LPS lamp) (triangles). When illuminated by the LPS source, all the WIL's are yellowish and tend to form two groupings, namely: (1) a greenish-yellow group for WIL's 1 and 3; (2) a reddish-orange group for WIL's 2,4,5, and 6. In comparison with the dark condition, the six WIL's tend to be more alike with the members of each color grouping being virtually indistinguishable, except for possible brightness differences. Note that WIL's 5 and 6 have nearly the same measured chromaticities, although in the RRWDS display they are designed to vary considerably in brightness level.

The expression "virtually indistinguishable" needs further clarification since it refers to chromatic differences only. For example, if the chromaticities of WIL's 5 and 6 were reproduced on large color chips having equal brightnesses and then shown side by side, the human color vision system would probably detect the chromatic difference. However, if the WIL's 5 and 6 test samples were then shown to the same subject sequentially (i.e. with a temporal interval between viewings), the subject's visual memory system may not detect these small chromatic differences. Therefore, if two colors lie close together on the chromatic diagrams, due to the effects of the SPD of the light source, then the effect of the light source may be interpreted as reducing color contrasts, leaving only brightness contrast as a means of distinguishing between WIL's. In the case of WILs #5 and 6, since the chromaticities are nearly the same in the dark, the similarity is not a function of the light source. Obviously, as the level of illumination is increased, the screen reflections are increased with the result that brightness contrasts are correspondingly reduced.

At high illuminance (86 fc), the LPS illuminant produced two groupings (see Figure 13), namely: (1) a greenish-yellow group (WIL's 1 and 3) and (2) an orange-yellow group (WIL's 2,4,5,6). Members of the orange-yellow group appear to be indistinguishable from each other, except for brightness differences, and barely distinguishable from the greenish-yellow WIL's. Visually, a white appeared to the author to be tinged with yellow-green at low illuminance but orange-pink under high LPS illuminance. The actual color names may vary from experimenter to experimenter, and therefore should be interpreted on a subjective rather than an objective basis. The shifts shown in Figures 12 and 13, however, depict objectively measured changes in physical chromaticity.

The effects of HPS lamps, which have a broader SPD than LPS, are shown in Figures 14 and 15. As might be expected on the basis of light intensity only, the low illuminance (1 fc) HPS light source (Figure 14) had little effect on the chromaticities of five of the six WILs, as compared to their chromaticity under dark conditions. The simple addition of the reflected HPS light did

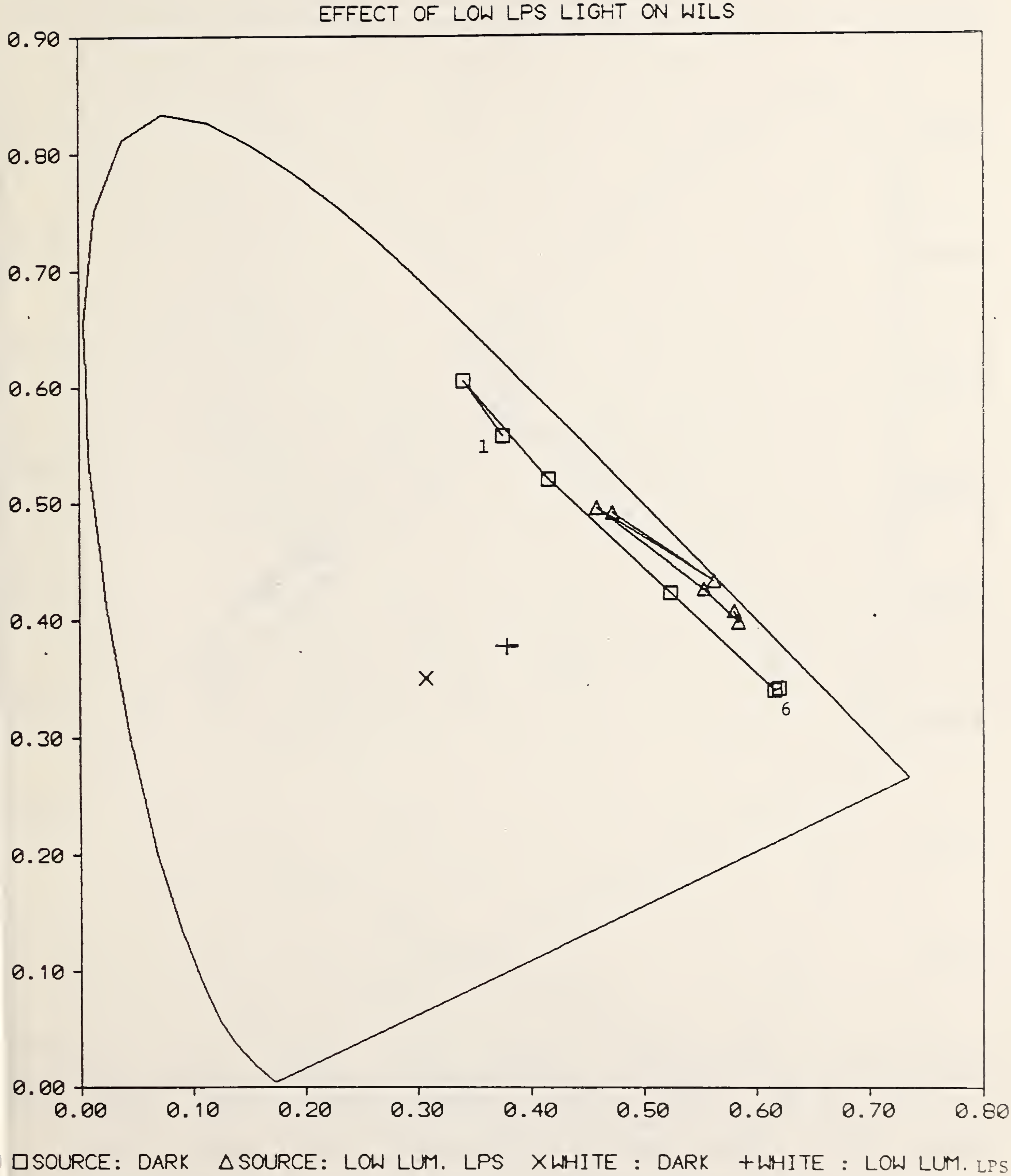

Figure 12. WIL chromaticities as a function of a low illuminance LPS source (approximately 41 fc at the CRT display).

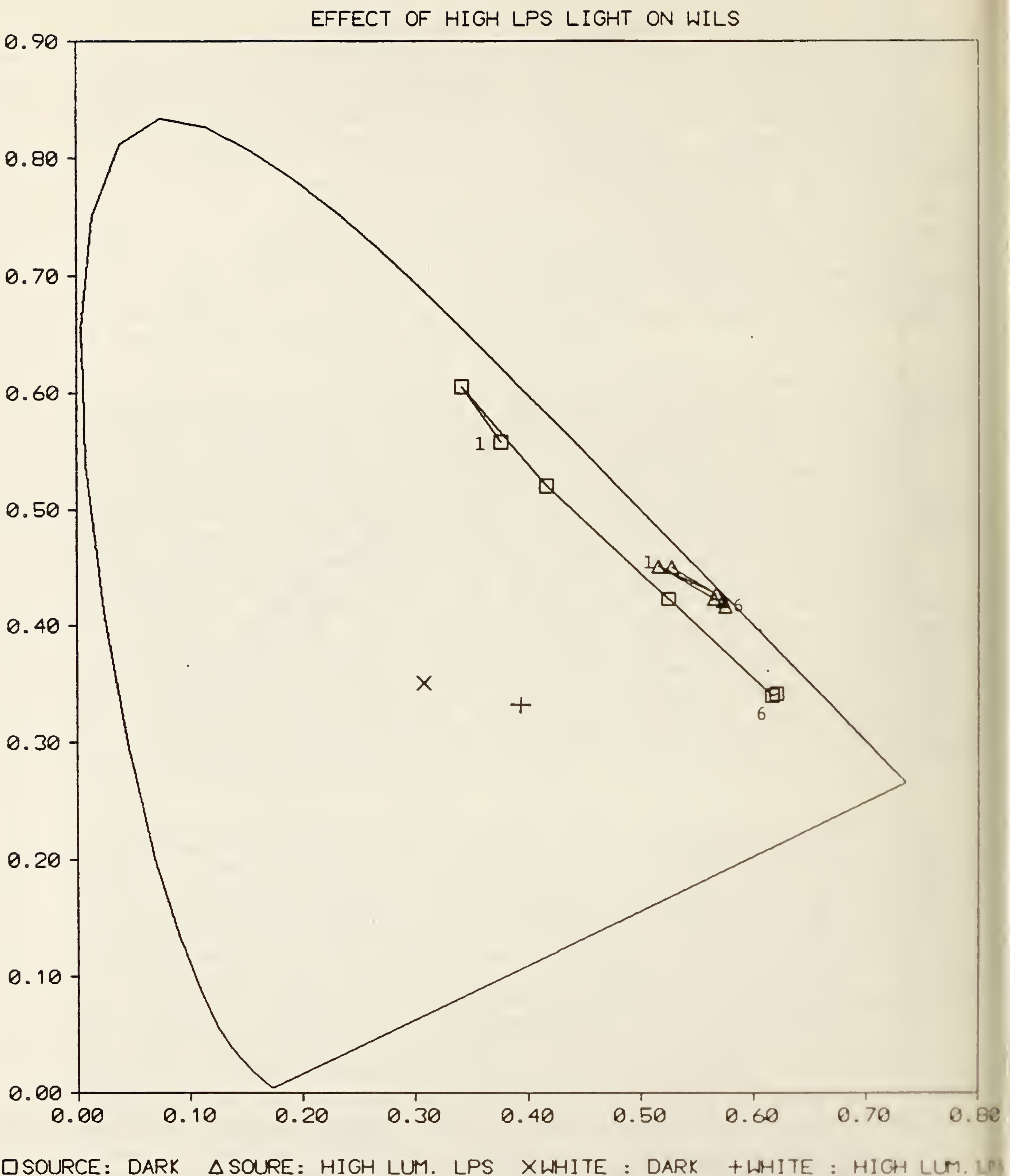

Figure 13. WIL chromaticities as a function of a high illuminance LPS source (approximately 86 fc at the CRT display).

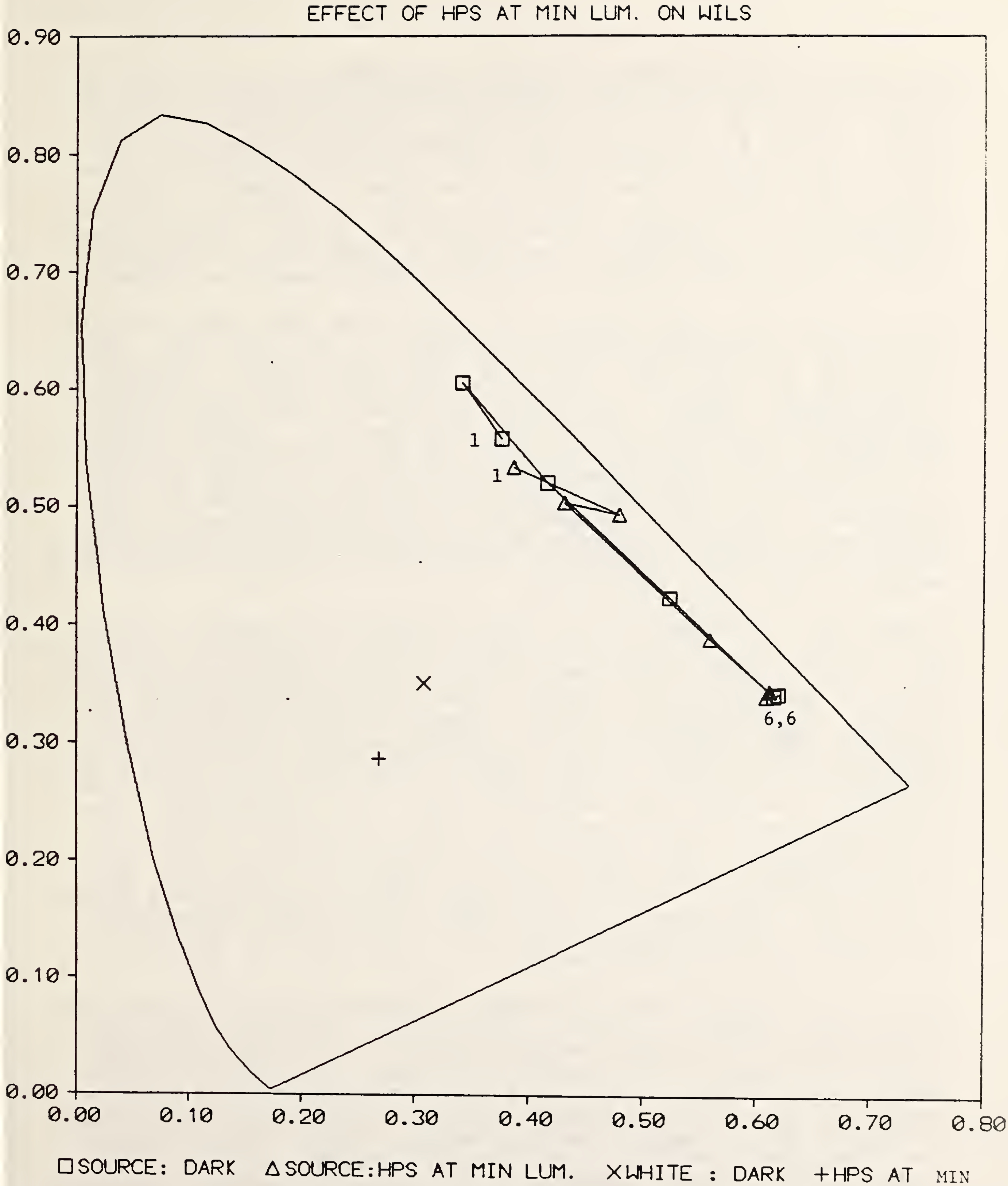

Figure 14. WIL chromaticities as a function of a low illuminance HPS source (approximately 1 fc at CRT display).

produce a fairly sizeable shift in the chromaticity of WIL 2, i.e. from a dark green to a dark yellowish-green. WIL 2 had the lowest luminance (0.28 fc at the time of measurement) of the six WILs. Since WIL 2 contributed proportionally little to it's total measured luminance under HPS, it shifted more than the other WILs towards the color of the room illuminant. Another consequence of the low luminance of WIL 2, is that if it is embedded in or adjacent to a bright WIL it will appear even darker due to the simultaneous contrast phenomenon. The amount of blue in the white target is curious and not easily explained.

At its maximum illumination of 76 fc, the HPS light source (Figure 15) produced chromaticity shifts in all six WILs. The dark WILs were shifted more than the bright WILs. Figure 15 indicates the WILs were shifted towards the yellow of the HPS light source, however, the HPS induced shifts were less than the corresponding shifts under an LPS light source. Similar to the LPS source, the superimposition of the HPS reflections resulted in two groups of WILs; namely one group formed by WILs 1,2, and 3, and the other formed by WILs 4,5, and 6. Figures 13 (high LPS) and 14 (high HPS) indicate that the superimposition of these lights sources results in more yellow saturated WIL colors rather than in the greater saturation of the WIL's original colors, as measured under dark conditions.

Comparison of Figures 13-20 versus Figures 3-12 should be done with care. Figures 13-20 are x,y or chromaticity plots of the WIL chromaticities objectively measured by a spectroradiometer. Figures 3-12 are a*,b* plots of the calculated perceived WIL colors. As discussed earlier, these calculations include the objective data in Figures 13-20, plus SR obtained luminance data, and plus known human visual system responses, i.e. a*,b* is chromaticity weighted by luminance. The a*,b* plots are closer to what a human may actually see. To illustrate, the chromaticities of WILs 5 and 6, as shown in Figures 13-20 for the dark condition, lie sufficiently close together so as to be indiscriminable on the basis of color alone, i.e. there is a lack of color contrast. On the other hand, Figures 2-12 indicate WILs 5 and 6 are discriminable on the basis of luminance differences, i.e. they can be discriminated on the basis of brightness contrasts as originally intended.

The overall effect of the cool-white fluorescent source, shown in Figure 16, tends to shift all the WIL colors towards the chromaticity of this light source which is not far from the equal energy white point (i.e. x=.3333, y=.3333). This shift towards white is greatest for the dark WIL's because the SR detects proportionately more of the spectral energy from the white illuminant than from the spectral energy of the dark WIL's. At low illuminance levels of cool-white fluorescent, WIL's 4, 5 and 6 should still be distinguishable by people with normal vision, although WIL's 4 and 6 may occasionally be confused. The optimum illuminance level for viewing the RRWDS CRT is, of course, full darkness. Since this would not allow safe movement of people,

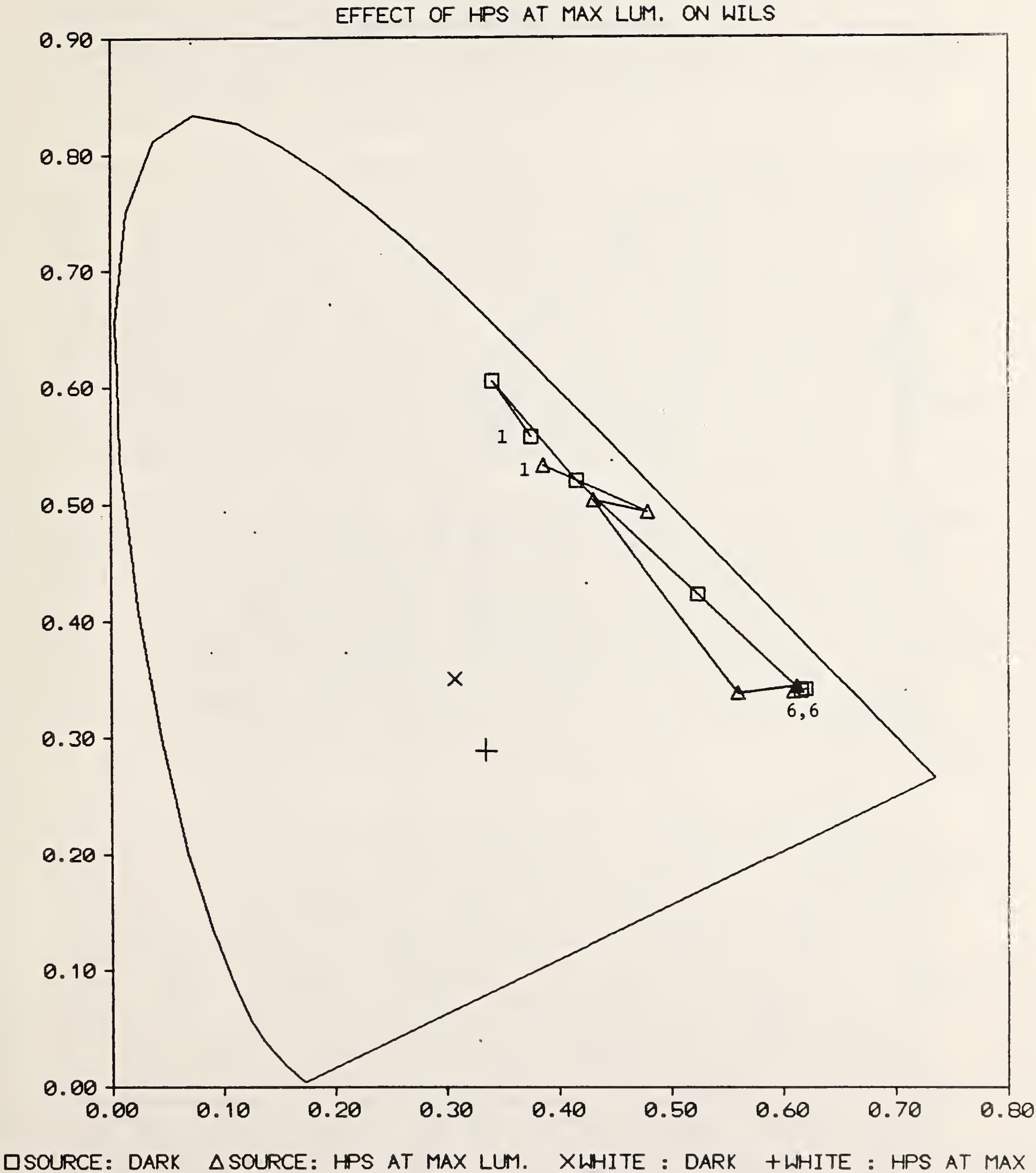

Figure 15. WIL chromaticities as a function of a high illuminance HPS source (approximately 76 fc at the CRT display).

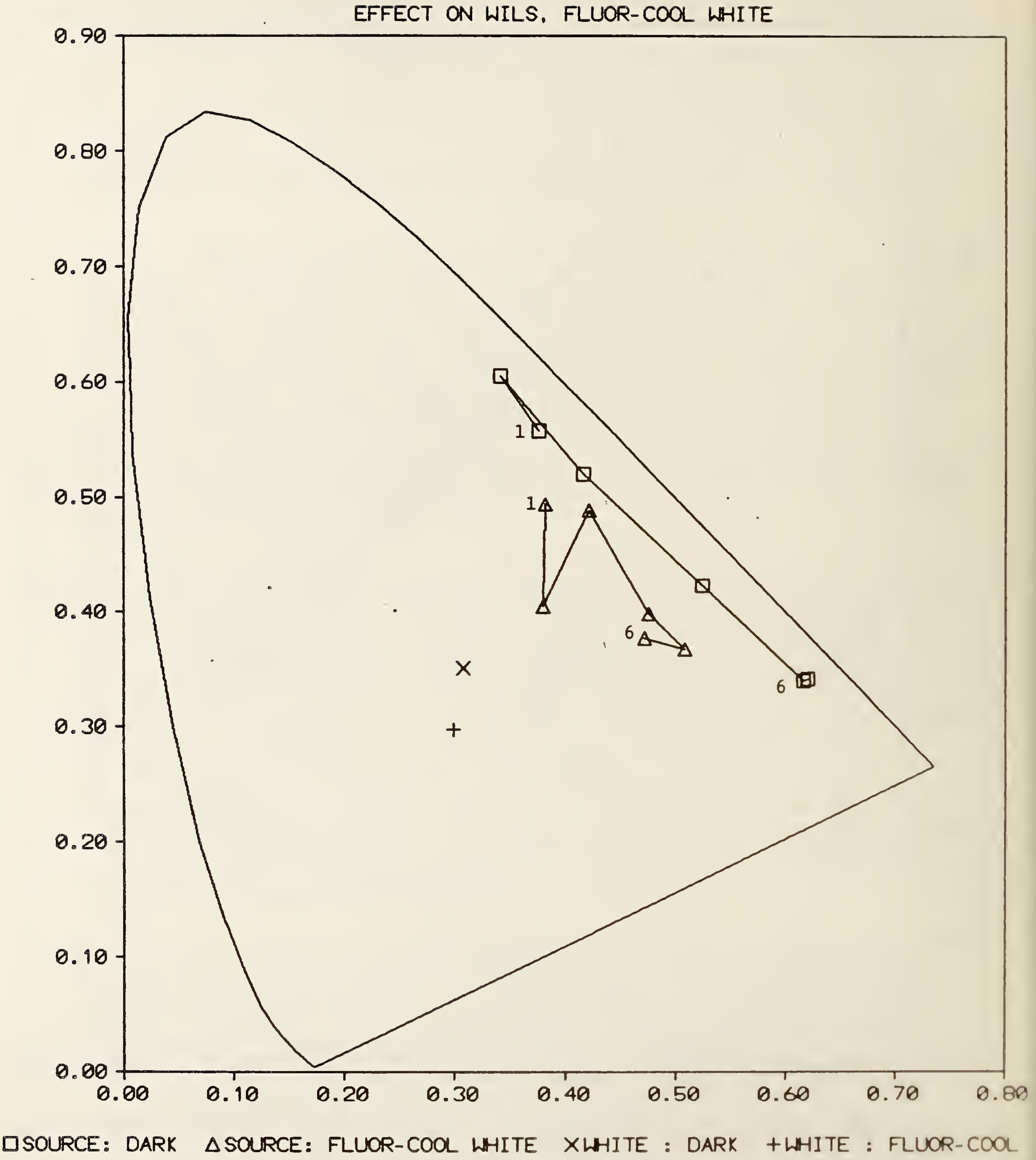

Figure 16. WIL chromaticities as a function of a cool-white fluorescent source (approximately 14 fc at the CRT display).

the preferred illuminance at the CRT's face appeared (to the author) to be around 1 to 5 fc. Five fc is about the average illumination level for dimly lit hallways. If higher illuminances are necessary for other operations, then a dark canopy (with sides) may be required or preferably, changes in the building lighting environment as recommended earlier.

Different types of fluorescent lamps will produce different color shifts in the WIL's as indicated by comparing the Color Classer fluorescent lamp (Figure 17) with the cool-white lamp (Figure 16). The cool-white lamp tended to shift all the WIL's more toward the equal energy point, than did the Color Classer lamp. The chromaticity of WIL 2 shifted almost to white under the cool-white lamp. As expected, the remaining dark WIL's 4 and 6 are shifted more to the white than the bright WIL's 1,3,5. Visual inspection of various weather conditions displayed on the RRWDS CRT indicates that the dark WIL's are often hard to discriminate when embedded in the bright member of their color pair. NBS has previously demonstrated minor modifications in the WIL chromaticities to enhance certain color contrasts, as well as the brightness contrast between WIL's and the display background.

The effects of a tungsten illuminant on the WIL chromaticities is presented in Figure 18. Examination of this figure indicates that a tungsten illuminant has the effect of reducing the relative contrasts between all six WIL's while still keeping their same relationship relative to that seen under dark conditions (except for the large color shift seen for WIL 2). Under tungsten light, WIL 2 shifted markedly towards the red whereas WIL's 5 and 6 shifted slightly the other way. What occurred for all illuminants was that the WIL colors shifted toward the illuminant chromaticity. In the case of tungsten light, this shift was towards yellow or a point actually located not far from WIL 2, as measured under tungsten.

Figure 19 presents the effects of a metal halide illuminant on the WIL chromaticities while Figure 20 presents the effects of mercury lamps. The effects of these light sources are discussed together because their effects are somewhat similar. As was the case for all illuminants, there were reductions in the color contrasts between the WIL's compared to the WIL's when measured under dark conditions. Both illuminants produced a major shift in WIL 2 and substantial shifts in WIL's 5 and 6. As one would expect, WIL #2 shifts significantly toward the white of the illuminant. Under the mercury lamps, WIL #6 shifted closer to WIL #4, i.e. away from the chromaticity of WIL #5. Perceptually, the dark red of WIL #6 and the tan-gold of WIL #4 become virtually indistinguishable. WIL #5 can be distinguished from them because of greater brightness. Since both illuminants produce considerable spectral energy in the shorter wavelengths (UV), high illumination levels (to be determined) will produce fluorescence and phosphorescence in tri-color phosphors as cited earlier. The addition of such fluorescence can significantly affect the chromaticities of the WILs (or any other color).

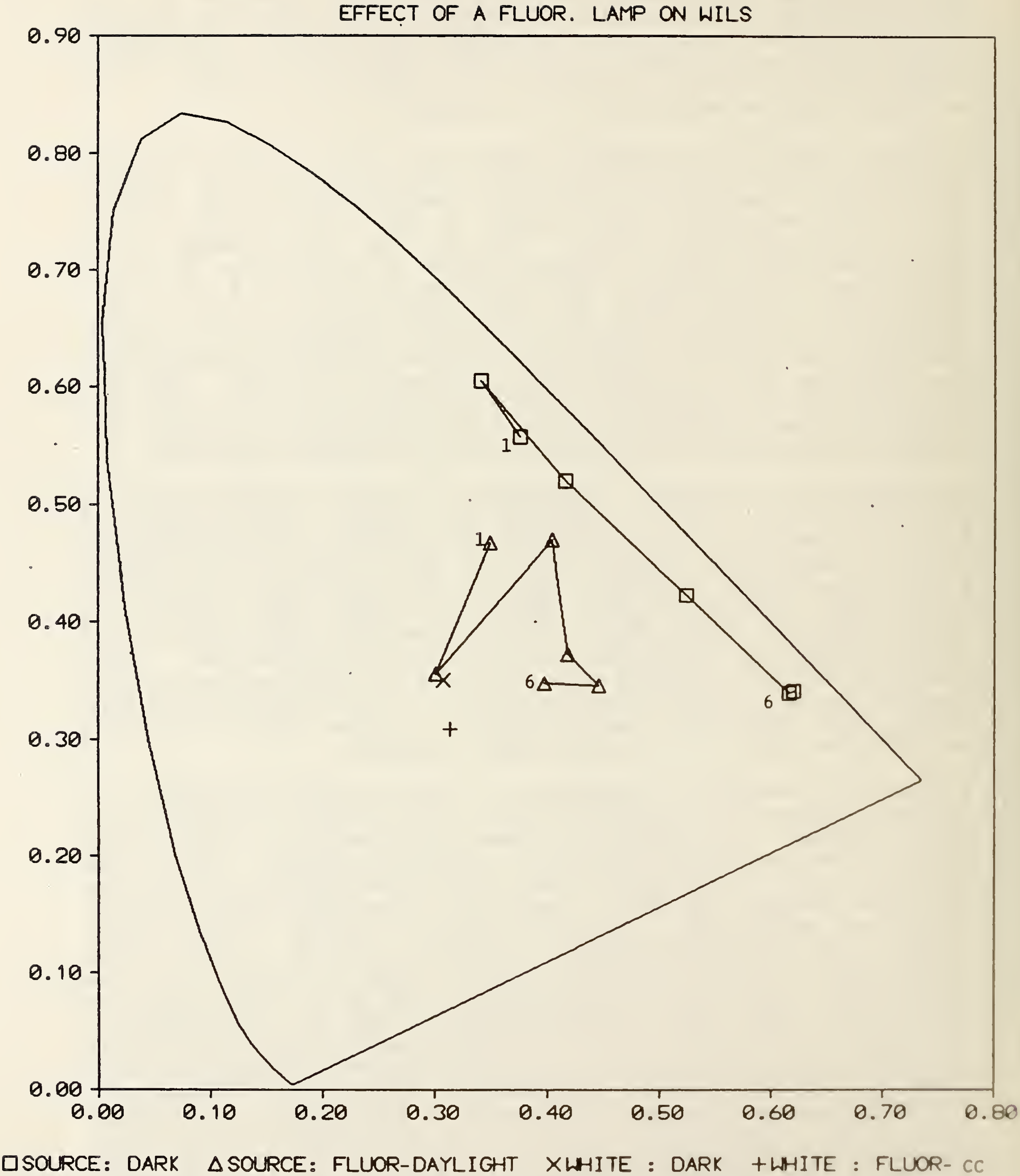

Figure 17. WIL chromaticities as a function of a color-classer fluorescent source (approximately 10 fc at the CRT display).

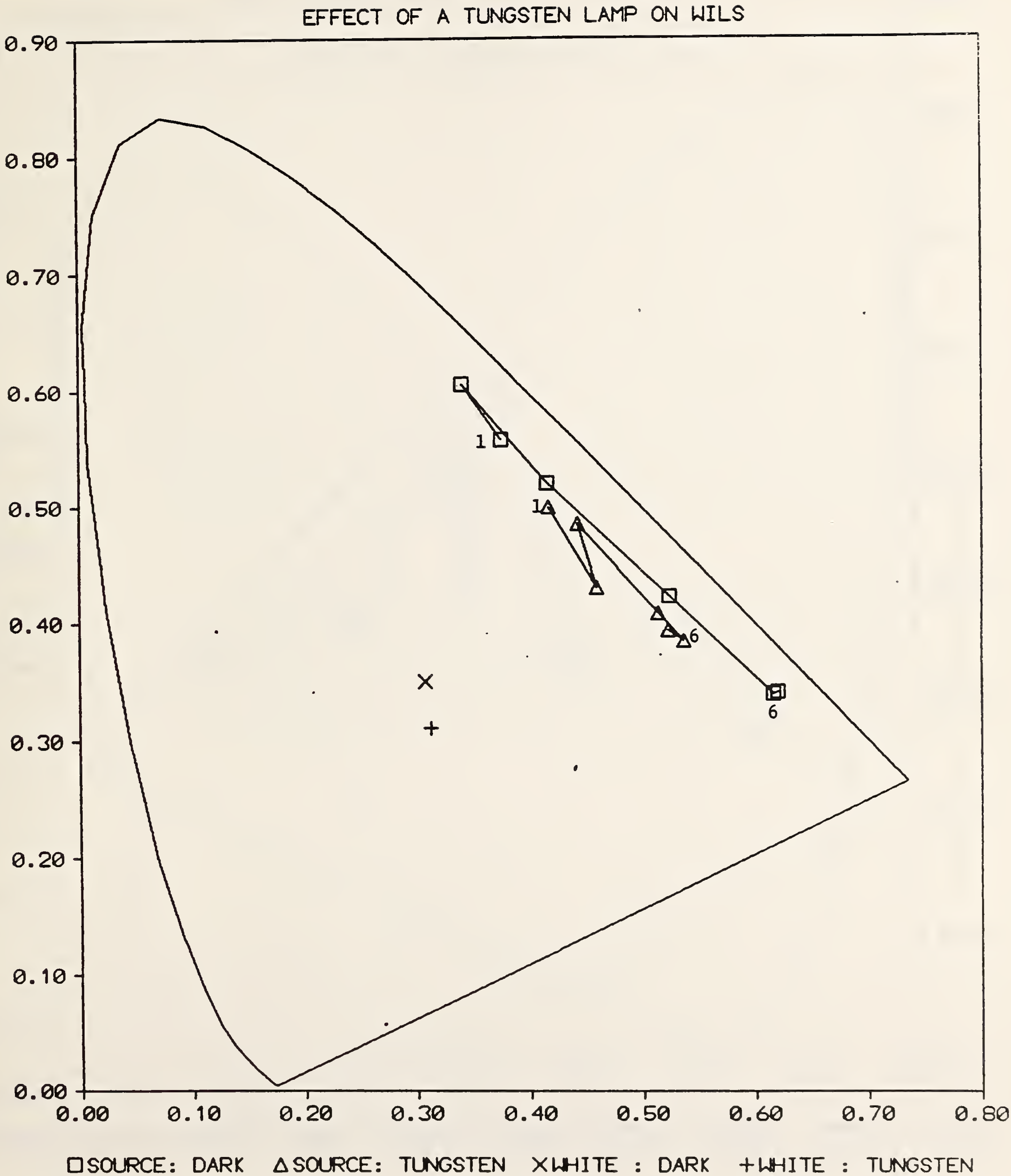

Figure 18. WIL chromaticities as a function of an incandescent source (approximately 3 fc at the CRT display).

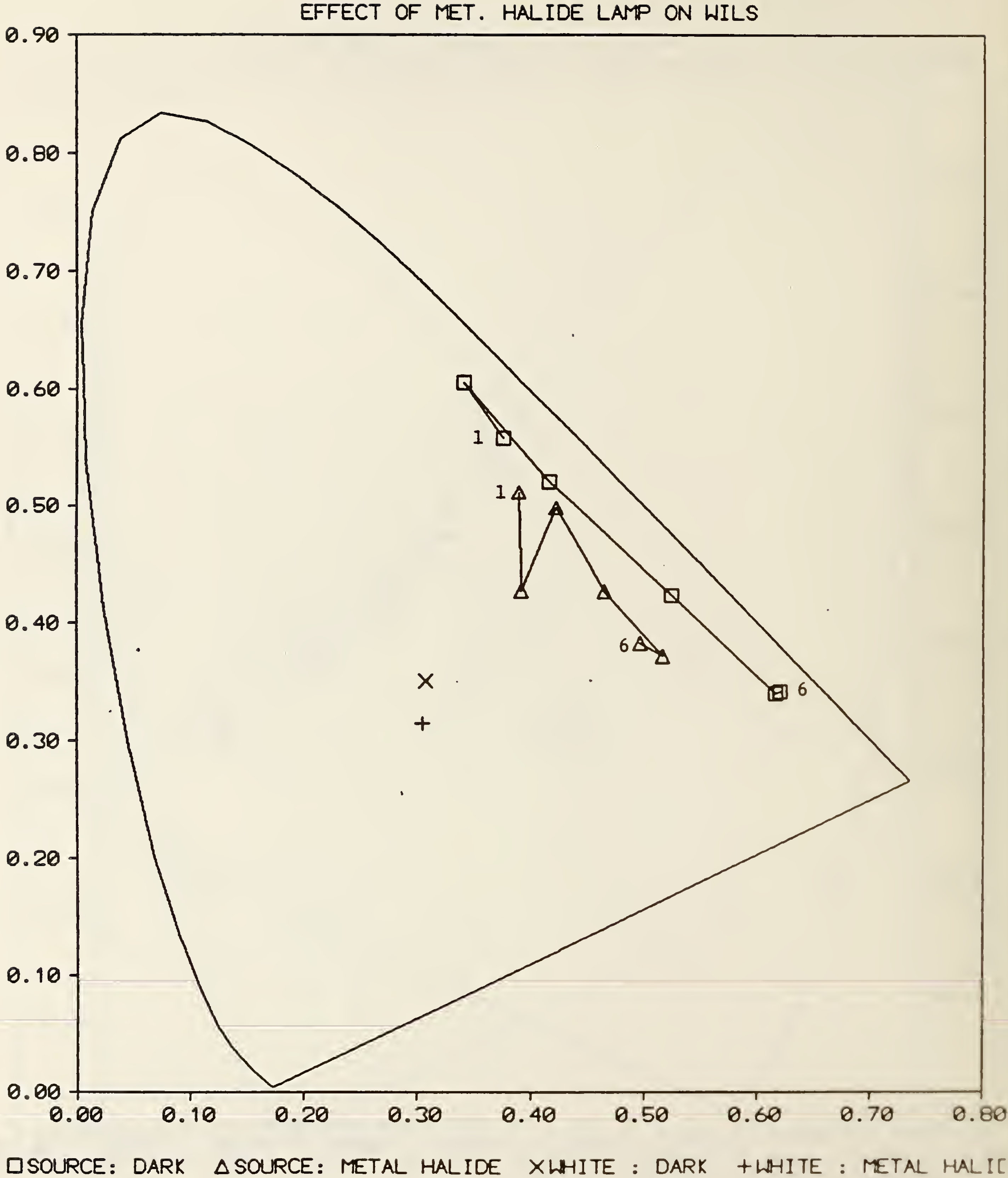

Figure 19. WIL chromaticities as a function of a metal halide source (approximately 8 fc at the CRT display).

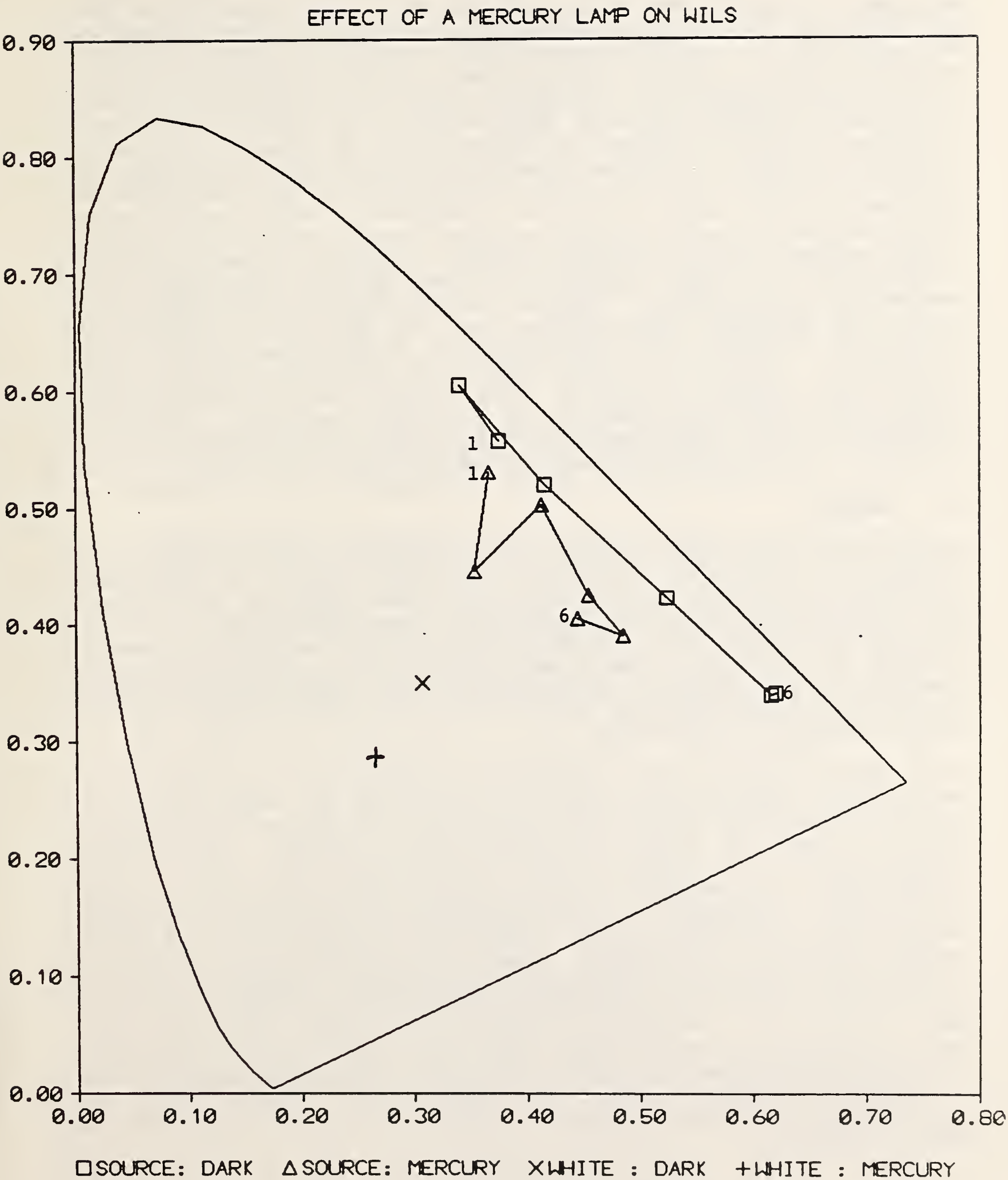

Figure 20. WIL chromaticities as a function of a mercury source (approximately 4 fc).

The above discussion of the effects of various ambient light sources on the chromaticities of the WIL's (as measured by the SR) indicate the critical role that a building's lighting system can play in the interpretation of weather information by a meteorologist. Although not a part of this investigation, an equal (or perhaps a more important) parameter involved in viewing color-coded, self-luminous displays is the role of the whole lighting geometry involved in the correct placement of the CRT display consoles. The data used in this study was objectively obtained by appropriate measuring instruments. To obtain data on effects noted by human observers, a subjective study, using human subjects would be required. Using human subjects is often required because the human visual response system contains complexities not yet possible to incorporate into objective measuring instruments. The principal such complexity is the process of chromatic adaptation, i.e. the ability of the eye to partially discount the color of the light source (for many sources), thereby seeing colors differently from those objectively present. This is the source of what is called the color constancy phenomenon. In the final analysis, it is, of course, not an instrument but a human who must decode the information provided by a color-coded display.

4.6 SUMMARY

The first NBS report of this FAA contract demonstrated the validity of a color calibrator for the RRWDS WIL's. Inexpensive, off-the-shelf parts and standard electronic circuits were used. The sensitivity of the color calibrator was sufficient to detect the smallest color change permitted by the systems dèsign, except at very low levels of the primary RGB colors. Color calibrator results were validated against calibrated laboratory measuring instruments and found to yield accurate and reliable results under laboratory conditions.

This report covers field validation of the color calibrator as well as the development of a RGB color look-up table (i.e. the tolerance ranges for the calibrator output voltages presented in Table 4) for use by field maintenance personnel. Due to the small number of field sites visited and large inter-site differences in the WIL chromaticities, the color calibrator look-up table needs further refinement through sampling of a much larger number of field sites. Despite the small number of field systems evaluated, the field validation results showed that the color calibrator can be a valuable tool in maintaining color consistency of the RRWDS WIL's. The color calibrator is both more accurate and consistent in measuring the WILs than the usual method of simply "eye-balling" them. In addition, the objectivity of the measurements taken by the color calibrator should have greater acceptance by the courts than "eyeballing" in establishing whether WIL colors were adjusted according to specifications.

Field experience using the color calibrator suggested some engineering modifications to the color calibrator's detector head to improve ease of manufacturing and reduce the cost of the final product. These modifications would allow the manufacturer to preset the dark current and sensitivity of each RGB photoreceptor and make the head a throw-away item. The discardable detector head would avoid the need for field technicians to make adjustments to the color calibrator except to exchange the quick-disconnect detector head.

The field tests also showed the significant effect of the total lighting geometry on the ability to discriminate between the WIL's. Field data indicated that any light source providing an illuminance greater than 1-5 fc on the RRWDS screen, whether located overhead or to a side, will reduce color discriminability and brightness contrasts. Consequently, the last part of this report presents objective data on the effect of room illumination, as reflected from the CRT display, on WIL chromaticity shifts as well as the loss of color and brightness contrast. These laboratory results indicate that the geometry, spectral composition and luminance of the ambient lighting should be considered in the placement of field CRT consoles.

Also, a review of the literature on color-coding, where color is used as the source of information, clearly indicates that the presence of irrelevant color or too many colors produces an interference effect that seriously degrades performance. (Obviously, as the number of colors in a color-coded display is increased, the amount of information that can be presented in the display is increased.) Thus, the problem with using too many colors is the potential for information overloading. The use of too many colors may increase the time to locate and make correct color discrimination as well as increase the amount of time validating the color against a color-code legend located on or near the display. The result may be that less time is available for extracting the desired information from the display. Although the literature does not provide clear cut answers for color coding, it would appear that more colors can be used in static or slow-changing displays than in dynamic faster-changing displays, especially if the latter are not made of neat, geometrical, and easily recognizable forms or patterns. Based on the research literature, the author suggests that the optimum number of colors for a weather display should be between six and ten colors to obtain good human performance in extracting weather information without overloading the observer.

Finally NBS suggests that the color calibrator be upgraded to a relatively inexpensive "true" CRT colorimeter. This colorimeter would still use the color calibrator detector head and add a small microprocessor with built-in hardware/software programs. These programs would use matrix algebra to calculate the International CIE (x,y) coordinates from the RGB outputs of the detector head. In order to keep the colorimeter inexpensive, the matrix algebra equations require that the chromaticities of a

CRT's RGB phosphors be known in advance. A much more expensive version--a true general colorimeter--would allow the instrument to measure the chromaticities of the RGB, store this information in memory, and then use the stored values in the matrix algebra equations. NBS recommends upgrading the color calibrator to a "true" CRT colorimeter because the output would be the WIL chromaticities in CIE coordinates which are the internationally recognized values for color measurement and specification. Hence, the colorimeter outputs would have an additional value in court test.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report is the final report on the development and field testing of an inexpensive color calibrator for the standardization of the Weather Intensity Level (WIL) colors used in the FAA's Radar Remote Weather Display System or RRWDS. The report covers the field validation of the color calibrator and, as an end product, the construction of a tentative look-up table that identifies whether the six WIL colors are within acceptable limits. The look-up table is tentative due to the small (5) number of field sites visited. The development of a color lookup table finalizes the validation of the color calibrator as a useful tool for calibrating the WIL colors used in RRWDS. Moreover, the color calibrator can be used to calibrate the colors of other tricolor display systems, provided an appropriate lookup table is developed.

In addition, this report includes a general review of significant literature on color-coding, since RRWDS color codes weather information. The report presents first-of-its-kind objective data on the effects of ambient room lighting on colors used in a self-luminous display. The effects were chromaticity shifts due to the presence of veiling reflections or glare from the face of the CRT console. This report may, accordingly, have significant impact on the design of building environments where color-coded CRT's are to be used.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

building lighting environments; cathode ray tube (CRT); chromaticity shifts; color calibrator; color coding; room illuminant reflections; self-luminous displays; specular glare from CRT's; veiling luminances; video display terminals (VDT)

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