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Visual Quality Assessment of Electrochromic and Conventional Glazings

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ABSTRACT

Variable transmission, "switchable" electrochromic glazings are compared to conventional static glazings using computer simulations to assess the daylighting quality of a commercial office environment where paper and computer tasks are performed. RADIANCE simulations were made for a west-facing commercial office space under clear and overcast sky conditions. This visualization tool was used to model different glazing types, to compute luminance and illuminance levels, and to generate a parametric set of photorealistic images of typical interior views at various times of the day and year. Privacy and visual display terminal (VDT) visibility is explored. Electrochromic glazings result in a more consistent glare-free daylit environment compared to their static counterparts. However, if the glazing is controlled to minimize glare or to maintain low interior daylight levels for critical visual tasks (e.g., VDT), occupants may object to the diminished quality of the outdoor view due to its low transmission (Tv=0.08) during those hours. RADIANCE proved to be a very powerful tool to better understand some of the design tradeoffs of this emerging glazing technology. Our ability to draw specific conclusions about the relative value of different technologies or control strategies is limited by the lack of agreed upon criteria or standards for lighting quality and visibility.

INTRODUCTION

Electrochromic windows can be actively controlled to modulate solar heat gain and daylight. This active device is essentially a large-area thin-film electrochemical cell. Transmittance and reflectance ranges, spectral characteristics, and speed of coloration and bleaching all depend on the specific electrode and ion-conducting materials used in the cell. The range of visible transmittance and color are particularly important in the study of visual quality. Transmittance ranges for precommercial prototypes are now exceeding 10:1 over practical switching times. Tungsten oxide, which is the most widely used electrode material, is deep blue in the colored state, but that color is moderated to varying degrees by doping or the choice of the other electrode. Some devices based on organic materials have a wide range of intense colors.

Although these glazings are not yet commercially available, substantive research has been done to estimate the energy-saving potential of these prototype electrochromic materials for commercial building applications (Selkowitz et al. 1994). For these studies, the transmission of the electrochromic window system is controlled to provide a design daylight illuminance level within the space. Combined with daylighting controls, computer simulations

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suggest that electrochromics will save significant energy and reduce peak demand when compared to conventional static low-e window systems in cooling-dominated climates.

Qualitative benefits of electrochromics have been explored less extensively, primarily because of the limited tools and methods that have been available to evaluate these issues. Electrochromic glazings should provide increased comfort for critical visual tasks, i.e. visual display terminals (VDT) use, because of their ability to respond to changing exterior daylight and sky luminance levels – but there have been no full-scale occupant studies since the materials are not yet readily available in large sizes for such testing. Glare, visual comfort, and privacy are complex issues that defy simple solutions provided by conventional simulation tools.

Research on electrochromic materials and devices has been governed by considerations of maximum optical range, color neutrality, switching speed and lifetime. These are indeed the important parameters for energy control, but the required values of the parameters and the acceptable tradeoffs are not well defined. For example, should researchers consider the readily achievable transmittance range of 10:1 to be adequate for now and move on to other pressing tasks? Perhaps consumers will demand 100:1 switching levels to achieve absolute privacy or glare control without conventional shading devices. The process is made more complex because the decisions are not wholly technical in nature. For example, switching speed, transmittance level for privacy, outside image quality, and desirable or objectionable colors are largely marketing issues relating to the perceptions of building occupants. Metrics have been developed to evaluate some of these factors; others must be evaluated for now based on focus groups and marketing surveys. Until now, neither the effect on interior illuminance nor the demonstrations of appearance have been readily available in either case to assist in assessing coating performance.

The RADIANCE visualization program (Ward 1990) provides researchers with the unique and powerful capability to model and display a continuous map of luminance within a three-dimensional space, to visualize the effect of an eye's adaptation, and to ascertain the impact of veiling reflections on images and characters displayed on a VDT screen. In this study, a parametric set of photorealistic images was generated using this simulation program to study luminance contrast, daylight levels, reflections on a VDT screen, and privacy. Quantitative and qualitative data are provided. Comparisons are made between electrochromic glazings and conventional glazings. Recommendations are given regarding material design and use within the commercial office environment.

METHOD

The RADIANCE visualization program takes a three-dimensional geometrical description of a space and a physical description of its surfaces, such as bi-directional transmission and reflectance data, color, and texture, then performs Monte Carlo ray-tracing calculations to determine luminance pixel by pixel from a specific view within the simulated space. A diffuse calculation is made by tracing rays that sample the sky hemisphere. Rays are used to trace some number of diffuse reflections from a surface to others illuminating it. The diffuse reflection for each pixel is not computed separately, but all computed values are cached. A weighted average of the cached values is used to compute pixels whose value is not known. RADIANCE is well suited for computation of the distribution of direct and reflected light distribution in a space. The resultant image is a photorealistic depiction of the space from a perspective view. Falsecolor contour images of the space can also be produced to quantify luminance distributions.

A west-facing 3.05 m wide by 4.57 m deep by 2.72 m high commercial office space was modeled in Phoenix, Arizona (33.02°N latitude). Four CIE clear and overcast sky days were modeled: June 21 (summer solstice), March/September 21 (equinox), December 21 (winter solstice), August 21 (clear sky only). These recommendations for electrochromic design (minimum T_v) represent a conservative position, given the peak clear sky conditions of August 21 and the high daylight availability of this climate. A 2.13 m high by 3.05 m wide flush-mounted window was modeled with a sill height of 0.91 m. No shading devices (e.g., venetian blinds) were modeled; direct sun begins to penetrate the west-facing space after the noon hour. No electric lighting was modeled in order to isolate the daylighting effects of the window system. The office includes assorted furniture with a workstation near the window. Interior surface reflectances were: 0.57 walls, 0.30 floor, 0.76 ceiling, 0.50 desk, 0.67 (0.05 specularity) book on desk. The unoccluded view from the first floor window shows a desert landscape with palm trees and low mountains in the distance.

The space contains a desk with a computer monitor. The VDT screen was modeled as a polygon with planar surfaces approximating the curved shape of a computer screen. Two images were displayed on a split monitor screen to visualize the effects of veiling reflections: 1) a color photograph to represent continuous surface images, and 2) white characters on a black background to represent written text. The luminance of the color photograph was modeled to match an average luminance of 38 cd/m^2. The luminance of the white characters was ~140 cd/m^2 and of the screen background ~2 cd/m^2.

The electrochromic glazings were modeled as homogeneous specular transparent surfaces with neutral color. The functional dependence on incident angle of transmittance and reflectance for the electrochromic was assumed to be the same as for clear glass. The visible transmittance of the electrochromic glazing can vary continuously between 0.88 and 0.08 (11:1). For comparison, clear glass (Tv=0.88) and tinted glass (T_v=0.41) were also modeled.

The electrochromic was controlled to admit sufficient daylight to meet but not exceed the design workplane illuminance of 500 lux at either the front or rear area of the office, hereafter referred to as electrochromic-f and electrochromic-r, respectively. The "front" area (1 m^2) of the office was defined by a ceiling-mounted photosensor with a 30° restricted field of view of only the desk work surface, the center of which is located 2.12 m from the sidewall and 1.37 m from the window wall. The "rear" area (4.6 m^2) was defined by a ceiling-mounted photosensor with a 60° restricted field of view, located along the centerline of the window width at a distance of 3.05 m from the window plane.

Since each RADIANCE visualization takes substantial computing time, a base set of data and images was produced for the clear glazing case for each hour from 8:00 to 18:00. Workplane illuminance data were generated for a 0.3 x 0.3 m grid of points throughout the office. The workplane illuminance level detected by the ceiling-mounted photosensor was then determined by averaging the illuminance levels at the workplane within the rear or front area (designated in the previous paragraph) "seen" by the photosensor. This average workplane illuminance, E_{clear}, was then used to determine the transmission level, $T_{v\ new}$, of the electrochromic glazing for that hour:

$$T_{v\ new} = T_{v\ clear} * E_{design} / E_{clear} \quad (1)$$

where,

$T_{v\ new}$	=	0.08 – 0.88, transmission range of the electrochromic glazing;
$T_{v\ clear}$	=	0.88, clear glazing transmission;
E_{design}	=	500 lux, design workplane illuminance;
E_{clear}	=	Average workplane illuminance "measured" by front or rear ceiling-mounted photosensor.

Workplane illuminance levels for the electrochromic, E_{ec}, and tinted glazings were then computed by applying a scale factor, S, to the clear glazing illuminance data:

$$S = T_{v\ new} / T_{v\ clear} \quad (2)$$

$$E_{ec} = S * E_{clear} \quad (3)$$

Photorealistic images and luminance levels were obtained by applying the same scale factor, S, to each pixel or luminance value of the base images.

RESULTS

Average workplane illuminance data are given in Table 1 (August 21, clear sky) and Figures 1-2 (December 21, March/September 21, June 21, clear and overcast sky). Visualizations and falsecolor luminance maps for the following views were generated for August 21 (clear sky), 8:00-18:00; a sample of these images are given in Figures 3-14[2] at 9:00, when the sun is out of the plane of the window and at 15:00, when direct sun enters the space. Data labels on the falsecolor images display the minimum or maximum scene luminance at the lower left hand point of the label. Room surface luminance data for August 21 are summarized in Table 2. VDT background and character luminance data for August 21 are also given in Table 3.

Inside View toward Window	Photorealistic and falsecolor luminance map showing a 120° view of the interior looking towards the west-facing window (Figures 3-4).
Inside View of North Wall	Photorealistic and falsecolor luminance map showing an elevation view of the long north wall as seen from a person sitting at the desk (Figures 5-6).
VDT View	Photorealistic and falsecolor luminance map showing a 60° view of the VDT screen and desk surface from a person sitting at the workstation (Figures 7-8).
VDT Text View	Falsecolor luminance map showing a small area on the VDT monitor for the purpose of studying veiling reflections (Figures 9-10).
View Looking Out Window	Photorealistic and falsecolor luminance map of a 140° view to the outside showing the exterior landscape (Figures 11-12).
Exterior View of Window	Photorealistic and falsecolor luminance map of the outside of the window showing the exterior landscape (Figures 13-14).

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2 The image labeling convention is [glazing type, hour of day]; e.g., "88% 9h" is clear glazing (Tv=0.88) at 9:00, "el_rear 9h" is the electrochromic-r, controlled by the rear zone photosensor, and "el-table 9h" is the electrochromic-f, controlled by the front zone photosensor located over the table or desk worksurface. For black and white reproductions of this paper, luminance levels of the falsecolor luminance maps can be ascertained by carefully studying the shades of gray in relation to the photorealistic images.

DISCUSSION

Illuminance Levels

For offices containing VDT screens, the Illuminating Engineering Society of North America (IESNA) recommends that illuminance levels are kept at or below 500 lux on the horizontal workplane (IES 1993a). For other tasks, such as paper or reading tasks, the illuminance levels can be less carefully controlled. Illuminance data for clear sky and overcast sky conditions on June 21, March/September 21, and December 21, and clear sky conditions on August 21 allow the following conclusions (Table 1, Figures 1-2).

The electrochromic-f and -r glazings (T_v=0.08-0.88) were able to maintain a constant daylight workplane illuminance at the design level of 500 lux for most sunny and overcast days, except when direct sun penetrated the space on sunny days or when overcast winter daylight levels were insufficient at the rear zone. For example, when direct sun was present, daylight illuminance levels were between 1460-3468 lux from 14:00 to 16:00 (June 21) at the front zone with the electrochromic-f at its lowest transmission (T_v=0.08). While not uncomfortable for typical office tasks, these illuminance levels may cause visual discomfort for VDT tasks. On overcast days with low daylight availability (December 21), daylight illuminance levels were between 2 and 286 lux at the rear zone with the electrochromic-r at its highest transmission (T_v=0.88). On the other hand, the clear and tinted glazing illuminance levels increased and decreased proportionally to daylight availability – and with the absence of shading devices, illuminance levels well exceeded the design level throughout the day, even on overcast days.

If it is necessary to control the interior illuminance due to task requirements, a variable transmission shading device (e.g., venetian blind) will be required for both static and electrochromic glazings to control workplane illuminance levels when direct sun penetrates the space and exterior illuminance levels are high. For the electrochromics, the number of daylight hours that the shading device must be deployed will be substantially less than both static glazings, permitting view. On sunny days, a shading device for the electrochromic-r will be required to control rear zone daylight levels at or below 500 lux from 15:00-17:00 from March 21 to September 21. Comparably for the tinted glazing, the shading device will be required from 8:00-16:00 from March 21 to September 21 and from 13:00-15:00 on December 21. In order to meet the 500 lux criteria and control direct sun without a shading device, the electrochromic-f would need to have a transmission level of T_v=~0.01 in its most colored state to achieve daylight levels at or less than 500 lux at the front zone. A comparison of the exterior views to the outdoors are given in Figures 11-12. For these hours when VDT task are being performed, occupants may object to the quality of the exterior view at this low transmission. Visual connection to the outdoors is diminished with glass transmittance values of this level, although it still may be preferable to the reduction in view quality associated with a shading device.

Visual Comfort

For office environments, IESNA provides lighting quality guidelines to reduce visual discomfort associated with glare, reduced contrast or visibility of a task, and veiling reflections. The ANSI/IESNA RP-1 VDT Lighting Standard (IES 1993) recommends that all room surfaces within peripheral view, including the window, not exceed 850 cd/m^2 given an average VDT luminance of 85 cd/m^2 (10:1 luminance ratio). For paper or reading task surfaces within close visual proximity, luminance levels should be maintained below ~255 cd/m^2 (3:1 luminance ratio). The following luminance ratios should not be exceeded:

Between paper task and adjacent VDT screen:	3:1
Between task and adjacent dark surroundings:	3:1
Between task and remote (non-adjacent) surfaces:	10:1
Between points anywhere in the field of view for a safe environment:	40:1

Given these recommendations, luminance levels and ratios were evaluated on the peak sunny day, August 21. Of special interest were luminance levels on the paper task, VDT, and surrounding window and wall surfaces within the focused visual field of a person sitting at the desk workstation 1.4 m from the window wall (60° view). RADIANCE luminance maps illustrate distribution, area, and intensity of luminance levels within the field of view (Figures 7-8, Table 2).

In general, the luminance of the window was higher in the morning than the afternoon, because the surrounding mountain landscape viewed by the window was directly illuminated by the rising sun (maximum luminance levels were 12,700 cd/m^2 (mountain) at 8:00 and 9400 cd/m^2 (ground) at 15:00). For the electrochromics, however, the transmission level set by daylight control determine window luminance levels. In the morning, when the sun was out of the plane of the window and interior daylight availability was moderate, the electrochromics were set to a high transmission state. Consequently, window luminance levels were also high at 2117-6990 cd/m^2. If controlled for visual comfort, the electrochromic at T_v=0.08 would be able to achieve less than a 16:1 luminance ratio at the peak 10:00 hour. A T_v of 0.05 would be required to attain the desired 10:1 VDT luminance ratio. This example demonstrates the importance of the control algorithm. Since the electrochromic was not controlled to respond to bright glare sources, visual comfort may be impaired even if task illuminance levels are being met. However, glare control conflicts with the control objectives for energy-efficiency, since daylight illuminance levels would be significantly diminished.

In the afternoon when direct sun was present (13:00-16:00), window luminance levels were lower than the morning case but still remained too high to meet the 10:1 ratio. Only the electrochromic-f, now controlled to its lowest transmission (T_v=0.08), was able to meet the standard 10:1-12:1 from 14:00 to 16:00. At dusk hours from 17:00 to 18:00, luminance ratios fall to more tolerable levels: 40:1 for clear glazing, 4:1-25:1 for and the electrochromics depending on the selected transmission.

The occupant may experience discomfort glare between local paper tasks and the VDT (3:1 required) when direct sun is present in the space. At a horizontal exterior illuminance level of 52-76 klux, the electrochromic-f at lowest transmission yielded 10-12:1 luminance ratios. A T_v of ~0.016 would provide sufficient control at peak sun conditions.

Remote wall surfaces within this VDT field of view included the window wall below the sill and sidewall. The luminance of the window wall below the sill posed no problems, being illuminated by only the interior surface of the room. However, high transient adaptation is required by the eye as it moves from this low lit surrounding surface to the extremely bright window surface. Overall, during morning hours, the tinted glazing was unable to maintain a 10:1 ratio; while the electrochromic-r with T_v=0.26-0.49 throughout this period was able to sustain luminance ratios below the standard 10:1.

Direct sun strikes a small triangular area of the north sidewall as it comes into the plane of the window (a full sidewall view is shown in Figures 5-6). The area and intensity of this source varied from 12:00 to 16:00 and was at its peak at 14:00. With a ratio of 6:1, only the electrochromic-f at T_v=0.08 was again able to meet the luminance ratio standard for remote surfaces.

While the electrochromic glazing is better able to consistently control luminance levels compared to the static glazings throughout the day, the low T_v of 0.08 is still unable to satisfy the IES Standard under direct sun conditions. Given the more stringent control of the front photocell, the electrochromic-f was controlled to its lowest transmission, T_v=0.08, from 11:00 to 17:00. A transmission of $T_v \approx 0.016$ would be required to meet the standard for local tasks during the peak conditions of this sunny climate. Windows that do not receive direct sun (e.g., north-facing or shaded by exterior obstructions such as trees or building overhangs) will require less transmission control. A practical alternative to ameliorate visual discomfort for the low-luminance VDT tasks would be to position the occupant's view of the VDT away from the window. Also it should be kept in mind that these IES values are recommendations and not absolute requirements.

VDT Visibility

Another important factor in evaluating visual comfort is the visibility of images displayed on a VDT screen located near the window. Visibility can be impaired by image reflections or washout of the screen. Reflected images can obscure text or create visual clutter that make it difficult to ascertain information on the screen. Contrast is reduced between the dark and light areas of the screen. Screen washout can occur when the VDT reflects light from high luminance wall, window, or ceiling surfaces. Absence of these reflections is taken as another indicator of good lighting quality.

Images of the VDT screen were generated with a color photograph on one half and white letters on a black background on the other half to visualize VDT visibility (Figures 7-8). There are no currently known metrics for judging and evaluating VDT visibility. In general, the greater the ratio of task luminance (white letters) to its background luminance, the better the contrast or visibility. As such, minimum background and maximum letter luminances were determined at a 8-18° viewing angle off normal for the peak sunny day, August 21 (Table 3, Figures 9-10).

A poster mounted on the wall behind the VDT screen created a veiling reflection in the dark areas of the VDT screen to varying degrees of clarity for the clear, tinted, and electrochromic-r glazings throughout the day. Discernible washout caused by the high ambient illuminance of this same wall surface (reflectance=0.57) occurred at the top of the color image and text for the clear glazing from 12:00 to 16:00 and to a lesser degree with the tinted glazing. For clear sky conditions in the early morning, the illuminance on the wall opposite the VDT screen was sufficient to cause reflections in the VDT. For the higher illuminance and direct sun conditions in the afternoon, the illuminance on this wall increased, causing a more clear and brighter reflection of the poster and an overall washed out appearance on the VDT screen.

The ratio of text to background luminance was between 7-16 for the clear glazing and 13-28 for the tinted glazing from 8:00-16:00. Higher ratios, indicating better contrast, of 17-48 and 30-48 were attained by the electrochromic-r and electrochromic-f, respectively, for the same hours. At 17:00 (Figure 10), stripes of light reflected across the screen caused luminance ratios to vary between 4 (stripe area) and 16 (dark area) for the clear glazing and 15 and 57 for the electrochromic-f. Direct sunlight was incident on a corner of the VDT screen at 13:00; with the electrochromics' low transmission (T_v=0.27, 0.08), VDT visibility still remained fairly good.

For this office condition, extreme daylight conditions were not tested. For example, if full direct sun was incident on the wall behind the VDT screen, as would occur if the VDT had been placed on the opposite side of the office, veiling reflections would increase significantly. As such, we conclude that given this daylight condition, VDT task luminance contrast is very good with the electrochromic-f glazing, and moderate with the tinted glazing. The clear glazing would result in poor VDT visibility.

Privacy

With the absence of shading devices, privacy can be a concern for occupants sitting near the window. The office interior is especially visible when direct sunlight is incident on the viewed object. A view from the exterior to the interior was produced by RADIANCE for the four glazing types for the peak clear day, August 21 (Figures 13-14), and examined to determine if privacy was attained.

The electrochromic-f provided excellent privacy for those times when the sun does not strike interior objects. Throughout the morning, the electrochromic-f glazing achieved good privacy, with a minimum visibility of interior objects at 11:00. RADIANCE views for the electrochromic glazings show that interior details cannot be discerned from 8:00-11:00. High luminance of the surrounding mountains and trees caused mirror reflections on the exterior surface of the electrochromic-f glazing and obscured interior views. In the afternoon, privacy was diminished due to direct sun, despite the low glazing transmission of T_v=0.08; at 16:00, the VDT monitor could be discerned slightly.

The clear and tinted glazings afforded very good privacy only during early morning (8:00) or late afternoon hours (18:00). Maximum privacy occurred at 10:00 for the clear glazing and at 11:00 for the tinted glazing. At 16:00, the VDT monitor could be discerned clearly and details of other interior objects (i.e., photos on the side wall) could be made out slightly. These effects might be changed slightly with the addition of interior electric lighting. These electrochromic glazings are not able to provide privacy at night with their minimum T_v=0.08; a much lower T_v would be needed.

CONCLUSIONS

Electrochromic windows with a transmission range of T_v=0.08-0.88 can maintain stable daylight workplane illumination levels within the design level of 500 lux in both the front and rear zones of an office space under overcast and sunny conditions for this sunny Arizona climate. However, if direct sun is present in the space, the transmission of the electrochromic at its most colored state would need to drop to $T_v \approx 0.01$ to limit interior daylight to 500 lux. The higher levels achieved at T_v=0.08 are acceptable for non-VDT tasks. Alternatively, a shading device can be used to control direct sun. Compared to the tinted glazing, the electrochromic glazing greatly reduces the number of shade-deployed hours throughout the year, permitting view.

To meet the IES RP-1 Standard for VDT tasks, the transmission of the electrochromic would need to drop to $T_v \approx 0.016$ to achieve adequate local task (3:1 luminance ratio) glare control under direct sun. As designed (T_v=0.08), the maximum luminance of 13:1 is close to the recommended 10:1 ratio. Variable transmission shading devices such as a venetian blind can be used to control high window luminance levels.

Throughout the peak clear day, August 21, the electrochromics enhanced VDT visibility by reducing the intensity of room surface luminance levels. In comparison, the clear and tinted glazing resulted in poor to moderate visibility, since VDT contrast was reduced. These limited RADIANCE parametrics did not test extreme daylight conditions. For example, if sunlight had been present on the wall behind the VDT screen, greater differences between the glazings may have been revealed.

Electrochromic windows dimmed down to 8% visible transmittance make it almost impossible for a person outdoors to see interior objects that are not directly illuminated by the sun, and thus will afford more privacy throughout the day than the clear or tinted glazing. White or highly reflective interior objects in direct sunlight will still be visible.

Electrochromic glazings need a minimum visible transmittance of ~1% to maintain illuminance and luminance values within the IES-recommended levels of 500 lux and 850 cd/m^2 for office environments with VDT tasks in Phoenix, Arizona. Given that transmission value, electrochromics can achieve privacy, a near glare-free environment, and constant interior daylight levels. However, such very low glass transmittance values will require the use of interior electric lighting (and significantly decrease energy efficiency) since daylight will be largely eliminated from the room. Furthermore, many office occupants may not accept such a low transmission glazing, since exterior view quality and connection to the outdoors will be diminished for those hours when there is direct sun or high exterior illuminance levels. Alternative fenestration designs with shading systems or other design strategies that split the exterior wall into a higher placed daylight admitting element and a lower, controlled transmission view window, may provide a more acceptable solution.

The RADIANCE program should continue to prove to be a valuable tool to explore such design alternatives while we wait for the commercial introduction of electrochromic glazings and the ability to conduct full-scale occupant evaluations. Newer images have been generated using real spectra from a variety of prototype devices as well as other improvements. An example of these new renderings is included in this paper (Figure 15).

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TABLE 1
RADIANCE Workplane Illuminance (Lux) on August 21, Clear Sky, Phoenix, AZ

Hour	Eh (lux)	Clear front	Clear rear	Tinted front	Tinted rear	EC-r front	EC-r rear	EC-r Tv	EC-f front	EC-f rear	EC-f Tv
8	51,652	1,231	901	573	420	683	500	0.49	500	366	0.36
9	65,972	1,729	1,202	806	560	719	500	0.37	500	348	0.25
10	75,946	2,316	1,464	1,079	682	791	500	0.30	500	316	0.19
11	81,547	2,883	1,634	1,343	761	882	500	0.27	500	283	0.15
12	81,651	3,135	1,689	1,461	787	928	500	0.26	500	269	0.14
13	76,402	3,234	1,653	1,507	770	978	500	0.27	500	256	0.14
14	66,534	8,838	1,599	4,118	745	2,764	500	0.28	803	145	0.08
15	52,470	33,131	1,558	15,436	726	10,634	500	0.28	3,012	142	0.08
16	34,504	18,634	21,790	8,682	10,152	1,694	1,981	0.08	1,694	1,981	0.08
17	13,709	4,672	1,069	2,177	498	2,185	500	0.41	500	114	0.09
18	2,283	388	210	181	98	388	210	0.88	388	210	0.88

Notes:
Front/Rear: Average daylight workplane illuminance (lux) at the front and rear zones of a west-facing office space.
Glass types: Clear (Tv=0.88), Tinted (Tv=0.41), Electrochromics EC-r and EC-f.
Eh: Horizontal exterior illuminance (lux) for a CIE clear sky distribution.
Electrochromic-f (EC-f) transmission is controlled by the front photosensor.
Electrochromic-r (EC-r) transmission is controlled by the rear photosensor.

TABLE 2

RADIANCE Room Surface Luminance Levels (cd/sq.m)
on August 21, Clear Sky, Phoenix, AZ

Hour		Clear Tv=0.88	Tinted Tv=0.41	EC-r Tv=0.08-0.88	EC-f Tv=0.08-0.88
8	Window	12,548	5,846	6,990	5,107
	Desk	170 - 283	56 - 170	56 - 170	56 - 170
	Wall	56 - >850	56 - 510	56 - 510	56 - 396
9	Window	14,355	6,688	5,971	4,163
	Desk	170 - 396	56 - 170	56 - 170	56 - 170
	Wall	170 - >850	56 - 736	56 - 736	56 - 510
10	Window	14,695	6,858	5,027	3,179
	Desk	283 - 623	170 - 283	56 - 170	56 - 170
	Wall	170 - >850	56 - >850	56 - 736	56 - 510
11	Window	14,463	6,640	6,640	4,421
	Desk	170 - 736	170 - 396	56 - 283	56 - 170
	Wall	170 - >850	170 - >850	170 - 736	56 - 510
12	Window	13,408	6,137	3,931	2,117
	Desk	170 - 736	170 - 396	170 - 283	56 - 170
	Wall	170 - >850	170 - >850	170 - 736	56 - 510
13	Window	12,954	6,044	3,942	2,011
	Desk	283 - >850	170 - >850	170 - >850	170 - 736
	Wall	283 - >850	283 - >850	170 - >850	170 - >850
14	Window	>850	>850	3,543	1,030
	Desk	14,766	6,891	283 - >850	170 - >850
	Wall	623 - >850	283 - >850	170 - >850	56 - 510
15	Window	>850	>850	>850	844
	Desk	14,641	6,828	4,694	170 - >850
	Wall	283 - >850	170 - >850	170 - >850	56 - 396
16	Window	>850	>850	56 - 396	56 - 396
	Desk	12,001	5,606	1,092	1,029
	Wall	170 - >850	170 - 736	56 - 170	56 - 170
17	Window	3,432	1,608	1,609	368
	Desk	170 - 396	56 - 170	56 - 170	<56
	Wall	56 - 623	56 - 283	56 - 170	<56
18	Window	2,262	1,056	2,262	2,262
	Desk	56 - 170	56 - 170	56 - 170	56 - 170
	Wall	56 - 170	56 - 170	56 - 170	56 - 170

Notes:
Data show either the maximum luminance or a discrete range of luminance levels: <56, 170, 283, 396, 510, 623, 736, and <850 cd/sq.m on that surface. These data were derived from RADIANCE falsecolor luminance maps similar to Fig. 7-8.
EC-r is the Electrochromic-r controlled by the rear photosensor.
EC-f is the Electrochromic-f controlled by the front photosensor.

TABLE 3

RADIANCE VDT Luminance (cd/sq.m), August 21, Clear Sky, Phoenix, AZ

Hour	VDT Surface	Clear	Tinted	EC-r	EC-f	Hour	Clear	Tinted	EC-r	EC-f
8	Background	9	5	6	5	14	17	9	6	3
	Letters	144	139	140	138		157	145	140	136
	Ratio	16	28	25	30		9	17	22	45
	Comments	A, B	B	B			A-C	A-C	B, C	C
9	Background	11	6	5	4	15	22	11	8	4
	Letters	146	140	139	138		162	147	143	136
	Ratio	14	24	26	32		7	13	17	39
	Comments	A, B	B				A-C	A-C	B, C	C
10	Background	9	5	4	3	16	14	8	3	3
	Letters	148	140	138	137		152	142	136	136
	Ratio	16	28	33	42		11	19	48	48
	Comments	A, B	B				A-C	B, C	C	C
11	Background	10	6	4	3	17	11	6	6	3
	Letters	149	141	138	137		173	152	152	138
	Ratio	15	25	33	44		16	25	25	52
	Comments	B	B	B			E	E	E	E
12	Background	11	6	4	3	18	6	3	6	6
	Letters	151	142	139	136		141	137	141	141
	Ratio	14	23	31	43		23	40	23	23
	Comments	A, B	B	B			B	B	B	B
13	Background	12	6	5	3					
	Letters	150	142	139	136					
	Ratio	12	22	29	42					
	Comments	A-D	A-D	A-D	A-D					

Notes:

These data are derived from RADIANCE falsecolor luminance maps similar to Fig. 9-10. Without daylight, background luminance is ~2 cd/sq.m and letter luminance is ~140 cd/sq.m.

EC-r is the Electrochromic-r controlled by the rear photosensor.

EC-f is the Electrochromic-f controlled by the front photosensor.

Comments:

A. Wash-out on the VDT screen

B. Poster seen on the VDT screen

C. Direct sun in the room

D. Direct sun incident on the VDT screen

E. Reflected stripes of light across VDT screen

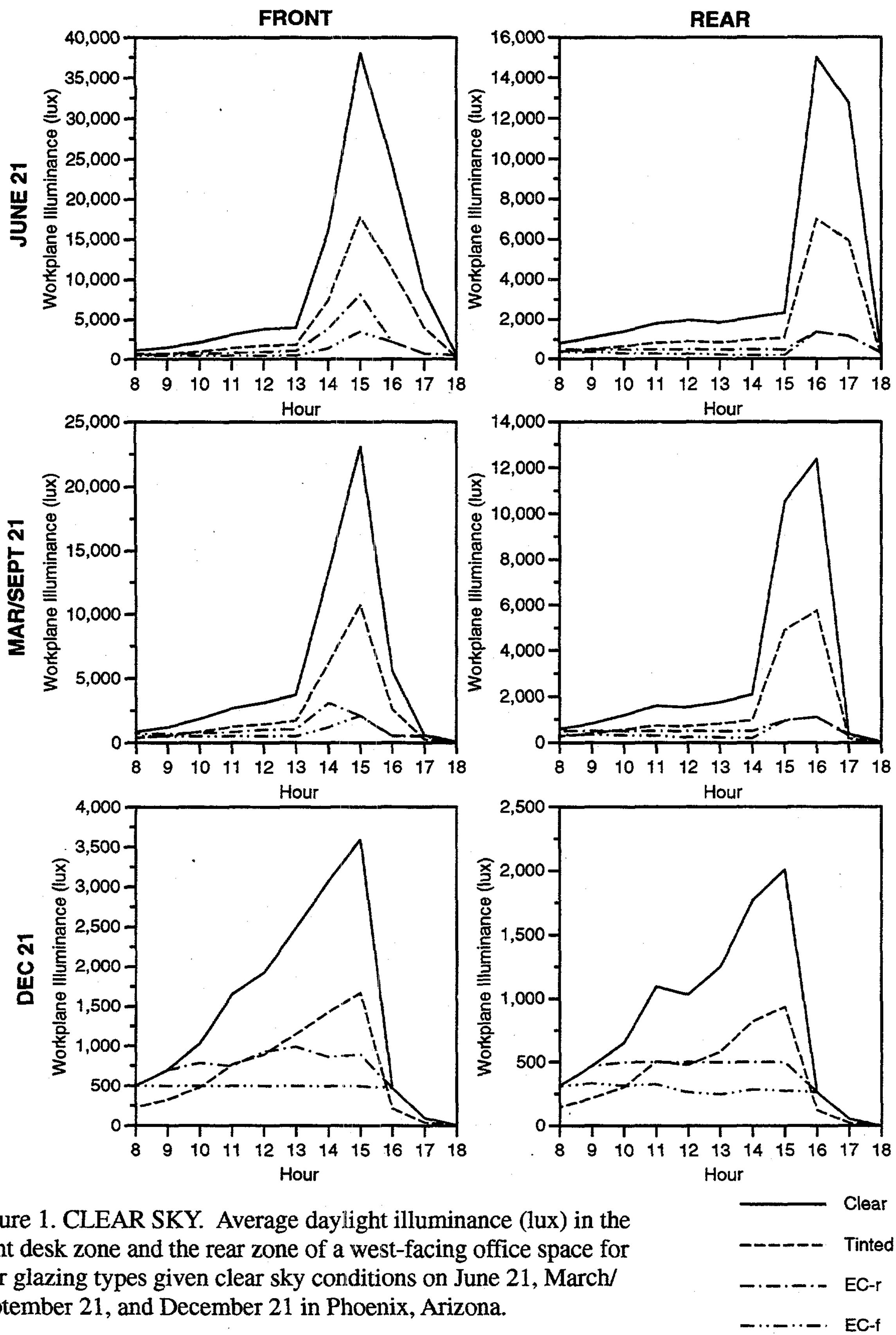


Figure 1. CLEAR SKY. Average daylight illuminance (lux) in the front desk zone and the rear zone of a west-facing office space for four glazing types given clear sky conditions on June 21, March/ September 21, and December 21 in Phoenix, Arizona.

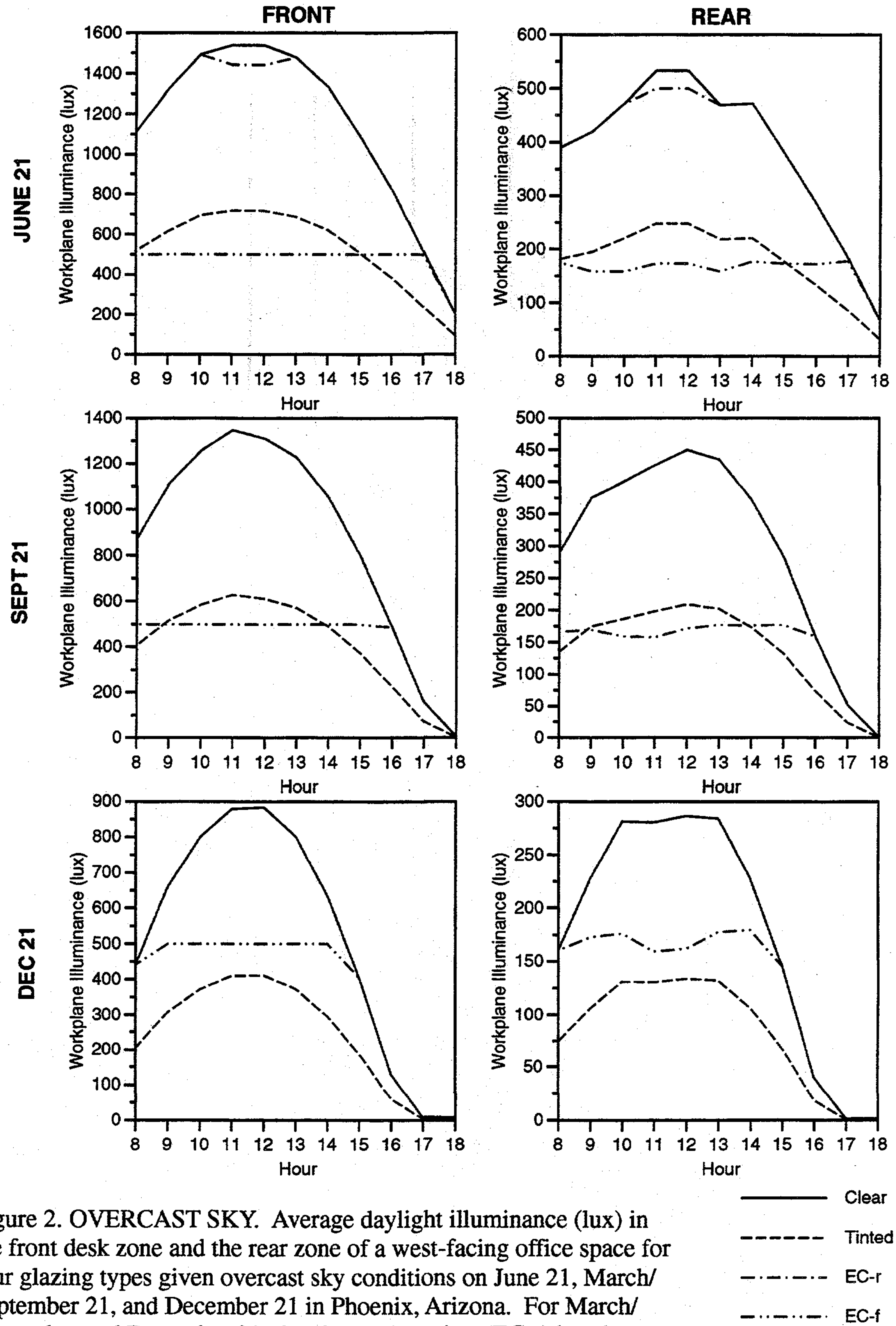


Figure 2. OVERCAST SKY. Average daylight illuminance (lux) in the front desk zone and the rear zone of a west-facing office space for four glazing types given overcast sky conditions on June 21, March/September 21, and December 21 in Phoenix, Arizona. For March/September and December 21, the electrochromic-r (EC-r) has the same values as the clear glazing for all hours.

Figure 3. Inside View toward Window. Photorealistic and falsecolor luminance map showing a 120° view of the interior looking towards the west-facing window. Clear sky, August 21, 9:00 in Phoenix, Arizona (see footnote on page 5 for labeling convention).

Figure 4. Inside View toward Window. Photorealistic and falsecolor luminance map showing a 120° view of the interior looking towards the west-facing window. Clear sky, August 21, 15:00 in Phoenix, Arizona.

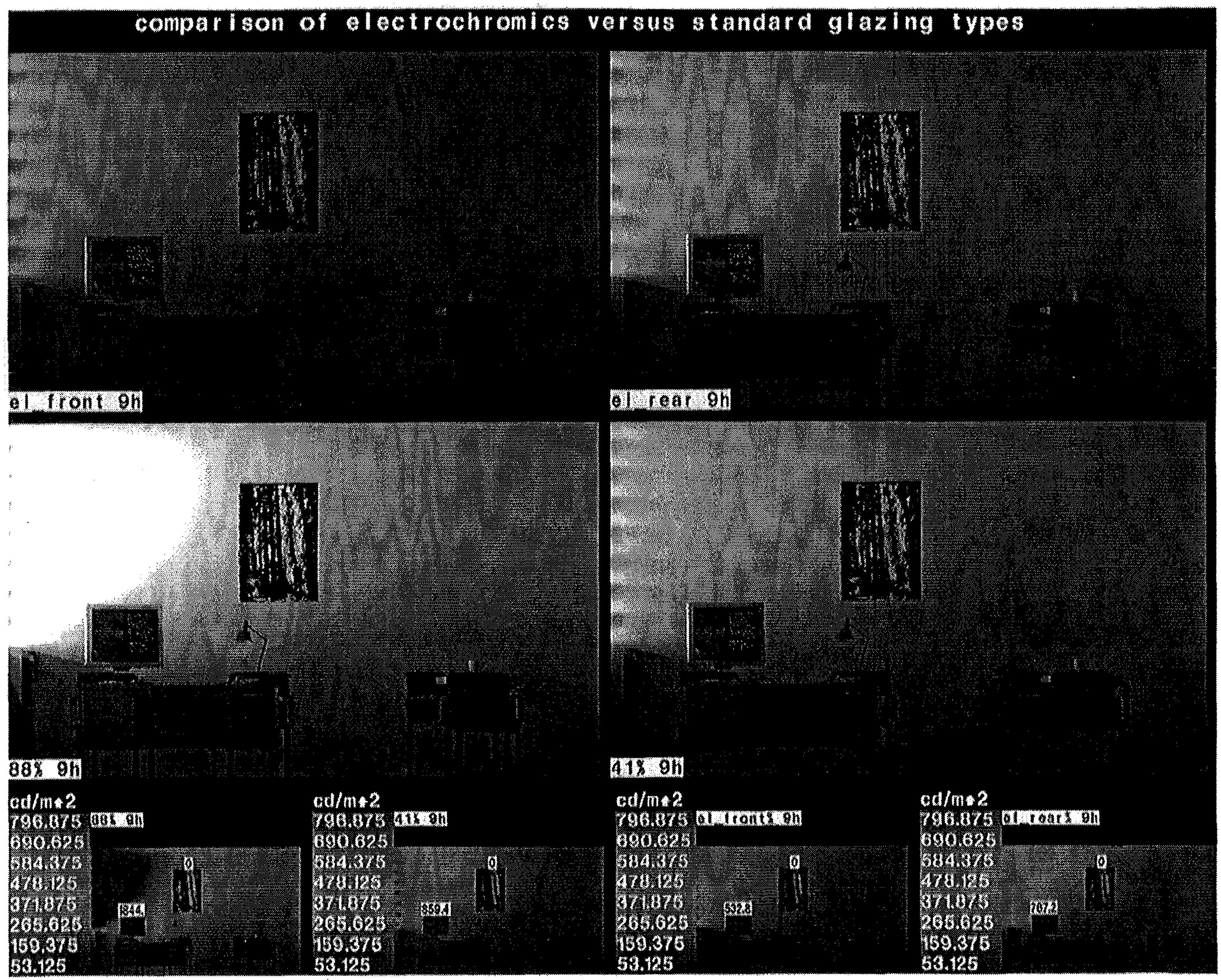
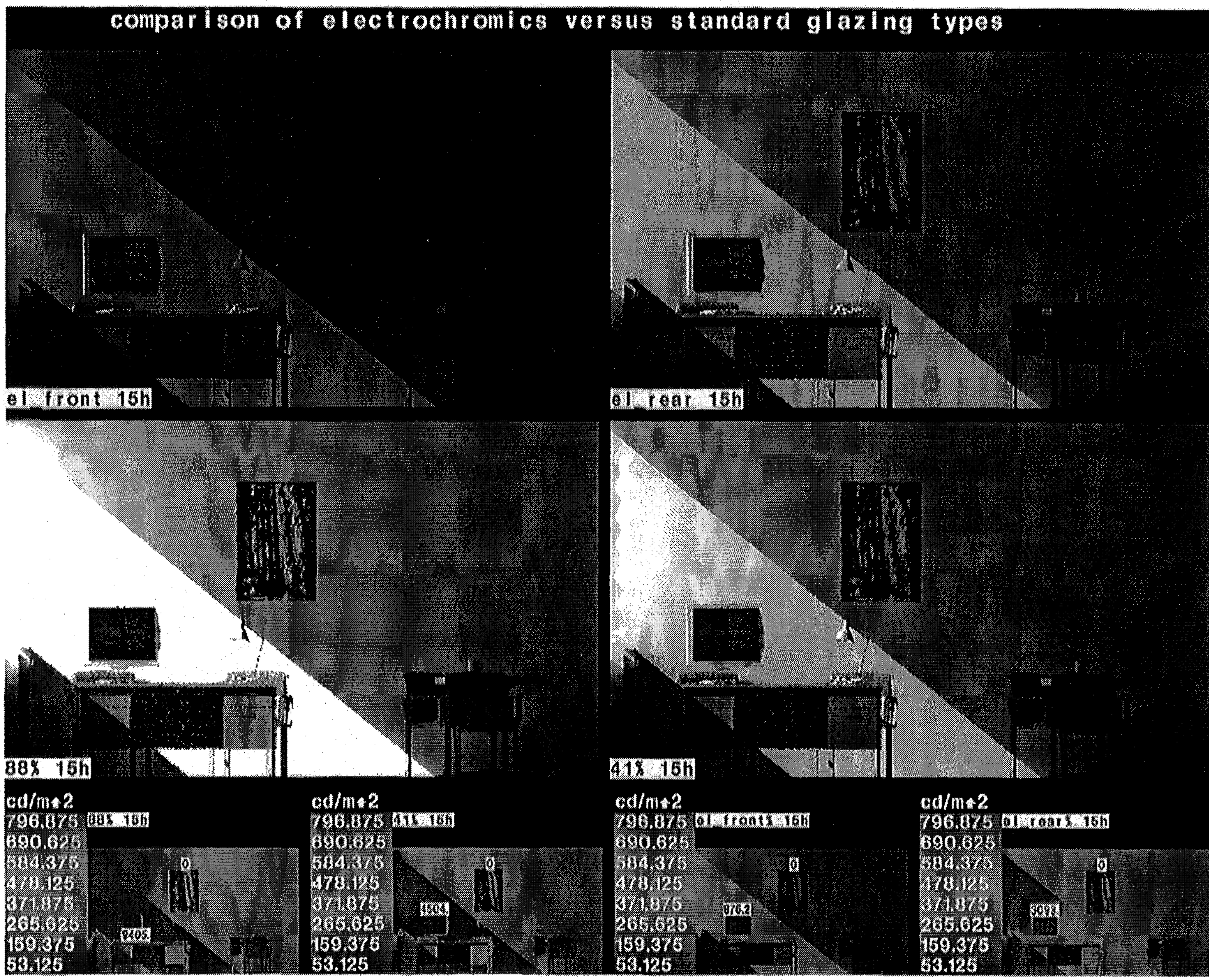


Figure 5. Inside View of North Wall. Photorealistic and falsecolor luminance map showing an elevation view of the long north wall as seen from a person sitting at the desk. Clear sky, August 21, 9:00 in Phoenix, Arizona.

Figure 6. Inside View of North Wall. Photorealistic and falsecolor luminance map showing an elevation view of the long north wall as seen from a person sitting at the desk. Clear sky, August 21, 15:00 in Phoenix, Arizona.



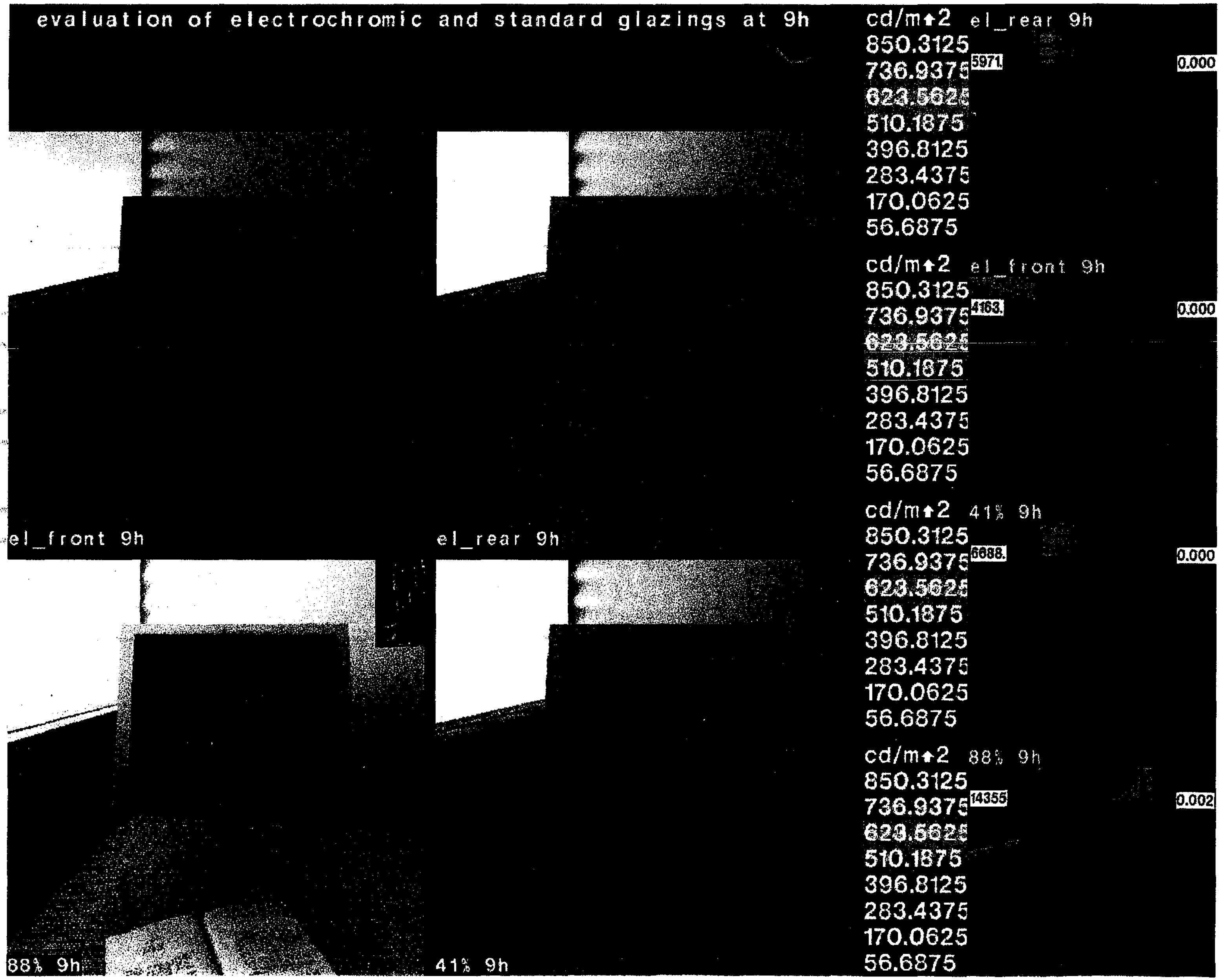


Figure 7. VDT View. Photorealistic and falsecolor luminance map showing a 60° view of the VDT screen and desk surface from a person sitting at the workstation. Clear sky, August 21, 9:00 in Phoenix, Arizona.

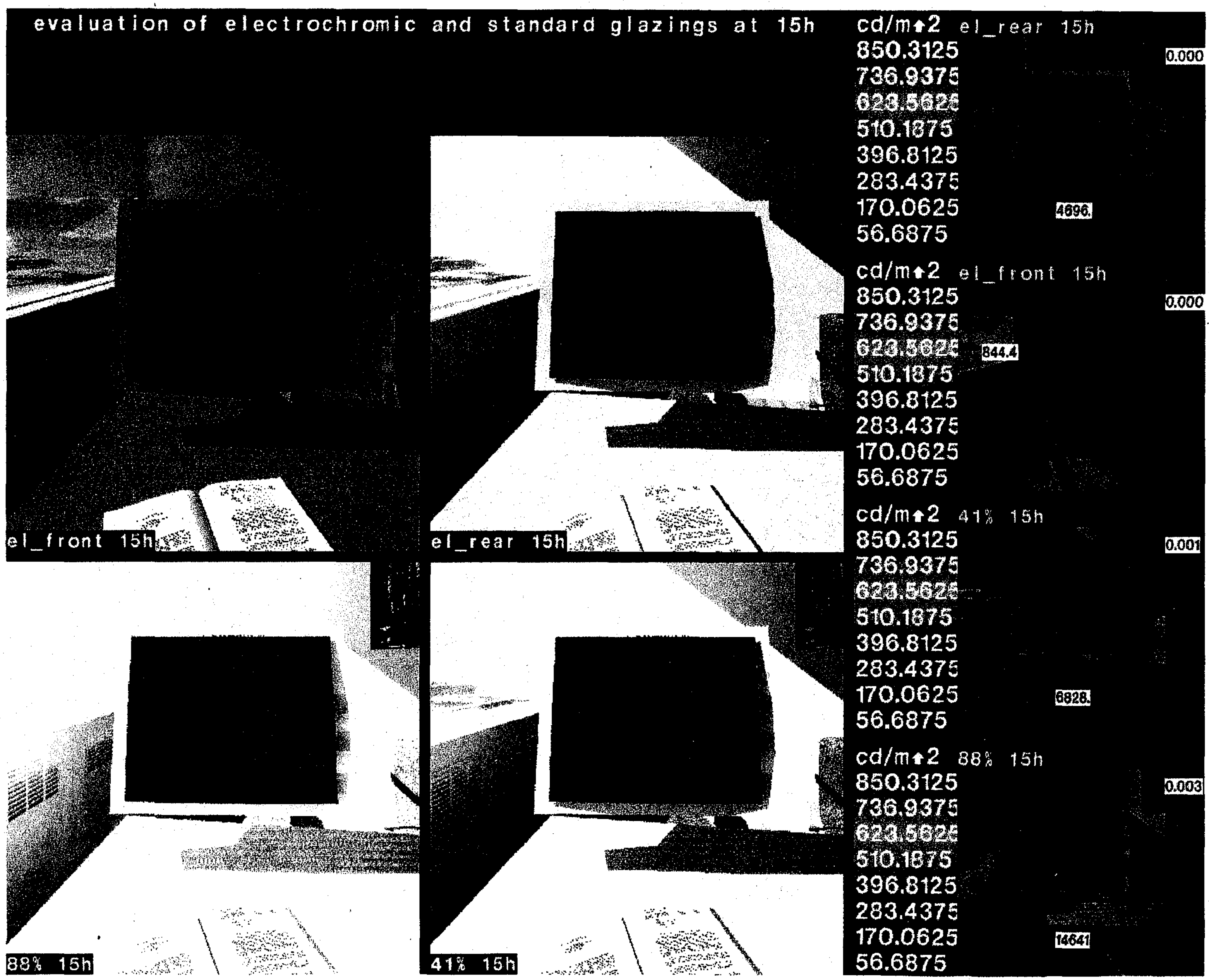


Figure 8. VDT View. Photorealistic and falsecolor luminance map showing a 60° view of the VDT screen and desk surface from a person sitting at the workstation. Clear sky, August 21, 15:00 in Phoenix, Arizona.

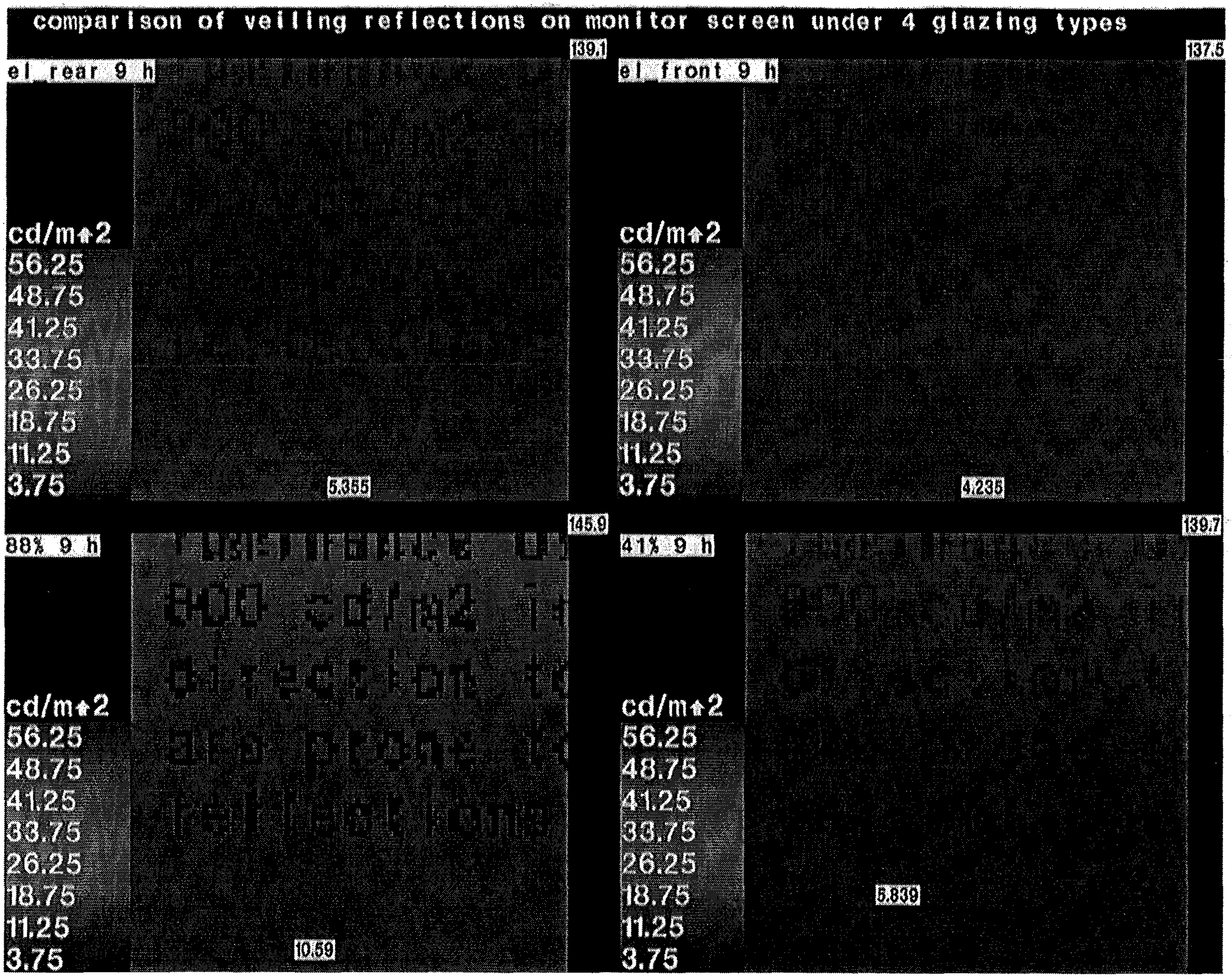
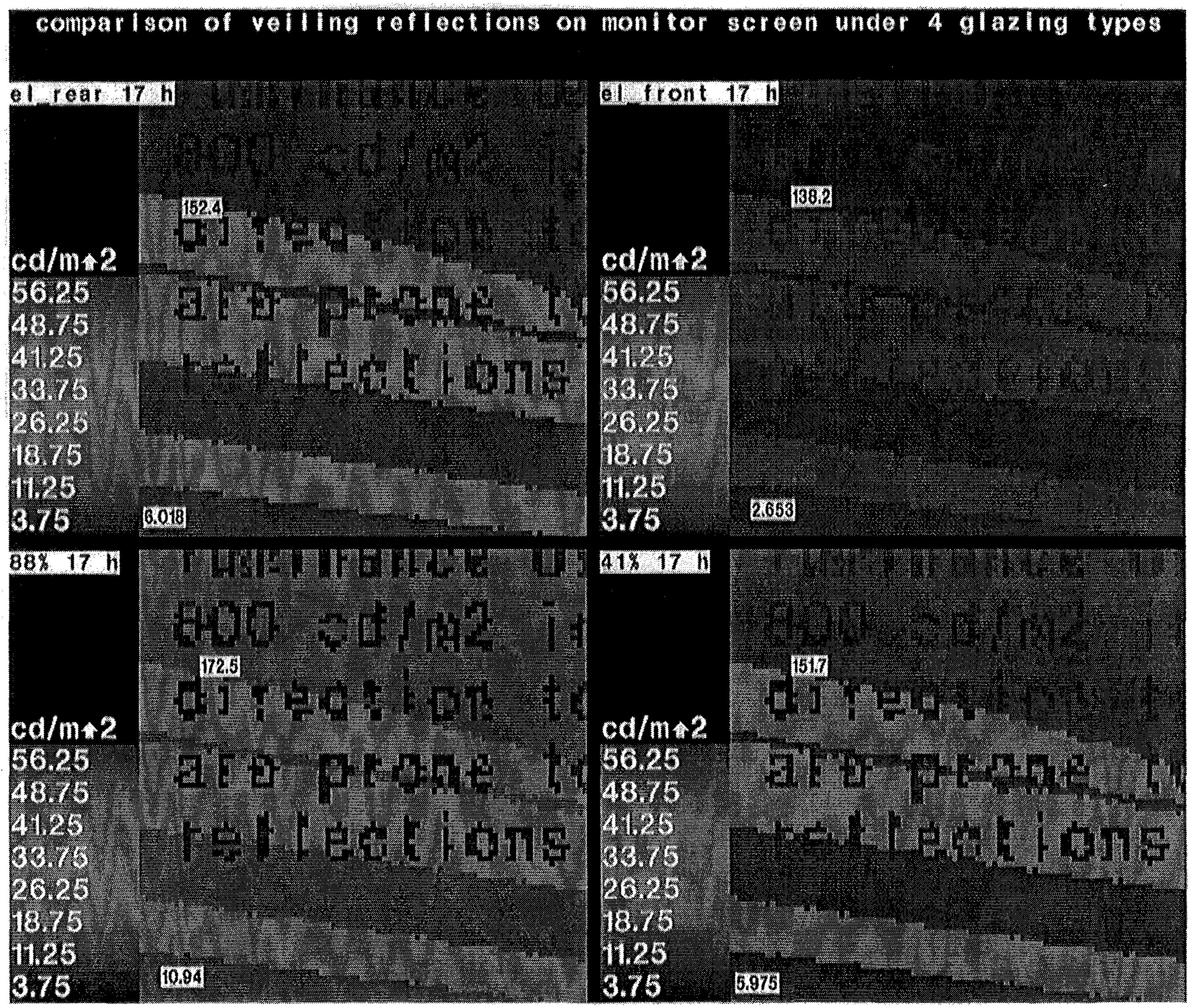


Figure 9. VDT Text View. Falsecolor luminance map showing a small area on the VDT monitor for the purpose of studying veiling reflections. Clear sky, August 21, 9:00 in Phoenix, Arizona.

Figure 10. VDT Text View. Falsecolor luminance map showing a small area on the VDT monitor for the purpose of studying veiling reflections. Clear sky, August 21, 17:00 in Phoenix, Arizona.



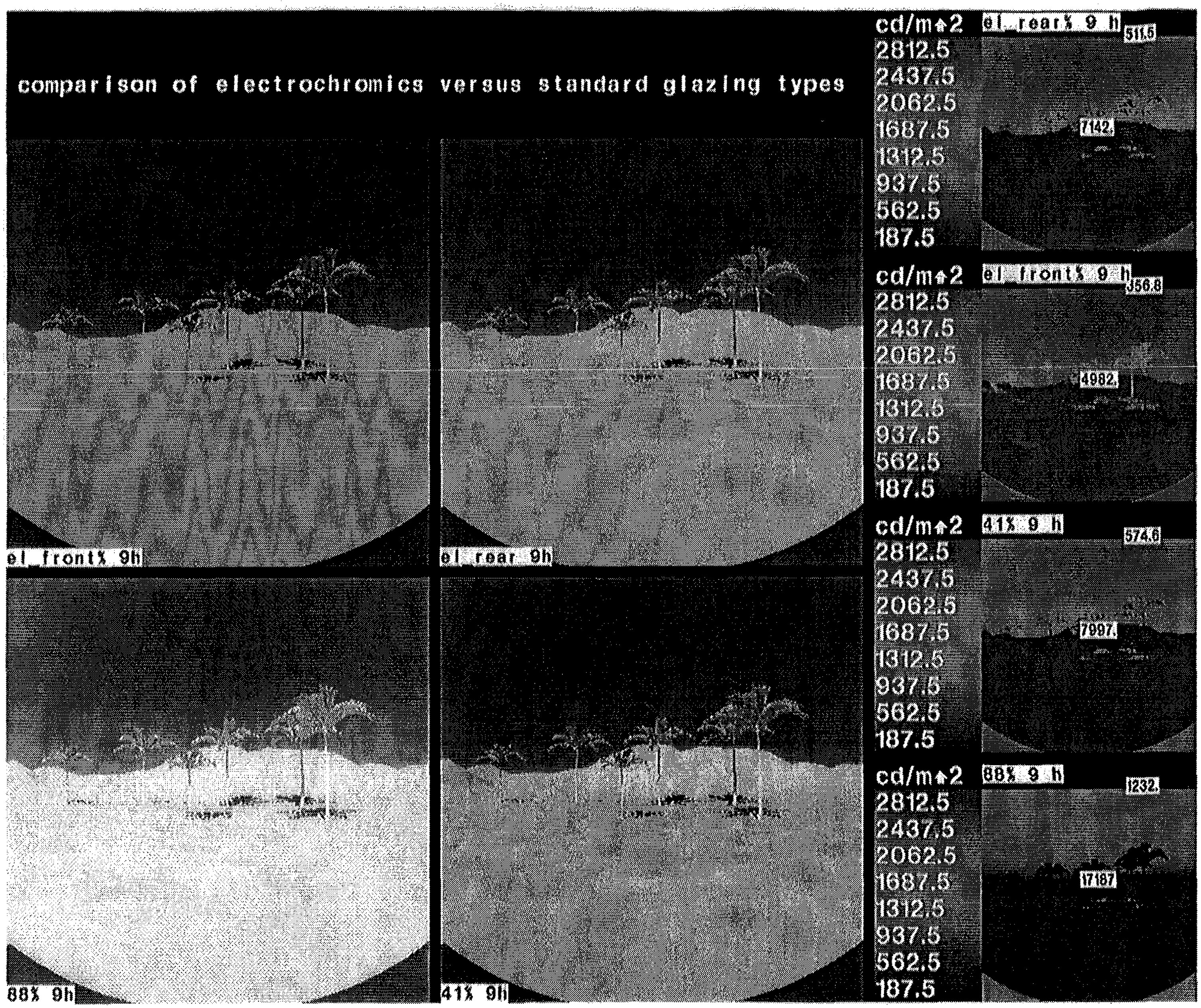


Figure 11. View Looking Out Window. Photorealistic and falsecolor luminance map of a 140° view to the outside showing the exterior landscape. Clear sky, August 21, 9:00 in Phoenix, Arizona.

Figure 12. View Looking Out Window. Photorealistic and falsecolor luminance map of a 140° view to the outside showing the exterior landscape. Clear sky, August 21, 16:00 in Phoenix, Arizona.

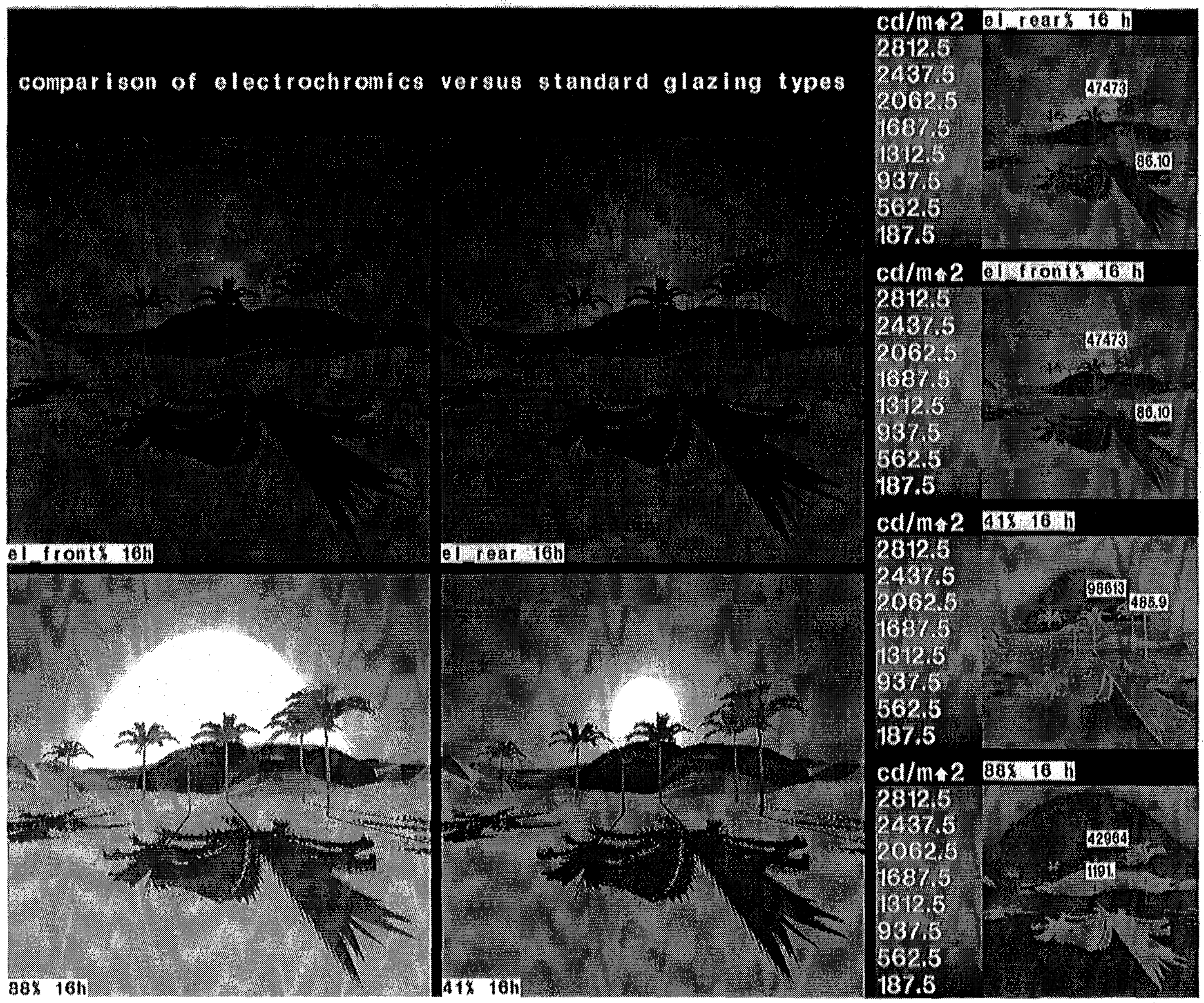
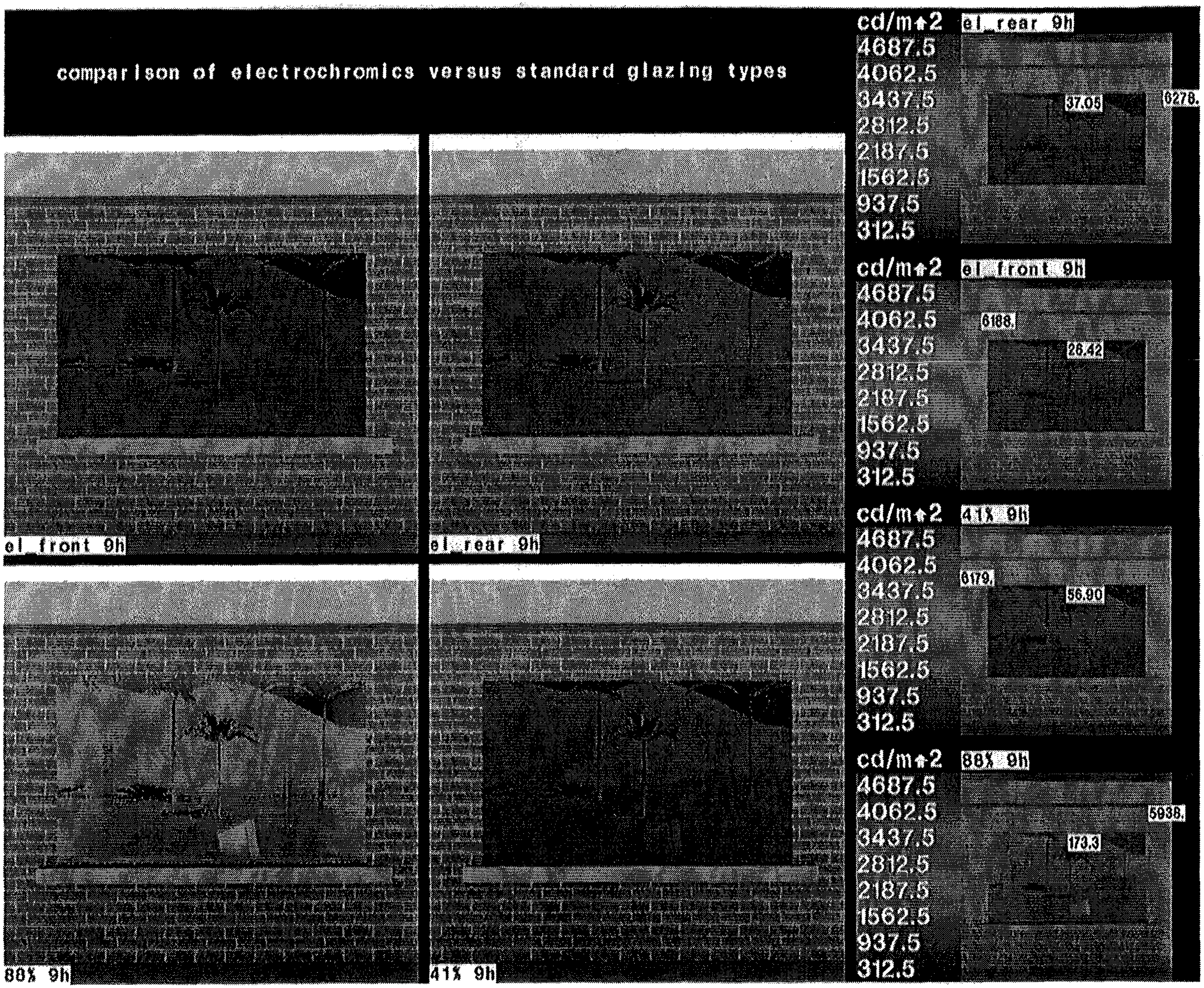


Figure 13. Exterior View of Window. Photorealistic and falsecolor luminance map of the outside of the window showing the exterior landscape. Clear sky, August 21, 9:00 in Phoenix, Arizona.



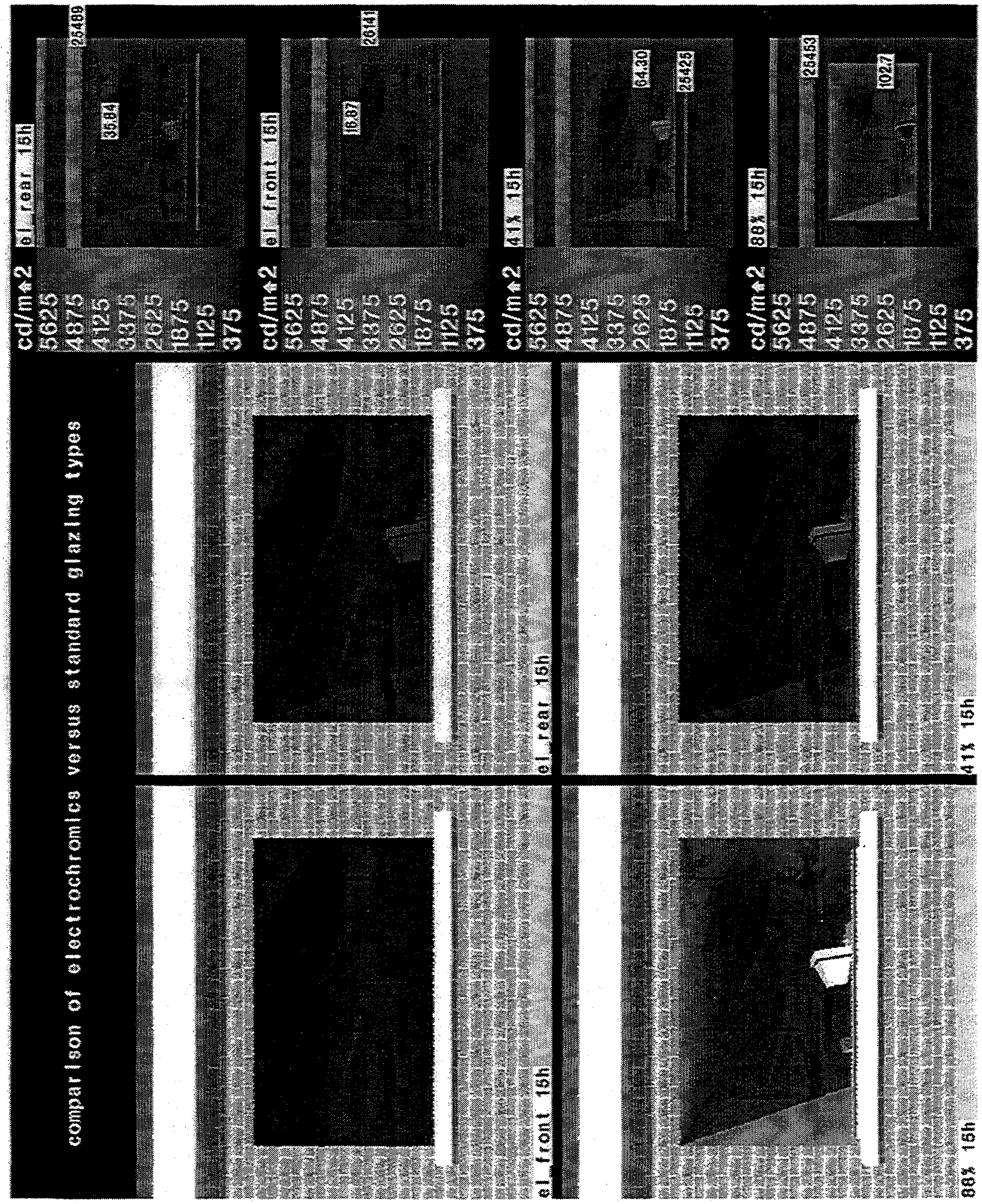


Figure 14. Exterior View of Window. Photorealistic and falsecolor luminance map of the outside of the window showing the exterior landscape. Clear sky, August 21, 15:00 in Phoenix, Arizona.

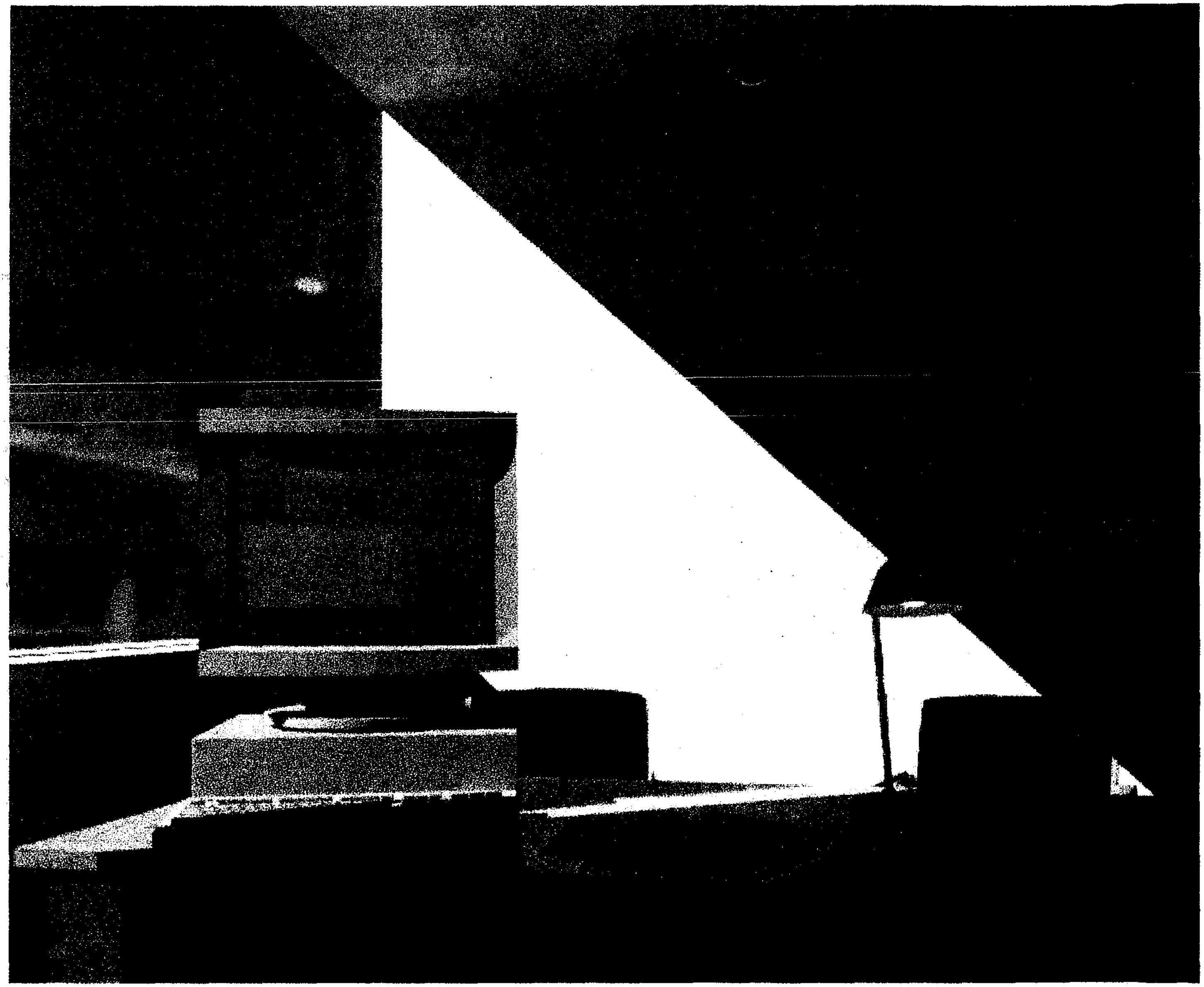


Figure 15. View of VDT screen with west-facing electrochromic (Tv= 0.30). Clear sky conditions, March 21, 15:00 in San Francisco, California.

In these more recent images, measured spectral data from electrochromic prototypes were used by RADIANCE to more accurately model color renditions. More accurate geometry and surface optical properties of the VDT were also incorporated.