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ABSTRACT

As part of a demonstration project to provide a comprehensive energy upgrade to a 294 m^2 (3168 ft^2) commercial building, an advanced skylight design was developed using optical light control materials and geometry to provide daylight to two adjoining offices. The skylight system was developed using outdoor physical model tests and simulation tools Limited on-site measurements and occupant polls were conducted. Market issues were addressed. The skylight systems were found to improve lighting quality and to control excessive daylight illuminance levels compared to a conventional diffusing bubble skylight. Daylighting principles developed in earlier work for vertical glazing systems (light shelves and light pipes) were shown to be applicable in skylight designs at full-scale.

INTRODUCTION

Daylighting (defined as the planned use of daylight to offset electric lighting needs) has a vast potential to offset energy use in buildings, thus reducing the use of fossil fuels and the negative impact on air quality. The average intensity of sunlight is on the order of 50,000-100,000 lux (4645-9290 fc), whereas humans require 200-1000 lux (19-93 fc) to perform most visual tasks with accuracy. If one can redirect ~1% of this total outdoor flux throughout a building, electric lighting would be a redundant system during daylight hours. This apparently simple concept has plagued many architects and engineers since the conception of windows. It's solution has been given lesser priority upon the advent of the "low-heat" fluorescent tube and centralized air-conditioning of the mid-1930s, and the replacement of the traditional re-entrant floor plan which served to bring daylight to the building center by a more profitable rectangular floor plan; e.g., the Lever House in New York City (Banham 1969).

Today, daylighting in U.S. commercial buildings is virtually non-existent. Sidelighting windows with low visible transmission glazing have been the standard since the 1970s. Occupancy-based or time-scheduled electric lighting controls have more recently been adopted, but photosensor control based on daylight is rarely used. With short-term economics as the dictating criteria, component-based prescriptive approaches to the design of energy-efficiency measures (EEMs) result in daylighting (with all of its acknowledged non-energy benefits) often being eliminated during the design or value engineering phase. More sophisticated design tools are needed to analyze and justify an integrated approach, where the building (windows,

lighting, and mechanical system) is regarded as a whole system rather than a conglomeration of parts.

Increased use of computers in work spaces may also be contributing to the decline of daylighting. The Illuminating Engineering Society (IES) Recommended Practice 1 (RP-1) Standard (IES 1993) puts stringent limits on both the quantity and acceptable distribution of light within the workplace. Core areas beyond a 5 m (16 ft) depth from the window wall (representing ~70% of the building's floor area) typically have a dark and gloomy quality, made more apparent by the juxtaposition to brightly overlit perimeter areas. Visual discomfort caused by the bright window plane, direct sun, and harsh luminance contrasts are the source of major complaints from occupants with computers seated near the window. Yet, high value is still placed on locations with a window, a view, and a connection to the outdoors; attributes that are deemed more prestigious than an interior private office. Research to quantify psychological, physiological, and productivity benefits are scarce, but new studies are in progress (e.g., Wu 1994).

Distributing admitted daylight flux poses a critical technical problem; spreading daylight evenly to attain a functional and comfortable lighting environment requires ingenuity. Commercial daylighting systems designed to increase daylight beyond the immediate perimeter zone are in short supply. Advanced daylighting systems are often hand-tailored and built for a particular building and clientele: Lockheed (Benton et al. 1990), CSAA Antioch (Beck 1995). The development of commercializable daylighting systems, applicable to a broad range of commercial building applications, has been a major objective of a multiyear research project (Lee et al. 1994). The constraints placed on the problem were pragmatic: achieve significant redirection of the daylight flux from typical windows to deep perimeter areas, improve lighting quality, minimize solar heat gains, and require minimal maintenance with only a marginal added cost to typical window systems.

The demonstration at the Palm Springs Chamber of Commerce represents a milestone in this research. Our earlier research work (Beltrán et al. 1994) produced design solutions, i.e., light shelves and light pipes, for vertical windows using reduced-scale or simulation tools. Several critical issues required a full-scale demonstration to resolve: 1) would the systems perform as projected, 2) would the lighting quality of the space be improved, and 3) would the systems be acceptable to occupants? This opportunity allowed us to complete the design cycle from simulations and reduced-scale tests to full-scale evaluation of performance, occupant acceptance, and industry potential. This design cycle is presented and discussed.

BACKGROUND

In 1993, Southern California Edison (SCE) began a multiyear demonstration program to focus on the impact of aggressive demand-side management strategies in the Coachella Valley region (Gudger 1993). We collaborated on the energy-efficiency retrofit of the Palm Springs Chamber of Commerce, a highly visible, publicly accessible building. The specific objectives were to 1) focus on obtaining near-optimum energy performance by designing glazing, lighting, and mechanical components as a system rather than as disparate, non-related parts, and 2) demonstrate new and emerging technologies (appropriate to the region) to verify algorithms and expedite commercialization. While innovative, a discussion of the energy-efficiency measures used to meet the first objective is not included here. The skylight system meets the second objective.

The Palm Springs Chamber of Commerce is located at 190 West Amado Road in Palm Springs, California, 33.19° North latitude, 173 km (108 miles) east of Los Angeles.[1] Built in 1953, the building is a single story, 294 m^2 (3168 ft^2) commercial office building with predominantly west-facing storefront windows along its 30.5 m (100 ft) length, and south storefront and north punched windows along its 9.75 m (32 ft) width (Figure 1). Building-wide measures were taken to reduce heat gains through the building envelope and within the building itself. The existing windows and lighting systems were replaced with spectrally selective, low-e, thermally broken windows, T8 lamps with dimmable electronic ballasts, pendant indirect/direct lighting fixtures, and occupancy/photosensor step lighting controls. Insulation was increased in the roof and walls. Light-redirecting skylights were added to the interior offices. By reducing building envelope and lighting heat gains, the existing 35.2 kWh (10 ton) air-conditioning unit was replaced by a 8.8 kWh (2.5 ton) two-stage indirect evaporative cooling system which is particularly appropriate for desert climates, and 17.6 kWh (5 ton) direct expansion compressors.

A DOE-2.1D (Winkelmann et al. 1993) building energy simulation analysis was conducted where all systems were modeled using standard algorithms.[2] The total annual electricity consumption was projected to be reduced from 151 to 80 kWh/m^2·yr (14.0 to 7.4 kWh/ft^2·yr), or 47%, and the total peak demand reduced from 101 to 56 W/m^2 (9.4 to 5.2 W/ft^2), or 44% (Lau 1994). Annual atmospheric emissions reductions of 11,477 kg/yr (25,303 lbs/yr) of CO_2 and 16 kg/yr (36 lbs/yr) of NO_x were estimated (SCE 1993). These marked reductions in energy use were attained by integrating existing commercial products that are on the market today. If used in new construction rather than as a retrofit, the economics for these choices would improve.

SKYLIGHT DESIGN

The design objectives of the daylighting systems were to maximize daylight efficacy and redirection per unit glazing area and to increase the uniformity of the distributed daylight within the interior year round. Due to the deep overhang on this building, the concepts from the earlier vertical window prototypes were not directly applicable but were adapted to a skylight design. A reflector was used beneath a small skylight aperture to reflect direct sunlight to the ceiling plane and to provide a more uniform and comfortable daylight distribution throughout the entire room cavity (i.e. walls, ceiling, and workplane surfaces). The glazing area was minimized to avoid significant cooling penalties. Variations of the skylight reflector/ diffuser concepts (with different design objectives) were built in the Menil Collection Gallery in Houston, Texas by Ove Arup in 1987 (Guazzoni 1987) and the Kimbell Art Museum in Fort Worth, Texas by Richard Kelly and Louis Kahn in 1972 (PA 1973).

The skylight design consists of three components (Figure 2): (1) a carefully engineered skylight aperture and light well that is restricted to control direct sunlight admission, (2) a reflector array composed in such a manner to reflect beam sunlight throughout the day and year

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[1] The climate of Coachella Valley is hot and dry with summer design temperatures of 45°C (113°F) dry bulb and 23°C (73°F) wet-bulb, and a winter design temperature of 0.56°C (31°F). The large demand growth in this region provides ample opportunities for cost-effective application of energy-efficiency measures, while the sunny, clear sky conditions provide good opportunities for daylighting. Global horizontal solar radiation levels range from 984.9 Btu/ft^2·day (3.1 kW/m^2·day) in the winter to 2791.2 Btu/ft^2·day (8.8 kW/m^2·day) in the summer. Skies are typically clear with low levels of precipitation.

[2] The daylighting performance of the optically complex skylight was not modeled. The combined effectiveness of the two stage evaporative cooling system was modeled as one stage.

to an area on the ceiling 4.6 m (15 ft) from the skylight aperture on both the north and south sides of the skylight, and (3) a lower diffusing panel that serves to distribute daylight coming through the reflector array to the space below the skylight. The distance of redirection had to be reduced to 4.6 m (15 ft) due to the restricted office size. Previous light shelf and light pipe designs redirect daylight to a depth of 9.2 m (30 ft).

Since the skylight aperture determines both the amount of solar heat gains and total incoming daylight flux, several design iterations were made to optimize this relationship using physical scale models.[3] In the final design, a single skylight with an area of 1.4 m^2 (15 ft^2) was used to daylight two adjacent 4.6 by 4.0 m (15x13 ft) offices. Spectrally selective glazing[4] similar to that used on the storefront windows was used. The lightwell was lined with a highly reflective (r=0.95) specular film and was shaped to block direct sun to the interior and to reflect sun to the southern reflector array.

The reflector array consists of a series of flat panels angled to reflect light from specific sun angles to the interior ceiling. The areas of the panels were varied according to daylight availability throughout the year. The array position relative to the skylight aperture was also shifted to balance the available daylight flux to the two rooms. A prismatic reflective film was applied to these panels to spread the outgoing reflected light ~10-12° and to avoid "hot spots" of intense daylight on the ceiling plane. The panels were spaced apart in the mid-section to allow sunlight to filter down to the area beneath the reflector array. A lower translucent panel was used to diffuse the light to the area below. A special film, designed to maximize transmittance with minimal back reflectance, was used on this panel; a cheaper prismatic or translucent lens may also suffice.

The skylight design was developed under several site-specific constraints: sloped ceilings, asbestos ceiling construction, mechanical screen obstructions on the roof, etc. The architect had the task of determining how the system would fit in the actual space, complying with building codes, and determining how a normal contractor could reasonably construct a geometry that mandated precise execution. Construction details were developed with the assistance of subcontractors prior to bid and the manufacturer, from whom we would purchase the various films. The design could be simplified a great deal for buildings with a uniform ceiling height of 2.7-3.0 m (9-10 ft).

DESIGN EVALUATION

The design was analyzed and evaluated using ray-tracing calculations, laser visualization in scale models, outdoor physical model tests, and RADIANCE visualization modeling (Ward 1990) over three iterations. Physical model tests were conducted outdoors in October and November 1993 under moderately clear weather to obtain a rough[5] indication of daylight performance. Data were collected with a four by four grid of Li-Cor illuminance sensors in a

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[3] The architect was a bit worried about the skylights performing too well during the summer: "I'd like perhaps the summer lighting to be dimmer simply because the occupant may perceive high light levels as too bright and therefore hot, when one comes in from +43°C (+110°F) outdoor air temperatures."

[4] The center of glass properties of this window system were: visible transmittance 0.62, solar heat gain coefficient 0.37, and U-value of 1.31 $W/m^2 \cdot °K$ (0.23 $Btu/h \cdot ft^2 \cdot °F$). Since the typical glazing material of diffusing bubble skylights (i.e. double-walled polycarbonate lens) provides little solar heat gain rejection, cooling energy savings will be obtained with the prototype system.

[5] Inaccuracies are introduced by the large variation in sky conditions and sky view as the model is tilted to simulate different solar positions.

simplified north and south room (e.g., no tilted ceiling plane, no soffits or windows, and an average room size). Measurements were taken for year round representative solar conditions: March 21/September 21 (equinox), June 21, and December 21 (solstice) at 9:00, 12:00, and 15:00. Several correction factors were applied to the data to account for dirt depreciation, differences in skylight glazing transmittance, transmittance of the transom glass, and outdoor illuminance levels at Palm Springs. The daylight performance of the skylight was compared to a base case skylight which had the same aperture opening and light well shape as the prototype, but used diffusing light well surfaces and glazing.

The RADIANCE ray-tracing computer program was used to refine the final details of the design after construction documents were completed. However, the reflectance and transmittance properties of the special daylighting films needed for accurate calculations were not available and could not be measured at the time – leading to inconclusive results. Bi-directional reflectance and transmittance properties of homogenous samples can be measured for all incoming hemispherical directions routinely using a goniophotometer. However, the films used in this design exhibit a non-homogeneous, three-dimensional microstructure that requires special measurement protocols. Additional work will be required to allow RADIANCE to routinely model complex designs such as this skylight.

As such, the results of the outdoor physical model tests on the second (not final) design iteration are given here. We attempted to answer two major questions with this evaluation: 1) is significant daylight redirection accomplished year round with the reflector array, and 2) is lighting quality improved?

Good daylight redirection was accomplished in the south room during the winter and summer, but in the north room, illuminance levels were lower or equal to the base case throughout the space. Workplane illuminance levels to a room depth of 4.5 m (14.75 ft) are shown in Figure 3 for the base case (dotted line) and prototype (solid line) under clear sky conditions. In the south room, illuminance levels furthest from the skylight aperture (sensor locations 3-4, 7-8, 11-12, and 15-16) were increased significantly compared to the base case during the winter solstice. During the summer solstice, while percentage differences were less, the prototype still increased illuminance levels through daylight redirection. In the north room, the illuminance levels in the area furthest from both skylight types were less than the design setpoint of 538 lux (50 fc). In the third design iteration, the skylight aperture was shifted slightly to favor the north reflector to address this problem. The reflector geometry was also redesigned to increase the reflector area for the winter period and to block direct sun which resulted from moving the skylight aperture.

As expected, daylight levels directly under the base case skylight were significantly higher than the prototype. However, the prototype was able to gain better control over the absolute illuminance levels throughout the year. For example (Figure 3), the base case yielded excessively high illuminance levels of 3000-12,000 lux (279-1115 fc), whereas the prototype reached levels of 1000-4500 lux (93-418 fc) in the south room. For overcast and cloudy conditions, the base case was found to admit ~26% more total daylight flux into the space simply because there were less intervening obstructions (i.e. reflector array) to the incoming daylight. For daylighting systems designed for direct sun, performance is nearly always compromised under diffuse sky conditions (Aizelwood et al. 1993). Fortunately, Palm Springs has predominantly clear weather. For climates with predominantly overcast sky conditions (Northern U.S. and European countries), this system would not compare favorably to a diffusing skylight system.

Daylight uniformity was significantly improved with the prototype skylight (Figure 4). Strong contrasts and gradients can be visually harsh; more diffuse soft light is often found to be more

pleasant. Note that most of the daylight flux from the base case skylight was directed downward to the area under the skylight. The prototype, however, distributed the daylight more evenly on all ceiling and wall surfaces. For all times throughout the year, the uniformity of daylight was significantly better than the base case's distribution; if the illuminance gradient, G, is defined as the ratio of maximum to minimum workplane illuminance, this gradient ($G_{base\ case}$=46) was on the order of five times that of the prototype ($G_{prototype}$=9) during summer noon hours.

SITE EVALUATION

A site visit was made upon near completion of construction in November 1994 to ameliorate outstanding issues of visual comfort and to assess the system's performance under occupied conditions. Evaluation of performance was made using a combination of luminance and workplane illuminance measurements,[6] direct observation of the solution in place, and polls of the occupants and architect to determine their specific concerns regarding the system. Limited measurements were used as a check to determine whether the skylight met the original design objectives. Detailed hourly energy monitoring by SCE is currently in progress.

Under partly cloudy conditions, we found that the final skylight design was able to meet the design workplane illuminance level (323-646 lux (30-60 fc)) within the space and achieve good uniformity through daylight redirection (Figure 5). Illuminance levels in the north room were comparable to the south, indicating that the final design iteration solved the flux imbalance between the two rooms identified in the physical model tests. Workplane illuminance levels ranged between 308-662 lux (29-62 fc) within the south (#105) and north (#106) rooms on November 18 at 10:00 and 14:00. Measurements for the south room included the daylight contribution from a south-facing window with the blinds closed. Illuminance levels were very uniform throughout both rooms; the maximum illuminance gradient was 1.7:1 for the two measurement periods. While there is no base case with which to compare illuminance levels, visual inspections showed that direct sun was being redirected to the ceiling plane across the full room depth. One can expect higher interior illuminance levels in the summer when exterior illuminance levels increase. Reducing the total daylight flux with lower transmission glazing or a smaller skylight opening would be beneficial for summer conditions but would not be beneficial for winter, low light, and overcast conditions.

The IES RP-1 Standard (IES 1993) was used to evaluate lighting quality, even though the standards were written for electric lighting applications within offices containing computer visual display terminals (VDT). The Standard recommends that significant luminance differences in large areas of the visual environment, which may cause disability or discomfort glare, be limited to a 3:1 maximum luminance ratio between local tasks and adjacent surroundings, and 10:1 between local tasks and remote surfaces. In addition, the average luminance of any 0.6 by 0.6 m (2x2 ft) area of the ceiling, walls, partitions or windows within the field of view should never exceed 850 cd/m^2 when performing tasks using the VDT. Measurements for both the local and remote surface view are given in Table 1.

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[6] Illuminance measurements were made under variable partly cloudy conditions using a tripod-mounted Tektronix J16 illuminance meter for indoor conditions and a hand-held Lite-Mate 3, Model 504 for exterior conditions. Luminance measurements were made using a Tektronix J6523 Luminance Probe (1° narrow angle). Exterior daylight levels remained fairly steady until 14:00, after which they fluctuated too widely for useful results. Photographs were taken using a 20 mm wide-angle lens and a fisheye lens.

All local task (computer and desk) and surrounding surfaces were within the recommended 3:1 luminance ratio (items a-d, Table 1) except for the skylight's lower panel. Within each of the four skylit rooms, the furniture, task, and position of the occupant relative to the skylight differed. The most critical lighting condition occurred in Room 105, where the occupant chose to place the VDT screen directly beneath the skylight's 2.13 m (7 ft) high horizontal diffusing panel (Figure 6). As such, the criteria for local tasks was not met, particularly during mid-day hours, since this panel (100-2130 cd/m^2) was directly in the occupant's field of view. A revision to the skylight was considered, where the slots between the central reflector array was covered with a translucent film to diffuse the daylight and reduce the overall luminance level, but not implemented due to cost. The skylight's vertical surface and reflectors were also a potential source of glare. However, no occupant faced these surfaces, nor did they place their VDT screen to face the surfaces so that veiling reflections in the screen would occur. If occupants had chosen to orient their workstations in such a manner, they may experience discomfort glare (similar to glare experienced if one faces a shaded window to perform a task).

Hot spots and light stripes on or near the ceiling caused by the reflected daylight exceeded the desired 10:1 luminance ratio (Figure 7 and 8). Excessively high luminance levels on the ceiling can cause visual discomfort and veiling reflections in a VDT screen similar to an unshielded luminaire. The stripes on the ceiling plane were measured and found to be with a near acceptable 12:1 luminance ratio (114-1653 cd/m^2). Hot spots of reflected sunlight on the upper portion of the back and side walls reached levels of 840-3690 cd/m^2 or 27:1; however, the area of these patches were typically small (<0.15 m^2 (1.6 ft^2)). Small direct downward sunlight patches near the skylight unit (4680-6310 cd/m^2, 47:1) were the result of incomplete and incorrect construction; vertical diffusing transom glass, installed later, reduced these levels. Observations at the occupant's current seated position showed no veiling reflections in the VDT screen from the ceiling plane. During other times or for other positions, veiling reflections may occur.

The hot spots and light stripes were due to daylight being redirected from different segments of the side and central reflector array and to the degree of light spread actually achieved by the prismatic film at full-scale. During design, we were reassured by the manufacturer that the film would provide a sufficiently diffused light (~10-12°) in full-scale. Earlier laser visualization tests at conceptual design showed incident light directed perpendicular to the linear film surface grooves was reflected with a ~10° spread, as intended. However, light incident at an oblique angle to the linear grooves of the prismatic film tended to be reflected in a more concentrated area. After the site visit, discussions with the manufacturer refined this hypothesis.[7] Other potential sources may be the butt edges between the side reflector surfaces or discontinuities and edges of the central reflector. Direct downward reflections may also have been caused by the acrylic material used for the construction of gussets and the lower soffit panel.

OCCUPANT ASSESSMENT

We informally polled occupants that worked in the skylit rooms to assess their visual comfort and perception of the skylight system design. This information was used primarily to

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[7] The film consists of an upper clear acrylic layer, a grooved prismatic layer designed to spread the reflected daylight, a vapor coated aluminum layer, and pressure sensitive adhesive. For oblique angles greater than 60°, there is increased reflection off the first acrylic surface with consequent diminished spreading from the lower prismatic layer. For example, at an angle of 80°, there is ~80% of total reflected light off the first clear acrylic surface. The concentrated light "beams" and specular hot spots of daylight may be caused by this front surface specular reflection at oblique sun angles.

troubleshoot problems with the design that could be remedied before all construction on the skylight system was completed. At the time of inquiries, from late November to mid-December, the skylight had been installed since the end of August, requiring only the vertical glazing at the skylight soffit for completion. These polls were *non-representative* due to the small sample size. Only two occupants, A and B, worked in the skylit spaces full-time. Occupant C worked on occasion in Occupant A's office using the computer. Occupant D used the lunchroom (Room 112) and was willing to be interviewed.

Occupants found that the daylight illumination in general was "just right" throughout most of the day when not overcast or when the sun was not blocked by exterior obstructions (e.g., mountain range, roof mechanical screen). Occupant A preferred to turn off (no dimming capability) the lights throughout the day (8:00-16:00), using the electric lights only in the early morning and late afternoon hours. Occupant B believed that the lighting could be turned off for a two to three hour period around noon. Occupant C had mixed opinions about whether the daylight levels were sufficient, saying that at times the lights could be turned off when working on the computer, but then later stating that the lights should probably be on even in the middle of the day.

Occupants A and C, who used the same computer located directly under the skylight (Figure 6), found the daylight illumination to be too bright during noon hours, citing problems with VDT task contrast and direct glare in the field of view. Both occupants, however, stated that glare discomfort, if experienced, had surprisingly no impact on work performance. None of the occupants ever noticed the brightness of the skylight reflectors upon entering the room. None of the occupants stated that the vertical aperture of the skylight was a source of glare. Occupants A and C do not work within the field of view of the vertical aperture. Occupant B has a side view of the vertical aperture.

Again surprisingly, the patterns of reflected daylight on the ceiling and walls were noted to varying degrees by the occupants. Occupants A and D never noticed them, whereas Occupants B and C noticed them sometimes. All occupants (A-D) liked the hot spots and variations in luminance and found them to be pleasant, nice, and friendly.[8] The visual interest provided by the skylight was received positively by all occupants. It was interesting to note that even though the reflected light patterns appear to make the space look busy, some occupants found the skylit rooms to be peaceful. Part of this may have to do with the soft distribution of daylight throughout the entire room cavity. Occupant B: "The subtle light is peaceful. Occupant Z works up at the front desk doing frantic phone work. She mentioned the peace and quiet when she came into my office... and she felt like she was more efficient doing her work here." The occupant, while acknowledging that the office location may be a contributing factor, attributed the sense of peacefulness to the skylight, "The room has a calm feeling... related to the room itself. It's different from working in an ordinary white square room."

Most occupants liked the appearance of the skylight system. At the time of the poll, the occupants had a clear view through the vertical aperture of the skylight reflector. The architect mentioned that he thought the appearance may be considered to be busy and cluttered. Occupant A and B liked its appearance, with occupant B saying that she enjoyed looking at the

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[8] Occupant A stated, "I like the feeling of sunlight... To me, the light gives me the feeling of my home environment because I have patches of light at home. I like this interplay of natural light. What I like most about the skylight is that it doesn't seem artificial. I feel like I'm outdoors but under the canopy of a tree."

reflectors, the patterns of light on the ceiling, and the soffit wood details. Occupant D found the complexity and its relationship to solar position intriguing.[9]

INDUSTRY POTENTIAL

Significant time and resources by all parties went into determining how the manufacturer's products could be used properly for the final construction (Figure 9). No one party had the ability to single-handedly design, engineer, and construct the skylight systems. For example, to facilitate construction of the lightwell, the architect envisioned a process to laminate the specular film to some lightweight substrate material that the contractor could cut at the job site, place on an inclined ceiling plane, and fasten easily. The film is very thin (0.0025") and requires careful lamination onto a smooth non-porous substrate. Before the construction bids were awarded, we discussed the idea of cutting the substrate (masonite or acrylic) to the final job site conditions, placing the pieces to verify fit, laminating the film to the substrate, then screwing the panels into place. We later learned that the lamination required special mechanical equipment, the cutting could not be accomplished using typical job site tools, the substrate had to be aluminum to accommodate differences in coefficient of expansion, and that one could not drill or cut the panels after the film has been applied.

To obtain a mass-marketable product that can be installed easily in the field, close cooperation by the manufacturer(s) will be essential. For this project, the manufacturer contributed substantial staff time and resources by furnishing product specifications, samples, cost data, and design assistance. The manufacturer remains interested in collaborating on projects at a level where a mass-manufactured product could be eventually realized. With the same objective, we will continue to pursue possibilities of some formal industry collaboration.

CONCLUSIONS

Building on earlier research to develop deep perimeter daylighting systems, an advanced optical skylight system was designed to redirect the daylight flux from a single glazed roof aperture to the back ceiling areas of two adjacent north and south rooms. The design employed geometry and a unique prismatic film to reflect direct sunlight throughout the year. Outdoor physical model measurements indicated that the designs provided more uniform and controlled daylight than a typical diffusing bubble skylight under clear sky conditions. A limited site visit revealed that illuminance levels were relatively uniform and met the design illuminance range. Luminance ratios were also found to be generally acceptable for tasks within local view; however, hot spots of reflected and direct sun were found to well exceed the accepted 10:1 luminance ratio. A non-representative number of occupants were polled for opinions about visual comfort and lighting quality; remarks were generally positive.

This demonstration allowed us to determine that light redirecting concepts appear to work well in full-scale, and gave us an opportunity to solve the engineering problems associated with a built product. This additional experience has been fed back into further development of earlier light shelf and light pipe prototypes for sidelighting windows, which we believe will have broader applicability than the skylight system.

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[9] "It's an attention getter... eye-catching. You come in and you go "What in the name is that?!" I like to trace the angles and think about how the sun angles are caught by the angles of the reflectors. I find the complexity pleasant. I like looking at how the light is reflected – it's fantastic. I don't understand the physics of it but I'm amazed at how the light is diverted to the ceiling and walls and how the angles are working with the sun..."

These daylighting systems succeed in both improving light redirection and balance throughout a deep perimeter space. Lighting energy savings, however, are based on total illuminance levels at a control point, where the associated distribution is discounted. Therefore, simple systems such as the diffusing bubble skylight that admit large uncontrolled amounts of daylight under all conditions (clear and overcast sky conditions) may, by simulation and calculations, appear to provide more savings than these advanced systems. In actual installations, improved lighting quality may in fact lead to greater than projected energy savings. For example, because light is being redirected to the ceiling plane, interior furnishings are less likely to interfere with daylight reaching the task location. Future work should determine how human factors affect the full energy-savings potential of advanced daylighting systems.

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TABLE 1. Luminance Ratios of Areas Viewed at Task Location (Room 105)

	Luminance (cd/m^2)	Lum. Ratio of:	Lum. Ratio	OK?	<850 cd/m^2?
Local View: Ratio < 3:1					
a. VDT screen (Room 105)	135	b/a	2:1	√	√
b. Paper-based visual task	267	b/c	3:1	√	√
c. Keyboard	84	b/c	3:1	√	√
d. Wall surfaces behind VDT	115-136	b/d	2:1	√	√
e. Skylight horizontal diffuser	100-2130	e/c	25:1	No	No
Remote View: Ratio < 10:1					
f. Surrounding wall surfaces	84-156	b/f	3:1	√	√
g. Daylit ceiling surface	114-1653	g/a	12:1	~√	No
h. Luminaires	9,680 - 11,720	h/a	87:1	No	No
i. Window with shade	123-224	i/a	2:1	√	√
j. Hot spots on walls (reflected sun)	840-3,690	j/a	27:1	No	No
k. Hot spots on wall (direct sun)	4,680-6,310	k/a	47:1	No	No

Measurements a-e taken while sitting at the occupant's desk. Measurements f-j taken while standing in the middle of the room at a 5'-0" height. Some of these luminance levels will vary considerably depending on the exterior daylight conditions and sun position. For these interior measurements on November 18, 1994 at 12 PM, the horizontal exterior illuminance level was measured at 57,700 lux.

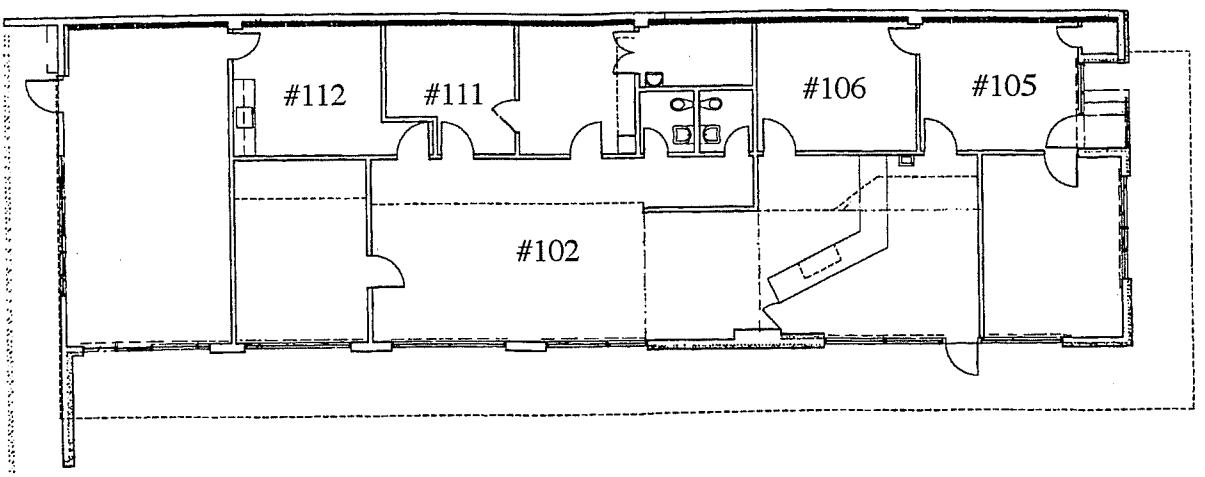

Figure 1. Floor Plan of the Palm Springs Chamber of Commerce (100 ft x 32 ft). South is to the right, west is at the bottom of the page.

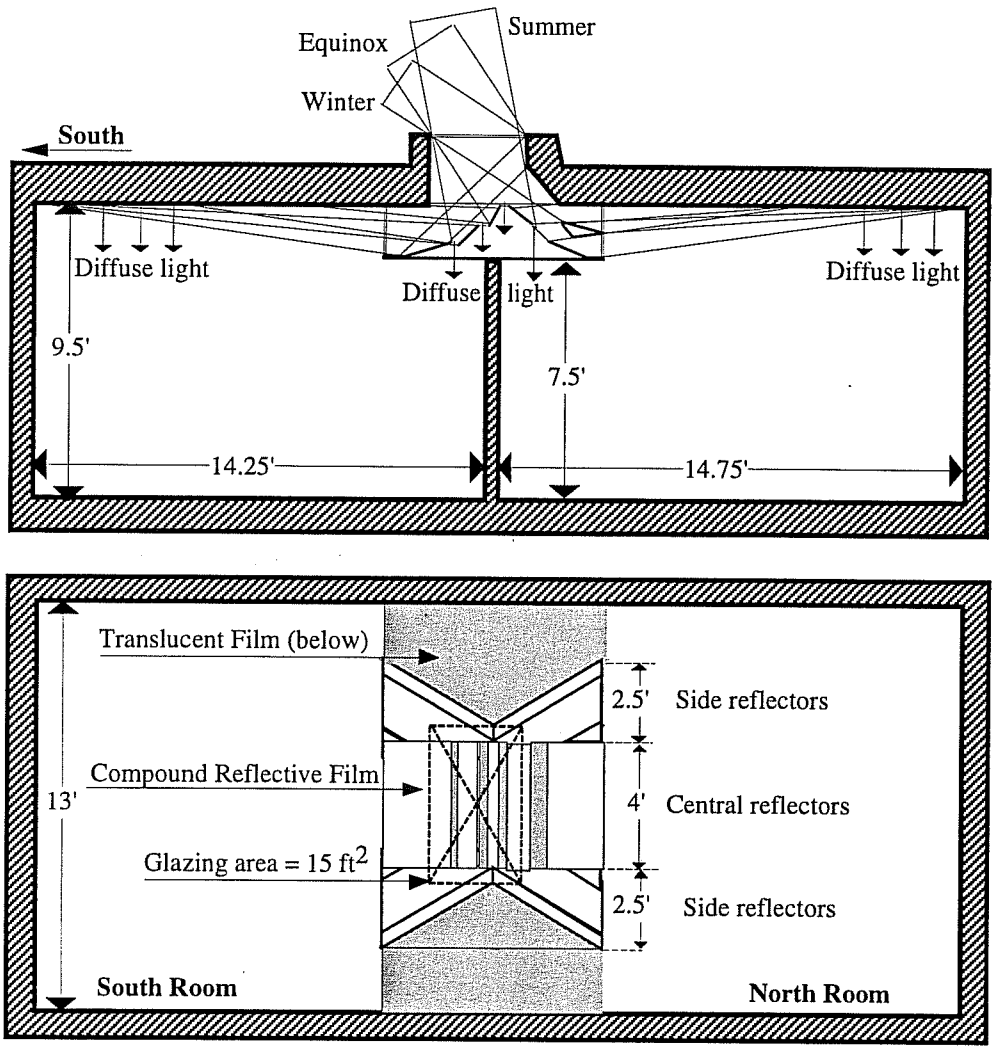

Figure 2. Prototype Design 3 Plan and Section

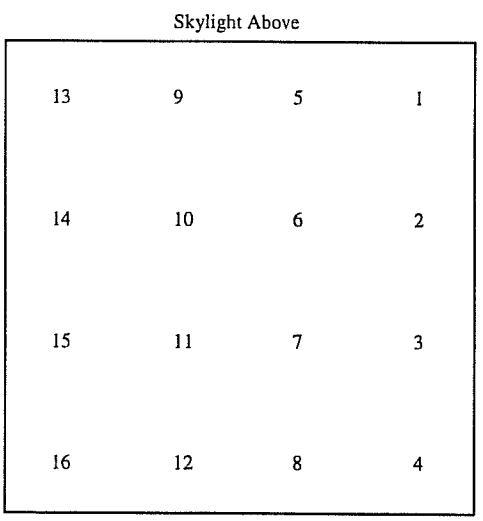

Figure 3a. Numbering convention of sixteen workplane illuminance sensors in the physical scale model.

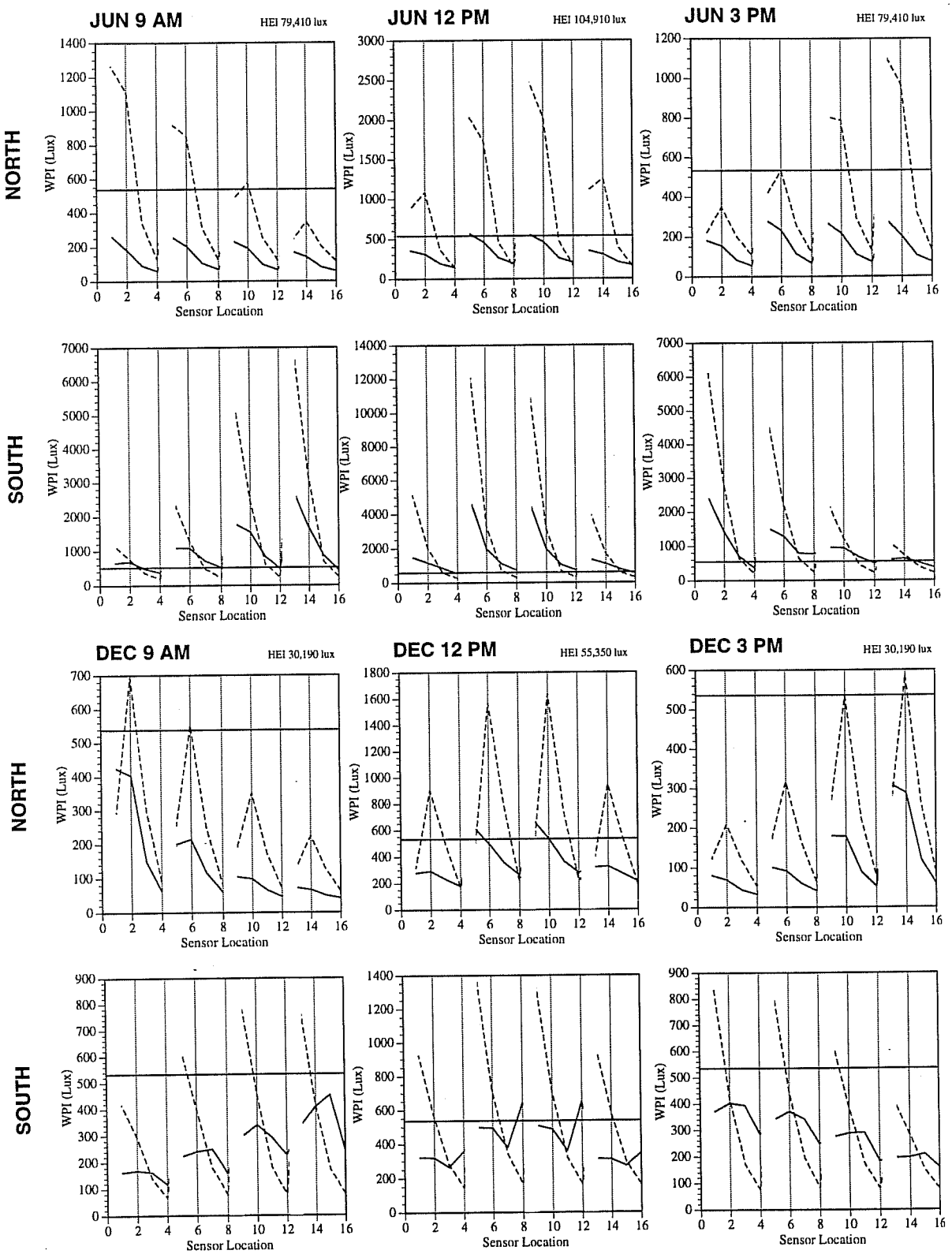

Figure 3b. Workplane Illuminance of 16 Sensor Measurements, Prototype 2: Outdoor Tests
Dotted line: Base case diffusing skylight; Solid line: Prototype Design; Horizontal Exterior Illuminance (HEI). Sensors are arrayed in four rows and columns, numbered from the righthand side of the room closest to the skylight to the back of the room, then across to the lefthand side of the room (see Figure 3a).

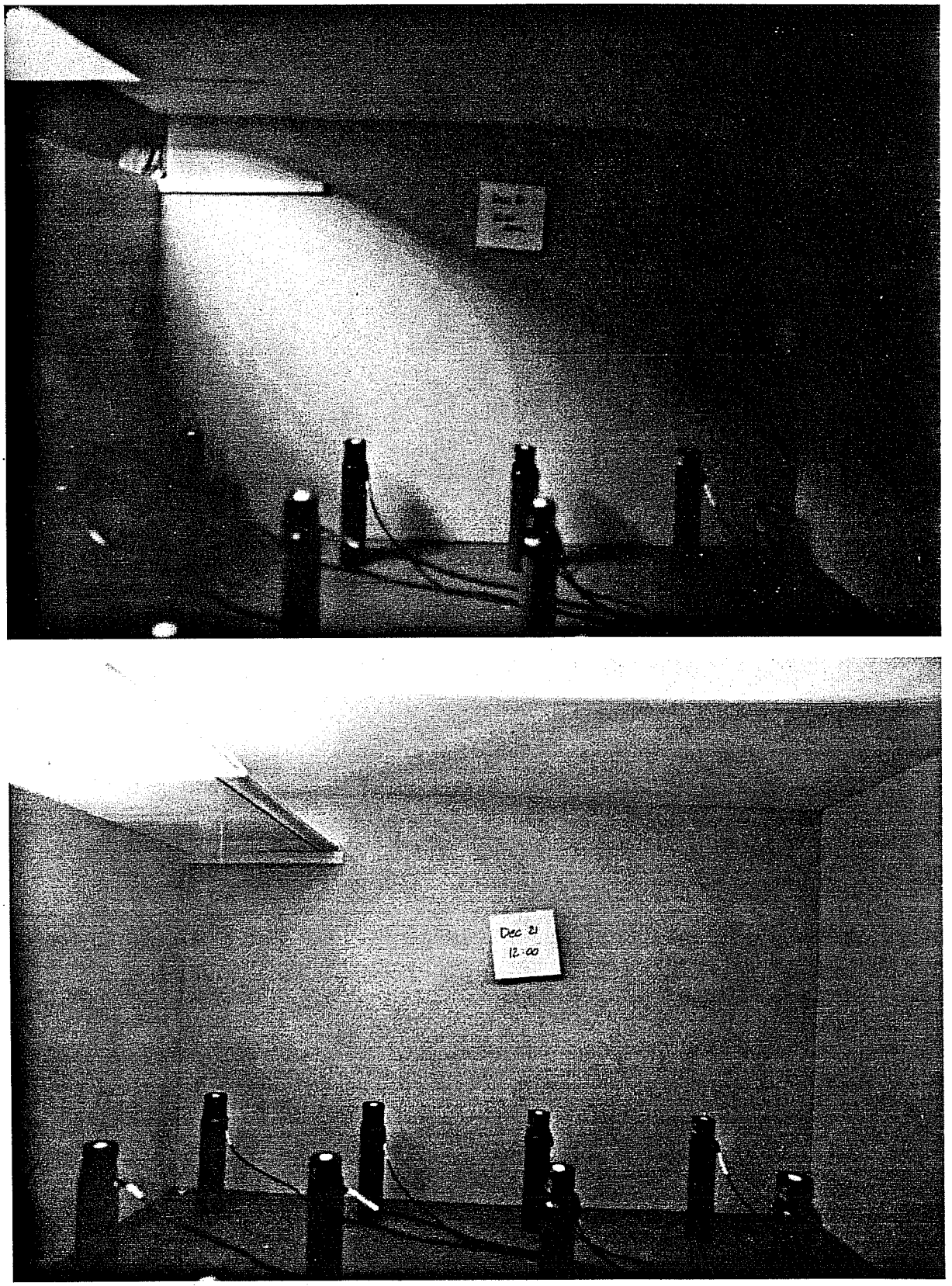

Figure 4. Photographs of Prototype 2 Outdoor Physical Model (looking towards the west wall) December 21st at Noon, Base Case (top) versus Prototype Skylight System (bottom) for North Room.

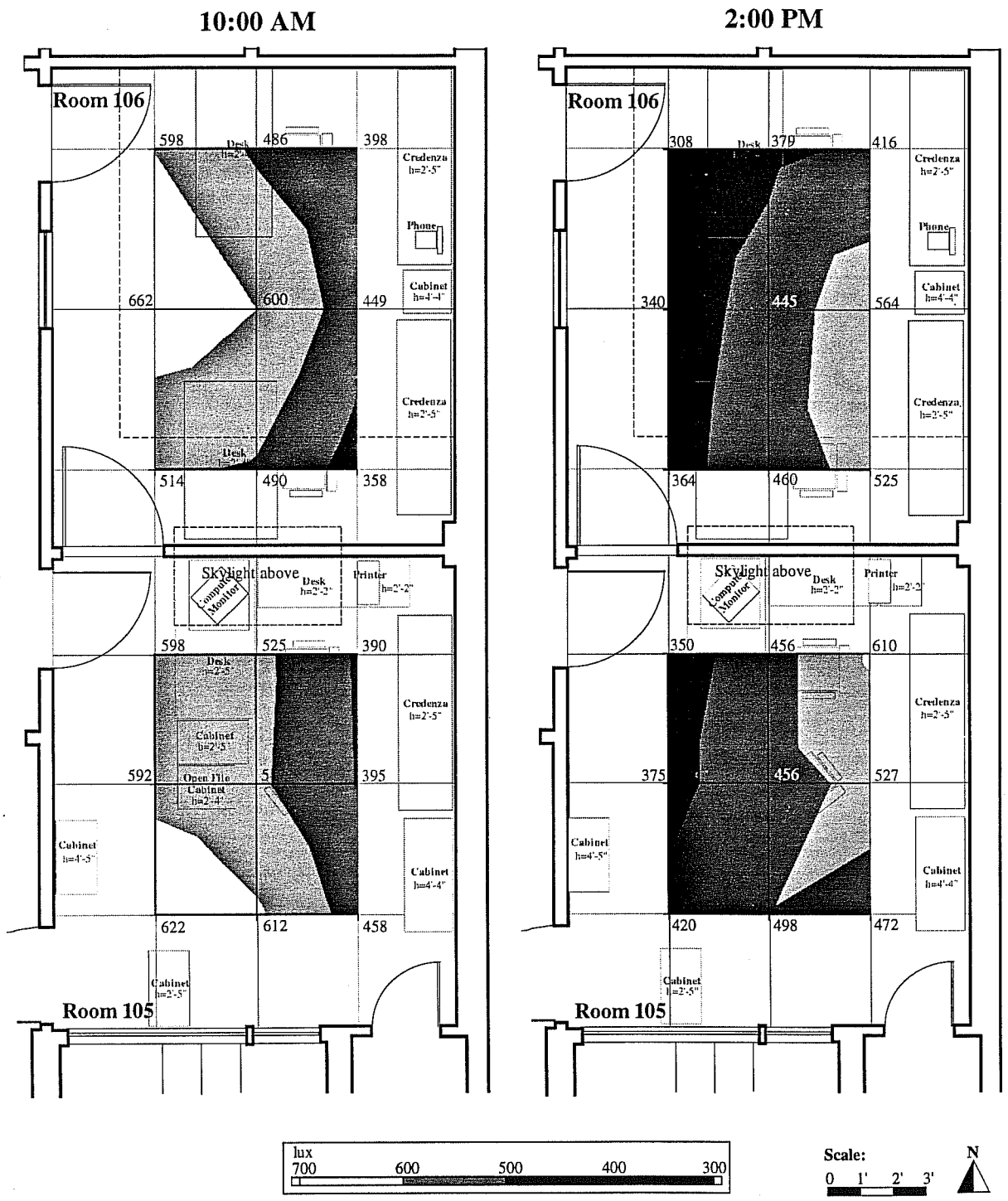

Figure 5. Workplane illuminance (lux) in Rooms 105 and 106 at 10:00 AM and 2:00 PM

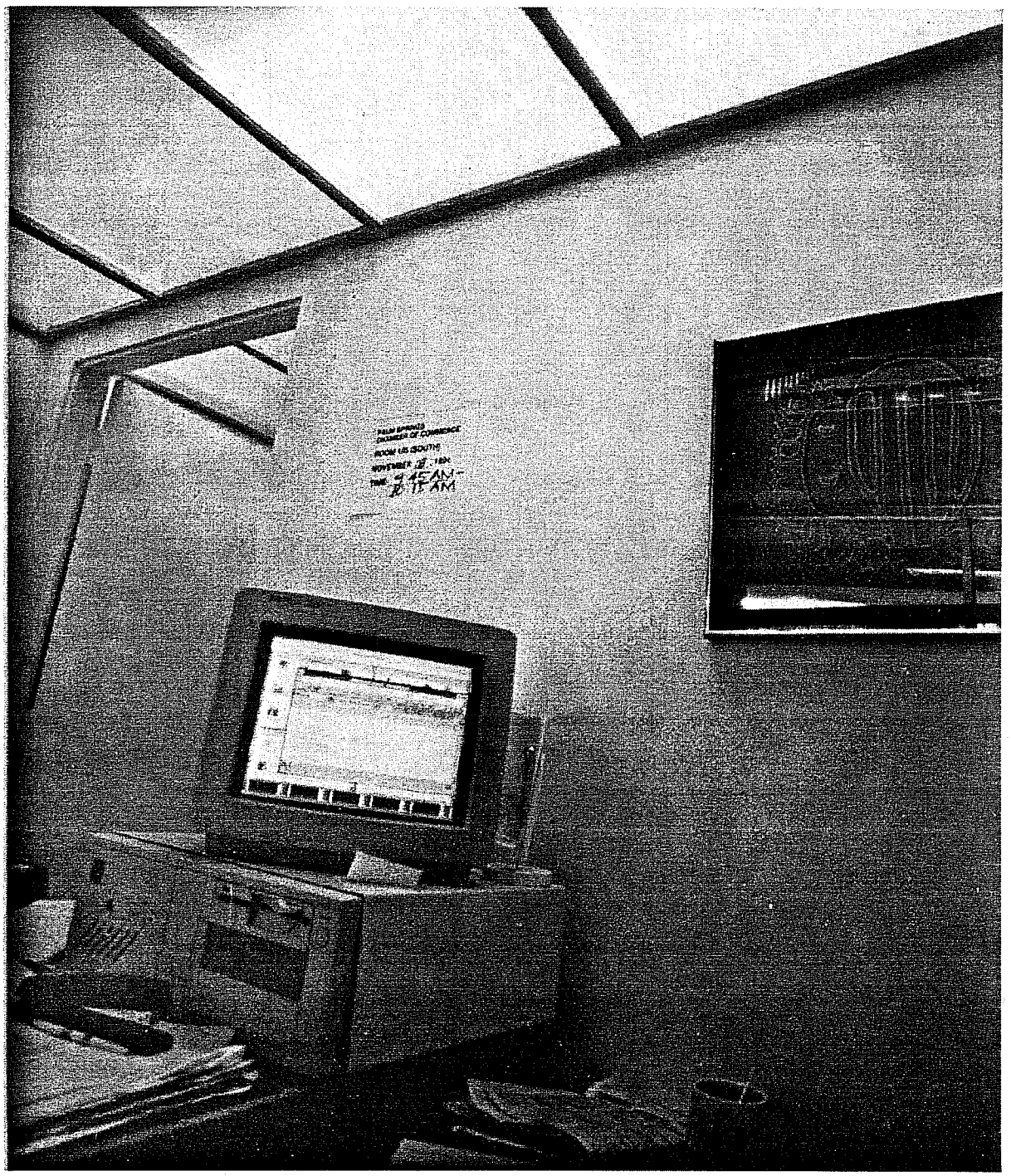

Figure 6. Luminance distribution at computer task in Room 105.

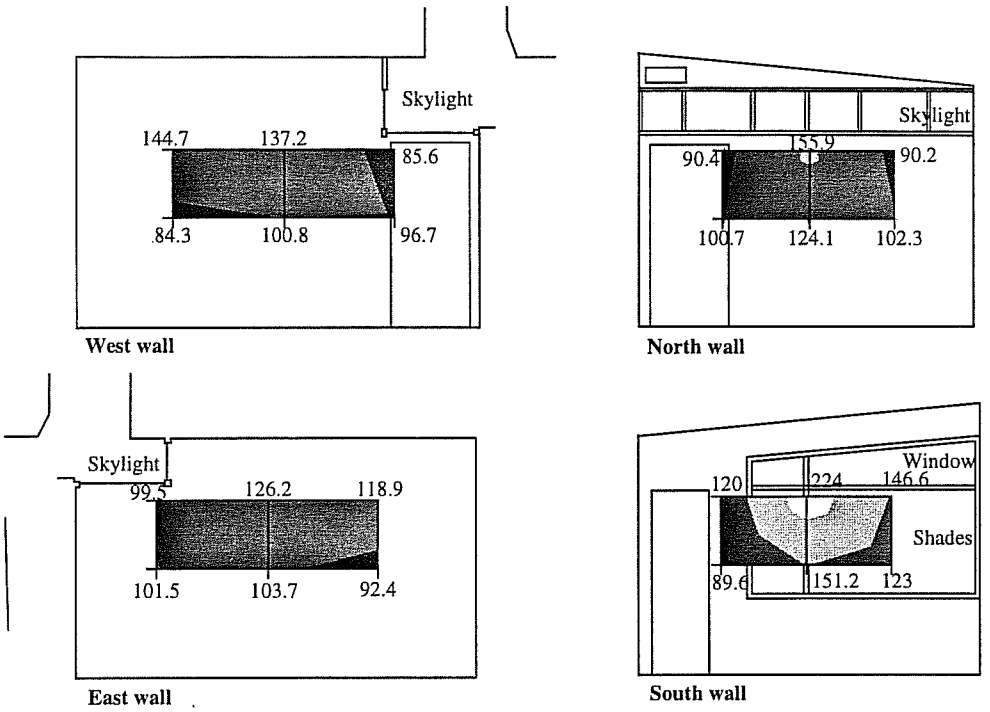

Figure 7a. Luminance on wall surfaces in Room 105 at 11:00 AM on November 18, 1994 with location of hot spots.

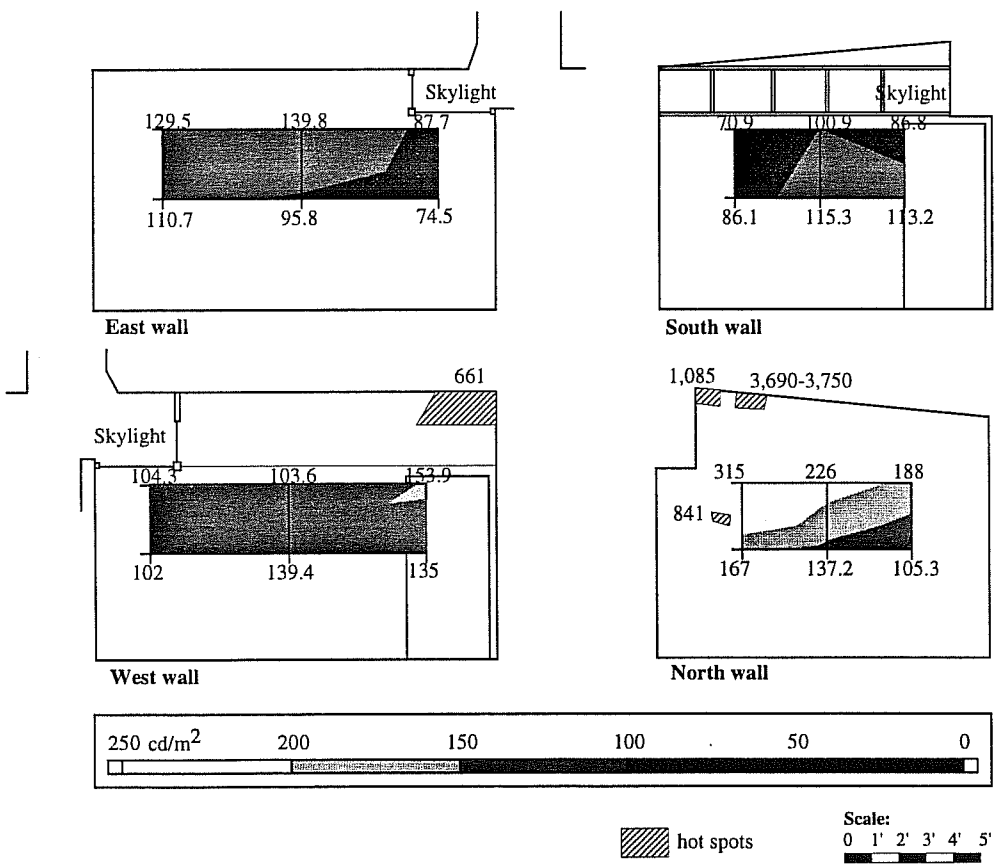

Figure 7b. Luminance on wall surfaces in Room 106 at 11:00 AM on November 18, 1994 with location of hot spots.

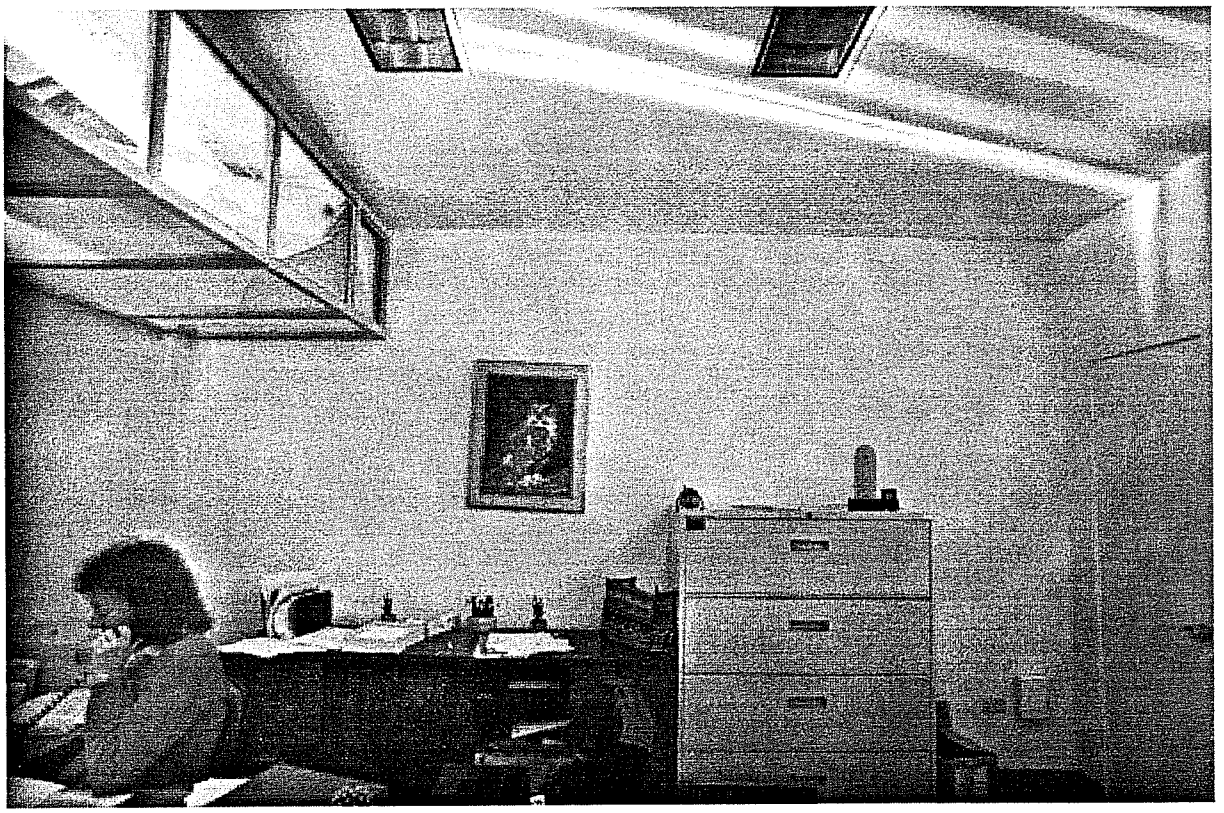

Figure 8. View of sidewall in South Room #105.

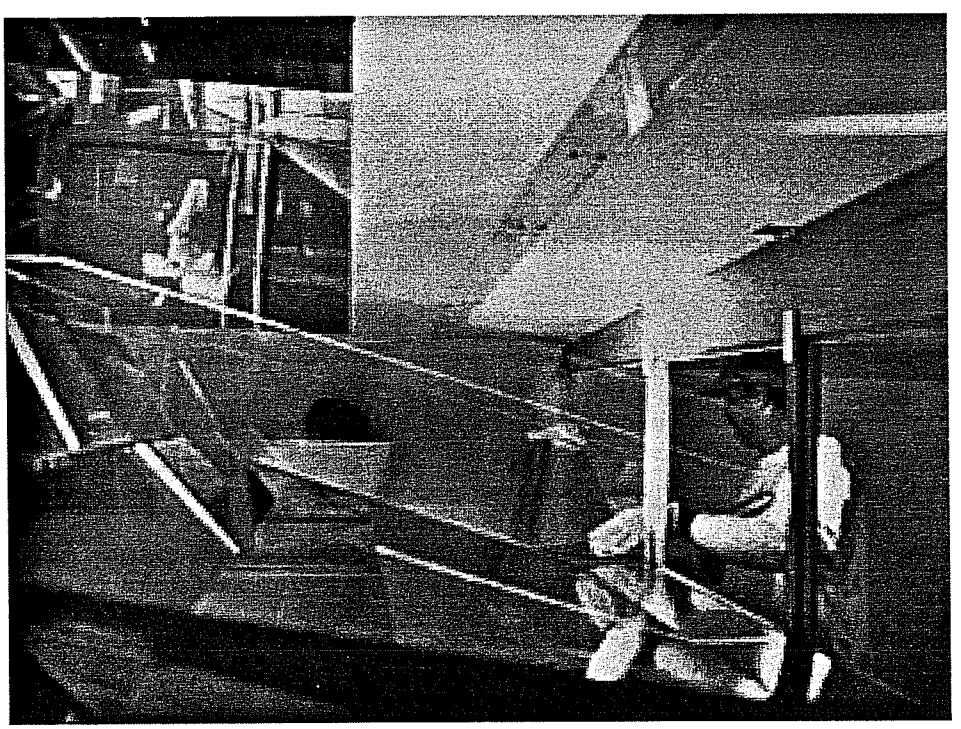

Figure 9. Central reflector blades with daylight film being positioned by the contractor on top of acrylic gussets.