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# Simulating the Energy Performance of Holographic Glazings

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## ABSTRACT

The light diffraction properties of holographic diffractive structures present an opportunity to improve the daylight performance in side-lit office spaces by redirecting and reflecting sunlight off the ceiling, providing adequate daylight illumination up to 30 ft (9.14 m) from the window wall. Prior studies of prototypical holographic glazings, installed above conventional "view" windows, have shown increased daylight levels over a deeper perimeter area than clear glass, for selected sun positions. In this study, we report on the simulation of the energy performance of prototypical holographic glazings assuming a commercial office building in the inland Los Angeles climate.

The simulation of the energy performance involved determination of both luminous and thermal performance. Since the optical complexity of holographic glazings prevented the use of conventional algorithms for the simulation of their luminous performance, we used a newly developed method that combines experimentally determined directional workplane illuminance coefficients with computer-based analytical routines to determine a comprehensive set of daylight factors for many sun positions. These daylight factors were then used within the DOE-2.1D energy simulation program to determine hourly daylight and energy performance over the course of an entire year for four window orientations.

Since the prototypical holographic diffractive structures considered in this study were applied on single pane clear glass, we also simulated the performance of hypothetical glazings, assuming the daylight performance of the prototype holographic glazings and the thermal performance of double-pane and low-e glazings. Finally, we addressed various design and implementation issues towards potential performance improvement.

## 2. INTRODUCTION

When combined with appropriate electric lighting dimming controls, the use of daylight for ambient and task illumination can significantly reduce energy requirements in commercial buildings. While skylights can effectively illuminate any part of one-story buildings, conventional side windows can illuminate only a 15 ft - 20 ft (4.57 m - 6.09 m) depth of the building perimeter. Even so, the overall efficacy of daylight is limited, because side windows produce uneven distributions of daylight. Achieving adequate illumination at distances further away from the window results in excessive illumination near the window, which increases cooling loads from the associated solar heat gain. As a result, the use of larger apertures and/or higher transmittance glazings, to introduce daylight deeper than 15 ft - 20 ft (4.57 m - 6.09 m), may prove ineffective with respect to saving energy, because the cooling load penalties may exceed the electric lighting savings.

The need for more uniform distributions of daylight admitted through side windows has stimulated significant research and development efforts in new fenestration designs and glazing technologies. Many of these approaches, including holographic glazings, rely on the common strategy of redirecting daylight and reflecting it off the ceiling towards the back of the room. In this paper we report on the simulation of the energy performance of prototype holographic glazings in commercial office buildings in a California climate. These prototype glazings, installed above conventional side windows, were designed to diffract the transmitted solar radiation and reflect it off the ceiling, providing adequate daylight illumination for typical office tasks up to 30 ft (9.14 m) from the window wall.

Past analyses of the daylight performance of Holographic Diffractive Structures (HDS) were based on outdoor measurements in a scale model that represented a 20 ft (6.09 m) wide by 30 ft (9.14 m) deep by 10 ft (3.05 m) high space with HDS glazing covering the top 4 ft (1.22 m) of the window wall.[1] These analyses showed that, when compared to clear glass, HDS introduced more daylight at a distance of 27.5 ft (8.38 m) from the window wall, for high sun altitudes (60° to 70°) at a plane normal to the window. However, these initial prototype HDS produced a rainbow effect, since different parts of the visible spectrum were diffracted at different angles. Moreover, these past analyses did not estimate total energy savings (heating, cooling and lighting) for the course of a whole year and for different window orientations, taking into account daylighting for all sun and sky conditions, and the cooling loads from solar heat gain associated with the use of daylight.

To overcome the undesired rainbow effect, a new generation of prototype holographic glazings were produced, using five-stripe Bands of Holographic Diffractive Structures (BHDS) designed to mix the diffracted radiation and eliminate the rainbow effect. The objective of this study was to estimate the energy performance of these new prototype BHDS.

## 3. METHODOLOGY

As explained in the previous section, the effectiveness of daylight utilization for energy savings depends on the balance of electric lighting savings due to daylighting and cooling load penalties due to solar heat gain. The performance of a fenestration system is dynamic and depends on the context of its application, which is characterized by parameters such as building type, window orientation and climate.

Considering the above, we decided to determine the energy performance of the BHDS assuming office building activities and schedules, for four orientations (North, East, South and West) and compare it with the energy performance of double pane low-E glazing with shading control, which represents current common practice with respect to energy-efficient glazings. We also decided to consider a California climate, because it offers the opportunity for proper consideration of the trade-off between electric lighting savings due to daylighting and cooling load penalties due to solar heat gain.

We selected a 20 ft (6.09 m) by 30 ft (9.14 m) space with 10 ft (3.05 m) height, with BHDS covering the whole width of the window wall from a 6 ft (1.83 m) to 10 ft (3.05 m) height, and low-E glazing covering the whole width of the window wall from a 3 ft (0.91 m) to 6 ft (1.83 m) height from the floor plane (Figure 1). We then compared the performance to the "base case" of an identical space with double low-E glazing with shading control, covering the whole width of the window wall from 3 ft (0.91 m) to 10 ft (3.05 m) height. The modeled space was considered as part of a 16,000 square feet office building, with 20 ft (6.09 m) by 30 ft (9.14 m) perimeter office spaces surrounding an 80 ft (24.36 m) by 80 ft (24.36 m) core zone.

In order to determine the energy performance of the BHDS samples, we had to determine their daylight and thermal performance. The optical complexity of the prototype sample gratings prevented us from using conventional, computer-based simulation methods. Thus, we employed a new method[2], which is based on the use of scale models to experimentally determine directional illuminance coefficients, which are then used with analytical, computer-based routines. This method allows us to simulate the daylight performance of fenestration systems and spaces of arbitrary complexity under any exterior conditions, and

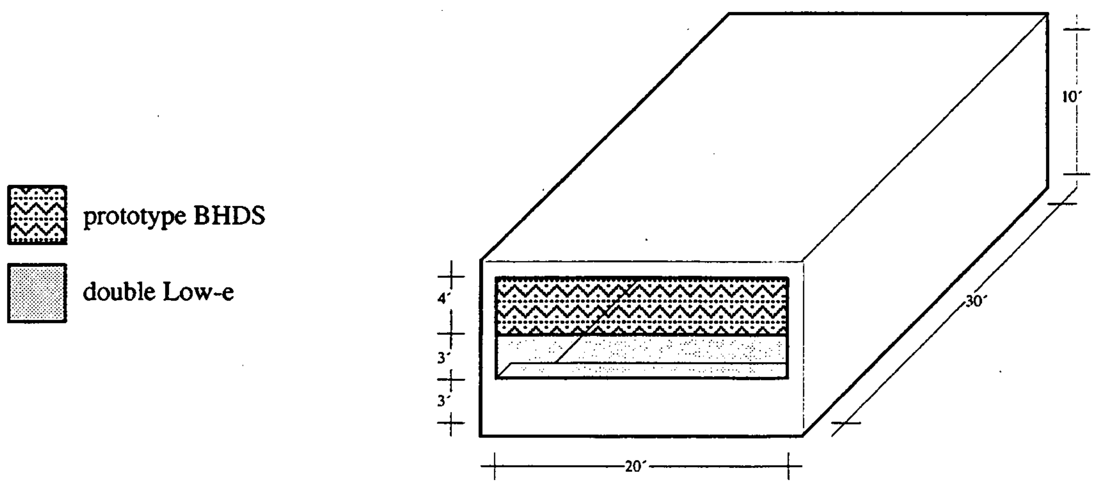


*Figure 1. The window configuration considered for the application of the holographic glazings. The same total aperture (7 ft by 20 ft) was considered with double low-e glazing for the "base case."*

use the results with the DOE-2.1D energy analysis computer program[3,4] that provides an hour-by-hour simulation of the operation of a building for the course of a whole year.

Since DOE-2.1D can model double low-e glazing using its internal algorithms, we decided to use the IDC method only for the BHDS aperture and then add the contribution of the lower, double low-e aperture. In this way we were able to consider a shading schedule for the lower aperture, using the internal algorithms of DOE-2.1D.

## 4. DAYLIGHT ANALYSIS

Following the IDC method, we constructed a half-inch-to-a-foot to scale model of the typical office space described in the previous section, with interior reflectance values of 0.76 for the ceiling, 0.44 for the walls and 0.21 for the floor. Using our scanning radiometer[5], we took measurements of workplane illuminance at 6 distances from the window wall (Figure 1) for 121 incoming directions of radiation, covering the whole hemisphere seen by the window.

In order to better understand the daylighting performance of the BHDS, we applied the IDC method using the same scale model with clear glass, and performed a comparative analysis for the San Francisco, CA, climate, considering four orientations (North, East, South and West) for twelve instances in a year (9:00 AM, 12:00 Noon and 3:00 PM, for March 21, June 21, September 21 and December 21). Daylight values for the sun, sky, and ground components were determined using the experimentally determined directional workplane illuminance coefficients of the photometric analysis. Values for the sun component were determined through interpolation on the measured coefficients. Values for the sky and ground components were determined through integration of the measured coefficients over the luminance distribution of the sky and the ground. We assumed the CIE overcast[6] and clear[7] sky luminance distributions and 0.2 uniform ground reflectance.

The results of the daylight analysis showed that the BHDS introduced more sunlight at the back of the room than clear glass when the sun was at high altitudes (75.5°) in front of the window, such as during the summer noon hours for a South-facing window (Figure 3). However, when the sun was at low altitudes (28.5°), such as during the winter noon hours for a South-facing window, the BHDS introduced less sunlight than clear glass (Figure 4). Clear glass always introduced more skylight than the BHDS throughout the room (Figure 5), which, in many cases, balanced out the higher sun component of the BHDS (Figure 3).

## 5. RADIOMETRIC AND PHOTOMETRIC ANALYSIS

Using a goniospectrometer and our scanning radiometer, we measured the bi-directional transmittance and reflectance of the BHDS for various incoming directions, for both the visible and the total solar spectra. Measurements were taken in steps of one degree (1°) with respect to the outgoing angles, for six incoming directions of radiation (0°, 15°, 30°, 45°, 60° and 75° incident angles). The total diffracted component was then calculated through summation, used to approximate integration over the outgoing range of interest:

$$T_d = \int_{(\vartheta = -28^\circ)}^{90^\circ} \frac{T(\vartheta)}{\Delta\vartheta} \cdot d\vartheta = \sum_{(\vartheta = -28^\circ)}^{90^\circ} \frac{T(\vartheta)}{\Delta\vartheta} \cdot 1^\circ \qquad (1)$$

where $T_d$ is the transmittance value at outgoing direction specified by $\vartheta$, and $\Delta\vartheta$ is the angular response of the detector.

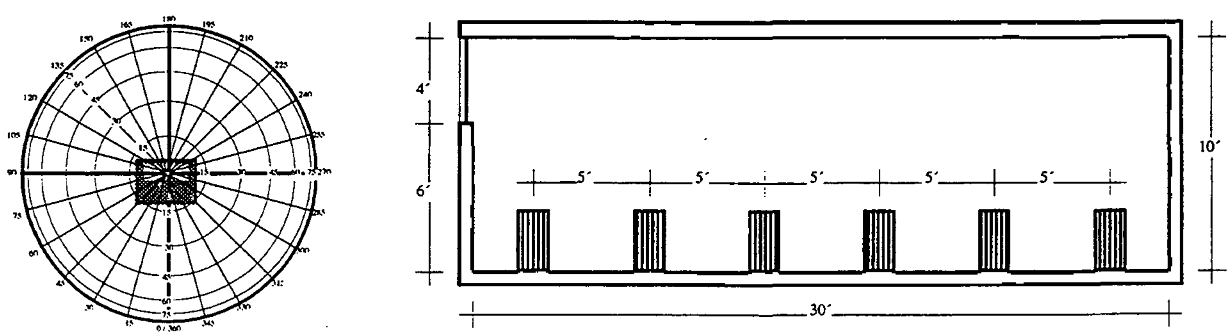


*Figure 2. The incoming directions of radiation and the workplane reference points considered for the determination of the directional illuminance coefficients.*

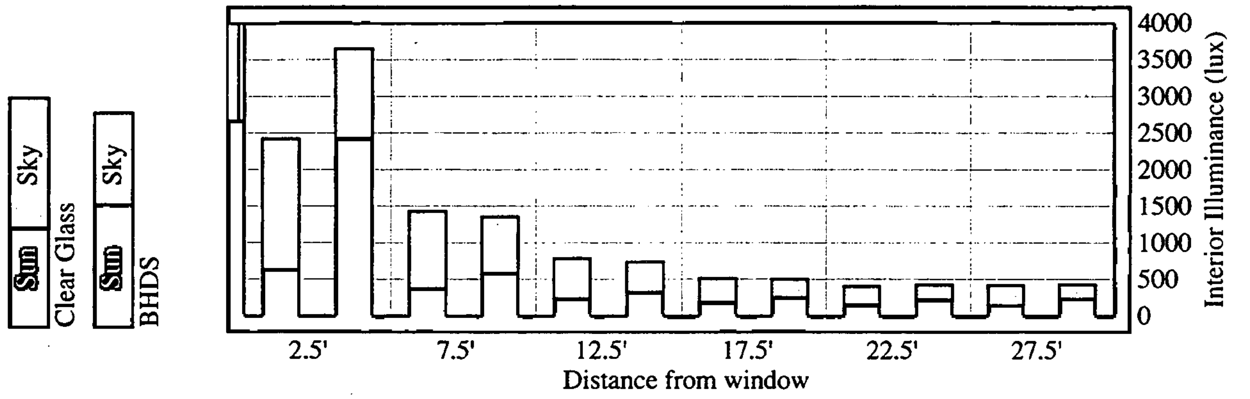


***Figure 3.*** *Workplane illuminance distribution for the CIE clear sky through South-facing clear glass and BHDS apertures at 12:00 Noon on June 21 for the San Francisco climate.*

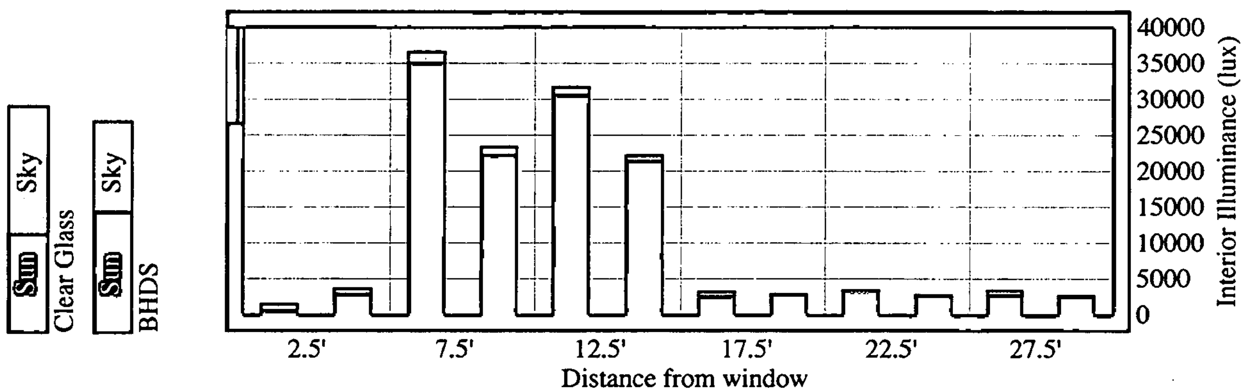


***Figure 4.*** *Workplane illuminance distribution for the CIE clear sky through South-facing clear glass and BHDS apertures at 12:00 Noon on December 21 for the San Francisco climate.*

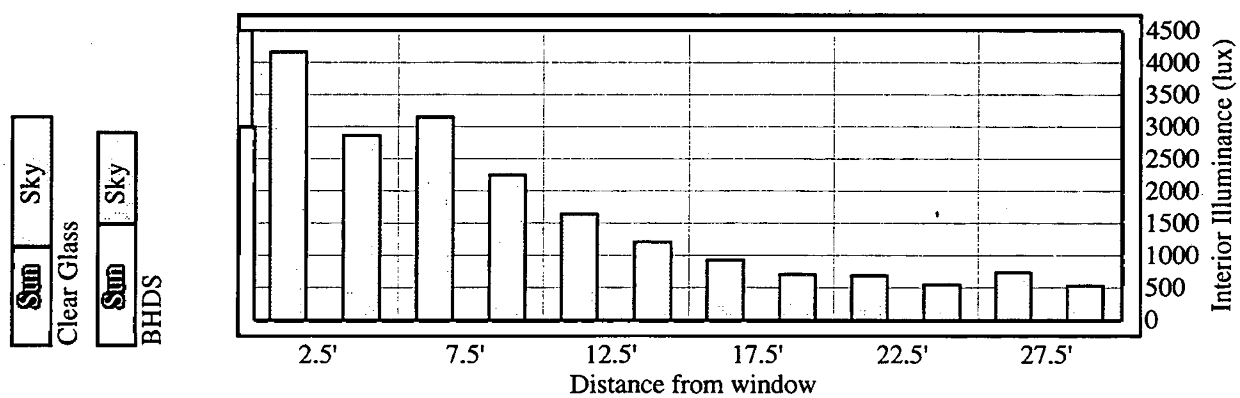


***Figure 5.*** *Workplane illuminance distribution for the CIE overcast sky through South-facing clear glass and BHDS apertures at 12:00 Noon on June 21 for the San Francisco climate.*

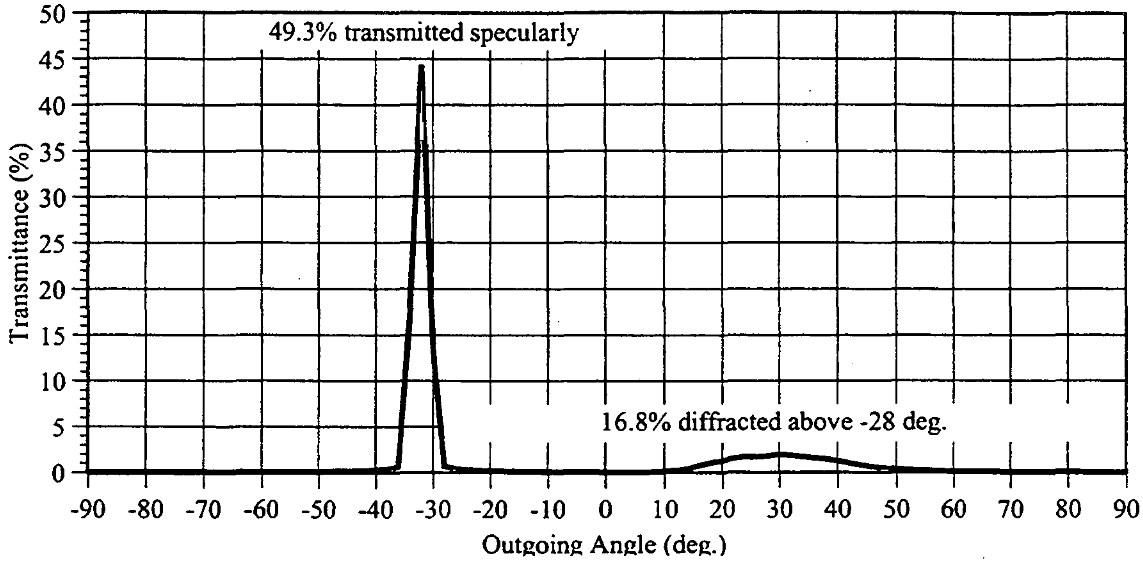


***Figure 6.** Average directional visible transmittance of the BHDS for maximum diffraction conditions (30° incident angle).*

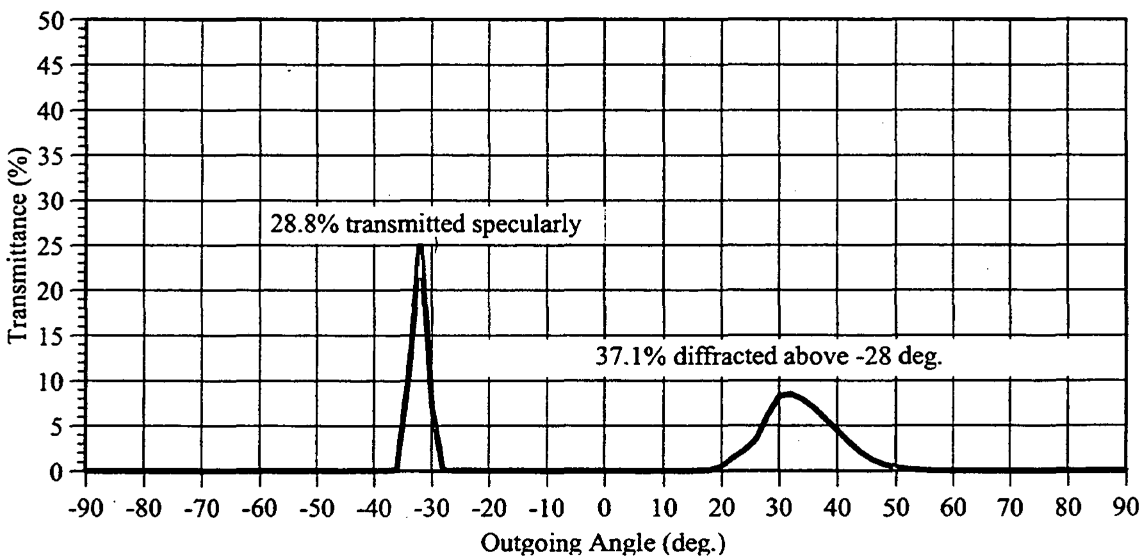


***Figure 7.** Average directional visible transmittance of the HDS for maximum diffraction conditions (30° incident angle).*

The results indicate that the BHDS redirected only a small fraction of the visible spectrum towards the ceiling, while the major part of the incident radiation was transmitted specularly (Figure 6), like through ordinary glass. With respect to the total solar spectrum, the measurements indicate that the BHDS do not redirect any of the non-visible part of the solar radiation. From the total solar spectrum transmittance and reflectance measurements we determined the shading coefficient of the BHDS for various incident angles, using the computer program WINDOW 3.1[8]. Due to the similarity of the thermal performance of the BHDS to that of clear glass, we modeled their solar heat gain performance following the DOE-2 algorithms.

We also measured the visible spectrum bi-directional transmittance of the HDS for comparison purposes. The results of these measurements indicate that the HDS diffract significantly more light towards the ceiling than the BHDS (Figure 7). It appears that the five stripe design to reduce the rainbow effect of the initial HDS, reduced the effectiveness of redirecting the light towards the ceiling. It is possible that the diffraction efficiency of the BHDS could be brought up to that of the HDS, through better construction and elimination of the spaces between the stripes.

## 6. ENERGY ANALYSIS

Using the DOE-2.1D energy analysis computer program, we modeled the typical office building discussed in the methodological section, considering the inland Los Angeles climate. We assumed the Title 24[9] recommended 1.5 W/ft2 (16.1 W/m2) installed lighting power density with continuous dimming controls for a desired workplane illuminance of 50 fc (537.5 lux). Daylighting levels were calculated for two reference points at 2.5 ft (0.76 m) workplane height from the floor and at depths of 12.5 ft (3.81 m) and 27.5 ft (8.38 m), controlling two independent electric lighting zones covering 42% and 58% of the floor area, respectively.

We considered two fenestration designs: one representing the "base case" with double low-E glazing of 0.33 Btu/hr/ft2/°F (1.82 W/m2/°C) U-value, 0.61 visible transmittance and 0.41 shading coefficient, and one for the application of BHDS above a low-E "view" window (Figure 1). The low-E glazing was modeled with the use of a diffuse shading device, which was deployed when the transmitted solar radiation exceeded 30 Btu/hr/ft2 (94.5 W/m2) or when the glare index exceeded a value of 20. When the shading device was deployed, the shading coefficient was reduced by 40% and the visible transmittance by 65%.

The luminous / thermal performance of the low-E glazing and the associated shade control was simulated using the internal algorithms of the DOE-2.1 energy analysis program. The simulation of the BHDS performance was performed through the development of a custom function called during the execution of the DOE-2 algorithms for every hour of a whole year. This function determined the performance of the BHDS aperture through interpolation among daylight factors derived from analytical routines, which were based on the experimental data from the scale model measurements. Daylight factors were determined for a large number of sun positions on a regular grid of 15° for solar azimuth and altitude.

We compared the base case low-E window (case A) to the holographic coatings as supplied (case B) and to three other hypothetical versions of the holographic glazings (cases C, D, E) which improved control of solar heat gains. These additional comparisons provide useful insights into the energy controls that would be desired in a holographic window system.

We first considered the actual BHDS sample properties, that is 1.07 U-value (single pane glass) and 0.88 shading coefficient (case B). When compared to a standard low-E window (case A), the results indicate that with respect to total electric energy requirements the BHDS are better than the base case for the North orientation by 3% and worse for the East, South and West orientations by 26%, 41% and 32%, respectively (Figure 8). With respect to peak electricity demand, the BHDS are worse than the base case for all orientations by 6%, 30%, 36% and 32%, for North, East, South and West, respectively (Figure 9).

For all orientations the BHDS have lower electric lighting energy use than the moderate transmittance (0.61) low-E glazing (Figure 10). However, the cooling penalties due to solar heat gain introduced through the BHDS (Figure 11) exceed the electric lighting savings, resulting in worse overall performance (Figure 8). The better performance of the BHDS for the North orientation occurs because the daylight savings exceed the smaller solar heat gain loads.

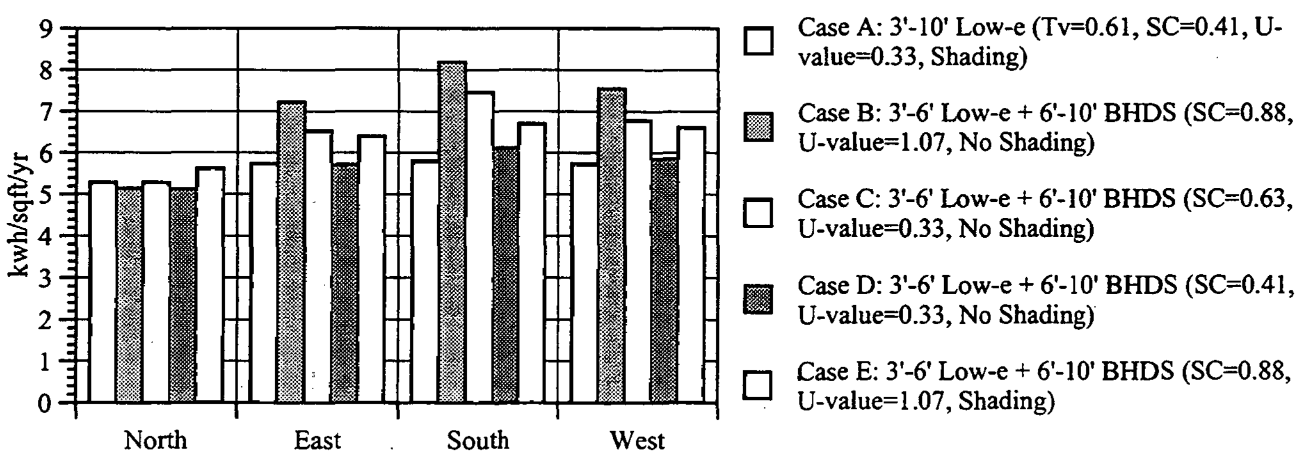


***Figure 8.*** *Total electric energy requirements by orientation for all cases considered.*

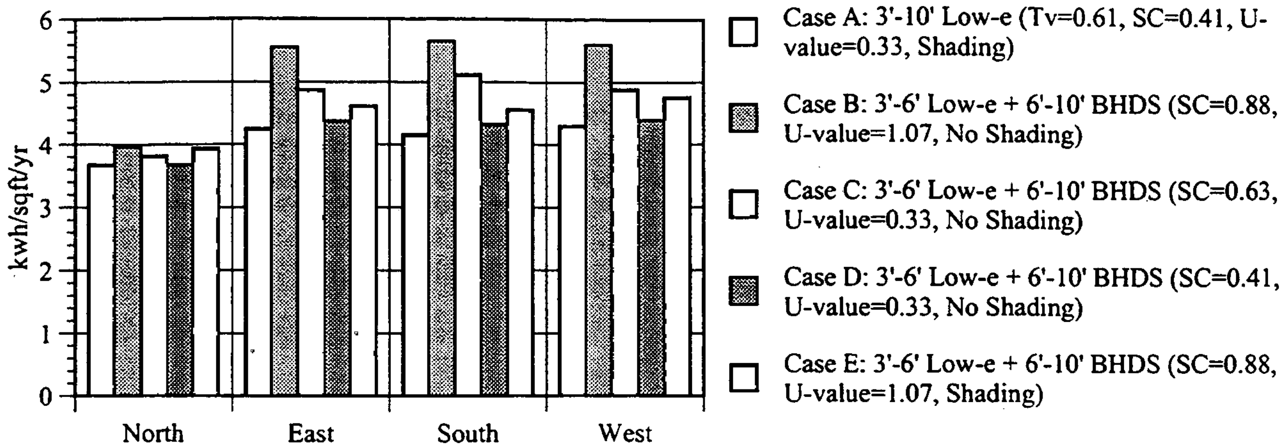


***Figure 9****. Peak electricity demand by orientation for all cases considered.*

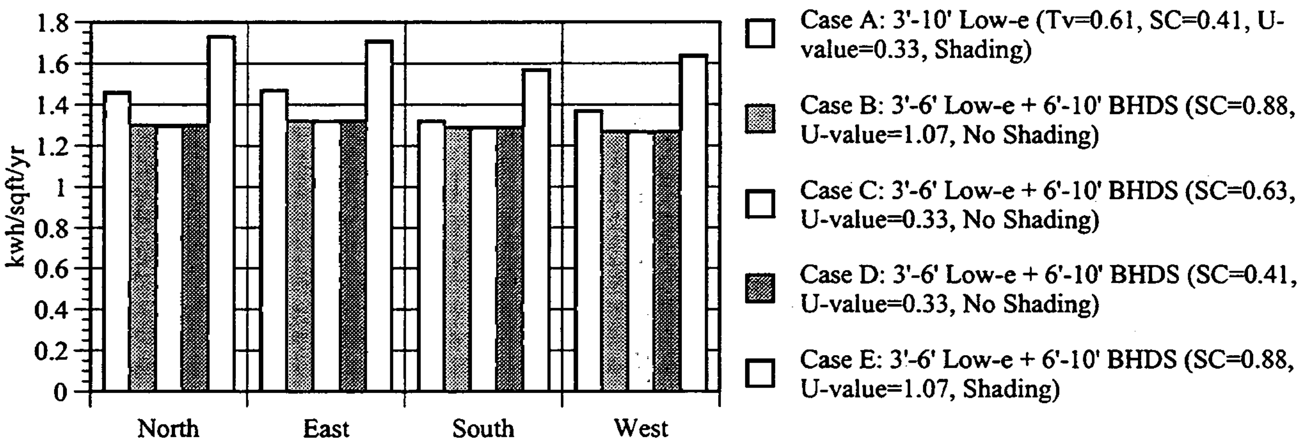


***Figure 10****. Electric lighting requirements by orientation for all cases considered.*

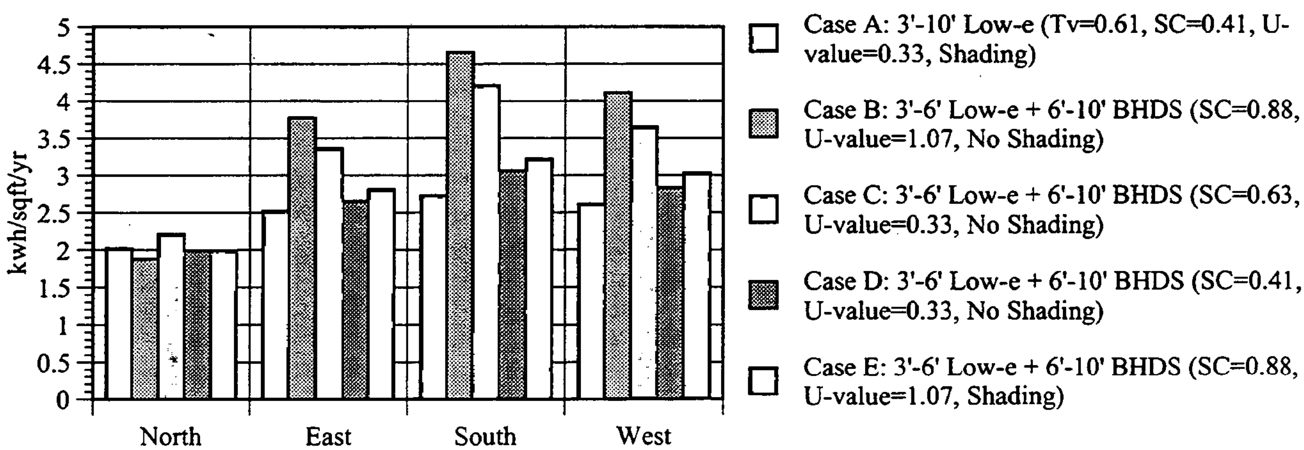


***Figure 11****. Cooling energy requirements by orientation for all cases considered.*

Since the thermal performance of the BHDS as supplied was the main reason for the low performance, we considered a hypothetical BHDS window (case C) with a U-value of 0.33 (double pane glass) and a much lower shading coefficient of 0.63, assuming the same daylight performance as in case B. The results are better with respect to case B but still worse than case A for all orientations (North, East, South and West) by 0.1%, 14%, 28% and 18% with respect to total electric energy requirements (Figure 8), and by 4%, 15%, 23% and 14% with respect to peak electricity demand, respectively (Figure 9).

Since cooling load was still a major problem, we considered a new hypothetical window (case D) with an even lower shading coefficient (0.41, equal to the low-E case), while still maintaining the original daylight properties as in case B. This reduction of the shading coefficient by 35% from case C brought the cooling loads down, near those (but still higher) of case A. The results with respect to case A for total electric energy requirements are only marginally better for North and East orientations, by 3% and 0.5%, respectively, and worse for South and West orientations, by 5% and 2%, respectively (Figure 8). With respect to peak electricity demand, they are marginally better for North orientation by 0.1%, and worse for all other orientations (East, South and West) by 3%, 4% and 2%, respectively (Figure 9).

Case D shows that the penalties due to increased solar heat gain through the BHDS are not only because of the higher shading coefficient but because of the lack of any solar control (shading) for direct sunlight. However, actively controlled shading for the BHDS aperture might defeat its purpose of utilizing sunlight to illuminate the back of the room. To explore this effect, we modified case B to include dynamic control of sunlight through the holographic window, modeling a shading device that reduced the magnitude of the transmitted radiation by 65%, without affecting the distribution of the transmitted radiation (case E). In this final analysis we considered a shading schedule for the BHDS that was triggered only by solar heat gain consideration. The results of this analysis showed that, when compared to low-E glass, the BHDS performed worse on all orientations (North, East, South and West) with respect to total electric energy requirements by 6%, 11%, 16% and 15%, respectively (Figure 8). The BHDS also performed worse with respect to peak demand for all orientations by 7%, 8%, 10% and 11%, respectively (Figure 9). While the shading control reduced the cooling loads considerably (Figure 11), it significantly reduced the daylighting benefits as well (Figure 10).

## 7. CONCLUSIONS AND RECOMMENDATIONS

The results of our analyses showed that these particular BHDS did not save significant electric energy or reduce peak electricity demand compared to conventional energy-efficient window systems in California office buildings. These BHDS redirected only a small part of the transmitted radiation (approximately 16% on the average), the rest being specularly transmitted, as through clear glass. The BHDS thus introduce high levels of daylight at the front of the room, where there is already more than enough daylight from the conventional "view" window.

Compared to a lower transmittance (0.61) low-E "base case" window, the BHDS reduced annual electric lighting requirements by up to 11% on the North orientation. However, they increased annual cooling loads by up to 71% on the South orientation. The luminous and thermal performance of the HDS was not significantly better than that of clear glass, which cannot efficiently illuminate more than 15 ft - 20 ft (4.57 m - 6.09 m) of a building's perimeter through side windows, since the solar heat gain penalties due to solar heat gain exceed the electric lighting savings due to daylighting.

The high specular component of the transmitted radiation and the angular response at low sun angles which redirects light to the ceiling at the front of the room, both reduce the overall effectiveness of the glazing. Much better control of the solar heat gain will also be required to provide significant annual energy savings. The challenge to provide an energy-efficient glazing requires the design and production of a coating, or array of coatings, that have good efficiency, proper directional control over an appropriate range of input conditions, and good spectral control to provide a pleasing interior lighting quality. Although this challenge has not yet been met, we believe that the potential benefits make this a worthwhile objective to pursue.

The holographic glazings tested in this study do not show significant savings in annual energy use or peak demand. While much technical progress has been made in their development over the past decade, there are still significant hurdles which must be overcome before these prototypes can become a viable, marketable product. We group these research and development needs into three areas, which are not mutually exclusive:

- Windows have an impact on many performance parameters, such as heating, cooling, lighting, peak demand, comfort, etc. An energy-efficient window whose objective is to reduce total energy use and peak demand must satisfy these often contradictory requirements. Development of a marketable holographic window can only be successful if refinements in the optical properties of the coatings are driven by a detailed understanding of performance criteria as a function of building type, orientation, latitude, climate, and time. Such performance criteria with respect to holographic windows do not currently exist.

• Glazing systems perform within the larger context of the window, as well as the building's interior. Parameters such as window width and height, ceiling height, interior surface reflections, etc., may greatly affect the performance of holographic glazings. While window components, such as low-E coatings, gas fills, and anti-reflective coatings, can be added to a holographic glazing to help control thermal gains and losses, they will increase cost and may reduce desirable properties in other performance areas. The integration of a holographic coating into a window and integration of the window into the curtain wall are largely unexplored issues at this time.

• While monochromatic laser measurements on HDS may show higher diffraction efficiency, the white measurements made for these study showed 35% - 40% for the best part of the HDS and only 16% - 20% for the best area of the BHDS, for the best possible incoming directions of radiation. If the banded holographic coatings are to be developed and marketed as energy-efficient devices, their white-light diffraction efficiency must be substantially improved, over a wide range of incoming directions of radiation. Diffraction efficiency criteria may be developed for specific building applications using computer simulations. However, such criteria are not currently available.

## 8. ACKNOWLEDGMENTS

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