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# Energy and Daylight Performance of Angular Selective Glazings

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# ENERGY AND DAYLIGHT PERFORMANCE OF ANGULAR SELECTIVE GLAZINGS

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## ABSTRACT

*This paper presents the results of a study investigating the energy and daylight performance of anisotropic angular selective glazings. The DOE-2.1E energy simulation program was used to determine the annual cooling, lighting and total electricity use, and peak electric demand. RADIANCE, a lighting simulation program, was used to determine daylight illuminance levels and distribution. We simulated a prototypical commercial office building module located in Blythe, California. We chose three hypothetical conventional windows for comparison: a single-pane tinted window, a double-pane low-E window, and a double-pane spectrally selective window. Daylighting controls were used. No interior shades were modeled in order to isolate the energy effects of the angular selective glazing. Our results show that the energy performance of the prototype angular selective windows is about the same as conventional windows for a 9.14 m (30 ft) deep south-facing perimeter zone with a large-area window in the hot, sunny climate of Blythe. It is theoretically possible to tune the angular selectivity of the glazing to achieve annual cooling energy reductions of 18%, total electricity use reductions of 15%, and peak electric demand reductions of 11% when compared to a conventional glazing with the same solar-optical properties at normal incidence. Angular selective glazings can provide more uniformly distributed daylight, particularly in the area next to the window, which will result in a more visually comfortable work environment.*

## INTRODUCTION

Research into the development of angular selective glass coatings is taking place in a number of countries including Australia, Canada, Japan, Sweden, and the United States (Smith 1997; Mbise et al.; Bader and Truong 1994; Maeda et al.; Smith, Dligatch and Ng). Individuals involved in these efforts previously helped develop the current state-of-the art in depositing conventional thin film coatings on glass. Angular selective coatings, however, are unique in that they are anisotropic, thus yielding a greater measure of control over the subsequent solar-optical characteristics of the glass. Angular selective glazings are designed to attenuate direct solar radiation, the main source of solar heat gains and glare, while transmitting a significant amount of diffuse skylight. A coating, produced by oblique evaporation, sputtering, and cathodic arc deposition, has anisotro-

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pic optical properties that can have different transmittance for light incident at equal angles at the two side of the surface normal. The coating can be designed for spectral and luminous selectivity. Transparent view is maintained for all directions. The columnar structure of the coating requires unique methods to measure, characterize, and model the thermal and daylighting performance of these glazings.

To provide some guidance for these material development efforts, we present an energy and daylighting analysis of prototypical angular selective glazings. We discuss results for a single-pane angular selective window, a double-pane window consisting of an exterior angular selective glazing and an interior spectrally selective glazing, and another double-pane angular selective window in which the solar-optical properties were modified to provide improved solar heat gain and light distribution characteristics.

## METHOD

The performance of angular selective windows was analyzed by using a modified version of the DOE-2 hour-by-hour building energy simulation program (Winkelmann et al. 1993) to evaluate the annual energy consumption and peak demand of a prototypical commercial office building module. Daylight distribution and illuminance levels were determined using the RADIANCE (Ward 1994) ray-tracing lighting simulation and rendering program. The module, Figure 1, consists of a 24.4 m (80 ft) square core zone, surrounded by four identical perimeter zones, each 24.4 m by 9.14 m (80 ft by 30 ft), facing four cardinal directions. Each perimeter zone is divided into four large office spaces of equal size, 6.1 m wide by 9.14 m deep (20 ft by 30 ft) with a floor-to-floor height of 3.81 m (12.5 ft) and floor-to-ceiling height of 3.05 m (10 ft). Each office has a 6.1 m by 2.1 m (20 ft by 7 ft) window with a 0.9 m (3 ft) sill height. The window-to-wall area ratio (WWR, window area expressed as a fraction of the floor-to-floor facade area) was fixed at 0.56. This represents 0.70 of the floor-to-ceiling wall area. No interior shades were modeled in order to isolate the effects of the angular selective glazings. Interior surface reflectances were 0.76 for the ceiling, 0.44 for the walls, and 0.21 for the floor.

Continuous dimming lighting controls reduced the electric lighting use within the perimeter zone to a maximum of 10% of full power with 0.01% light output. The design illuminance was set at 538 lux (50 fc). The installed lighting power density was set at 16.1 W/m$^2$ (1.5 W/ft$^2$). Using RADIANCE-generated daylight factors within DOE-2, daylight levels were calculated at two reference points in each perimeter zone at a height of 0.8 m (2.5 ft) above the floor and at depths of 3.8 m (12.5 ft) and 8.4 m (27.5 ft) from the window wall. Each reference point controlled 50% of the electric lights within the space.

System coil loads were calculated for each perimeter zone. To isolate zone loads from the

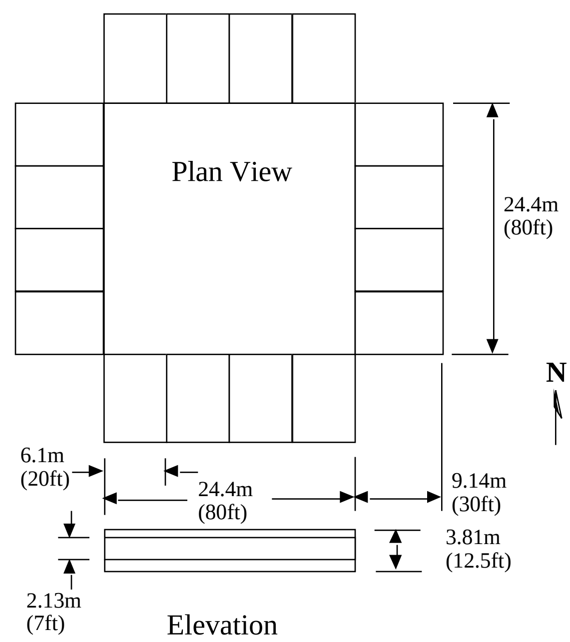



Figure 1. Commercial office building module used in the simulations. Each perimeter zone is partitioned into four offices, each 6.1 m x 9.1 m (20 ft x 30 ft). The core zone has a floor area of 594.6m$^2$ (6400ft$^2$).

***TABLE 1.*** Window Solar-Optical and Thermal Properties

| GLAZING | TSOL | SHGC | TVIS | U-Factor W/m$^2$˚C | U-Factor Btu/h-ft$^2$˚F |
|---|---|---|---|---|---|
| Angular Selective | | | | | |
| Single-pane | 0.56 | 0.64 | 0.48 | 5.78 | 1.00 |
| Double-pane Base | 0.31 | 0.39 | 0.38 | 1.96 | 0.35 |
| Double-pane Tuned | 0.31 | 0.39 | 0.72 | 1.96 | 0.35 |
| Conventional | | | | | |
| Single-pane Tinted Gray | 0.56 | 0.64 | 0.48 | 5.78 | 1.00 |
| Double-pane Bronze Low-E | 0.31 | 0.39 | 0.38 | 1.96 | 0.35 |
| Double-pane Spec. Selective | 0.31 | 0.39 | 0.72 | 1.96 | 0.35 |

**Note:** TSOL, SHGC, and TVIS are center-of-glass values at ASHRAE summer conditions: 35˚C (95˚F) outside temperature, and 24˚C (75˚F) inside temperature, 3.3 m/s (7.5 mph) wind speed, and near-normal incident solar radiation of 783 W/m$^2$ (248 Btu/h-ft$^2$). U-factor are values at ASHRAE winter conditions: -17.8˚C (0˚F) outside temperature, and 21.1˚C (70˚F) inside temperature, 6.71 m/s (15 mph) wind speed, and zero incident solar radiation.

building system interactions, a separate single-zone constant-volume variable-temperature HVAC system was assigned to each zone. A constant heating system efficiency (0.6) and cooling system coefficient of performance (3.0) was used to convert these loads to energy usage.

The simulations were done for a building located in Blythe, California. Blythe has a hot, sunny climate and is located southwest of Los Angeles at a latitude of 33.6˚N and a longitude of 114.7˚. It has 1256 (2269) cooling degree days at a base temperature of 23.9˚ C (75˚ F) and 598 (1077) heating degree days at a base temperature of 18.3˚ C (65˚ F).

## Glazing Descriptions

We analyzed both single- and double-pane angular selective windows. Results were compared to conventional windows with the same solar-optical properties at normal incidence as the angular selective windows. The single-pane angular selective glazing was the primary prototype for this study (Smith 1997). Direct solar transmittance (TSOL) and visible transmittance (TVIS) properties are shown in Figure 2 as a function of window surface solar altitude and azimuth. Values of TSOL and TVIS at normal incidence are 0.56 and 0.48, respectively. The solar heat gain coefficient (SHGC) at normal incidence, calculated by the WINDOW4.0 program (Finlayson et al. 1993), is 0.64. Superimposed on the plots in Figure 2 are sunpath angles for March 21, June 21, and December 21 for a south-facing window at a latitude of 33˚N.

Two double-paned angular selective windows were also analyzed. Initially, we combined the single-pane angular selective glazing, described above, with an inner pane of spectrally selective glass with the solar-optical properties shown in Figure 3. This resulted in the properties presented in Figure 4. Values of TSOL and TVIS at normal incidence are 0.31 and 0.38, respectively, with a SHGC of 0.39. DOE-2 analysis of these windows indicated that improved solar heat gain and daylight performance could be obtained by revising the distribution of the solar-optical properties, so we created a new theoretical, tuned single-pane angular selective glazing, which is shown in Figure 5. This tuned glazing exhibits increased TVIS for surface solar

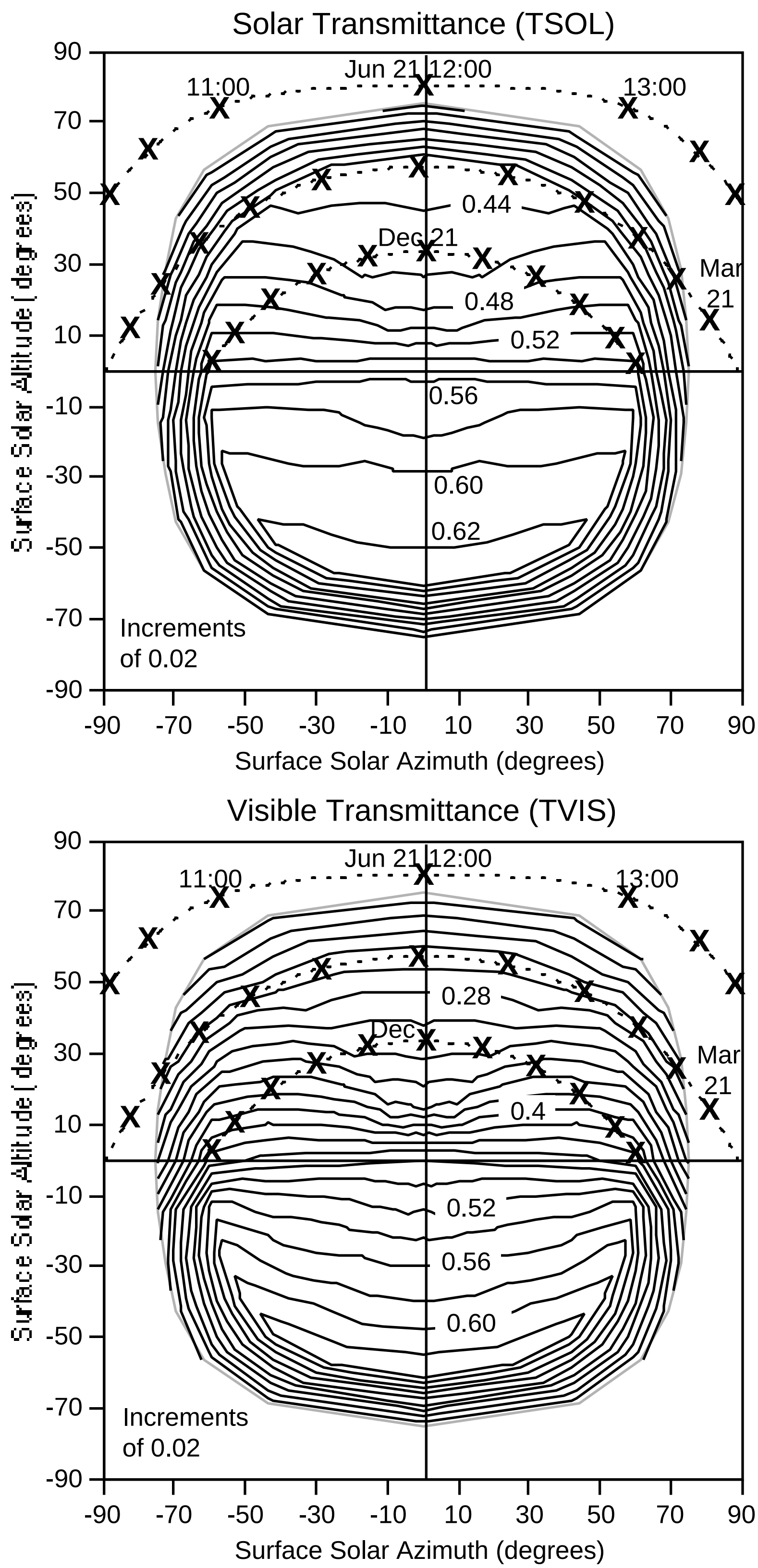



Figure 2. Single Pane Angular Selective Glazing TSOL and TVIS Distribution

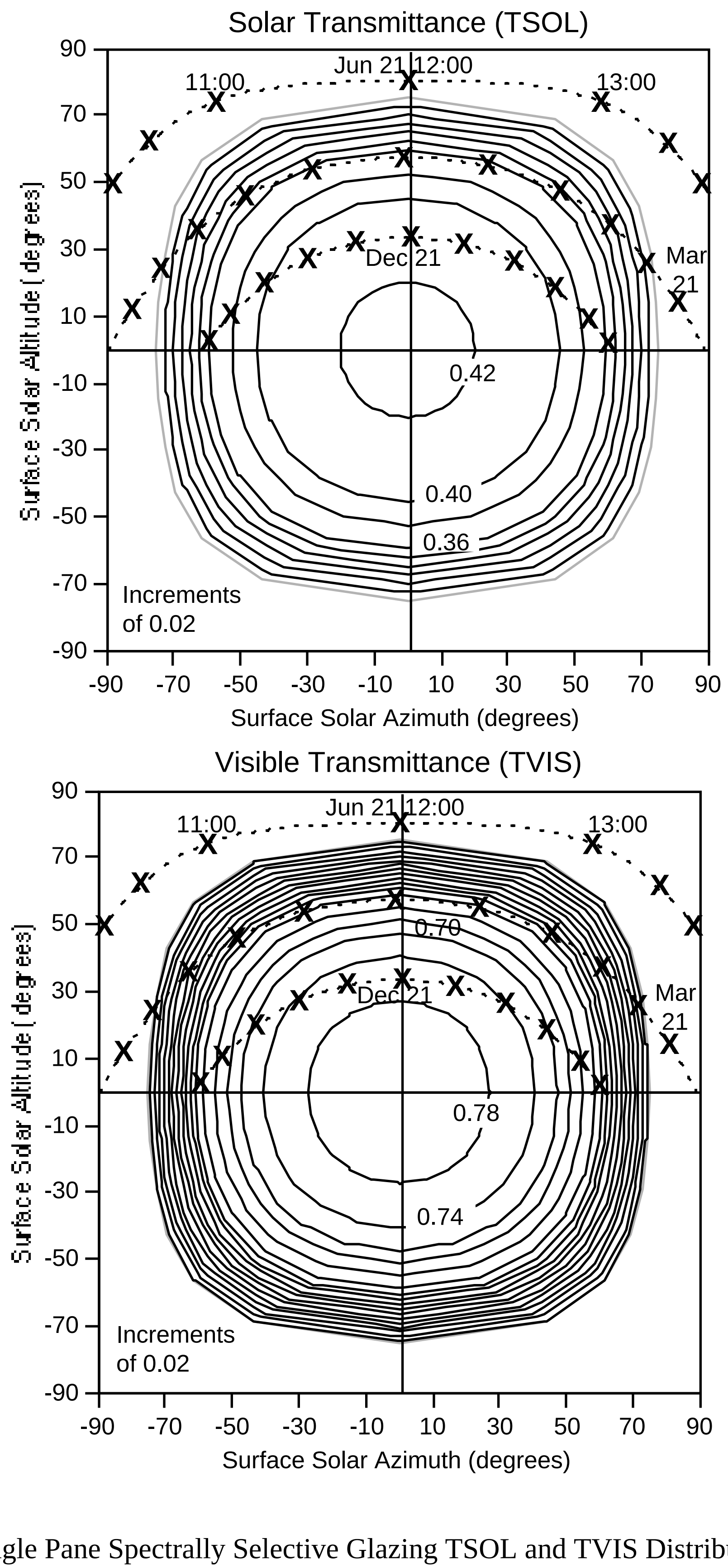



Figure 3. Single Pane Spectrally Selective Glazing TSOL and TVIS Distribution

altitude angles between 0-25˚ (for increased daylight admission during the winter) and decreased TVIS between 25-60˚ (for increased solar control during the summer), at 0˚ surface solar azimuth. It was also designed to decrease TSOL for all solar angles compared to the base angular selective glazing. This glazing was then combined with the same inner pane of spectrally selective glazing (Figure 3) to create the double-pane window presented in Figure 6.

The angular selective windows were compared to three theoretical conventional windows that have the exact same solar-optical properties at normal incidence: 1) a single-pane tinted gray window, 2) a double-pane low-E window, which consists of an exterior bronze tinted glazing and an interior clear low-E glazing (e=0.20 on surface #3), and 3) a spectrally-selective window, which is similar to the second low-E window, except that its TVIS is greater. Table 1 presents the solar-optical and thermal properties of the window systems. The values for SHGC and U-Factor were calculated using the WINDOW4 program.

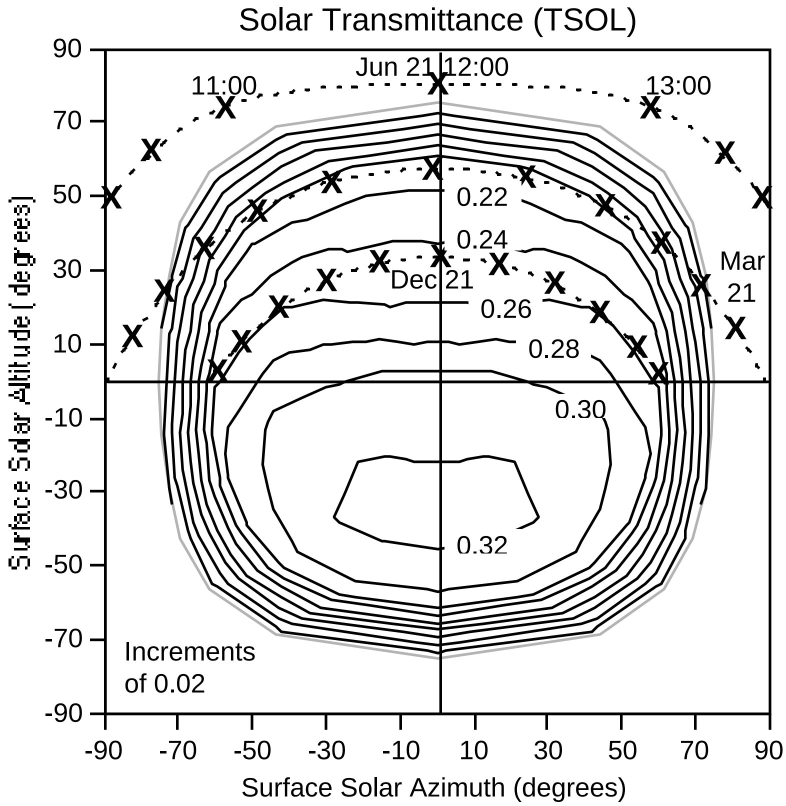
Although the properties at normal incidence of the angular selective and conventional windows are the same, there are differences at off-normal angles of incidence. The typical relationship of TSOL and TVIS to the angle of incidence is constant for conventional homogeneous glazings. This results in a surface solar altitude and azimuth plot showing TSOL and TVIS values as concentric contours, centered about the origin (Figure 3). The angular selective glazings analyzed in this study tend to have properties that vary with surface solar altitude, but are almost constant across a large range of surface solar azimuth angles. This is particularly prevalent at high surface solar altitude angles. For example, the sunpath angle for a south-facing window on March 21 indicates that the TSOL and TVIS values of the conventional glazings (Figures 3 and 7) do not vary significantly between ±35˚ surface solar azimuth; whereas, the TSOL and TVIS values of the base angular selective glazing (Figure 2) do not vary significantly between ±50˚ surface solar azimuth. This lack of variation may be important in maintaining a uniform daylight distribution within a space and in providing better control of incident solar radiation and cooling loads throughout the day.

## ENERGY PERFORMANCE

The energy-efficiency strategy in cooling-load-dominated commercial building applications is to reduce a) cooling by reducing solar and electric lighting heat gains and b) electric lighting use with daylighting. Figure 8 and Tables 2-5 show the annual cooling (includes chiller and fan energy) and lighting electricity consumption in Blythe, California for a 223 $m^2$ (2400 $ft^2$) south-facing perimeter zone. The cost of electricity was \$0.08/kWh.

As seen in Table 2, the cooling energy performance of the single-pane angular selective window is slightly less (4%) than the comparable single-pane gray glazing while the double-pane base and tuned angular-selective windows yield 4% and 18% reductions, respectively, compared to their low-E and spectrally-selective window counterparts, which have the same solar-optical properties at normal incidence. It should be mentioned that one could also use interior shades with conventional windows or define a conventional window with a lower SHGC to achieve similar reductions in required cooling.

Using double-pane versus single-pane windows results in a corresponding reduction in cooling energy use for both the angular selective and conventional windows. The double-pane angular selective windows have 42% (base) or 52% (tuned) lower annual cooling energy use than the single-pane angular selective window. The cooling energy use reductions of the conventional double-pane to single-pane windows are approximately the same percentage.



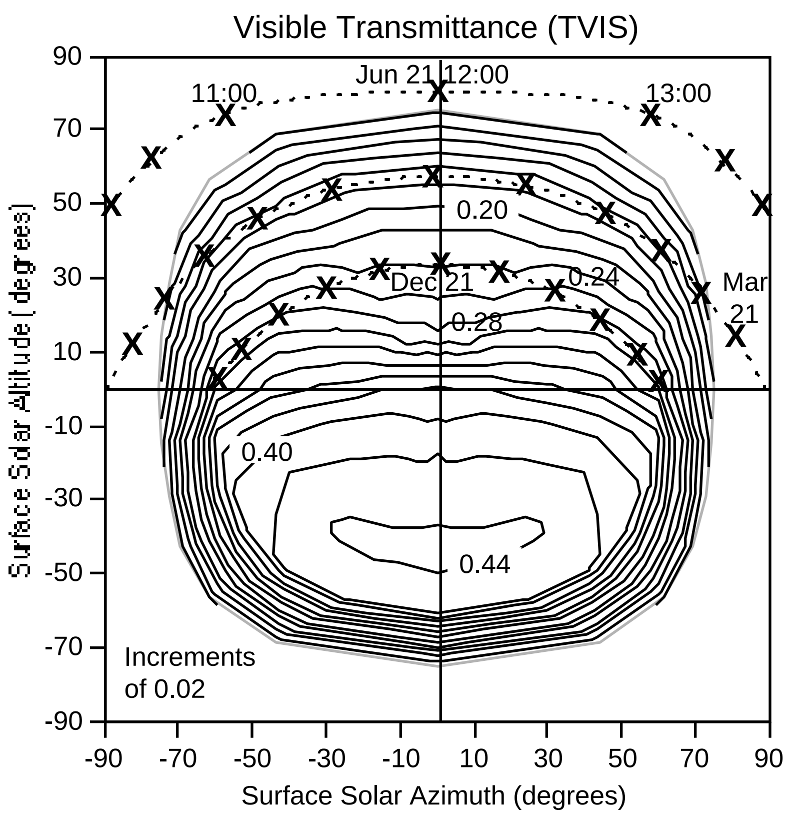




Figure 4. Double Pane Angular Selective Glazing TSOL and TVIS Distribution

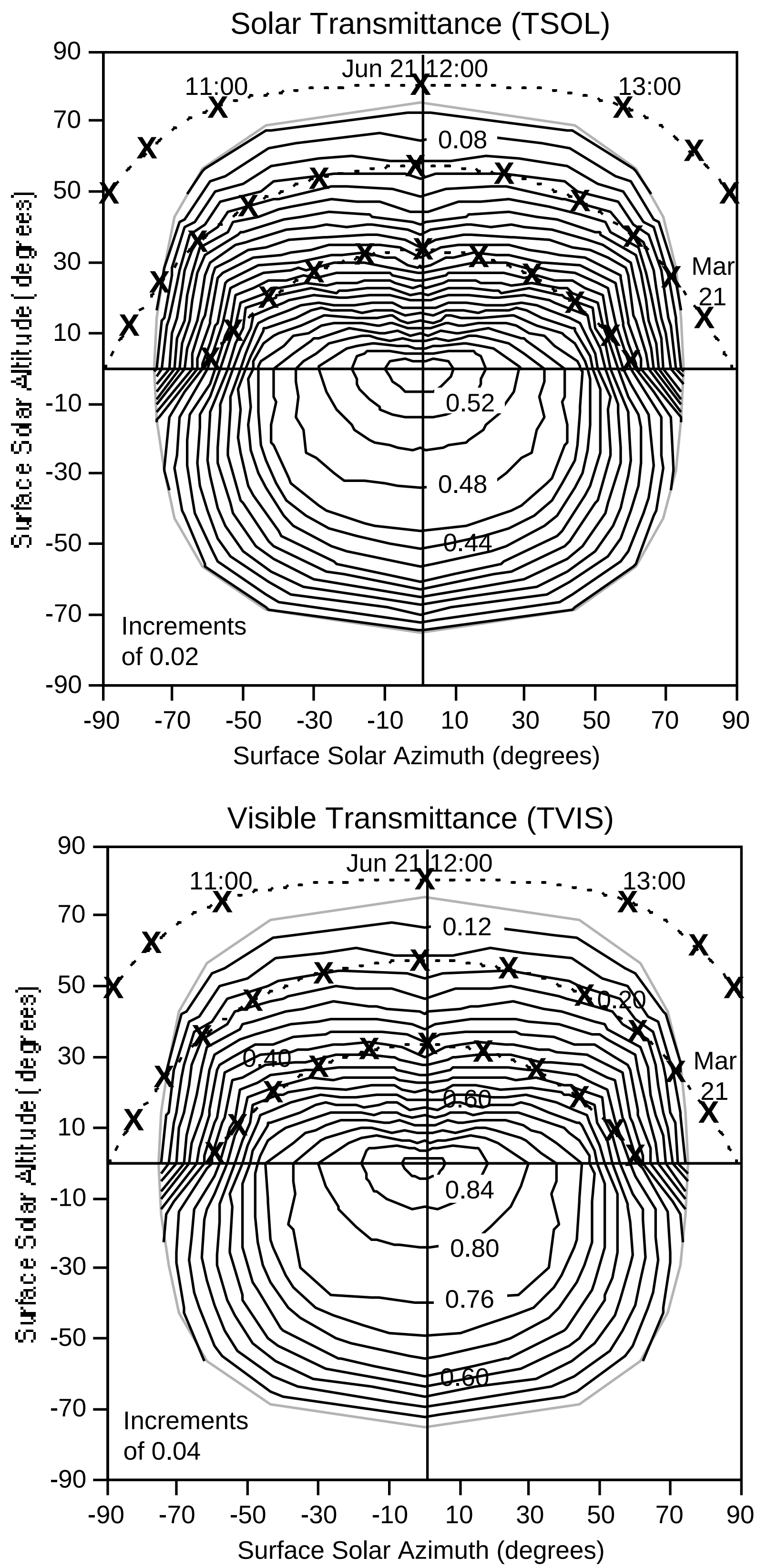
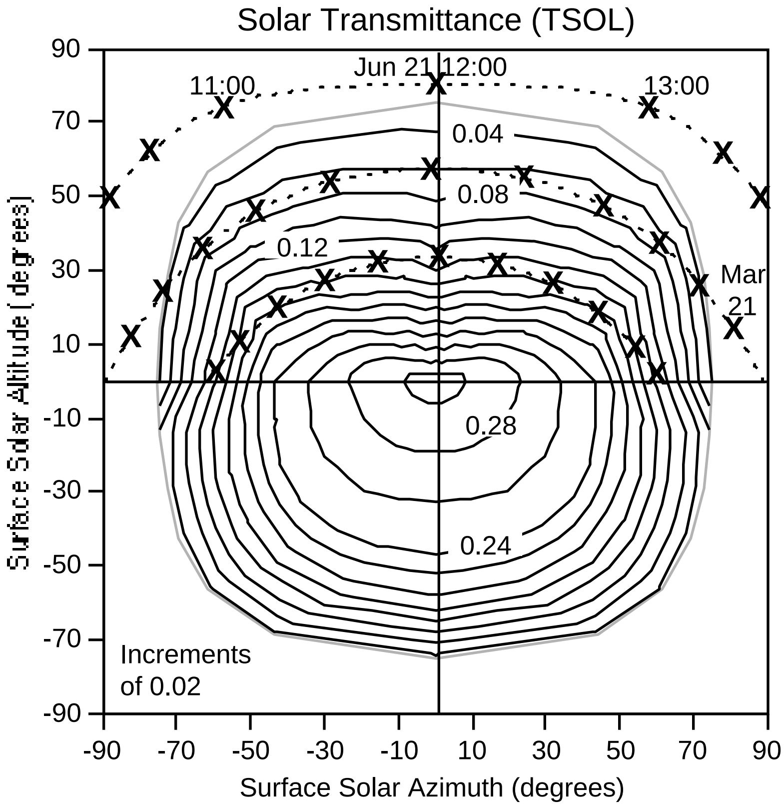



Figure 5. Single Pane Angular Selective Glazing with Tuned TSOL and TVIS Distribution



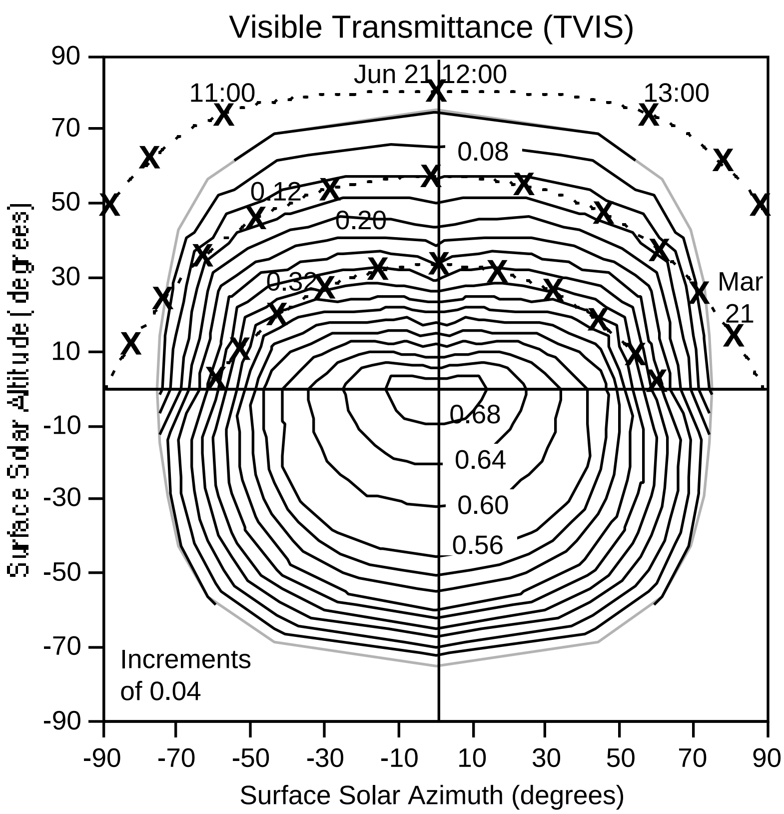
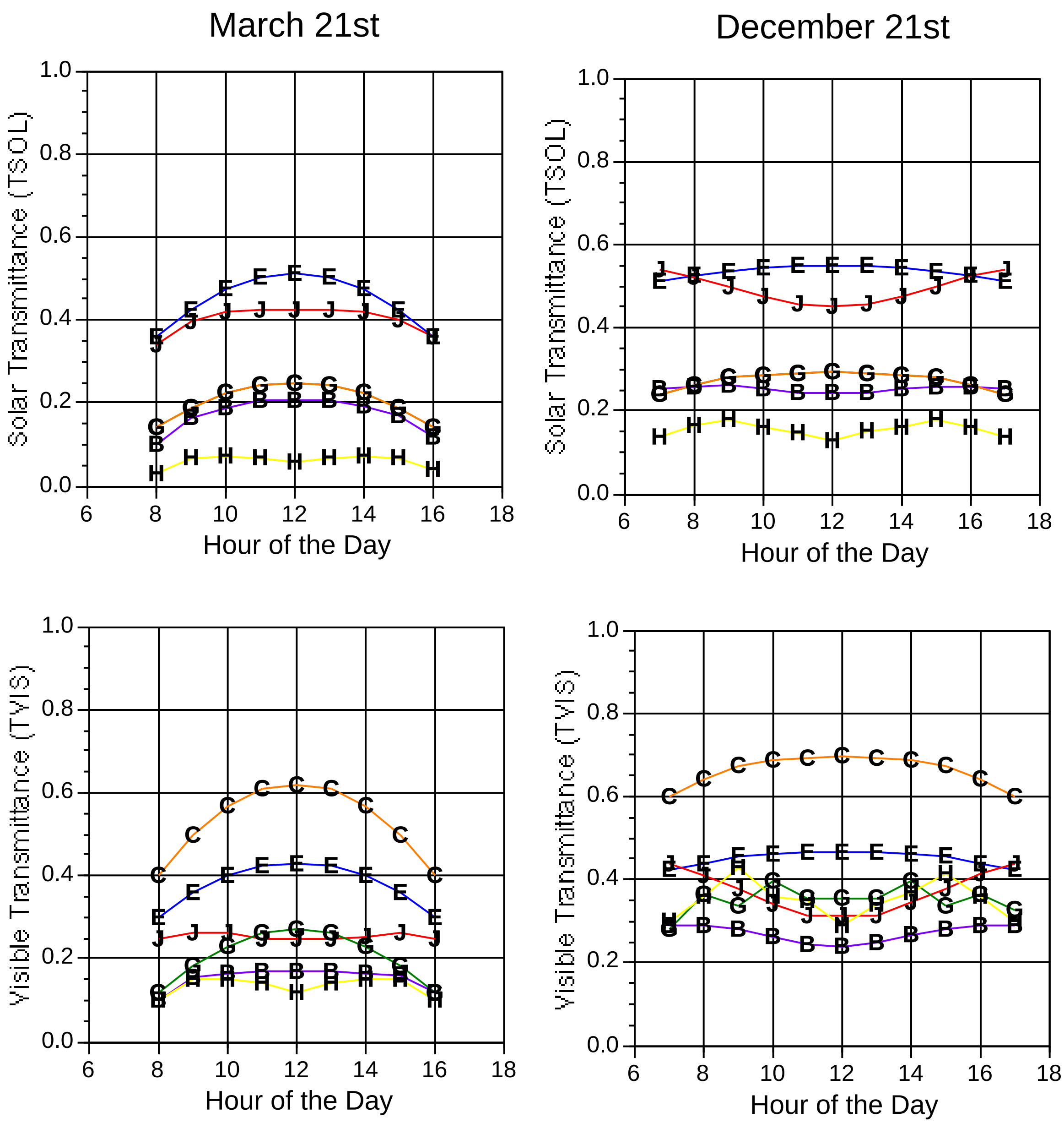




Figure 6. Double Pane Angular Selective Glazing with Tuned TSOL and TVIS Distribution



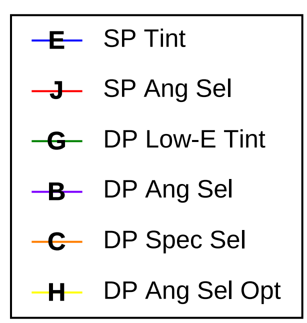
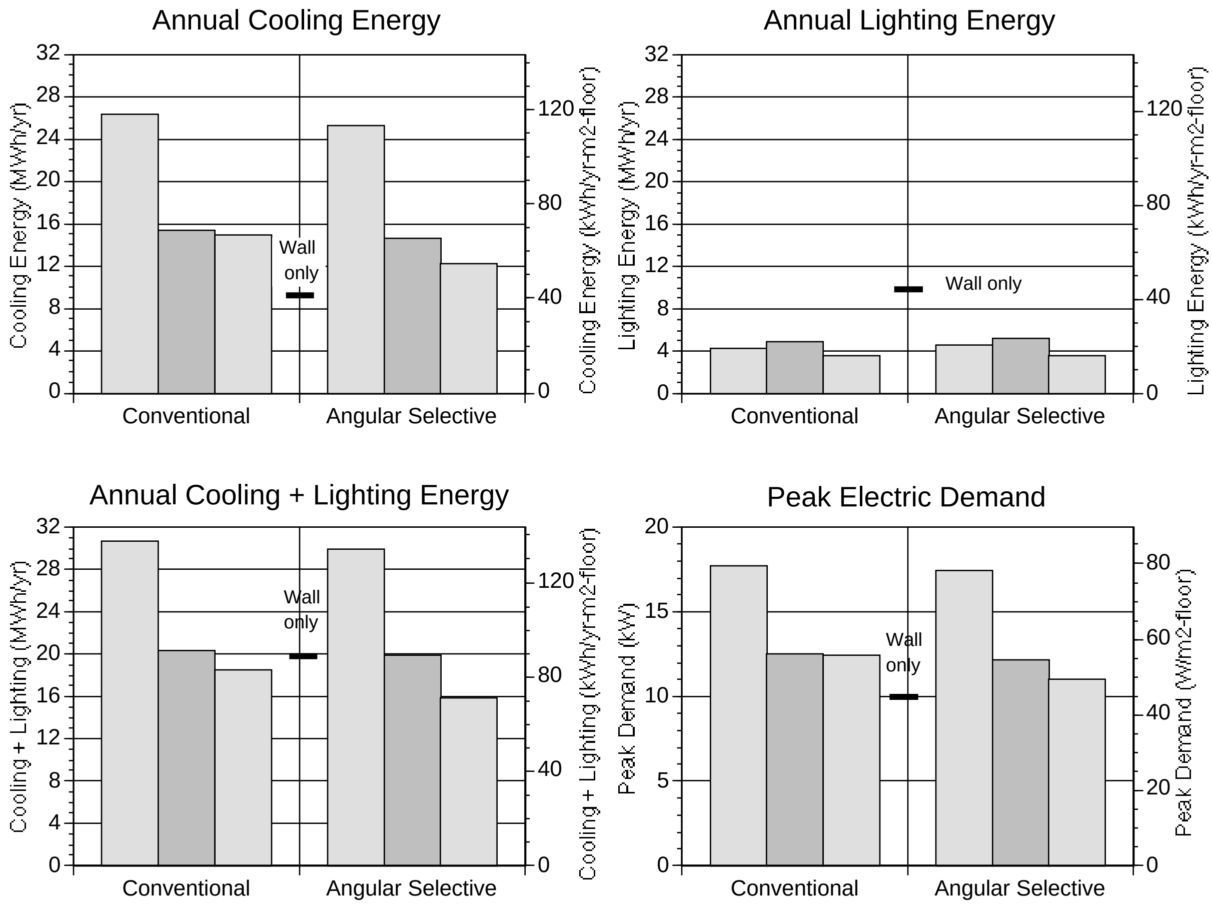




Figure 7. TSOL and TVIS variation during March 21 and December 21 at 33˚N latitude for angular selective and conventional windows facing south.




| GLAZING | SHGC | TVIS | U-Factor |
|---|---|---|---|
| SP Tint | 0.64 | 0.48 | 5.78 (1.00) |
| DP Low-E Tint | 0.39 | 0.38 | 1.96 (0.35) |
| DP Spec Selective | 0.39 | 0.72 | 1.96 (0.35) |
| SP Ang Sel | 0.64 | 0.48 | 5.78 (1.00) |
| DP Ang Sel | 0.39 | 0.38 | 1.96 (0.35) |
| DP Ang Sel Tuned | 0.39 | 0.72 | 1.96 (0.35) |

Figure 8. Annual electricity consumption due to cooling (chiller and fans) and lighting, and peak electricity demand for a south-facing perimeter zone in a large prototypical commercial office building module located in Blythe, California. Window-to-wall ratio is 0.56. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m$^2$ (1.5 W/ft$^2$).

The reason for the lower required cooling of the tuned angular selective window is related to its lower average TSOL over the course of the day. The TSOL values of the single- and double-pane base angular selective windows are lower than their corresponding hypothetical conventional window counterparts; however, the tuned angular selective window is significantly lower than the others (Figure 7). Its double-pane TSOL value varies from 0.07 in March to 0.14 in December and is almost constant throughout the day. The conventional spectrally selective double-pane window with the same TSOL properties at normal incidence has a large variation during the day: in March, from a low of 0.14 in the early morning to 0.25 at midday and in December, from 0.24 to 0.29.

Differences in lighting energy performance is a function of the visible transmittance and area of the window. For a perimeter zone without windows, the required annual lighting (10.09 MWh) is almost equal to the required cooling (9.6 MWh), as seen in Figure 8 (denoted on graph

*TABLE 2.* Annual Cooling Energy, South Zone

| Glazing | Total Energy | Energy per Floor Area | | Calculated Energy Cost per Floor Area | |
|---|---|---|---|---|---|
| | MWh | $kWh/m^2$ | $kWh/ft^2$ | $\$/m^2$ | $\$/ft^2$ |
| Angular Selective | | | | | |
| Single Pane | 25.35 | 113.67 | 10.56 | 9.09 | 0.85 |
| Double Pane Base | 14.67 | 65.78 | 6.11 | 5.26 | 0.49 |
| Double Pane Tuned | 12.22 | 54.79 | 5.09 | 4.38 | 0.41 |
| Conventional | | | | | |
| Single Pane Tinted Gray | 26.30 | 117.93 | 10.96 | 9.43 | 0.88 |
| Double Pane Bronze Low-E | 15.34 | 68.87 | 6.39 | 5.50 | 0.51 |
| Double Pane Spec. Selective | 14.96 | 67.08 | 6.23 | 5.37 | 0.50 |
| Perimeter Zone (no windows) | 9.60 | 43.05 | 4.00 | 3.44 | 0.32 |

*TABLE 3.* Annual Lighting Energy, South Zone

| Glazing | Total Energy | Energy per Floor Area | | Calculated Energy Cost per Floor Area | |
|---|---|---|---|---|---|
| | MWh | $kWh/m^2$ | $kWh/ft^2$ | $\$/m^2$ | $\$/ft^2$ |
| Angular Selective | | | | | |
| Single Pane | 4.60 | 20.63 | 1.92 | 1.65 | 0.15 |
| Double Pane Base | 5.19 | 23.27 | 2.16 | 1.86 | 0.17 |
| Double Pane Tuned | 3.63 | 16.28 | 1.51 | 1.30 | 0.12 |
| Conventional | | | | | |
| Single Pane Tinted Gray | 4.38 | 19.64 | 1.83 | 1.57 | 0.15 |
| Double Pane Bronze Low-E | 4.96 | 22.24 | 2.07 | 1.78 | 0.16 |
| Double Pane Spec. Selective | 3.63 | 16.28 | 1.51 | 1.30 | 0.12 |
| Perimeter Zone (no windows) | 10.09 | 45.24 | 4.20 | 3.62 | 0.34 |

with “wall only”), and Table 3. With daylighting, we are able to reduce this value 65%, when using the tuned angular selective or spectrally selective conventional double-pane window. However, all other windows also perform very well due to the large glazing area (WWR=0.56); the largest lighting requirement occurs with the base double-pane angular selective window.

The sum of the annual cooling and lighting electricity use is also shown in Figure 8 and Table 4. The base angular selective windows reduce total annual energy use by only 2% compared to their conventional window counterparts, while the tuned angular selective window reduces annual energy use by 15%. The variation with window type tends to be the same as the required cooling values, since the lighting energy is al-

**TABLE 4.** Annual Cooling and Lighting Energy, South Zone

| Glazing | Total Energy | Energy per Floor Area | | Calculated Energy Cost per Floor Area | |
|---|---|---|---|---|---|
| | MWh | kWh/m² | kWh/ft² | $/m² | $/ft² |
| Angular Selective | | | | | |
| Single Pane | 29.95 | 134.30 | 12.48 | 10.74 | 1.00 |
| Double Pane Base | 19.85 | 89.01 | 8.27 | 7.12 | 0.66 |
| Double Pane Tuned | 15.85 | 71.07 | 6.60 | 5.69 | 0.53 |
| Conventional | | | | | |
| Single Pane Tinted Gray | 30.65 | 137.43 | 12.77 | 10.99 | 1.02 |
| Double Pane Bronze Low-E | 20.30 | 91.02 | 8.46 | 7.28 | 0.68 |
| Double Pane Spec. Selective | 18.59 | 83.36 | 7.75 | 6.67 | 0.62 |
| Perimeter Zone (no windows) | 19.74 | 88.51 | 8.22 | 7.08 | 0.66 |

**TABLE 5.** Peak Electric Demand, South Zone

| Glazing | Peak Electric per Floor Area | | Total Peak Electric |
|---|---|---|---|
| | W/m² | W/ft² | kW |
| Angular Selective | | | |
| Single Pane | 78.08 | 7.25 | 17.41 |
| Double Pane Base | 54.61 | 5.08 | 12.18 |
| Double Pane Tuned | 49.37 | 4.59 | 11.01 |
| Conventional | | | |
| Single Pane Tinted Gray | 79.46 | 7.38 | 17.72 |
| Double Pane Bronze Low-E | 56.23 | 5.23 | 12.54 |
| Double Pane Spec. Selective | 55.51 | 5.16 | 12.38 |
| Perimeter Zone (no windows) | 45.15 | 4.20 | 10.07 |

most constant across window types. The tuned angular selective window has a total energy requirement that is 20% less than the perimeter zone with no windows. The only other window with a total energy use that is less than the perimeter zone without windows is the conventional spectrally selective double-pane window (6%). The greatest total annual energy use is required by the conventional single-pane window.

Figure 8 and Table 5 show the peak electric demand for each of the windows. The variation is proportional to the annual electric consumption discussed above. The tuned angular selective window reduced the peak demand by 11%, while the base angular selective windows reduced the peak demand by only 2-3%, compared to their conventional window counterparts.

## DAYLIGHT PERFORMANCE

A detailed daylight analysis of an individual office space was performed to determine how angular selective windows modify the intensity and distribution of daylight. Workplane illuminance levels due to daylight only were calculated at six reference points in increments of 1.5 m (5 ft) along the centerline of the space, starting at 0.8 m (2.5 ft) from the window wall, at a height of 0.8 m (2.5 ft). Illuminance levels were calculated at noon on December 21, March 21, and June 21 for the south-facing perimeter zone.

In general, the conventional spectrally selective double-pane window introduces more daylight into the space than the other windows on all three days at noon and throughout the space, due to its higher TVIS (Figure 7). The three conventional windows have an exponential decay daylight distribution along the centerline of the space as one proceeds away from the window, while the distributions of the three angular selective windows are more uniform.

Figure 9 presents the workplane illuminance distribution under CIE clear sky conditions, with Figure 10 showing the same data as Figure 9, but with an expanded vertical scale to help one visualize the daylight distribution at the rear of the space. The illuminance levels at the first reference point (0.8 m, 2.5 ft$^2$), for all window types, are excessively high (10,000-42,000 lux) on December 21 and March 21 due to direct sun. However, there is a reduction in illuminance when comparing the conventional windows to the angular selective windows. For example, in December, both the single- and double-pane angular selective windows have values that are 30-35% lower than their conventional window counterparts. When comparing the illuminance level of the tuned angular selective window to the spectrally selective window, the difference in illuminance at 0.76 m (2.5 ft) from the window is 59% in December, which increases to 79% in March. These illuminance data demonstrate the principle design feature of angular selective glazings, which can attenuate direct solar radiation while transmitting a significant amount of diffuse light. These differences can again be more clearly seen in the comparison of TVIS between conventional and angular selective windows in Figure 7.

At a depth of 8.38 m (27.5 ft) away from the window, shown best in Figure 10, the tuned angular selective window admits 6-82% more daylight than the other window types, except for the spectrally selective window: the tuned angular selective window provides workplane illuminance values of 407 lux, 194 lux, and 169 lux on December 21, March 21, and June 21, while the conventional spectrally selective window provides 582 lux, 275 lux, and 203 lux. In general, the tuned angular selective window has greater workplane illuminance levels than the two base angular selective windows.

The horizontal illuminance distributions produced by the angular selective windows across the entire depth of the space are more uniform, as indicated by the ratio of the workplane illuminance at 0.76 m (2.5 ft) from the window to the illuminance at 8.38 m (27.5 ft) from the window. The tuned angular selective window produced ratios of 30:1 (December), 45:1 (March), and 6:1 (June), while the spectrally selective window produced ratios of 50:1, 150:1, and 15:1, respectively. These illuminance ratios were similar with the other two angular selective windows.

To give additional insight into the daylight performance of angular selective glazings, we also modeled a smaller office with dimensions of 3.05 m by 4.6 m (10 ft by 15 ft) with a ceiling height of 2.6 m (8.5 ft). The window was also south-facing and was 3.05 m wide by 1.1 m high (10 ft by 3.5 ft). The interior surfaces reflectances were the same used in the large office space. Again, no interior shades were modeled. The resulting daylight illuminance distribution is similar to the large space under CIE clear and overcast conditions with the tuned angular selective window introducing more daylight than the conventional windows (except for the double-pane spectrally selective window) at the back of the space and at all times. Near the window, the three angular selective windows introduce lower, more controlled levels of illumination than the conventional windows.

## CONCLUSIONS

We compared the energy and daylight distribution performance of three types of angular selective windows to conventional windows with the same solar-optical properties at normal incidence. The comparison was made for a deep, south-facing commercial office perimeter zone with a large window, with no interior shades, and a continuous dimming daylighting control system in the hot, sunny climate of Blythe, California.

The base single- and double-pane angular selective windows did not significantly reduce the annual energy consumption and peak electric demand when compared to their conventional window counterparts. However, we defined a theoretical solar-optical distribution of a tuned angular selective glazing, which resulted in a reduced annual cooling energy use of 18%, a reduced total annual electricity use of 15%, and a reduced peak electric demand of 11%, when compared to a conventional spectrally selective window with the same solar-optical properties at normal incidence.

The daylight distribution analysis showed that all the angular selective windows resulted in more uniform workplane illuminance levels at noon on solstice and equinox days throughout the 9.1 m (30 ft) deep space. Conventional windows with a visible transmittance greater than about 0.50 tend to introduce excessively high levels of illumination near the window, with low levels at the back of a space, resulting in a visually uncomfortable environment. Lower TVIS values result in a similar distribution but with even lower illuminance levels in the rear, thus requiring more artificial lighting. Currently producible angular selective glazings do not necessarily increase the workplane illuminance levels in the back of a room, but they do produce a more uniform light distribution across this deep space. The tuned angular selective window has the best daylight illuminance distribution with the lowest illumination nearest the window and relatively high illumination in the back. Space size did not have an effect on the relative daylight distribution of the glazings analyzed.

It is recommended that additional energy, daylight distribution, and visual comfort studies be performed to better understand the effects of angular selective windows at different times of the year and for different window orientations. Future work should also investigate the use of angular selective glazings in sloped skylights.

## ACKNOWLEDGMENTS

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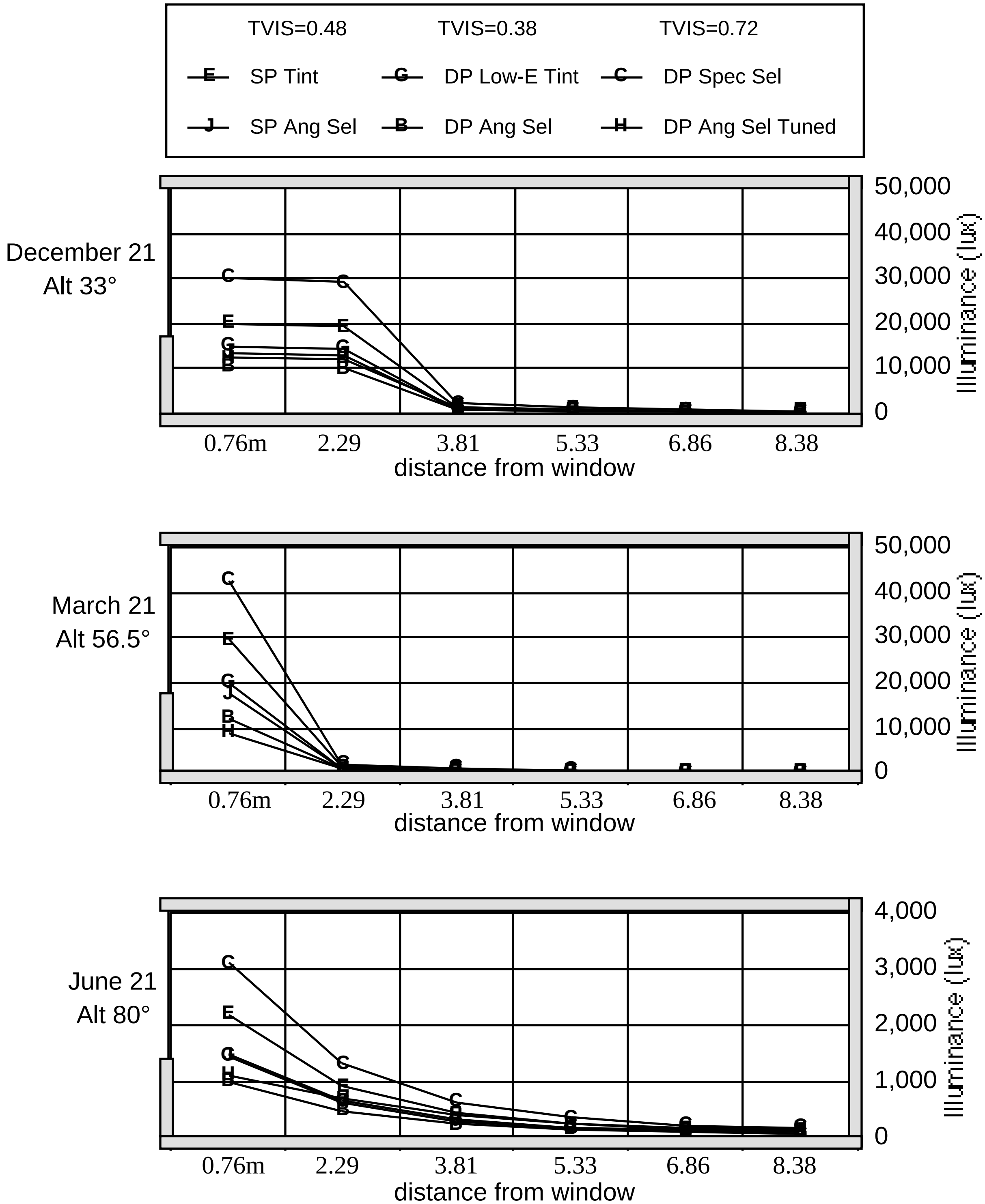


Figure 9. Workplane illuminance distribution in a south-facing perimeter space at noon with a window-to-wall ratio of 0.56 in Blythe, California.

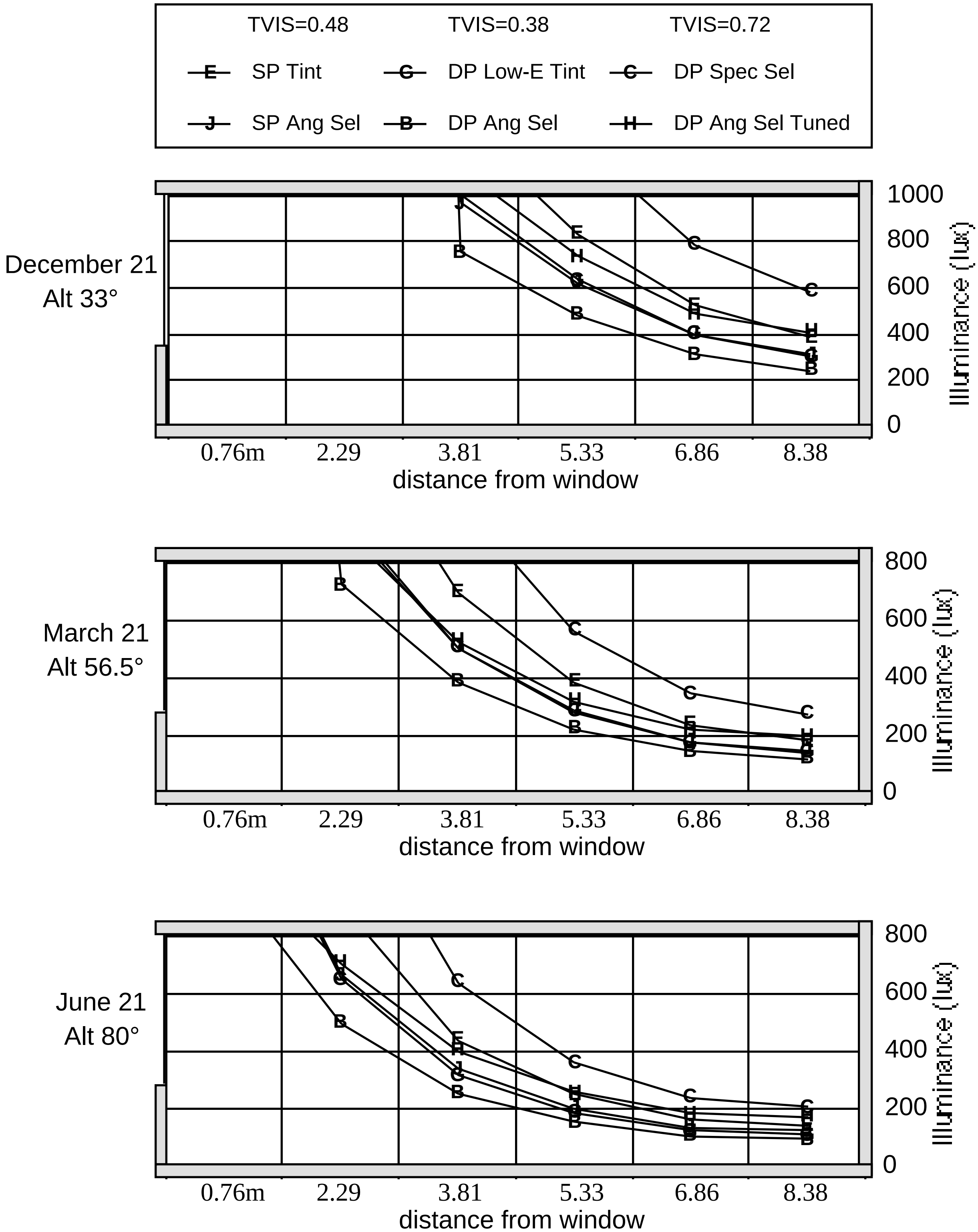


Figure 10. Workplane illuminance distribution with an expanded vertical scale in a south-facing perimeter space at noon with a window-to-wall ratio of 0.56 in Blythe, California.