CHAPTER IX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 SUMMARY

9.1.1 Summary of Study Objective and Experimental Design

The goal of this study was to provide building designers with significant daylighting and sunlighting performance data for sunlit atria with different well and canopy configurations which can be referenced during the early stages of an atrium design. To meet the goal, this study focused on parametric evaluations of the effects of atrium and canopy configurations with different geometric configurations and glazing options on illuminance levels at the atrium floor and luminance distributions on the atrium walls.

To overcome the limitations of conventional photometric instruments, several instrumentation systems were developed. The instrumentation systems developed, validated and used throughout in this study included a video-based luminance mapping system to determine geometric and photometric daylighting parameters and an integrating box to measure Hemispherical Transmittance (HT) of canopy systems.

In this study, the two primary dependent variables were Daylight Factor (DF) and Sunlight Illuminance Ratio (SIR). A secondary dependent variable was Luminance Ratio (LR) on atrium walls calculated from wall luminances determined by the video-based luminance mapping system. Two additional dependent variables were Sunlight Patch Location (SPL) and Sunlight Patch Size (SPS) to quantify the geometric properties of sunlight patches on the atrium walls, which were also determined using the luminance mapping system.

The primary independent variables were atrium Well Index (WI) and outdoor condition. The outdoor condition included overcast sky, clear sky without sun, and direct sun. Another type of independent variable, which was called "confounding independent variables", was concerned with the geometric and photometric properties of the canopy systems which consisted of 36 different configurations (see Table 4.8).

The constants included wall and floor reflectances which were determined by considering real situations in which atrium walls usually contain large areas of glass window and bright solid materials and the floor usually includes low-reflectance trees and ground-cover plants.

9.1.2 Summary for Atrium Daylighting

First of all, in order to observe the effects of atrium Well Index (WI) on illuminance levels under clear sky and overcast sky conditions, the average DF value at each WI value without canopy was examined. From this initial analysis, it was learned that the average DF values of 49 % (clear sky) and 66 % (overcast sky) at WI = 0.6 reduced to 7 % (clear sky) and 14 % (overcast sky) at WI = 2.4. These reductions were considered the primary effects of the atrium well configuration. Figure 9.1 shows the reduction patterns of the average DF values without canopy for clear sky and overcast sky conditions. As shown in the figure, the average DF values under overcast sky were about 12 % higher than they were under clear sky condition. The overall higher average DF values under overcast sky was attributed to the high-luminance zenith area of the overcast sky to which the top opening faces.

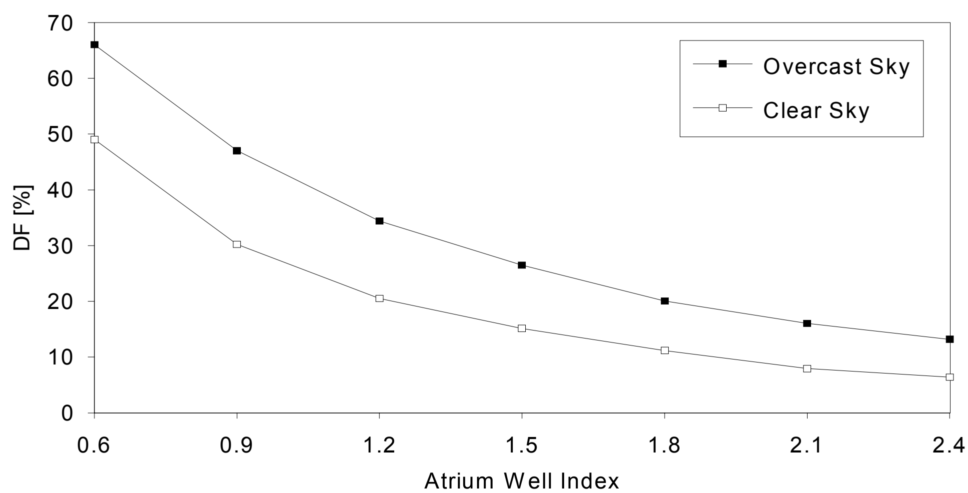


Figure 9.1 Daylight Factors without Canopy for Clear Sky and Overcast Sky Conditions

Furthermore, to identify the major factor for the reductions in DF values with increasing well height, the data obtained from the atria with flat-black interiors were utilized to determine the portions of the Sky Components (SC) and the Internally Reflected Components (IRC) in corresponding DF values. From this analysis, it was learned that the reductions in DF values at higher WI values were mainly due to the reductions in SC values. These reductions were not offset by increases in the IRC for uncovered atria.

The average DF values obtained inside the seven different atria with all of the 36 canopy systems under clear sky and overcast sky conditions were analyzed to examine confounding effects of the various canopy systems on the daylight illuminance levels.

In general, the sawtooth canopies (No. 01 through 16) with higher aperture-to-floor-area ratios resulted in higher DF values. The skylight types (No. 17 through 28) showed that the variations in glazing property caused dramatic changes in DF values. Meanwhile, the waffle skylights (No. 29 through 36) demonstrated that the geometric configuration (i.e., Waffle Well Index or WWI) had much stronger impact than the reflectances of the waffle surfaces. From ET differences between the center position and the other positions under clear and overcast skies, it was learned that the waffle skylights distributed daylight more evenly throughout the space under clear sky than under overcast sky. This was because the light rays from the high-luminance horizon area of clear sky are blocked by the waffle structure and diffusely reflected into the space.

When the DF values obtained with canopies were converted into Effective Transmittances (ET) by dividing them by corresponding Base Case Daylight Factor (BCDF) values obtained without canopy, it was learned that the sawtooth canopies and skylights had constant ET values even though the atrium WI values changed. However, the ET values for waffle skylights increased as the atrium WI value increased. From this analysis it was learned that DF values without canopy could be determined using existing empirical formulas or computer models, and DF values with canopies could be determined by multiplying them by the ET values obtained from this scale model study.

When the impacts of the glazing materials were examined for the two sky conditions, the ET values of the canopies with transparent glazing materials were almost identical. However, the canopy with translucent glazing resulted in about 10 % higher ET values for clear sky than for overcast sky. This was because the BCDF measured without canopy did not include the light flux from the high-luminance horizon area of clear sky, but it was captured by the diffuse glazing material and added to the canopy DF values.

It must be noted that all of the results from this daylight distribution analysis will be valid for canopy systems which cover the entire floor area. If the same types of canopy systems are installed above limited parts of the floor area, the daylight distributions on the same floor positions will show totally different results.

The luminance distributions in atria with different WI values were measured using the video-based luminance mapping system. From this analysis, it was learned that window areas located above 50° elevation angle from a floor position caused specular reflections toward that position. In real buildings, the specular reflections at window glass can be easily observed when one sees a window glass at certain angles.

To analyze the luminance distributions on the atrium wall surface, a new term "Luminance Index" (LI) was developed and used to compare the luminance distribution characteristics at different WI values. Then, the Luminance Ratios (LR) were calculated from the average LI values on solid wall areas and those on contiguous window areas. As a result, the Luminance Ratios for uncovered atria under diffuse skies were within the maximum LR values recommended by IESNA (See Table 2.2) even in shallow atria.

The effects of canopy systems on the luminance distributions on three walls (south, north, and west) were examined with six different canopy systems. From this analysis it was learned that the LI values for sawtooth canopies were higher than the others, because the solid panels of sawtooth canopies blocked more sky area and the relative luminance on the walls became high. All of the LR values with canopies under the diffuse sky were also within the recommended 1:3/1 range.

9.1.3 Summary for Atrium Sunlighting

The impacts of atrium well configuration on interior sunlight illuminance levels were examined with Base Case Sunlight Illuminance Ratio (BCSIR) values for uncovered atria which had four different Well Index values (0.6, 1.2, 1.8 and 2.4). The artificial sun was located at nine different altitude angles representing the noon sun altitudes on three different days of the year in three different geographic locations (Houston, TX; Oklahoma City, OK; and Minneapolis, MN).

First of all, the impact of atrium well configuration on interior sunlight illuminance levels were broadly examined with the minimum, maximum, average, and standard deviations of the BCSIR values. In this analysis, the great standard deviation values at certain combinations of sun altitude angles and WI values implied that the direct sunlight illuminated partial floor areas, so that the floor positions exposed to the sun and those at shaded floor positions received light flux with substantially different intensities. In real situations, since the direct beam sunlight illuminance is much higher than diffuse daylight illuminance, greatly uneven illuminance distributions are expected in these cases. On the contrary, at certain conditions, the SIR differences were very small. In these cases, the small values of standard deviations implied that most of the floor positions were either exposed to the sun or shaded by the atrium structure.

When the minimum and maximum (mostly maximum) SIR values were examined, it was shown that some SIR values exceeded 100 % especially at high sun altitude angles. This was because the illuminance measured at the floor positions which were fully exposed to the sunlight consisted of both the Direct Sun Component (DSC) and the Internally Reflected Component (IRC).

Another interesting feature observed during the measurement procedure was that the light reflected from the atrium well surfaces did not uniformly illuminate the entire floor area due to high-intensity specular reflections from interior windows. Furthermore, it was also learned that accurate positioning of photometric sensors in terms of the elevation and horizontal locations in scale models were very important to minimize measurement errors especially for sunlight illuminance measurement.

From this initial analysis with sunlight, it was concluded that the major factors which determine the sunlight illuminance levels at a floor position included:

1) the geometric relationship between the sun and the atrium well structure which determines the proportions of shadow areas and exposed areas on interior surfaces including walls and floor,

2) the geometric relationships between the floor positions and atrium well surfaces which determine the Configuration Factors (CF) of high-luminance interior surfaces fully exposed to the sun,

3) the reflectances of wall surfaces which determine the intensity of Internally Reflected Component (IRC) of sunlight,

4) and the locations and areas of specular glazed windows which determine the intensity as well as the direction of specularly reflected light.

The effects of canopy configurations on sunlight illuminance levels at the seven floor positions were examined with a total of 17 canopy configurations. For this test, four different atria with WI values of 0.6, 1.2, 1.8 and 2.4 were assumed in three different seasons for the three different geographic locations. The minimum, maximum, average, and standard deviations of the SIR values in two extreme climates (Houston summer and Minneapolis winter) and one intermediate climate (Oklahoma City fall) were analyzed to determine the characteristic performances of the canopy systems.

At a high sun altitude angle (84°), the sawtooth canopies with sloping apertures recorded larger standard deviations in SIR values than were recorded for sawtooth canopies with vertical apertures. This was because the large horizontally projected aperture areas and the solid panels of the former created repetitive patterns of large bands of fully exposed and shaded areas on the atrium floor, which caused repetitive fluctuations in illuminance levels proportional to the number of units and pitches of the open and opaque areas. In general, the flat horizontal skylight (No. 19) and the pyramid skylight (No. 27) with tinted transparent glazing also caused high SIR values and large standard deviations at all WI values. Again, the waffle skylights also resulted in high SIR values and large standard deviations. A notable feature at the high sun altitude angle was the consistent performances of the skylight systems with translucent glazing (No. 20 and 28). The SIR values for these canopies were always low and the standard deviations were also very low. When the SIR values of the skylights with translucent glazing were examined at different WI values, it was found that as the WI value increased, the SIR values decreased. This was because the beam sunlight is totally diffused when it is transmitted through the glazing material and the skylight performed like a diffuse sky. Therefore, the decreasing Configuration Factor (CF) of the opening area seen from floor positions with increasing WI value caused lower SIR values.

At a medium sun altitude angle (54.5°), sawtooth canopies with south-facing vertical apertures (No. 04S, 08S, and 12S) caused much higher SIR values and large standard deviations at the two lower WI values (0.6 and 1.2) and lower SIR values and small standard deviations at the two higher WI values (1.8 and 2.4). However, the sawtooth canopies with north-facing vertical apertures (No. 04N, 08N, 12N) showed consistently low SIR values at all WI values. Meanwhile, the skylights with transparent glazing (No. 19 and 27) showed still relatively high SIR values and large standard deviations at WI = 0.6 and WI = 1.2. Another notable feature was much reduced SIR values and standard deviations of waffle skylights at the two higher WI values. Especially, at WI = 1.2 (atrium A4), the average of the SIR values with the three waffle skylights (No. 33, 34, and 36) was about 14 % lower than that for the three sawtooth canopies (No. 04S, 08S, and 12S). Meanwhile, the average standard deviation of the three waffle skylights was about 30 % lower than that of the three sawtooth canopies. These two phenomena indicated that at this specific WI value and the sun altitude angle, the south-facing apertures admitted the direct beam sunlight on partial area of the floor, while the vertical structures of waffle skylights blocked most of the beam sunlight and reflected diffuse light toward the atrium space.

At a low sun altitude angle (22.0°), the impact of atrium well configuration was the most profound in determining the sunlight illuminance levels at floor positions. Installed canopies either reduced or increased the Base Case SIR. A notable feature was that several canopy configurations showed higher SIR values than the Base Case SIR (BCSIR) values measured without canopy. Especially, the sawtooth canopies with south-facing apertures (No. 04S, 08S, and 12S) always showed higher SIR values than each BCSIR at each WI value. This was because the bottom surfaces of the solid panels caught the low-altitude sunlight and reflected it toward the atrium space. Another notable feature was observed with the skylights with translucent glazing. The translucent glazing material at this low sun angle acted similarly to sawtooth canopies. It also caught low-altitude incoming sunlight and diffusely transmitted it toward the atrium space.

At all nine different sun altitude angles, the most dramatic changes in the average SIR values with the varying sun altitude angles were observed with waffle skylights (No., 33, 34, and 36). In addition, when the average SIR values of the waffle skylights at each sun altitude angle were compared at different WI values, it was also known that WI values also affected the SIR values. From these two observations, it was concluded that the waffle skylight systems were the most geometry-sensitive canopy systems. The large horizontal opening area and the opaque waffle walls played totally different roles at different sun altitude angles and different WI values. At high sun altitude angles, the opaque waffle walls do not block the beam sunlight, but the transmission characteristics of the horizontal apertures mainly determine the intensity and spatial distributions of transmitted sunlight. On the contrary, at medium to low sun altitude angles, the waffle walls substantially block the beam sunlight and play a major role in determining the interior illuminance levels and spatial distribution.

From the analysis of luminance distribution maps on the walls, it was noted that, at the high sun angle, the LI values on the north wall were slightly higher than the other walls, because the sun was still biased to the south direction. However, at the low sun angle, the LI values on the high elevation of the north wall increased as the WI increased. Especially the sawtooth canopies with vertical apertures effectively kept the direct sunlight from intruding into the atrium spaces at sun altitude angles, but they created large areas of sunlight patches on the north wall at solar noon hours.

When the sun is at the low altitude, for all WI values the floor positions were completely shaded by the atrium well structures. At this condition, the sunlight illuminances at the floor positions were solely due to the reflected sunlight from the atrium wall surfaces A notable phenomenon at this low sun altitude angle was the large differences in luminances between the solid walls and the windows. This was because the incident angles on the window areas were small, so that no specular reflections occurred on the glass surfaces, while the low incident angle on the vertical solid wall areas which were exposed to the sun received high-intensity sunlight.

As discussed in Chapter 2, a qualitative lighting objective in atria may be to create sparkle. This objective can be achieved by allowing some direct sunlight into the atrium space. The sunlight patches on the atrium wall surfaces were investigated in terms of their locations (SPL) and sizes (SPS). A total of 10 canopy systems were selected for this test. After completing the luminance mapping, the elevation angles and Configuration Factors (CF) of sunlight patches on the north walls and the two side walls were determined by the thresholding algorithm of the image analysis software which was discussed in Chapter 3. Then, to calculate the percent coverage of the sunlight patch areas on each wall, the CF sum of sunlight patch areas were divided by the CF value of a corresponding wall. Since, the video images were captured at the center floor position, the CF values of four walls were the same at a given WI value. From this analysis, it was learned that the sizes and locations of sunlight patches were purely dependent upon the geometric relationship among wall orientation, canopy aperture, and the sun. In addition, the major spatial patterns of sunlight patches were primarily decided by the geometric patterns of the solid wall and window glass areas and the sub-patterns were decided by the geometric feature of the structural members of canopy systems.

9.1.4 Summary for Canopy Selection

In order to identify suitable canopy systems for different well configurations and different geographic locations, the monthly mean exterior illuminance data published by the National Renewable Energy Laboratory, Golden, Colorado were utilized. With the illuminance of 1000 lux as minimum threshold for the growth of interior plants and trees the following steps were followed.

1) The daylight availability data (outdoor illuminance levels from diffuse skies) were converted to Design Daylight Factors (DDF) considering the illuminance criterion (1000 lux) for three different seasons - heating, intermittent, and cooling.

2) An initial test was conducted to see if the atria without canopy provide enough daylight under overcast and clear sky conditions without considering the effects of direct sunlight.

3) Then, the DF values obtained without glazing materials (sawtooth canopies and waffle skylights) were corrected by considering the Hemispherical Transmittances (HT)

of glazing materials, Framing Factors (FF), and Light Loss Factors (LLF) to simulate more realistic conditions.

4) Comparisons were made between canopy-covered DF values and the DDF values under overcast sky condition.

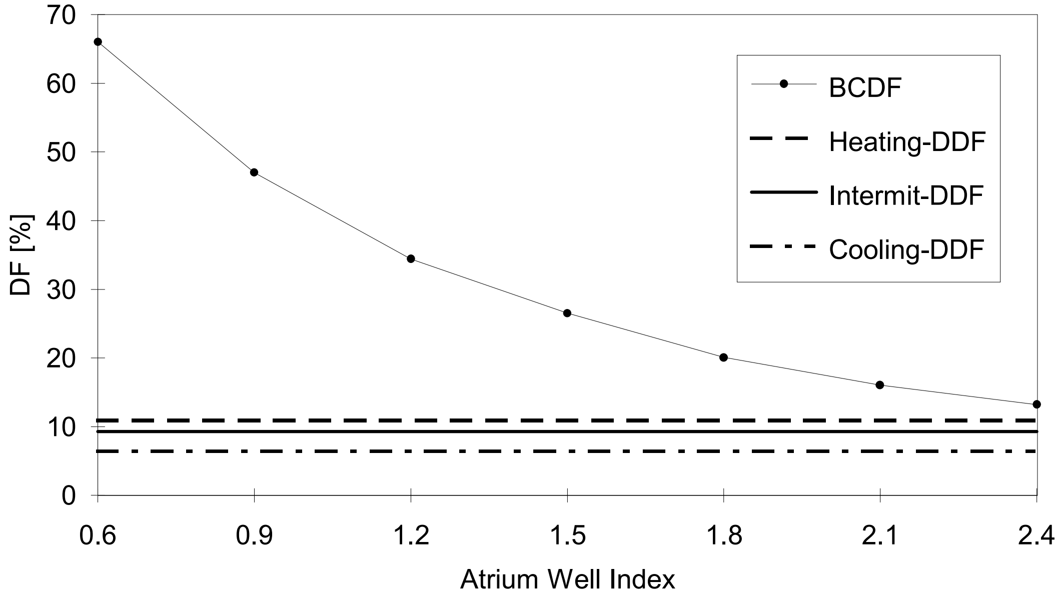
5) For clear sky condition, Design Sunlight Illuminance Ratios (DSIR) were calculated, whose values represent required Sunlight Illuminance Ratios (SIR) to compensate for the deficits of clear sky DF values measured with canopies.

6) Final selections of suitable canopy systems were made for different well configurations and geographic locations with the considerations of DDF, DSIR, and Sunlight Patches.

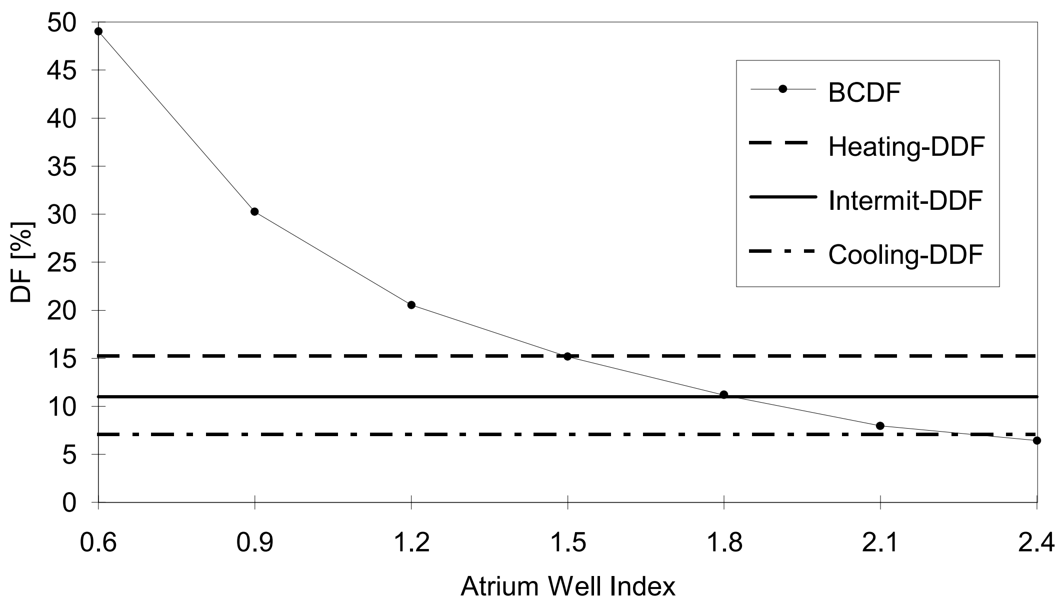
Figures 9.2 through 9.4 show the overcast and clear sky Base Case DF (BCDF) values for Houston, Oklahoma City, and Minneapolis, respectively. As indicated in the figures, the overcast DF values for shallow atria without canopy far exceeded the DDF values. This implies a large number of choices in canopy selection, while the small differences between the BCDF values for deep atria and the DDF imply a limited number of choices. These three figures indicate that at all of the three geographic locations, atria with Well Index values higher than 1.5 may not be suitable under overcast sky condition.

Most of all, these three figures demonstrate that canopy systems must be selected with the consideration of not only the prevailing climatic conditions, but also the atrium configuration. In addition, the lower DF values from clear sky indicate that some amount of direct sunlight should be allowed into the atrium space to enhance the illuminance levels on the atrium floor. In this matter, the way of admitting sunlight into the atrium space became another important issue. It must provide enough illumination to plants, while it must be admitted in a way that the occupants do not feel glare. In addition, it must be admitted to add visual interest and sparkle to the atrium. Prevention of solar heat gain in summer, especially in hot climates is also extremely important.

Following the canopy selection procedure, it was learned that sawtooth canopies with south-facing vertical apertures were the most versatile canopy type at all geographic locations. They can provide not only effective sun-shading at high sun altitudes, but also desirable sparkles. The final list of selected canopy systems can be found in Table 8.16. However, it must be noted that those canopies were for four-sided atria. If the atrium type becomes different, different canopies will be selected. In this matter, further research would be necessary with different atrium types.

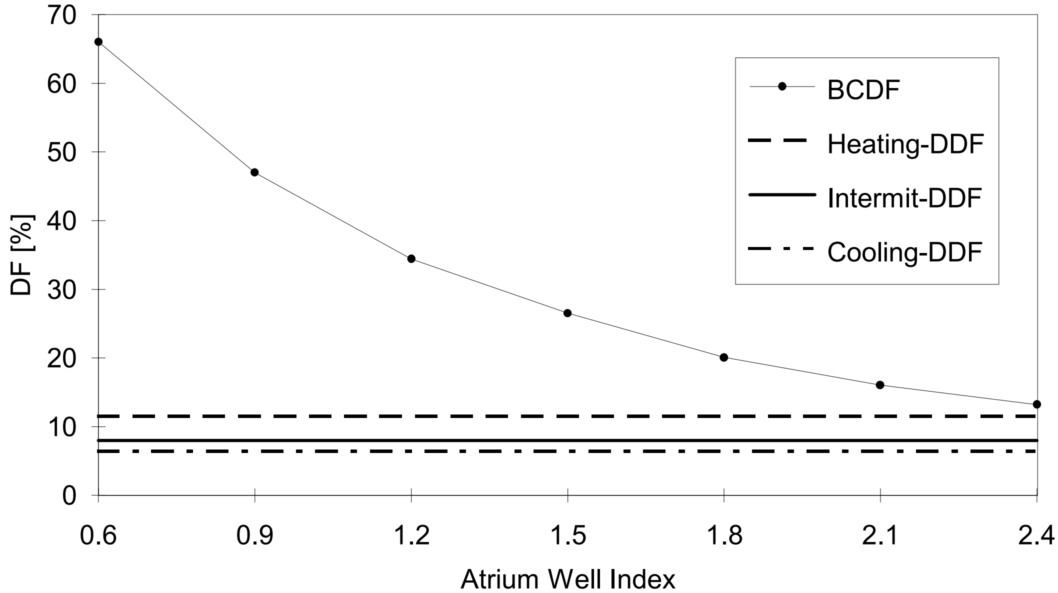


a. Design Daylight Factors for Overcast Sky

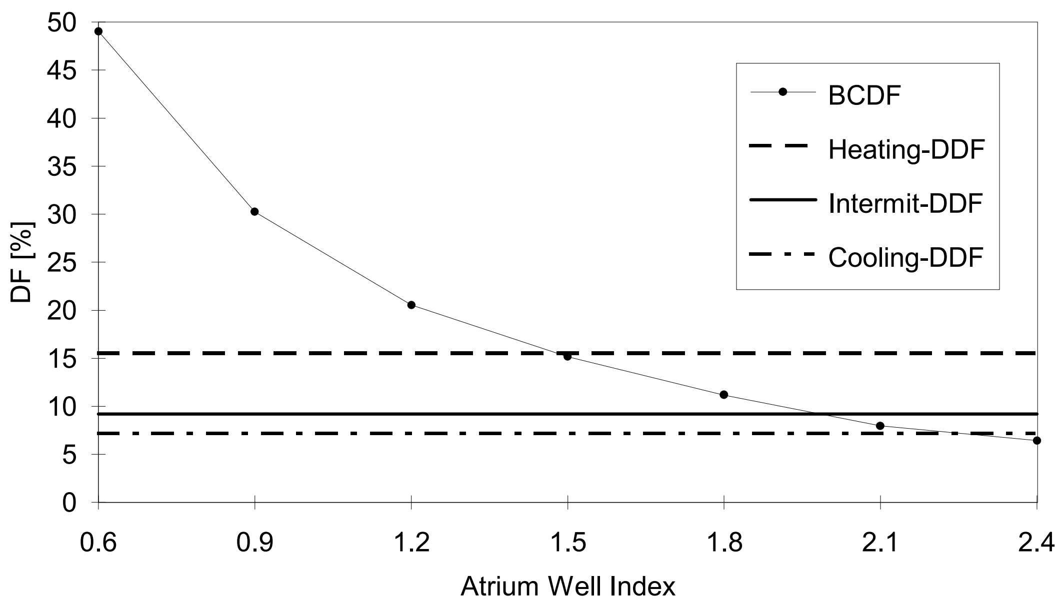


b. Design Daylight Factors for Clear Sky

Figure 9.2 Overcast Sky and Clear Sky Base Case DF and DDF Values for Houston, TX

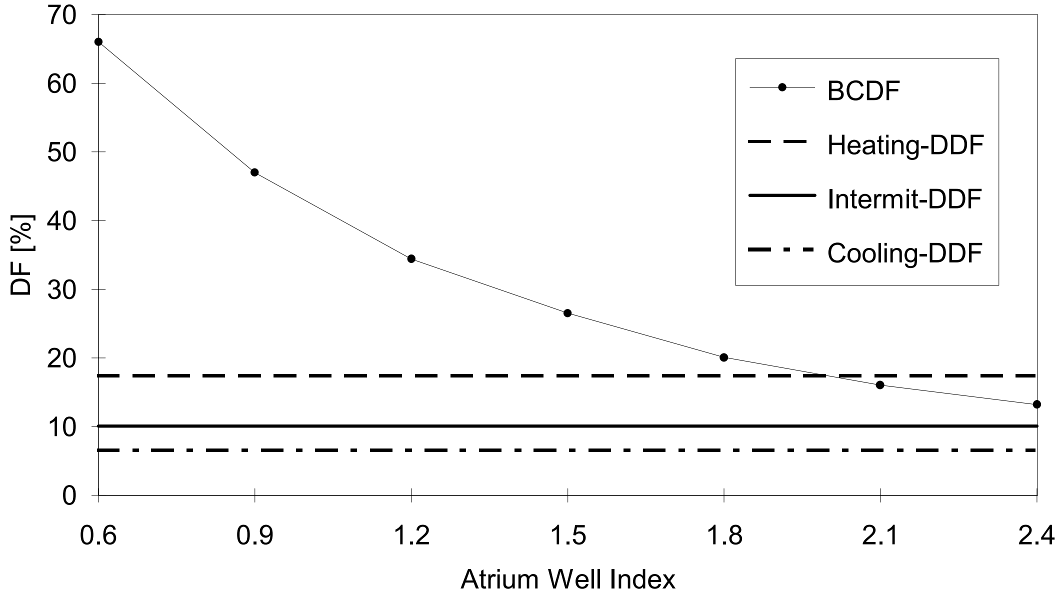


a. Design Daylight Factors for Overcast Sky

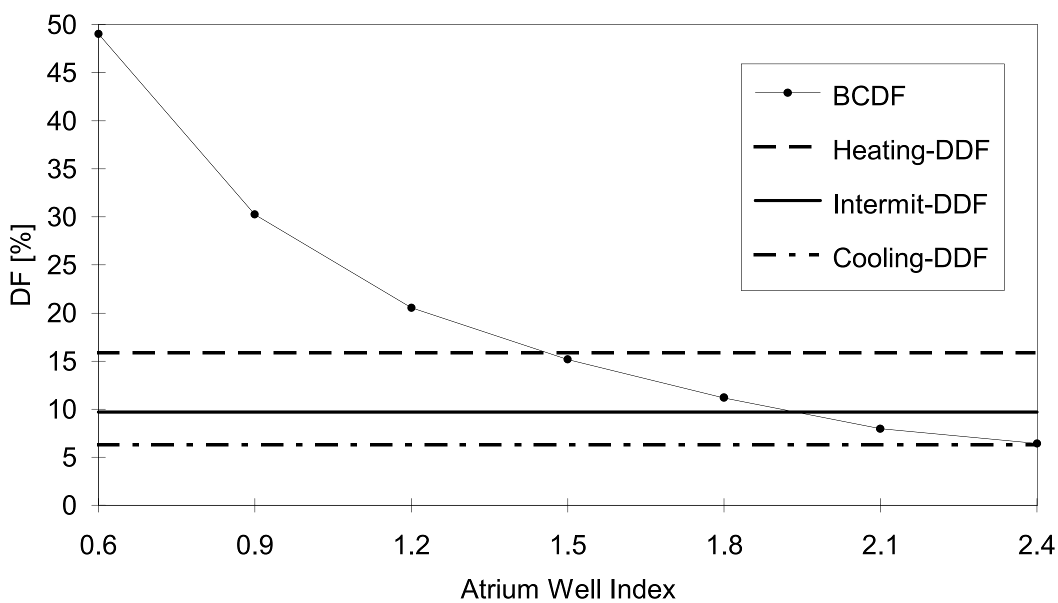


b. Design Daylight Factors for Clear Sky

Figure 9.3 Overcast Sky and Clear Sky Base Case DF and DDF Values for Oklahoma City, OK



a. Design Daylight Factors for Overcast Sky



b. Design Daylight Factors for Clear Sky

Figure 9.4 Overcast Sky and Clear Sky Base Case DF and DDF Values for Minneapolis, MN

9.2 CONCLUSIONS

The increasing number of atrium spaces which represent major design features in newly constructed non-residential buildings may be attributed to several reasons. One major reason is that the daylighting and sunlighting values contribute a great deal to the aesthetic potential of an atrium. Building designers now widely acknowledge that atrium spaces serve many functions in a variety of building types.

However, they often face several obstacles in the early stages of an atrium design, especially in hot climates where excessive solar gain may be admitted. Most obstacles revolve around the absence of daylighting design/evaluation tools by which designers can readily predict the range of illuminance levels at the atrium floor and luminance distributions within the field of view. With such prediction tools and information building designers could make decisions on atrium physical parameters that would provide adequate daylighting illuminance levels and allow some limited sunlighting for sparkle and interest, without causing glare and excessive solar heat gain problems.

This study presented such instrumentation systems and empirically obtained daylighting and sunlighting performance data. The conclusion and recommendation statements made in this section follow the same sequence which this study followed. First, conclusion statements on the instrumentation systems and daylighting design tools were made. These were followed by conclusion statements on daylighting and sunlighting performance observed from the parametric measurements.

9.2.1 Conclusions for Instrumentation Systems

None of the daylighting evaluation tools are perfectly accurate and none can model accurate sky conditions for an entire year. Even though daylighting studies using physical scale models can produce realistic interior luminous environments, it takes much time to evaluate various design options under different sky and sun conditions. On the other hand, computer models produce quick answers for different design options, but usually for relatively simple geometries under limited sky conditions. The video-based luminance mapping system developed in this study also has merits and shortcomings. One major shortcoming of this system is that it must depend upon physical scale models to evaluate different architectural design options. Consequently, the accuracy of the results and required time will depend upon the accuracy of geometric and surface modeling of scale models.

However, this system can be a powerful tool in evaluating existing spaces with any geometries and any types of indoor furnishing and lighting systems. In contrast to conventional measurements using banks of photometric sensors and luminance meters, it visualizes luminance distributions and produces consistent numeric outputs even under rapidly changing sky conditions. Furthermore, as demonstrated in Appendix B, it can separate interreflected and direct components of daylight with one shot of an interior image. This will be a very useful feature when the current system is applied to scale model studies. The user can evaluate the interactions between different windows or skylights and indoor surfaces under different sun and sky conditions.

In addition, as demonstrated in the quantification of geometric properties of sunlight patches on the atrium walls, this instrumentation system can serve as a data collection tool for studies dealing with occupants' environmental satisfaction in sunlit atria.

The integrating box constructed in this study enables the quantification of light flux transmitted through atrium canopies. Since a Hemispherical Transmittance (HT) of a canopy system determined with this instrument represents a net effect of the canopy. Another database set of Coefficients of Utilizations (CU) of atrium well configuration can be established using the equations of the Lumen Method for toplighting provided by IESNA (IESNA 1993, p. 373). With the CU values, if the HT value of a designed canopy system is known, corresponding DF values could be calculated for different atrium configurations. In this study, the integrating box was mainly used to determine the optical transmittance of glazing materials. These equipment items are installed in the Daylighting Laboratory at Texas A&M University.

9.2.2 Conclusions for Daylighting and Sunlighting Prediction Methods

In this study, Daylight Factors (DF) without canopy system were called "Base Case Daylight Factors" (BCDF). The BCDF values were obtained for a wide range of atrium Well Index (WI) values from scale model measurements. The BCDF values may be referenced during the early stages of an atrium design to find the DF values available from diffuse skies for uncovered atria.

Other existing empirically based DF prediction models or a detailed computer model may also be used to determine the BCDF values, because the DF values in uncovered atria can be closely approximated by those tools. However, one merit of the BCDF values presented in this study is that they account for the specular reflections at the interior windows. Most of the previous empirical prediction models did not take into account the specular reflections at windows during the algorithm development procedures. In addition, mathematical computer models usually assume a fixed low reflectance, say 15 %, for window glass area, because specular reflection of diffuse sky is very difficult to solve by mathematical methods.

Furthermore, once a canopy system is to be installed on the atrium, to estimate resulting DF values with complex structural configurations and various glazing options of the canopy become extremely difficult. Therefore, to simplify the estimation of resulting DF values with canopies, a preliminary database including ratio of canopy-covered DF values to the BCDF values were established. In this study, the ratio was called "Effective Transmittance". The results of the scale model measurements revealed that the ET value of a canopy system, except for waffle skylights, was almost constant throughout the wide range of WI values. For the waffle skylights, a set of simple linear regression equations was prepared to approximate the ET values using WI values. Using the BCDF and ET values along with appropriate glass transmittances and Light Loss Factors (LLF), building designers can readily determine fairly accurate daylighting illuminance levels on atrium floor positions.

From the analysis with sunlight illuminance data, it was concluded that parametrically assessing sunlight on each floor position was not meaningful, because even a small geometrical misplacement of a canopy system can dramatically change the sunlight illuminance level at a floor position. Therefore, statistical values of Sunlight Illuminance Ratio (SIR) were used to characterize the combined effects of atrium well and canopy configurations. With this information, building designers may predict minimum, maximum, and average sunlight illuminance levels at atrium floor positions. In addition, they may want to minimize the standard deviations of the sunlight illuminance levels on the atrium floor.

Also, a methodology was presented to select suitable canopy systems for different atrium well configurations and geographic locations considering the impacts of atrium canopy systems on daylight and sunlight illuminances at the atrium floor positions.

The new terms developed in this study include "Luminance Index" (LI), "Sunlight Patch Location" (SPL), and "Sunlight Patch Size" (SPS). These new terms were proven to be effective in quantifying atrium daylighting and sunlighting environments based on the mapped luminances on atrium wall surfaces. The LI enables designers not only to compare luminance distribution characteristics between different well configurations, but also to calculate Luminance Ratios (LR), which can explain potential glare problems in a luminous environment.

9.2.3 Conclusions for Atrium Daylighting and Sunlighting Performances

The daylight and sunlight illuminance levels and luminance distributions are primarily determined by the atrium well configuration. Especially, the atrium Well Index (WI), which relates the height of atrium to the floor area, plays a major role in determining the lighting quantity and quality without canopy. Especially at medium to low sun altitude angles, the atrium well configuration mainly determines illuminance levels and luminance distributions in the atrium space, due to its shading effect.

Then, canopy systems play confounding roles by determining quantity of light flux admitted into the atrium space and spatial distributions of the admitted light.

Among the parameters involved in canopy systems, the geometric configurations of solid structures, which determine the size and orientation of canopy apertures, have the most profound impacts on atrium daylighting and sunlighting. In this study, the level of impact of canopy systems on atrium daylighting and sunlighting was explained with the Effective Transmittance (ET) values of canopy systems. Smaller ET values indicate stronger impacts of canopy systems. Consequently, sawtooth canopies and waffle sky lights with solid structures have stronger impacts on both the illuminance levels and luminance distributions inside atrium spaces under diffuse skies and direct sunlight conditions.

The sawtooth canopies with south-facing apertures cause uneven distributions of illuminance levels on the atrium floor and luminances on atrium wall surfaces. Especially the sloping solid panels play completely different roles at different sun altitude angles. At high sun altitude angles, the solid panels effectively keep the direct sunlight from penetrating into the atrium space. On the contrary, at low sun altitude angles, the bottom surfaces of sawtooth panels reflect the sunlight toward the atrium space to enhance the illuminance level.

The waffle skylights have stronger impacts on the daylighting condition in shallow atria than in deep atria. This is because, as the well height increases, more opening areas of the waffle skylight become visible and less waffle wall areas become visible at the floor positions. In addition, the waffle structure is an effective shading device at medium to low sun altitude angles.

Another very important parameter which has profound impacts on atrium daylighting and sunlighting is the light transmission characteristics of glazing material of skylights. The linear structural members of skylights have relatively minor impacts on both the illuminance levels and luminance distributions in the atrium space. However, glazing materials with different transmittance and transparency greatly affect the illuminance levels on the atrium floor and spatial distribution of luminances on the wall surfaces. Especially, a translucent glazing material plays totally reverse roles at different sun altitude angles. At high sun altitudes, the translucent glazing material provide less light to atrium floor positions than a transparent glazing material with a similar transmittance value. However, at low sun altitudes the translucent glazing material acts similarly to sawtooth canopies. It also catches low-altitude incoming sunlight and diffusely transmits it toward the atrium space.

The luminance distributions in atrium spaces usually do not exceed the maximum Luminance Ratio (LR) recommended by IESNA (see Table 2.2) under diffuse skies. However, under direct sun conditions, shallow atria with transparent skylights may cause discomfort glare. Problems with daylight and/or sunlight glare are most often caused by sidelighting windows that allow direct view to the sky and/or sunlight. In this context, toplighting concepts of atria can be considered effective ways to control visual glare by separating the daylight apertures from the direct line of sight at the bottom floor level. However, some cases, such as shallow atria with horizontal glazing or south-facing sawtooth canopies, may have glare potential if beam sunlight is admitted into the atrium space and occupants are allowed to view the sky though the fenestration. Reflected glare may occur when the admitted beam sunlight is reflected from specular surfaces such as interior windows toward the occupants. Discomfort glare may be caused by an extreme brightness contrast between the canopy opening and structure.

9.3 RECOMMENDATIONS

Based upon the previously stated summaries and conclusions, the following recommendations are made for effective daylighting and sunlighting design of an atrium space.

1) Since the atrium well configuration, in terms of atrium Well Index, has a primary impact on atrium daylight and sunlight illuminance levels at the atrium floor level, four-sided atria with WI values higher than 1.5 are not recommended for all latitudes. If the building program requires a higher WI value than 1.5, particular canopy types may be appropriate. If no contribution from canopy is made, other atrium configurations must be considered. Even though it was not dealt with in this study, a three-sided atrium with a vertical glazed wall facing north or south with proper sun-shading devices may be considered.

2) A sawtooth canopy with vertical apertures facing north (without sparkle) or south is the most effective under clear sky conditions. Although there is less daylight available from the sky vault, this canopy system can best control the direct sun. Especially, in hot climates, the need to restrict solar gain is the most critical concern in canopy selection.

3) The atrium can contribute to the heating function of the building in cold climates. Therefore, the canopy system must provide the largest possible south-facing apertures in cold climates. Regarding this concern, toplighting concepts may not provide optimal solutions in cold climates. If the building program requires a four-sided deep atrium, sawtooth canopies with high surface reflectance and large south-facing apertures are recommended. The high-reflectance solid panels facing toward the atrium space may also reduce glare potentials, especially in shallow atria, by reducing the contrasts between the sky patches seen through the apertures and the adjacent solid panels. As a modification for conventional sawtooth canopies which usually have opaque sides, transparent or translucent side walls may be considered to admit more daylight and sunlight. Even though it was not dealt with in this study, orienting and proportioning the atrium to achieve maximum southern exposure increases the solar and sunlighting potentials.

4) In geographic locations which have both heating and cooling seasons, horizontal sunshades on southern orientations keep out high-altitude summer sun while admitting low-altitude winter sun rays. In this context, skylight systems with full

horizontal openings are not recommended. With this type of skylights, although the sun can be effectively admitted into the atrium space in the winter to provide direct-gain heating, there is no way to keep it out in the summer. If the atrium Well Index needs to be higher than 1.5, as the same in cold climates, sawtooth canopies with south-facing apertures, which can provide desirable sunlight sparkles, or translucent-glazed skylights (without sunlight sparkles) is recommended.

5) However, when the building program requires the atrium space to have a completely diffuse lighting condition, such as a museum for display of art works, climatic impact may no longer be a great concern. In such a case, only two canopy types are recommended - a sawtooth canopy with north-facing apertures or a skylight with heavy-translucent glazing material.

Finally, several recommendations for future studies to extend the findings from this study are as follows:

1) A study with the currently investigated canopies for different atrium types, such as two-sided and three-sided atria, is recommended to find different characteristic performances of the same canopies, in terms of DF, SIR, ET, LR, SPL, and SPS.

2) A study with additional canopy systems which were not dealt with in this study is also recommended to establish a more comprehensive database of the daylighting and sunlighting performances. For example, roof monitors and sloped skylights

3) A study with the video-based luminance mapping system and the newly developed quantifiers of sunlight patches (SPL and SPS) is recommended to take into account the occupants' satisfaction levels due to the amenity provided by limited sunlight penetrations.

4) The video-based luminance mapping system needs to be calibrated in higher luminous environments than the sky simulator in order to be effectively used in actual atrium buildings with direct sun penetrations. The current settings of the system are suitable for use in sky simulators which provide maximum illuminance level of 7500 lux.

5) Finally, concerning the technical difficulties in the measurements of sunlight illuminance and luminance distributions observed in this study due to not perfectly parallel light rays of the artificial sun, a smaller than 20 x 20 in. scale model may be recommended.