CHAPTER VIII

SELECTION OF CANOPY SYSTEMS AND FIELD APPLICATION

8.1 SELECTION OF CANOPY SYSTEMS

8.1.1 Selection Criteria and Procedure

Atrium canopies present all the challenges of normal window and skylight design, which are well covered in the standard texts. Beyond that they have problems of construction and maintenance created by their size and slope. However, addressing those problems is out of scope of this study.

The two basic, interacting considerations are the way in which light and/or view are to be admitted. Requirements of admitting and distributing light in the atrium, while taking into account the function of the atrium as a climate-modifier, will suggest the form of canopy systems. The most important factor in determining success is the level of light provided. High illuminance levels in the atrium are essential for the life of plants. When plants are healthy there is a tangible feeling of hope, expectancy and pleasure.

However, if an atrium is designed for a purpose other than a usual lobby area which usually involves interior plants, the lighting design criteria become different. For example, in a museum for display of art works, which adopts a toplighting canopy, the daylighting design objective is to obtain best diffuse daylight. In such a case, the sunlight must be completely blocked and/or diffused before it is admitted into the atrium space, because the high ultraviolet spectra of sunlight may alter the molecular structure of many organic base materials of art works (Navvab 1993). Therefore, selection of canopy systems must be made according to the program of designed atrium space.

As discussed in Chapter 2, illuminance of 1000 lux for at least 12 hours per day for interior plants recommended by the Illuminating Engineering Society of North America (IESNA 1981, pp. 19-32) was chosen as the illuminance criterion in this study. In addition, limited amount of sunlight transmitted into the atrium space not only enhances the illuminance level, but also creates sparkles which enhance liveliness and visually interesting mood without causing glare problems. Therefore, if the atrium is not designed for a museum, limited amount of sunlight, say 25 % of a wall area (Boubekri et al. 1991), may be admitted even in hot climates.

Next, the function of the atrium as a climate-modifier should be considered. In hot climate, the need to restrict summer solar gain is often the most critical concern in canopy selection. On the contrary, in cold climates, admitting direct solar gain in the prevailing heating season should be considered. Meanwhile, in temperate climates, restricting summer solar gain and admitting winter sun should be considered.

The procedure of selecting suitable canopy systems for different well configurations and different geographic locations is as follows:

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

2) Examine if the atria without canopy provide enough daylight (BCDF) under overcast and clear sky conditions without considering the effects of direct sunlight.

3) Correct the DF values obtained without glazing materials (sawtooth canopies and waffle skylights) by considering the Hemispherical Transmittances (HT) of glazing materials, Framing Factors (FF), and Light Loss Factors (LLF) to simulate more realistic conditions.

4) Compare overcast canopy-covered DF values with the DDF values.

5) Calculate Design Sunlight Illuminance Ratios (DSIR) for clear sky which are required to compensate for the deficits of clear sky DF values measured with canopies.

6) Select suitable canopy systems considering DDF, DSIR, and Sunlight Patches.

8.1.2 Design Daylight Factors (DDF)

The outdoor illuminance levels published by the National Renewable Energy Laboratory, Golden, CO (formerly Solar Energy Research Institute) were obtained and utilized to determine the DDF values for the three different geographic locations including Houston*, TX, Oklahoma City, OK, and Minneapolis, MN.

The DDF values were calculated by the relationship shown in Equation 8.1. Using this relationship, the DDF values represent the required Daylight Factors (DF) to satisfy the illuminance criterion.

* The outdoor illuminance data for Houston, TX were not available. Instead, San Antonio (28.3°N and 96.5°W) data were used.

$$DDF = \frac{E_{crit} \times 100}{E_{do}} [\%] \tag{8.1}$$

where DDF = Design Daylight Factor [%]
E_{crit} = illuminance criterion [lux] (1000 lux)
E_{do} = outdoor horizontal illuminance available from unobstructed diffuse sky [lux]

In this study, even though the time period required was a minimum of 12 hours per day, the monthly average outdoor illuminance levels within the time frame of 08:00 through 17:00, which covers 10 hours per day, were selected, because winter months did not provide that long periods of daylight hours. Therefore, the remaining two hours were assumed to be provided by artificial light. Table 8.1 shows the monthly average DDF values for the three different geographic locations.

TABLE 8.1
Design Daylight Factors for Three Different Geographic Locations

Month	Houston, TX	Okla. City	Minneapolis
Jan	10.7 %	12.1 %	17.7 %
Feb	10.3 %	11.3 %	16.1 %
Mar	8.1 %	8.4 %	10.0 %
Apr	6.6 %	6.7 %	7.5 %
May	5.8 %	5.8 %	6.3 %
Jun	5.6 %	5.5 %	6.0 %
Jul	5.8 %	5.7 %	6.3 %
Aug	6.6 %	6.6 %	7.4 %
Sep	8.1 %	8.3 %	9.8 %
Oct	10.4 %	11.5 %	16.7 %
Nov	15.5 %	12.2 %	17.9 %
Dec	11.9 %	13.8 %	25.0 %

Then, the above DDF values were grouped and averaged for different seasons to take into account the seasonal local climatic conditions. ASHRAE (ASHRAE 1985, p. 24.2) recommended to group December though February (12, 1, and 2) for the heating season and June through September (6, 7, 8, and 9) for the cooling season. However, in this study, a somewhat different grouping was made considering the prevailing climatic condition at each geographic location.

For Houston, TX, the heating and cooling seasons included the same months as recommended by ASHRAE. For Oklahoma City, OK, the heating season included November through March (11, 12, 1, 2, and 3) and the cooling season included June through September (6, 7, 8, and 9). For Minneapolis, MN, the heating season included November through March (11, 12, 1, 2, and 3) and the cooling season included only June through August (6, 7, and 8). All the other months not enlisted were considered intermittent-operation season. Table 8.2 shows the seasonal average overcast and clear sky DDF values for the three geographic locations.

TABLE 8.2

Seasonal Averages of Design Daylight Factors for Three Geographic Locations

Geographic Location	Season	Month	Overcast Sky DDF	Clear Sky DDF
Houston	Heating	12, 1, 2	10.9 %	15.2 %
	Intermit.	3, 4, 5, 10, 11	9.3 %	11.0 %
	Cooling	6, 7, 8, 9	6.5 %	7.1 %
Oklahoma City	Heating	11, 12, 1, 2, 3	11.5 %	15.5 %
	Intermit.	4, 5, 10	8.0 %	9.2 %
	Cooling	6, 7, 8, 9	6.5 %	7.2 %
Minneapolis	Heating	11, 12, 1, 2, 3	17.4 %	15.9 %
	Intermit.	4, 5, 9, 10	10.1 %	9.7 %
	Cooling	6, 7, 8	6.6 %	6.3 %

8.1.3 Diffuse Sky Daylight Illuminances without Canopy

The measured DF values without canopy were compared with the above overcast sky and clear sky DDF values. Figures 8.1 through 8.3 show the overcast 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.

The BCDF values for deep atria in Minneapolis shown in Figure 7.3 indicate that atria with WI values higher than 2.1 may require supplementary lighting for plants under overcast sky conditions in the heating seasons even without any canopy installed. It also indicates that, in a high-latitude location where the heating season must be given the highest priority, a four-sided atrium type might not be appropriate if the building program requires a high-rise structure.

Most of all, these three figures demonstrate that canopy systems must be selected with consideration of not only the prevailing climatic conditions, but also the atrium configuration.

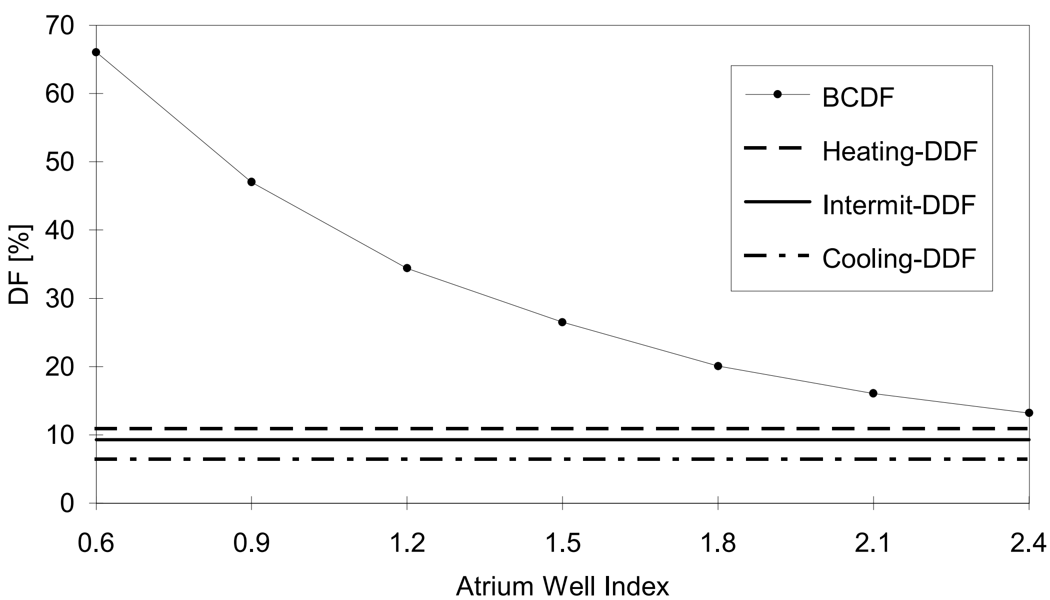

Figure 8.1 Overcast Sky Base Case DF and DDF Values for Houston, TX

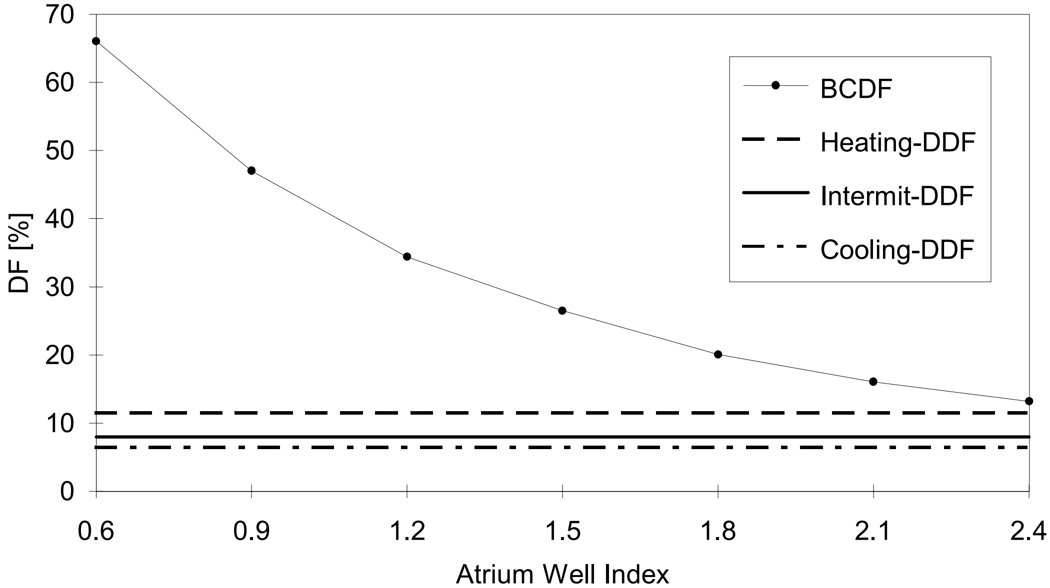

Figure 8.2 Overcast Sky Base Case DF and DDF Values for Oklahoma City, OK

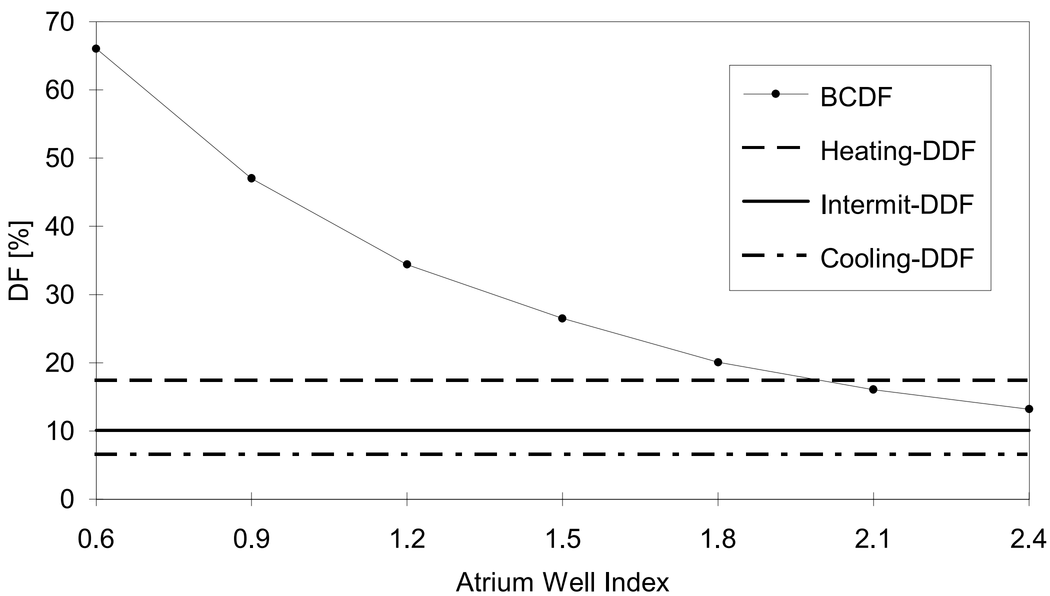

Figure 8.3 Overcast Sky Base Case DF and DDF Values for Minneapolis, MN

Figures 8.4 through 8.6 show the clear sky Base Case DF (BCDF) values compared with the DDF values for Houston, Oklahoma City, and Minneapolis, respectively. These three figures indicate that four-sided atria with WI = 1.5 is the marginal well configuration without canopy which can benefit from clear sky daylight even without direct sun component throughout the year. However, as clear skies during daylight hours are always accompanied by direct sunlight, the illuminance levels are expected to dramatically increase due to direct sunlight illuminance. The effects of direct sunlight will be discussed in a subsequent section.

Furthermore, these three figures also imply the different functions of the atria as climate-modifiers in different geographic locations. Figure 8.4 implies a need for critical solar gain control for atria in hot climates with WI values ranging from 0.6 to 2.4, because those atria can provide enough daylight not only under overcast sky, but also under clear sky even without direct sunlight. Figure 8.4 also indicates that atria higher than WI = 1.5 may require some amount of direct sunlight penetration not only to enhance the illuminance levels, but also to help reduce heating energy requirements during the heating seasons. Meanwhile, Figures 8.5 and 8.6 imply that shallow atria in temperate and cold climates can benefit from clear sky daylight and direct solar gain during the heating seasons and deep atria require a positive gain of direct sunlight with suitable canopies.

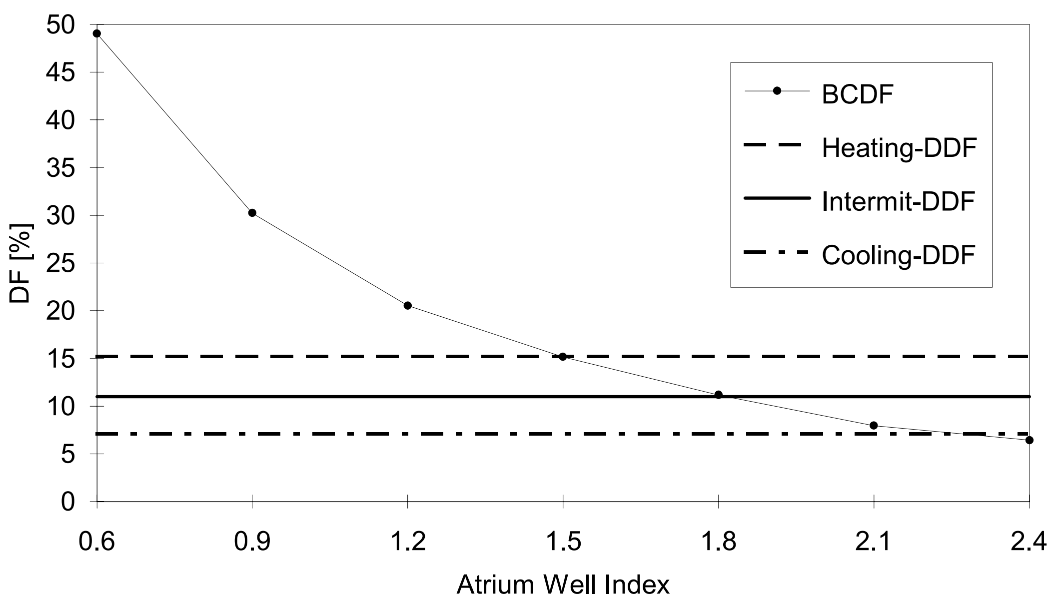

Figure 8.4 Clear Sky Base Case DF and DDF Values for Houston, TX

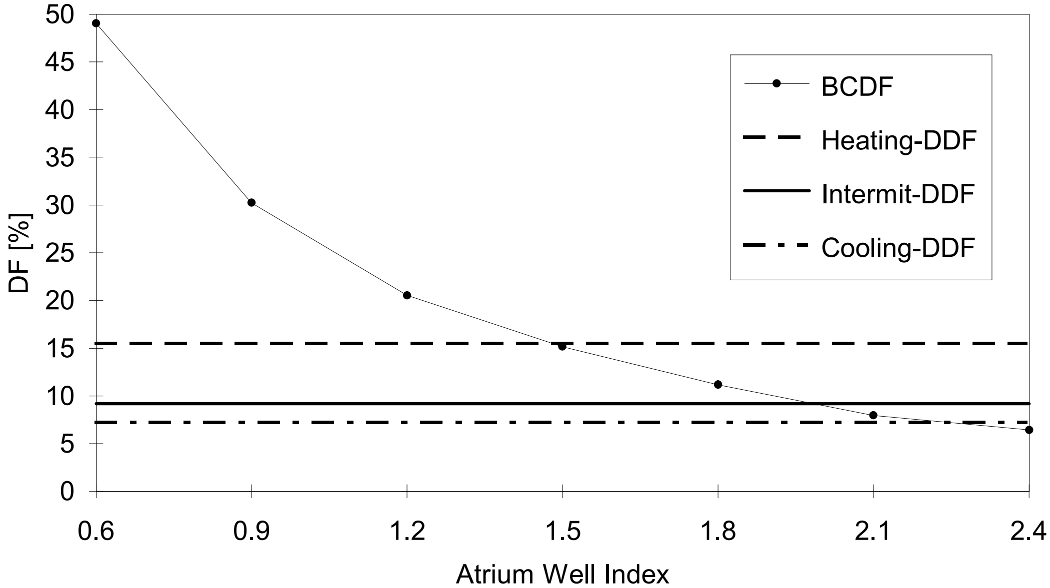

Figure 8.5 Clear Sky Base Case DF and DDF Values for Oklahoma City, OK

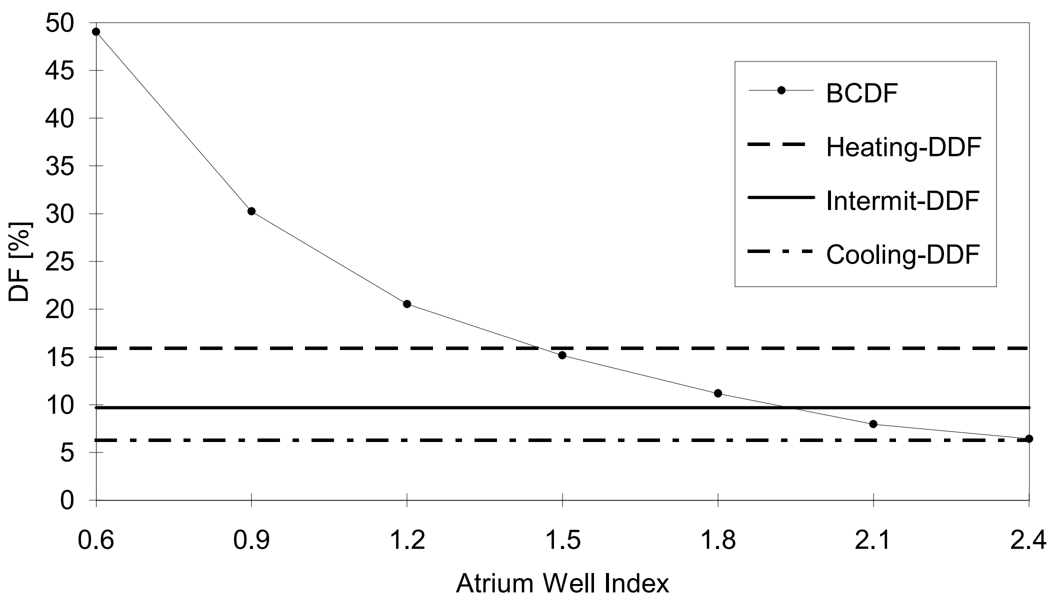

Figure 8.6 Clear Sky Base Case DF and DDF Values for Minneapolis, MN

8.1.4 Candidate Canopies for Overcast Sky

Before comparing the DF values of canopies with the DDF values, the DF values measured without glazing materials, which included sawtooth canopies and waffle skylights, were corrected by considering possible light reduction factors. It was assumed that the sawtooth canopies had a clear transparent glazing material with window frames and waffle skylights had tinted transparent glazing material without frame. With these assumptions, the DF values were corrected by the relationship shown in Equations 8.2 and 8.3, respectively for sawtooth canopies and waffle skylights. Furthermore, the DF values obtained with the glazed skylight systems were also corrected by considering the LLF values which account for dirt on window glasses as given by Equation 8.4.

$$CDF = DF \times HT \times FF \times LLF \quad \text{(for sawtooth canopies)} \tag{8.2}$$

$$CDF = DF \times HT \times LLF \quad \text{(for waffle skylights)} \tag{8.3}$$

$$CDF = DF \times LLF \quad \text{(for glazed skylights)} \tag{8.4}$$

where CDF = Corrected Daylight Factor [%]
HT = Hemispherical Transmittance [%]
FF = Framing Factor [%]
LLF = Light Loss Factor

For the HT values, because the sawtooth canopies had different aperture slope angles, the average (87.6 %) of overcast and clear sky HT values was used. The FF value for the sawtooth canopies was assumed to be 90 %. Table 8.3 shows the LLF values for different locations and glass slope conditions. The LLF values for clean areas were used in this study.

TABLE 8.3
Glazing Light Loss Factors (IESNA 1993, p. 369)

Location	Vertical	Sloped	Horizontal
Clean Areas	0.9	0.8	0.7
Industrial Areas	0.8	0.7	0.6
Very Dirty Areas	0.7	0.6	0.5

After calculating the CDF values, those values were compared for different geographic locations and all of the seven atrium WI values. Figures 8.7 through 8.10 show the plots of overcast sky CDF values and DDF values at four different WI values for Houston, TX. Figures 8.11 through 14 show the overcast CDF values and DDF values for Oklahoma City, OK. Figures 8.15 through 18 show those values for Minneapolis, MN.

As an initial step, the candidate canopies for overcast sky condition were selected if a canopy CDF values exceeded the DDF values for cooling seasons, which were the minimum values in all cases. However, for Houston and Oklahoma City, if the CDF value of a canopy was too large, it was excluded from the selection. Such cases were marked and identified on Figures 8.7, 8.8, 8.11, and 8.12. For Minneapolis, since this location would favor passive heating effect of direct sunlight during the prevailing heating season, all canopies showing larger CDF values than the DDF values were selected as candidates. Table 8.4 shows the list of candidate canopies.

TABLE 8.4

List of Candidate Canopies for Overcast Sky

Location	WI	Candidate Canopies (See Table 4.8)
Houston	0.6	2,3,4,6,7,8,11,12,13,14,15,13,19,20,23,24,27,28,29,30,33
	0.9	3,4,7,8,12,13,14,15,16,19,23,27,29,33,34
	1.2	4,8,12,13,14,15,16,18,19,23,27,29,33,34
	1.5	13,14,18,22,26,27
	1.8	18,22,26
	2.1	18,22,26
	2.4	26
Oklahoma City	0.6	2,3,4,7,8,11,12,13,14,15,16,18,19,20,22,23,24,26,27,28,29,30,33,34
	0.9	3,4,7,8,12,13,14,15,16,19,23,27,29,33,34
	1.2	13,14,15,18,19,23,27,29,33
	1.5	13,14,18,22,26,27
	1.8	18,22,26
	2.1	22,26
	2.4	26
Minneapolis	0.6	2,3,4,7,8,11,12,13,14,15,16,19,20,23,27,28,29,30,33,34
	0.9	3,4,7,8,12,13,14,15,16,18,19,22,23,26,27,28,33,34
	1.2	13,14,15,18,19,22,23,26,27,29,33
	1.5	13,14,18,22,26,27
	1.8	18,22,26
	2.1	22,26
	2.4	26

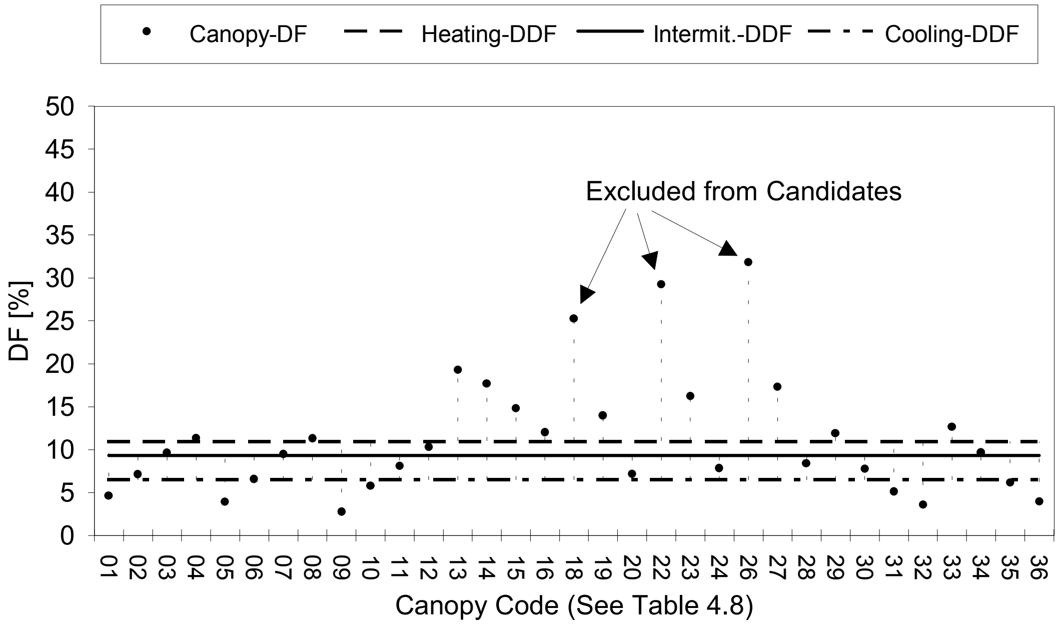

Figure 8.7 Overcast Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Houston, TX

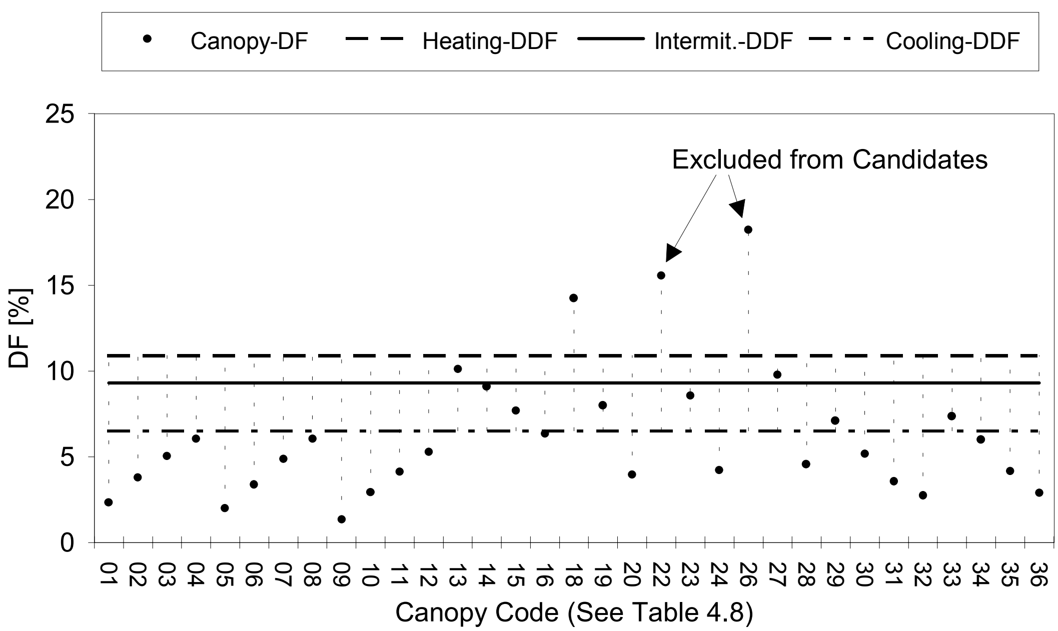

Figure 8.8 Overcast Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Houston, TX

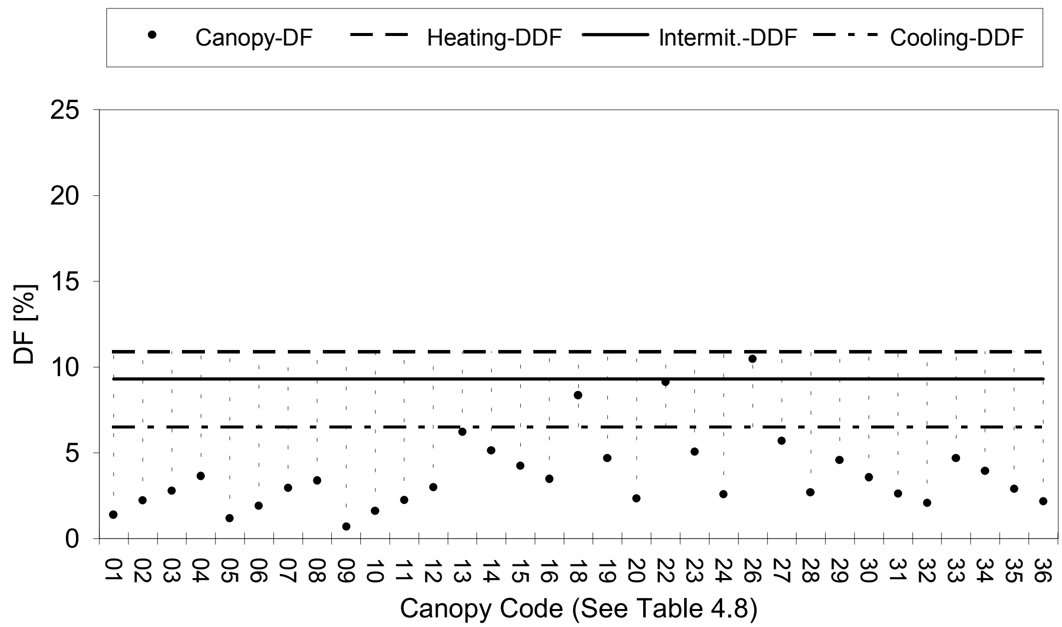

Figure 8.9 Overcast Sky CDF and DDF Values at WI = 1.8 (Atrium A6) in Houston, TX

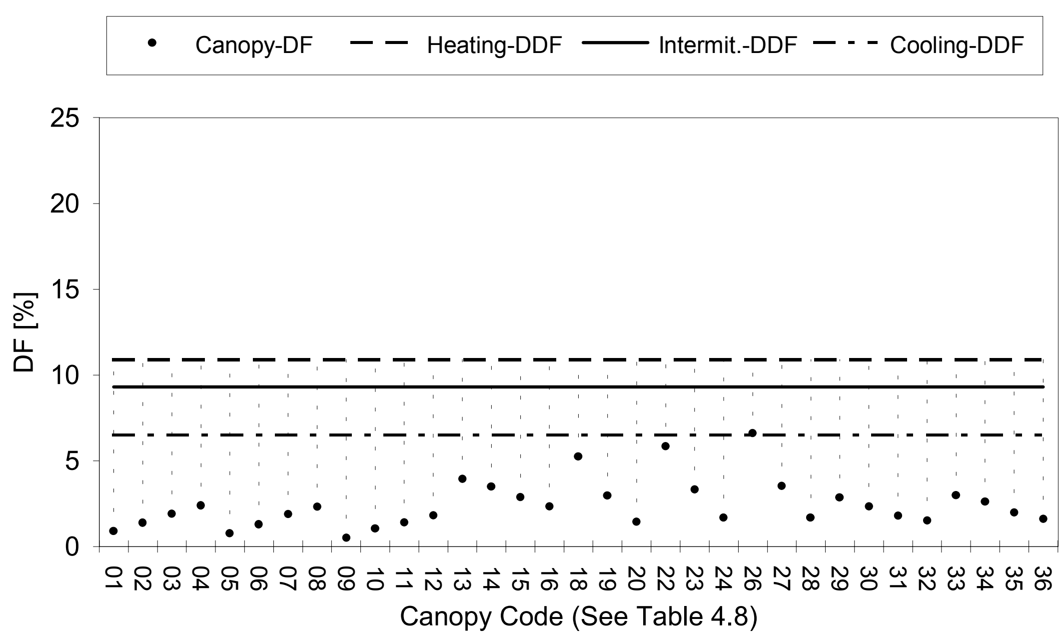

Figure 8.10 Overcast Sky CDF and DDF Values at WI = 2.4 (Atrium A8) in Houston, TX

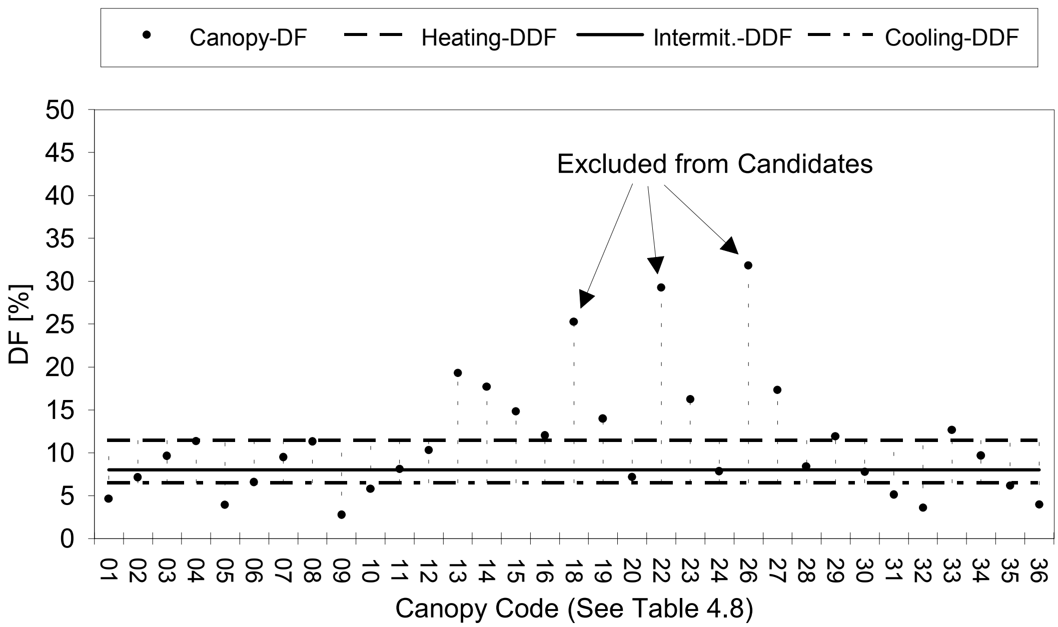

Figure 8.11 Overcast Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Oklahoma City, OK

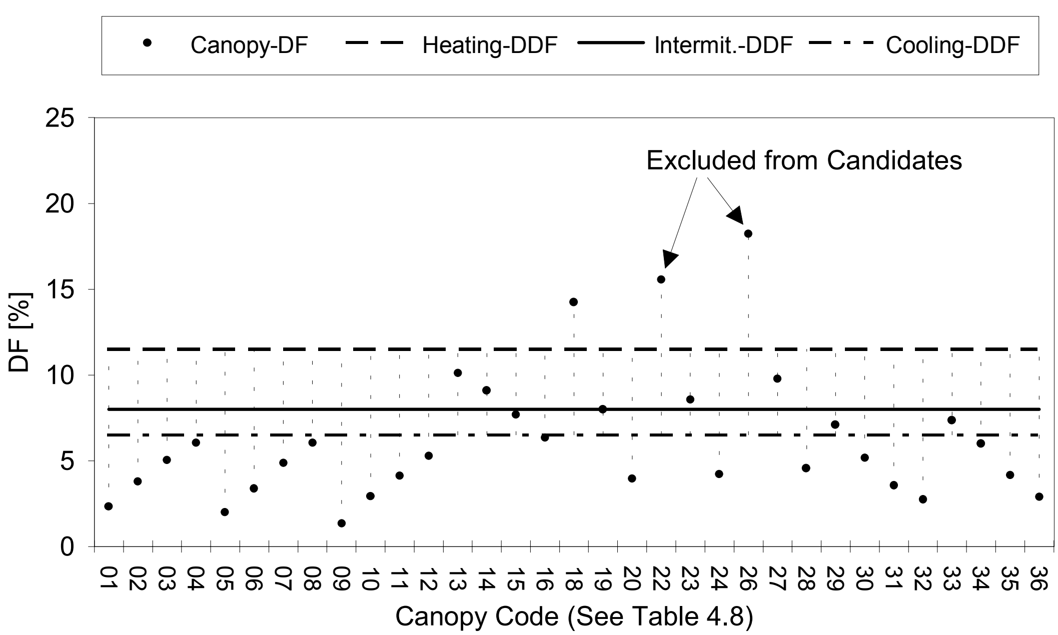

Figure 8.12 Overcast Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Oklahoma City, OK

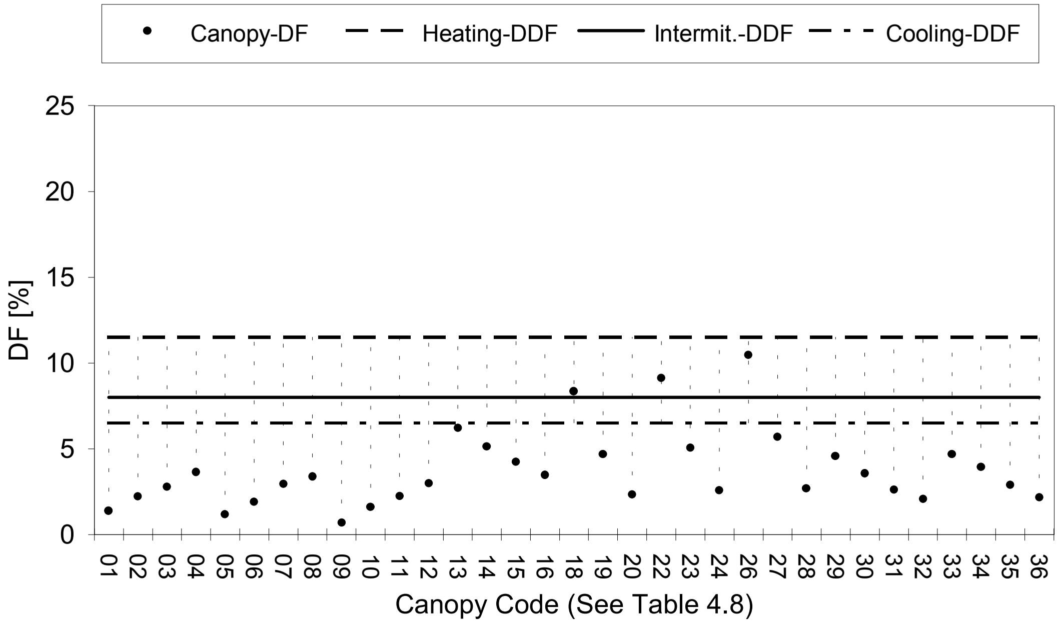

Figure 8.13 Overcast Sky CDF and DDF Values at WI = 1.8 (Atrium A6) in Oklahoma City, OK

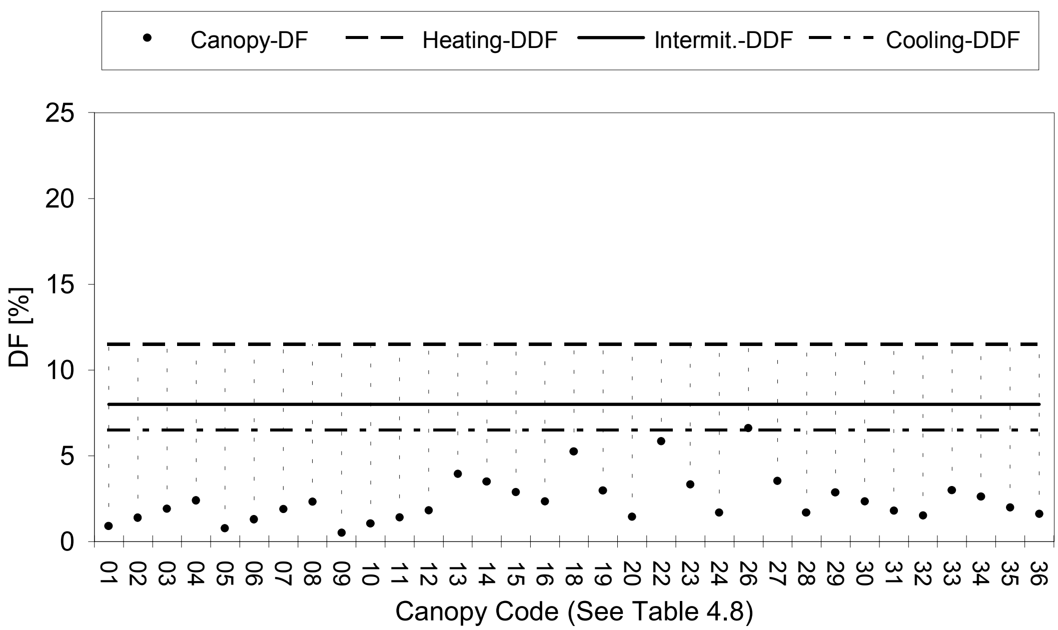

Figure 8.14 Overcast Sky CDF and DDF Values at WI = 2.4 (Atrium A8) in Oklahoma City, OK

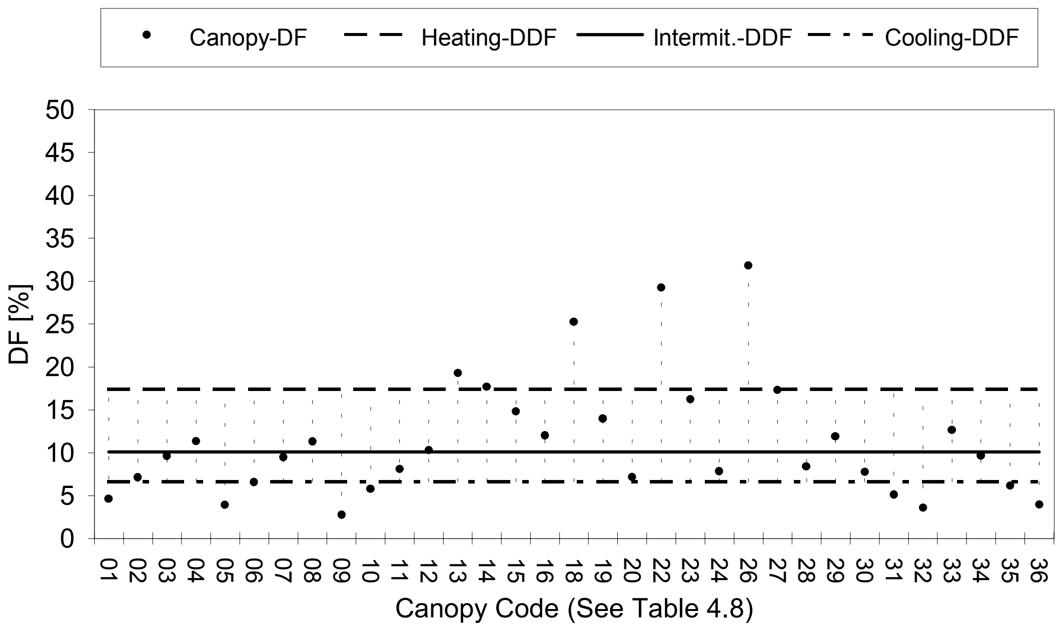

Figure 8.15 Overcast Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Minneapolis, MN

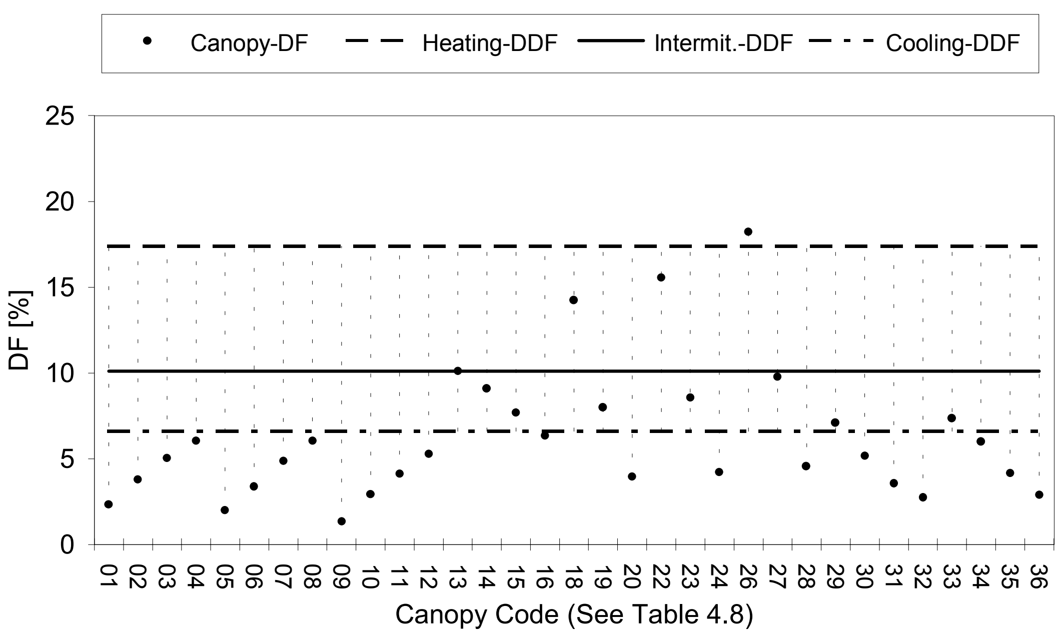

Figure 8.16 Overcast Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Minneapolis, MN

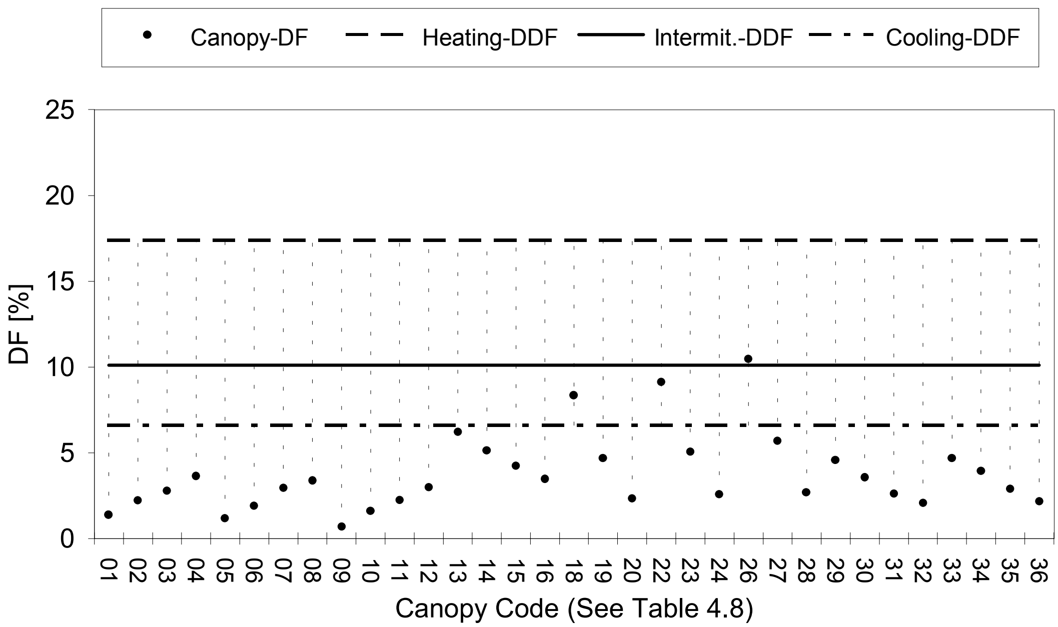

Figure 8.17 Overcast Sky CDF and DDF Values at WI = 1.8 (Atrium A6) in Minneapolis, MN

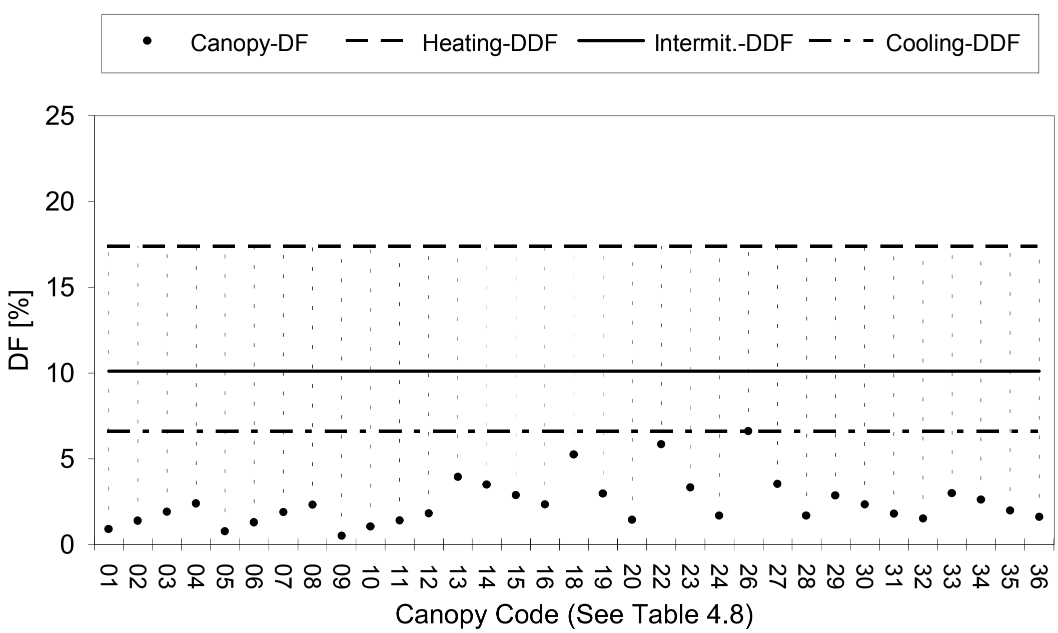

Figure 8.18 Overcast Sky CDF and DDF Values at WI = 2.4 (Atrium A8) in Minneapolis, MN

8.1.5 Candidate Canopies for Clear Sky with Sun

A clear sky always involves direct sunlight. Therefore, the candidate canopies should be selected by considering both illuminances from the sky and sunlight. Since, the sunlight illuminances were not conducted at all possible sun altitude angles for the three geographic locations, a new term "Design Sunlight Illuminance Ratio" (DSIR) was developed whose relationship is shown in Equation 8.5.

$$DSIR = \frac{(E_{crit} - E_{dic})}{E_{so}} \times 100\,[\%] \tag{8.5}$$

where E_{crit} = illuminance criterion [lux] (1000 lux)
E_{dic} = indoor horizontal illuminance calculated for clear sky [lux]
E_{so} = outdoor horizontal illuminance from direct sunlight only [lux]

Using this relationship, a DSIR value represents the amount of direct sunlight illuminance that must be provided by a canopy system to compensate for the deficient illuminance from clear sky only.

Prior to discussing the resulting DSIR values, the DF values measured under clear sky condition were examined with clear sky DDF values. As the same in the overcast sky cases, the canopy DF values were corrected using the previous Equations 8.2 through 8.4. Figures 8.19 through 24 show several selected examples for WI = 0.6 and WI = 1.8 in the three different geographic locations.

As shown in the figures, for the shallow atrium, most canopies provided the required illuminance levels for the cooling seasons even without direct sunlight. However, when the atrium WI value reached 1.2, only several canopies met the required DDF values for cooling seasons without sunlight. None of the canopies met the required DDF values for heating seasons. Therefore, to compensate for the deficient illuminance levels, two strategies should be considered - direct sunlight or electric light.

When direct sunlight is considered to compensate for the deficient illuminance levels, the DSIR values determined by Equation 8.5 can be used to examine if the canopy systems meet the determined DSIR values. Consequently, canopy systems showing very low DF values should have large DSIR values, and may not meet the DSIR values. On the contrary, canopy systems showing large DF values should have low or negative DSIR values, and they may mostly meet the DSIR values.

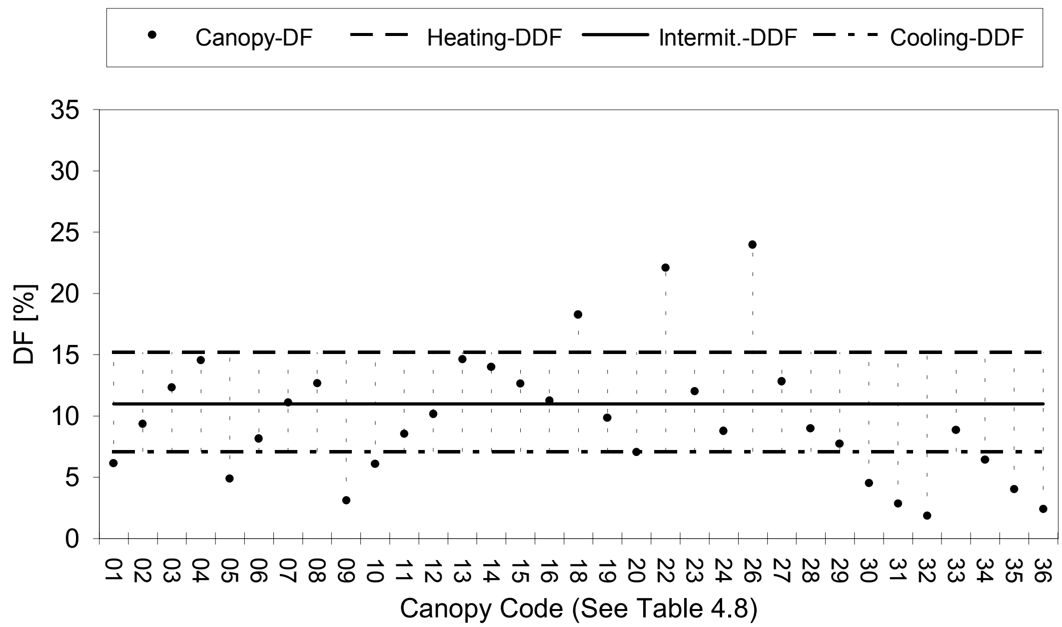

Figure 8.19 Clear Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Houston, TX

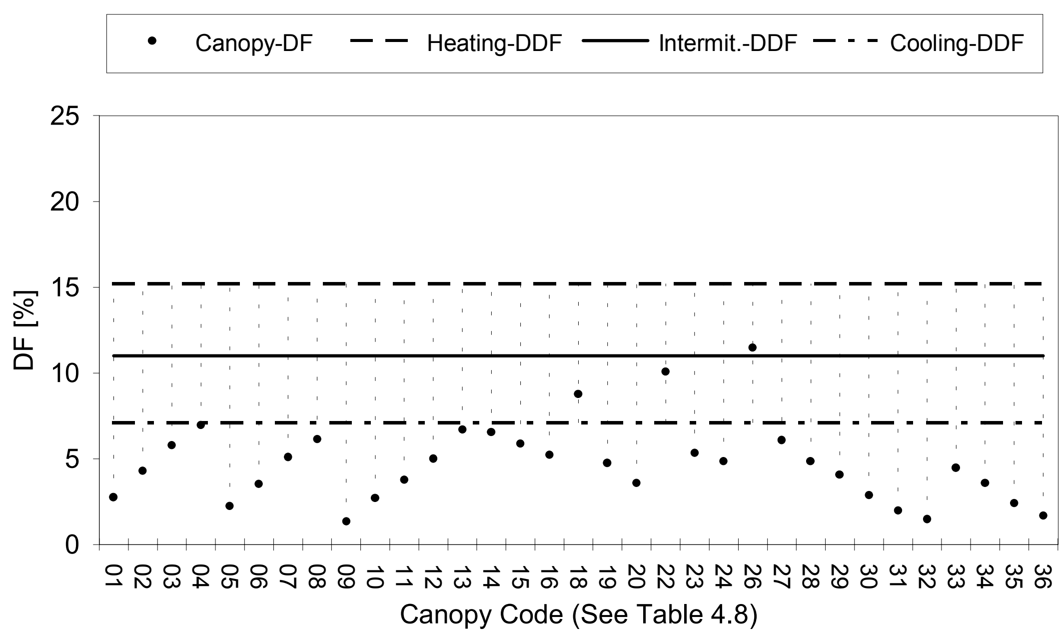

Figure 8.20 Clear Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Houston, TX

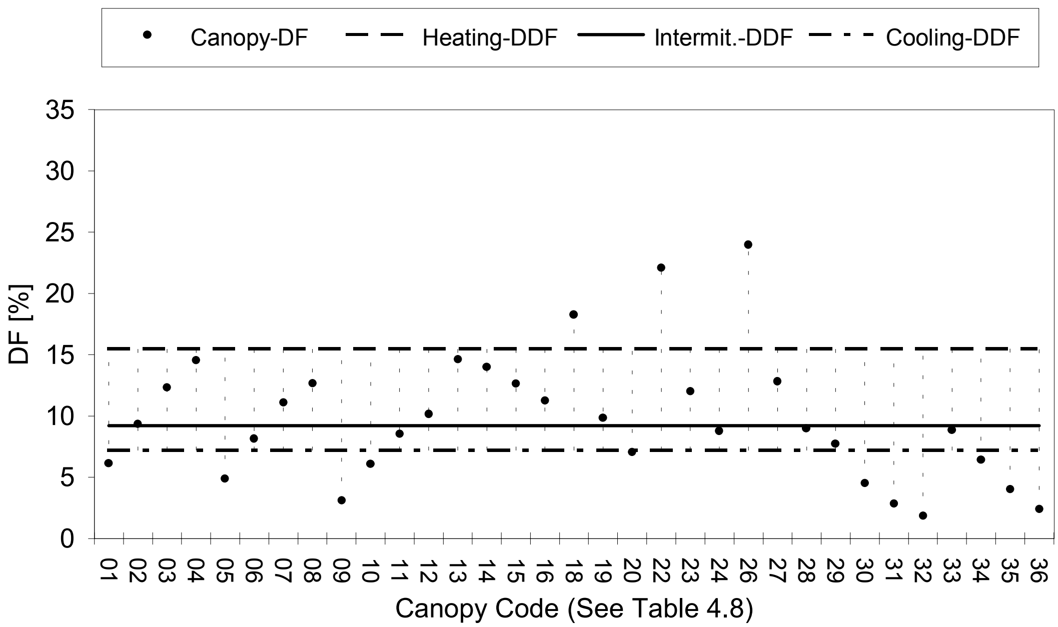

Figure 8.21 Clear Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Oklahoma City, OK

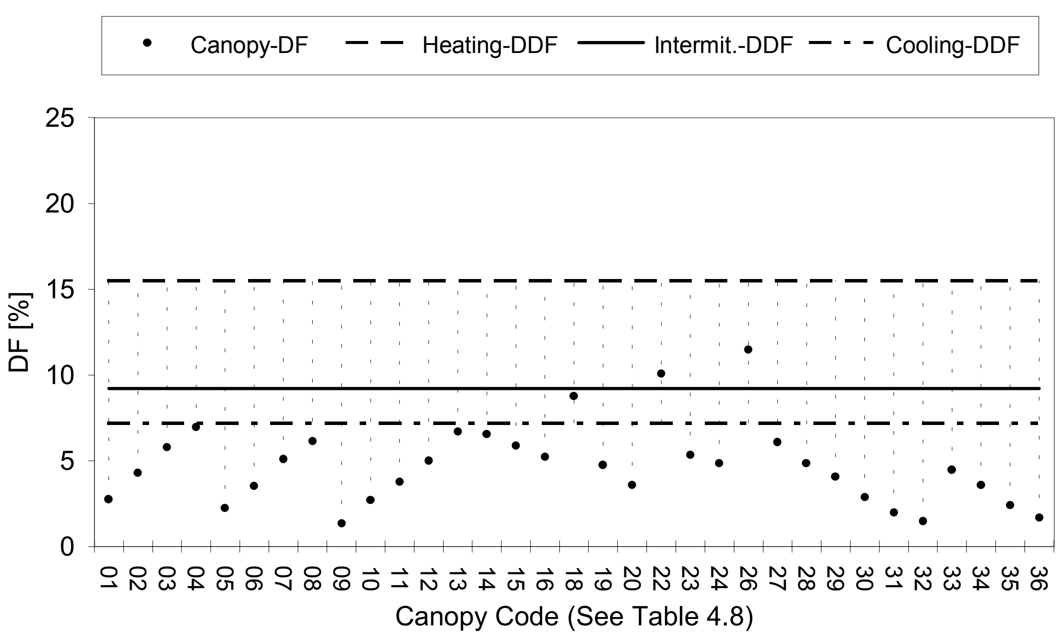

Figure 8.22 Clear Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Oklahoma City, OK

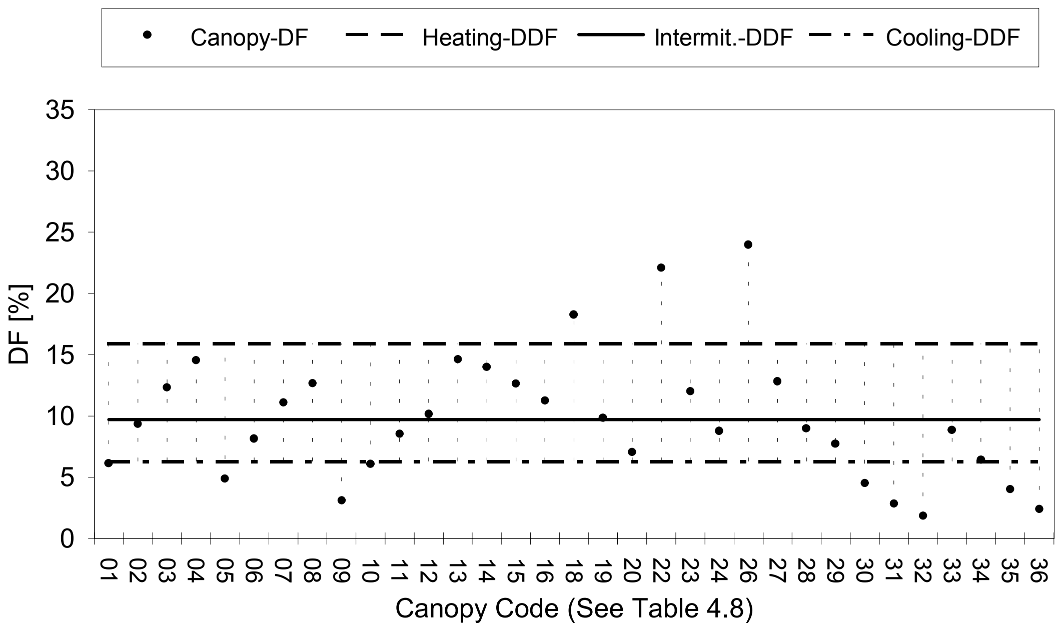

Figure 8.23 Clear Sky CDF and DDF Values at WI = 0.6 (Atrium A2) in Minneapolis, MN

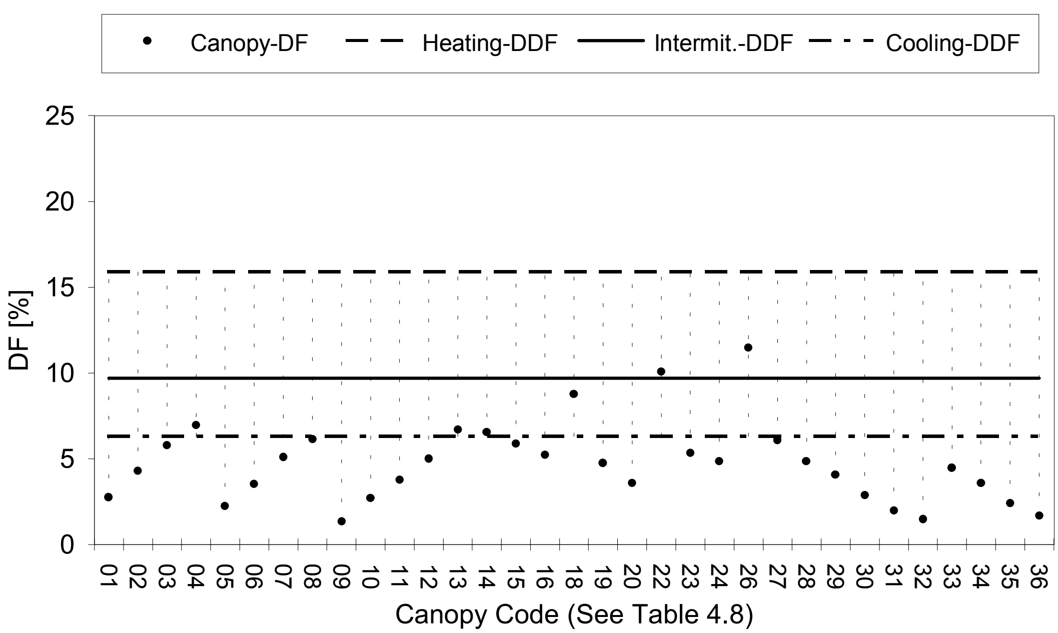

Figure 8.24 Clear Sky CDF and DDF Values at WI = 1.2 (Atrium A4) in Minneapolis, MN

Together with the basic concept of DSIR, the characteristic performances of canopy systems at different sun altitude angles in different geographic locations investigated in Chapter 7 need to be applied to select suitable canopy systems for different well configurations.

First, to calculate the DSIR values, the monthly average outdoor illuminance levels were determined. Table 8.5 shows the actual monthly average outdoor illuminance levels from clear sky and direct sun for the three geographic locations.

Second, the outdoor illuminance levels were used to determine the seasonal average values of the outdoor illuminance levels. Table 8.6 shows the average clear sky and sunlight outdoor illuminance levels for the three geographic locations.

TABLE 8.5

Monthly Average Outdoor Illuminance Levels from Clear Sky and Direct Sun

Month	Houston		Oklahoma City		Minneapolis	
	Sky [lux]	Sun [lux]	Sky [lux]	Sun [lux]	Sky [lux]	Sun [lux]
Jan	6952	38998	6532	31800	5232	20543
Feb	7023	46052	6734	39820	6013	30193
Mar	8243	55346	8097	51043	7670	43271
Apr	11039	61544	10967	59235	10523	55184
May	14598	60623	14588	59812	14122	58289
Jun	15932	61116	15956	60833	15887	58698
Jul	16415	58889	16408	58156	16707	53948
Aug	14952	55435	14853	53365	15349	46078
Sep	11130	50904	10920	46929	10833	37815
Oct	8535	42094	8148	36537	7471	26154
Nov	7412	33832	6933	30492	5697	18786
Dec	6569	34563	6024	27027	4576	15074

TABLE 8.6

Seasonal Average Outdoor Illuminance Levels from Clear Sky and Direct Sun

Geographic Location	Season	Month	Clear Sky Illuminance [lux]	Sunlight Illuminance [lux]
Houston	Heating	12, 1, 2	6864	39871
	Intermit.	3, 4, 5, 10, 11	9965	50688
	Cooling	6, 7, 8, 9	14607	56586
Oklahoma City	Heating	11, 12, 1, 2, 3	6864	36036
	Intermit.	4, 5, 10	11234	55325
	Cooling	6, 7, 8, 9	14534	54821
Minneapolis	Heating	11, 12, 1, 2, 3	5838	25573
	Intermit.	4, 5, 9, 10	10737	44631
	Cooling	6, 7, 8	15981	52908

Figures 8.25 through 8.30 show examples with WI = 0.6 and WI = 1.2 for the three geographic locations. All of the DSIR values at the seven WI values for the three geographic locations are presented in Tables 8.7 through 8.10.

The suitable canopy systems for different well configurations and geographic locations can be selected with the following criteria.

1) For hot climates, give the highest priority to the DSIR values for the cooling season and minimize direct sunlight penetration. For shallow atria in this climate, consider sawtooth canopies with small DSIR values as tentative candidates, because they can effectively control direct sunlight in the cooling season. However, for deep atria in hot climate, skylights may have to be considered, because the atrium well structure will shade the atrium floor during most of the daylighting hours in cooling seasons.

2) For temperate climates, give the same priority to the DSIR values for both heating and cooling seasons. Then, the same criteria may be established as in the hot climate. The canopy systems in this climate should effectively shade the atrium space during the cooling season, and should allow direct sunlight penetration during the heating season.

3) For cold climates, give the highest priority to the DSIR values for the heating season.

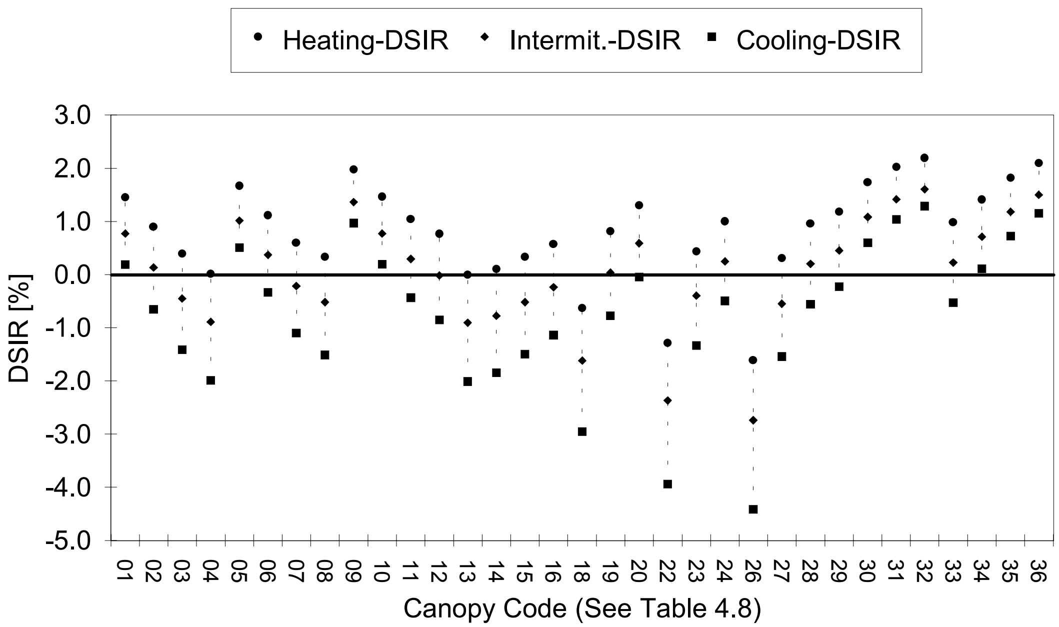

Figure 8.25 Design Sunlight Illuminance Ratios at WI = 0.6 (Atrium A2) in Houston, TX

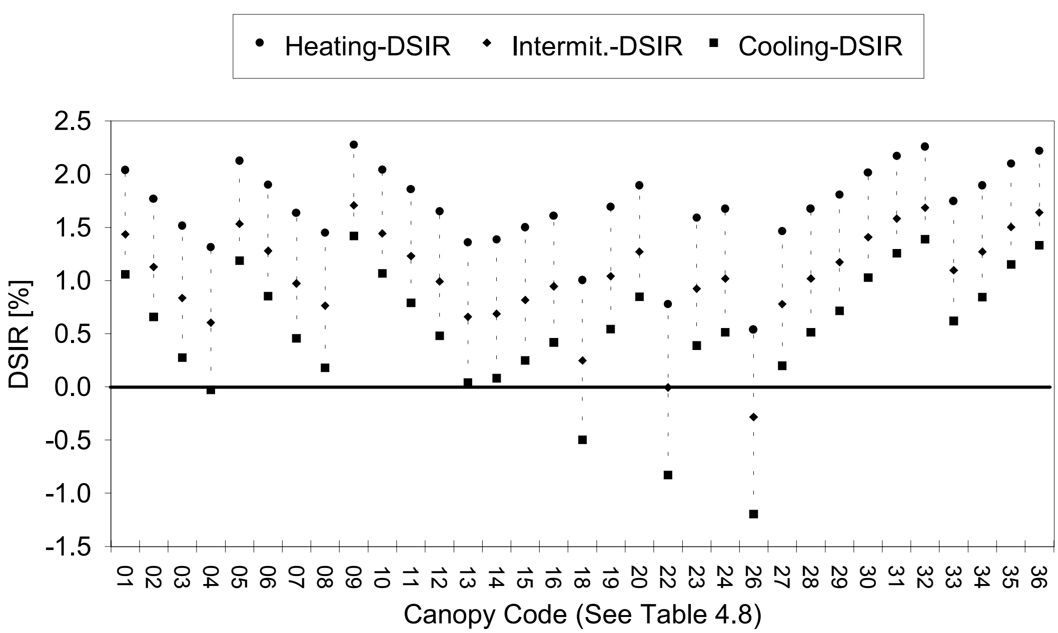

Figure 8.26 Design Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) in Houston, TX

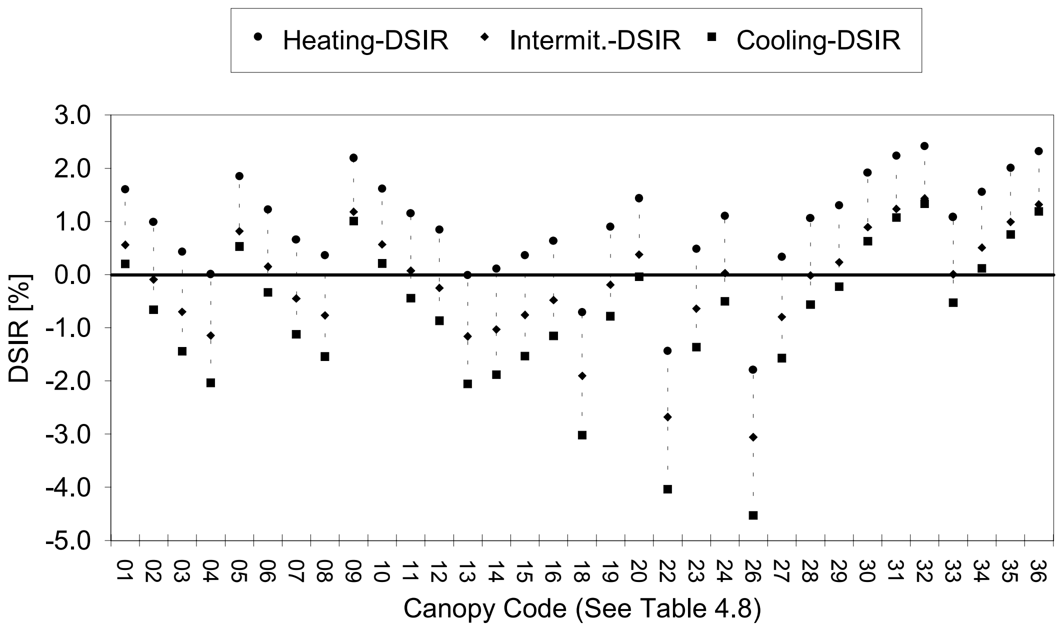

Figure 8.27 Design Sunlight Illuminance Ratios at WI = 0.6 (Atrium A2) in Oklahoma City, OK

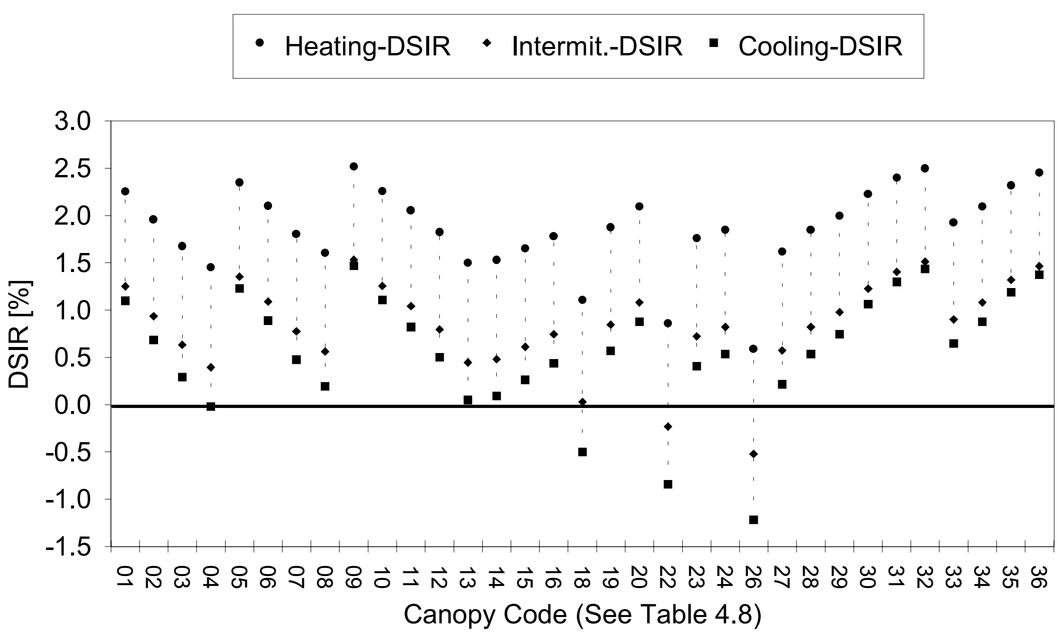

Figure 8.28 Design Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) in Oklahoma City, OK

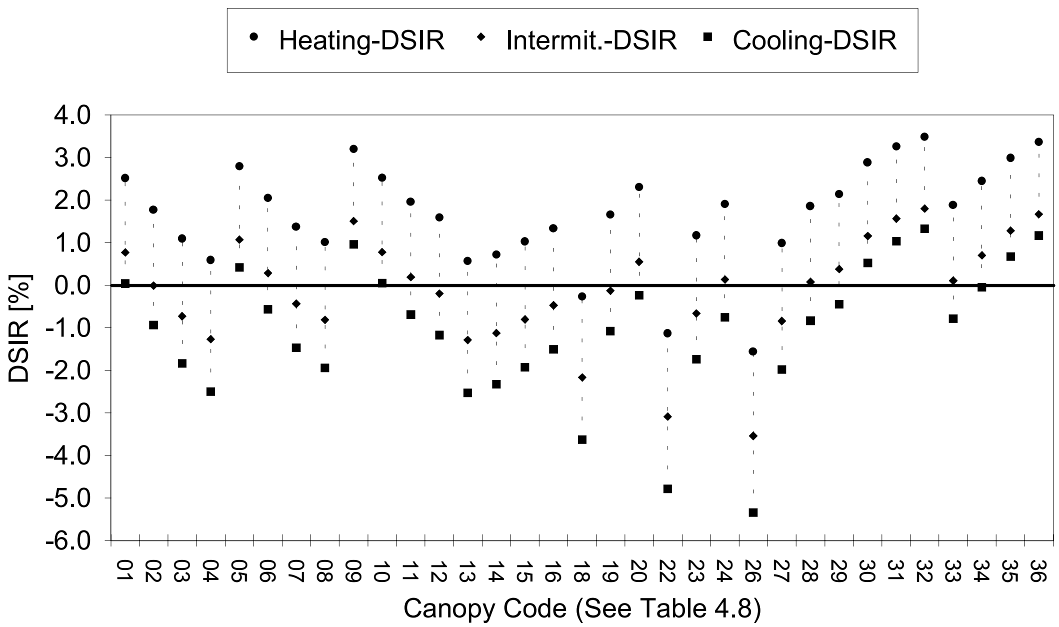

Figure 8.29 Design Sunlight Illuminance Ratios at WI = 0.6 (Atrium A2) in Minneapolis, MN

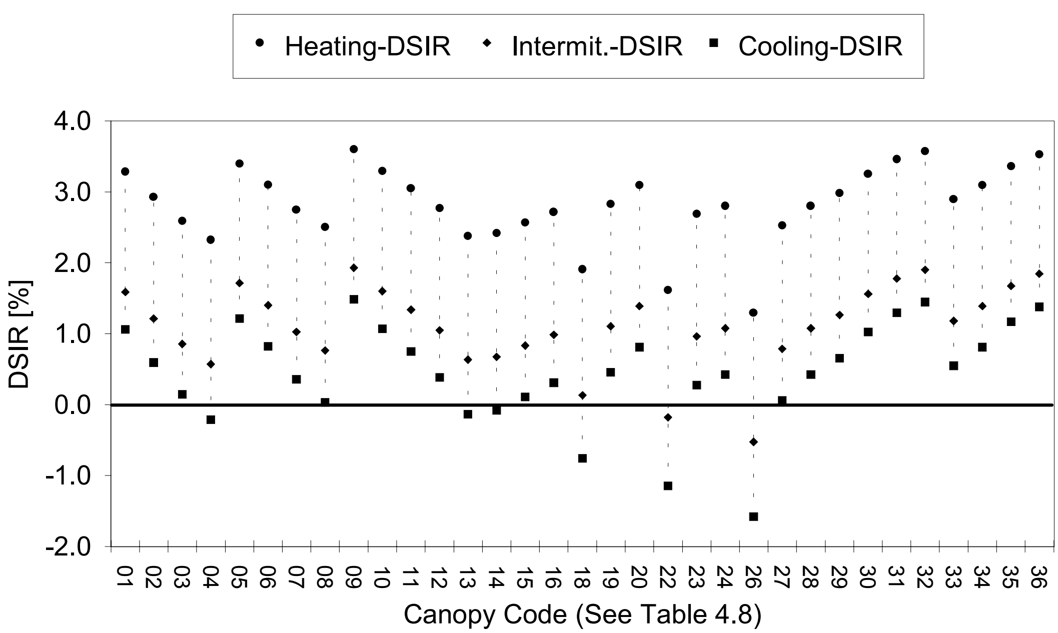

Figure 8.30 Design Sunlight Illuminance Ratios at WI = 1.2 (Atrium A4) in Minneapolis, MN

TABLE 8.7

Design Sunlight Illuminance Ratios for Houston, TX

(Cooling Season DSIR Values [%])

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	0.2	0.8	1.1	1.2	1.3	1.5	1.5
02	-0.7	0.3	0.7	1.0	1.2	1.3	1.4
03	-1.4	-0.2	0.3	0.7	1.0	1.2	1.3
04	-2.0	-0.6	0.0	0.5	0.8	1.1	1.2
05	0.5	1.0	1.2	1.4	1.5	1.5	1.6
06	-0.3	0.5	0.9	1.1	1.3	1.5	1.5
07	-1.1	0.0	0.5	0.8	1.0	1.2	1.4
08	-1.5	-0.3	0.2	0.6	0.9	1.2	1.3
09	1.0	1.2	1.4	1.5	1.6	1.7	1.7
10	0.2	0.7	1.1	1.2	1.4	1.5	1.5
11	-0.4	0.3	0.8	1.1	1.2	1.4	1.5
12	-0.9	0.0	0.5	0.8	1.1	1.2	1.4
13	-2.0	-0.6	0.0	0.5	0.9	1.1	1.3
14	-1.8	-0.5	0.1	0.6	0.9	1.1	1.3
15	-1.5	-0.3	0.2	0.7	1.0	1.3	1.3
16	-1.1	-0.1	0.4	0.8	1.1	1.3	1.3
18	-3.0	-1.4	-0.5	0.1	0.7	0.9	1.0
19	-0.8	0.0	0.5	0.9	1.2	1.2	1.4
20	-0.1	0.5	0.8	1.0	1.2	1.5	1.5
22	-3.9	-2.0	-0.8	-0.1	0.5	0.8	0.9
23	-1.3	-0.4	0.4	0.8	1.1	1.2	1.4
24	-0.5	0.1	0.5	0.8	1.1	1.2	1.4
26	-4.4	-2.4	-1.2	-0.4	0.2	0.6	0.8
27	-1.5	-0.5	0.2	0.6	1.0	1.2	1.3
28	-0.6	0.0	0.5	0.8	1.1	1.2	1.5
29	-0.2	0.3	0.7	1.0	1.2	1.3	1.4
30	0.6	0.8	1.0	1.2	1.3	1.4	1.5
31	1.0	1.2	1.3	1.4	1.4	1.5	1.5
32	1.3	1.4	1.4	1.5	1.5	1.5	1.6
33	-0.5	0.1	0.6	0.9	1.1	1.3	1.4
34	0.1	0.5	0.8	1.1	1.2	1.4	1.4
35	0.7	1.0	1.1	1.3	1.4	1.5	1.5
36	1.1	1.2	1.3	1.4	1.5	1.5	1.5

* See Table 4.8 for Canopy Code

TABLE 8.8
Design Sunlight Illuminance Ratios for Oklahoma City, OK
(Heating Season DSIR Values [%])

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	1.6	2.1	2.3	2.4	2.5	2.6	2.6
02	1.0	1.7	2.0	2.2	2.3	2.5	2.5
03	0.4	1.3	1.7	2.0	2.2	2.4	2.4
04	0.0	1.0	1.5	1.8	2.1	2.3	2.4
05	1.8	2.2	2.3	2.5	2.6	2.6	2.7
06	1.2	1.8	2.1	2.3	2.4	2.6	2.6
07	0.7	1.5	1.8	2.1	2.2	2.4	2.5
08	0.4	1.2	1.6	1.9	2.1	2.3	2.4
09	2.2	2.3	2.5	2.6	2.6	2.7	2.7
10	1.6	2.0	2.3	2.4	2.5	2.6	2.6
11	1.1	1.7	2.1	2.3	2.4	2.5	2.6
12	0.8	1.5	1.8	2.1	2.3	2.4	2.5
13	0.0	1.0	1.5	1.9	2.1	2.3	2.4
14	0.1	1.1	1.5	1.9	2.1	2.3	2.4
15	0.4	1.2	1.7	2.0	2.2	2.4	2.4
16	0.6	1.4	1.8	2.1	2.3	2.4	2.4
18	-0.7	0.4	1.1	1.5	2	2.1	2.2
19	0.9	1.5	1.9	2.1	2.3	2.4	2.5
20	1.4	1.8	2.1	2.2	2.4	2.5	2.6
22	-1.4	0.0	0.9	1.4	1.8	2.1	2.1
23	0.5	1.2	1.8	2.1	2.3	2.3	2.5
24	1.1	1.5	1.8	2.1	2.3	2.4	2.5
26	-1.8	-0.3	0.6	1.2	1.6	1.9	2.1
27	0.3	1.1	1.6	1.9	2.2	2.3	2.4
28	1.1	1.5	1.8	2.1	2.3	2.3	2.5
29	1.3	1.7	2.0	2.2	2.3	2.4	2.5
30	1.9	2.1	2.2	2.4	2.4	2.5	2.6
31	2.2	2.3	2.4	2.5	2.5	2.6	2.6
32	2.4	2.5	2.5	2.5	2.6	2.6	2.7
33	1.1	1.6	1.9	2.1	2.3	2.4	2.5
34	1.6	1.8	2.1	2.3	2.4	2.5	2.5
35	2.0	2.2	2.3	2.4	2.5	2.5	2.6
36	2.3	2.4	2.5	2.5	2.5	2.6	2.6

* See Table 4.8 for Canopy Code

TABLE 8.9
Design Sunlight Illuminance Ratios for Oklahoma City, OK
(Cooling Season DSIR Values [%])

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	0.2	0.8	1.1	1.3	1.4	1.5	1.6
02	-0.7	0.3	0.7	1	1.2	1.4	1.5
03	-1.4	-0.2	0.3	0.7	1	1.2	1.3
04	-2.0	-0.6	0.0	0.5	0.8	1.1	1.2
05	0.5	1.1	1.2	1.4	1.6	1.6	1.7
06	-0.3	0.5	0.9	1.1	1.3	1.5	1.6
07	-1.1	0.0	0.5	0.8	1.1	1.3	1.4
08	-1.5	-0.3	0.2	0.7	0.9	1.2	1.3
09	1.0	1.2	1.5	1.5	1.6	1.7	1.7
10	0.2	0.7	1.1	1.3	1.4	1.5	1.6
11	-0.4	0.3	0.8	1.1	1.3	1.5	1.5
12	-0.9	0.0	0.5	0.9	1.2	1.3	1.5
13	-2.1	-0.6	0.0	0.6	0.9	1.1	1.3
14	-1.9	-0.6	0.1	0.6	0.9	1.1	1.3
15	-1.5	-0.3	0.3	0.7	1	1.3	1.4
16	-1.2	-0.1	0.4	0.9	1.1	1.3	1.4
18	-3.0	-1.5	-0.5	0.1	0.7	0.9	1.1
19	-0.8	0.1	0.6	0.9	1.2	1.3	1.4
20	0.0	0.5	0.9	1	1.3	1.5	1.5
22	-4.0	-2.1	-0.8	-0.1	0.5	0.9	0.9
23	-1.4	-0.4	0.4	0.8	1.2	1.2	1.5
24	-0.5	0.1	0.5	0.9	1.2	1.3	1.5
26	-4.5	-2.4	-1.2	-0.4	0.2	0.6	0.9
27	-1.6	-0.5	0.2	0.6	1	1.2	1.3
28	-0.6	0.0	0.5	0.9	1.1	1.2	1.5
29	-0.2	0.3	0.7	1	1.2	1.3	1.4
30	0.6	0.9	1.1	1.2	1.4	1.4	1.5
31	1.1	1.2	1.3	1.4	1.5	1.5	1.6
32	1.3	1.4	1.4	1.5	1.5	1.6	1.7
33	-0.5	0.1	0.6	0.9	1.2	1.3	1.4
34	0.1	0.5	0.9	1.1	1.3	1.4	1.5
35	0.8	1.0	1.2	1.3	1.4	1.5	1.6
36	1.2	1.3	1.4	1.4	1.5	1.6	1.6

* See Table 4.8 for Canopy Code

TABLE 8.10

Design Sunlight Illuminance Ratios for Minneapolis, MN

(Heating Season DSIR Values [%])

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	2.5	3.1	3.3	3.4	3.5	3.7	3.7
02	1.8	2.6	2.9	3.2	3.4	3.5	3.6
03	1.1	2.2	2.6	3.0	3.2	3.4	3.5
04	0.6	1.8	2.3	2.8	3.0	3.3	3.4
05	2.8	3.3	3.4	3.6	3.7	3.7	3.8
06	2.1	2.8	3.1	3.3	3.5	3.7	3.7
07	1.4	2.3	2.8	3.1	3.3	3.5	3.6
08	1.0	2.1	2.5	2.9	3.1	3.4	3.5
09	3.2	3.4	3.6	3.7	3.7	3.8	3.8
10	2.5	2.9	3.3	3.4	3.6	3.7	3.7
11	2.0	2.6	3.0	3.3	3.5	3.6	3.7
12	1.6	2.3	2.8	3.1	3.4	3.5	3.6
13	0.6	1.8	2.4	2.8	3.1	3.3	3.5
14	0.7	1.9	2.4	2.9	3.1	3.3	3.5
15	1.0	2.1	2.6	3.0	3.2	3.5	3.5
16	1.3	2.3	2.7	3.1	3.3	3.5	3.5
18	-0.3	1.1	1.9	2.4	2.9	3.1	3.3
19	1.7	2.4	2.8	3.2	3.4	3.4	3.6
20	2.3	2.8	3.1	3.2	3.4	3.6	3.7
22	-1.1	0.6	1.6	2.3	2.8	3.1	3.2
23	1.2	2.0	2.7	3.1	3.3	3.4	3.6
24	1.9	2.4	2.8	3.1	3.4	3.5	3.6
26	-1.6	0.2	1.3	2.0	2.5	2.8	3.1
27	1.0	1.9	2.5	2.9	3.2	3.4	3.5
28	1.9	2.4	2.8	3.1	3.3	3.4	3.6
29	2.1	2.6	3.0	3.2	3.4	3.5	3.6
30	2.9	3.1	3.3	3.4	3.5	3.6	3.7
31	3.3	3.4	3.5	3.6	3.6	3.7	3.7
32	3.5	3.5	3.6	3.6	3.7	3.7	3.8
33	1.9	2.5	2.9	3.1	3.3	3.5	3.6
34	2.4	2.8	3.1	3.3	3.4	3.6	3.6
35	3.0	3.2	3.4	3.5	3.6	3.6	3.7
36	3.4	3.4	3.5	3.6	3.6	3.7	3.7

* See Table 4.8 for Canopy Code

Before comparing the DSIR values with the Sunlight Illuminance Ratios (SIR) obtained without glazing material (sawtooth canopies and waffle skylights), the SIR values were again corrected by considering the glass transmittance and the Light Loss Factors (LLF). As with the overcast sky cases, the sawtooth canopies were assumed to have clear transparent glazing and the waffle skylights were assumed to have tinted transparent glazing.

For the sawtooth canopies with vertical and sloping apertures, the transmittance of glass material was calculated by the previous Equation 6.4. For waffle skylights, the glass transmittance values were determined from the SIR values for flat horizontal skylights measured with and without tinted glazing material, because both types would have glazing material with the same orientation. Equations 8.6 and 8.7 were used to correct the original SIR values respectively for the sawtooth canopies and waffle skylights.

$$CSIR = SIR \times \tau_{\theta} \times FF \times LLF \text{ (for sawtooth canopies)} \quad (8.6)$$

$$CSIR = SIR \times \tau_{h} \times LLF \text{ (for waffle skylights)} \quad (8.7)$$

where CSIR = Corrected Sunlight Illuminance Ratio [%]
τ_{θ} = transmittance of sunlight at incident angle θ
τ_{h} = transmittance of flat horizontal skylight

Then, the CSIR values at the nine different sun altitude angles (3 times in 3 seasons) were grouped and averaged for heating, intermittent, and cooling seasons. Tables 8.11 through 8.14 show average CSIR values for WI values 0.6, 1.2, 1.8, 2.4, respectively. The candidate canopy systems were selected by comparing the DSIR shown in the previous Tables 8.7 through 8.10 and the CSIR values in Tables 8.11 through 8.14.

Finally, Table 8.15 shows the candidate canopy systems for clear sky condition. As indicated in the table, for shallow atria in Houston, south-facing sawtooth canopies with small aperture areas and north-facing sawtooth canopies with large aperture areas were dominantly selected. For deep atria in Houston, some tinted-transparent and translucent skylights and waffle skylights were selected. For atria in Oklahoma City, mostly south-facing sawtooth canopies and translucent skylights were selected. Finally, for atria in Minneapolis, almost the same canopies as in Oklahoma City were selected as the candidates for clear sky condition.

TABLE 8.11

Averages of Corrected SIR Values for WI = 0.6

Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]	Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]
04S	22.3	28.0	15.2	04N	0.9	1.3	2.1
08S	18.4	27.6	9.4	08N	1.9	2.8	3.7
12S	13.8	29.8	10.8	12N	1.5	2.4	3.2
13S	7.7	19.1	26.6	13N	2.3	13.3	28.4
16S	10.9	16.1	17.4	16N	1.2	1.9	7.3
19	2.3	12.3	20.3				
20	6.2	7.0	7.5				
27	3.7	9.8	24.5				
28	6.2	6.1	6.0				
33	1.7	11.2	24.2				
34	0.9	7.5	20.9				
36	0.3	1.2	15.0				

TABLE 8.12

Averages of Corrected SIR Values for WI = 1.2

Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]	Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]
04S	11.5	16.4	5.3	04N	0.8	0.8	1.3
08S	9.4	10.6	7.7	08N	1.0	1.7	2.2
12S	7.4	10.4	9.3	12N	0.9	1.4	1.9
13S	3.3	5.4	23.1	13N	1.3	11.1	19.5
16S	5.0	6.0	17.6	16N	0.7	1.1	1.5
19	1.3	6.6	16.0				
20	3.1	3.6	3.7				
27	1.7	6.9	18.0				
28	3.0	3.1	3.2				
33	0.8	4.1	17.8				
34	0.4	3.6	15.6				
36	0.3	0.7	12.0				

* See Table 4.8 for Canopy Code

TABLE 8.13

Averages of Corrected SIR Values for WI = 1.8

Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]	Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]
04S	6.9	5.2	9.7	04N	0.6	0.5	1.0
08S	5.7	4.5	7.3	08N	0.9	0.8	1.4
12S	4.7	4.1	7.6	12N	0.9	0.7	1.2
13S	1.8	3.5	32.4	13N	0.8	2.2	9.1
16S	2.4	3.4	18.7	16N	0.6	0.7	2.8
19	0.7	2.5	15.9				
20	2.0	2.1	2.3				
27	0.8	2.1	16.5				
28	1.8	1.7	2.0				
33	0.5	1.9	16.4				
34	0.3	1.1	13.9				
36	0.3	0.5	7.7				

TABLE 8.14

Averages of Corrected SIR Values for WI = 2.4

Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]	Canopy Code *	Heating [%]	Intermit. [%]	Cooling [%]
04S	4.6	3.2	4.8	04N	0.2	0.4	0.5
08S	3.8	2.9	3.9	08N	0.5	0.6	0.8
12S	3.3	2.1	7.6	12N	0.5	0.5	0.8
13S	1.0	2.1	6.2	13N	0.6	1.0	20.4
16S	1.5	2.3	4.8	16N	0.3	0.4	5.8
19	0.5	1.2	10.2				
20	1.5	1.3	1.6				
27	0.6	1.3	17.7				
28	1.4	1.1	1.3				
33	0.4	1.1	12.7				
34	0.3	0.7	9.9				
36	0.2	0.3	7.1				

* See Table 4.8 for Canopy Code

TABLE 8.15

List of Candidate Canopies for Clear Sky with Sun

Location	WI	Candidates for Clear Sky *
Houston	0.6	01, 02, 04N, 05, 06, 08N, 09, 10, 12N, 16N
	0.9	01, 02, 04N, 05, 06, 08N, 09, 10, 12N, 16N
	1.2	01, 02, 04N, 05, 06, 08N, 09, 10, 12N, 16N
	1.5	01, 02, 04N, 05, 06, 08N, 09, 10, 12N, 16N
	1.8	01, 02, 04N, 05, 06, 08N, 09, 10, 12N, 16N
	2.1	03, 04S, 07, 08S, 13N, 16S, 19, 20, 27, 28, 34, 36
	2.4	03, 04S, 07, 08S, 13N, 16S, 19, 20, 27, 28, 34, 36
Oklahoma City	0.6	04S, 04N, 08S, 08N, 16N, 28
	0.9	04S, 08S, 12S, 20, 28
	1.2	04S, 08S, 12S, 20, 28
	1.5	04S, 08S, 12S, 20, 28
	1.8	04S, 08S, 12S, 20, 28
	2.1	04S, 08S, 12S, 20, 28
	2.4	04S, 08S, 12S, 20, 28
Minneapolis	0.6	04S, 08S, 13S, 16S, 19, 20
	0.9	04S, 08S, 12S, 13S, 16S, 19, 20, 28
	1.2	04S, 08S, 12S, 13S, 16S, 19, 20, 28
	1.5	04S, 08S, 12S, 13S, 16S, 19, 20, 28
	1.8	04S, 08S, 12S, 20, 28
	2.1	04S, 08S, 12S, 20, 28
	2.4	04S, 08S, 12S, 20, 28

* See Table 4.8 for Canopy Code

8.1.6 Selected Canopy Systems

Final selection was made by considering the candidate canopies for overcast sky and those for clear sky with sun. Table 8.16 shows the final list of selected canopy systems for different WI values and different geographic locations. During the final selection process, it was found that many of the candidate canopies for atria having WI values lower than 1.5 satisfied the illuminance criterion under both sky conditions. However, at higher WI values, candidate canopies which satisfied the two different sky conditions were not found. In those cases, the clear sky candidates were chosen, because the clear sky candidates were selected by considering the prevailing thermal-conditioning seasons. Even though extra tests on the sunlight patches were not conducted, most of the canopies, except the translucent-glazed skylights and north-facing sawtooths, were previously tested and proved to cast desirable sunlight patches on the wall areas.

TABLE 8.16

List of Selected Canopies

Location	WI	Candidate Canopies (See Table 4.8 for Canopy Code)	
Houston	0.6	02, 04N, 06, 08N, 12N, 16N	
	0.9	04N, 08N, 12N, 16N	
	1.2	04N, 08N, 12N, 16N	Hot summers require shading
	1.5	04N, 08N, 12N, 16N	from roof canopy.
	1.8	04N, 05, 06, 08N, 09, 10, 12N, 16N	
	2.1	04S, 07, 08S, 13N, 16S, 19, 20, 27, 28, 34, 36	
	2.4	04S, 07, 08S, 13N, 16S, 19, 20, 27, 28, 34, 36	
Oklahoma City	0.6	04S, 04N, 08S, 08N, 16N, 28	
	0.9	04S, 08S, 12S	
	1.2	04S, 08S, 12S, 20, 28	
	1.5	04S, 08S, 12S, 20, 28	
	1.8	04S, 08S, 12S, 20, 28	
	2.1	04S, 08S, 12S, 20, 28	
	2.4	04S, 08S, 12S, 20, 28	
Minneapolis	0.6	04S, 08S, 13S, 16S, 19, 20	
	0.9	04S, 08S, 12S, 13S, 16S, 19, 28	
	1.2	13S	Cold winters require
	1.5	04S, 08S, 12S, 13S, 16S, 19, 20, 28	enhancement of solar
	1.8	04S, 08S, 12S, 20, 28	access.
	2.1	04S, 08S, 12S, 20, 28	
	2.4	04S, 08S, 12S, 20, 28	

8.2 FIELD APPLICATION

8.2.1 Scale Model Study

To demonstrate the application of the findings from this study, an existing four-sided atrium building on the campus of Texas A&M University (Kleberg Animal and Food Science Center) was selected. The atrium Well Index (WI) was determined to be 0.85 from a construction drawing for the building. The reflectance of solid wall area was determined to be 52 % from an on-site measurement. About half of the wall surfaces were glazed. The canopy system for the atrium building was a combination of a central waffle skylight whose opening area covers about half of the floor area and clerestory around the perimeter of atrium top below the waffle structure. Figure 8.31 shows the interior of the actual building.

Figure 8.31 Photo of Interior View of Kleberg Animal and Food Science Center, Texas A&M University, College Station, TX

A 20(w) x 20(l) x 17 (h) in. atrium scale model which duplicated major features of the actual building was constructed. A scale model of the waffle canopy structure was also constructed. Figure 8.32 shows the exterior view of the atrium scale model with the existing canopy scale model. Then, the daylighting illuminance levels at the seven floor positions were measured with the existing canopy and other canopies constructed for the parametric lighting measurements under clear and overcast sky conditions in the sky simulator. Figures 8.33 through 8.37 show various scale models of canopy systems installed on the atrium model.

To demonstrate the use of the average Effective Transmittances (ET) which were shown in Tables 6.7 and 6.8, the Base Case Daylight Factors (BCDF) of WI = 0.9 for clear and overcast skies previously shown in Table 6.1 were used to calculate the DF values with most of the canopy scale models involved in the parametric lighting measurements. However, for the waffle skylights, the ET values at WI = 0.9 were used, because the waffle skylights resulted in different ET values at different WI values. If the average ET values of the waffle skylights were used, the resulting DF values should be higher than the measured DF values, because WI = 0.9 was the second lowest atrium Well Index value and the ET increased as the WI increased. From the scale model measurements, the ET values of the existing canopy were determined as 14.2 % and 11.5 %, respectively for clear sky and overcast sky conditions.

The measured DF values were compared with the calculated DF values. Figures 8.38 and 8.39 show the plots of the measured and calculated DF values for clear sky and overcast sky, respectively. Even though the difference in the wall reflectances was 33 %, the resulting DF values were very close. This feature again implies that, in atrium spaces, the most dominant component in DF value is often the Sky Component (SC). Most of all, the two figures demonstrate that the ET data are useful in estimating atrium DF values under diffuse skies. With the ET data, the designer may, first calculate BCDF values for a designed atrium space using existing empirical models (Boyer and Kim 1988; Degelman et al. 1988) or a detailed computer model (LBL 1985), and then can find resulting DF values for various canopy options.

Figure 8.32 Photo of Existing Canopy Scale Model Installed on Kleberg Atrium Building Scale Model

Figure 8.33 Photo of 4-Unit Sawtooth Canopy Installed on Kleberg Atrium Building Scale Model

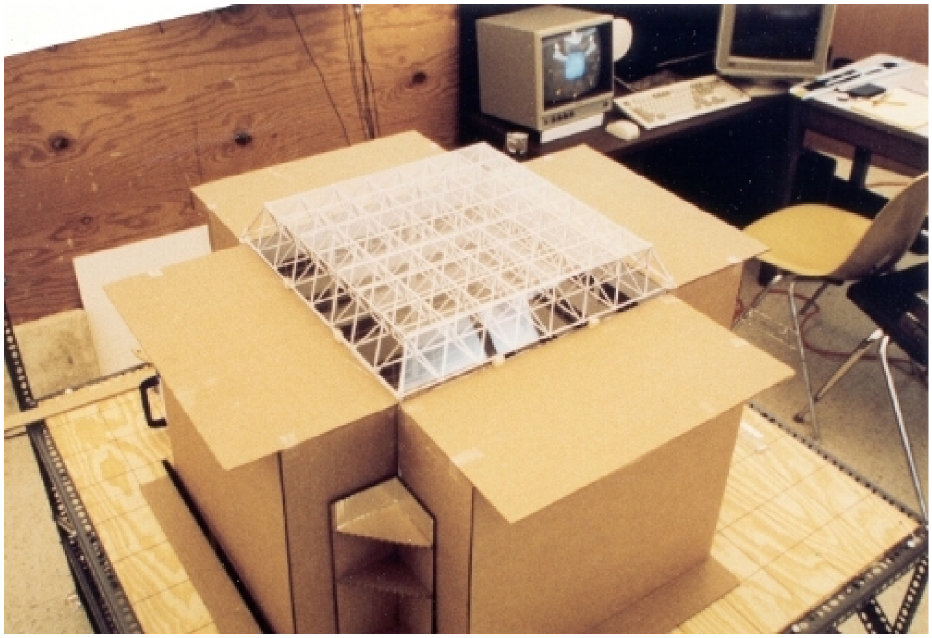

Figure 8.34 Photo of Flat Horizontal Skylight Installed on Kleberg Atrium Building Scale Model

Figure 8.35 Photo of Barrel Vault Skylight Installed on Kleberg Atrium Building Scale Model

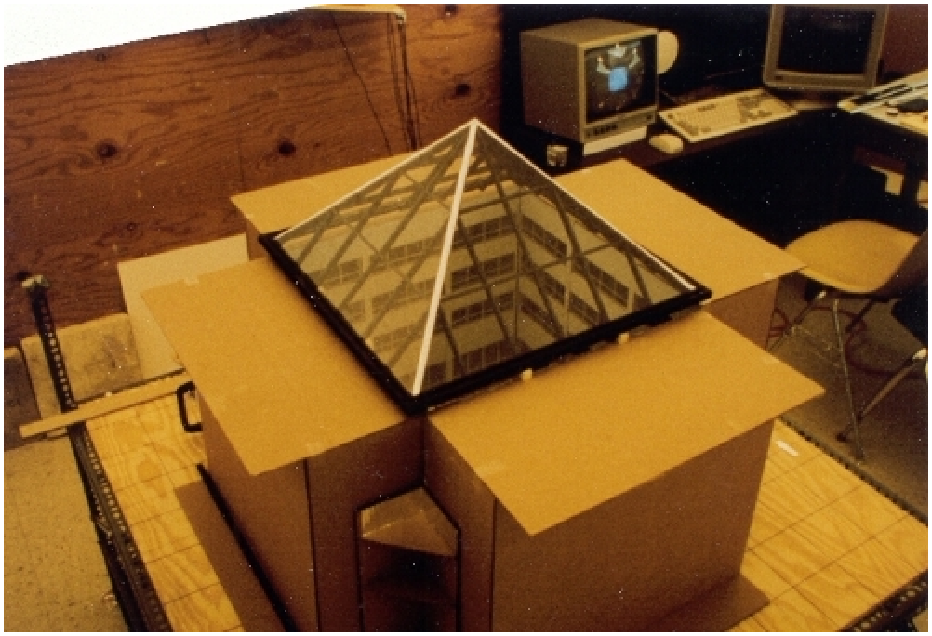

Figure 8.36 Photo of Pyramid Skylight Installed on Kleberg Atrium Building Scale Model

Figure 8.37 Photo of Waffle Skylight Installed on Kleberg Atrium Building Scale Model

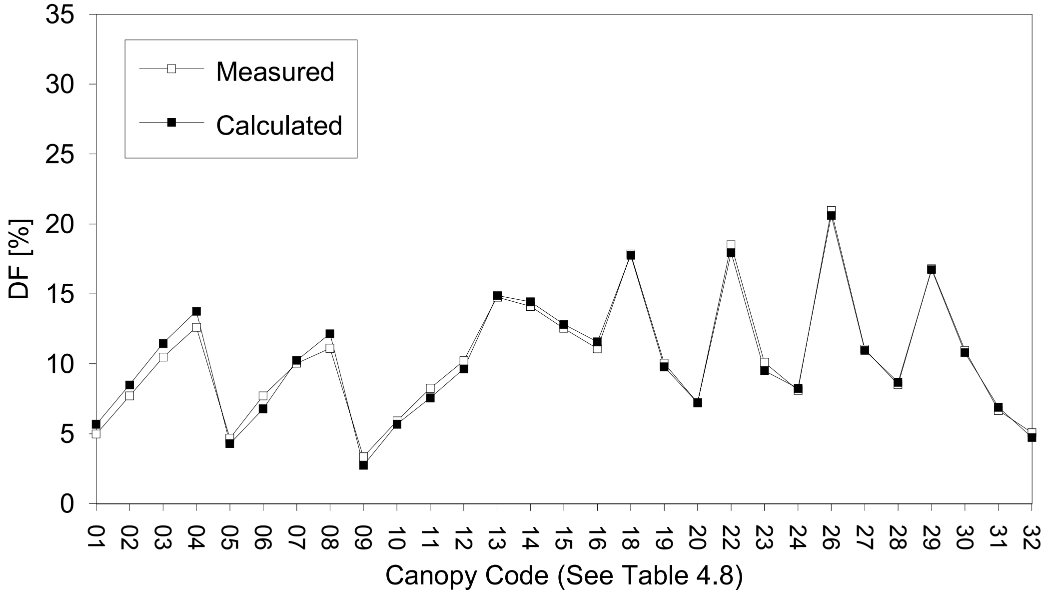

Figure 8.38 Measured and Calculated Daylight Factors in Kleberg Atrium Building for Clear Sky

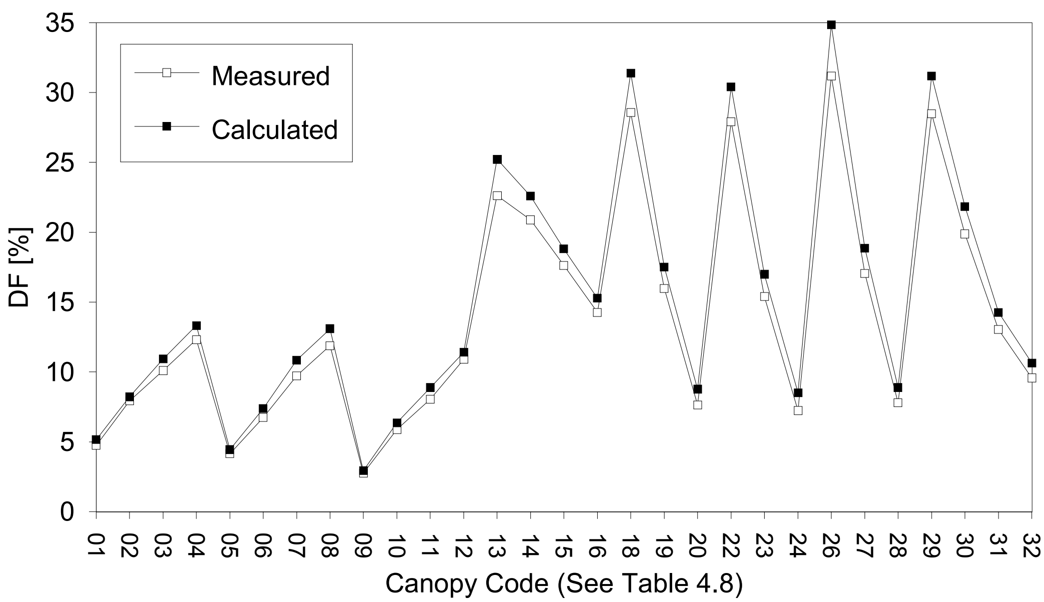

Figure 8.39 Measured and Calculated Daylight Factors in Kleberg Atrium Building for Overcast Sky

Finally, the average DF value for overcast sky obtained from the scale model measurement was compared with that for an on-site measurement conducted in a previous study (Kim et al. 1985). The average DF value 6.15 % measured without glazing material was corrected to 3.7 % using the previous Equation 8.4 to account for the Hemispherical Transmittance of the glazing material (0.88 for clear transparent glazing) and the Light Loss Factor (0.7 for horizontal glazing). The average DF value from the previous study (Kim et al. 1985) was 3.4 %. This good agreement proved that scale model photometry is a very accurate method in estimating the Daylight Factors in the atrium space during the early stages of a design process.

8.2.2 Actual Building Study

An actual building study was conducted for two different sky conditions. The first on-site lighting measurement was conducted at 2:00 p.m. on June 21 under a rainy sky with only a photometric sensor to examine if the atrium provided enough light for the interior plants under the unfavorable sky condition. The average illuminance at the floor positions was measured at 950 lux even under the rainy sky.

Another on-site lighting measurement was made at noon on September 21 under a clear sky condition with full sunlight. At that time, the video-based luminance mapping system as well as a photometric sensor were involved. With the mapped luminances, the Luminance Index values on south, north, and west wall areas were calculated. In addition, the Sunlight Patch Location (SPL) and Sunlight Patch Size (SPS) on the north wall area were determined with the digital image analysis program. Since the luminance in the field was much higher than the sky simulator, in which the video-based luminance mapping system was calibrated, the pixels for the opening area were saturated. However, the sunlight patches were still distinct. Figure 8.40 shows the LI values on the three walls. As indicated in the figure, the average luminance of the sunlight patch area was about 6 times that of other wall area. This value was far below the maximum Luminance Ratio 20 recommended by IESNA (see Table 2.2). In addition, as shown in Figure 8.41, the SPS (total Configuration Factors of the sunlight patch areas) was calculated as 0.0052. This value represented 2.9 % of the Configuration Factor of the north wall viewed from the center floor position. Figure 8.41 also shows the segmented sunlight patches along the solid wall area due to the waffle walls.

From this field measurement, it was concluded that the video-based luminance mapping system required further calibration with a much higher luminance situation.

Nevertheless, it was a convenient tool to determine geometric information of daylighting and sunlighting related elements for this actual building study.

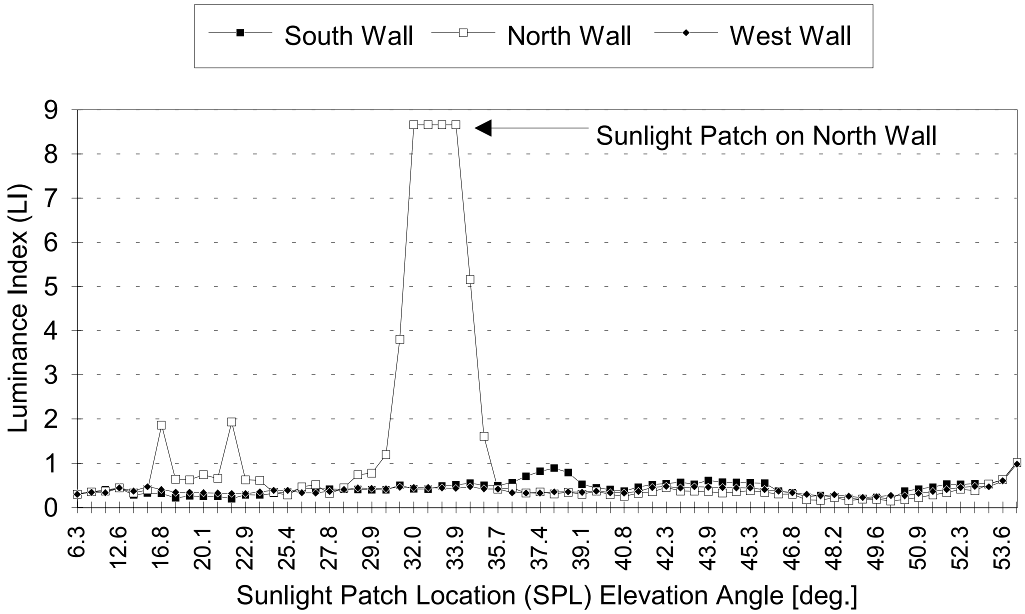

Figure 8.40 Luminance Index Values on Three Walls of Kleberg Atrium Building under Clear Sky with Sun

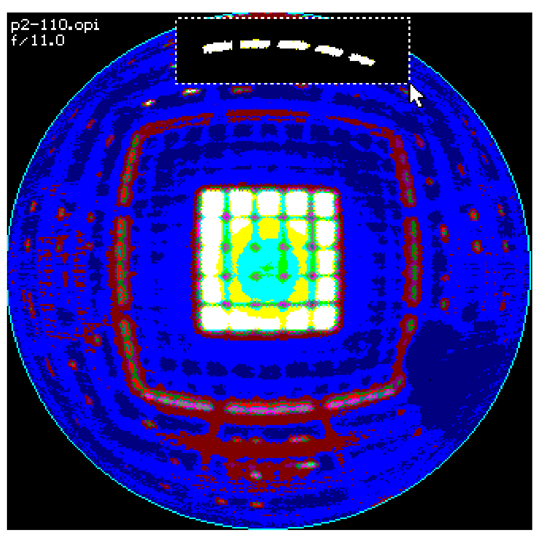

Figure 8.41 Sunlight Patches on North Wall of Kleberg Atrium Building (SPL = 27°-31°, SPS = 0.0052, 2.9 % of North Wall)