CHAPTER VI

DATA ANALYSIS AND RESULTS FOR DIFFUSE SKIES

6.1 DAYLIGHT ILLUMINANCE LEVELS IN ATRIA

6.1.1 Average Daylight Factors without Canopy

The Daylight Factor (DF) data calculated from the measured daylight illuminance levels under the simulated clear and overcast sky conditions were analyzed to examine how the geometric configuration of atrium well affected interior daylight illuminance levels.

First of all, in order to observe overall pictures of the effects of atrium Well Index (WI) on illuminance levels under clear sky and overcast sky conditions, the average DF value at each WI was calculated and plotted as shown in Figure 6.1. As indicated in the figure, the reduction patterns of the average DF values, as WI increased, for the two different sky conditions were very similar to each other. However, the average DF values under overcast sky were average about 12 % higher than they were under clear sky condition.

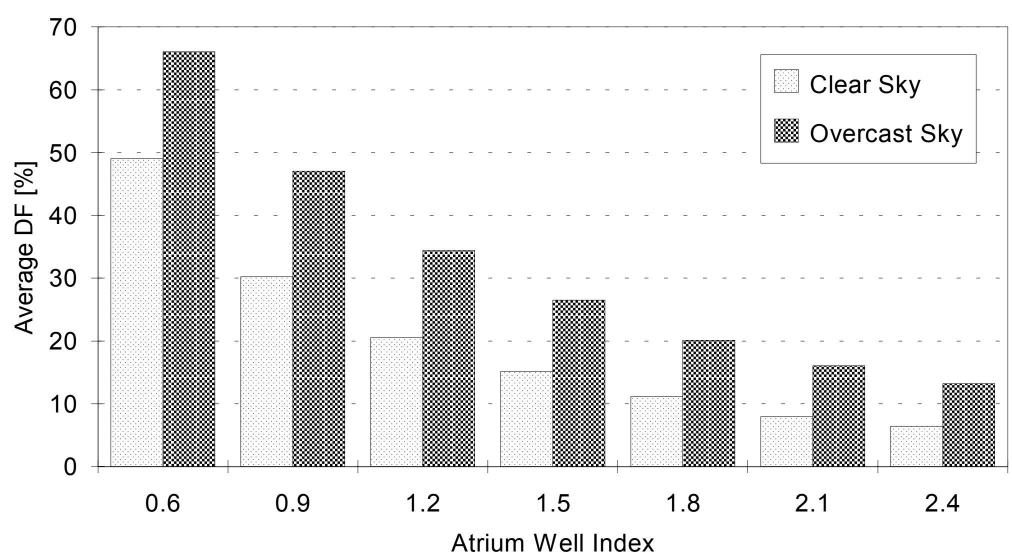


Figure 6.1 Average Daylight Factors under Clear Sky and Overcast Sky Conditions without Canopy

The average DF values at the lowest WI (0.6) were determined as 49 % and 66 %, respectively for clear sky and overcast sky conditions. These two values indicated that the shallow atrium already blocked 51 % of externally available daylight under clear sky and 34 % under overcast sky. Again, the average DF values at the highest WI (2.4) were determined as 7 % and 14 % for clear sky and overcast sky, respectively. These values indicated that the deep atrium blocked 93 % of the available daylight under clear sky and 86 % under overcast sky. These reductions can be considered the primary effects of the atrium well. Meanwhile, the different DF values under different sky conditions might be considered the effect of different luminance distributions on clear sky and overcast sky vaults. The overall higher average DF values under overcast sky might be attributed to the fact that the overcast sky has higher luminances near zenith than those on clear sky, to which the top opening faces.

To examine more closely the effects of atrium well configuration, the data obtained from the atria with flat-black interiors were utilized. Since the flat-black interior had near zero reflectance, the measured illuminances were converted into Sky Components (SC). Then, Internally Reflected Components (IRC) were obtained by subtracting SC values from corresponding DF values. Table 6.1 summarizes the DF, SC, and IRC values. Then, the SC and IRC values were plotted in Figures 6.2 and 6.3 for clear sky and overcast sky conditions, respectively. The average SC and IRC values under both sky conditions decreased as WI increased. It was noted that the SC values were always greater than the IRC values even in deep atria. The average portions of IRC values in DF values were 39.9 % for clear sky and 31.4 % for overcast sky. Finally, it was concluded that the reduction patterns of DF values were mainly dominated by SC values.

TABLE 6.1

Measured Average DF and SC and Calculated IRC Values without Canopy

WI	Clear Sky			Overcast Sky		
	DF [%]	SC [%]	IRC [%]	DF [%]	SC [%]	IRC [%]
0.6	49.03	33.03	16.00	66.03	49.96	16.07
0.9	30.24	19.20	11.04	47.01	34.07	12.94
1.2	20.54	12.09	8.45	34.40	24.17	10.23
1.5	15.16	8.40	6.76	26.51	18.13	8.38
1.8	11.17	6.30	4.87	20.09	13.60	6.49
2.1	7.96	4.79	3.17	16.03	10.31	5.72
2.4	6.43	3.79	2.64	13.20	8.09	5.11

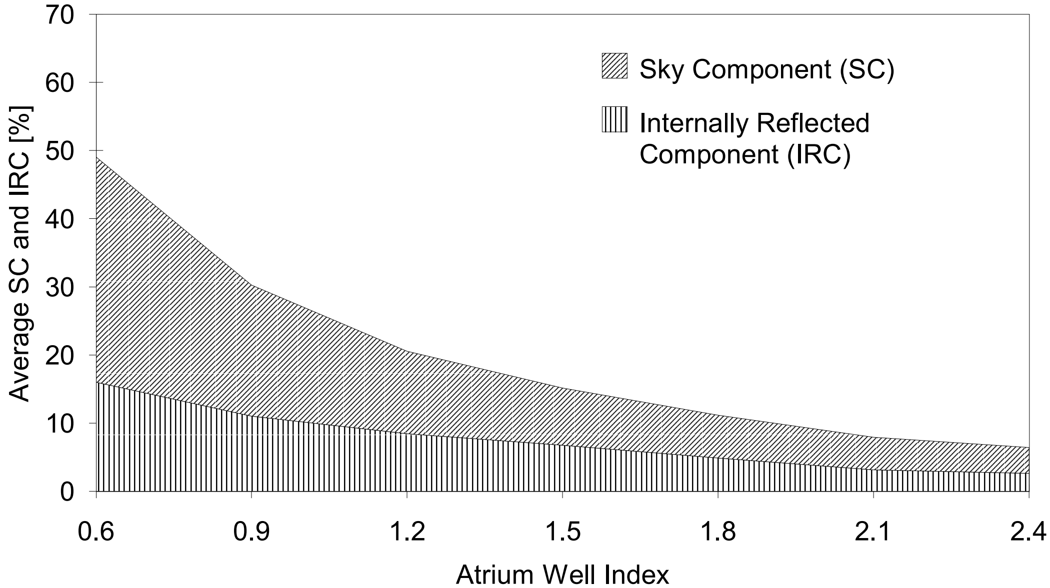


Figure 6.2 Average SC and IRC under Clear Sky without Canopy

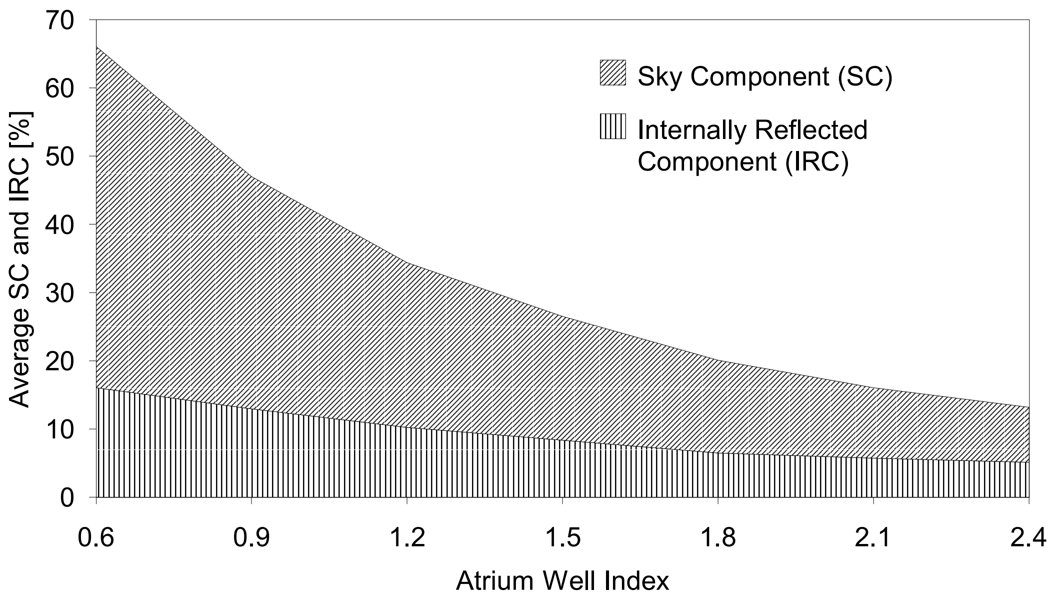


Figure 6.3 Average SC and IRC under Overcast Sky without Canopy

Since it was concluded that the reduction patterns of DF values were mainly the reductions in SC values as WI increased, it is again needed to examine why SF values decreased as WI increased with the observed patterns.

For this purpose, the different WI values which are purely geometric properties need to be examined in terms of Sky Factors (SF). Here, SF is a different property from SC. As discussed in Chapter 2, SC is the photometric property which is a portion of DF. On the other hand, SF indicates a purely geometric relationship between the opening and a point of interest on atrium floor, which can be called "configuration factor" of the opening at that point. However, SF can also be considered photometric property when the sky is totally diffuse and uniform (Hopkinson et al. 1966, p. 71).

As shown in Figure 6.4, when a vertical line is drawn from point P perpendicularly to the opening, the opening can be divided into four rectangular sectors. Then, the Sky Factor of the sector 1 defined by width W1, length L1, and height H can be calculated by Equation 6.1 (Higbie 1934, p. 167; Hopkinson et al. 1966, p. 110). Then, the SF of the whole opening can be obtained by calculating and summing the four configuration factors.

$$SF_i = \frac{1}{2\pi}\left(\frac{w_i}{\sqrt{h^2+w_i^2}}\tan^{-1}\frac{l_i}{\sqrt{h^2+w_i^2}} + \frac{l_i}{\sqrt{h^2+l_i^2}}\tan^{-1}\frac{l_i}{\sqrt{h^2+l_i^2}}\right) \tag{6.1}$$

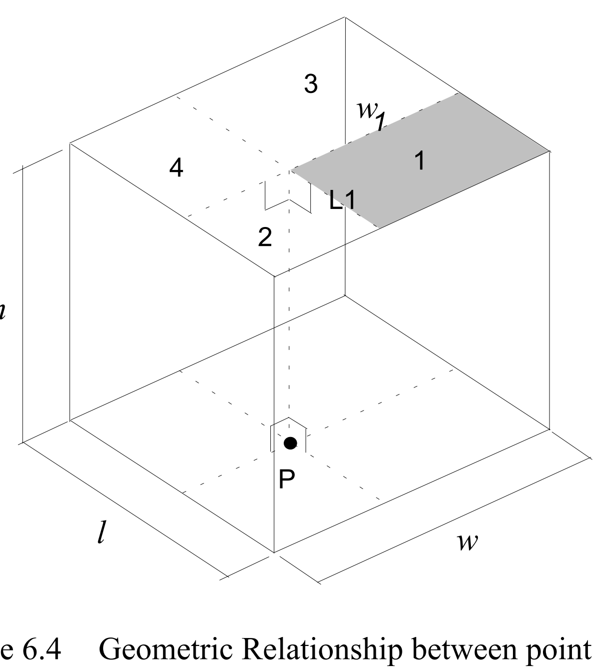


Figure 6.4 Geometric Relationship between point P and Horizontal Opening to Calculate Sky Factor

After calculating SF values at the seven floor positions using Equation 6.1, the averages of calculated SF values and the measured SC values in Table 6.1 were compared as shown in Figure 6.5. As indicated in the figure, the reduction patterns in SC values were closely related with that of SF. In other words, the configuration factor of the opening mainly determine the reduction patterns in Sky Components (SC).

The different magnitudes between the different sky conditions might be attributed to the different sky luminance distributions. Overcast sky has the highest luminance at zenith area and clear sky has the lowest at zenith area, while the calculated SF values represent "SC of a totally diffuse uniform sky". Since the atrium top opening faces the zenith area, it can be easily concluded that the different weights in sky luminance distribution determines the magnitudes of Sky Factors at different Well Index values.

Figures 6.6 through 6.9 show several examples of calculated SF values at every 0.5" (1 ft) interval.

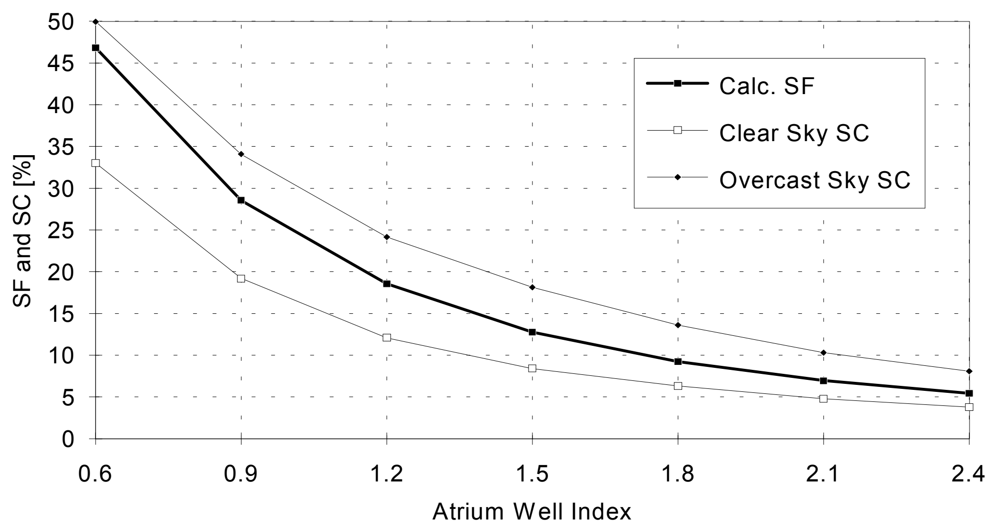


Figure 6.5 Averages of Calculated Sky Factors (SF) and Measured Sky Components (SC) without Canopy

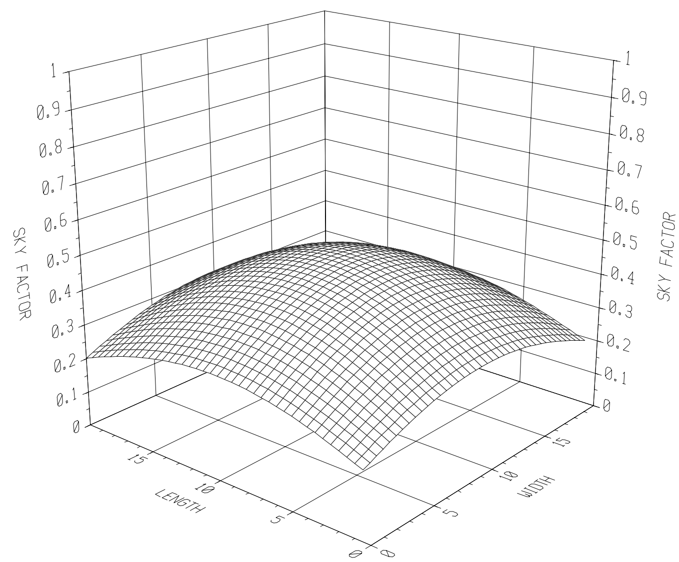


Figure 6.6 Calculated Sky Factor at WI = 0.6 (Atrium A2)

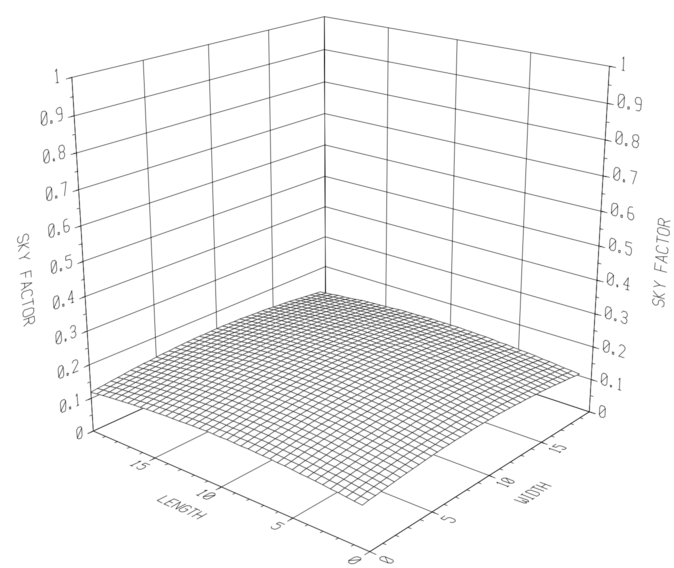


Figure 6.7 Calculated Sky Factor at WI = 1.2 (Atrium A4)

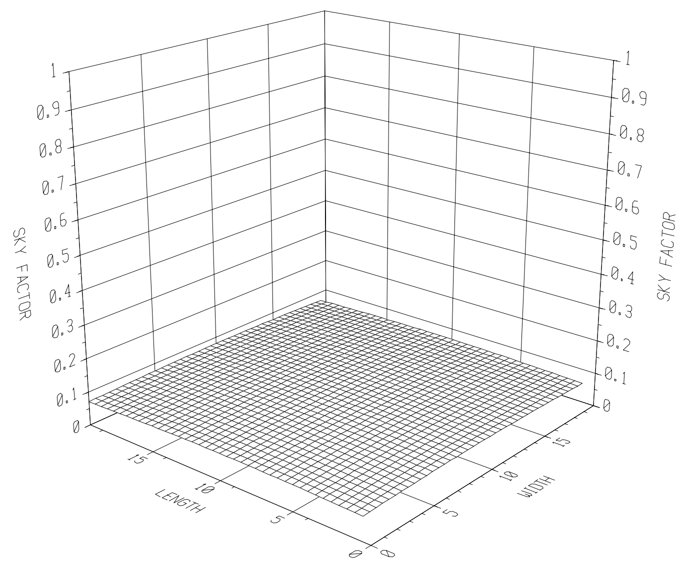


Figure 6.8 Calculated Sky Factor at WI = 1.8 (Atrium A6)

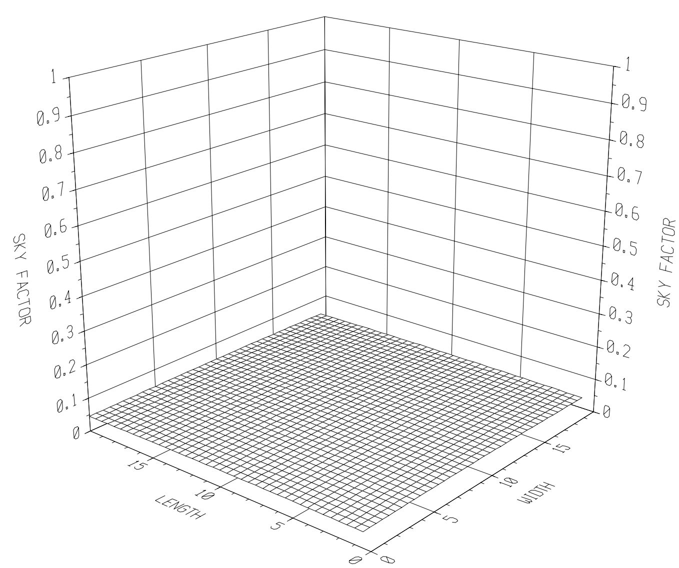


Figure 6.9 Calculated Sky Factor at WI = 2.4 (Atrium A8)

6.1.2 Daylight Factors and Distributions without Canopy

As discussed in Chapter 4, the Base Case Daylight Factors (BCDF) were defined as the DF values on the seven points calculated from the measured illuminance levels inside atria without canopy systems. Tables 6.2 and 6.3 show the BCDF values at the seven different WI values for clear sky and overcast sky conditions, respectively.

TABLE 6.2
Measured Base Case DF Values for Clear Sky

WI	Floor Position (See Figure 5.1)							Ave
	1	2	3	4	5	6	7	
0.6	47.5	57.1	43.5	47.8	48.5	49.8	49.0	49.03
0.9	29.6	34.8	26.8	29.0	30.1	30.8	30.6	30.24
1.2	20.7	22.9	19.5	20.6	20.6	20.0	19.5	20.54
1.5	14.8	16.3	13.4	14.4	15.7	16.2	15.3	15.16
1.8	10.8	12.0	10.4	11.0	11.8	11.0	11.2	11.17
2.1	7.5	8.7	7.5	8.0	8.0	8.0	8.0	7.96
2.4	6.4	7.0	6.4	6.3	6.3	6.3	6.3	6.43

TABLE 6.3
Measured Base Case DF Values for Overcast Sky

WI	Floor Position (See Figure 5.1)							Ave
	1	2	3	4	5	6	7	
0.6	65	76.3	57.5	65.7	65.5	67.5	64.7	66.03
0.9	46.7	53.9	41.7	46.9	46.5	47.2	46.2	47.01
1.2	34.1	39.3	32.9	33.6	33.6	33.7	33.6	34.40
1.5	27.1	29.7	24.1	25.1	26.4	26.4	26.8	26.51
1.8	20.2	22.0	20.1	19.1	20.3	20.3	19.3	20.09
2.1	16.2	17.4	14.5	15.4	16.1	16.8	15.8	16.03
2.4	12.8	14.3	12.9	13.2	13.1	13.0	13.1	13.20

Figures 6.10 and 6.11 show the BCDF values at the seven floor positions at the seven WI values for clear sky and overcast sky, respectively. It was noted that the DF values on the center floor position (No. 2) were always higher than those on other positions, for both sky conditions. However, the differences were higher in shallow atria than they were in deep atria. The differences between DF values on the center floor position and the average DF values on the remaining floor positions are presented in Table 6.4. As shown in the table, the largest differences were 9.42 % for clear sky and 11.98 % for overcast sky. For both sky conditions, the differences became smaller as WI increased. This might be easily explained by the calculated SF values shown in the previous Figures 6.6 through 6.9.

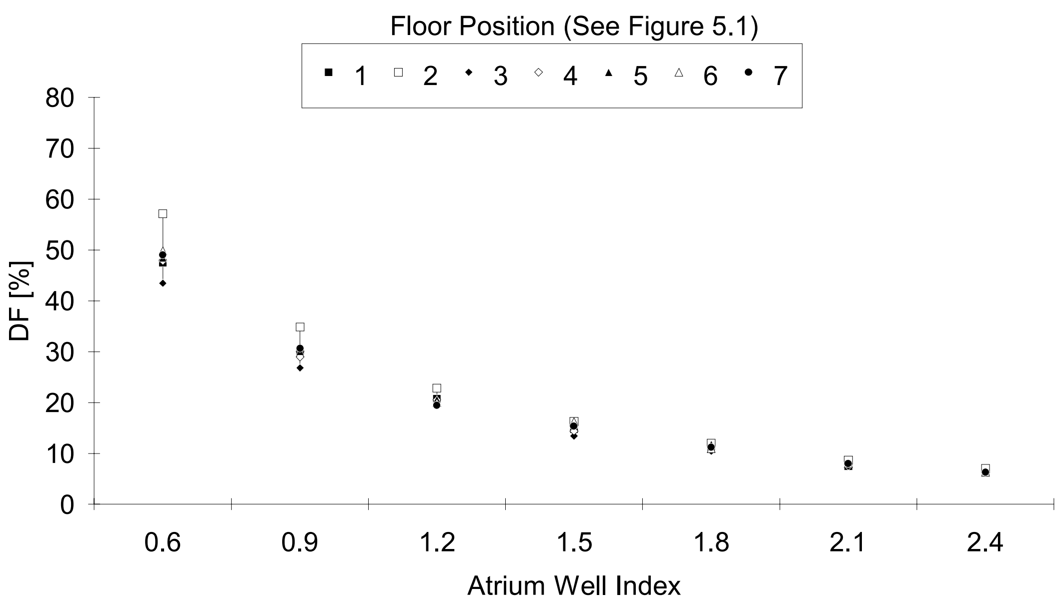


Figure 6.10 Base Case DF Distributions under Clear Sky

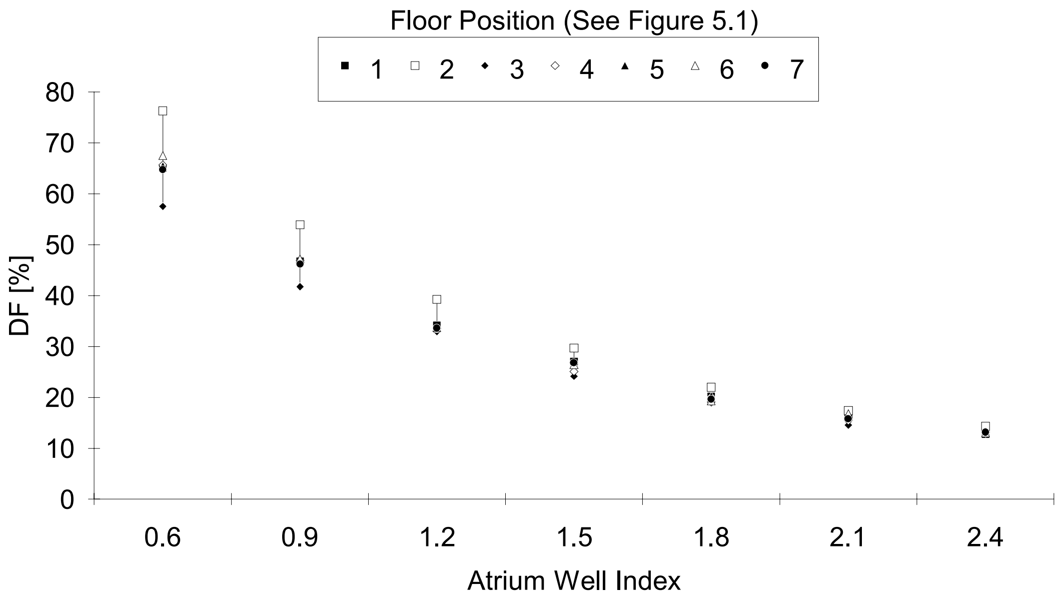


Figure 6.11 Base Case DF Distributions under Overcast Sky

TABLE 6.4
DF Differences between Center Floor Position
and Average of Remaining Positions

WI	Clear Sky	Overcast Sky
0.6	9.42	11.98
0.9	5.32	8.03
1.2	2.75	5.72
1.5	1.33	3.72
1.8	0.97	2.23
2.1	0.87	1.60
2.4	0.67	1.28

6.1.3 Average Daylight Factors with Canopies

The average DF values obtained inside the seven different atria with the 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.

First, the average DF values obtained with the canopy systems are presented in Tables 6.5 and 6.6 for clear sky and overcast sky, respectively. Then, the measured average Base Case DF (BCDF) values and those of canopy systems are comparatively plotted for each of the seven WI values to observe general trends of the canopy effects as shown in Figures 6.12 through 6.25.

At a first glance of the figures, even without calculations on the reductions in the average DF values due to the canopy systems, two notable phenomena were observed. First, it was clearly observed that each canopy system performed differently under the two different sky conditions. Second, it was also observed that there were certain predictable trends in the absolute DF values as canopy configuration varied.

The first phenomenon can be related to the effects of the sky luminance distribution and the orientation of canopy aperture. As discussed in the previous sections, the BCDF values were different for the two different sky conditions. By the same token, for a canopy system, different luminance distributions on the sky patches seen through the aperture will provide different light flux to the floor positions and other interior surfaces.

On the other hand, when the changing patterns of DF values are examined across the different canopy systems, it can be noted that the different geometric and photometric configurations of the canopy systems have certain predictable relationships with the resulting DF values.

For example, 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. Finally, the waffle skylights (No. 29 through 36) proved that the geometric configuration (i.e., Waffle Well Index or WWI) has stronger impact than the reflectances of the waffle surfaces.

TABLE 6.5

Average Daylight Factors for Clear Sky with 36 Canopy Configurations

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	8.60	5.21	3.84	2.90	2.29	1.49	1.24
02	13.14	7.81	6.03	4.24	3.24	2.30	1.84
03	17.30	10.66	8.11	5.77	4.36	3.04	2.57
04	20.41	12.84	9.76	7.01	5.31	3.57	3.09
05	6.86	3.97	3.14	2.19	1.34	1.39	0.83
06	11.43	6.81	4.96	3.59	2.64	1.49	1.34
07	15.59	9.61	7.13	5.21	3.91	2.81	2.16
08	17.80	11.34	8.63	6.09	4.70	3.17	2.79
09	4.34	3.27	1.89	1.49	1.06	0.50	0.57
10	8.56	6.03	3.80	2.99	2.03	1.49	1.23
11	11.99	8.06	5.30	3.84	2.81	1.96	1.46
12	14.23	9.71	7.00	5.10	3.37	2.81	1.84
13	23.09	14.49	10.57	7.51	5.44	4.17	3.04
14	22.07	14.16	10.31	7.30	5.31	4.03	2.94
15	19.97	12.71	9.29	6.54	4.89	3.14	2.71
16	17.76	11.33	8.26	5.73	4.04	2.99	2.71
17	29.86	20.46	14.19	10.34	7.44	5.74	4.47
18	26.11	17.80	12.53	9.23	6.17	4.80	3.97
19	14.06	9.53	6.77	4.73	3.39	2.99	2.19
20	10.06	6.99	5.10	4.17	2.99	1.70	1.49
21	31.61	21.14	14.37	10.31	7.37	5.63	4.44
22	27.61	18.37	12.57	8.94	6.33	4.53	4.16
23	15.04	10.26	6.67	4.64	3.14	2.99	1.71
24	10.97	8.06	6.07	4.47	3.01	2.51	1.56
25	34.20	23.37	16.24	11.60	8.13	6.16	4.61
26	29.94	20.09	14.34	10.37	7.60	5.86	4.47
27	16.01	11.03	7.59	5.57	3.89	2.99	2.49
28	11.26	8.41	6.07	4.59	3.31	2.93	1.53
29	23.04	16.74	12.13	9.06	6.83	5.37	4.33
30	13.47	10.77	8.53	6.59	5.21	4.40	3.33
31	8.46	6.89	5.89	4.64	3.79	3.10	2.59
32	5.56	4.74	4.37	3.63	3.10	2.61	1.94
33	26.40	18.94	13.24	10.21	7.51	5.93	4.41
34	19.11	14.50	10.63	8.19	6.07	4.67	3.84
35	12.01	9.26	7.13	5.70	4.40	3.60	2.99
36	7.14	6.07	5.02	4.26	3.53	3.01	2.57

* See Table 4.8 for Canopy Code

TABLE 6.6

Average Daylight Factors for Overcast Sky with 36 Canopy Configurations

Canopy	Atrium Well Index						
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4
01	6.46	4.61	3.27	2.41	1.93	1.49	1.26
02	10.01	7.33	5.31	4.06	3.11	2.30	1.94
03	13.46	9.74	7.06	5.39	3.91	3.06	2.69
04	15.94	11.21	8.49	6.64	5.09	3.80	3.33
05	5.53	3.91	2.81	2.21	1.67	1.23	1.07
06	9.20	6.66	4.74	3.67	2.69	2.01	1.79
07	13.29	9.54	6.84	5.34	4.13	3.04	2.64
08	15.83	11.49	8.49	6.46	4.73	3.73	3.24
09	3.86	2.77	1.90	1.37	0.97	0.83	0.70
10	8.13	5.81	4.11	3.24	2.24	1.73	1.47
11	11.40	8.14	5.79	4.46	3.14	2.51	1.96
12	14.46	10.41	7.41	5.71	4.20	3.19	2.54
13	30.47	21.30	15.98	12.39	9.80	7.23	6.19
14	27.90	19.63	14.32	10.98	8.11	6.76	5.49
15	23.37	16.63	12.15	9.11	6.68	5.50	4.54
16	18.96	13.61	10.02	7.35	5.45	4.41	3.68
17	41.39	31.09	23.37	18.27	13.67	10.31	8.64
18	36.11	27.16	20.34	15.94	11.93	9.14	7.49
19	19.96	15.01	11.39	8.87	6.70	5.09	4.23
20	10.26	7.63	5.64	4.44	3.33	2.56	2.06
21	42.36	31.21	22.94	17.57	13.43	10.23	8.67
22	36.57	26.84	19.46	14.96	11.40	8.74	7.31
23	20.29	14.79	10.71	8.27	6.34	5.04	4.14
24	9.80	7.37	5.26	4.13	3.21	2.64	2.10
25	46.71	35.29	26.20	20.17	15.41	12.47	9.61
26	39.77	29.87	22.77	17.23	13.09	10.70	8.27
27	21.66	16.39	12.24	9.39	7.11	5.76	4.43
28	10.46	7.59	5.69	4.36	3.36	2.69	2.11
29	35.46	27.01	21.11	16.57	13.61	10.81	8.49
30	23.13	18.91	15.40	12.69	10.60	8.76	6.96
31	15.20	12.36	10.57	9.02	7.76	6.59	5.33
32	10.73	9.23	8.13	7.16	6.21	5.50	4.51
33	37.71	28.34	21.83	16.97	13.97	11.24	8.90
34	28.73	22.50	17.80	14.22	11.70	9.69	7.81
35	18.43	15.07	12.44	10.19	8.63	7.31	5.93
36	11.87	9.93	8.60	7.40	6.44	5.60	4.77

* See Table 4.8 for Canopy Code

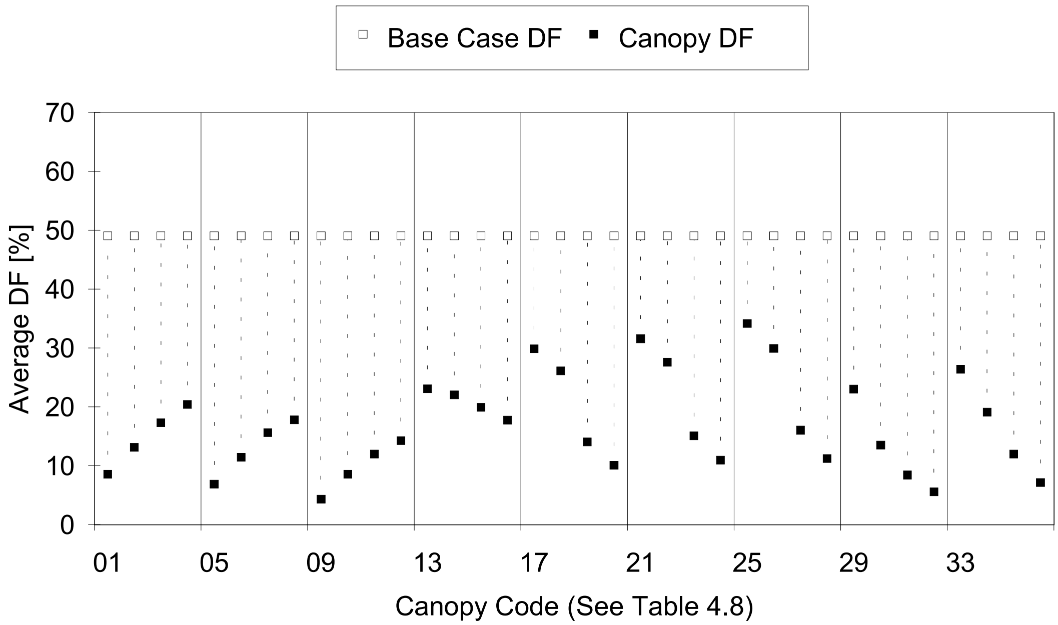


Figure 6.12 Clear Sky Average Daylight Factors at WI = 0.6 (Atrium A2) with 36 Canopy Configurations

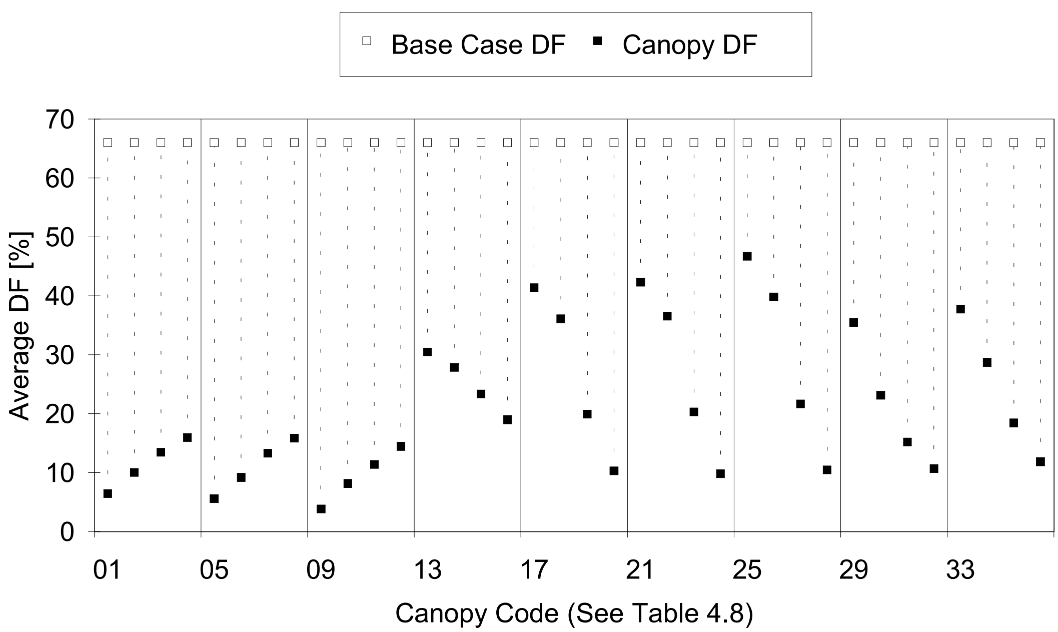


Figure 6.13 Overcast Sky Average Daylight Factors at WI = 0.6 (Atrium A2) with 36 Canopy Configurations

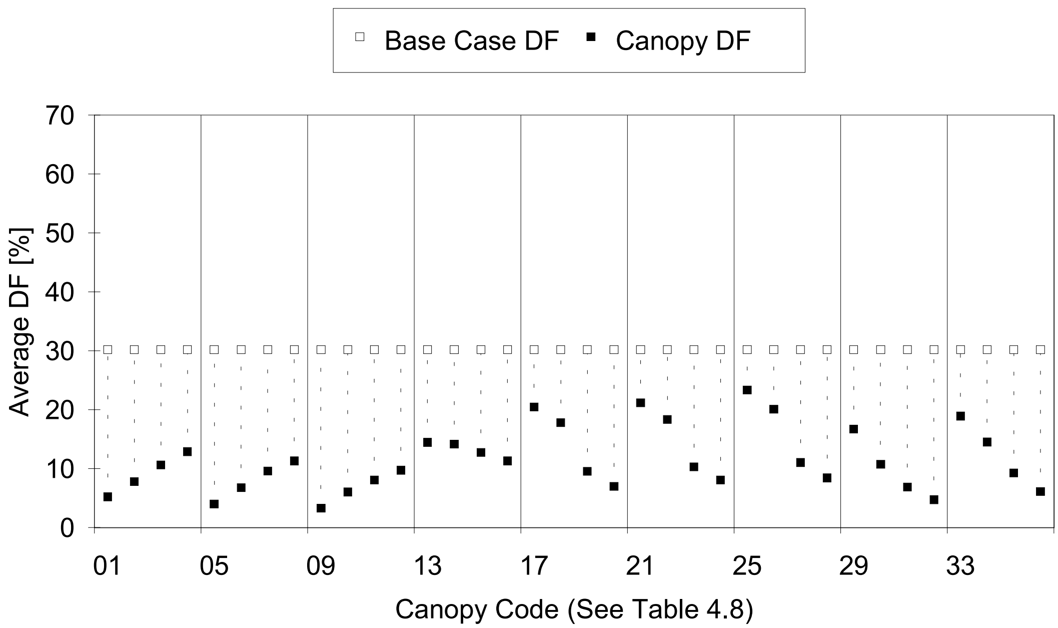


Figure 6.14 Clear Sky Average Daylight Factors at WI = 0.9 (Atrium A3) with 36 Canopy Configurations

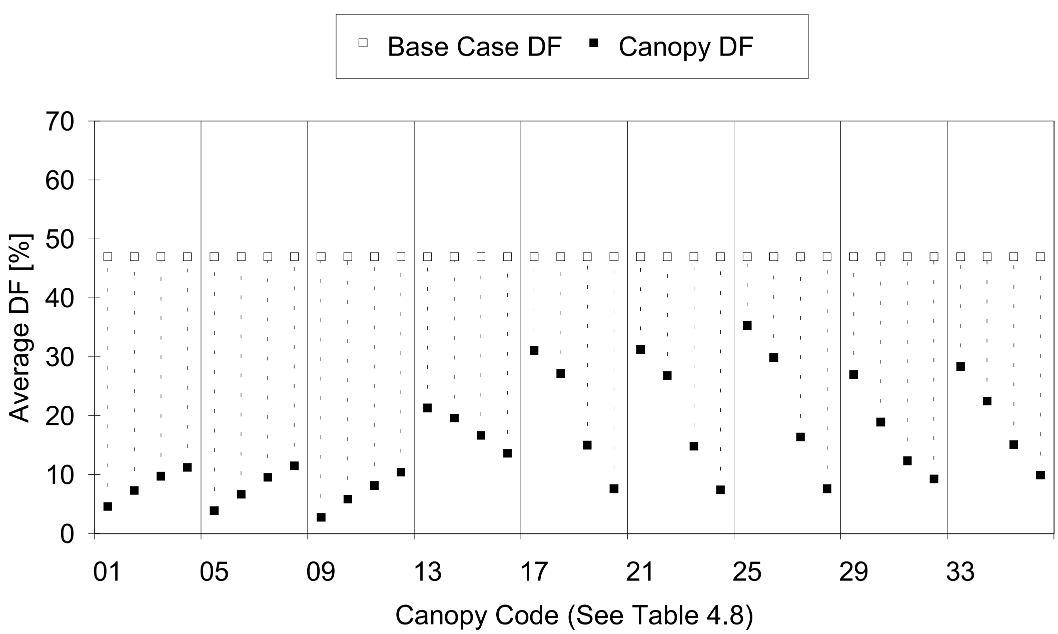


Figure 6.15 Overcast Sky Average Daylight Factors at WI = 0.9 (Atrium A3) with 36 Canopy Configurations

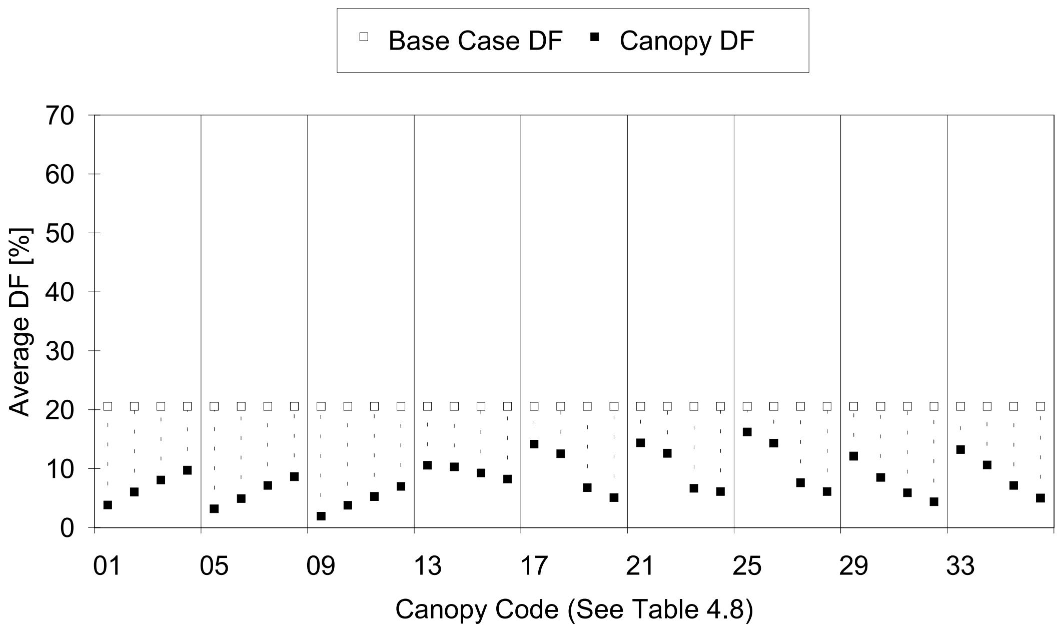


Figure 6.16 Clear Sky Average Daylight Factors at WI = 1.2 (Atrium A4) with 36 Canopy Configurations

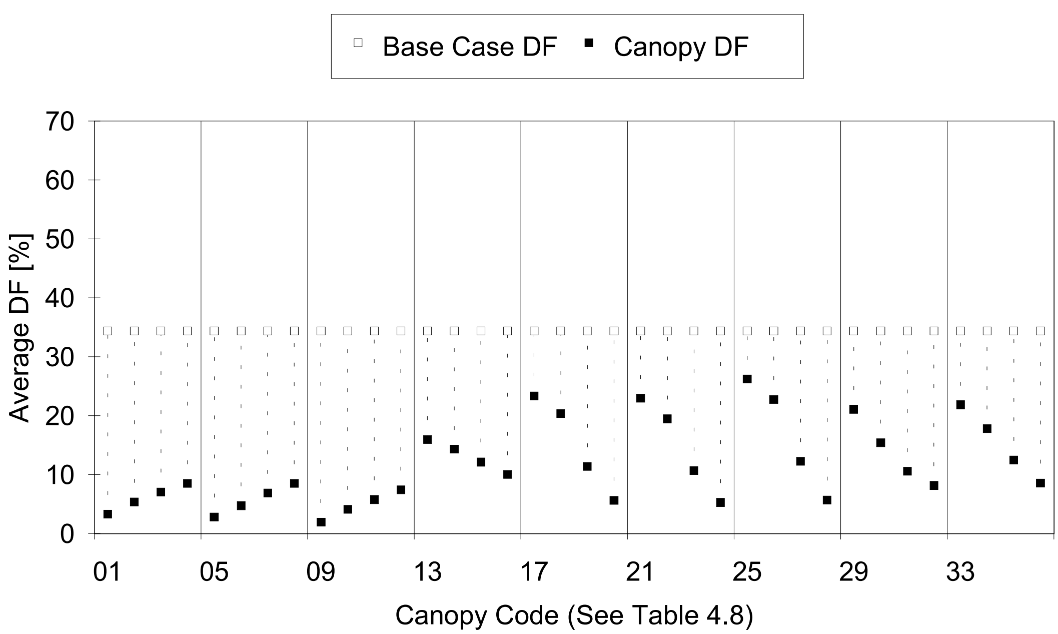


Figure 6.17 Overcast Sky Average Daylight Factors at WI = 1.2 (Atrium A4) with 36 Canopy Configurations

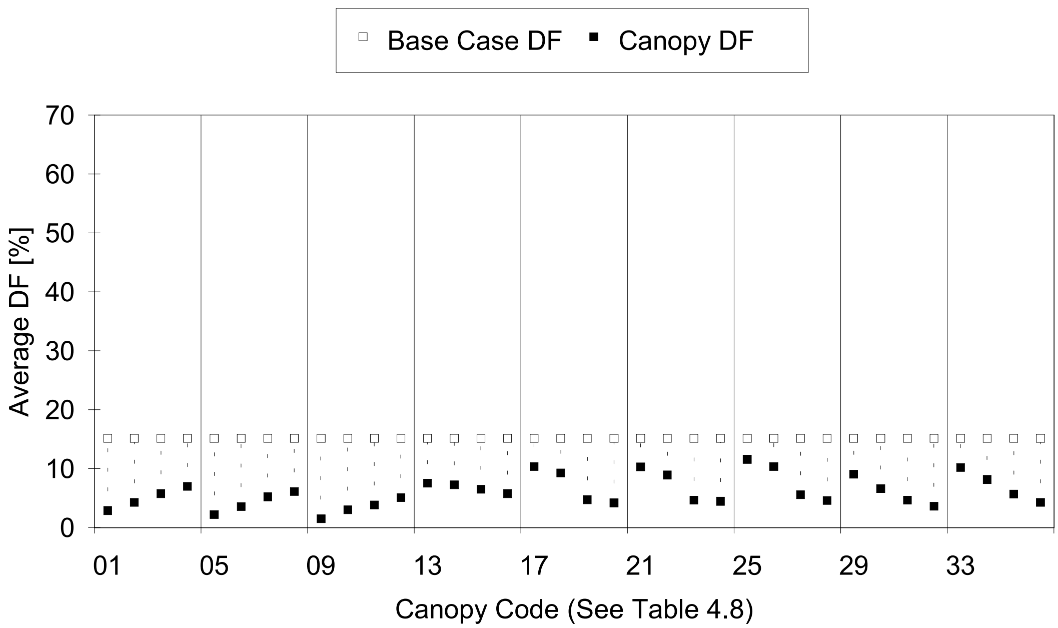


Figure 6.18 Clear Sky Average Daylight Factors at WI = 1.5 (Atrium A5) with 36 Canopy Configurations

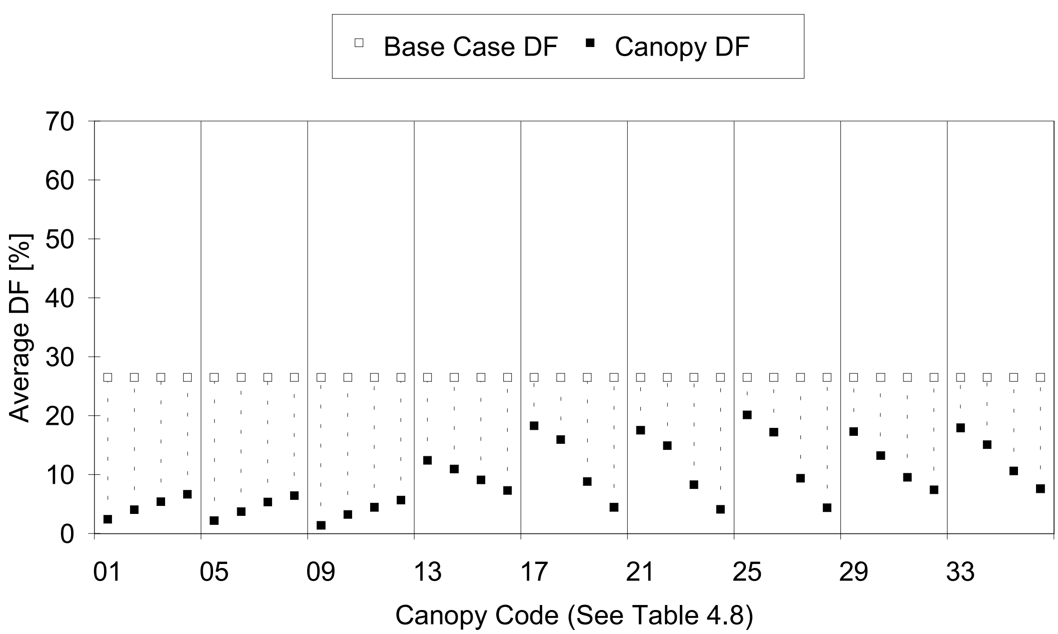


Figure 6.19 Overcast Sky Average Daylight Factors at WI = 1.5 (Atrium A5) with 36 Canopy Configurations

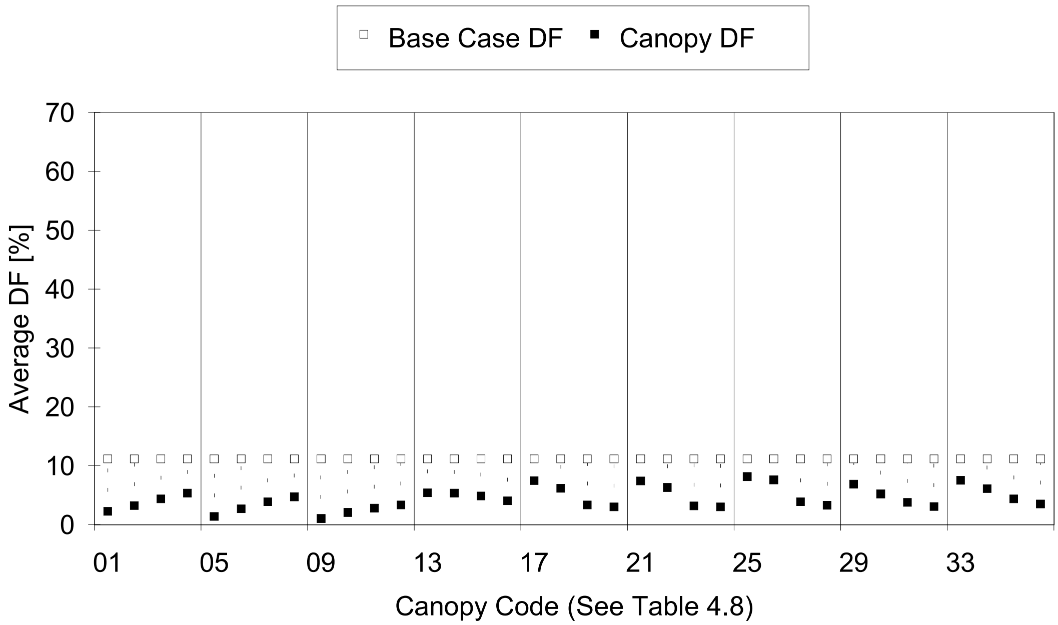


Figure 6.20 Clear Sky Average Daylight Factors at WI = 1.8 (Atrium A6) with 36 Canopy Configurations

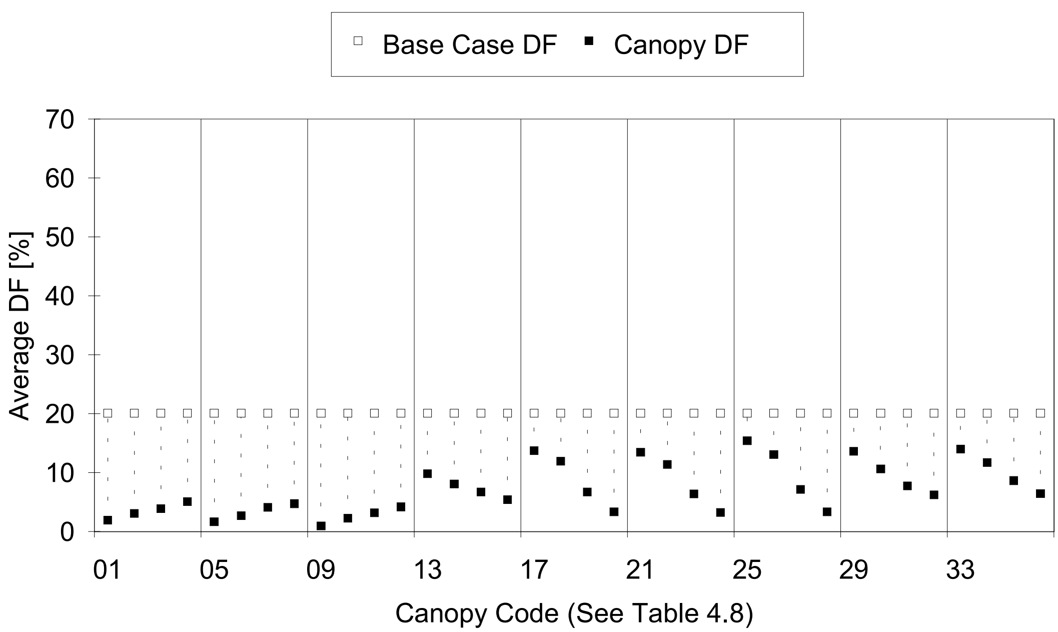


Figure 6.21 Overcast Sky Average Daylight Factors at WI = 1.8 (Atrium A6) with 36 Canopy Configurations

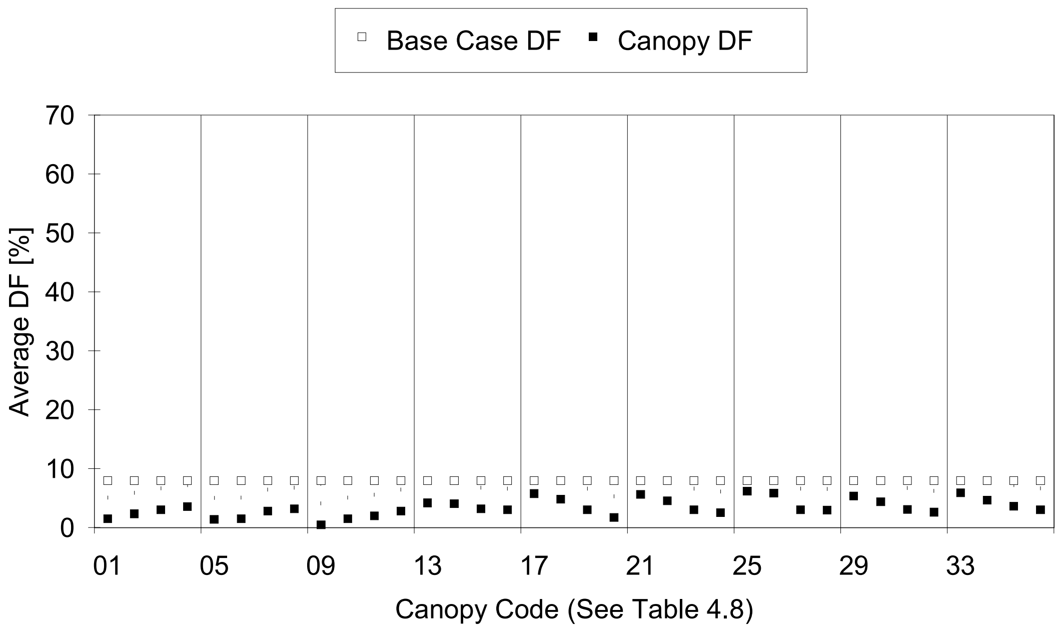


Figure 6.22 Clear Sky Average Daylight Factors at WI = 2.1 (Atrium A7) with 36 Canopy Configurations

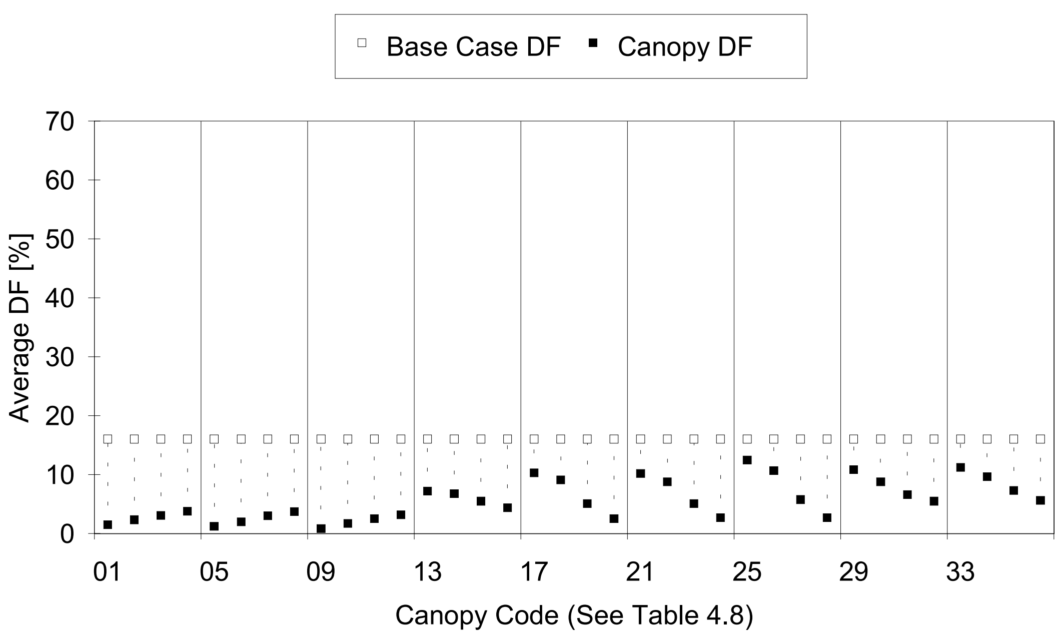


Figure 6.23 Overcast Sky Average Daylight Factors at WI = 2.1 (Atrium A7) with 36 Canopy Configurations

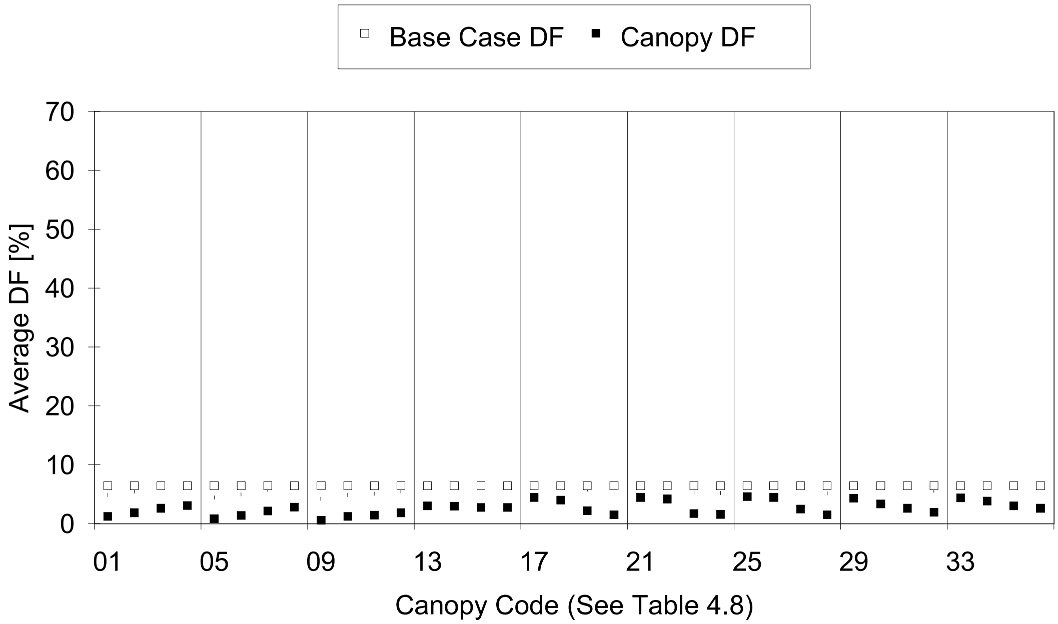


Figure 6.24 Clear Sky Average Daylight Factors at WI = 2.4 (Atrium A8) with 36 Canopy Configurations

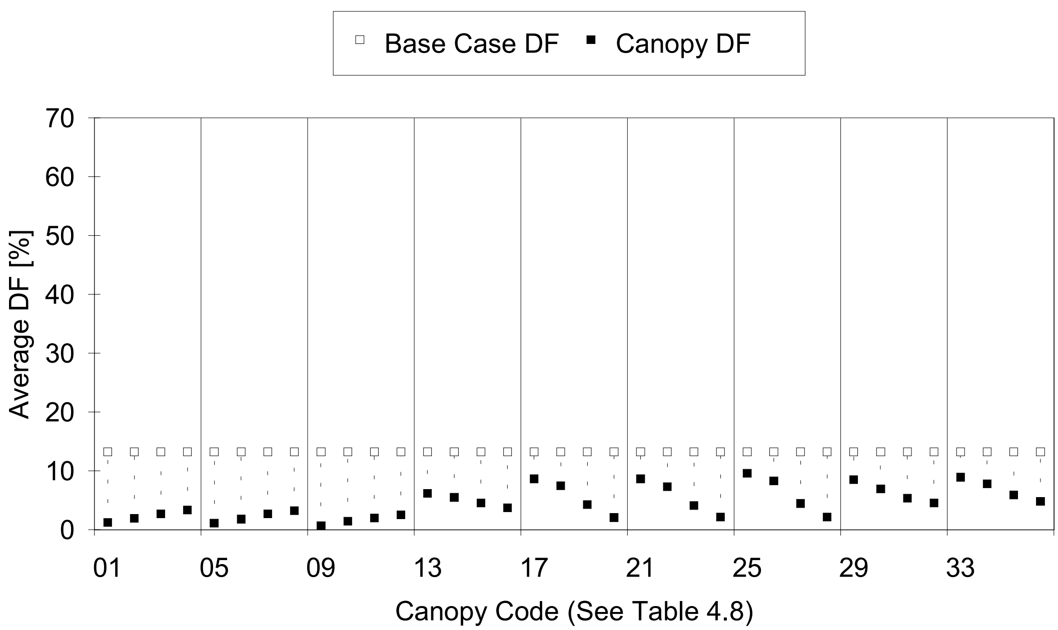


Figure 6.25 Overcast Sky Average Daylight Factors at WI = 2.4 (Atrium A8) with 36 Canopy Configurations

Before performing canopy-by-canopy analyses, all of the DF values measured with canopy systems were converted into the Effective Transmittances (ET) by dividing them by corresponding BCDF values as shown in Equation 6.2.

$$ET = \frac{DF}{BCDF} \times 100 \, [\%] \qquad (6.2)$$

where ET = Effective Transmittance of canopy-well combination

DF = Daylight Factor measured with canopy

BCDF = Base Case Daylight Factor (without canopy)

The ET is a convenient measure of the daylighting performances of canopy systems, because it implies two different properties: quantity of transmitted daylight and level of canopy impact on the BCDF. In this study, the canopy impact was examined in terms of the percent difference between the canopy DF values and the BCDF as shown in Equation 6.3.

$$\text{canopyimpact} = \left(\frac{BCDF - DF}{BCDF} \right) \times 100[\%] = (100 - ET) \quad [\%] \qquad (6.3)$$

When the ET values are compared between different canopy systems at a fixed WI value, a higher ET value implies that more daylight is transmitted (i.e., a higher illuminance level), and it also implies less canopy impact on atrium daylighting at that WI value. On the other hand, when the ET values of a given canopy system are compared at different WI values, a higher ET value does not necessarily imply a higher illuminance level, but it implies less impact of the canopy system on atrium daylighting. Therefore, it must be noted that, in any case, the higher the ET values, the lower the canopy impacts, and vice versa.

Tables 6.7 and 6.8 show the calculated ET values for clear sky and overcast sky, respectively. When the ET values are read across the rows in the tables for different canopies at each WI value, periodical fluctuations in the ET values can be observed for different geometric and photometric configurations of the canopy systems. In this case, higher ET values imply higher illuminance levels and less impact on atrium daylighting. However, when the ET values of a given canopy system are read across the columns in the tables for different WI values, higher ET values do not necessarily indicate higher illuminances because of the differences in the BCDF values at the different WI values.

TABLE 6.7

Effective Transmittances of Canopy Systems for Clear Sky

Canopy Code *	Atrium Well Index 0.6	0.9	1.2	1.5	1.8	2.1	2.4	Ave. ET [%]
01	17.54	17.24	18.71	19.13	20.46	18.67	19.33	18.73
02	26.81	25.84	29.35	27.99	29.03	28.90	28.62	28.08
03	35.29	35.24	39.50	38.08	39.00	38.24	39.98	37.90
04	41.64	42.47	47.50	46.28	47.57	44.87	48.07	45.48
05	13.99	13.13	15.30	14.42	12.02	17.41	12.89	14.17
06	23.31	22.53	24.13	23.66	23.66	18.67	20.89	22.41
07	31.79	31.79	34.70	34.40	35.04	35.37	33.56	33.81
08	36.31	37.51	42.00	40.15	42.07	39.86	43.33	40.18
09	8.86	10.82	9.18	9.80	9.46	6.28	8.89	9.04
10	17.45	19.93	18.50	19.70	18.16	18.67	19.11	18.79
11	24.45	26.64	25.80	25.35	25.19	24.60	22.67	24.96
12	29.02	32.12	34.08	33.65	30.18	35.37	28.67	31.87
13	47.09	47.90	51.46	49.58	48.72	52.42	47.33	49.21
14	45.02	46.81	50.21	48.16	47.57	50.63	45.78	47.74
15	40.73	42.04	45.20	43.17	43.73	39.50	42.22	42.37
16	36.22	37.46	40.19	37.79	36.19	37.52	42.22	38.23
17	60.90	67.64	69.05	68.24	66.62	72.17	69.56	67.74
18	53.26	58.86	60.99	60.89	55.24	60.32	61.78	58.76
19	28.67	31.51	32.96	31.20	30.31	37.52	34.00	32.31
20	20.51	23.10	24.83	27.52	26.73	21.36	23.11	23.88
21	64.48	69.91	69.96	68.05	65.98	70.74	69.11	68.32
22	56.32	60.75	61.20	59.00	56.65	56.91	64.67	59.36
23	30.68	33.92	32.48	30.63	28.13	37.52	26.67	31.43
24	22.38	26.64	29.55	29.50	26.98	31.60	24.22	27.27
25	69.76	77.28	79.07	76.53	72.76	77.38	71.78	74.94
26	61.07	66.41	69.82	68.43	68.03	73.61	69.56	68.13
27	32.66	36.47	36.93	36.76	34.78	37.52	38.67	36.26
28	22.96	27.82	29.55	30.25	29.67	36.80	23.78	28.69
29	47.00	55.36	59.04	59.75	61.13	67.50	67.33	59.59
30	27.48	35.62	41.52	43.45	46.68	55.30	51.78	43.12
31	17.25	22.77	28.65	30.63	33.89	38.96	40.22	30.34
32	11.33	15.68	21.28	23.94	27.75	32.85	30.22	23.29
33	53.85	62.64	64.46	67.39	67.26	74.51	68.67	65.54
34	38.99	47.95	51.74	54.01	54.35	58.71	59.78	52.22
35	24.50	30.61	34.70	37.61	39.39	45.24	46.44	36.93
36	14.57	20.08	24.44	28.09	31.56	37.88	40.00	28.09

* See Table 4.8 for Canopy Code

TABLE 6.8

Effective Transmittances of Canopy Systems for Overcast Sky

Canopy	Atrium Well Index							Ave.
Code *	0.6	0.9	1.2	1.5	1.8	2.1	2.4	ET [%]
01	9.78	9.81	9.51	9.11	9.60	9.27	9.52	9.51
02	15.17	15.59	15.45	15.30	15.50	14.35	14.72	15.15
03	20.38	20.72	20.51	20.31	19.49	19.07	20.35	20.12
04	24.15	23.85	24.67	25.05	25.32	23.71	25.22	24.57
05	8.37	8.33	8.18	8.35	8.32	7.66	8.12	8.19
06	13.93	14.16	13.79	13.85	13.37	12.57	13.53	13.60
07	20.12	20.30	19.89	20.15	20.55	18.98	20.02	20.00
08	23.97	24.43	24.67	24.35	23.54	23.26	24.57	24.11
09	5.84	5.89	5.52	5.17	4.84	5.17	5.30	5.39
10	12.31	12.37	11.96	12.23	11.17	10.78	11.15	11.71
11	17.27	17.32	16.82	16.81	15.65	15.69	14.83	16.34
12	21.90	22.15	21.55	21.55	20.91	19.88	19.26	21.03
13	46.15	45.31	46.45	46.71	48.79	45.10	46.86	46.48
14	42.25	41.75	41.63	41.41	40.40	42.16	41.61	41.60
15	35.40	35.37	35.32	34.35	33.25	34.31	34.42	34.63
16	28.71	28.96	29.13	27.72	27.12	27.54	27.87	28.15
17	62.68	66.12	67.94	68.91	68.07	64.35	65.48	66.22
18	54.69	57.76	59.14	60.13	59.39	57.04	56.71	57.84
19	30.23	31.94	33.10	33.46	33.36	31.73	32.03	32.26
20	15.53	16.23	16.40	16.76	16.57	15.95	15.58	16.15
21	64.15	66.39	66.69	66.27	66.86	63.81	65.69	65.70
22	55.39	57.10	56.56	56.41	56.76	54.55	55.41	56.02
23	30.72	31.45	31.15	31.20	31.58	31.46	31.39	31.28
24	14.84	15.68	15.28	15.57	16.00	16.49	15.91	15.68
25	70.75	75.05	76.16	76.08	76.74	77.81	72.84	75.06
26	60.23	63.54	66.20	64.98	65.15	66.76	62.66	64.22
27	32.80	34.85	35.59	35.40	35.42	35.92	33.55	34.79
28	15.84	16.13	16.53	16.43	16.71	16.76	16.02	16.35
29	53.70	57.46	61.38	65.41	67.78	67.47	64.29	62.50
30	35.03	40.23	44.77	49.89	52.77	54.63	52.71	47.15
31	23.02	26.28	30.73	36.05	38.62	41.09	40.37	33.74
32	16.25	19.63	23.63	27.91	30.94	34.31	34.20	26.70
33	57.12	60.29	63.46	67.62	69.56	70.14	67.42	65.09
34	43.51	47.86	51.74	56.73	58.25	60.43	59.20	53.96
35	27.91	32.06	36.17	40.09	42.96	45.63	44.91	38.53
36	17.98	21.12	25.00	28.61	32.08	34.94	36.15	27.98

* See Table 4.8 for Canopy Code

In general, as indicated in the two previous tables, not much differences are observed across the columns for canopies 01 through 28. However, increasing trends of the ET values across the columns are observed for canopies 29 through 36, which are waffle skylight systems. The subsequent analyses will be conducted on canopy-by-canopy basis for clear sky and overcast sky conditions, simultaneously.

1) Sawtooth with vertical aperture: Figures 6.26 through 6.31 show the ET values of sawtooth canopies (01 through 12) for clear and overcast skies, respectively. As shown in the figures, most of the ET values did not vary substantially at different WI values. Some observed deviations might be attributed to unknown measurement errors. However, as the trend across the WI values was almost flat, the unknown errors might be mitigated if the average values are used for future applications.

As indicated in Figures 6.26 through 6.31, the ET values for overcast sky were always lower than they were for clear sky. Again, this phenomenon is related to the orientation of the sawtooth apertures and the different sky luminance distributions. As previously discussed, the low ET values of these canopies for overcast sky imply that light flux from the higher-luminance zenith area, which produced higher BCDF values, is blocked by the opaque panels of sawtooth canopies. It was also noted that the ET values increased in larger margins for clear sky as the aperture area increased than for overcast sky. The average ET increase for clear sky was 8.4 % as the vertical-aperture-to-floor-area ratio increased by 0.2, compared to 5.2 % for overcast sky.

Another notable phenomenon was concerned with the different number of units which showed different ET values. This phenomenon can be observed when Figures 6.26 (2-unit canopies), 6.28 (4-unit canopies), and 6.29 (8-unit canopies) for clear sky are examined. Even though the sawtooth canopies had the same total aperture area when the slope angles of the sawtooth panels are the same, the sawtooth canopies with fewer number of units, which has actually larger aperture area of each unit, resulted in higher ET values, which mean less reductions of BCDF values. By calculating the absolute ET differences between canopies with equal aperture areas, it was determined that the average ET value of 2-unit sawtooth canopies was about 4.9 % higher than that of 4-unit canopies, 4-unit canopies showed about 6.5 % higher ET values than 8-unit, and 2-unit canopies showed about 11.5 % higher ET values than 8-unit canopies. However, for overcast sky, the number of units affected the ET values by only minimal margins.

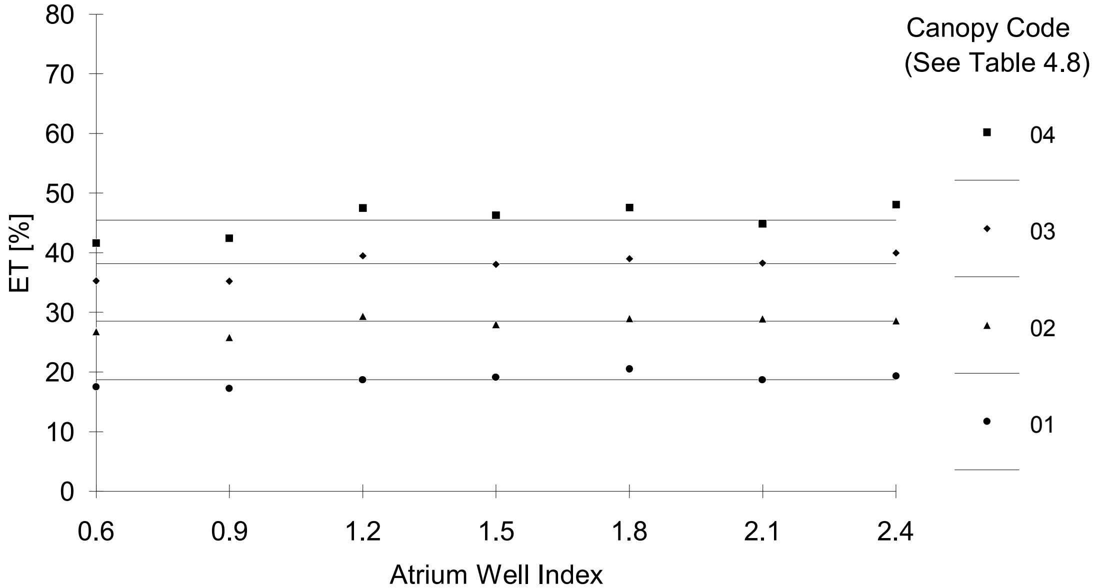


Figure 6.26 Clear Sky Effective Transmittance of 2-Unit Sawtooth Canopies with Vertical Apertures

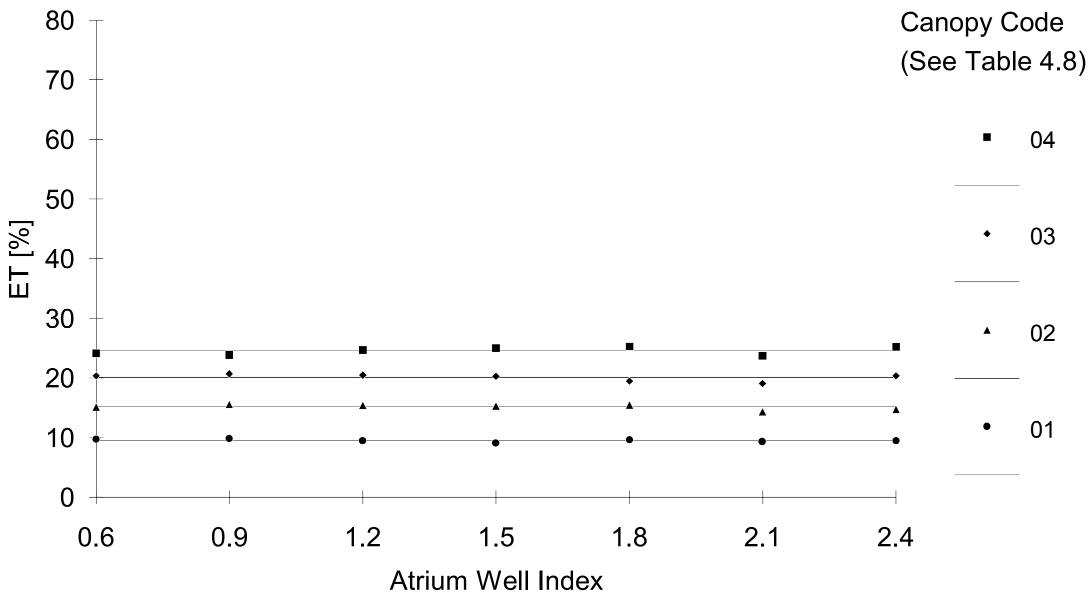


Figure 6.27 Overcast Sky Effective Transmittance of 2-Unit Sawtooth Canopies with Vertical Apertures

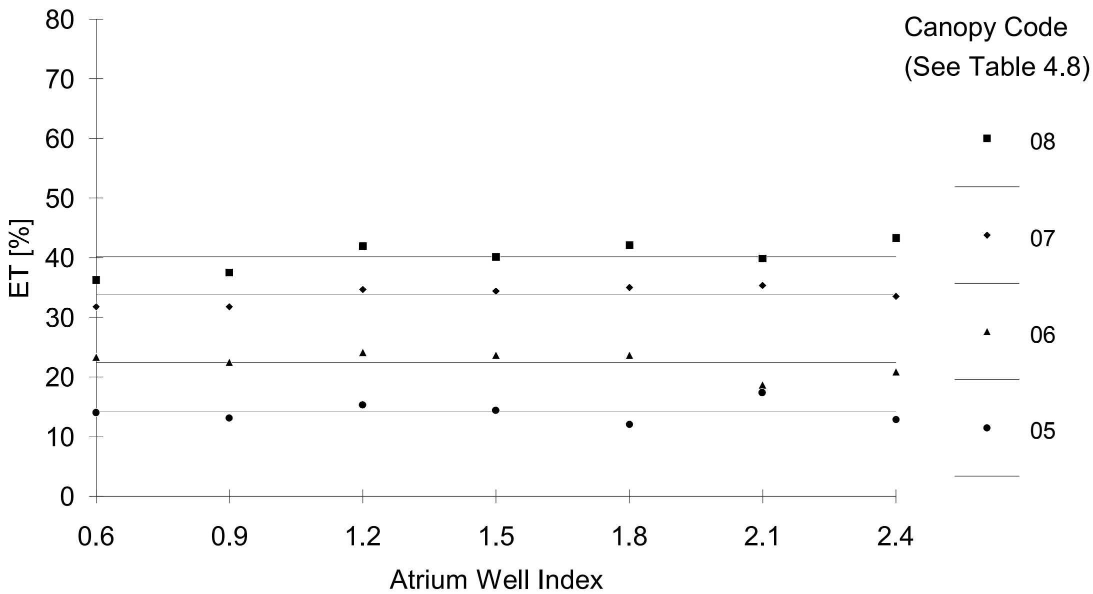


Figure 6.28 Clear Sky Effective Transmittance of 4-Unit Sawtooth Canopies with Vertical Apertures

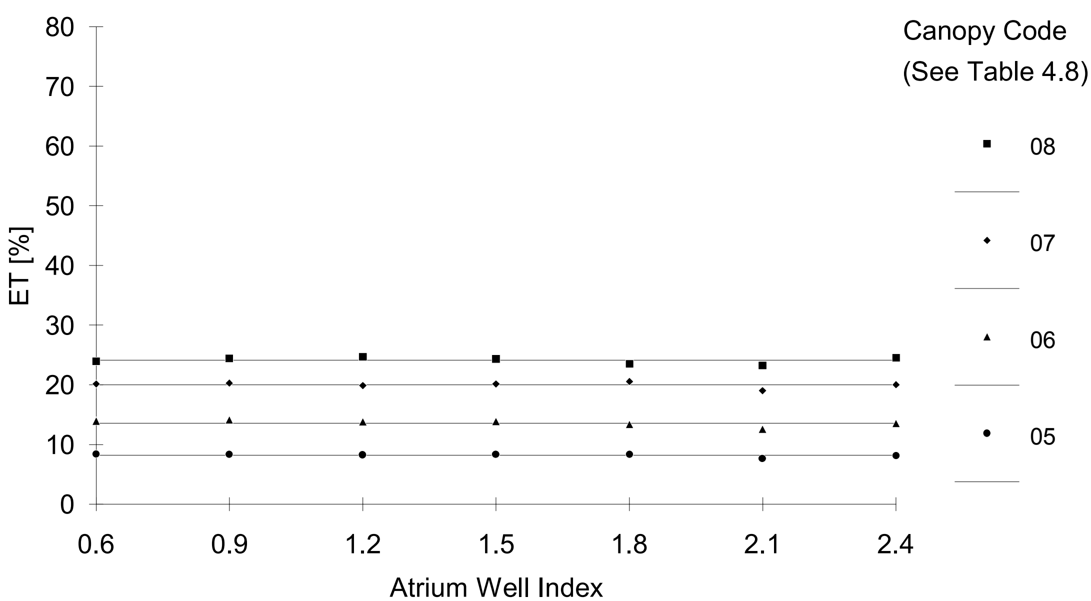


Figure 6.29 Overcast Sky Effective Transmittance of 4-Unit Sawtooth Canopies with Vertical Apertures

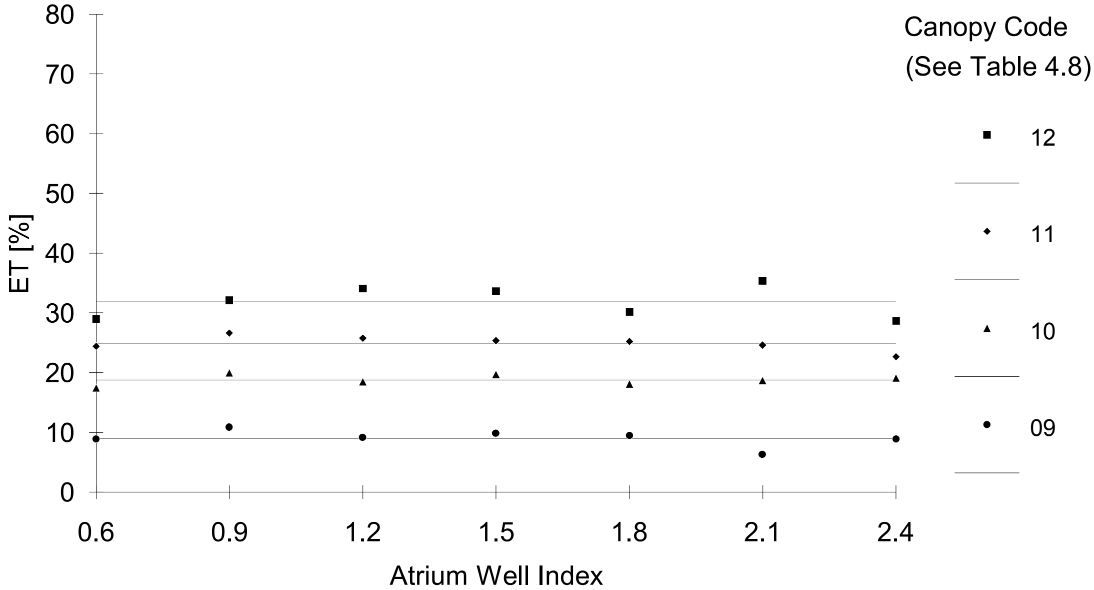


Figure 6.30 Clear Sky Effective Transmittance of 8-Unit Sawtooth Canopies with Vertical Apertures

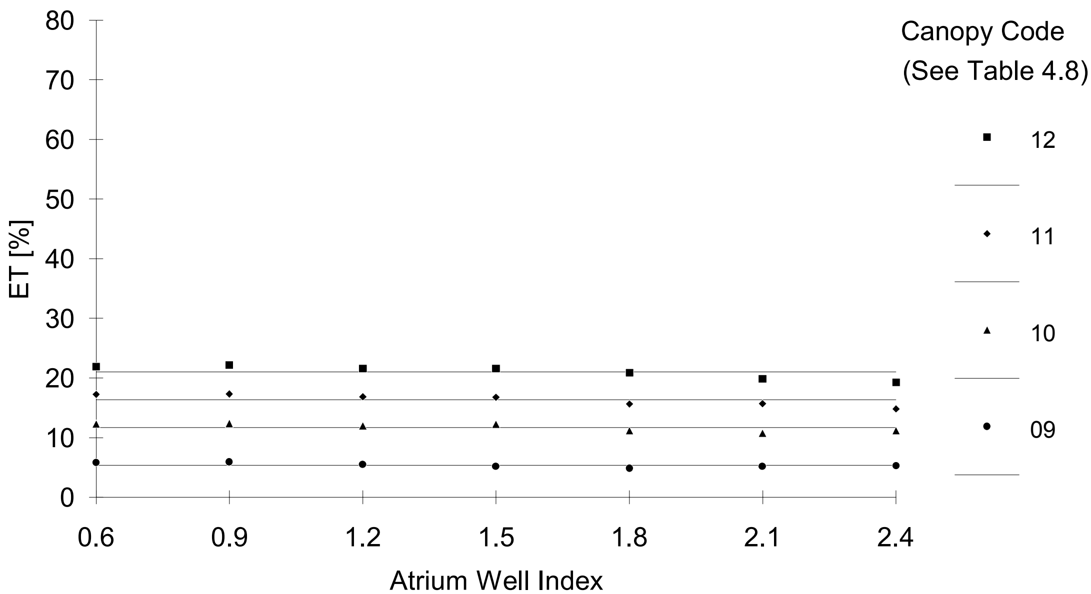


Figure 6.31 Overcast Sky Effective Transmittance of 8-Unit Sawtooth Canopies with Vertical Apertures

2) Sawtooth with sloping aperture: Figures 6.32 and 6.33 show the ET values of these canopies for clear sky and overcast sky, respectively. The ET trends across the WI values were the same as sawtooth canopies with vertical apertures. However, overall ET magnitudes were larger than those for vertical sawtooth canopies. This effect was more prominent for overcast sky. Furthermore, a reverse phenomenon was observed in the reductions of the ET values as the slope angle increased, which decreased the horizontally-projected-aperture-to-floor-area ratio. As shown in Figure 6.33, more reductions occurred for overcast sky than clear sky. This also can be connected to the difference in sky luminance distributions.

The increased slope angle not only reduces the horizontally projected area of the aperture, but also changes the location of sky area viewed from the floor positions and the interior surfaces. Therefore, the high-luminance zenith area is blocked by the sawtooth panels and the low-luminance sky area to which the opening faces might cause more reductions in daylight illuminance levels. However, it must be noted, as stated before, that the higher ET values for clear sky do not indicate higher DF values. Actual DF values were higher for overcast sky because of the higher BCDF values as shown in Tables 6.5 and 6.6.

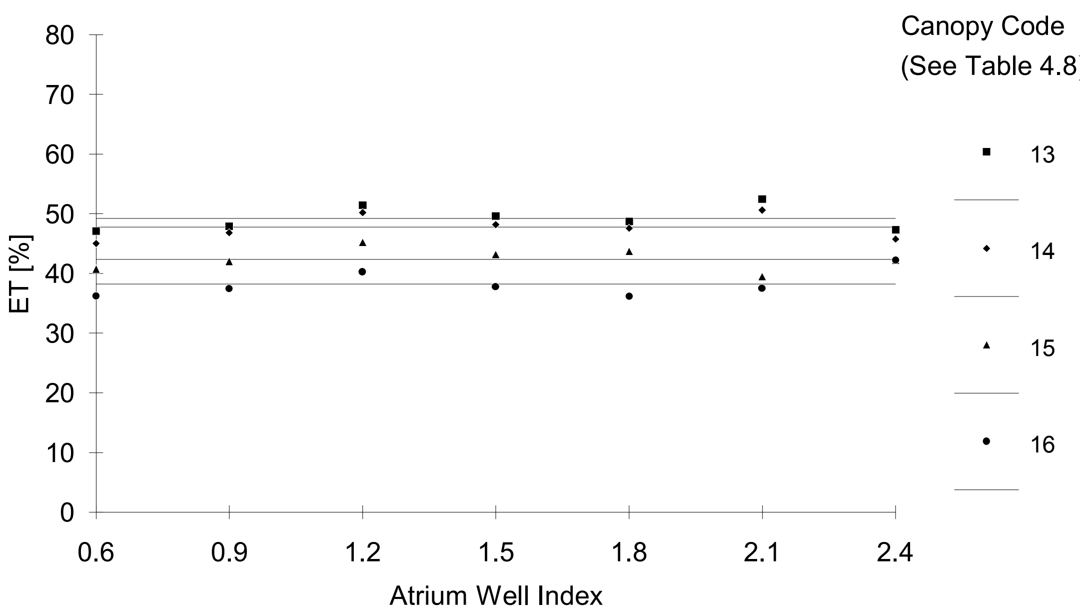


Figure 6.32 Clear Sky Effective Transmittance of 4-Unit Sawtooth Canopies with Sloping Apertures

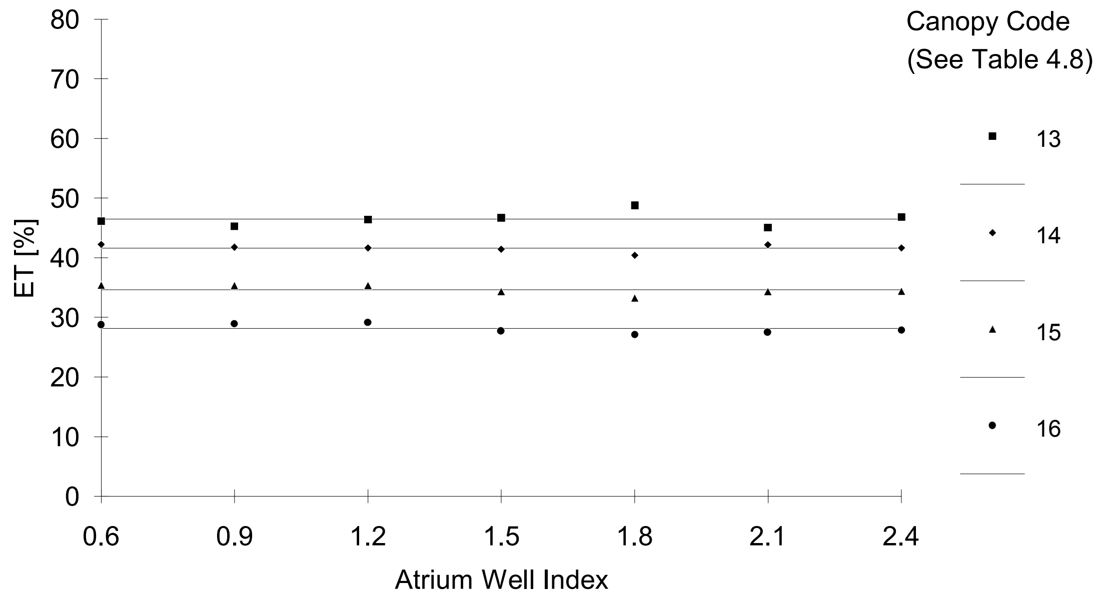


Figure 6.33 Overcast Sky Effective Transmittance of 4-Unit Sawtooth Canopies with Sloping Apertures

3) Flat horizontal, barrel vault, and pyramid skylights: Figures 6.34 through 6.39 show the ET values of these three canopy types. Even though some off values were observed, the trends were still almost the same as previous ones. From these canopy types, the effects of Framing Factor (FF, see Table 4.8) and the Hemispherical Transmittance (HT) and translucency of glazing material were examined.

The calculated FF values (44% for canopy 17, 36 % for canopy 21, and 17 % for canopy 25) had some degree of correlation with the ET values. For clear sky, the average ET values increased as the FF values decreased. But, for overcast sky, the average ET value of canopy 21 was 0.5 % lower than that of canopy 17, even though the FF was decreased from 44 % to 36 %. This might be due to the varying FF value at different viewing angles. Canopy 21 which has the lowest FF value always showed the highest ET values.

The effect of the Hemispherical Transmittance of glazing material was examined from the ratio of the average ET values of glazed canopies (No. 18, 19, 20, 22, 23, 24, 26, 27, and 28) to the average ET values of the unglazed canopies (No. 17, 21, and 25). Table 6.9 shows the average ET values of glazed canopy systems and the calculated ET values using the corresponding HT values. As indicated in the table, the ET values of glazed canopies were linearly correlated with the effects of the glazing Hemispherical Transmittance (HT) except for the white translucent material under overcast sky. The calculated ET value of the canopies with the white translucent glazing material was about 6 % higher than the average of measured ET value. This might be connected to the geometric forms of the canopy systems and the sky luminance distribution. When the ET values of the canopies with the white translucent materials (No. 20, 21, and 28) were examined for the two sky conditions a very different result was observed. While the average ET values of transparent glazing (No. 18, 19, 22, 23, 26, and 27) were almost the same for clear and overcast skies, the average ET values of translucent glazing were about 10.6 % higher for clear sky than they were for overcast sky. This was because the BCDF did not include the light flux from the high-luminance horizon area of clear sky, but the it was captured by the diffuse glazing material and added to the canopy DF values.

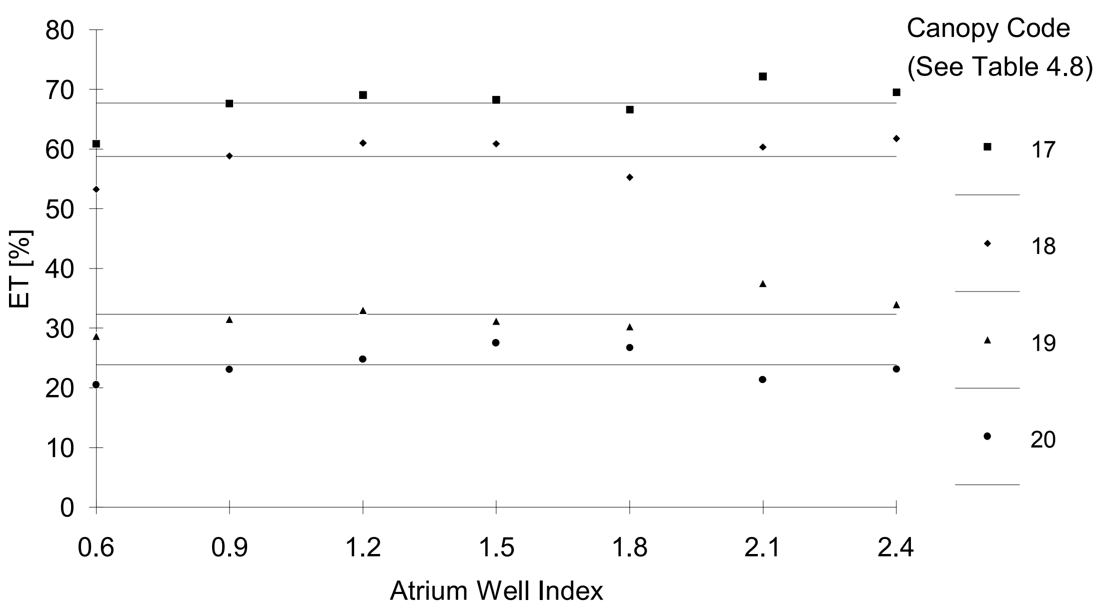


Figure 6.34 Clear Sky Effective Transmittance of Flat Horizontal Skylights

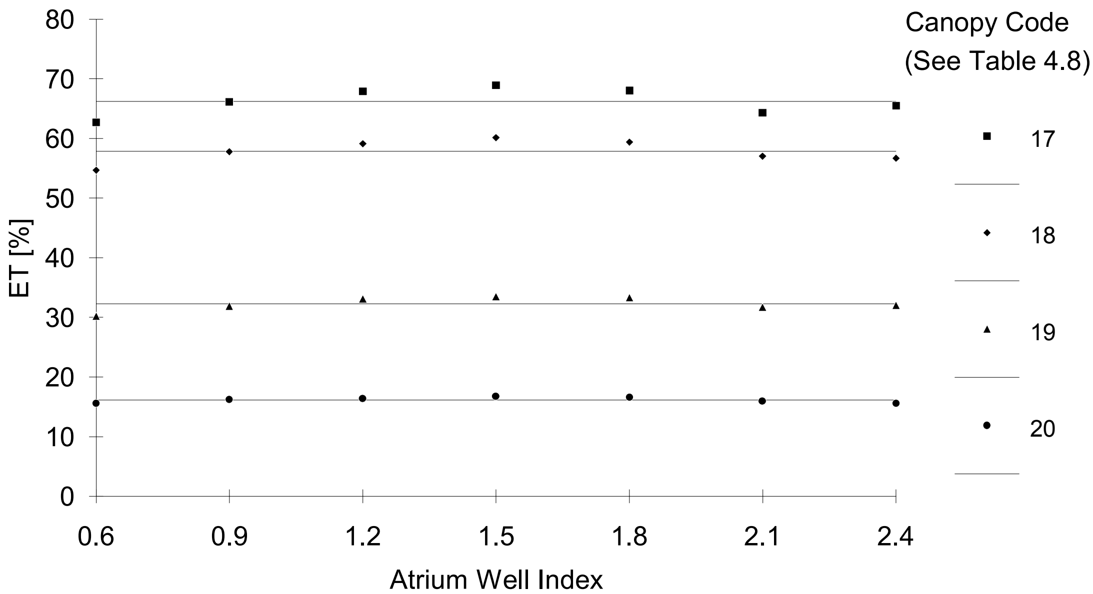


Figure 6.35 Overcast Sky Effective Transmittance of Flat Horizontal Skylights

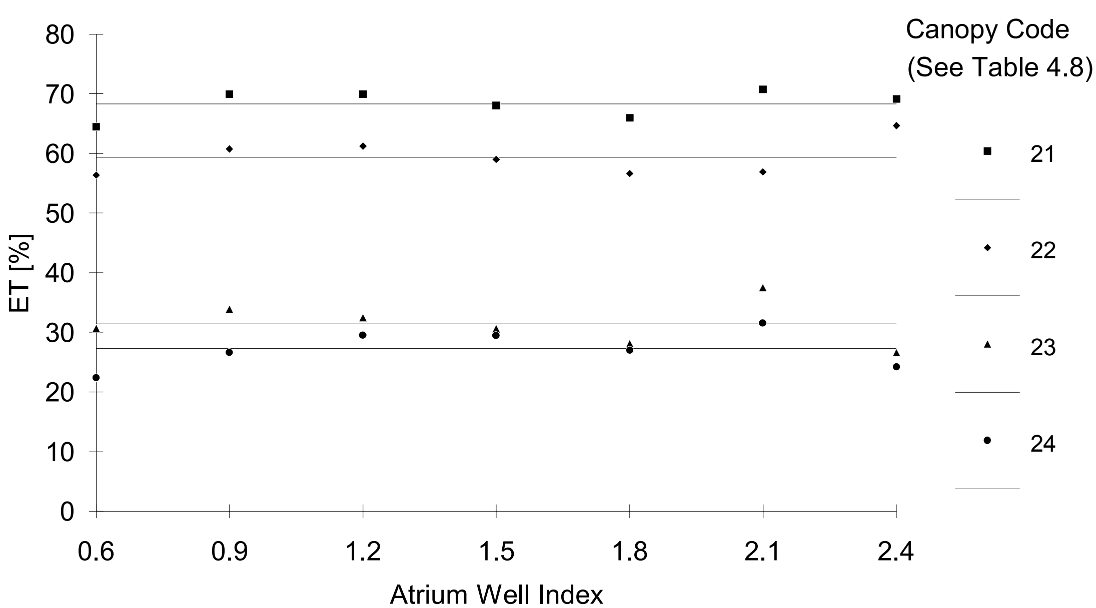


Figure 6.36 Clear Sky Effective Transmittance of Barrel Vault Skylights

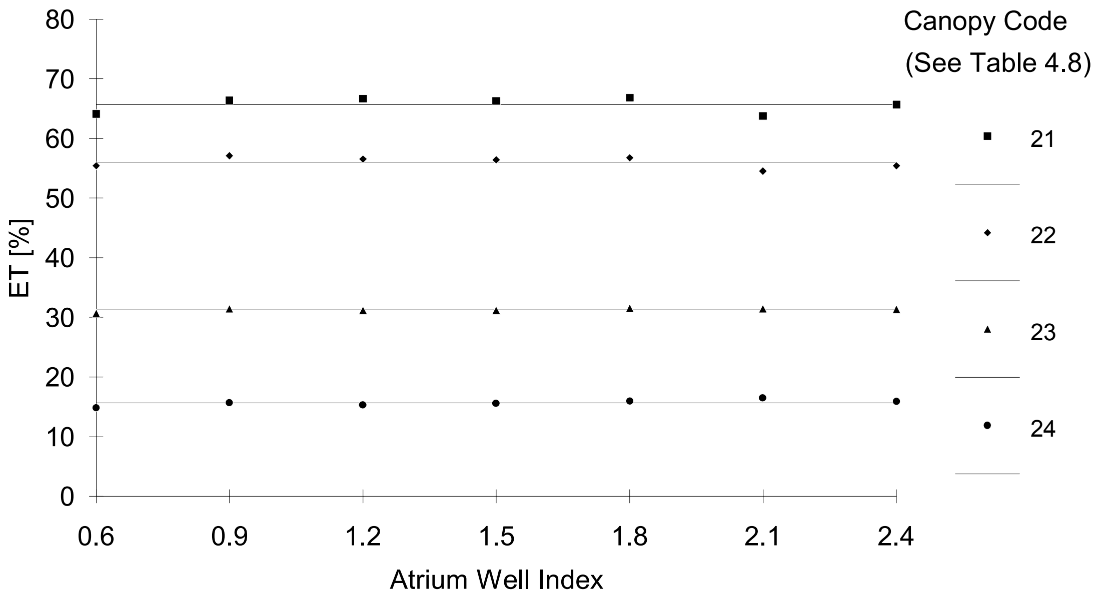


Figure 6.37 Overcast Sky Effective Transmittance of Barrel Vault Skylights

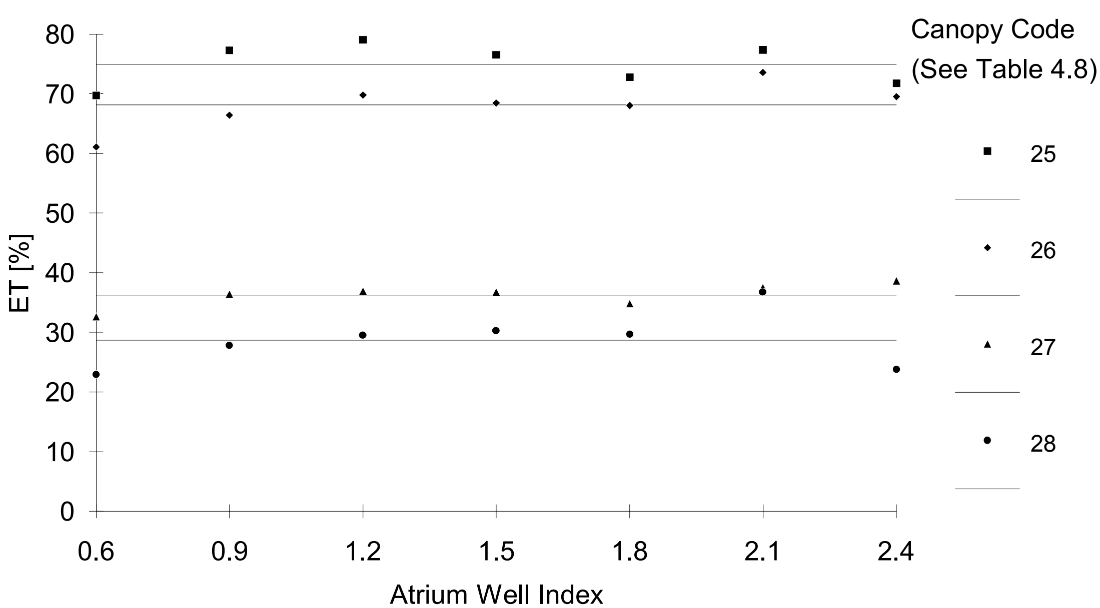


Figure 6.38 Clear Sky Effective Transmittance of Pyramid Skylights

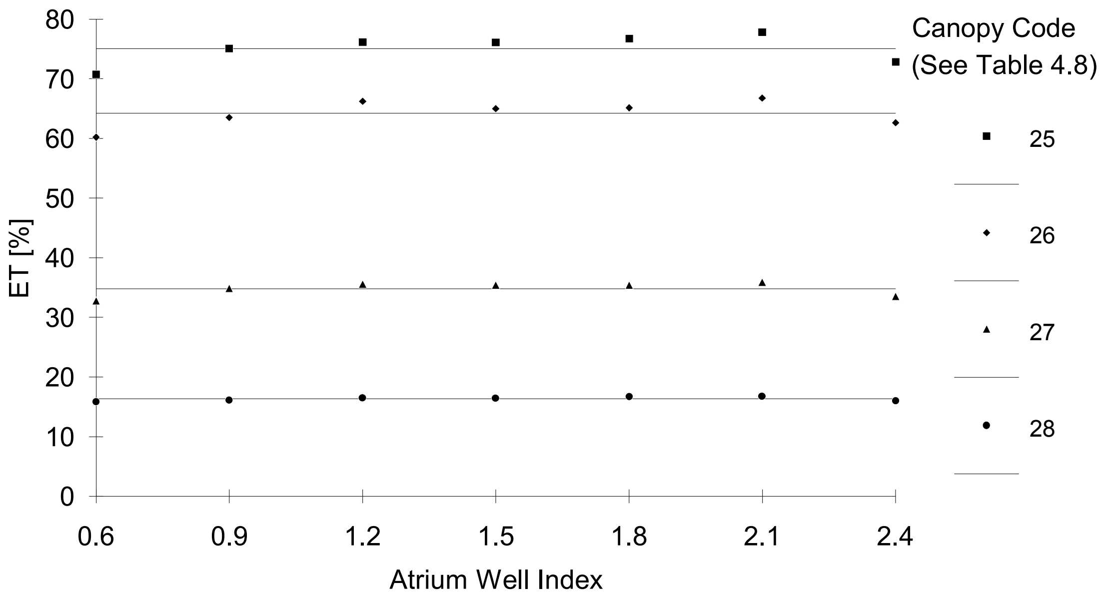


Figure 6.39 Overcast Sky Effective Transmittance of Pyramid Skylights

TABLE 6.9

Average Measured ET Values and Calculated ET Values with HT Values

Description of Glazing Material	Clear Sky Average Unglazed ET = 70.33 %			Overcast Sky Average Unglazed ET = 67.66 %		
	HT [%]	Meas. ET [%]	Calc. ET [%]	HT [%]	Meas. ET [%]	Calc. ET [%]
Clear Transparent	86.4	62.08	60.77	88.7	59.63	60.01
Tinted Transparent	46.9	33.33	32.98	49.1	32.78	33.22
White Translucent	39.5	26.61	27.78	32.1	15.99	21.72

where ET = Effective Transmittance

HT = Hemispherical Transmittance

4) Waffle skylights: From the ET values presented in Tables 6.7 and 6.8, the average percent differences of the ET values with different reflectance and different Waffle Well Index (WWI) were calculated for each sky. For clear sky condition, the average percent difference in ET values was +5.4 % with the reflectance increased from 30 % to 85 % and -25.7 % with the WWI values increased by 0.5. Meanwhile, for overcast sky, those values were calculated as +8.4 % with the reflectances and -24.5 % with the WWI values. The absolute magnitudes of the percent differences indicated that the geometric configuration of the waffle structure had more impact on interior daylighting illuminance level than the reflectance of the waffle surface. However, the effects of the high surface reflectance must not be underestimated, because it had the positive impact on the interior illuminance levels.

Figures 6.40 and 6.41 show the ET values of waffle skylights with 30 % surface reflectances for clear sky and overcast sky, respectively. Figures 6.42 and 6.43 show those of waffle skylights with 85 % surface reflectance for clear and overcast skies, respectively.

As shown in the figures, all of the waffle skylights had different trends from those of the previous canopy systems. In general, the ET values increased as atrium Well Index increased. This indicated less impact of the canopy system on atrium daylighting (or less reductions from BCDF). The ET trends were observed to be almost the same for both sky conditions. Therefore, both the decreased ET values with the increased WWI values and the increased ET values with the increased WI values might be attributed to geometric relationship between the atrium well and the waffle structure. In other words, 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. This peculiar daylighting performance of the waffle skylight system is visually demonstrated in Section 6.4 with captured video images using the video-based luminance mapping system.

Even though the waffle skylights with low WWI values showed curvilinear trends, for the simplification, linear regression equations were obtained to approximate the ET values with WI values which can be applicable through this study. Tables 6.10 and 6.11 present the linear regression equations for clear sky and overcast sky, respectively.

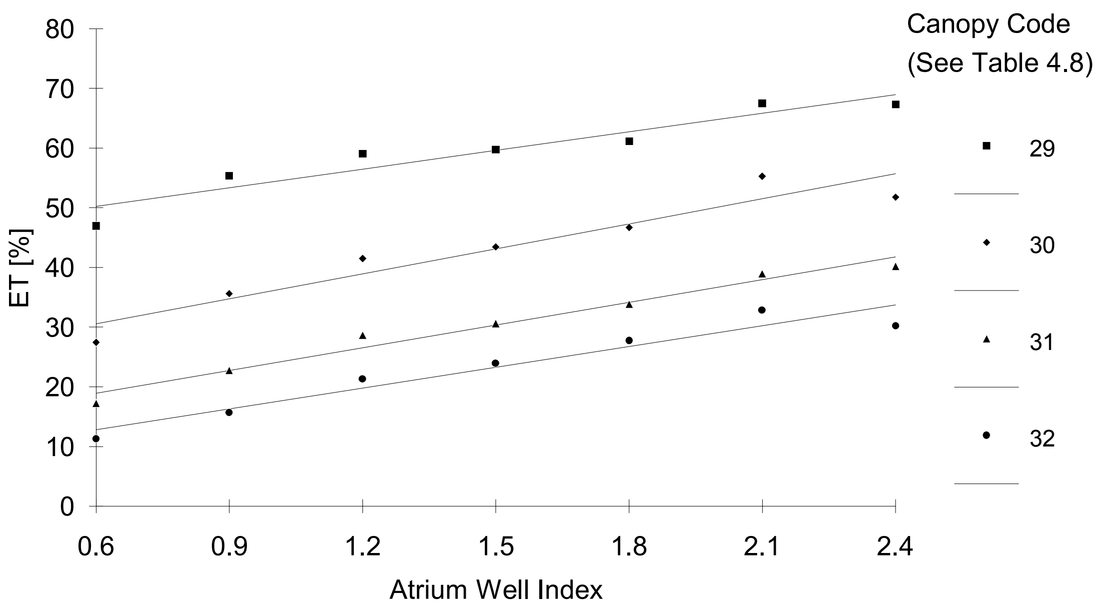


Figure 6.40 Clear Sky Effective Transmittance of Waffle Skylights with 30 % Reflectance

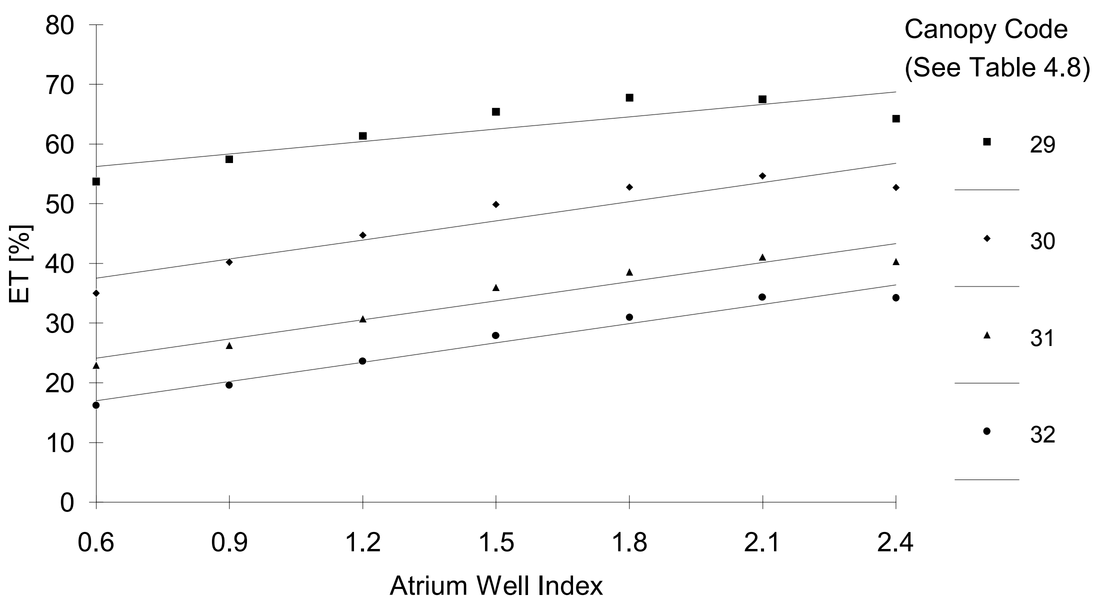


Figure 6.41 Overcast Sky Effective Transmittance of Waffle Skylights with 30 % Reflectance

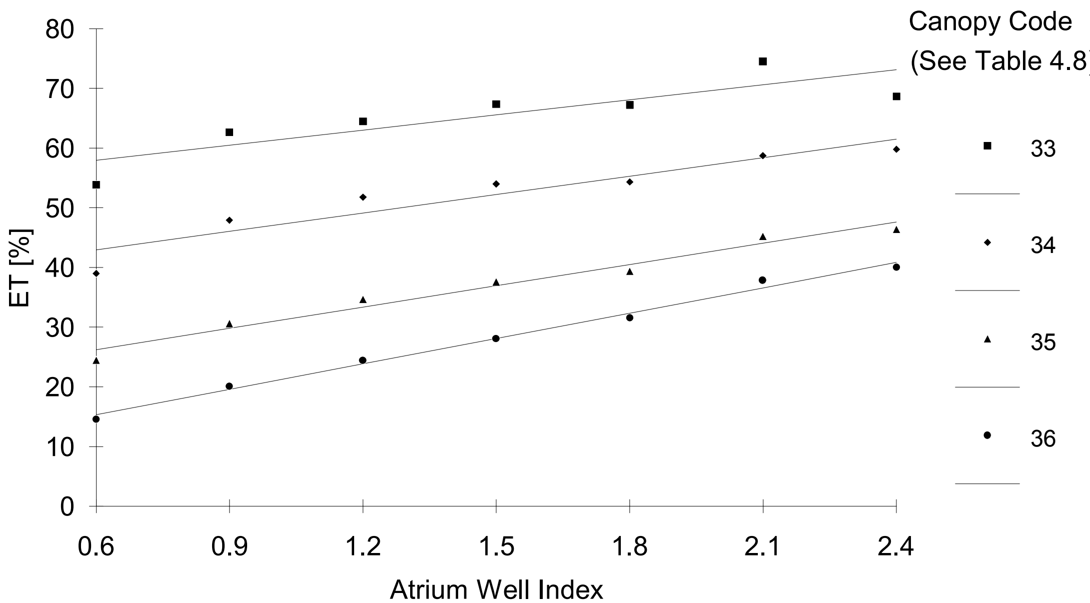


Figure 6.42 Clear Sky Effective Transmittance of Waffle Skylights with 85 % Reflectance

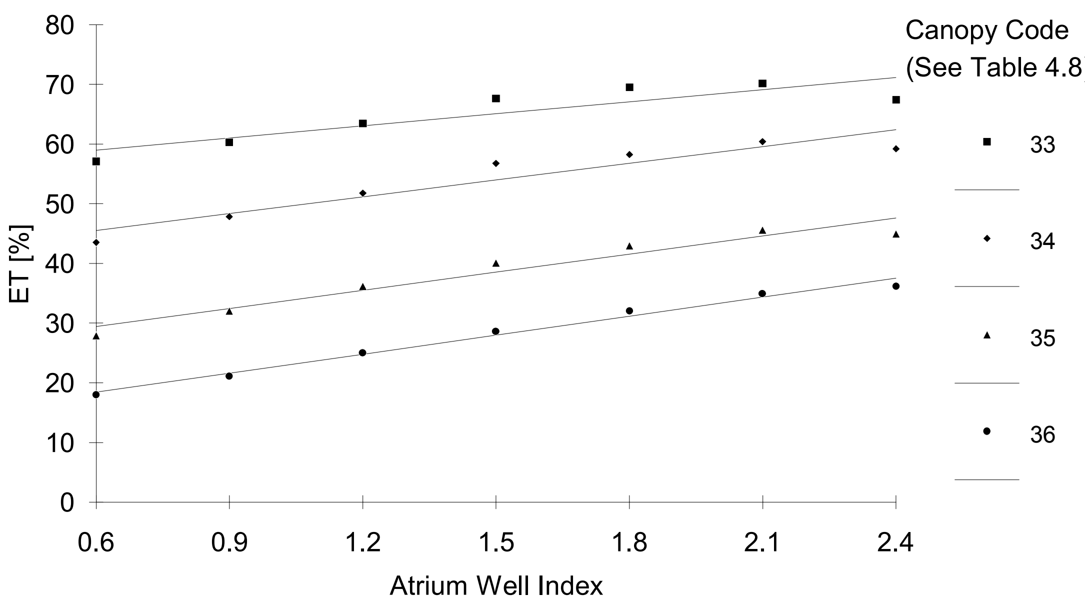


Figure 6.43 Overcast Sky Effective Transmittance of Waffle Skylights with 85 % Reflectance

TABLE 6.10

Linear Regression Equations to Approximate ET Values of Waffle Skylights for Clear Sky

Waffle Reflectance	WWI	Linear Regression Equation for ET [%]	R^2
30 %	0.5	ET = 43.9857 + 10.4018 WI	0.9037
	1.0	ET = 22.1472 + 13.9788 WI	0.9127
	1.5	ET = 11.3140 + 12.6829 WI	0.9740
	2.0	ET = 11.3140 + 12.6829 WI	0.9305
85 %	0.5	ET = 52.8601 + 8.4525 WI	0.8412
	1.0	ET = 36.7674 + 10.2987 WI	0.8892
	1.5	ET = 19.1116 + 11.8774 WI	0.9729
	2.0	ET = 68.3420 + 14.1693 WI	0.9918

TABLE 6.11

Linear Regression Equations to Approximate ET Values of Waffle Skylights for Overcast Sky

Waffle Reflectance	WWI	Linear Regression Equation for ET [%]	R^2
30 %	0.5	ET = 52.1086 + 6.9260 WI	0.8181
	1.0	ET = 21.1035 + 10.6960 WI	0.8829
	1.5	ET = 17.7474 + 10.6595 WI	0.9339
	2.0	ET = 10.5294 + 10.7774 WI	0.9683
85 %	0.5	ET = 54.9547 + 6.7543 WI	0.8839
	1.0	ET = 39.9041 + 9.3709 WI	0.8968
	1.5	ET = 23.3633 + 10.1130 WI	0.9424
	2.0	ET = 12.0492 + 10.6214 WI	0.9862

6.1.4 Daylight Illuminance Distributions with Canopies

The impacts of various types of canopy systems on the daylight illuminance distributions on the atrium floor work plane were tested with the Effective Transmittance (ET) values on the center line atrium positions (1, 2 and 3). Since the ET values of a given type of canopy system showed consistent trends at different WI values, this test was performed with the middle value of Well Index (WI = 1.5, atrium A5) and several selected canopy systems which were representative among the different canopy groups. The tested canopy systems included 4-unit sawtooth canopies with vertical apertures (No. 05, 06, 07, and 08), 4-unit sawtooth canopies with sloping apertures (No. 13, 14, 15, and 16), pyramid skylights (No. 25, 26, 27, and 28), and waffle skylights with 85 % surface reflectance (No. 33, 34, 35, and 36).

Figures 6.44 and 6.45 show the ET distributions of 4-unit sawtooth canopies with vertical apertures. As revealed in the figures, for both sky conditions, the different aperture areas in terms of vertical-aperture-to-floor-area ratio affected both the absolute magnitudes and distribution patterns of ET values. As expected, the increased aperture area resulted in higher ET values. When the ET distributions were examined, the floor position 3 located close to the back wall (north wall) showed the highest ET values, while the floor position 1 located close to the front wall (south wall) showed the lowest ET values. The ET values at the floor position 3 were average and about 1.5 times those of the floor position 1. Another notable feature was the different impacts of aperture area and sky condition on the ET gradient between the floor position 2 and 3. For clear sky, the ET values at position 3 were about 1.3 times those at position 2, while those at position 3 were about 1.2 times those at position 2 for overcast sky. These phenomena can be considered typical effects of sawtooth canopy systems due to the orientation of the apertures which affects the Sky Factors (SF) of the sawtooth apertures at the floor positions.

Figures 6.46 and 6.47 show the ET distributions of 4-unit sawtooth canopies with sloping apertures. From the ET magnitudes and distribution features, the impact of horizontally-projected-aperture-to-floor-area ratio and the sloping angle of the aperture can be determined. At the lowest slope angle which provided the largest area of horizontally projected aperture, the center ET values were highest for both sky conditions. However, as the slope angle increased, the ET values at the floor position 3 also increased. Finally, the aperture with 60° slope angle which was similar to vertical aperture resulted in highest ET values at floor position 3.

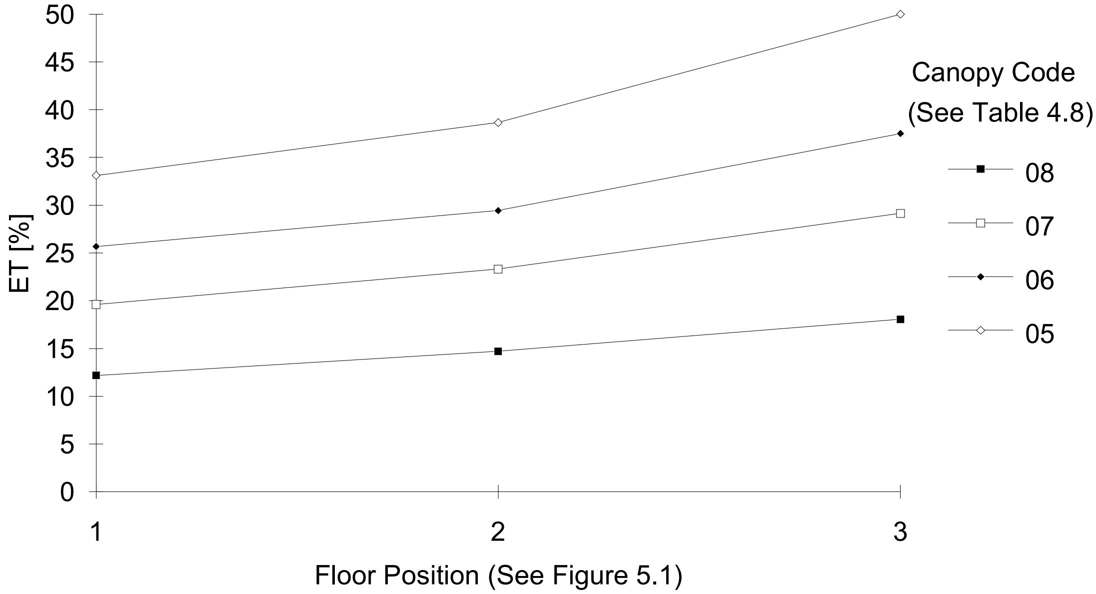


Figure 6.44 Clear Sky ET Distributions of 4-Unit Sawtooth Canopies with Vertical Apertures (WI = 1.5)

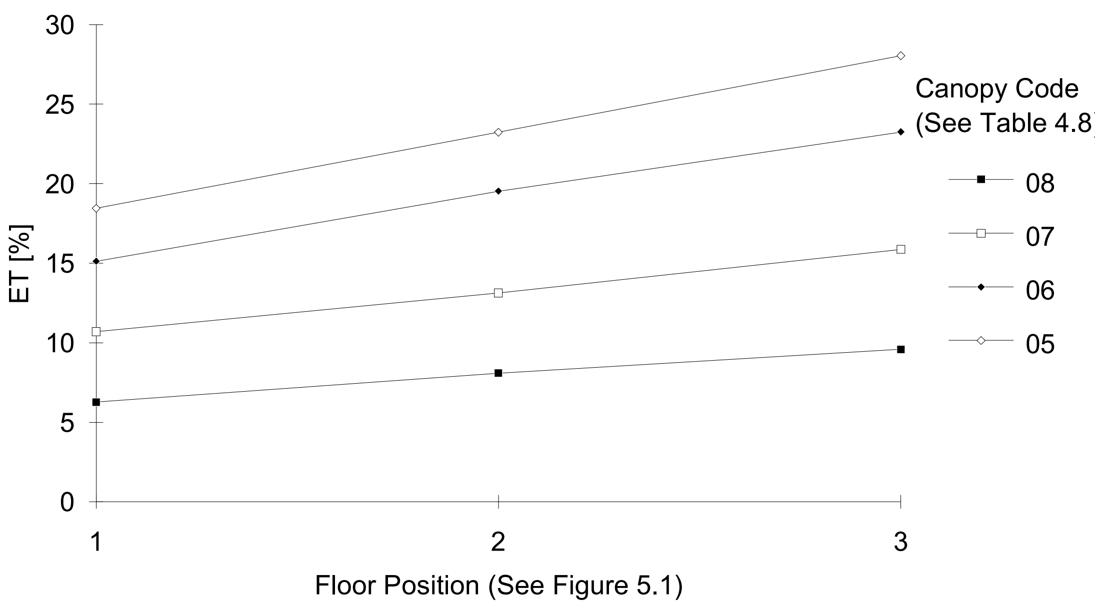


Figure 6.45 Overcast Sky ET Distributions of 4-Unit Sawtooth Canopies with Vertical Apertures (WI = 1.5)

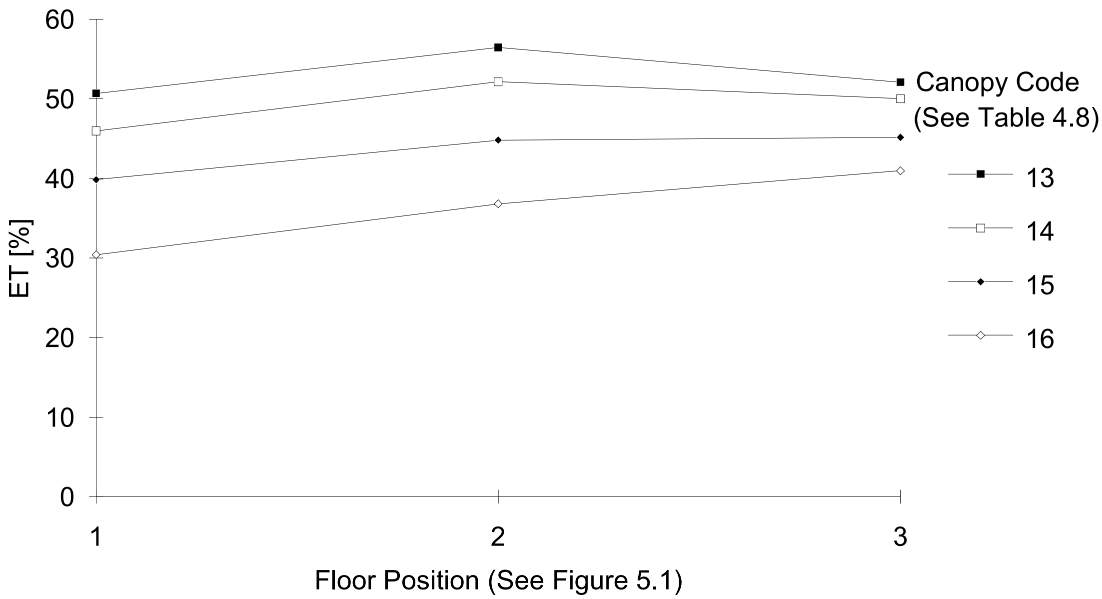


Figure 6.46 Clear Sky ET Distributions of 4-Unit Sawtooth Canopies with Sloping Apertures (WI = 1.5)

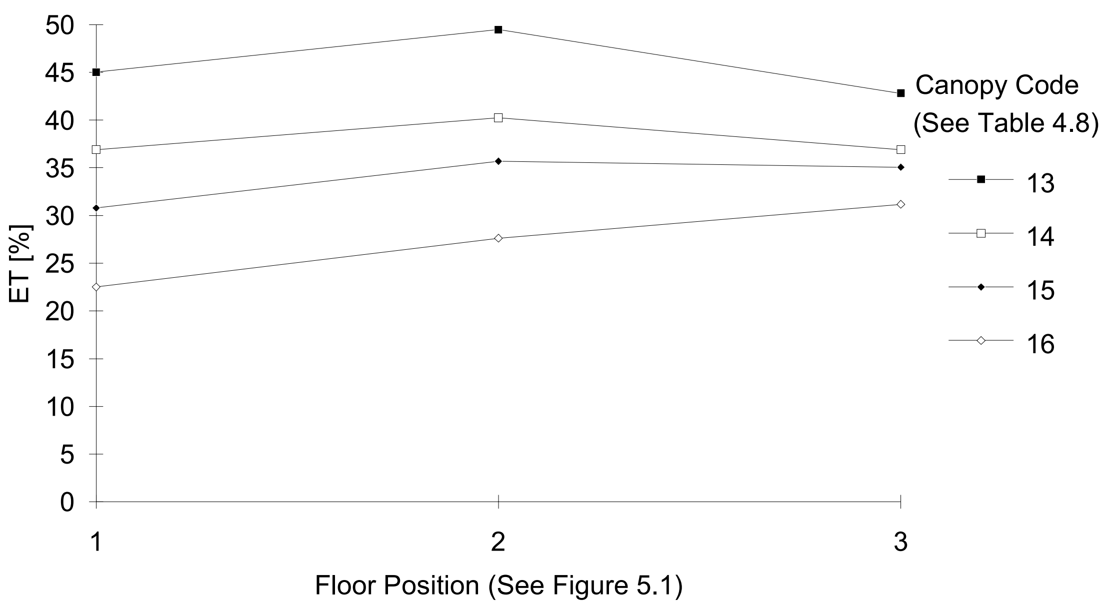


Figure 6.47 Overcast Sky ET Distributions of 4-Unit Sawtooth Canopies with Sloping Apertures (WI = 1.5)

Figures 6.48 and 6.49 show the ET values of pyramid skylights with different glazing materials. As shown in the figures, for both sky conditions, the ET distribution features were similar to the Base Case DF (BCDF) distributions, which was previously given in Table 6.2. Since the canopy shape was symmetrical, the ET values at floor position 1 and 3 were almost the same and those at floor position 2 were always the highest due to the highest Sky Factor of atrium opening area at that floor position.

When the impact of the glazing materials were examined for the two sky conditions, the ET values of the canopies with transparent glazing materials (No. 26 and 27) were almost identical as discussed in the previous section. However, the canopy with translucent glazing (No. 28) again showed about 10 % higher ET values for clear sky than for overcast sky because of the same reason discussed in the previous section. Furthermore, the differences between the center ET value and the other ET values were reduced. This might be due to the light diffusing character of the white translucent glazing material so that the transmitted diffuse light is more evenly distributed throughout the space.

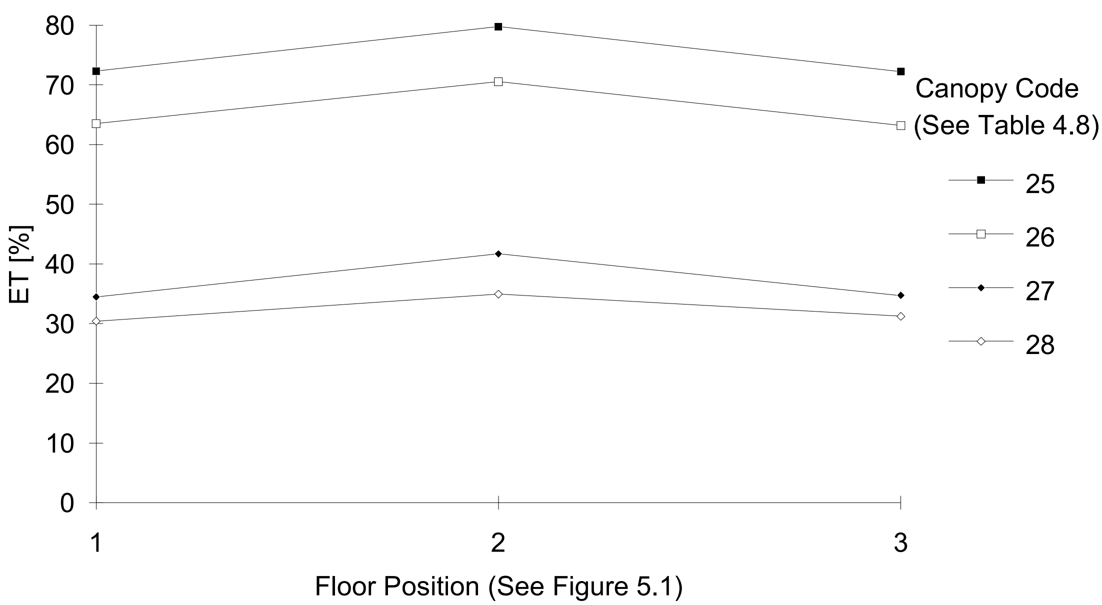


Figure 6.48 Clear Sky ET Distributions of Pyramid Skylights (WI = 1.5)

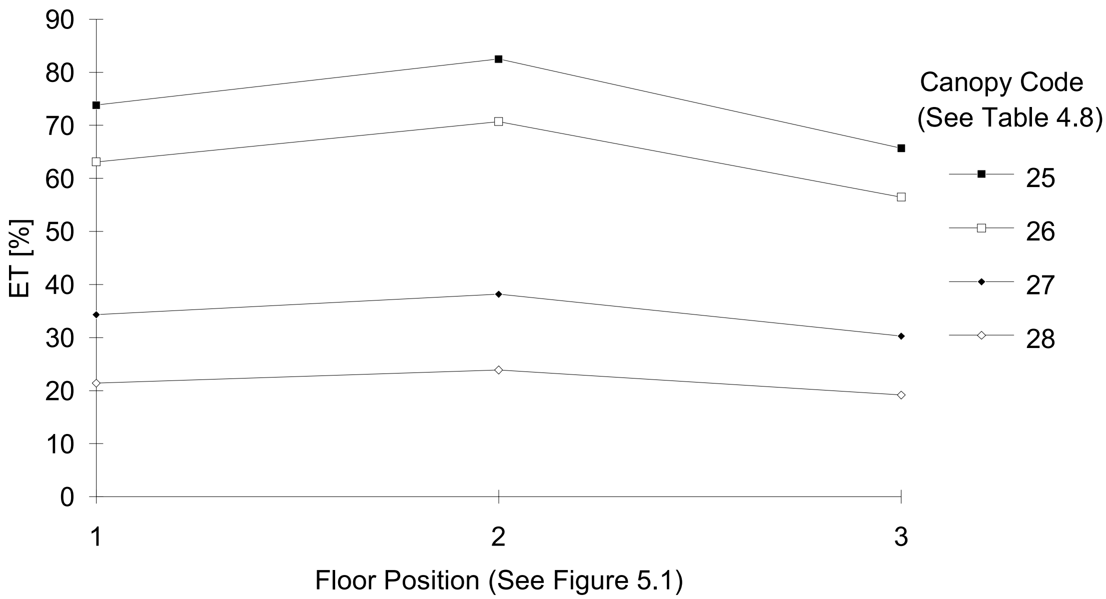


Figure 6.49 Overcast Sky ET Distributions of Pyramid Skylights (WI = 1.5)

Figures 6.50 and 6.51 show the ET distributions of waffle skylights with 85 % waffle surface reflectance. The overall magnitudes for the two sky conditions were almost equal. However, one notable feature was the ET differences between the center position and the other positions. For clear sky, the ET values at the center floor position averaged 1.05 times those of other positions. For overcast sky, the ET values at the center floor position averaged 1.13 times those of other positions. Therefore, it can be concluded that a waffle skylight system distributed daylight more evenly throughout the space under clear sky than under overcast sky, 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. In other words, it can be said that the waffle structure had more impact on atrium daylighting under clear sky than under overcast sky.

In closing this section, 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.

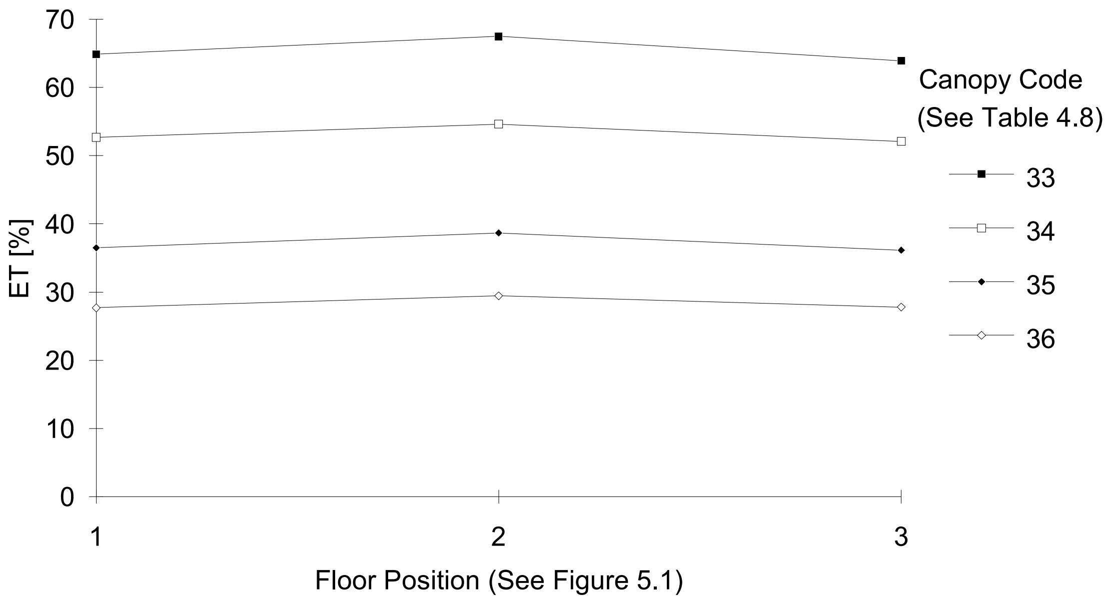


Figure 6.50 Clear Sky ET Distributions of Waffle Skylights with 85 % Reflectance (WI = 1.5)

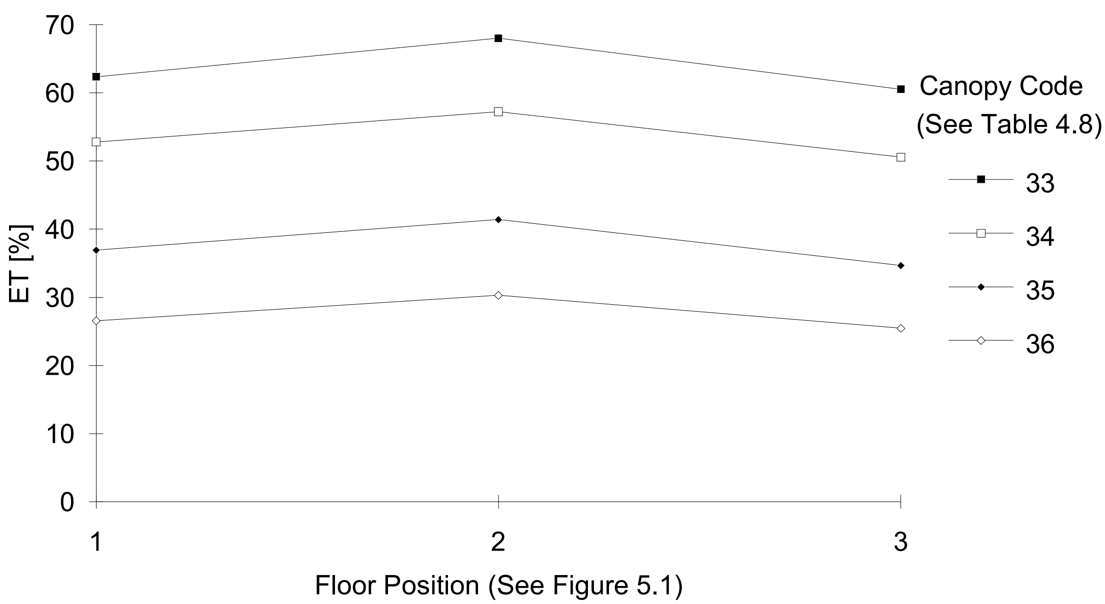


Figure 6.51 Overcast Sky ET Distributions of Waffle Skylights with 85 % Reflectance (WI = 1.5)

6.2 DAYLIGHT LUMINANCE DISTRIBUTIONS IN ATRIA

6.2.1 Video Image Capture

The luminance distribution in atria with different WI values were measured using the video-based luminance mapping system. The measurements were conducted under overcast sky condition with four WI values (0.6, 1.2, 1.8, and 2.4). The fisheye lens of the luminance mapping system was located at the center floor position. Figure 6.52 shows the height and elevation angles of solid walls and windows relative to the location of the fisheye lens. Figures 6.53 through 6.56 show the orthographically projected video images of daylight luminance distributions.

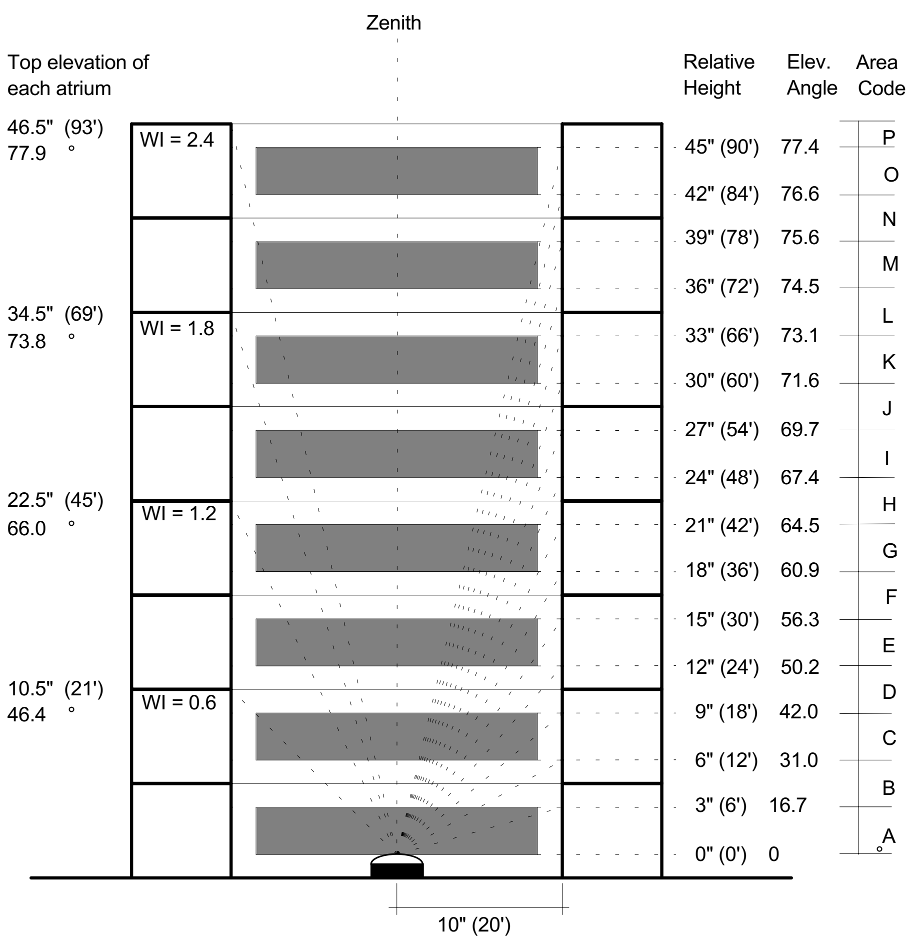
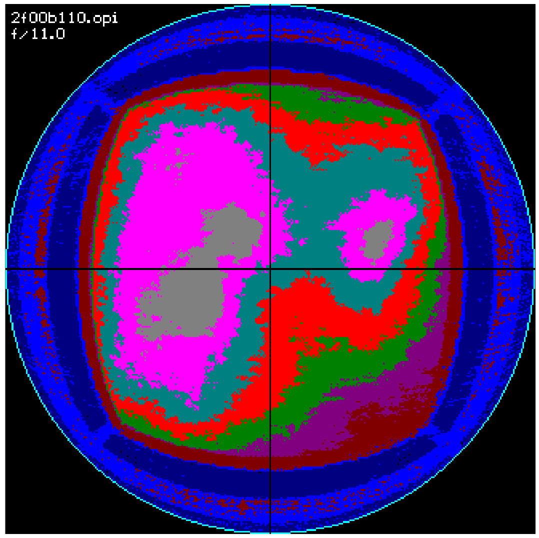
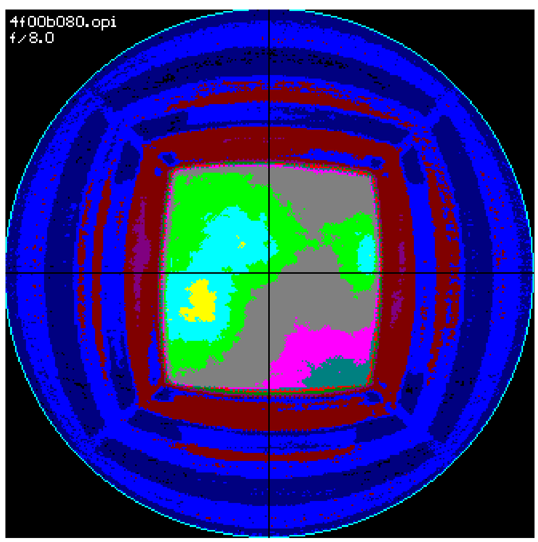


Figure 6.52 Height and Elevation Angles Relative to Fisheye Lens



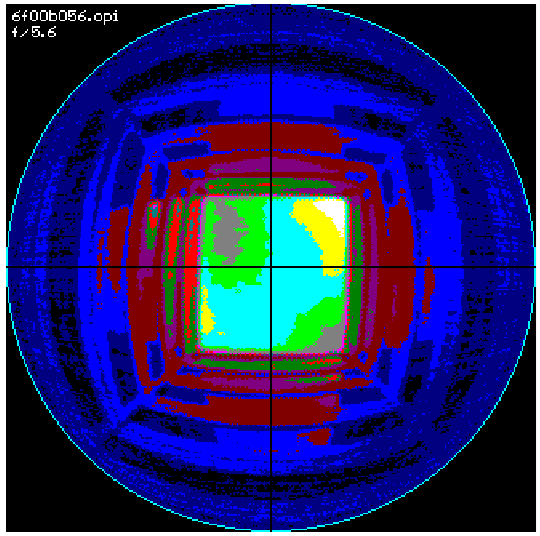
South

Figure 6.53 Video Image of Daylight Luminance Distribution at WI = 0.6 (Atrium A2, f/11) without Canopy



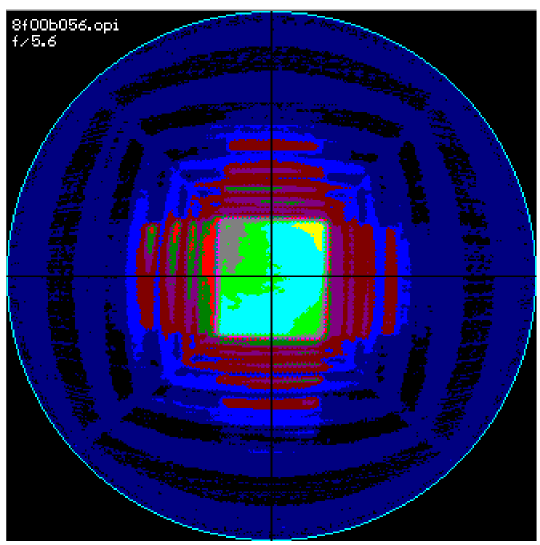
South

Figure 6.54 Video Image of Daylight Luminance Distribution at WI = 1.2 (Atrium A4, f/8) without Canopy



South

Figure 6.55 Video Image of Daylight Luminance Distribution at WI = 1.8 (Atrium A6, f/5.6) without Canopy



South

Figure 6.56 Video Image of Daylight Luminance Distribution at WI = 2.4 (Atrium A8, f/5.6) without Canopy

The previous figures show that the sky factor (i.e., configuration factor) of the atrium opening became smaller and the portions of interior surfaces became larger as the WI values increased. To examine if the fisheye lens of the luminance mapping system was located at the correct geometric location (1.5 in. above the center floor position), the Sky Factors (SF) determined from the captured images were compared with those calculated by Equation 6.1. The thresholding algorithm discussed in Chapter 3 was used to single out the opening areas from the whole orthographic projection images. Figure 6.57 shows the orthographic projection image of the opening at WI = 1.2 (atrium A4). The SF values determined from the captured images and those calculated are presented in Table 6.12. The average percent difference was 1.49 %, which indicated very agreements.

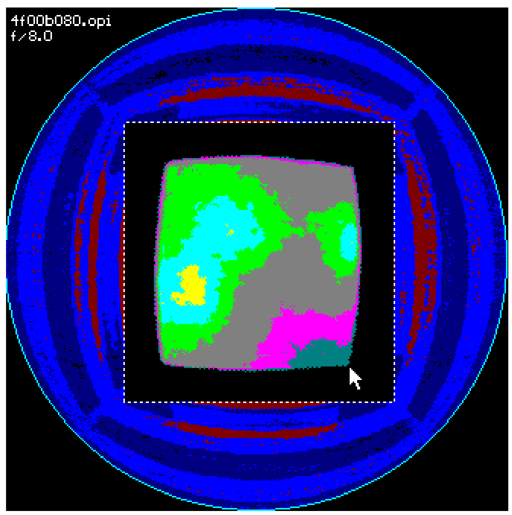


Figure 6.57 Orthographic Projection Image of Opening Area at WI = 1.2 (Atrium A4, Opening SF = 20.3 %)

TABLE 6.12
Sky Factors Calculated and Determined from Captured Video Images

WI	Calculated SF	SF from Image	Percent Difference
0.6	53.0 %	52.8 %	0.38 %
1.2	20.0 %	20.3 %	1.50 %
1.8	9.8 %	10.2 %	4.08 %
2.4	5.6 %	5.6 %	0.00 %

6.2.2 Specular Reflection at Window Glass without Canopy

As shown in the previous Figures 6.53 through 6.56, beginning at WI value of 1.2 (atrium A4), specular reflections at the windows became distinct. The previous Figures 6.55 and 6.56 show more clearly that all windows beginning at the third floor caused specular reflections and the widths of the specular reflection areas had the same widths of the orthographically projected opening images. In addition, all four wall surfaces had almost the same reflection characteristics under overcast sky condition.

The observed specular reflections can be explained by considering the transmittance of window glass varying with incident angle of light. Rivero (1958, as cited by Hopkinson et al. 1966, p. 93) introduced a simple relation given in Equation 6.4 which approximates the glass transmittances at varying incident angles.

$$T_\theta = 1.018\ T_o\ (\cos\theta + \sin^3\theta\cos\theta) \tag{6.4}$$

where T_θ = transmittance of a single pane of glass at a given angle of incidence θ
T_0 = transmittance at normal incidence

Figure 6.58 shows the transmittance curve calculated by Equation 6.2 at every 1° angle of incidence with 92 % of normal transmittance of the clear plastic sheet used for the atrium scale models (see Table 2.4).

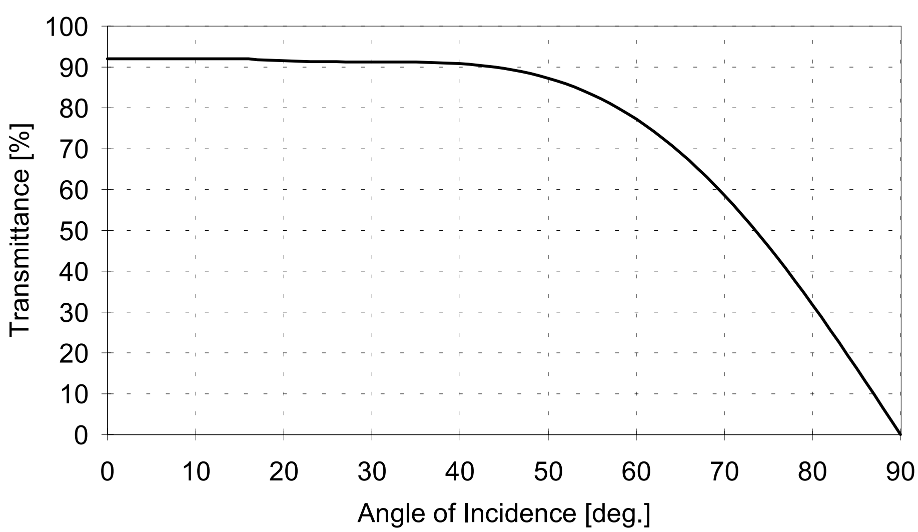


Figure 6.58 The Variation of the Glazing Transmittance with Angle of Incidence

As shown in Figure 6.58, the transmittance declines sharply at incident angles greater than 50°. Figure 6.59 shows the relationship between the incident angle of a light ray to a spot on the atrium wall and the elevation angle subtended by the spot and the fisheye lens. This figure indicates that the incident angle of a light ray is equivalent to the elevation angle. The geometric relationship between the atrium surfaces and the fisheye lens in Figure 6.52 showed that the elevation angle at the bottom line of the window glass on the third floor was 50.2°. Since the remaining portion of light which is not transmitted through a glass material must be reflected at the surface and absorbed into the glazing material, the specular surfaces located above 50° elevation angle can cause specular reflection of the light rays from the sky. For this reason, the window areas which are coded as E, G, I, K, M, O in Figure 6.52 could reflect the sky image toward the floor position.

In real buildings, the specular reflections at window glass can be easily observed when one sees a window glass at certain angles. In addition, one can feel varying brightness of the glass surface (i.e., the intensities of reflected light) due to varying transmittance and reflectance with varying angle of incidence. The impact is magnified substantially when direct sunlight is reflected from such specular surfaces. Sunlight impact will be addressed more fully in a subsequent section.

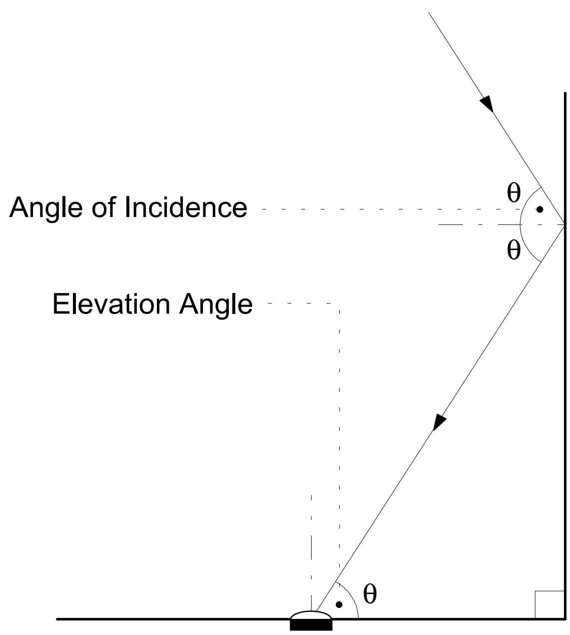


Figure 6.59 Incident Angle of Light and Elevation Angle of Wall Element

6.2.3 Daylight Luminance Distributions without Canopy

To analyze the luminance distributions on the atrium wall surface, the luminances on the center lines of the south wall surfaces were determined from the captured images, because the luminance distributions on the four walls were almost identical to one another. For this analysis, a new term "Luminance Index" (LI) was developed and used to compare the luminance distribution characteristics at different WI values.

The use of Luminance Index (LI) was necessary because the luminance mapping was performed inside the sky simulator which has a fixed dome surface as discussed in Chapter 5. The varying distance from the atrium top to the simulated sky vault due to the varying height of the atrium well caused different absolute luminance values. However, under a real sky the absolute luminance value must be a constant number at the top levels of atria even though the atrium height varies.

The Luminance Index was defined as the ratio of point luminance to the average field luminance recorded by the video-based luminance mapping system, which has a relationship shown in Equation 6.5.

$$LI = \frac{Lp}{\overline{L}} \tag{6.5}$$

where Lp = luminance of a wall element [cd/m²]
$\overline{L}$ = average luminance of hemispherical field including sky recorded by the video-based luminance mapping system [cd/m²]

The concept of Luminance Index (LI) is exactly the same concept as that of the "conventional" Luminance Ratio (LR) which is defined as the ratio of the average luminance of visual task area to the average luminance of surrounding field. In the case of the conventional LR, the field is connected to the view field of the human eye. However, in the LI, the field is the entire hemispherical luminous field which illuminates a point on the work plane. Then, the Luminance Ratio (LR) in this study was calculated from the average LI values on two contiguous wall areas encoded A through P in Figure 6.52.

If Equation 6.5 is related to Equation B.17 in Appendix B, the Luminance Index (LI) can be calculated from the mapped point luminance and measured illuminance as shown in Equation 6.6.

$$LI = \frac{\pi L_p}{E_p} \tag{6.6}$$

where Ep = illuminance at floor position [lux]

As indicated in Equations 6.5 and 6.6, the LI is the weight of the point luminance relative to the average field luminance (including sky luminances) which determines the illuminance at a floor position. With the relationship, a higher LI value of a wall element indicates more light reflected from the wall element, and vice versa. If this concept is related to that of Daylight Factor, a higher value of LI indicates less Sky Component (SC) and more Internally Reflected Component (IRC).

Figure 6.60 shows the plots of the LI values. The average LI value for each wall area which was shown in Figure 6.52 are presented in Figures 6.61 through 6.64. Table 6.13 presents them in numeric values.

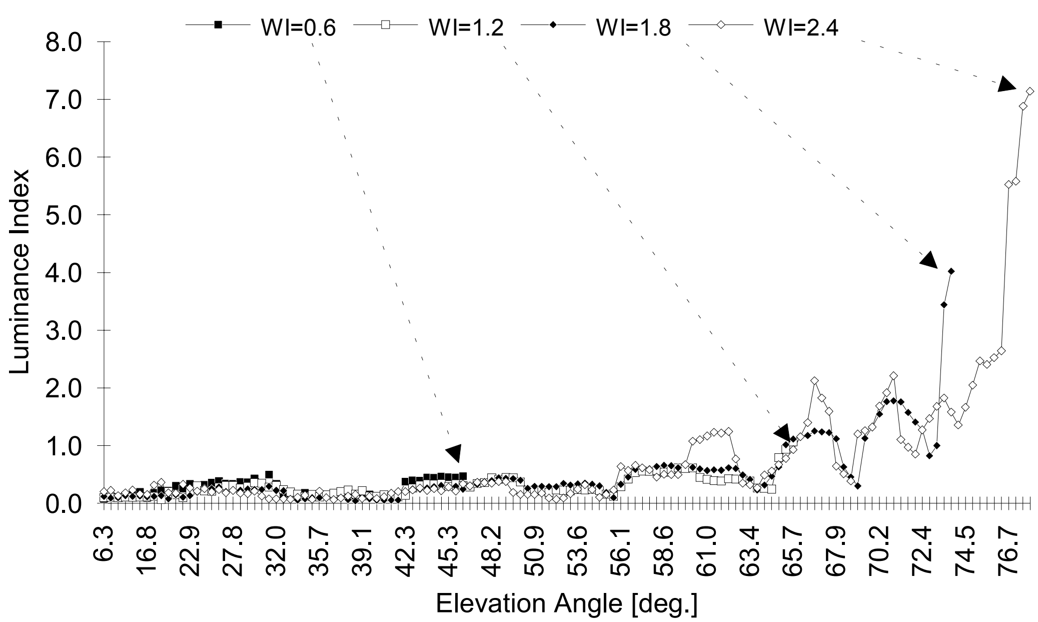


Figure 6.60 Daylight Luminance Index Values on Atrium Wall Center Line for Different Well Index Values without Canopy

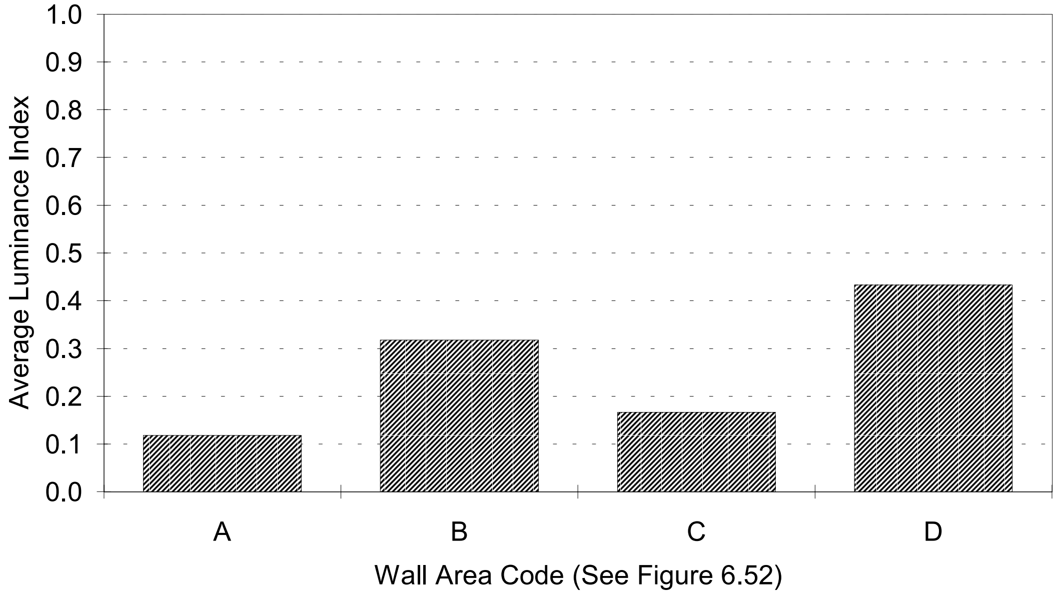


Figure 6.61 Average Daylight Luminance Index Values on Atrium Wall Areas at WI = 0.6 (Atrium A2) without Canopy

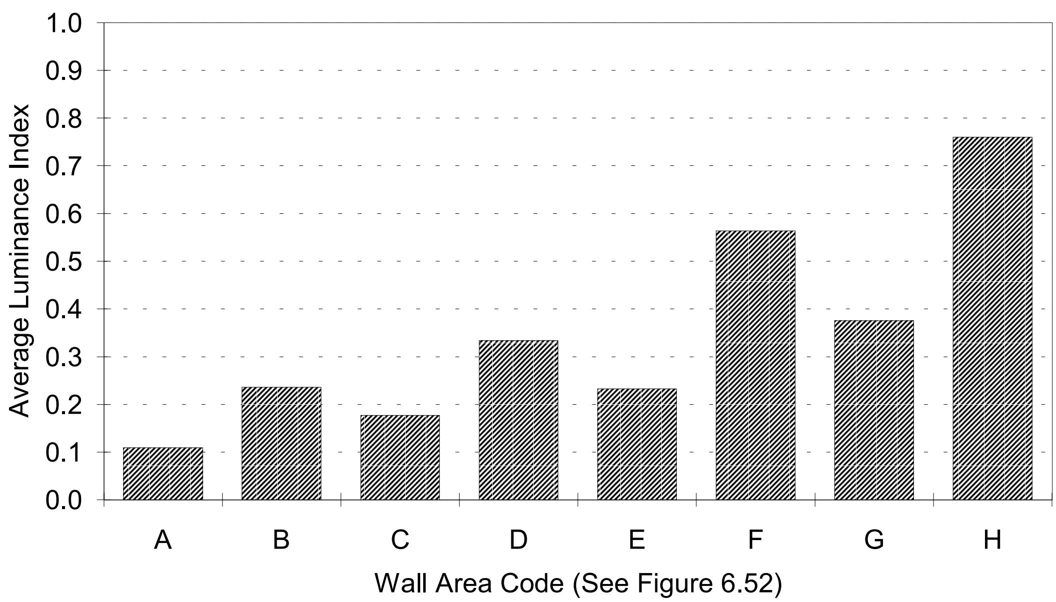


Figure 6.62 Average Daylight Luminance Index Values on Atrium Wall Areas at WI = 1.2 (Atrium A4) without Canopy

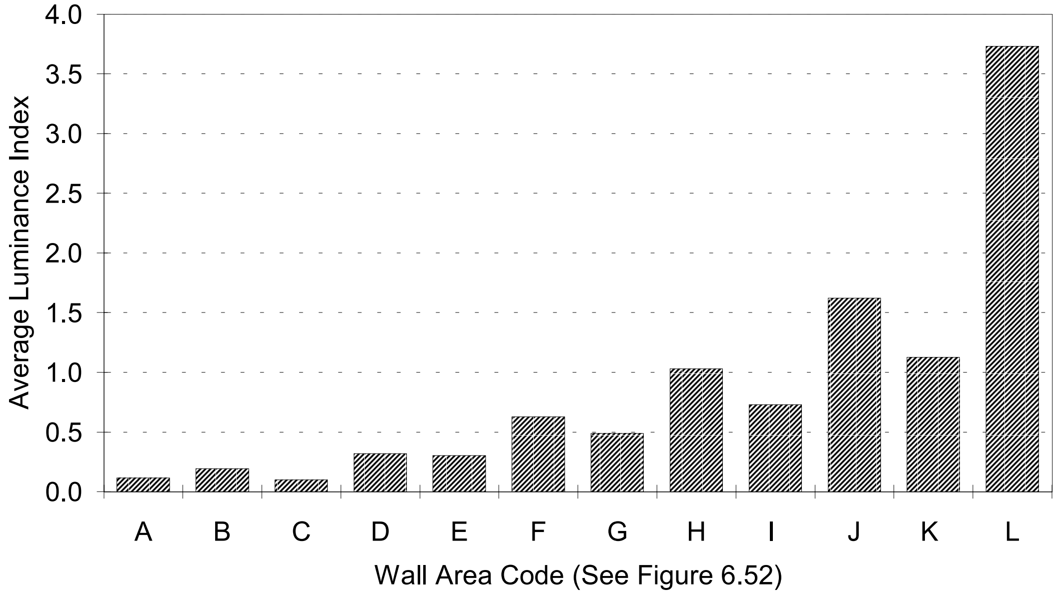


Figure 6.63 Average Daylight Luminance Index Values on Atrium Wall Areas at WI = 1.8 (Atrium A6) without Canopy

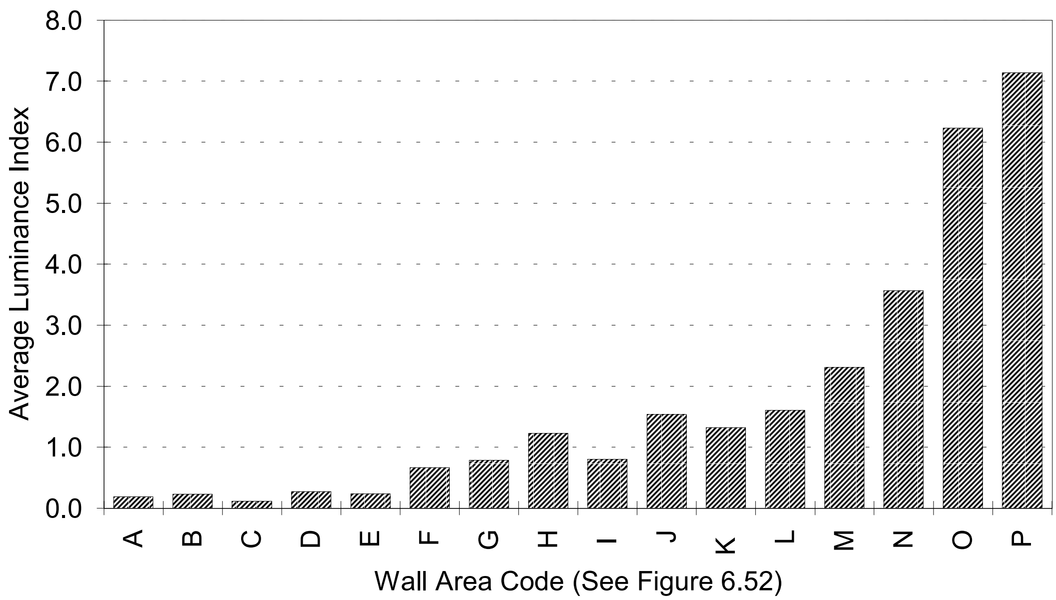


Figure 6.64 Average Daylight Luminance Index Values on Atrium Wall Areas at WI = 2.4 (Atrium A8) without Canopy

TABLE 6.13
Average Daylight Luminance Index Values on
Atrium Wall Areas without Canopy

Wall Area	Atrium Well Index			
Code *	0.6	1.2	1.8	2.4
A	0.1178	0.1095	0.1168	0.1873
B	0.3176	0.2359	0.1942	0.2273
C	0.1661	0.1768	0.1002	0.1146
D	0.4333	0.3337	0.3188	0.2712
E		0.2327	0.3024	0.2337
F		0.5636	0.6263	0.6665
G		0.3750	0.4885	0.7852
H		0.7600	1.0311	1.2271
I			0.7303	0.8031
J			1.6223	1.5362
K			1.1263	1.3200
L			3.7313	1.6057
M				2.3078
N				3.5657
O				6.2313
P				7.1400

* See Figure 6.52 for Wall Area Code

As expected, the LI values for lower WI values were less than those of higher WI values. This implies that, at lower WI values (i.e., shallow atria), the effects of luminances on the wall area on the illuminance level at the floor position are minimal.

At higher WI values, as shown in Figures 6.63 and 6.64 and Table 6.13, even though the luminances both on the solid wall and glazed areas decreased as the elevation angle decreased, luminances of the glazed areas at high elevations were even higher than those of solid wall areas at low elevations. It was also noted that, at the higher WI values, the luminance reductions from the top elevation to about 2/3 elevation of the wall area were very sharp.

Finally, Tables 6.14 through 6.17 present the Luminance Ratios (LR) between the adjacent solid areas and glazed areas for each WI value.

TABLE 6.14

Daylight Luminance Ratios at WI = 0.6 (Atrium A2) without Canopy

Area Code	Luminance Ratio
A : B	1.0 : 2.7
B : C	1.9 : 1.0
C : D	1.0 : 2.6

TABLE 6.15

Daylight Luminance Ratios at WI = 1.2 (Atrium A4) without Canopy

Area Code	Luminance Ratio
A : B	1.0 : 2.2
B : C	1.3 : 1.0
C : D	1.0 : 1.9
D : E	1.0 : 1.4
E : F	1.0 : 2.4
F : G	1.5 : 1.0
G : H	1.0 : 2.5

TABLE 6.16

Daylight Luminance Ratios at WI = 1.8 (Atrium A6) without Canopy

Area Code	Luminance Ratio
A : B	1.0 : 1.7
B : C	1.9 : 1.0
C : D	1.0 : 1.9
D : E	1.1 : 1.0
E : F	1.0 : 2.1
F : G	1.0 : 1.3
G : H	1.0 : 2.1
H : I	1.4 : 1.0
I : J	1.0 : 2.2
J : K	1.1: 1.4
K : L	1.0 : 3.3

TABLE 6.17

Daylight Luminance Ratios at WI = 2.4 (Atrium A8) without Canopy

Area Code	Luminance Ratio
A : B	1.0 : 1.2
B : C	2.0 : 1.0
C : D	1.0 : 2.4
D : E	1.2 : 1.0
E : F	1.0 : 2.9
F : G	1.0 : 1.2
G : H	1.0 : 1.6
H : I	1.5 : 1.0
I : J	1.0 : 1.9
J : K	1.2: 1.0
K : L	1.0 : 1.2
L : M	1.0 : 1.4
M : N	1.0 : 1.5
N : O	1.0 : 1.7
O : P	1.0 : 1.5

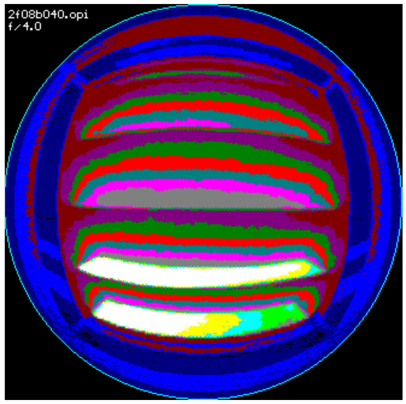
6.2.4 Daylight Luminance Distributions with Canopies

The effects of canopy systems on the distributions of wall luminances were examined with the video images captured at the center floor position in atria with three different WI values (0.6, 1.2, and 1.8). The atria with WI values higher than 1.8 were excluded in this analysis, because the luminances with canopies were too low to be captured by the video-based luminance mapping system. A total of six canopy systems were selected for this test, which included 4-unit sawtooth canopy with 45° panel slope angle (No. 08), 4-unit sawtooth canopy with 15° aperture slope angle (No. 13), flat horizontal skylight with tinted transparent glazing (No. 19), pyramid skylight with white translucent glazing (No. 28), and waffle skylights with 0.5 WWI (No. 33) and 2.0 WWI (No. 36).

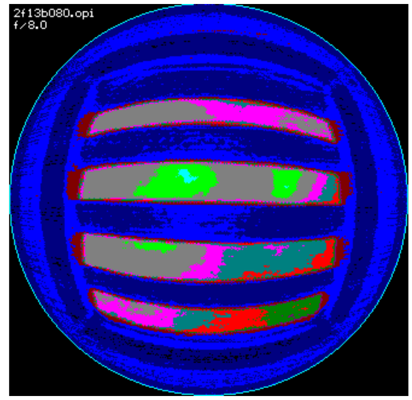
In the previous analysis with the uncovered atria for diffuse skies, only the luminances on the south walls were analyzed and compared for different WI values, because the luminance distribution patterns on the four walls were almost symmetrical. However, in this test, the luminances on the south, north, and west walls were analyzed, because the sawtooth canopy produced asymmetrical luminance distributions on the different walls.

The video images in Figure 6.65 show the luminance distribution patterns in atria A2 (WI = 0.6) with the six different canopy systems. As shown in the images, the luminance distributions on the four walls with skylight systems (No. 19, 28, 33, and 36) were almost symmetrical. However, as shown in image "a", the sawtooth canopy caused higher luminances on the north wall than on the other walls, because the north wall was exposed to the sky through the canopy openings. Slight specular reflections also occurred on the north, east, and west windows on the second floor.

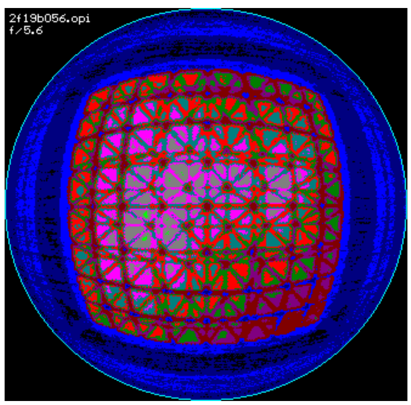
Figure 6.66 through 6.71 show the LI values on the south, north, and west walls for each canopy configuration. When the LI values shown in Figures 6.66 and 6.67 were compared with the others, the LI values for sawtooth canopies were higher, because the solid panels of sawtooth canopies blocked more sky area and the relative luminance on the walls became high. The lowest LI values were observed in Figure 6.69 which shows the LI values for pyramid skylight with translucent glazing material. It indicated that the translucent glazing material caused less luminances on the walls, and the illuminance at the floor position was mostly provided by the canopy itself. The Luminance Ratios (LR) between adjacent areas on the three walls were calculated and presented for the six canopy systems in Table 6.18.



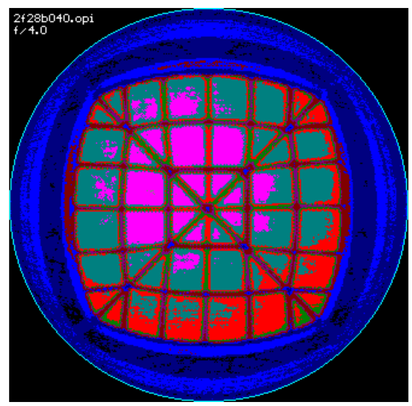
a. Sawtooth Canopy 08 (f/4)



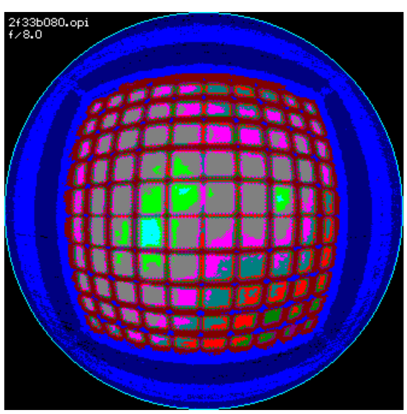
b. Sawtooth Canopy 13 (f/8)



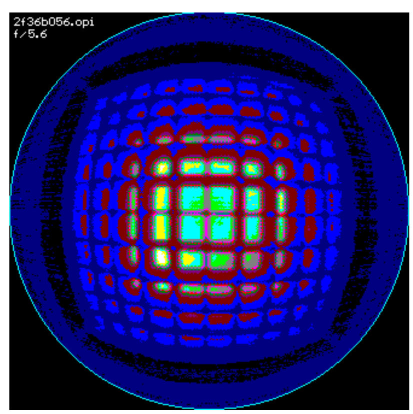
c. Flat Skylight 19 (f/5.6)



d. Pyramid Skylight 28 (f/4)



e. Waffle Skylight 33 (f/8)



f. Waffle Skylight 36 (f/5.6)

Figure 6.65 Video Images of Daylight Luminance Distributions at WI = 0.6 (Atrium A2, North is up) with Various Canopy Configurations (See Table 4.8)

Figure 6.66 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Sawtooth Canopy 08 (See Table 4.8)

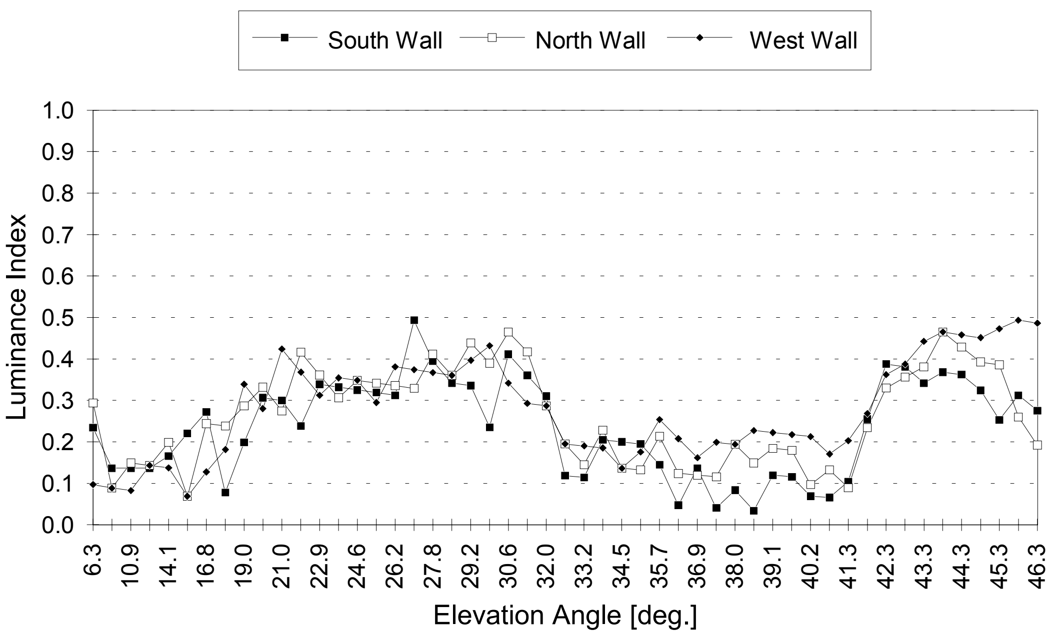


Figure 6.67 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Sawtooth Canopy 13 (See Table 4.8)

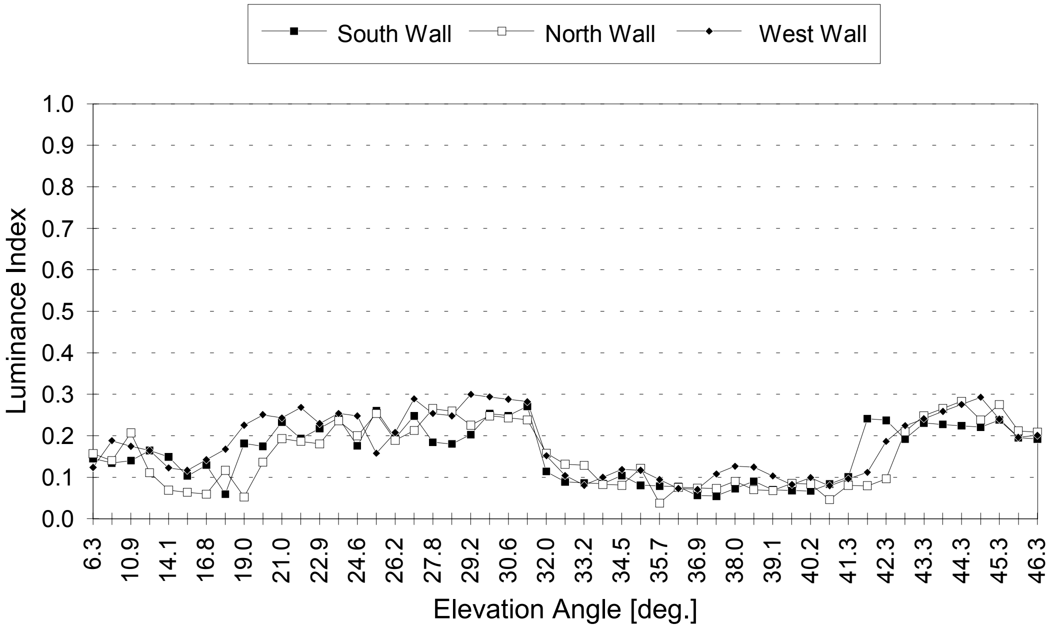


Figure 6.68 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Flat Skylight 19 (See Table 4.8)

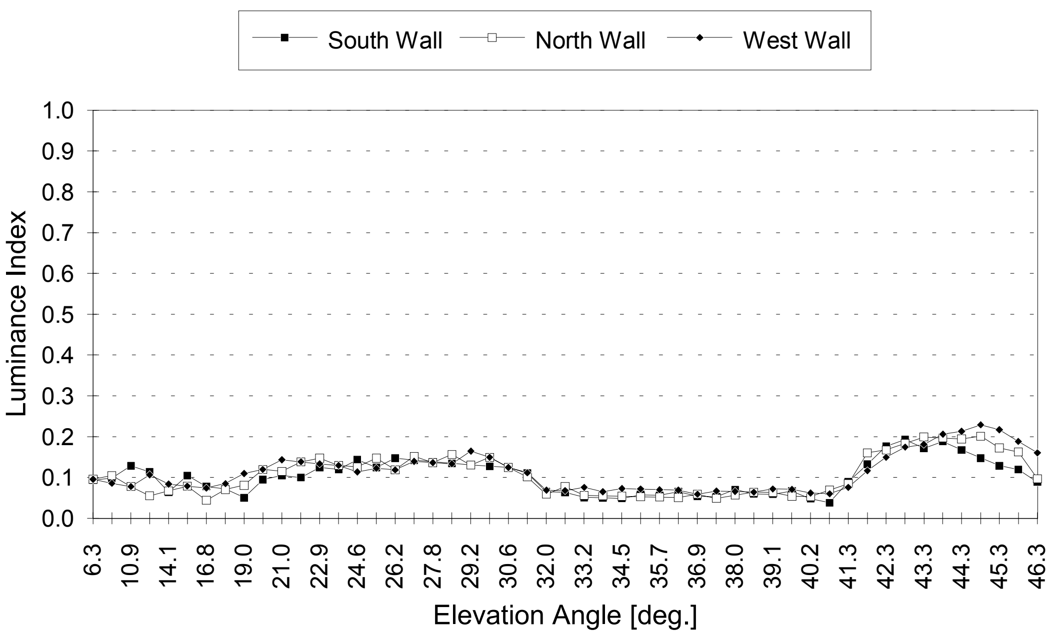


Figure 6.69 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Pyramid Skylight 28 (See Table 4.8)

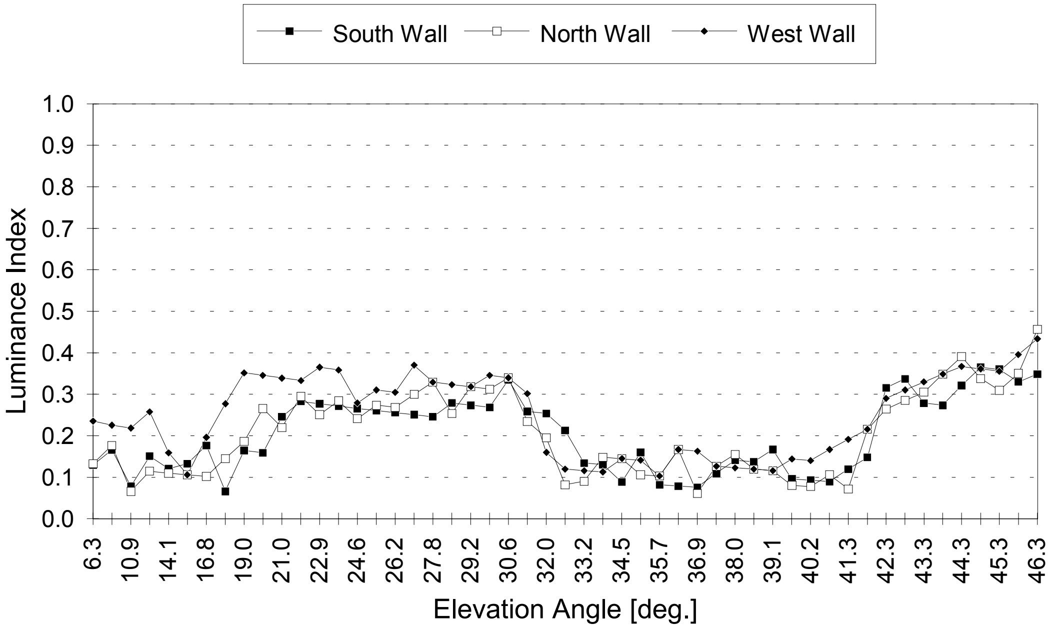


Figure 6.70 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Waffle Skylight 33 (See Table 4.8)

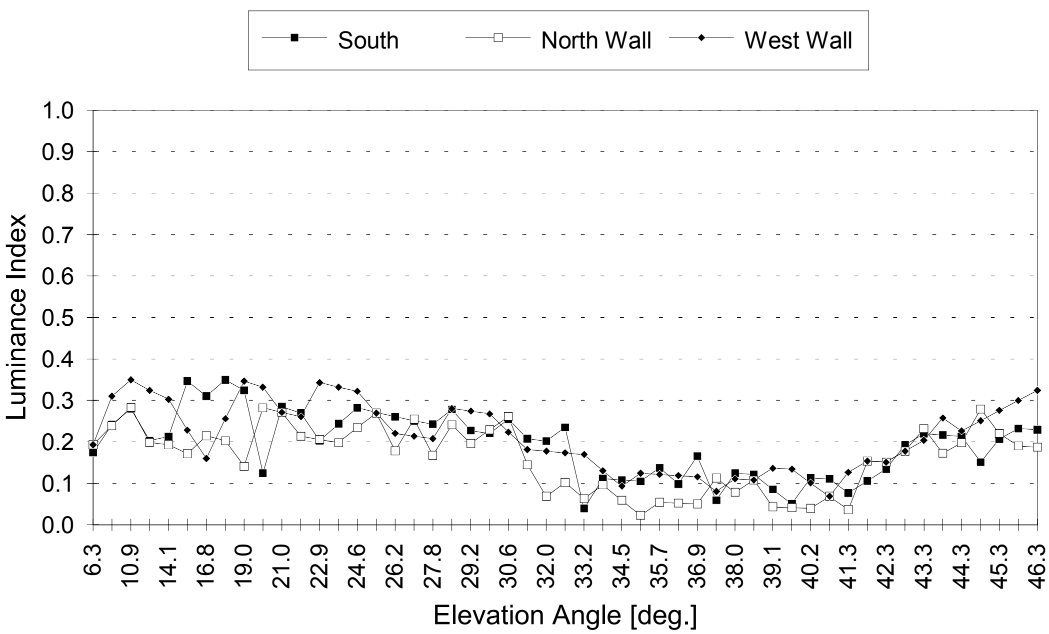


Figure 6.71 Daylight Luminance Index Values on Three Walls at WI = 0.6 (Atrium A2) with Waffle Skylight 36 (See Table 4.8)

TABLE 6.18

Daylight Luminance Ratios at WI = 0.6 (Atrium A2) with Canopies

* CC	** WO	Area Code ***										
		A:B	B:C	C:D	D:E	E:F	F:G	G:H	H:I	I:J	J:K	K:L
08	S	1:2.7	1.5:1	1:2.5	This is a two-story atrium. The wall areas "E" through "L" do not exist.							
	N	1:5.2	1.9:1	1:2.3								
	W	1:2.4	1.6:1	1:3.0								
13	S	1:1.7	2.2:1	1:2.3								
	N	1:2.1	2.1:1	1:2.0								
	W	1:2.2	1.6:1	1:2.1								
19	S	1:1.4	2.0:1	1:2.2								
	N	1:1.5	2.0:1	1:2.4								
	W	1:1.6	2.0:1	1:2.1								
28	S	1:1.2	1.8:1	1:2.4								
	N	1:1.7	1.9:1	1:2.6								
	W	1:1.5	1.8:1	1:2.6								
33	S	1:1.8	1.8:1	1:2.4								
	N	1:2.3	2.1:1	1:2.7								
	W	1:1.7	2.2:1	1:2.3								
36	S	1:1.0	2.2:1	1:1.7								
	N	1:1.0	3.0:1	1:2.7								
	W	1:1.0	2.2:1	1:1.9								

Note: * CC = Canopy Code (See Table 4.8)

** WO = Wall Orientation (See Figure 5.1)

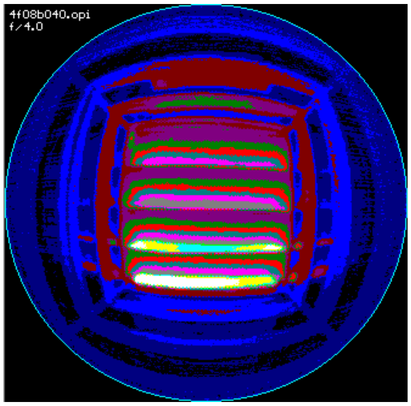
*** See Figure 6.52 for Area Code

The video images in Figure 6.72 show the luminance distribution maps at WI = 1.2 (atrium A4) with the six canopies. The LI values with the six canopies at this WI value are plotted in Figures 6.73 through 78. The Luminance Ratio (LR) values at WI = 1.2 are presented in Table 6.19.

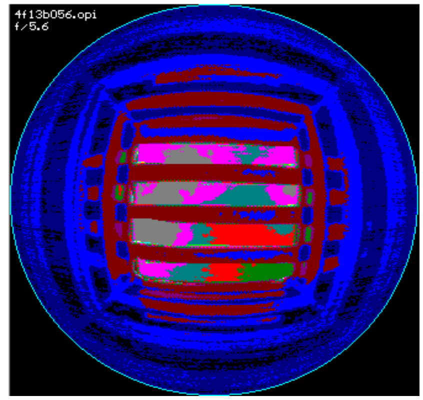
The figures show that the LI values at WI = 1.2 became higher than they were at WI = 0.6, which indicated less contribution of sky luminance and more contribution of the wall luminance on illuminance level at the floor position. In Figure 6.72, images "c" through "f" show that the skylights (No. 19, 28, 33, and 36) again caused very symmetrical luminance distributions on the four walls. However, images "a" and "b" indicate that the sawtooth canopies (No. 08 and 13) began to show notable changes at this increased WI value because of the orientation of the canopy apertures and the increased elevation angles of the wall elements subtended at the fisheye lens, which caused stronger specular reflections at particular wall elements. The sawtooth canopy 08 caused specular reflections at a large portion of the north window for the third floor and at small segmented areas of the east and west windows for the third and fourth floors. Figure 6.73 shows that the luminances on the top portions of the north wall were higher than those on the other walls; and those on the west wall were higher than those on the south wall. Again, this figure shows that the luminances on the solid wall areas were still higher than those on the window areas even though specular reflections occurred at the windows.

On the other hand, the sawtooth canopy with sloping apertures (No. 13) caused much different luminance distributions. With this canopy, the luminance distributions on the north and south walls were almost equal. However, those on the two side walls were different. Owing to the higher Sky Factor (SF) of the sawtooth apertures viewed from the two side walls, specular reflection patches on the east and west windows for the third and fourth floors were prominent. As shown in Figure 6.74, the fluctuations of the LI values on the west wall did not synchronize with those of south and north walls at the high elevation angles. This phenomenon indicated that the luminances at the east and west windows were higher than those on the solid walls at the high elevation angles.

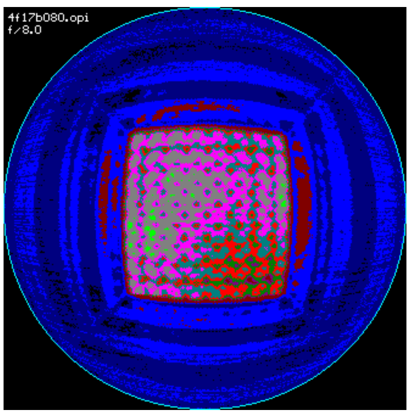
A notable phenomenon was concerned with the Sky Factor (SF) of the waffle skylight with WWI = 2.0 (No. 36) shown in the previous Figure 6.71 and the image "f" in Figure 6.72. When comparing the two images, it was found that even though the WI value doubled, the visible direct sky area did not diminish; even the latter looks larger than the former. This explains why waffle skylight systems resulted in higher Effective Transmittance (ET) values at higher WI values, which were discussed in the previous Section 6.2.1.



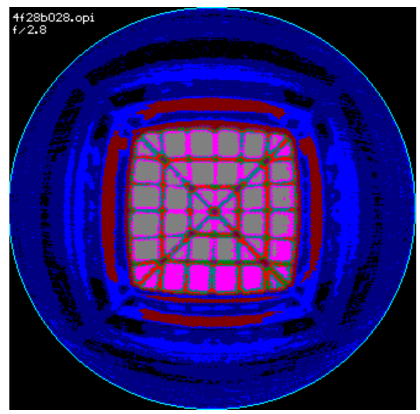
a. Sawtooth Canopy 08 (f/4)



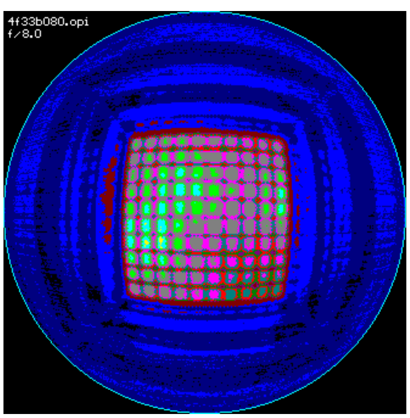
b. Sawtooth Canopy 13 (f/5.6)



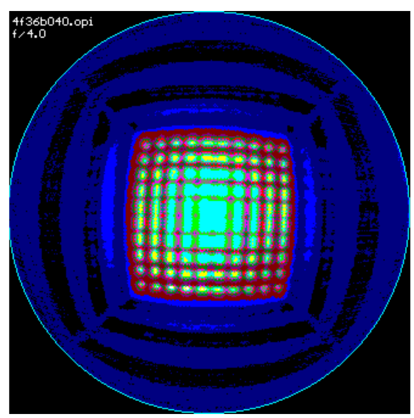
c. Flat Skylight 19 (f/4)



d. Pyramid Skylight 28 (f/2.8)



e. Waffle Skylight 33 (f/8)



f. Waffle Skylight 36 (f/4)

Figure 6.72 Video Images of Daylight Luminance Distributions at WI = 1.2 (Atrium A4, North is up) with Various Canopy Configurations (See Table 4.8)

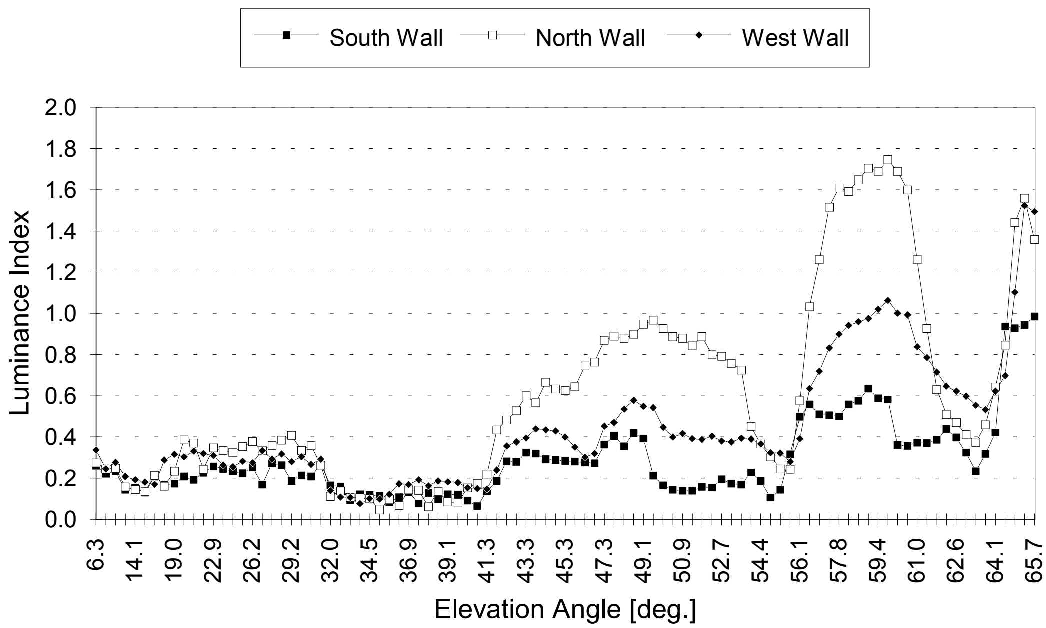


Figure 6.73 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Sawtooth Canopy 08 (See Table 4.8)

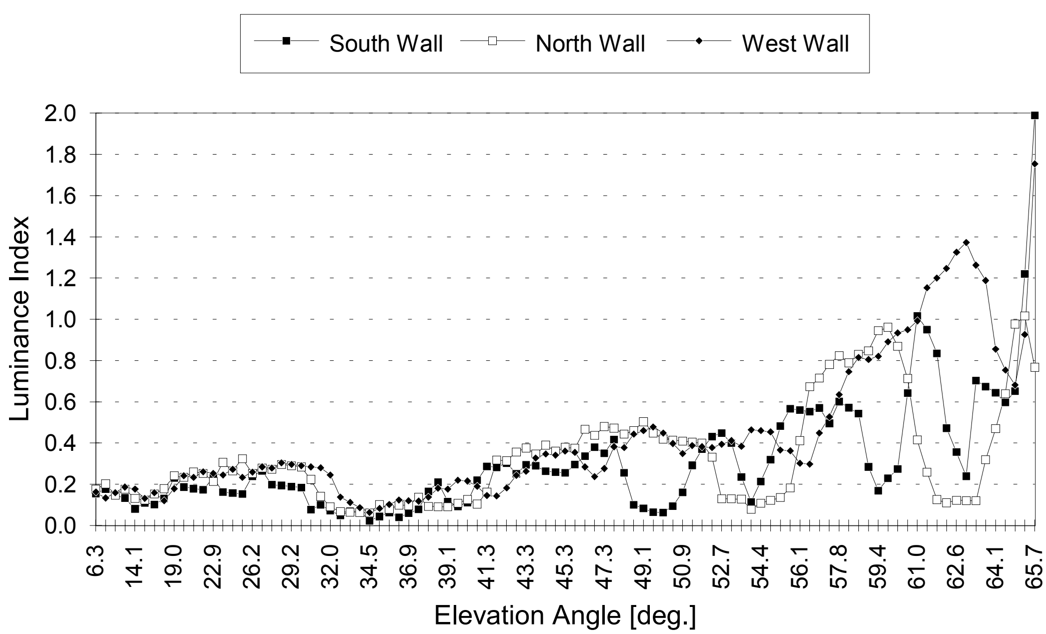


Figure 6.74 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Sawtooth Canopy 13 (See Table 4.8)

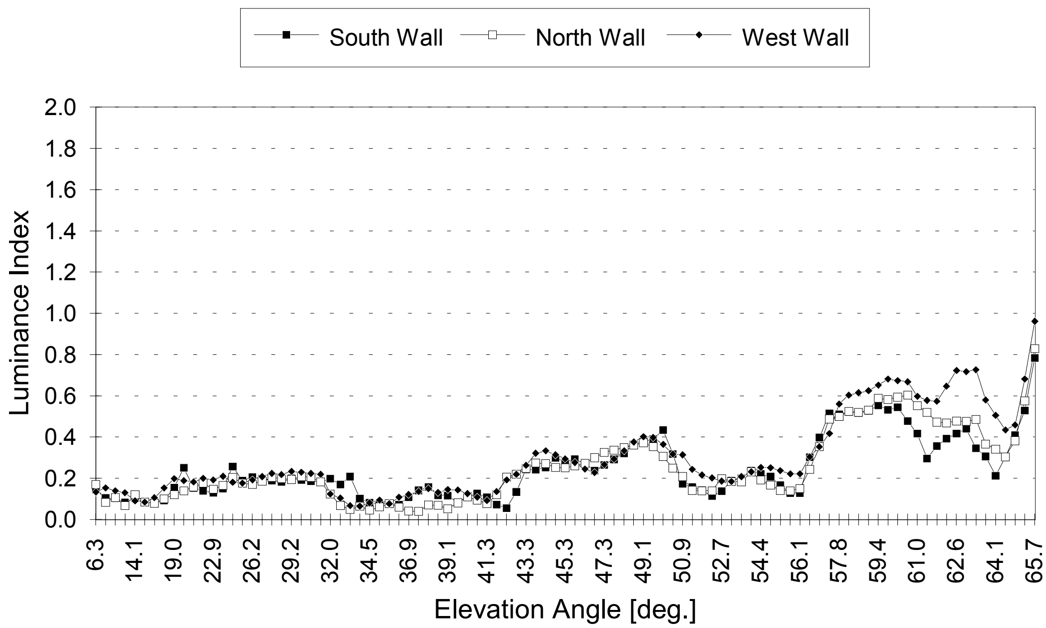


Figure 6.75 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Flat Skylight 19 (See Table 4.8)

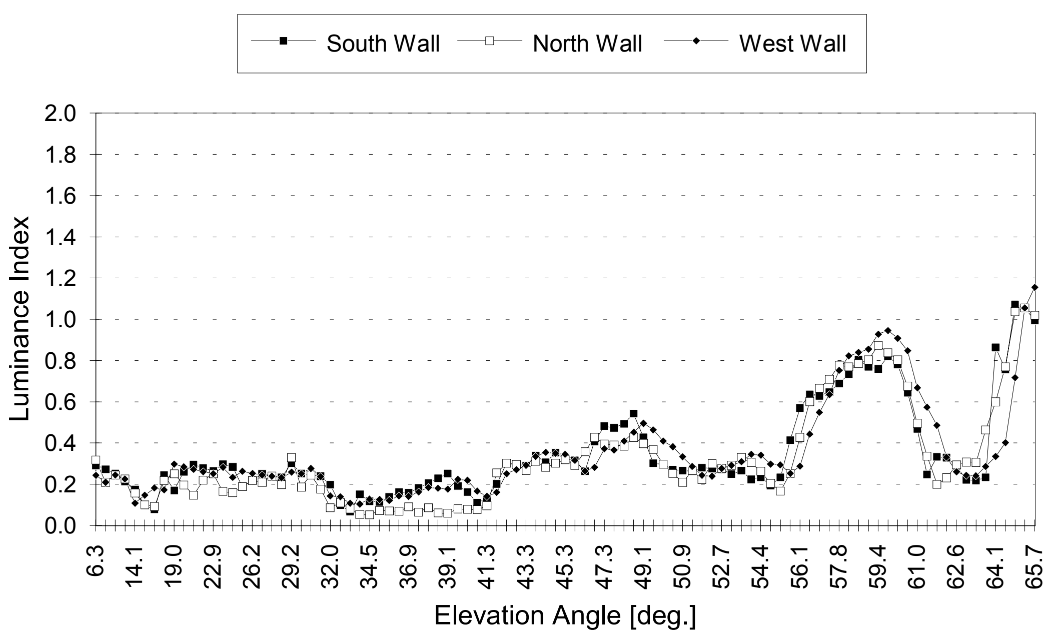


Figure 6.76 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Pyramid Skylight 28 (See Table 4.8)

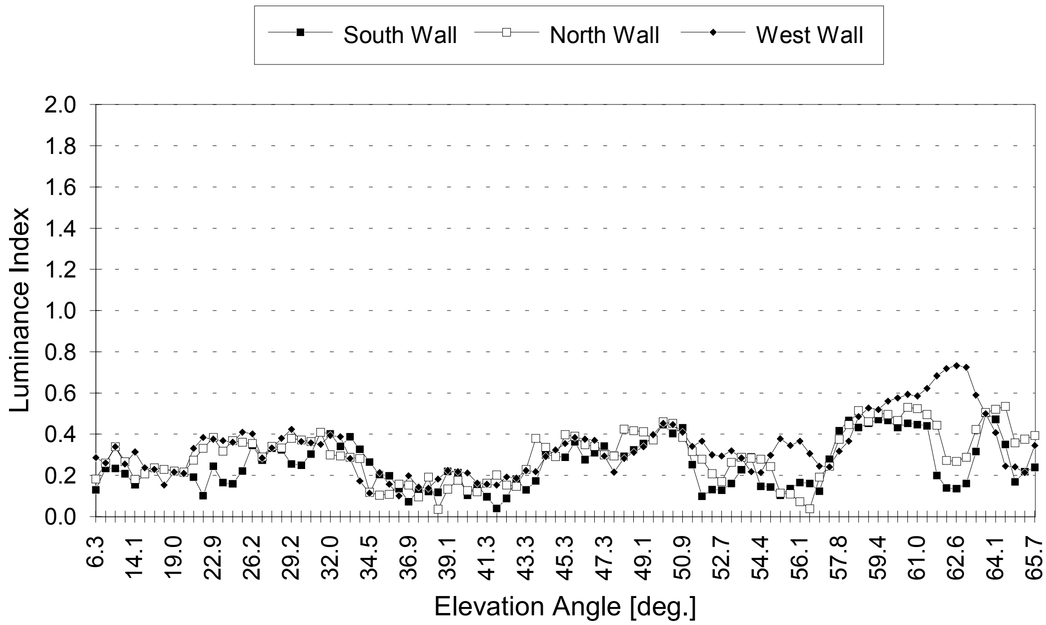


Figure 6.77 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Waffle Skylight 33 (See Table 4.8)

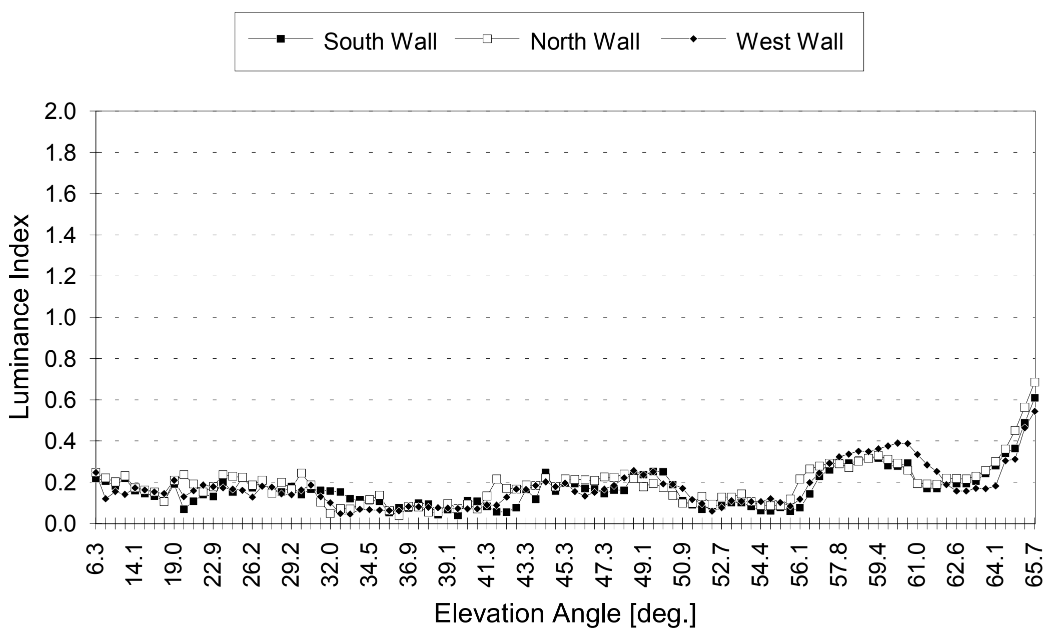


Figure 6.78 Daylight Luminance Index Values on Three Walls at WI = 1.2 (Atrium A4) with Waffle Skylight 36 (See Table 4.8)

TABLE 6.19

Daylight Luminance Ratios at WI = 1.2 (Atrium A4) with Canopies

* CC	** WO	Area Code ***										
		A:B	B:C	C:D	D:E	E:F	F:G	G:H	H:I	I:J	J:K	K:L
08	S	1:1.1	1.7:1	1:2.4	1.3:1	1:2.3	1.4:1	1:2.6	This is a four-story atrium. The wall areas "I" through "L" do not exist.			
	N	1:1.6	2.4:1	1:5.4	1.2:1	1:2.5	2.5:1	1:2.1				
	W	1:1.3	1.9:1	1:2.8	1:1.0	1:2.2	1.4:1	1:1.8				
13	S	1:1.4	1.6:1	1:2.1	1:1.5	1:1.2	1:1.5	1:1.7				
	N	1:1.6	2.4:1	1:3.7	1.6:1	1:3.2	3.6:1	1:3.7				
	W	1:1.6	1.7:1	1:2.3	1:1.1	1:2.0	1:1.6	1.1:1				
19	S	1:1.8	1.5:1	1:2.3	1.6:1	1:2.7	1.4:1	1:1.4				
	N	1:1.7	2.2:1	1:3.7	1.7:1	1:2.9	1.1:1	1:1.1				
	W	1:1.7	1.7:1	1:2.6	1.3:1	1:2.4	1:1.1	1:1.0				
28	S	1:1.3	1.5:1	1:2.2	1.2:1	1:2.3	2.0:1	1:2.7				
	N	1:1.1	2.4:1	1:3.7	1.1:1	1:2.6	2.1:1	1:2.7				
	W	1:1.3	1.6:1	1:2.3	1.2:1	1:2.7	2.1:1	1:2.2				
33	S	1:1.2	1.2:1	1:14	1.6:1	1:2.2	1.3:1	1.3:1				
	N	1:1.3	1.8:1	1:1.9	1.6:1	1:1.9	1:1	1:1.0				
	W	1:1.2	1.6:1	1:1.5	1:1	1:1.4	1:1.4	2.4:1				
36	S	1:1.2	1.6:1	1:1.8	2.0:1	1:3.3	1.4:1	1:2.2				
	N	1:1.0	2.2:1	1:2.1	1.5:1	1:2.3	1.3:1	1:2.3				
	W	1:1.0	2.2:1	1:2.5	1.7:1	1:3.0	1.6:1	1:1.9				

Note: * CC = Canopy Code (See Table 4.8)
** WO = Wall Orientation (See Figure 5.1)
*** See Figure 6.52 for Area Code

Finally, Table 6.20 summarizes the Luminance Ratios (LR) between two adjacent areas at WI = 1.8 (atrium A6).

TABLE 6.20
Daylight Luminance Ratios at WI = 1.8 (Atrium A6) with Canopies

* CC	** WO	Area Code ***										
		A:B	B:C	C:D	D:E	E:F	F:G	G:H	H:I	I:J	J:K	K:L
08	S	1:1.2	1.9:1	1:1.6	1.3:1	1:2.1	2.0:1	1:3.1	1.2:1	1:2.3	1:1.0	1:1.9
	N	1:1.2	2.8:1	1:4.4	1:1.7	1:1.4	1:1.7	1:3.1	1:2.3	1.5:1	1.9:1	1:1.5
	W	1:1.0	2.6:1	1:2.8	1:1.3	1:1.6	1:1.2	1.1:1	1:1.7	1:1.3	1:1.1	1:1.3
13	S	1:1.3	2.0:1	1:2.6	1:1.1	1:1.6	1:3.6	1:4.5	2.2:1	1:4.9	1:1.2	1:1.0
	N	1:1.2	2.4:1	1:3.8	1:1.0	1:1.9	1:1.9	1.5:1	1:2.1	1.5:1	2.0:1	1:1.6
	W	1:1.0	2.0:1	1:2.7	1:2.4	1.1:1	1:2.1	1.8:1	1:2.6	1.4:1	1:1.7	1:1.1
19	S	1:1.0	1.7:1	1:2.1	1.2:1	1:2.1	1.2:1	1:1.6	1.6:1	1:2.3	1.1:1	1.6:1
	N	1.1:1	2.6:1	1:3.3	1:1.0	1:1.9	1:1.2	1.1:1	1:1.9	1.1:1	1:1.4	1.3:1
	W	1:1.0	1.9:1	1:2.3	1.1:1	1:1.7	1:1.3	1.4:1	1:2.1	1.1:1	1:1.4	1:1.0
28	S	1.1:1	2.0:1	1:2.2	1:1.2	1:1.5	1:1.0	1:1.5	2.0:1	1:2.9	1:1.0	1:1.0
	N	1.4:1	2.0:1	1:2.3	1:1.1	1:1.7	1:1.1	1:1.1	1.7:1	1:2.7	1:1.0	1:1.0
	W	1:1.0	2.0:1	1:2.2	1:1.3	1:1.6	1:1.3	1.3:1	1:1.3	1:1.6	1:1.3	1:1.2
33	S	1:1.5	1.7:1	1:2.1	1:1.0	1:1.9	1.3:1	1:2.1	1.3:1	1:1.9	1.3:1	1:1.8
	N	1:1.4	2.5:1	1:2.9	1:1.0	1:1.6	1:1.3	1:1.0	1:1.1	1:1.6	1:1.4	1.4:1
	W	1:1.2	2.0:1	1:2.1	1:1.2	1:1.6	1:1.3	1.4:1	1:1.8	1:1.1	1:1.5	1.4:1
36	S	1:1.8	2.0:1	1:1.9	1:1.0	1:1.7	1.3:1	1:2.4	1.7:1	1:2.4	1.4:1	1:2.7
	N	1:1.5	2.5:1	1:2.3	1:1.0	1:2.0	1:1.0	1:1.1	1.1:1	1:2.8	1:1.2	1:1.2
	W	1:1.7	2.0:1	1:3.1	1:1.1	1:1.7	1:1.5	2.0:1	1:1.9	1:1.4	1:2.4	1.1:1

Note: * CC = Canopy Code (See Table 4.8)
** WO = Wall Orientation (See Figure 5.1)
*** See Figure 6.52 for Area Code