

# Glass in daylighting design, an experimental investigation of the impact of glass types

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This paper reports on an experimental study that investigated the impact of clear and diffusing glass types on the design and performance of daylighting systems. Scale models of toplighting and sidelighting systems were tested in the lab under the standard CIE overcast sky. Quantitative analysis of the test results documented, with a good level of accuracy, the impact of different glass types on the overall efficiency of daylighting systems, and showed their impact on the distribution of light intensities inside the spaces tested. The findings and recommendations of this study should be helpful to architects and engineers who do design (or engineer) daylighting systems.

Conference theme: Building performance studies, zero energy, and carbon-neutral buildings.

Keywords: daylighting, glass, angle of incidence, visible transmittance, daylight factor.

## INTRODUCTION

Because architectural design, by nature, is a trial and error process, experimental research in architecture is of a paramount importance. Experimental research complements the design process and helps to make it more effective (Mansy 2006). The subject of this paper was initiated by an observation that took place during the design process. The observation initiated a question; and later triggered an experimental pursuit in order to answer that question. In order to reach a scientific answer, an experiment was set up in the daylighting laboratory to test the impact of different glass types on the performance of daylighting systems. This paper reports on this experiment; its description, setup, findings, and conclusion.

## 1. THE OBSERVATION

The design and performance of daylighting systems is influenced by many factors, including the visible transmittance of the glass type to be used for windows and skylights. This is why, during the building construction process, the design firm should verify the visible transmittance of the glass before its approval for construction.

When the author was asked to verify the visible transmittance (VT) of glass by laboratory testing, the test was performed twice; first, using a beam of light, and second, under a three-dimensional artificial sky dome. The measured VT value was different in each test. In other words, the actual VT of glass depends not only on the glass type, but also on the nature of the light source. The question posed was: which value

should be used in the design of the daylighting system and the prediction of its performance?

## 2. THE HYPOTHESIS

In order to explain why the measured VT depends on the geometry of the light source, a hypothesis was established, which was: the reason was the higher tendency of light energy to be reflected off glass with greater angles of incidence (Fig. 1). A secondary reason was thought to be the ability of glass to diffuse light.

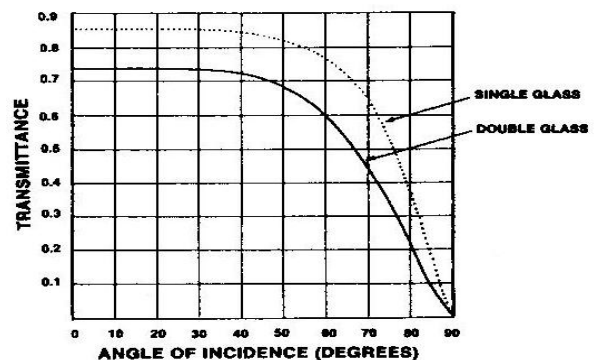


Figure 1: Transmittance vs. angle of incidence (Mazria 1979)

## 3. IMPORTANCE TO THE DESIGN PROCESS

In a typical case when scale models are used to test and predict the performance of daylighting systems, these models are built to represent the geometry of the

space, the design of aperture (windows and skylights), and the finishing materials. Then, the model is tested under the appropriate sky condition (usually overcast sky) with bare openings, i.e., unglazed openings. In order to take the effect of glass type into consideration, the manufacturer-supplied VT is used as a modifier for the measured daylight factors.

Laboratory results showed that this method of using the same VT value as a modifier for the measured Daylight Factor (DF) at all points yields inaccurate results. Another source of inaccuracy is the fact that the glass VT depends on the nature of the light source.

For accurate prediction of the performance of daylighting systems, the appropriate VT value should be used in the analysis, or (at least) the designer should be aware of the potential inaccuracy of results obtained from testing daylighting models with bare openings; i.e., unglazed windows and skylights.

#### 4. THE EXPERIMENTS

In the light of the proposed hypothesis and in order to investigate the impact of different glass types on the performance (especially the distribution) of daylighting systems, two experiments were performed. The first experiment investigated the impact of different glass types (clear and diffuse glass) on the performance of toplighting, i.e., skylights, and the second experiment investigated the impact of clear glass on the performance of sidelighting, i.e., windows.

##### 4.1. Toplighting

The scale model built to test toplighting represented a square space that is 9.14m x 9.14m (30ft x 30ft), with a 3m (10ft) floor-to-ceiling height. The skylight was assumed to be 3m x 3m (10ft x 10ft) and located at the center of the space.

The model was tested under the standard CIE overcast sky as simulated by the artificial sky dome in the daylighting laboratory (Fig. 2). The model was tested four times to take readings for the base case (unglazed opening) and for three different glass types. For that, four sets of Daylight Factor (DF) readings were obtained from the light sensors inserted inside the model (Fig. 3). Each set of DF readings consisted of 40 readings, taken by the eight sensors along five lines inside the model (A, B, C, D, and E).

Tables 1 through 4 show the measured DF values. Because the skylight is centered in the space, DF readings are symmetrical around the center point.

Table 1 shows the DF distribution of the base case, which is the unglazed skylight. Average DF = 13.21%, maximum DF = 37.49%, minimum DF = 3.72%, min-to-max = 9.93%, and standard deviation = 9.54%.

Table 2 shows the DF distribution with the use of a clear glass sample with VT = 91.96%. Average DF = 11.60%, maximum DF = 34.55%, minimum DF = 2.91%, min-to-max = 8.43%, and standard deviation = 8.87%.

Table 3 shows the DF distribution with the use of a diffusing Plexiglas sample with VT = 61.89%. Average DF = 7.50%, maximum DF = 20.65%, minimum DF =

2.18%, min-to-max = 10.55%, and standard deviation = 5.24%.

Table 4 shows the DF distribution with the use of both of the clear glass and the diffusing Plexiglas with a combined VT = 59.79%. Average DF = 6.92%, maximum DF = 19.36%, minimum DF = 1.98%, min-to-max = 10.23%, and standard deviation = 4.92%.

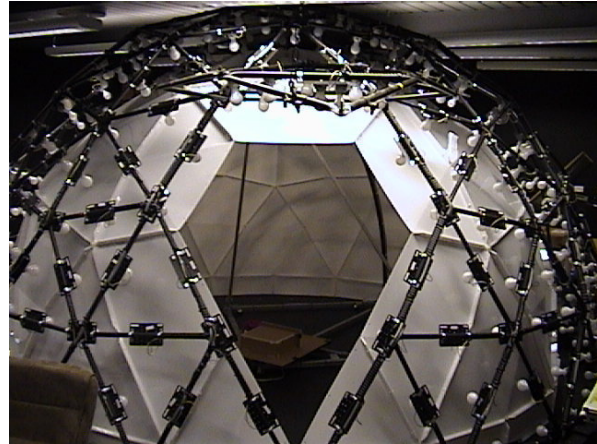


Figure 2: The Artificial sky dome

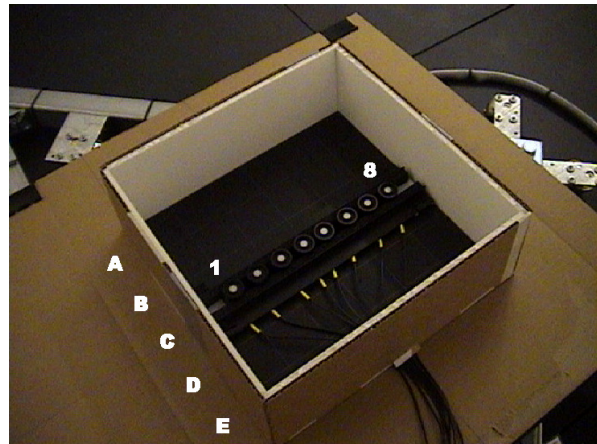


Figure 3: Light sensors inside the toplighting model

Table 1: DF distribution, toplighting, base case (unglazed skylight).

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	3.72%	6.89%	9.06%	6.89%	3.72%
Sensor 2	4.89%	12.02%	16.86%	12.02%	4.89%
Sensor 3	6.22%	19.72%	28.88%	19.72%	6.22%
Sensor 4	7.12%	25.38%	37.49%	25.38%	7.12%
Sensor 5	7.12%	25.38%	37.49%	25.38%	7.12%
Sensor 6	6.22%	19.72%	28.88%	19.72%	6.22%
Sensor 7	4.89%	12.02%	16.86%	12.02%	4.89%
Sensor 8	3.72%	6.89%	9.06%	6.89%	3.72%

Average DF = 13.21%

**Table 2:** DF distribution, clear glass (VT=91.96%)

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	2.91%	5.74%	7.68%	5.74%	2.91%
Sensor 2	3.95%	10.40%	14.92%	10.40%	3.95%
Sensor 3	5.12%	17.49%	26.40%	17.49%	5.12%
Sensor 4	5.96%	22.69%	34.55%	22.69%	5.96%
Sensor 5	5.96%	22.69%	34.55%	22.69%	5.96%
Sensor 6	5.12%	17.49%	26.40%	17.49%	5.12%
Sensor 7	3.95%	10.40%	14.92%	10.40%	3.95%
Sensor 8	2.91%	5.74%	7.68%	5.74%	2.91%

Average DF = 11.60%

**Table 3:** DF distribution, Plexiglas (VT=61.89%)

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	2.18%	4.06%	5.05%	4.06%	2.18%
Sensor 2	2.87%	7.02%	9.43%	7.02%	2.87%
Sensor 3	3.62%	11.24%	15.98%	11.24%	3.62%
Sensor 4	4.16%	14.25%	20.65%	14.25%	4.16%
Sensor 5	4.16%	14.25%	20.65%	14.25%	4.16%
Sensor 6	3.62%	11.24%	15.98%	11.24%	3.62%
Sensor 7	2.87%	7.02%	9.43%	7.02%	2.87%
Sensor 8	2.18%	4.06%	5.05%	4.06%	2.18%

Average DF = 7.50%

**Table 4:** DF distribution, clear glass + Plexiglas (VT=59.79%)

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	1.98%	3.71%	4.57%	3.71%	1.98%
Sensor 2	2.60%	6.44%	8.71%	6.44%	2.60%
Sensor 3	3.29%	10.39%	14.94%	10.39%	3.29%
Sensor 4	3.79%	13.20%	19.36%	13.20%	3.79%
Sensor 5	3.79%	13.20%	19.36%	13.20%	3.79%
Sensor 6	3.29%	10.39%	14.94%	10.39%	3.29%
Sensor 7	2.60%	6.44%	8.71%	6.44%	2.60%
Sensor 8	1.98%	3.71%	4.57%	3.71%	1.98%

Average DF = 6.92%

#### 4.2. Comparative analysis

The quantitative analysis (in Tables 1 through 4) provides an understanding of the impact of different glass types on the efficiency of toplighting systems and the light distribution they provide.

Consistently, the measured overall efficiency of the daylighting system (compared to the baseline), is lower than what the glass VT may suggest. With the use of clear glass, the average DF = 87.83% of the baseline ( $11.60/13.21 = 87.83\%$ ), which is lower than the VT of the clear glass (VT = 91.96%). With the use of diffusing Plexiglas, the average DF = 56.73% of the baseline ( $7.50/13.21 = 56.73\%$ ), which is lower than the VT of the Plexiglas (VT = 61.89%). With the use of both the clear glass and diffusing Plexiglas, the average DF = 52.38% of the baseline ( $6.92/13.21 = 52.38\%$ ), which is lower than the combined VT of both samples (combined VT = 59.79%).

The reason for this range of approximately 4-8% reduction in the measured DF values seems to be the geometry of the sky dome as a hemisphere. Light received from the lower sky tends to be reflected off the glass because of its larger angle of incidence, which reduces the total amount of light that may penetrate into the space through the skylight.

Quantitative analysis of the DF readings also shows a better distribution (closer to uniform distribution) of light in space compared to the baseline. Standard Deviation in Tables 2, 3, and 4 is consistently lower than the 9.54% of table 1.

Tables 5 through 8 show the comparison between the relative light distributions due to the use of the three glass samples tested, compared to the baseline.

**Table 5:** Relative DF distribution, base case (unglazed skylight)

Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.10	0.18	0.24	0.18	0.10
Sensor 2	0.13	0.32	0.45	0.32	0.13
Sensor 3	0.17	0.53	0.77	0.53	0.17
Sensor 4	0.19	0.68	1.00	0.68	0.19
Sensor 5	0.19	0.68	1.00	0.68	0.19
Sensor 6	0.17	0.53	0.77	0.53	0.17
Sensor 7	0.13	0.32	0.45	0.32	0.13
Sensor 8	0.10	0.18	0.24	0.18	0.10

**Table 6:** Relative DF distribution, clear glass

Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.08	0.17	0.22	0.17	0.08
Sensor 2	0.11	0.30	0.43	0.30	0.11
Sensor 3	0.15	0.51	0.76	0.51	0.15
Sensor 4	0.17	0.66	1.00	0.66	0.17
Sensor 5	0.17	0.66	1.00	0.66	0.17
Sensor 6	0.15	0.51	0.76	0.51	0.15
Sensor 7	0.11	0.30	0.43	0.30	0.11
Sensor 8	0.08	0.17	0.22	0.17	0.08

**Table 7:** Relative DF distribution, Plexiglas

Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.11	0.20	0.24	0.20	0.11
Sensor 2	0.14	0.34	0.46	0.34	0.14
Sensor 3	0.18	0.54	0.77	0.54	0.18
Sensor 4	0.20	0.69	1.00	0.69	0.20
Sensor 5	0.20	0.69	1.00	0.69	0.20
Sensor 6	0.18	0.54	0.77	0.54	0.18
Sensor 7	0.14	0.34	0.46	0.34	0.14
Sensor 8	0.11	0.20	0.24	0.20	0.11

**Table 8:** Relative DF distribution, clear glass + Plexiglas

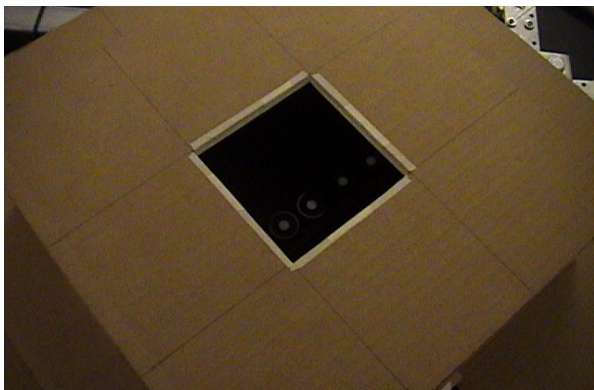
Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.10	0.19	0.24	0.19	0.10
Sensor 2	0.13	0.33	0.45	0.33	0.13
Sensor 3	0.17	0.54	0.77	0.54	0.17
Sensor 4	0.20	0.68	1.00	0.68	0.20
Sensor 5	0.20	0.68	1.00	0.68	0.20
Sensor 6	0.17	0.54	0.77	0.54	0.17
Sensor 7	0.13	0.33	0.45	0.33	0.13
Sensor 8	0.10	0.19	0.24	0.19	0.10

Data in Tables 4 through 8 show the contrasting impact of clear glass and diffusing glass, compared to the baseline. Table 6 shows relatively lower light intensities around the perimeter of the space due to the fact that the perimeter of the space receives its light from the lower part of the sky, from which light tends to be more reflected off the glass. However, Table 7 shows relatively higher light intensities around the perimeter of the space due to the fact that the diffusing glass tends to diffuse the light into space. Table 8 shows a very close light distribution to the baseline, most likely due to the fact that the two opposing impacts of clear glass and diffusing glass balanced each other.

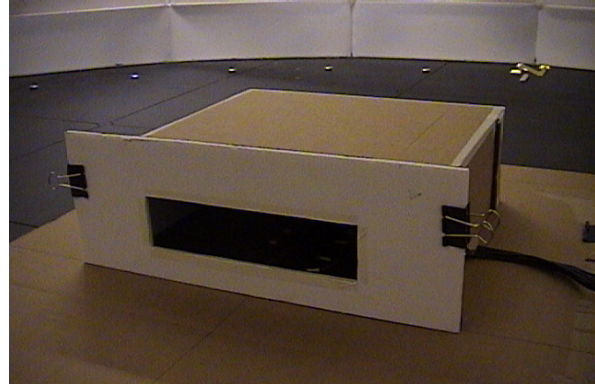
**4.3. Sidelighting**

The scale model built to test sidelighting is identical in its dimensions and materials to the one built for toplighting. Instead of the skylight, a single window is placed in one exterior wall. The area of the window is exactly of the same area of the skylight. Refer to fig. 4 and 5.

The model was tested under the standard CIE overcast sky twice. First test was for an unglazed window to be considered the baseline for comparison. Second test was for a window with the same clear glass sample used for the skylight. No test was performed for diffusing glass since this glass is unlikely to be used for windows



**Figure 4:** Skylight in the toplighting model (base case)



**Figure 5:** Window in the sidelighting model (base case)

Tables 9 and 10 show the DF values measured in the two tests.

Table 9 shows the DF distribution of the base case, which is the unglazed window. Average DF = 4.03%, maximum DF = 13.56%, minimum DF = 1.79%, min-to-max = 13.22%, and standard deviation = 3.06%.

Table 10 shows the DF distribution with the use of the clear glass sample. Average DF = 3.48%, maximum DF = 11.07%, minimum DF = 1.59%, min-to-max = 14.38%, and standard deviation = 2.56%.

**Table 9:** DF distribution, sidelighting, base case (unglazed window).

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	6.58%	12.41%	13.56%	12.41%	6.58%
Sensor 2	4.96%	7.56%	8.06%	7.56%	4.96%
Sensor 3	3.55%	4.47%	4.81%	4.47%	3.55%
Sensor 4	2.74%	3.13%	3.29%	3.13%	2.74%
Sensor 5	2.34%	2.42%	2.50%	2.42%	2.34%
Sensor 6	1.96%	2.03%	2.11%	2.03%	1.96%
Sensor 7	1.86%	1.86%	1.94%	1.86%	1.86%
Sensor 8	1.79%	1.79%	1.83%	1.79%	1.79%

Average DF = 4.03%

**Table 10:** DF distribution, clear glass (VT=91.96%)

Sensor	DF readings				
	A	B	C	D	E
Sensor 1	5.64%	10.64%	11.07%	10.64%	5.64%
Sensor 2	4.28%	6.53%	6.72%	6.53%	4.28%
Sensor 3	3.13%	3.90%	4.05%	3.90%	3.13%
Sensor 4	2.38%	2.78%	2.82%	2.78%	2.38%
Sensor 5	2.06%	2.18%	2.18%	2.18%	2.06%
Sensor 6	1.73%	1.81%	1.81%	1.81%	1.73%
Sensor 7	1.66%	1.66%	1.66%	1.66%	1.66%
Sensor 8	1.59%	1.59%	1.59%	1.59%	1.59%

Average DF = 3.48%

**4.4. Comparative analysis**

The quantitative analysis (in Tables 9 and 10) provides an understanding of the impact of clear glass on the efficiency of sidelighting systems and the light distribution they provide.

Similar to the toplighting experiment, the measured overall efficiency of the sidelighting system (compared to the baseline) is lower than what the glass VT may suggest. With the use of clear glass, the average DF = 86.31% of the baseline ( $3.48/4.03 = 86.31\%$ ), which is lower than the VT of the clear glass (VT = 91.96%). The reason for this approximately 6% drop in overall efficiency is that light received from the higher part of the sky dome tends to be reflected off the glass.

Similar to the toplighting experiment, it seems that clear glass provides better distribution compared to the base case. This is evident when the standard deviation of 2.56% is compared to the 3.06% of the base case.

Tables 11 and 12 show the comparison between the relative light distribution due to the use of the clear glass sample compared to the baseline.

**Table 11:** Relative DF distribution, base case (unglazed window).

Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.49	0.92	1.00	0.92	0.49
Sensor 2	0.37	0.56	0.59	0.56	0.37
Sensor 3	0.26	0.33	0.35	0.33	0.26
Sensor 4	0.20	0.23	0.24	0.23	0.20
Sensor 5	0.17	0.18	0.18	0.18	0.17
Sensor 6	0.14	0.15	0.16	0.15	0.14
Sensor 7	0.14	0.14	0.14	0.14	0.14
Sensor 8	0.13	0.13	0.13	0.13	0.13

**Table 12:** Relative DF distribution, clear glass

Sensor	Relative DF				
	A	B	C	D	E
Sensor 1	0.51	0.96	1.00	0.96	0.51
Sensor 2	0.39	0.59	0.61	0.59	0.39
Sensor 3	0.28	0.35	0.37	0.35	0.28
Sensor 4	0.22	0.25	0.25	0.25	0.22
Sensor 5	0.19	0.20	0.20	0.20	0.19
Sensor 6	0.16	0.16	0.16	0.16	0.16
Sensor 7	0.15	0.15	0.15	0.15	0.15
Sensor 8	0.14	0.14	0.14	0.14	0.14

## CONCLUSIONS

Conclusions of this paper cover more than one aspect of the design of daylighting systems. Based on the test results of this experimental study, conclusions can be summarized as follows.

Design of daylighting systems:

- When testing scale models is adopted as the design-assisting tool to design daylighting systems, it is recommended not to perform the test with an unglazed aperture. It is recommended to use a small sample of the selected glass in the test.
- If using glass samples to perform the test is not possible (or not convenient), the designer may choose to extrapolate the final results based on the results of his/her experimental test of unglazed

aperture and the results of this paper or a similar experiment.

Impact of glass types on the performance of *toplighting* systems:

- Compared to an unglazed skylight, clear glass tends to reduce the relative light intensities around the perimeter of the space. Compared to the baseline, up to 20% reduction was measured at the corners of the space. This reduction enforces the uneven distribution of light intensities inside the space.
- Compared to an unglazed skylight, diffusing glass tends to increase the relative light intensities around the perimeter of the space. Up to 10% increase was measured at the corners of the space. This increase helps achieve a more even distribution of light intensities inside the space.
- Compared to an unglazed skylight, all glass types tend to transmit less amounts of light than what the measured VT may suggest. A range of 4-8% additional reduction in the transmitted light was measured due to the glass samples tested.

Impact of clear glass on the performance of *sidelighting* systems:

- Compared to an unglazed window, clear glass tends to help mitigate the uneven distribution of light intensities inside the space. Marginal impact was measured.
- Compared to an unglazed window, clear glass tends to transmit less amounts of light than what the measured VT may suggest. A range of 6% additional reduction in the transmitted light was measured due to the glass sample tested.

Verification of glass visible transmittance:

- Since the VT value measured under the sky dome is found to be lower than the value tested under a beam of light, it is important to test the glass type, intended to be used for a certain application, under a sky dome. Then, use the lab-measured VT value in the quantitative analysis of the daylighting system. This measure should assure the accuracy of the analysis and avoid downsizing the system.

Green buildings rating systems:

- Developers of rating systems, such as LEED and Green Globes, may take note of the results of this research and bring it to the attention of architects who implement these rating systems.

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