AN EMPIRICAL STUDY AND ANALYSIS OF DAYLIGHT PENETRATION THROUGH A LIGHT PLENUM

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ABSTRACT

Lighting accounts for approximately 54% of the annual energy consumption of office buildings,[1] and can effectively be reduced through daylighting. The simplest way to provide daylighting into a typical office space has been to use unilateral sidelighting. Discomfort and visibility glare from unilateral sidelighting cause the occupant to close drapes or blinds and turn on luminaries, resulting in an inefficient use of daylighting. One daylighting concept that has been developed to alleviate this problem is the light plenum.

A light plenum can be added economically to an office space by using a hung ceiling simultaneously as a return air and light plenum. The appropriate opaque ceiling panels could be replaced with transparent ones to get the light to the rear of the space. The question is how much light can be expected to be transferred to the rear of the room and how different plenum opening configurations would affect those light levels.

The results imply that a hung ceiling light plenum can provide adequate light to the rear of the room to balance the high brightness ratios created by unilateral sidelighting. Also, certain plenum opening configurations are more advantageous for certain sky conditions and orientations, and there are some which are of no benefit.

INTRODUCTION

ARTIFICIAL LIGHT AND HEAT GAIN

Energy studies concerned with high-rise office buildings have revealed that artificial lighting systems can be a major source of heat gain within the built environment.[2] This heat gain can account for almost one-half of the annual cooling load cost in a building that is heavily dependent upon artificial lighting as illustrated in Figure 1.

The figure shows that artificial lighting can be the major source of energy expense in a building. Without artificial lighting, the cost of operating the lighting system is eliminated, and the cooling load is reduced significantly. The heating load during the cooler seasons increases by only a slight amount in the absence of the heat generated by the lights. Designing for optimal daylight utilization in an interior space offers an economical means of illuminating interiors and insures a reduction in the consumption of energy resources.

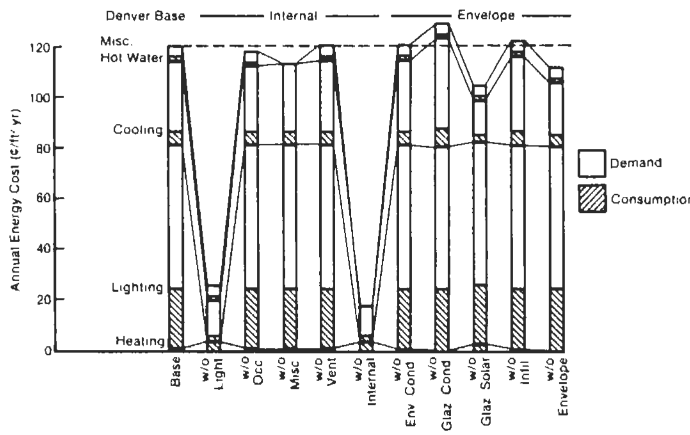

Fig. 1. Elimination Parameters: Denver Base Building.

DAYLIGHTING DESIGN PRECEDENCE

Before artificial lighting technology was developed, designers of the built environment responded to daylight as a primary source of interior illumination. The evidence of this can be seen in numerous examples of architecture that were built before the twentieth century. The hypostyle halls of early Egyptian temples utilized clerestory window openings to admit sunlight. Cathedrals of the Italian Renaissance utilized upper galleries with rows of windows which reflected daylight through concave or splayed openings in the ceiling of the gallery into nave spaces. Later examples such as the Larkin Building (1906), designed by Frank Lloyd Wright, utilized daylight by organizing office spaces around an inner atrium.

With the availability of inexpensive fossil fuels and the corresponding development of artificial lighting and air conditioning, daylighting design in buildings has been neglected. The economics of present day energy consumption will no longer allow environmental designers the luxury of neglecting daylighting design. Appropriate daylighting design offers both economic advantages and opportunities for a higher quality source of illumination. In consideration of the dwindling natural resources and a need for a better work environment, it has become the task of designers to research and develop innovative applications in architecture that are responsive to the natural environment.

EVOLUTION OF THE LIGHTING PLENUM

Unilateral Sidelighting. Previous attempts to reduce artificial lighting in high-rise buildings

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have resulted in one primary window configuration, the unilateral sidelight. The essential problem to be overcome in daylighting design of this type is the issue of discomfort glare. Often a window (unilateral sidelight) can create a great deal of contrast between the window and surrounding interior surfaces. To those inside the space, the light from the window often appears overly bright, contrasting with the light levels in the room. This condition creates what is known as discomfort glare. Artificial lighting, as illustrated in Figure 2, is one means of balancing interior light levels with unilateral sidelighting to eliminate this discomfort. Another more common solution is to pull the drapes or blinds and light the space entirely with artificial light.

This uneven contrast between the "front" and "back" of the room is a product of extreme illumination gradients or extreme variation of light levels over the given distance.[3] The ratio of the two extreme illumination levels within the space is referred to as the brightness ratio. The window configuration depicted in Figure 2 will result in a high brightness ratio from the "front" of the room (window) to the "rear" of the room. The discomfort glare previously described in the depicted space is the direct result of a high brightness ratio. The composite illumination gradient provided by artificial lighting balances the brightness ratio which makes the incoming daylight more acceptable.[4] This window configuration, therefore, does not effectively solve the problem of reducing the need for artificial lighting.

Unilateral Sidelighting with Splayed Ceiling. Splayed ceiling and window surfaces have been utilized as a means of reducing the apparent contrast between the window and surrounding wall surfaces by eliminating dark shadows. However, the problem of a high brightness ratio is unchanged. Artificial light is required to balance daylight for acceptable interior illumination (see Figure 3).

Unilateral Sidelighting with Overhang and Light Shelf. The addition of an upper window portion with a projecting reflective surface as seen in Figure 4, allows more daylight to be reflected into the rear of the room. The overhanging ledge provides a shading device which reduces contrast from sidelighting of the main window and also reflects ground light into the space. However, most typical office spaces employ a standard drop ceiling which serves as return air plenum or mechanical space. This particular daylighting application would not be compatible with the typical office space where a drop ceiling is utilized without additional floor to ceiling height.

The configuration in Figure 4 offers the most promising daylighting conditions depicted thus far, but the illumination gradient can still drop sharply at the back of the room. However, the light shelf concept has led to other possibilities.

Unilateral Sidelighting with Light Plenum. Recently, it was conceived that the light shelf could be extended to the back of the room to create a highly reflective "plenum" which would contain daylight going into the interior space of a room, allowing the designer to put the daylight closer to where it is desired. This window configuration utilizes a standard drop ceiling and an additional upper window as a means of transmitting daylight into interior space (see Figure 5). The increased illumination from the plenum space reduces the potential for discomfort glare by balancing the illumination gradient with light from the rear of

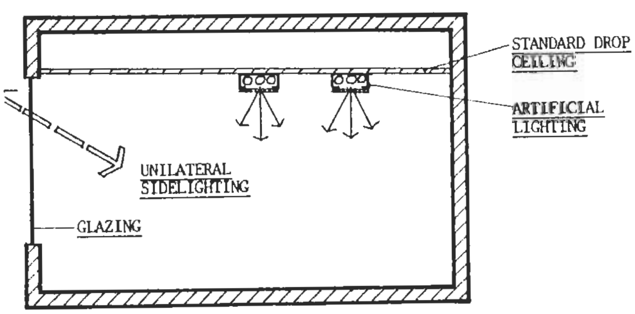


Figure 2. Unilateral Sidelighting.

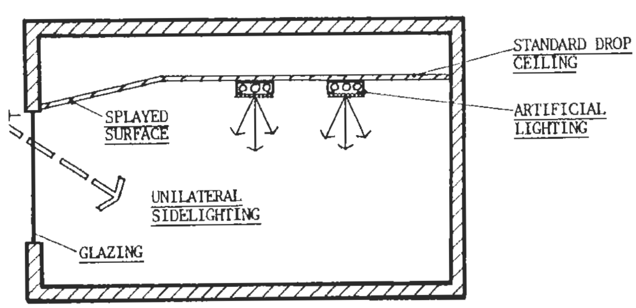


Figure 3. Unilateral Sidelighting with Splayed Ceiling.

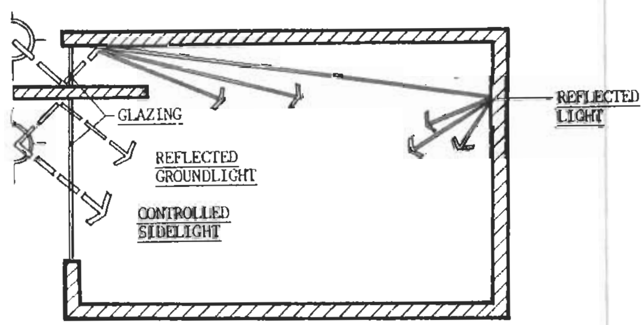


Figure 4. Unilateral Sidelighting with Light Shelf.

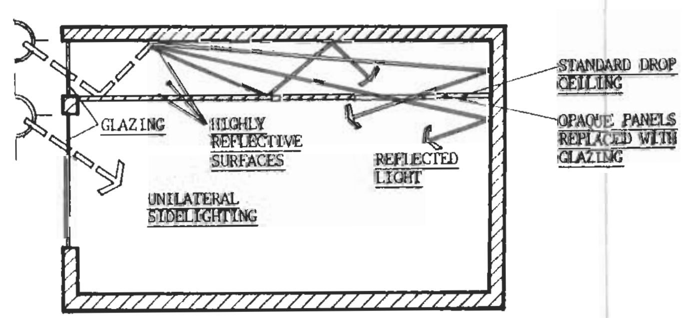


Figure 5. Unilateral Sidelighting with Light Plenum.

the room. By reducing the brightness ratio within the office space, the quality of the available daylight is improved offering a greater promise of reducing the need for artificial light during daylight hours.

The ultimate advantage of the concept of the light plenum lies in its economic applicability to typical office building types. Office buildings designed to utilize a drop ceiling primarily as a return air plenum with corridor mechanical duct systems or perimeter supply offer the best opportunity for an economical adaptation to a daylighting plenum. The quantity and quality of daylight penetration into the interior space through the light plenum must depend on the configuration of the drop ceiling openings which admit the light. Therefore, it has become necessary to investigate the performance characteristics of various opening configurations and to make the corresponding information and data available to environmental designers.

PURPOSE OF RESEARCH

The purpose of this study is to provide information regarding the use of light plenums for architectural daylighting. This information will be examined on the basis of its applicability to office buildings which utilize drop ceilings as return air plenums. The testing of a typical scale model office space will be used to yield data concerning daylight penetration characteristics of various opening configurations in a drop ceiling.

OBJECTIVES

*To design and build a scale model office with a standard drop ceiling utilized as a light plenum.

*To test a simulated light plenum for a variety of ceiling openings and record data concerning daylighting factors (ratio of penetrated light to available exterior light).

*To compile test data and determine optimum plenum opening configurations.

*To provide a catalog of light plenum opening configurations along with their performance characteristics with regard to tested light penetration levels at work surface height.

PROCEDURE

MODEL DESIGN AND CONSTRUCTION

Dimensions and Scale. The test model dimensions were chosen on the basis of a compiled average of typical structural dimensions of office spaces. In order to initially compile these standards, several builders, developers, and architects were consulted. These dimensions are labeled in Figure 6 which is an isometric section of the test model. The scale of the test model is 1-1/4"=1'-0". This scale was chosen for the ease and efficient placement of light sensors and ceiling panels. The drop ceiling is modeled after a standard 2' x 2' T-Rail system.

Material Reflectances. The IES Handbook recommendations for reflectances in a typical office ceiling, wall and floor are listed as follows:

Ceiling 80%
Wall 50%
Floor 20%

Matte boards that simulate these reflectances were chosen for the interior of the model. The following list indicates the color and reflectance of the matte board used in the model construction.

SURFACE	COLOR	REFLECTANCE
Ceiling	Cream	83%
Wall	Sand	53.5%
Floor	Pyro-Brown	18.6%
Plenum	White	90%

The white side of cream pebble grain matte board was chosen for the light plenum surfaces, including the drop ceiling "panels". The white side of the pebble grain matte board has a reflectance of 90%, which should effectively represent the surface reflectance of a painted plenum space.

Model Construction. The drop ceiling T-Rail system is constructed of prefabricated plastic T stock. The long axis rails are continuous while the short axis rails are cut and glued with a cyanoacrylate glue. The T-Rails were assembled over a marked grid on a flat surface in order to retain a consistent framework for 2' x 2' square drop-in panels of opaque matte board and .100 inch thick transparent Plexiglas panels.

The light plenum and Plexiglas plenum window were constructed as a "box lid" which enables quick repositioning of plenum grid panels for testing, simply by removing the "lid" of the model (see Figure6).

The model was attached to a plywood base. The base and model were mounted to a heavy-duty video camera-type tripod which allows swing and tilt of the model to the desired orientation for testing.

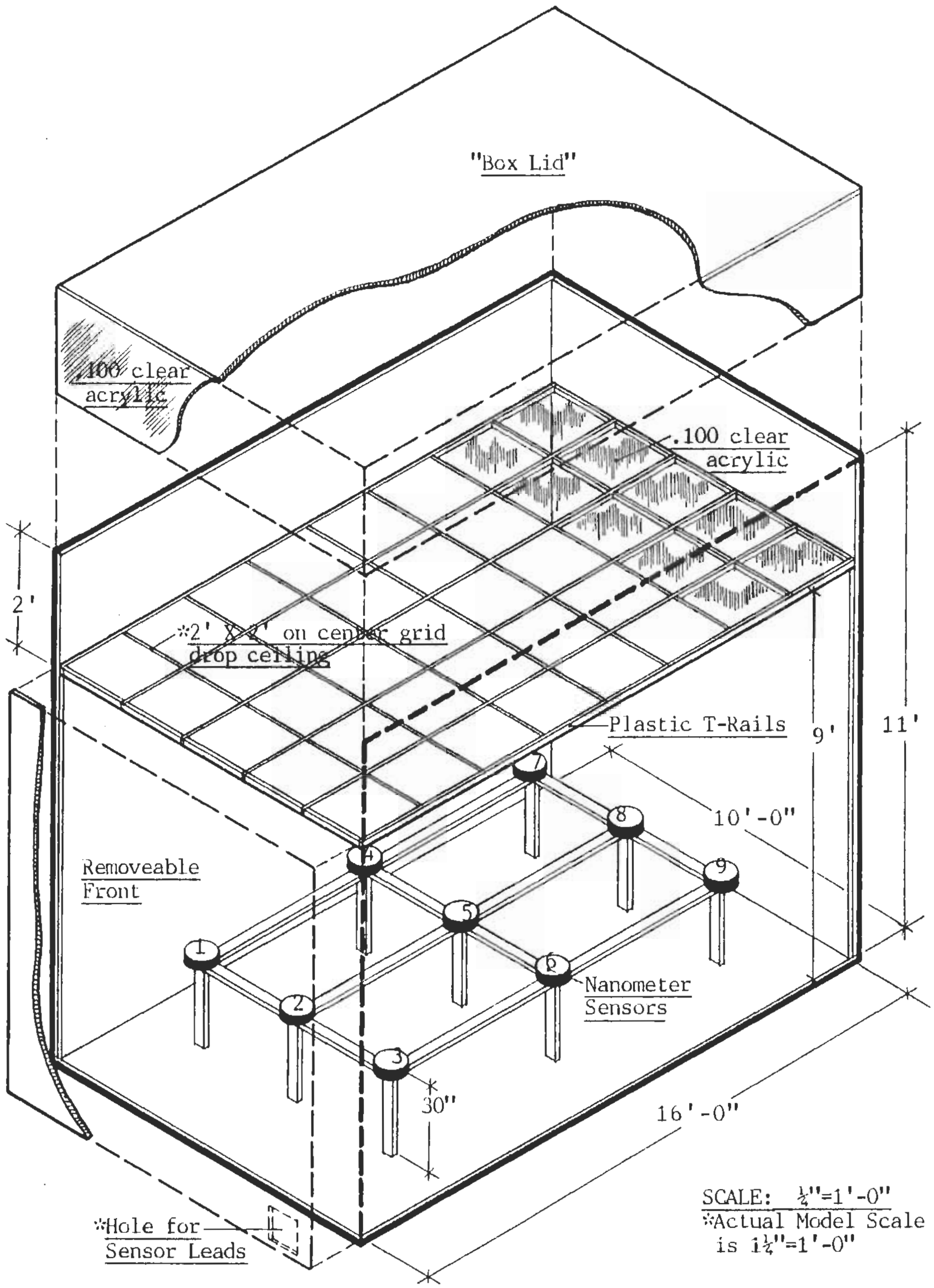
INITIAL FIELD TESTING

Testing Conditions. The northern portion of a clear sky in the northern hemisphere provides the most consistent and least amount of daylight of any of the sky conditions. In order to establish the optimum plenum opening configurations, all tests were made to a northern orientation with the assumption that the better opening configurations would be those which performed best under the least favorable sky conditions. It was assumed that the plenum opening configurations that performed well under clear sky, north light conditions would perform better with the other orientations which provide more available light, especially direct beam, depending on the time of day or date with regard to sun angles.

The light plenum was tested by itself by not including the window aperture in the front of the office space. In this manner, only the penetrated light from the plenum source would be detected by the sensors without interference from other sources of light.

Testing. For testing, the fully assembled model was mounted to the video camera tripod and

Figure 6. Test Model Isometric



nine nanometer sensors from a Megatron Daylighting Model Meter were attached to their respective positions as shown in Figure 6 . The sensor leads were then taped together and brought out of the front panel of the model, which, in turn, was taped into place to prevent light leaks. After installing an opening configuration of clear Plexiglas panels into the ceiling grid, the "box lid" (plenum) was secured into place to prevent light leaks. The following procedure was conducted for each test:

1. Plenum window was oriented perpendicular to true north at the simulated time and date of March 21st, 12:00 noon according to a fixed sundail attached to the top of the model.
2. Time and date were recorded.
3. Available horizontal illumination (Eh) and available vertical illumination (Ev) readings were taken with a Spotmate Footcandle Light Meter, and recorded. These readings were taken flush with the top of the model for Eh and flush with the plenum window for Ev.
4. Light level readings for each sensor were recorded respectively. The Megatron took readings in lux, which were later converted to footcandles.
5. The post-test Eh and Ev readings were taken and recorded to determine whether the post-test sky illumination was more than $\pm 5\%$ over the period of the test. If this tolerance was met, it was assumed that the lighting conditions were constant during testing.
6. Final time was recorded.

All Megatron sensor readings were measured in lux and had to be converted to footcandles in order to calculate the daylight factor. After each test was completed, the process was repeated for a total of 35 different plenum opening configurations. These are not included in this paper, but can be obtained upon request.

Plenum Opening Performance Criteria. The performance of the plenum opening configurations was judged on the basis of:

1. High Brightness Ratio resulting from an illumination gradient where the illumination in the back of the room is greater than in the front of the room.
2. The quantity of light penetration at each sensor point.

The illumination gradient (Figure 7) or distribution of light over the sensors at test points determines the brightness ratio between opposite sides of the room. A high brightness ratio from the "rear" of the room to the "window side" of the room is desirable so that the plenum light will not contribute to the sidelighting. This would enable the designer to use the light from the plenum as a second source of light to balance the illumination gradient of the sidelight (window) to create a more qualitative brightness ratio (see Figure 7).

The other criterion for optimum plenum opening performance was determined to be the actual illumination level at each sensor point. In order for the penetrated daylight from the light plenum to be useful, there must be a sufficient quantity of light provided by the light plenum. If adequate illumination through the plenum can be accomplished, task lighting as well as ambient lighting needs can then be achieved with daylight.

FINAL FIELD TESTING

There were nine plenum ceiling configurations from the Initial Field Testing that performed the best based on the previously discussed criteria. These nine "best" plenum opening configurations were the subject of the final field tests.

The final testing was done using the following parameters:

1. The test procedure, as laid out in Initial Field Testing, was used.
2. Tests were done for all four orientations (North, South, East, and West).
3. Each orientation was tested for a simulated date and time of March 21st, 12 noon, using a sundial attached to the top of the model.
4. All tests were done on the same day within three hours of each other under clear sky conditions to insure consistency of sky illumination.
5. There were nine configurations tested for four orientations for a total of thirty-six tests in all.

FIELD TESTING COMMENTS

A cross reference of final field testing results with initial field testing indicates that initial clear day field testing results are valid even though the tests were conducted on different days. This consistency of data supports the initial choice of the nine "best" configuration alternatives determined by the initial field testing.

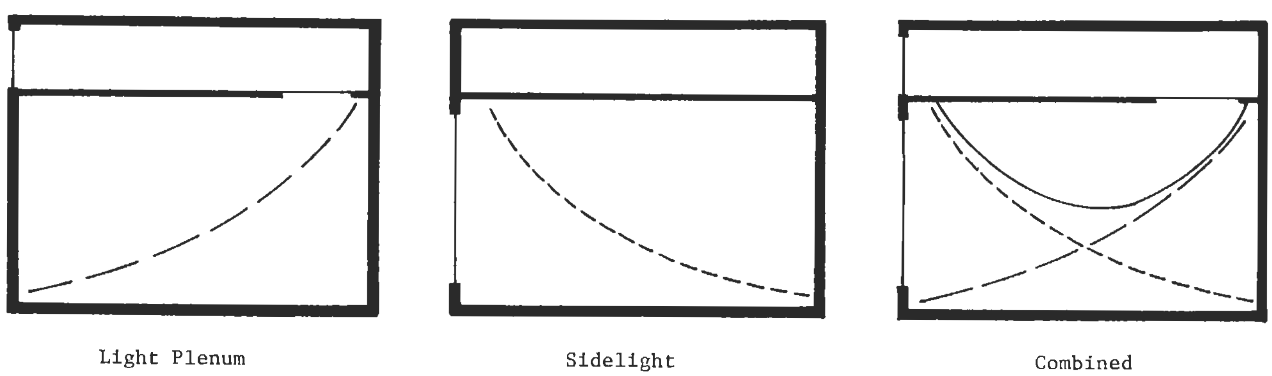


Figure 7. Ilumination Gradient of Combining a Light Plenum with Sidelighting.

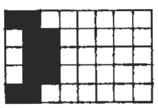
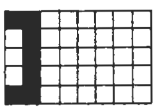
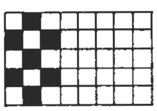
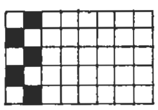
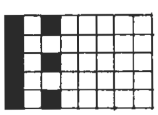
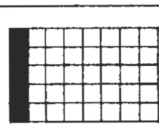
RESEARCH RESULTS

DATA

Table 1 is a list of compiled data from final field testing for nine plenum opening configurations which were chosen from initial field testing. This table shows the selected results of the nine plenum configurations and their performance in all four orientations. For each configuration, there are five rows of data tablulated in the table. The first row is the outside illumination level taken on the vertical (Ev). The second is the outside illumination level taken on the horizontal (Eh). The next three rows of data refer to three sensor points. These sensor points are #2, #5, and #8, (see Figure 5 for placement) which run the length of the space through the center axis as shown in Figure 6. The third row of data is the actual footcandle readings taken in the modeled space. The fourth row shows the daylight factor of each of the sensor points, using the Ev to calculate it. The fifth or final row of data is the daylight factor, using the Eh to calculate it.

The daylight factor is calculated by dividing the sensor reading in the space by the outside illumination level (horizontal or vertical). This provides a factor that can be used to determine the

Table I. Final Field Test Data Summary

	NORTH			WEST			SOUTH			EAST			
Opening Configuration	2	5	8	2	5	8	2	5	8	2	5	8	Test
A. 		908			1040			9790			893		Ev
		3780			3450			3680			3970		Eh
	2.2	5.1	8.9	2.7	5.8	9.3	17.2	40.8	74.4	2.1	4.9	8.5	FC
	.0024	.0056	.0098	.0026	.0056	.0089	.0018	.0042	.0076	.0024	.0055	.0095	DFv
	.00059	.0014	.0023	.00077	.0017	.0027	.0047	.011	.02	.00052	.0012	.0021	DFh
B. 		903			1010			9670			893		Ev
		4110			3540			3940			3990		Eh
	1.9	4.4	8.2	2.1	4.8	8.8	13.8	32.3	62.0	1.7	4.1	7.4	FC
	.0021	.0049	.0099	.0021	.0048	.0087	.0014	.0033	.0064	.0019	.0046	.0083	DFv
	.00046	.0011	.002	.00058	.0014	.0025	.0035	.0082	.016	.00043	.001	.0019	DFh
C. 		887			1020			9880			869		Ev
		3960			3570			3650			3380		Eh
	1.5	2.9	5.1	1.7	3.2	6.1	10.3	19.9	40.8	1.4	2.6	5.2	FC
	.0017	.0033	.0057	.0017	.0031	.006	.001	.002	.0041	.0016	.003	.006	DFv
	.00037	.00074	.0015	.00048	.00089	.0017	.0028	.0055	.0011	.00041	.00076	.0015	DFh
D. 		841			960			9310			826		Ev
		3330			3390			3360			3110		Eh
	1.5	3.5	6.4	1.9	3.7	6.6	13.3	28.4	51.0	1.6	3.1	5.6	FC
	.0018	.0042	.0076	.0020	.0039	.0069	.0014	.0031	.0055	.0019	.0038	.0068	DFv
	.00044	.001	.0019	.00056	.0011	.002	.004	.0084	.015	.0005	.001	.0018	DFh
E. 		827			934			9320			808		Ev
		3420			3320			3420			3140		Eh
	1.4	2.7	5.0	1.6	2.6	4.8	10.3	19.1	35.9	1.5	2.4	4.4	FC
	.0017	.0033	.006	.0017	.0028	.0051	.0011	.002	.0037	.0018	.0030	.0054	DFv
	.0004	.00078	.0015	.00047	.00077	.0014	.003	.0056	.01	.00047	.00076	.0014	DFh
F. 		809			900			8970			796		Ev
		3160			3320			3290			3030		Eh
	1.8	4.2	6.8	1.8	3.6	6.5	12.9	29.2	50.1	1.9	3.8	6.3	FC
	.0022	.0052	.0084	.002	.004	.0072	.0014	.0033	.0056	.0024	.0048	.0079	DFv
	.00057	.0013	.0022	.00054	.0011	.0019	.0039	.0089	.015	.00063	.0013	.0021	DFh
G. 		874			999			9680			891		Ev
		3170			3410			3330			3300		Eh
	1.7	3.9	6.9	1.8	4.0	7.1	12.1	27.5	50.5	1.7	3.5	6.4	FC
	.0019	.0045	.0080	.0018	.004	.0071	.0013	.0028	.0052	.0019	.0039	.0072	DFv
	.00046	.0011	.0019	.00053	.0012	.0021	.0036	.0083	.015	.00052	.0011	.0019	DFh
H. 		854			976			9620			837		Ev
		3390			3360			3260			3170		Eh
	2.9	6.6	9.3	3.0	6.6	9.3	21.5	51.4	80.7	2.8	6.2	8.9	FC
	.0034	.0077	.012	.0031	.0068	.0095	.0022	.0053	.0084	.0033	.0074	.0011	DFv
	.00086	.002	.0027	.0009	.002	.0028	.0066	.016	.025	.0009	.002	.0028	DFh
I. 		779			878			8900			751		Ev
		3310			3290			3150			3020		Eh
	1.2	2.4	4.4	1.3	2.2	3.7	8.6	16.4	27.9	1.3	2.1	3.8	FC
	.0015	.0031	.0056	.0015	.0025	.0042	.00097	.0018	.0031	.0017	.0028	.0051	DFv
	.00036	.00074	.0013	.00039	.00067	.0011	.0027	.0052	.0089	.00043	.0007	.0013	DFh

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inside illumination level at that given point given any corresponding outside illumination level, assuming the same sky conditions exist. The Eh or Ev must correspond to the DFh or DFv. Illumination levels in a room cannot be determined by using an Eh reading with a DFv. The DF can also be used to compare one plenum opening configuration to another. The DFh of the three sensor points were plotted into an illumination gradient curve for each configuration and each orientation (see Table 2).

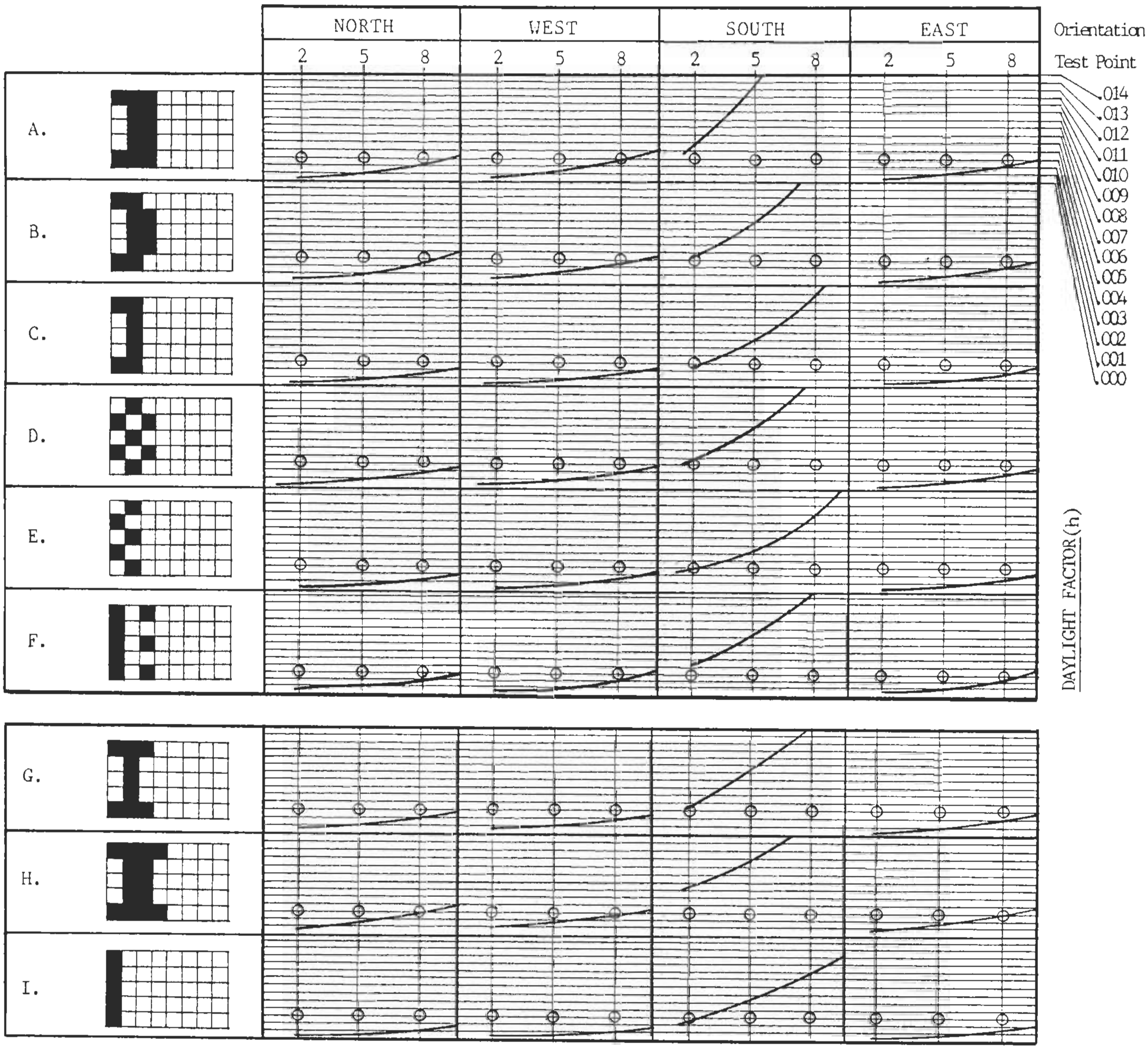
The illumination gradient curves in Table 2 can be used to quickly relate the brightness ratio of any particular configuration and the orientation. Steeper lines denote a greater brightness ratio in comparison to other configurations. To compare the quantity of light provided by different configurations compare the heights of the respective curves. Higher curves indicate a greater quantity of light.

RESULTS

1. An effective combination of Brightness Ratio and Quantity of Light can be obtained from the light plenum to be helpful in reducing the discomfort glare of a unilaterally sidelit office space.

2. The South orientation of every configuration had the greatest Brightness Ratio and Quantity of Light. The direct sunlight is responsible for

Table 2. Daylight Factor Gradients of Light Plenum Configurations.



this result. The West and East orientations can be expected to respond in the same manner as the South at different times of the day. This would happen in the morning for East orientations and in the afternoon for West orientations.

3. The North, East, and West orientations of each configuration had an almost equal Brightness Ratio and Quantity of Light. This can be attributed to the almost identical sky conditions that they were exposed to at simulated time of the day (12 noon). It can be expected that the southern orientations will respond in the same way during the early morning and late afternoon hours of the day, since little direct sunlight will hit that side at those times.

4. No one configuration was the best for sky conditions with direct sunlight and without direct sunlight. For example, the best configuration for a sky without any direct sunlight can be seen in Table 2 for configurations A and H. Whereas, from the same table, one can see that for a clear sky with direct sunlight the best configurations are C, E, or F.

5. An overcast sky condition should respond similarly to the North sky orientation. An overcast sky like the north clear sky at 12 noon has no direct sunlight and an illumination gradient that is at its lowest at the horizon and highest at the zenith.

6. The area of plenum opening determines the overall quantity of light in the space, but may have a detrimental effect on the brightness ratio. A direct comparison of light levels in footcandles between different opening configurations will reveal that the footcandle level is directly related to the number of openings. In other words, more openings will result in greater quantities of light. However, initial field testing indicated that too many openings can result in low brightness ratios which are not conducive to a balanced composite illumination gradient between the plenum source and the sidelight. For this reason, opening configurations with high light quantities and low brightness ratios were rejected from final field testing.

CONCLUSION

SUMMARY

Based on the scale model test results, the light plenum undoubtedly provides a means of reflecting daylight to the interior of an office space. This light also appears to be in quantities and proportions sufficient to provide a means of countering the discomfort glare from unilateral sidelighting, and that the configuration of the openings into the space has a noticeably different effect under different sky conditions. Also, different plenum opening configurations should be considered to optimize the light plenum to the specific demands of the day, month and time of the peak energy demand and consumption charges.

It is also the opinion of the researchers that an environmental designer confronted with an office building that is lighting-load dominant should consider using sidelighting with a light plenum as a daylighting source. This would enable the designer to reduce the effect of the lighting load on the energy cost of the building in a cost effective way without changing the current building technology for this type of building.

FURTHER RESEARCH

There are several areas that the authors feel need more study pertaining to the use of light plenums. These areas will require a full-scale prototype of a light plenum to obtain usable results. Some of these areas are:

1. To find the affect of different glazing types on the light plenum. For instance, how would translucent, grooved, prismatic, or fresnal glazing perform?
2. To find the cost effective optimal plenum depth and its affect on the performance of the plenum.
3. To find the affect of reflective shelves on the outside of the light plenum's glazing in gathering more light.
4. To test existing hung ceiling panels to find out their effects on the distribution of light inside the space.

ENDNOTES

[1] Evans, B. H., "Daylight in Architecture, Architectural Record, 1981, p. 35.

[2] Solar Energy Research Institute, The Design of Energy-Responsive Commercial Buildings, (New York: John Wiley and Sons, 1985), p. 226.

[3] Egan, David M., Concepts in Architectural Lighting, (New York: McGraw-Hill Book Company, Inc., 1983), p. 94.

[4] Ibid., p. 202.

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