MEASUREMENTS AND COMPARISONS OF LIGHTSHELF PERFORMANCE IN TWO TEXAS OFFICE BUILDINGS

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ABSTRACT

Natural light (daylighting) in office buildings is often used to supplement or eliminate the artificial lighting otherwise required. When daylight can be effectively admitted and distributed, then energy is conserved, and the dependence on electric lighting is reduced. Traditional means of admitting daylight in offices are windows, skylights, atriums, light courts, and lightshelves.

This study involves two significant Texas office buildings: Lockheed Company's Facilities Systems Division in Austin and Shell Oil Company's Woodcreek Offices near Houston. Both of these installations have used lightshelves to aid in energy reduction. The Lockheed building was designed with the lightshelf locations determined by the orientation of the various facades and open light courts. On the other hand, the Shell facility was conceived and built on the concept of lightshelves and uses them on every facade, both on the exterior and interior of the building and around their many covered atriums.

This paper compares and contrasts the lightshelves in these two installations based on a number of criteria. Specific considerations at each location include the orientation of the glazed wall with the lightshelf, the magnitude of the external illumination at the noon equinox times of measurement, and the effectiveness of each system at daylight distribution at various depths from the glazing. The reduction effect of atrium/light court configurations is also considered. Graphics and empirical data are included which indicate these factors as well as various brightness ratios and subjective assesments which serve as an indication of lighting quality for each facility.

Finally, tentative conclusions are drawn based on the field data which indicate the effectiveness of each lightshelf system and lightshelves in general. Additional suggestions are made regarding alterations to each installation which could make each one more effective at daylight distribution as well as maximizing energy savings.

INTRODUCTION

The intent of this study is to document the daylighting measurements inside two significant Texas office buildings taken at noontime on two fall days (Tue. Sept. 21,1986 and Thurs. Oct. 2,1986). Since the sky conditions varied between locations, correlations may exist between the lightshelf type and orientation and the intensity of daylight distribution into the office areas tested. The relative glass transmissivities and reflectivities of the interiors of the "lightshelf-lit" areas of each building are examined and compared.

The traditional method of daylight calculation has been to use data based on diffuse illuminance in the overcast sky, and equations based on the physics of light. This methodology is commonly called the Daylight Factor Method and was developed by Hopkinson (1). J. W. Griffith then developed some calculation methods based on extensive studies of models under an artificial sky which allowed predictions of clear sky as well as diffuse sky results (2). Recently these calculation methods have been adapted for predicting daylighting impacts on buildings, but a major shortcoming of these methods is that they are not directly applicable to lightshelf studies and other types of configurations at present.

The findings of this study represent a portion of a larger daylighting project conducted at Texas A&M University. That project was designed to evaluate a variety of atrium configurations (3) by actual measurements as well as by scale model studies in A&M's 28 ft. diameter by 12 ft. high sky simulator. The results of the present work are included with various lightshelf configurations tested in the simulator as well. A series of new algorithms have already been developed which will be used to evaluate new atrium designs and to study potential energy saving alterations to existing atria (4). Similarly, algorithms which predict the resulting daylight distribution of several lightshelf types may be developed.

The specific objective of this study is the comparison of actual daylight illumination levels inside various office areas of the two existing buildings as a result of distribution by the lightshelf system. Comparisons will indicate the results at both facilities based on glazing orientation and depth of penetration of daylight into the test areas. It is anticipated that these comparisons will indicate the actual effectiveness of each lightshelf type at daylight distribution.

DESCRIPTION OF PROJECTS

The Buildings-

The first facility investigated was the Lockheed Missiles and Space Company's campus built near Austin, Texas in 1985-6. Lockheed has two buildings which utilize lightshelves as a part of an energy reduction strategy. Not only are the lightshelves used to minimize electricity usage, but to enhance occupant productivity. The project architect for Lockheed was Mike Shea of Jacobs Engineering Group of California (5).

Each 2-story building houses offices and design labs with the overall areas of #310 and #312 being 215,000 and 225,000 sq. ft. respectively. Each building uses the lightshelves on strategically selected exposures ranging from due east to south. Being similar in plan, each building has a small triangular open atrium or light court which borders on work areas that use lightshelves. The longer side of the light court in each case is a circulation zone and is glazed with reflective glass. Other lightshelf locations are in open planned working bays and in some cases in private office areas. A plan of the Lockheed buildings is shown in Figure 1.

The Shell Oil Company Woodcreek Exploration and Production Office, built in 1980-1, is located off Interstate 10 near Houston, Texas. Shell has put together an attractive 800,000 sq. ft. facility on a tree studded campus setting. Seven individual 'buildings' each with its own 4- or 5-story central glazed atrium comprise the Shell facility. The architects for the project were Caudill Rowlett and Scott (CRS) of Houston, Texas. A plan of the Shell facility is shown in Figure 2.

A guiding concept in the design of this complex was reduction of operating expenses, while providing individual offices with views for the highly valued inhabitants (6). This was addressed by allowing the structure to operate as a solar shade minimizing the direct sun allowed to hit the building fascade, while reflecting diffuse light into the offices. The HVAC system was designed to act as a perimeter lightshelf system, circling each floor of offices, both inside (towards the atrium), and outside.

Since the lightshelf system is employed on the entire perimeter of all seven buildings, measurements are obtained at various floor levels and on each exposure. However, primary emphasis was given to thorough documentation of the true north and south exposures. Secondary emphasis was given to the interior or atrium exposures.

Glazing Transmissivities-

Transmissivities of glazing materials are calculated from measurements of available normal illuminance immediately outside the desired glazing, divided into the measured available light immediately inside the test glazing. Expressed as a percentage, this transmissivity indicates how much of the available light is allowed to pass through

Because daylighting was emphasized from the conceptual stages, scale model testing was performed throughout the design of the facility to predict the daylighting levels. This testing was extensive and included modeling of entire building pods (to test atrium cover types for daylight transmission) and individual office modules. A small scale and a full size office model were used by the architects and a daylighting consultant to test the daylight potential at various exposures and to demonstrate the concept to executives and occupants (7). Measurements obtained at the facility can be compared to predicted results and inferences made about any similarities or differences encountered.

the glazing.

At Lockheed, the significant glass data for windows was obtained from manufacturers data and the original architectural specifications. The glass above the lightshelf was 1/4" clear glass with a transmissivity of 89 percent and a shading coefficient of 0.95. This clear glass is where the maximum portion of the daylighting penetrates, and is then reflected into the room off the lightshelf (Fig. 3).

The lightshelf itself shades the view glazing below, so all daylight admitted through it is diffuse. The lower glazing is 1/4" thick tinted glass, with a transmissivity of 75 percent and a shading coefficient of 0.69.

The glass is all by the same manufacturer in identical frames and presents no noticable difference to the observer. However, the tinted lower glass provides easier viewing due to the shade from the lightshelf and the lower glass transmissivity.

At Shell Woodcreek, transmissivities were measured to determine the data for each of the three glazing types. A tinted glazing is used for both the atrium and exterior sides of each triangular building. The glazing transmissivity of this typical window is 74 percent. The second type of glazing is located above the lightshelves and corridor walls. This glazing is a common clear glass with a transmissivity of 86 percent. The use of clear glass allows maximum penetration of daylight in the lightshelf application, while the less transmissive tinted glass is used in windows where views are important (see Fig. 4).

Finally, the skylight transmissivity above the seven Shell atriums is the same in each atrium, and measures about 37 percent.

Material Reflectances-

Measured reflectances of the primary materials at the Lockheed buildings and at Shell Woodcreek can be found in Table I :

Table I
MEASURED REFLECTANCES OF MATERIALS (%)

	Lockheed	Shell Woodcreek
Lightshelf :		
Interior Shelf (White)	54	--
Exterior Shelf (White Metal)	65	--
HVAC/Lightshelf (Metal)	--	60
Interiors :		
Typical Wall (White)	71	74
(Beige)	--	39
Carpet	9	12.4
Ceiling Tiles	54	--
Concrete Ceiling (White)	--	50
Concrete Columns	--	30
Floor Tile (Atrium)	--	40
Plants	--	4.7
Grass (Lightcourts/Exterior)	11	--

AVAILABLE EXTERIOR ILLUMINANCE

Unobstructed total illumination readings were taken at each facility at about noon (Central Daylight Savings Time). The horizontal Global reading at the Lockheed facility on September 18,1986 was 8890 fc., while the reading at Shell Woodcreek on October 2,1986 was 9065 fc.

Solar Energy Research Institute (SERI) daylight availability data indicate a typical Global reading for Waco, Texas for noon in mid-September to be 7900 fc. (8). The reading at Lockheed is 11 percent higher than the SERI data for Waco, while the Woodcreek reading is higher than the SERI data by 13 percent. However, the two sites differ from one another by only 2 percent at about 12 noon.

Figure 5 illustrates the comparison of exterior conditions at each measurement site as compared to SERI typical data for four local Texas cities. Data was gathered for Austin, Fort Worth, Port Arthur and San Antonio, and is shown in the figure as a band of data (San Antonio being the high end and Port Arthur the low end. The measured exterior illumination values at both locations is shown with the SERI data for comparison.

Measurements at both locations were obtained with a digital, hand-held photometer.

FUNCTION OF LIGHTSHELVES

Design Objectives-

Each time light hits a surface it is partially absorbed and partially reflected. The color, texture and specific material in each case determines the proportions of incoming light which gets reflected versus being absorbed. As Figure 6 shows, the light must then be reflected at least one more time to become useful in the work areas of the room. It is the goal of lightshelf systems to project reflected light as deep into the space as possible. In other words, to take vertical sunlight or overhead diffuse skylight and distribute it horizontally. As a December 1984 study by Burt,Hill Kosar, Rittelmann and Associates (9) clearly states, the physics of reflecting light off common building materials and color works against this.

Flat paints (even white), common ceiling tiles, and concrete to name a few, fail to reflect light in a specular fashion as water or a mirror would. Rather, they reflect in a diffuse manner with the prime reflected component at a perpendicular angle (90 degrees) to the reflecting surface. A horizontal lightshelf would therefore reflect primarily vertically (back up at the ceiling), and light finally contributed to the space would be very diffuse. This is contrary to commonly practiced lightshelf design which assumes a specular reflection and deep penetration of light into spaces. Studies by both Burt, Hill et. al.(9), and Lawrence Berkeley Labs (LBL) (10), are conclusive that simple lightshelves do not provide improved penetration of daylight under most sky conditions.

The buildings of this study each exhibit efforts to deal with this phenomenon in a particular way. The Lockheed lightshelf is sloped away from the glazing so that its primary reflected componant is directed into the space rather than straight up towards the ceiling. The ceiling slopes down from the window wall (11 ft.) to the work bay (10 ft.), so that the light reflected off the ceiling is also better dispersed to the work areas.

Shell Woodcreek used a rounded HVAC duct as the lightshelf. Since it is not flat and horizontal, light reflected from it is redirected into the space and at the ceiling. An exposed structural concrete system was used for the ceiling; and to help disperse light, it was painted white. The Shell facility also deals solely with diffuse light (no direct sun) on all facades as a result of its structural/shading system.

Prototypical Distribution-

The distribution study by Burt, Hill et al. (9), states the following about daylighting with conventional window walls; "It is important to note that the amount of daylight provided by the lower view glazing is generally sufficient to cost effectively dim those light fixtures within 15 to 20 ft. of the building perimeter". They indicate standard glazing can provide reductions of electrical lighting costs by even 40 percent at 20 feet into a space. Figure 7 shows a graphic comparison of illumination distribution profiles for lightshelves by several **prominent** researchers. The LBL profile deals with clear sky conditions and a lightshelf glazed only above the shelf (10). The curves by Fuller Moore are for overcast conditions and show a profile for glazing with and without a lightshelf (11). Burt, Hill, Kosar and Rittelman's profiles are also overcast sky curves for a test facility with and without a lightshelf (9).

Finally, there is a band of measurements included which represent scale model studies by Ben Evans on the Shell facility under overcast sky conditions (7). Also in this band of data are the clear sky measurements taken at the Shell building for both north and south exterior exposures. It is interesting to note that the band including both scale-model and actual measurements of the Shell facility falls significantly below all the predicted values by a factor of at least three. It needs to be recognized that actual built environments often fall to produce final results which are as high as those predicted at the design stages. Perhaps a "safety factor" of 3 or 4 needs to used during preliminary daylighting system design so that actual values fall in more useful ranges in the final built environment, as previously suggested by Boyer (12).

INTERIOR ILLUMINANCE LEVELS

Lockheed-

At Lockheed, the spaces utilizing the lightshelves for distribution are open-plan work bays with sloping ceilings (11 down to 10 ft.). Because of this design, these ceilings tend to provide deeper penetration and distribution of daylight. Few walls and obstructions keep the absorption and reflection of the incoming daylight to a minimum. There are several factors which keep Lockheed from realizing its daylighting and energy savings potential. These areas of concern are discussed now, and in a later section possible improvement strategies are given as well.

The first factor deals with the lighting system, which is arranged in a grid of 3-tube flourescent fixtures; the first row of which is about 6 ft. from the window walls. The problem is that the entire grid of lights for the whole side of the open plan bay is switched centrally and without control over individual fixtures or rows of lights. Simply this means that all the lights burn at all the occupied times whether fully occupied or only a few workers are present on a weekend. This eliminates any lowered electric usage from the supplemental daylight, and any savings in cooling costs from lowered heat gain from light fixtures. This situation also presents problems in taking measurements since entire banks of lights over workers desks could not be turned off during our visit.

A second factor which affects Lockheed and many open plan facilities, is the partition system and plan layout. Individual "offices" are set up using panel system partitions which are all at least 5 ft. high, and many covered in a coarse, dark blue cloth. These are attractive, but they pass no daylight to their occupants. This limits light at any workers desk area to only the light coming from above (some of the lightshelf light may have been arriving, but due to the grid light system this could not be documented.).

The arrangement of the partitions, "hallways" and barriers might be considered with respect to allowing the most possible light to penetrate as far as possible. The first row of cubicles could start 6 or 8 ft. from the window wall, and be open on the side facing the glass. This allows circulation at the windows, and lets the light begin to disperse in the space before blockage occurs.

Shell Woodcreek-

In Shell Woodcreek the typical area served by the lightshelf is a private office about 10 ft. wide by 16 ft. deep. Extensive testing of the Shell designs was done by both the architects and daylighting researcher Ben Evans, on small scale and full size models. Test measurements were made and studied in a sky simulator and in Houston sky conditions (the latter in a full scale mock-up model) (7). This preliminary testing indicated that the lower glazing would admit high amounts of daylight into the space from 5 to 7 ft., while the high glazing would deliver light levels of over 30 footcandles even to the rear wall of the office.

A major shortcoming at the Shell facility is the failure of the occupants to use the specially-designed lighting system as it was intended to function. Additionally, the indiscriminant use of mini-blinds on the windows by occupants reduced or eliminated a great deal of the daylight from the typical office.

The lighting system was designed to be switchable by the occupant from his/her desk so that on any occasions when it was dark, (heavy overcast), or at night etc., they could rely on ceiling reflected flourescent lighting. The switching was intentionally designed to be at the desk area (by the window) so switching could occur as the need arose. During the course of occupancy though, the switches have all moved back to the wall beside the door, where they are used to turn the lights on upon entry and off upon exit at days end. The lights now burn full time despite the significant daylight contributions which were measured in north and south facing offices.

The mini-blind phenomenon began when some executives felt exposed to scrutiny from windows across a courtyard and installed blinds to screen their views. Once the first blinds were installed, all workers were alerted to the privacy issue; and the blinds became a status issue. Once the blinds were installed, the issue of turning out lights and using daylight became a moot point. There were some locations which rated close to discomfort levels in terms of brightness ratios (see section following), but glare and brightness were not key reasons given for the use of blinds.

Distribution Profiles-

Numerous sets of measurements were taken throughout the buildings, the data was sorted by floor and orientation, and then plotted and compared to existing prediction profiles. The database for Lockheed was severely limited by an inability to take measurements deeper into spaces than 3 ft. (the lighting system was unable to be selectively switched on/off). At Shell data were collected around interior atriums on all floors, and to the true north and south exterior exposures.

Figure 8 illustrates trends which show groupings of selected Lockheed measurements in both unobstructed (exterior locations), and partially obstructed or obstructed view locations (in the light courts). There is an obvious difference in the data which clearly show a decrease in the daylighting in lightcourt locations vs. exterior locations, even though these courts are not covered.

Figure 9 illustrates the ranges of three basic groupings of Shell measurements. The highest band of illumination values occurs in the perimeter offices facing due south. The next highest values occur at north-facing exterior offices, while the lowest values occur at interior atrium offices at various floor levels.

One curious thing worth noting in the Shell curves is that the 5th floor reading for the north-facing exterior offices. This curve not only falls outside the band, but has a very different shape. The profile for this curve begins to decay until about 5-7 ft. from the glazing where an increase in daylight values is noticed. From this new elevated point, the profile again shows a classic decay curve. It is the opinion of the researchers that this profile represents a typical lightshelf curve, where the primary contribution from the shelf occurs several feet from the glass as indicated by the LBL curve in Figure 7. When this curve is combined with a classic decay curve for a viewing window, a resulting profile is similar to that in Figure 9. This probably occured only in the top floors due to the elevated position, and the much greater sky component available from the horizon to a top floor location.

A similar trend is noticed in the only deep measurement obtained at Lockheed which is shown in Figure 8. This is inconclusive by itself but indicates a strong lightshelf contribution several feet into the office, in addition to that of the window glazing which had begun to decay. The data profiles for both buildings clearly show a variation in the magnitude of illuminance which seems strongly related to location in plan and elevation. The south-facing side of Shell outperforms the north- facing offices by about 2 1/2 times, and atrium locations fall below that. Lockheed shows the same tendancy for the atrium-like light court exposures to provide up to about 2 1/2 times less daylight to the perimeter offices than do the exterior locations tested.

All this indicates that different orientations need to be treated independantly to maximize or tailor daylighting to the different needs of the various exposures. And, the needs of covered atriums and open light courts require additional study to further define the reductions in daylight which occur as a product of depth and configuration.

The resulting daylight distribution profile for a lightshelf will depend on many factors including shelf design and materials, sky conditions, orientations, transmissivities, reflectivities etc. Yet, results of this study supported by the LBL component curve for direct sun above the lightshelf, tend to indicate a characteristic profile which varies significantly from the curves of Moore, Evans, and Burt Hill Kosar Rittelmann. This suggests that much care must be excercised in conducting preliminary evaluations to determine the expected performance of lightshelf systems.

LIGHT QUALITY ASSESSMENTS

Brightness Ratios-

Brightness ratios indicate the relative contrast of the darkest spot in a field of view as compared to the brightest spot in the same field. It can be used as an indicator of the amount of glare in a particular field of view. If the ratio of the spot brightness readings of the darkest to lightest spots exceeds 1:20, then the view may be considered to be too bright; and people may have trouble adjusting their eyes to the range of brightness present. Researchers have determined that ratios of 1:20, and below, generally fall in accepted comfort ranges (13).

Spot brightness readings were taken at both facilities to determine brightness ratios for a typical office space in the lightshelf test areas. At Lockheed, the reading of the view out the glass above the lightshelf was 948 fc, while a reading at a dark location below the window was only 93 fc. This results in a brightness ratio of 1:10. The measurement at Shell, looking at the sky through the glass above the lightshelf, was 3000 fc while the dark spot in that field of view was only 101 fc. The brightness ratio at Shell was 1:30 through the high window. These values represent typical maximum rates.

The ratio at Shell appears to exceed the comfort range by a good margin, but it is difficult to get in a position to see out the upper pane of glass as a natural view. This only occurs at distances greater than 15 feet from the windows, where the relative brightnesses are less severe and non-offensive.

However, a typical brightness ratio out of the regular window glass for Lockheed was 1:1.6, while at Shell it was 1:10. Since these readings more accurately represent the normal situation, it is considered to be adequate in both situations.

Note that the brightness readings at Lockheed were taken in one of the lightshelf locations at a light court, and very likely would have yielded higher readings (approaching Shell's) if the location were in an exterior location.

STRATEGIES FOR IMPROVEMENT

Improvement Strategies-

As previously mentioned, there are areas of concern in both facilities where attention should be focused to use the current system to its best potential, and to alert designers of pitfalls in current trends.

The need to develop a lighting system which can be used in conjunction with the daylight contribution is essential. This would ideally be a self-adjusting light sensitive meter that could vary the electric light levels down during high daylight periods, and up at night etc. Secondly, the lighting system should be arranged in banks that are switchable or variable in rows which run parallel to the exterior windows. These suggestions deal with large rooms and open plan situations. Lockheed could do some wiring adjustments to allow the light banks to be turned down or off independently by timer or manually. They could simply remove two bulbs from each fixture at the windows, one bulb from each fixture in the second row , and in this way force the acceptance of daylight and reduce light-generated heating loads.

Atrium readings in both buildings came out vastly lower than readings taken on exterior exposures. Designers need to gain greater understanding of the ways atrium geometries affect light reduction by mutual shielding, shape and size. As mentioned, some studies of this nature are currently underway at Texas A&M.

The margin of error from predictive studies and model measurements needs to be documented so that results in the schematic stages can be used to more accurately predict actual building results. This stems from variances between the scale model prediction of performances at Shell and actual measured results (especially in the atrium). Perhaps a "safety factor" can be built into predictive calculations as it is in steel design etc. to help ensure more adequate daylighting levels.

Buildings are multi-sided objects and need to be studied accurately in that fashion at preliminary stages. To test only north and south exposures fails to deal with problems that face building sides on the east and west exposures. Sunrises and sunsets provide wholly different problems than noontime sun. Controls for sun and daylight such as shading and transmissivities need to be dealt with in terms of orientation at the early stages to work properly later.

Some education of building operations personel, as well as occupants, as to the hours these special systems work is necessary to keep them from using lights all day in offices where more than adequate daylight is provided. Also, closing blinds or blocking windows with cardboard or partitions must be avoided if maximum benefit is desired. By the same token more care by designers needs to be taken to help provide visual comfort by limiting brightness and glare which will help keep blinds etc. from appearing, and the privacy issue must be tactfully addressed.

Care needs to be given to open plan arrangements so that maximum dispersal of daylight is possible and it is not blocked by partitions of excessive height, nor by plan arrangements. A good general approach is to use daylighting and overhead electric lighting to provide general illumination for circulation and simple tasks, while providing individuals with switchable task lighting for reading,writing and typing chores. This will reduce overall lighting requirements and costs related to lighting use and cooling costs of heat produced by lighting.

Future Work-

Daylighting measurements have been obtained in several buildings of three basic atrium configuration types (linear, 3-sided, and 4-sided) (4). Several types of lightshelf systems are also being investigated. Extensive scale model tests of these building configurations are then conducted in the sky simulator at Texas A&M University. These simulator tests are conducted with various sun and sky conditions.

Subsequently the development of algorithms will aid in the accurate prediction of daylighting and energy performance in atriums and lightshelf applications (14). These algorithms, based on the physics of light, are adjusted according to empirically derived coefficients from scale model and actual building studies such as the ones reported here. These algorithms can then be simplified to act as preliminary design tools for prediction at the conceptual and schematic design phases of the architectural design process.

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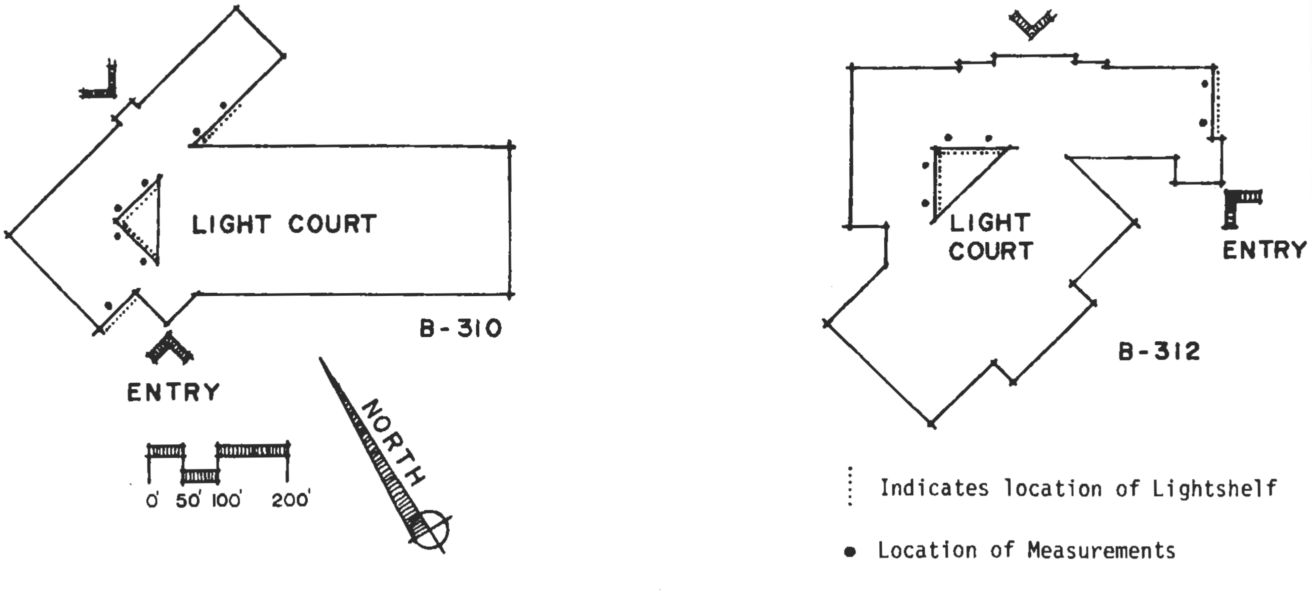


FIGURE 1. BUILDING PLANS FOR LOCKHEED / AUSTIN

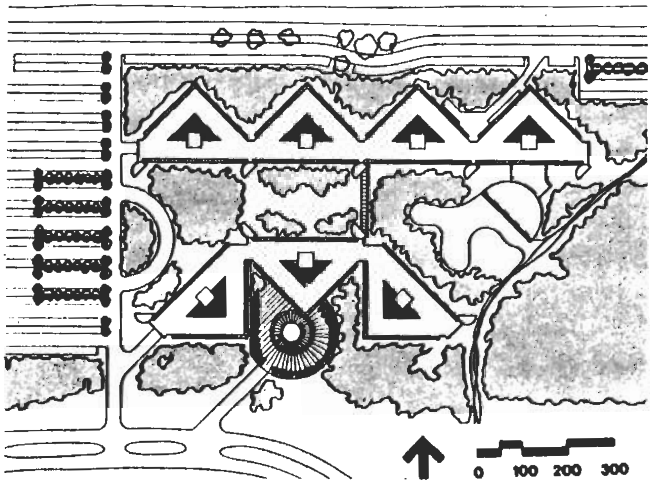


FIGURE 2. PLAN OF SHELL WOODCREEK HOUSTON FACILITY

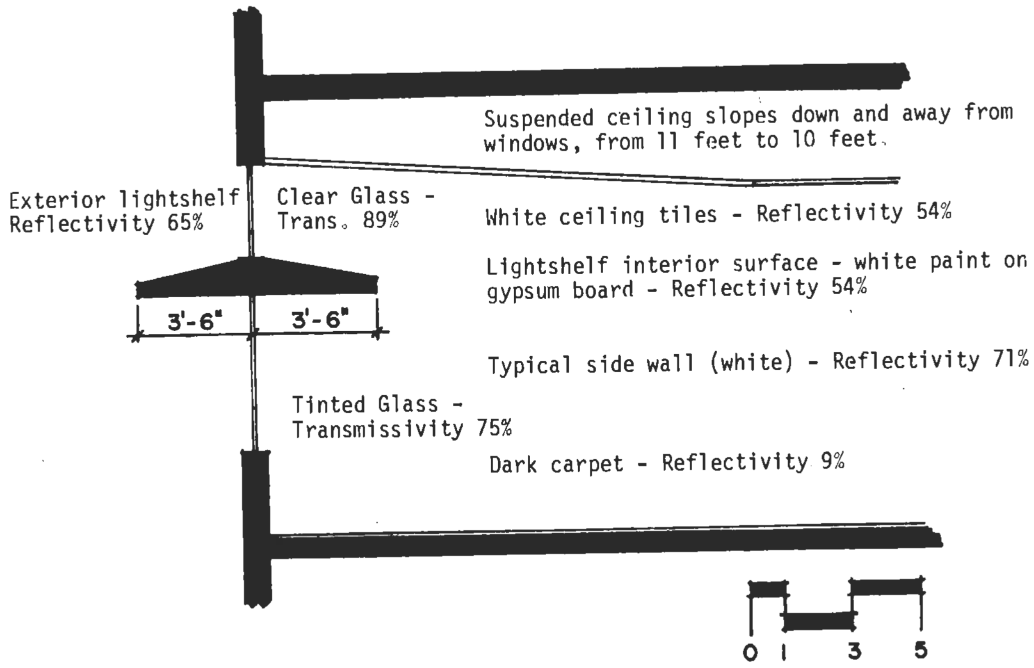


FIGURE 3. ROOM SECTION @ LOCKHEED / AUSTIN

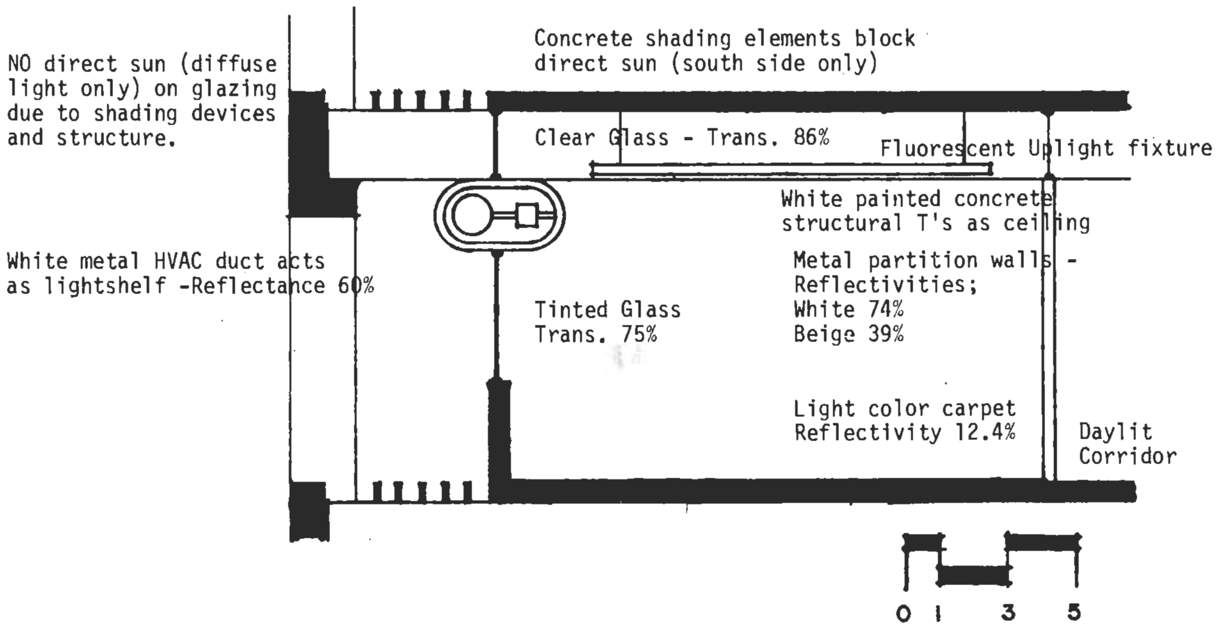


FIGURE 4. ROOM SECTION @ SHELL WOODCREEK / HOUSTON

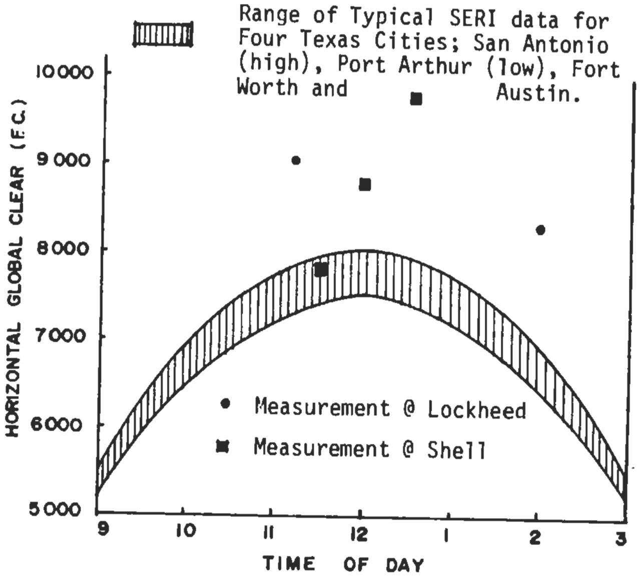
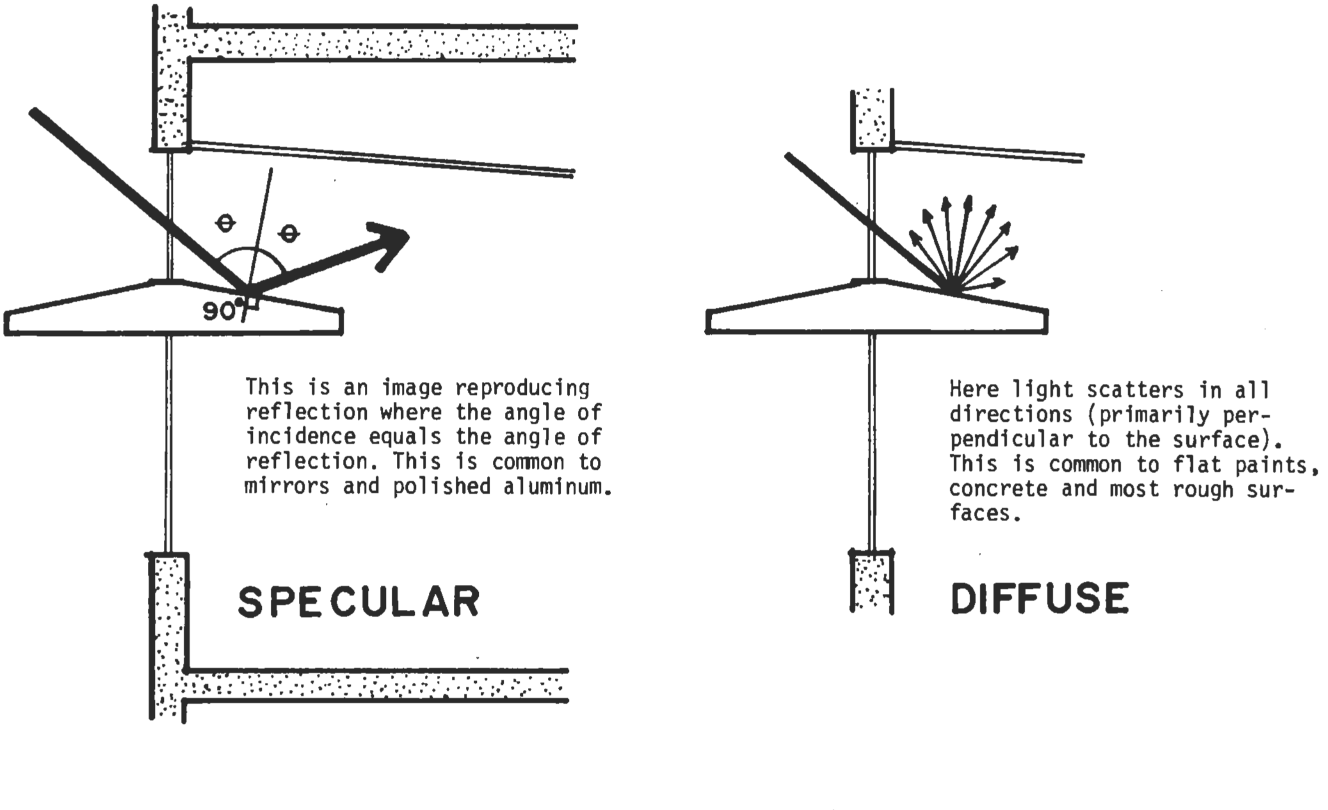


FIGURE 5. COMPARISON OF MEASURED EXTERIOR ILLUMINANCE WITH STANDARD SERI DAYLIGHT AVAILABILITY DATA



This is an image reproducing reflection where the angle of incidence equals the angle of reflection. This is common to mirrors and polished aluminum.

SPECULAR

Here light scatters in all directions (primarily perpendicular to the surface). This is common to flat paints, concrete and most rough surfaces.

DIFFUSE

FIGURE 6. ASSUMED SPECULAR REFLECTION vs. TYPICAL DIFFUSE REFLECTION

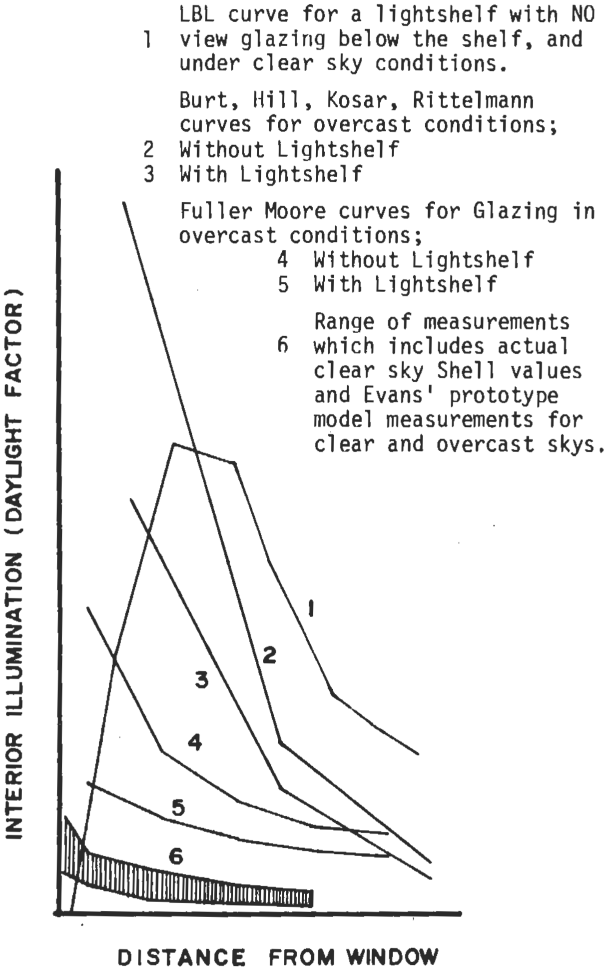


FIGURE 7. PROTOTYPICAL LIGHTSHELF DISTRIBUTION PROFILES

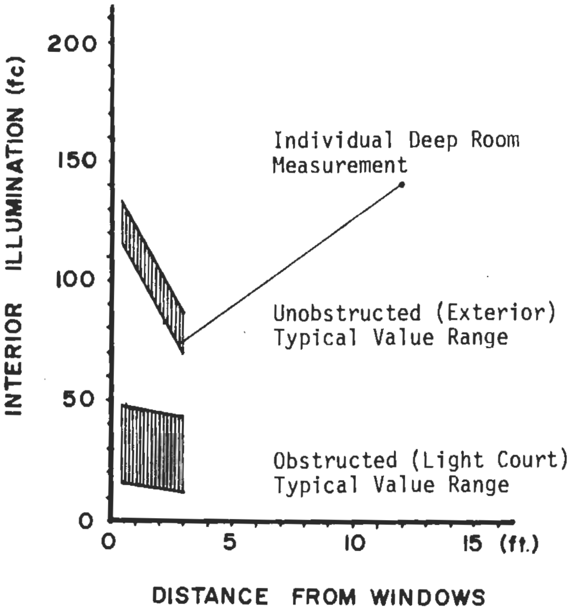


FIGURE 8. DISTRIBUTION PROFILES FOR LOCKHEED / AUSTIN

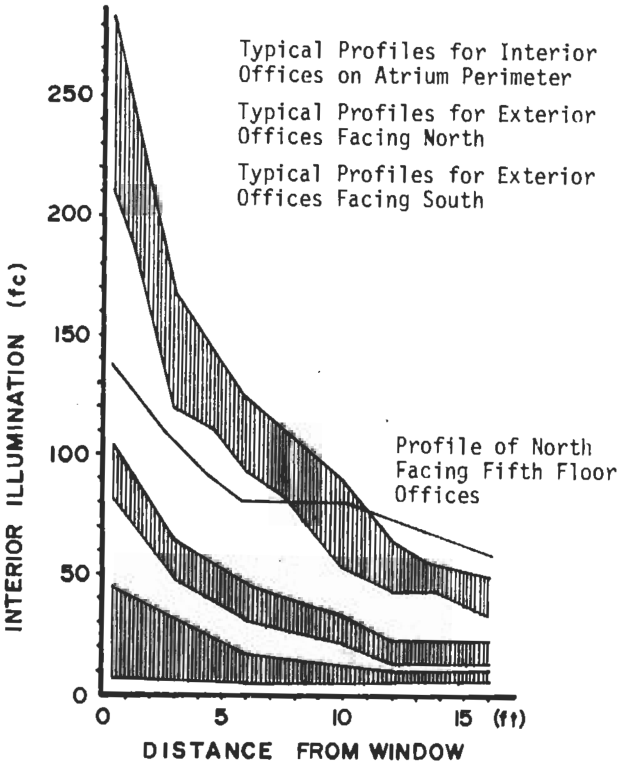


FIGURE 9. DISTRIBUTION PROFILES FOR SHELL WOODCREEK / HOUSTON