FIELD ASSESSMENT OF DAYLIGHTING SYSTEMS AND DESIGN TOOLS
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Field Performance of Daylighting Systems and Design Tools

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Abstract

The performance of three buildings equipped with photoelectrically-controlled lighting systems was assessed. Detailed monitoring of illumination levels and lighting power demand were carried out at two of the buildings. Lighting and thermal interactions were examined in detail at one of the buildings. It was found that the designers and/or contractors had made conflicting decisions that resulted in negligible energy savings (e.g., the use of tinted glass admitting relatively little daylight in combination with lighting control systems dependent on the admission of daylight). The systems were also ineffectively operated because building users and operators had little understanding of the technology.

Studies were also conducted to better define the accuracy and appropriate application of scale model photometry as a design tool.

Résumé

On a évalué le fonctionnement de trois bâtiments dotés de systèmes d'éclairage jumellés avec des contrôles photo-électriques. On a enregistré de façon détaillée les niveaux d'éclairage et l'utilisation de la consommation électrique de deux des batîments. Un des bâtiments a été le sujet d'un suivi de l'impact de l'éclairage sue les systèmes de contrôles thermiques. Les données indiquent que certaines décisions ont été prises résultant en une économie d'énergie beaucoup moins importante que possible. Par exemple, on a posé des fenêtres a vitrage teinté qui permettent peu de d'éclairage naturel des endroits où les contrôles photo-électriques auraient pu meximiser les épargnes d'énergies. De plus, les divers systèmes étaient utilisés inefficacement en raison du manque de compréhension de la part des occupants et gestionnaires des bâtiments.

On a également exécuté l'étude afin de déterminer la précision at l'application la plus appropriée de la photométrie fondées sur des maquettes à échelle réduit comme outil de conception.

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1.0 EXECUTIVE SUMMARY

Electric lighting is a major expense in the operation of commercial and institutional buildings, making large demands on nonrenewable fuels. The combustion of fossil fuels also has adverse environmental impacts. A simulation study funded by Natural Resources Canada (then Energy Mines and Resources Canada) showed that exploitation of daylight in conjunction with photoelectrically-controlled dimming systems should provide substantial reductions in electricity use and be cost-effective in Canada [1]. The significance of daylighting as a potential energy conservation measure has also been recognized by major industry organizations such as the American Society of Heating, Refrigerating and Air-conditioning Engineers and the Illuminating Engineering Society of North America [2-3]. Studies also suggest that people prefer spaces with daylight and views [4-8]. Very little data is available on the performance of daylighting systems and, prior to this study, none was available for Canadian buildings. Measured data from two buildings (one in the United States and one in England) showed that large reductions in lighting power use were realized [9-10]. According to the terms of reference of this study, office buildings in Calgary equipped with photoelectrically-controlled dimming systems were to be identified and their performance evaluated. The three buildings that were identified and assessed in this study did not achieve any lighting energy use reductions because:

i) glazings with low visible transmittances were used (presumably as an approach to controlling solar gains), thus allowing minimal quantities of daylight to enter perimeter spaces,

ii) in one building, the dimming zone extended to the core of the building, so that any level of dimming would have reduced light levels in spaces lacking windows (the degree of dimming had therefore been reduced to a negligible fraction of normal electric light output), and

iii) in the other two buildings, the building operators has disabled the dimming controls for various reasons such as worker complaints regarding the appearance of dimmed lamps in comparison with those not in the dimming zone (the differing luminaire colour being attributed by workers to faulty lighting).

In addition, efforts were made to evaluate the performance of a high school built in 1990 and designed to exploit daylight. Daily readings of gas and electric meters over a two year period showed that it had an annual energy use per unit floor area at the median for seven Calgary high schools. The daylit high school had clear (high visible transmittance) glazing, but lacked photo-electric dimming controls. Further, it was furnished with 300 personal computers, significantly increasing plug loads beyond those in the other schools. Further study is required (and is currently underway) to determine the energy end uses in the building so that the contribution of daylighting to energy conservation can be more accurately identified.

Recommendation 1: Buildings with well-constructed and operated daylighting systems (including those with photo-electric dimming controls) should be identified or developed (either through retrofit or new construction) to show effective use of daylighting technology.

The C2000 program to create demonstration energy efficient commercial buildings may help meet this need.

Recommendation 2: That training courses be provided for the building industry on the effective application of daylighting concepts.

The research showed that decisions regarding daylighting made by some members of the building design and construction team (e.g., the architect specifying the envelope and the electrical engineer specifying the lighting control system) were in conflict and that some decisions showed a complete lack of understanding of the technology.

The scope of monitoring was also unusual in that illuminances, lighting power demand, *and* cooling rates were monitored (the few preceding studies, including one carried out by a U.S. National Laboratory, addressed only illuminances and lighting power demand [9-10]). This is significant because knowledge of effects of lighting energy use reductions on cooling can allow for more accurate estimates of return on investment for energy conservation measures related to lighting. Results from the one office building that was intensively instrumented indicated that internal heat sources (lights, people, and equipment) had relatively little effect on cooling rates. This finding differs from that for a full-scale test zone constructed in a laboratory chamber by the U.S. National Institute for Standards and Technology in the United States, in which lighting did have a substantial effect on cooling requirements [11]. Apart from the information obtained, this study led to improvements in previously developed protocols for monitoring building performance.

Recommendation 3: Further studies of lighting-cooling interaction in real buildings should be conducted to quantify the interactions that actually occur and thus provide better information for estimating energy savings and life-cycle costs.

The study also provided improved knowledge of the accuracy and appropriate application of daylighting design tools.

1.0 RÉSUMÉ

L'éclairage électrique représente une portion considérable du coût d'exploitation des immeubles commerciaux et de séjour permanent et exige la consommation d'une grande quantité de combustibles non renouvelables. De plus, l'utilisation des combustibles fossiles est nuisible pour l'environnement. Une étude en simulation financée par Ressources naturelles Canada (anciennement Énergie, Mines et Ressources Canada) indique que l'exploitation combinée de l'éclairage naturel et d'un système de gradation à commande photoélectrique devrait réduire considérablement la consommation d'électricité des bâtiments et constituer une technique rentable au Canada [1]. L'importance de l'éclairage naturel comme mesure possible d'économie d'énergie a également été reconnue par de grandes organisations industrielles comme l'American Society of Heating, Refrigerating and Air-conditioning Engineers et l'Illuminating Engineering Society of North America [2, 3]. Les études montrent en outre que les gens préfèrent les locaux offrant un éclairage naturel et une vue sur l'extérieur [4 à 8]. On dispose de très peu de données sur le rendement énergétique des systèmes d'éclairage naturel et, avant la présente étude, il n'en existait aucune sur les bâtiments canadiens. Les mesures effectuées dans deux bâtiments situés aux États-Unis et en Angleterre ont permis de constater que l'utilisation de ces systèmes entraînait d'importantes réductions de la consommation d'électricité d'éclairage [9, 10]. L'objectif de la présente étude était de trouver à Calgary des bâtiments munis de systèmes de gradation à commande photoélectrique et d'en évaluer le rendement. Dans les trois bâtiments observés, ces systèmes n'ont entraîné aucune réduction de la consommation d'énergie d'éclairage, pour les raisons suivantes :

i) comme on avait utilisé des vitrages à faible transmittance visible (probablement dans le but de limiter les gains solaires), il entrait très peu de lumière naturelle dans les locaux périphériques;

ii) dans un des bâtiments, la zone reliée au système de gradation s'étendait jusqu'au centre des étages, de sorte que toute diminution de l'éclairage électrique entraînait une baisse d'éclairement dans les locaux sans fenêtres (on ne réduisait donc presque pas l'éclairage électrique par rapport à son niveau normal);

iii) dans les deux autres bâtiments, le responsable de l'entretien avait mis hors-circuit les commandes du système de gradation pour diverses

raisons, notamment parce que les occupants se plaignaient du fait que les lampes dont l'intensité avait été réduite n'avaient pas le même aspect que les lampes situées à l'extérieur de la zone reliée au système de gradation (on attribuait cette différence de couleur entre les luminaires à une défectuosité du système d'éclairage).

On a en outre évalué le rendement énergétique d'une école secondaire construite en 1990 et conçue pour exploiter l'éclairage naturel. La consommation énergétique annuelle par unité de surface, calculée à partir des lectures des compteurs à gaz et à électricité effectuées quotidiennement pendant deux ans, était égale à la médiane obtenue pour sept écoles secondaires de Calgary. L'école observée était munie de vitrages transparents (à forte transmittance visible), mais ne possédait pas de système de gradation à commande photoélectrique. De plus, comme 300 ordinateurs personnels y étaient utilisés, la charge des prises de courant était beaucoup plus élevée que dans les autres écoles. D'autres recherches sont nécessaires (et sont actuellement en cours) pour déterminer l'utilisation finale de l'énergie dans les bâtiments observés, afin qu'on puisse évaluer plus exactement l'économie d'énergie réalisée grâce à l'éclairage naturel.

Recommandation 1 : On devrait identifier les bâtiments qui comportent un système d'éclairage naturel bien construit et bien exploité (y compris ceux qui sont munis d'un système de gradation à commande photoélectrique) ou créer de tels bâtiments en les construisant de toutes pièces ou en modernisant des édifices existants afin de démontrer l'utilisation efficace des techniques d'éclairage naturel.

Le programme C-2000 encourage la construction d'immeubles commerciaux mettant en application des technologies à haut rendement énergétique et peut aider à atteindre cet objectif.

Recommandation 2 : On devrait donner aux membres de l'industrie de la construction des cours sur l'application efficace des concepts fondés sur l'éclairage naturel.

Les études ont montré que certains membres de l'équipe de conception et de construction des bâtiments (par ex., l'architecte qui détermine les caractéristiques de l'enveloppe et l'ingénieur électrique qui détermine celles du système de commande d'éclairage) prenaient des décisions contradictoires quant à l'éclairage naturel ou ne possédaient pas une connaissance suffisante de cette technologie.

Les paramètres observés, soit l'éclairement, la puissance d'éclairage et la vitesse de refroidissement, étaient plus nombreux que dans les quelques études antérieures - dont une a été menée dans un laboratoire national américain - qui ne portaient que sur l'éclairement et la puissance d'éclairage [9, 10]. Cette différence est importante car en déterminant l'effet d'une réduction de la consommation d'énergie d'éclairage sur le refroidissement, on peut évaluer plus exactement les bénéfices d'un investissement dans des mesures d'économie d'énergie liées à l'éclairage. Les données obtenues sur le seul édifice à bureaux dans lequel on a effectué des mesures systématiques indiquent que les sources internes de chaleur (la lumière, les occupants et les appareils) ont une incidence relativement faible sur la vitesse de refroidissement. Ce résultat va à l'encontre de la conclusion d'une étude américaine sur une zone d'essai construite en grandeur réelle dans un laboratoire du U.S. National Institute for Standards and Technology [11]. Outre l'information obtenue, la présente étude a permis d'améliorer des protocoles d'évaluation du rendement énergétique des bâtiments.

Recommandation 3 : On devrait mener d'autres études quantitatives sur l'interaction entre l'éclairage et le refroidissement dans des bâtiments réels afin d'obtenir l'information nécessaire pour évaluer plus exactement les économies d'énergie et les coûts du cycle de vie.

La présente étude a également permis d'acquérir de nouvelles connaissances sur l'exactitude et les méthodes d'utilisation des instruments de conception de l'éclairage naturel.

2.0 PROJECT OBJECTIVES

The project objectives were to:

1. Assess the viability of daylighting systems in terms of technical, organizational, ergonomic and fiscal criteria, and

2. Assess the accuracy and value of currently-available daylighting design tools.

2.1 The Need for Measured Data

Energy Mines and Resources has funded theoretical research on the use of daylighting in commercial buildings [1]. Findings indicated that daylighting should be a cost-effective strategy for achieving energy efficient building operation. The researcher recommended that further computer simulation and ergonomic studies be conducted. However, it is necessary to augment computer simulation studies with field assessment of the performance of daylighting systems, taking into account technical, ergonomic, organizational, and fiscal considerations; simulations involve many assumptions that may deviate widely from real conditions. In the past decade, the number of daylighting systems for which measured data has been published is very small (e.g., see references 9-10, 12-13); the published accounts focus on photometric results and energy efficiency. Ergonomics, organizational, and fiscal considerations are generally treated casually or not at all. The Seattle Lighting Laboratory, a regional technology transfer centre funded by both U.S. and Canadian utilities, identifies monitored data from daylit buildings as one of the most important requirements in gaining acceptance of daylighting [14].

A number of daylighting systems have been constructed in Calgary, but most installations have been developed in the absence of any analysis based on system performance in the field. Further, no systematic studies had previously been made to determine the effectiveness of these systems.

Knowledge of the performance of systems in terms of fiscal and ergonomic effects is essential in appropriate application. Inappropriate application from an ergonomic perspective can have significant effects on worker satisfaction and performance. Even a one percent decrease in performance for a single clerical worker represents an annual value of about $250, taking into account overhead. This need only be multiplied by the thousands of office workers that might be exposed to daylighting systems to illustrate the cost of poor choices.

The most effective way to communicate new technologies to the design professions is through demonstration projects [15]; this is yet another reason for field studies leading to case studies based on monitored performance.

2.2 The Need for Improved Design Tools

If building designers are to employ daylighting as part of a building systems concept, they should have reliable information on design tools as well as on performance of representative systems. Design tools are also a means of transferring knowledge to professionals.

Despite the fact that computer simulation and scale-model photometry are widely used in daylighting design and to validate other design aids [e.g., see 16], comparatively little work has been done on the validation of techniques and development of standardized procedures for their application [17-18]. If design tools are inappropriately applied, or used without knowledge of tolerances, either over- or under-design may result. The cost of over- or under-design for a single project can be substantial.

2.3 The Need for Improved Evaluation Protocols

It will be important to evaluate daylighting systems in geographic areas of Canada other than the Prairies. Effective and standardized procedures are required to ensure that the resources invested in these efforts provide useful returns.

3.0 FIELD PERFORMANCE OF DAYLIGHTING SYSTEMS

The comprehensive field assessment of daylighting systems (lighting demand and HVAC system effects) carried out in this project goes beyond previous research efforts carried out by U.S. National Laboratories and others. Earlier studies have been restricted to daylighting effects on illuminance levels and lighting power demand [9-10, 12-13]. Other aspects of daylighting systems that should be considered are ergonomic, environmental impact, organizational, and financial performance. The ergonomic aspect has to do with occupant preferences, comfort, satisfaction, and productivity. The environmental impact aspect has to do with such factors as requirements for the use of nonrenewable energy resources and systemic environmental effects of the lighting systems used (e.g., a system requiring more cooling may increase the requirement for thermal electric generation and consequent generation of CO_2 and acid gases). The organizational aspect has to do with the operation of buildings - for instance, the scheduling of system operations or the renovation of spaces to meet changing occupant requirements. The financial aspect has to do with return on investment or relative cost of technologies.

3.1 Literature Review - Performance of Daylighting Systems

3.1.1 Case Studies of Sidelit Buildings with Photoelectric Dimming Controls

Performance of a photoelectric dimming system in a 56, 000 m^2 (600, 000 ft^2) office building in the San Francisco area (38^{o} north latitude) was reported in 1986 [10]. The structure had five floors, with a floor plate extending 28 m (90 ft) from the exterior to the atrium. The design incorporated features such as a floor-to-ceiling height sloping from 15 ft (4.5 m) at the perimeter to about 3 m (10 ft) at the center of the floor plate and light shelves to increase daylight penetration. It appears from photographs of the site that the building is unaffected by major sky obstructions.

It was concluded that:

- the architectural features of the building were providing in excess of 350 lx (the target ambient level) for most of the day in the north and south exterior zones; the lower (view) glazing had transmittances of 17 percent on the south side and 41 percent on the north side, while the upper (daylighting) glazing was clear (no transmittance provided). Photographs of the interior indicate that light-colored high-reflectance finishes were used on the walls as well as the ceiling

- it was estimated that the annual energy use for lighting was about 20 kWh/m^2 (1.9 kWh/ft^2), but could be reduced to about 16 kWh/m^2 (1.5 kWh/ft^2) with "tuning" of the controls (assuming 3750 hours of daytime occupancy per annum)

- the area directly below the south-side light shelf was found to be too dim (due to the low transmittance view glazing and the exterior shading element) and required continual supplemental lighting during the summer

- comparison of electrical power use for ambient lighting with concurrent interior illuminance measurements revealed widespread variation in the performance of the electric light control systems (which resulted in excess electricity use in some areas)

- measurement of light levels on days when the building was unoccupied suggested that significant potential for dimming was not being realized

More recently, the performance of another dimming system in a 3000 m^2 (32,000 ft^2) office building near Birmingham, UK (52.5° north latitude) was reported [9]. It is a four story structure, with a floor plate extending 7.5 to 11 m (24 to 36 ft) from the perimeter to the core, and a photo-electrically controlled dimming zone 5 to 7 m (15 to 21 ft) deep. The building has a 3 m (10 ft) floor to ceiling height and is fitted with exterior and interior light shelves. The glazing transmittance is 60 percent. The photoelectric dimming system has a local manual override. The researcher-designers concluded that:

- based on measurements between April and September of 1987, it was estimated that the annual energy use for lighting would be about 17 kWh/m^2 (1.6 kWh/ft^2), with 9 kWh/m^2 (0.8 kWh/ft^2) being the estimate for the daylit areas with dimming controls (for 50 to 60 hours use per week, equivalent to about 2600 to 3100 hours per annum)

- the response of the manual override was found to be unacceptably slow; the control software left one group of lights near the core permanently on, irrespective of daylight availability and user wishes

- horizontal illuminance was an average of 360 lx with uniformity of 0.8

The electricity use in the dimming zones would be about 11 kWh/m^2 (1 kWh/ft^2), for the 3750 hours of annual operation used to estimate consumption in the study described above. A building drawing a steady 22 W/m^2 for lighting would use about 81 kWh/m^2 (7.5 kWh/ft^2) over the same period.

Neither of these studies reported the power factor for the lighting systems.

3.1.2 Laboratory Study of Sidelighting with Photoelectric Dimming Controls

Rubenstein, Ward, and Verdeber used 1:3 scale models to evaluate control systems for automatic dimming in sidelit spaces [19]. They concluded that, of a number of control strategies, closed-loop proportional control using a sensor with a wide field of view but shielded from direct sunlight from the window was most effective at providing "a specified minimum lighting level at the task [workplane] surface" [20]. The wide field of view would reduce the effects luminance changes in small areas of the field of view, luminance changes that might misrepresent room conditions to a fully shielded photosensor. It was noted that integral control using a fully shielded sensor allowed light levels to drop as much as 20 percent below the desired level at about 3 m (10 ft) from the window wall in a 4.5 by 2.7 by 4.5 m (15 x 9 x 15 ft) (w·h·d) model office [21] incorporating glazing with a visible transmittance of 88 percent and ceiling, wall, and floor reflectances of 83 percent, 51 percent, and 23 percent respectively [22].

3.2 Literature Review and Theory - Protocols for Field Assessment

3.2.1 Assessment of thermal control systems

The evaluation of thermal control systems has received the most attention in terms of protocols for the evaluation of building systems. A literature review is provided in Appendix A. The key elements used in this study are summarized here.

The questions to be answered should be stated in specific terms and the experiment designed to answer the questions in those terms.

A major difficulty in assessing building performance is controlling for the many variables, especially climatic and human behaviour effects. Three types of experimental design may be used to offset these difficulties:

1. the test-reference design, in which the energy performance of a group of buildings is compared with that of a control group,
2. the before-after design, in which a comparison is made of energy use before and after the implementation of an energy conservation measure,
3. the on-off design, only viable with reversible conservation measures, in which energy consumption is measured during a number of repeated on-off cycles.

Factors affecting error are:

1. the accuracy of values provided by sensors (e.g., a sensor may be exposed to confounding influences, such as radiation; sensors must be calibrated and subsequently recalibrated as appropriate)
2. the representativeness of the sensor position

3. sampling errors (e.g., due to reading interval)

Accuracy can be enhanced by direct measurement of sub-system performance. While relatively expensive, this provides the best knowledge of equipment dynamics.

The use of a monitoring system that provides easy real-time assessment of system performance and on-site historical trending (graphing of performance over time) is a significant advantage in quality control in data collection.

3.2.2 Assessment of daylighting systems

Only a few publications have been issued on procedures for the field assessment of illuminances and lighting power demand [9-10, 13]. Most of the work has been carried out by, or in association with, the Windows and Daylighting Group at Lawrence Berkeley Laboratory (LBL). Their findings have been consolidated into the *Daylighting Performance Evaluation Methodology* [23]. This method focuses on the determination of the daylighting contribution to reduction in lighting power demand on an annual basis by using data obtained by measurement over a period of two to four weeks.

In evaluating daylighting systems, the LBL procedure requires that the following be monitored:

1. daylight availability (global and diffuse illuminances)
2. interior illumination
3. lighting power demand

"Typical" daylit spaces are identified to create a manageable monitoring situation. It is noted that, for thermal analysis, one-hour measurement intervals are typical because of the time required for thermal effects to occur. Shorter, unspecified, intervals are recommended for lighting measurements. Daylight availability may be measured with an unobstructed photocell to determine the global illuminance, and a photocell shaded by a shadowband to determine the diffuse illuminance, as is discussed below under "Methods and procedures." The rest of the LBL report focuses on use of simulation to determine annual performance based on the short-term measured data. A case study is also provided.

3.2.3 Ergonomic assessment of daylighting systems

Daylighting systems are used in conjunction with supplementary lighting systems, so both should be considered in ergonomic assessments. Rea, Pasini and Jutras comment "surprisingly, there are no accepted methods for evaluating the performance of lighting systems in existing buildings." [24]

Public Works Canada (PWC) has sponsored the development of a "Tenant Questionnaire Survey Assessment Method," a simple approach to assessing occupant ratings of office building performance [25-26]. It addresses air quality (21 percent of variance in scales evaluated), office noise (7 percent), spatial comfort (4 percent), thermal comfort (4 percent), lighting (3 percent), privacy (3 percent), and building system noise (2 percent). The most important factors for worker productivity were identified as spatial comfort, office noise control, and privacy. The most important factors for worker satisfaction were identified as spatial comfort, privacy, and *lighting* (italics added). The lighting portion of the survey asks occupants to rate three aspects of lighting (all questions have 5 point rating scales) : 1) "electrical lighting," 2) "how bright lights are," and 3) "glare from lights."

Additional work on ergonomic assessment of lighting has been undertaken more recently under the auspices of PWC [24]. A kit was used to evaluate lighting conditions, the visual task, and the visual capabilities of the workers. A video imaging system was used to scan workstations to determine the "visual performance potential of the visual scene." The "Tenant Questionnaire Survey" [25-26] was also administered to the occupants. It is noted in the results section that there were discrepancies in acuity test results obtained by two test methods for one workstation, and that this may have been due to the presence of daylight at the workstation. This suggests that the study did not differentiate electric and daylight effects.

A difficulty in dealing with both illumination and ergonomic assessments of daylight is its constant variability. Further, video-scanning and other equipment is relatively costly, while horizontal illuminances measured with basic illuminance meters do not provide sufficient information "in assessing the quality of the visual environment" [27].

The author has been collaborating with Mr. M. Navvab of the College of Architecture and Urban Planning of The University of Michigan in the development of a performance indicator that can be determined with a hand-held illuminance meter but provides much of the information obtainable with more complex systems. This indicator is the ratio of the illuminance on a vertical surface at a point in space to the illuminance on a horizontal surface at the same point in space (the "VH ratio"). Tests have been conducted by physical experiment and computer simulation to examine features such as the stability of the VH ratio relative to the stability of other performance indicators such as the daylight factor under a range of sky conditions and information provide on qualities such as glare and contrast. A paper on progress to date will be presented at the 1993 annual conference of the Illuminating Engineering Society (see Appendix F). Preparations are now being made to field test the measure in terms of its relationship to factors such as occupant satisfaction with lighting conditions.

3.3 Methods and Procedures

The efforts reported in the literature on performance of daylighting systems were limited to measurement of electricity use for lighting. Total energy use was estimated. Thus, the study broke new ground in terms of assessment procedures.

In defining the monitored data to be collected, the research questions were

- How do dimming systems respond to sky conditions (what are the interior illuminances and lighting power demands for various sky conditions)?
- How do thermal control systems respond to changes in lighting power demand?

An A-level (intensive) monitoring protocol was therefore developed to provide information on the illumination performance, lighting power demand, and energy use effects of the daylighting systems examined. It involved continuous measurement of these parameters at intervals of four minutes or less, four minutes corresponding to a one degree change in sun position. A B-level (less intensive) monitoring protocol was also used to compare energy use at a daylit high school with energy use at six high schools without special daylighting features. The B-level monitoring protocol involved daily readings of utility meters, providing information on electric demand and use and natural gas demand.

The literature on ergonomic assessment protocols indicated that there were none that specifically addressed daylight. As noted above, work was conducted on a performance indicator that could allow such studies to be conducted with less cost, but further development will be required before it can be applied. The researcher is also collaborating with Mr. M. Navvab of the College of Architecture and Urban Planning of the University of Michigan in the assessment and development of a questionnaire that would provide user ratings of both daylight and electric lighting systems. Building operators and selected occupants were interviewed regarding technical, organizational, and human factors aspects of performance.

It had been intended that data collected in the course of monitoring also be used to assess tools for daylighting estimation. However, due to tenant concerns regarding security and disruptions, comparative assessments of model and full-scale photometry were carried out in test cells in unoccupied portions of one of the test sites. The advantage of this approach was that the test cells were very similar to those used in earlier research on the subject. This work is discussed in Section 4.

Where monitoring must be restricted to a single zone (as may often be the case due to equipment limitations and the need to minimize disruption of occupants), use of an east- or west-facing zone can be advantageous because such zones are alternately exposed to and sheltered from direct solar radiation for half of each day. Because direct sunlight has a major impact on cooling requirements, glare, and other significant aspects of building performance, this can be very useful in extending the range of data collected.

The following data products were required to meet the objectives of the project:

- electricity used for lighting
- heat transferred to and from the spaces of interest
- illuminances in the spaces of interest
- daylight availability

Because the position of the sun in the sky changes by 1 degree every 4 minutes, a 4-minute measurement interval (or fraction thereof) was selected to be the maximum interval between measurements. Illuminances, air flow rates, and cooling air temperatures were actually recorded at 30 second intervals. Lighting power demand was measured at 5 minute intervals at the first test site, the minimum interval possible with the single-channel monitoring system made available by the City of Calgary Electric System. The researcher subsequently obtained a ten channel system capable of recording measurements at shorter intervals.

All sensors were calibrated before measurements were initiated. The photocells, which are known to change in response over the first couple of years after manufacture, were re-calibrated before measurements were initiated at the second test site (calibration coefficients did change for a few of these sensors). Photocells were placed at work plane (desk top) level. The placement of other sensors varied from building to building and will be discussed below.

Monitoring of heating energy transfer on a building zone basis proved to be impractical. Determination of fluid flow rates would have required insertion of a transducer in perimeter radiation pipes or use of non-invasive (e.g., ultrasonic) transducers. The former was not acceptable to the building operators due to the disturbance and possible resulting damage (e.g., from leaks). Due to the small diameter of the piping in a given zone, the ultrasonic transducers available to the researcher could not be used. While determination of fluid temperatures would be less difficult (energy transfer is proportional to the temperature change and fluid flow rate), attaching sensors to perimeter radiation systems is certainly one of the more difficult aspects of monitoring due to the confined enclosures and the need to work directly in offices (e.g., as opposed to installing transducers in ducts, which can be done in the service zone above suspended ceilings).

The literature review (see Appendix A) indicated that the two most significant variables in assessing building energy use are occupant behaviour and weather. The most effective experimental design therefore appeared to be "test-reference," in which simultaneous measurements are made for a test area and a control area, combined with an "on-off" approach. It was planned that simultaneous measurements, with similar operating conditions, be made to determine the comparability of occupancy effects on energy use for the test and control areas (simultaneous measurement would ensure that weather conditions were identical). One might call this "calibration" of the test area to ensure that it has a constant and identifiable relationship to the control. The continuous data collection would ensure that abnormal patterns over short periods would be detected (e.g., late night lighting usage in only one of the control or the test areas). The dimming capability could then be switched off for short test periods (e.g., one week).

Establishment of a base level of performance by following the proposed experimental design was to have provided data for both simultaneous and sequential comparisons. Data were processed during collection to control for instrumentation and other problems. Raw data (e.g., voltages) were stored rather than values determined from raw data (e.g., cooling rates). This reduced the necessity of repeating experiments or "reconstructing" data should alternative analyses be desired or problems identified with data analysis procedures. For instance, determination of cooling provided by the air handling system can be determined by measuring the air flow rate and the supply and ambient room temperatures. The energy transfer is a function of the flow rate and the difference between the supply and room temperatures. Individual inspection of the three contributing values would better ensure that the data are correct than inspection of the energy flow determined from these values (e.g., the relationship between temperatures and between temperature and flow rate can be examined over time).

All three of the "test-reference", "before-after," and "on-off" experimental designs were used (see subsection 3.2.1 above). Experiments were designed to determine cooling requirements for the test and control zones, so that they could be compared in accordance with each of these experimental designs. In the case of Building A, a floor-to-floor comparison was planned for the test-reference experimental design, until it was learned that the dimming system was zoned so as to be dysfunctional. In the case of Building B, a zone-to-zone comparison was used for the test-reference experimental design. Air flows were determined by measuring pressure differentials at each of the four variable air volume boxes in each zone, and applying constants supplied by the manufacturer. Supply air temperatures were also measured so that the cooling rate could be determined (i.e., it is a function of the volume of air delivered, the ambient-delivery air temperature differential, and the specific heat of air). Time-series plots of daylight, electric lighting, and combined illuminances allowed for ready visual determination of trends.

During initial operation of the data acquisition system, collected data were plotted and checked at intervals of an hour or less. Graphing of data quickly indicated any abnormalities, which did occur and required correction of sensor installations.

The following criteria were applied in selecting the hardware (see literature review in Appendix A):

- on-line processing and read-out in simple terms
- state-of-the-art methods should be avoided
- reliability should be emphasized over accuracy
- more emphasis should be placed on software needs and requirements

In the case of Building A, illuminances were logged in an unfurnished test cell measuring 2.7 by 2.7 by 7.3 m (9 x 9 x 24 ft) (w·h·d) that was erected at the perimeter of an adjacent building in the same complex as Building A (to avoid disruption of tenants and to provide a test space comparable to that used in earlier researcher on photometric methods [18]). Its fenestration, glazing, and spatial geometry were the same as those in Building A. The test cell had an unobstructed east-facing view of the sky. The interior surfaces of the test cell had wall and floor reflectances of 0.40 and a ceiling reflectance of 0.80. These values are close to the IES recommended values for ceiling (0.70), walls (0.50) and floor (0.20) [28].

In the case of Building B, illuminances were logged within a typical office.

3.4 Building and Site Descriptions

The buildings studied were identified through contacts with the Building Owners and Managers Association (Calgary) and other persons involved in the local building industry. An effort was made to identify all local buildings employing photo-electrically controlled dimming systems. As far as the researcher knows, the following list is exhaustive.

3.4.1 Office Building A

Building A is an office building that was constructed around 1982. Its gross floor area is 280, 000 ft^2 (26, 000 m^2) on 12 floors. The perimeter to core depth is 12 m (40 ft). The fenestration consist of ribbon (continuous) windows running from 0.77 m (2.5 ft) to 2.5 m (8 ft) above floor level. No shading devices or light shelves are used. The floor-to-ceiling height is 2.8 m (9 ft). The sky view to the south is partially obstructed by a five story building in the same complex.

3.4.2 Office Building B

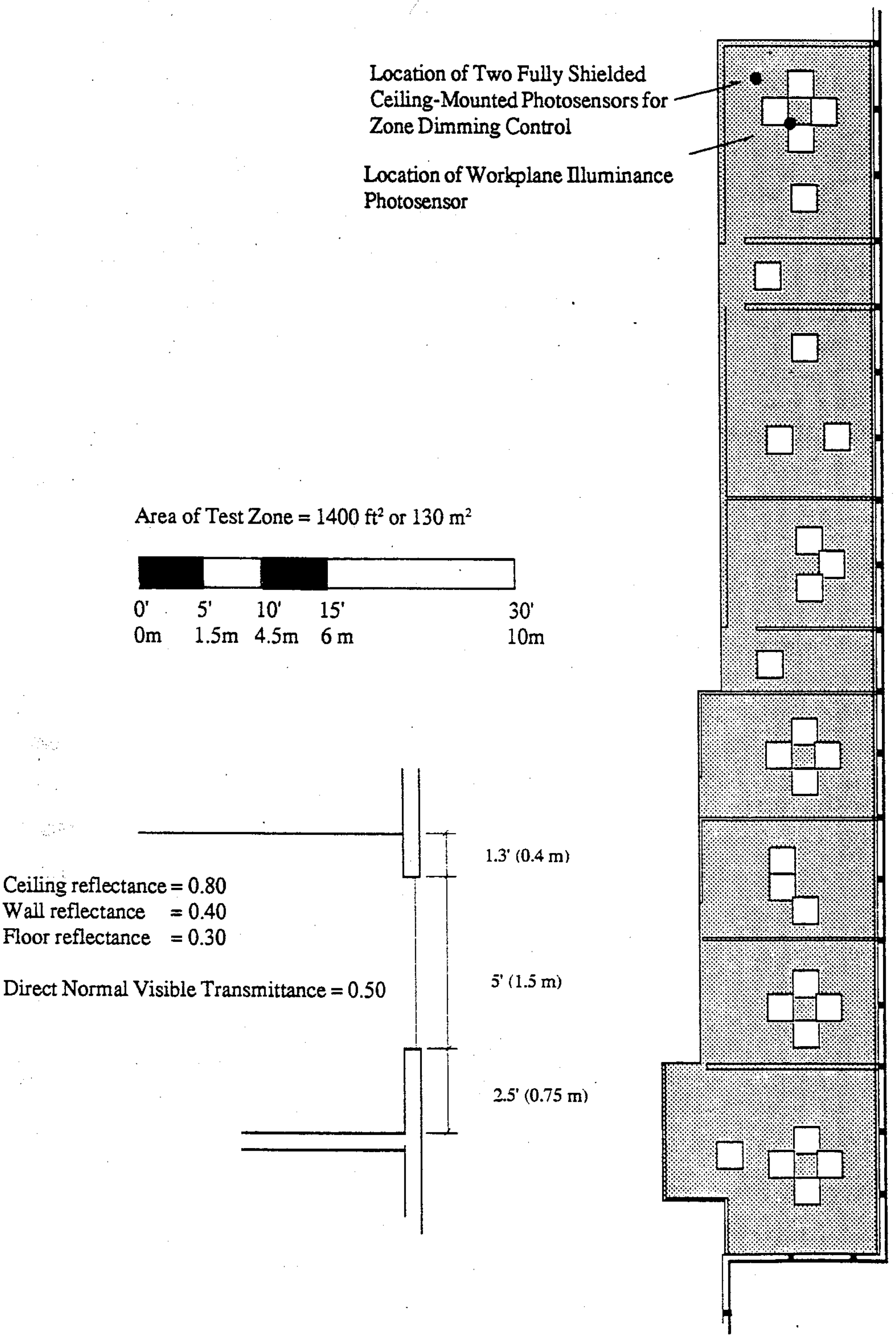
Building B is an office building that was constructed around 1985. Its gross floor area is about 24, 000 m^2 (260, 000 ft^2) on 12 floors. The perimeter to core depth is variable, due to the deep irregular plan of this atrium building. A section, showing the window height and placement, may be found in Figure 3.1. No shading devices or light shelves are used.

3.4.3 Office Building C

Building C includes two towers that was constructed around 1985. One tower has a gross floor area of about 39, 000 m^2 (420, 000 ft^2) on 42 floors, while the other has a gross floor area of about 30, 000 m^2 (320, 000 ft^2) on 32 floors. The fenestration consist of ribbon (continuous) windows. No shading devices or light shelves are used. The glazing has a direct normal visible transmittance of about 0.50.

3.4.4 Daylit High School

The school has a gross floor area of 37, 500 m^2 (390, 000 ft^2) and a capacity of about 1200 students. It opened in the fall of 1991. The staggered section of the school and the opening to the upper floor allows daylight to penetrate areas of the school further from the edge of the building's "footprint." Most of the spaces in the school are well-illuminated by daylight during much of the day.


Location of Two Fully Shielded Ceiling-Mounted Photosensors for Zone Dimming Control

Location of Workplane Illuminance Photosensor

Area of Test Zone = 1400 ft² or 130 m²

Ceiling reflectance = 0.80
Wall reflectance = 0.40
Floor reflectance = 0.30

Direct Normal Visible Transmittance = 0.50

Figure 3.1 - Plan and Window Wall Section of the 5th Floor East-Facing Test Zone at Building B.

3.5 Instrumentation and Data Collection Procedures

3.5.1 Lighting power demand

Lighting power demand was measured at Office Building A using a Dranitz measurement system supplied and installed by the City of Calgary Electric System. The Dranitz system also allows voltages, currents, and power factors to be determined. Because it is a single channel system, only one circuit could be measured at a time. As well, the minimum measurement interval is 5 minutes for the system that was available.

A Synergistic C180 measurement system was acquired by the researcher. It can monitor up to 10 circuits simultaneously, providing current, voltage, power, and power factor values. Measurement intervals can be less than a minute. The instrument obtained was used at Building B, where the lighting for one test zone was on two circuits and the lighting for the other test zone was on a single circuit. At the 2-minute measurement interval used, the device could store data for 10 days for the three circuits of interest. The data was retrieved by uploading to a portable personal computer. The system is designed so that the data can be stored to computer in a common spreadsheet format.

3.5.2 Illuminances, temperatures, air flows

The Doric Digitrend 245A data logger, with 16-bit analogue-to-digital converters and high sensitivity (1 μV), was used in the building performance studies. This allowed for a very wide range of light levels to be measured (2 lux to 120,000 lux, the range from a very dark area to direct sunlight); 12-bit analogue-to-digital converters cannot cover such a wide range. This eliminated the need to use amplifiers with photocells, which can introduce nonlinearities, or different ranges, which can complicate immediate identification of light measurement errors. The Doric is operated under the supervision of an IBM-compatible personal computer and can monitor up to 100 channels at intervals of as little as 2 seconds by adding "front end modules" to which 20 channels can be connected (this capacity can be further extended by the use of "satellites"). It includes built-in functions for measuring many parameters including voltages and temperatures from thermocouples and other sensors. Used in combination with *The Fix* data logging and control software (supplied by Intellution), the overall system allows quick development of customized on screen real-time displays, historical trending, uploading of data in spreadsheet-compatible format, simulated multi-tasking, and other features that meet the objectives stated in the literature on monitoring protocols. The researcher had previous experience with this system, and therefore expected to reduce set up time.

The Fix requires a driver specific to the data logger being operated. Because *The Fix* had been updated, the driver supplied by the manufacturer of the Doric would no longer function. Further, this manufacturer was no longer maintaining its driver for *The Fix*. By good fortune, a Calgary engineering company that had also developed a Doric driver for *The Fix* was located. The researcher worked with the company to develop an updated driver.

Illuminances were measured using Licor L210S photometric sensors. These were connected to 560 ohm resistors to generate the voltage inputs required by the data loggers. The sensors were calibrated relative to a photometer that had been calibrated using a source traceable to the National Research Council of Canada.

Temperatures were measured using AD (Analogue Devices) 590KH integrated circuit temperature transducers. These were calibrated at two temperatures by using an ice bath and a scientific thermometer. Readouts were also compared at room temperature.

Pressure differentials at variable air volume boxes were measured using Setra pressure transducers. This choice was based on the experience of the Department of Mechanical Engineering at the University of Alberta, which had used the sensors extensively in building performance studies. The sensors were calibrated at the Department's measurement laboratory in Edmonton.

Measurements were stored at 30 second intervals and stored in a customized compressed format used by the data acquisition software. It was then transferred to common spreadsheet formats. This allowed easy exchange among application software and minimized custom programming.

3.6 Data Analysis and Results

3.6.1 Building A

Monitoring of Building A did not proceed beyond monitoring of lighting power demand and illuminances, as it was determined that the photoelectric control system was zoned so that all spaces (including those not receiving daylight) were on the dimming circuits. The dimming system was set so that minimal dimming was occurring (despite the insistence of the building managers that the lights were being dimmed substantially during the day). The intended approach had been to compare two floors of the building. Permission to carry out measurements was obtained from the owner and from the tenant occupying the third and fourth floors. These floors were selected because the tenant occupied the entire floor plate on both levels and the space use was the same (office). The local electric utility provided staff and equipment to monitor the electric usage of the lighting circuits. Electricity use data were logged at 5 minute intervals, the shortest interval allowed by the data logger.

The lighting electrical use characteristics, as measured by a recording meter with power factor measurement capabilities, are shown in Table 3.1. The large difference in lighting power loads on the 3rd and 4th floors was surprising given that the occupancy and lighting systems appeared to be the same based on a walk through inspection. The values obtained for power factors on some circuits were also suspicious. It was initially thought that the meter, which had recently been rewired, was giving erroneous readings (note the unusual power factors). However, testing showed that it appeared to be reading correctly.

Table 3.1 - Lighting Power Demand on the 3rd and 4th Floors at Building A in June, 1991.

	Phase A		Phase B		Phase C		Total	
Floor	kW	P.F.	kW	P.F.	kW	P.F.	kW	P.F.
3rd	7	0.83	1	-0.19	12	0.68	20	0.86
4th	6	-0.62	10	-0.90	16	0.92	32	-0.98

A hand-held meter was used to compare electric current (since all line voltages are about 340) on the 3rd, 4th, 11th, and 12th floors (see Table 3.2). It is evident that the phases were unevenly loaded, and that the 3rd floor appears to have a significantly different lighting power demand from the 4th floor.

Table 3.2 - Lighting Electricity Use on Selected Floors at Building A in June, 1991 (347 volt circuits).

	Current (amps)		
Floor	Phase A	Phase B	Phase C
3rd	20	17	48
4th	28	36	55
11th	28	28	32
12th	27	25	41

Lighting power demand was plotted against daylight availability for June 21, 1991, a day when there were substantial variations in sky luminance (see Figures 3.2 and 3.3). It is evident that there does not appear to be any relationship between lighting power demand and daylight availability.

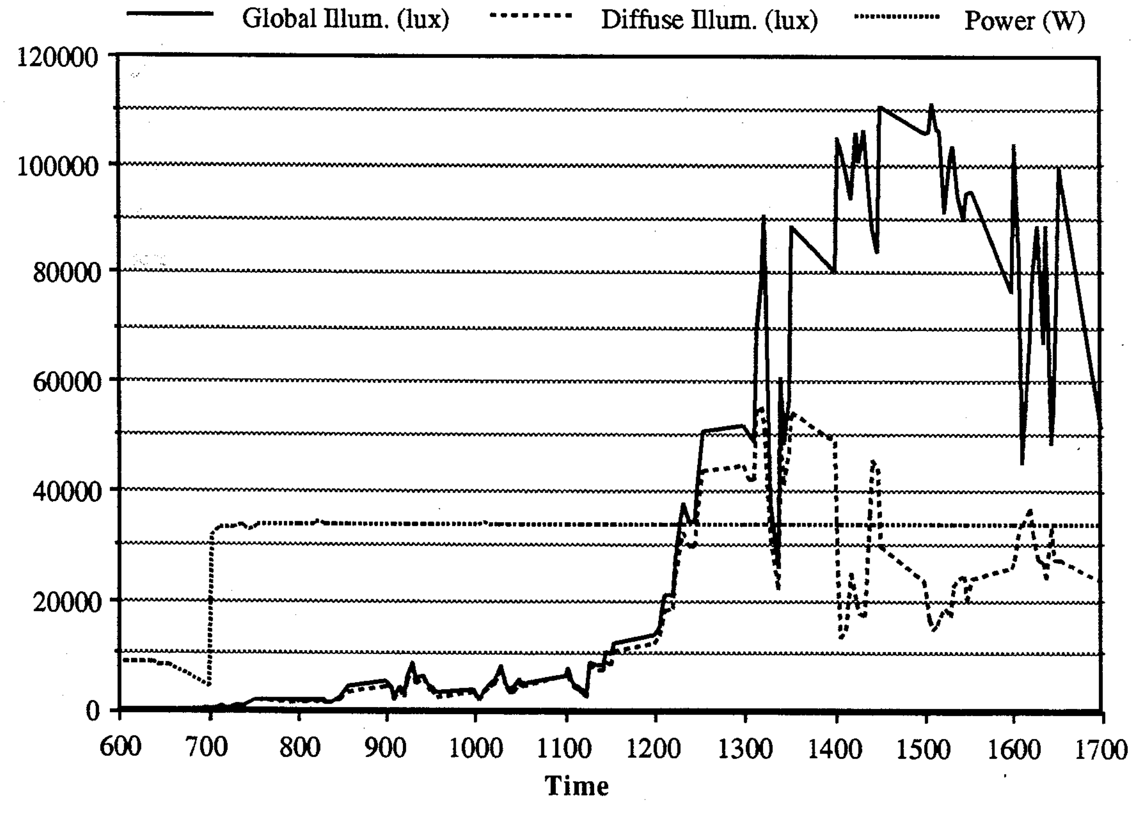


Figure 3.2 - Daylight Availability and Lighting Electric Power Demand (3rd Floor) at Building A on June 21, 1991

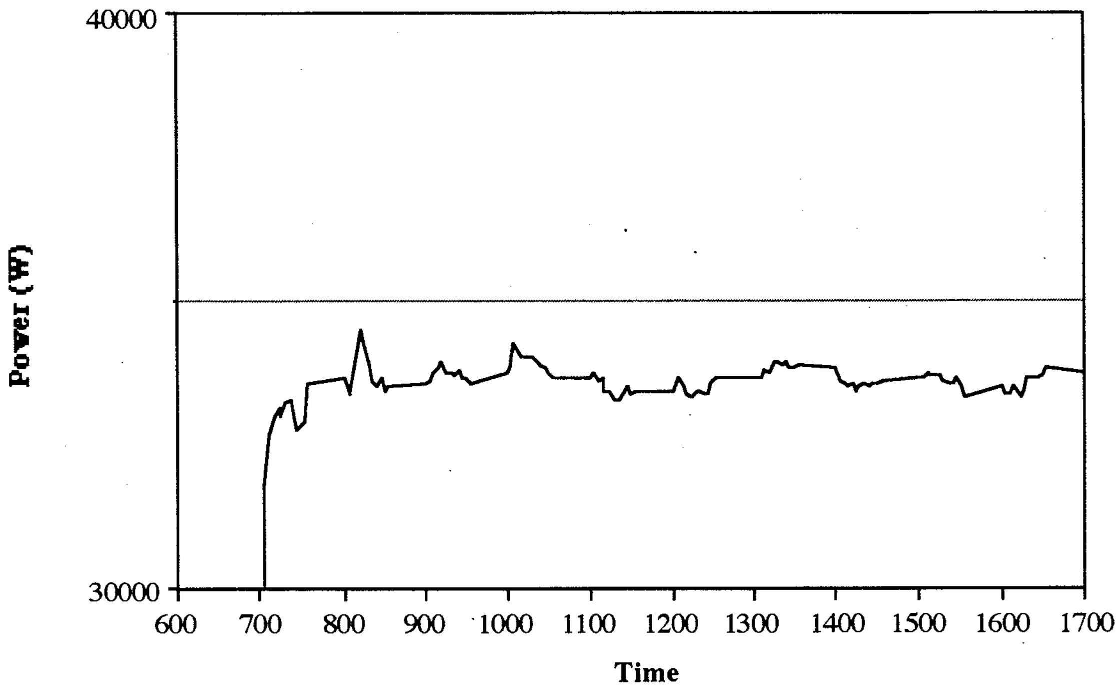


Figure 3.3 - Detail of Lighting Electric Power Demand at Test Building A (3rd Floor) on June 21, 1991

Enquiries were directed through the building operator to the company maintaining the lighting control system. He reported that each floor was divided into three zones for lighting, all of which were subject to photo-electrically controlled dimming. These zones extended from the perimeter to the core, so that spaces receiving little or no daylight were on the same dimming circuit as perimeter offices. The degree of dimming had been reduced to a negligible level in order to avoid "blacking out" users at the core of the building.

The daylight factor at the center of the test cell (3.6 m from the window wall) was 1.1 percent, representing an illuminance of only 110 lx with a global illuminance of 10, 000 lx. A significant factor in the low daylight levels was the glazing, with a direct normal transmittance that was determined by measurement to be only 0.48. The daylight factors 1.6 m (5 ft) and 5.2 m (17 ft) from the window wall (the MAX and MID positions [29]) were 5.2 and 0.4 percent respectively, so the uniformity of illumination provided by daylighting was poor.

Daylighting concepts were poorly applied in the photo-electrically controlled dimming system at Building A in that 1) the perimeter and core lighting were not on separate zones and 2) the fenestration and glazing choices resulted in relatively low interior daylight levels.

Assuming 3750 hours of occupancy and using the aggregate 20 kW demand measured for the 3rd floor of Building A, the annual energy use for lighting at Building A would be 35 kWh/m^2. Values determined by other researchers were 20 kWh/m^2 for a building in the San Francisco area [10] and 11 kWh/m^2 for a building in the United Kingdom [9] (both office buildings with fenestration incorporating light shelves and other special daylighting features). An independent audit by a government energy conservation office estimated annual light use at 120 kWh/m^2. The discrepancies in lighting system performance measurements and estimates were not investigated further because the photo-electrically controlled dimming system was not making any difference to performance.

3.6.2 Building B

Permission to carry out measurements was obtained from the owner-tenant, an organization occupying the entire structure. The building is divided into a large number of zones for lighting control, the smallest being about 140 m^2. The building operator had deactivated the photo-electrically controlled dimming system throughout the building, but agreed to reactivate it in one exterior zone (on the 5th floor) for the purposes of this study.

The plan of the 5th floor test zone selected for study is shown in Figure 3.1. The zone faces due east and has an unobstructed view of the sky. The upper 0.3 m of partitions is glazed to allow for light transfer between offices. The building core is 13 m from the window wall in this part of the building. A 6th floor zone immediately above the 5th floor test zone, identical in area and lighting power demand, was made available for comparison testing. The occupancy of the test zones (administrative offices) did not change during the study. Each zone accommodates 7 or 8 employees, mainly in individual offices. The installed lighting power demand is about 3.2 kW for each of the test zones, or about 23 W/m^2.

The glazing has a direct normal visible transmittance of about 0.50. Offices are provided with venetian blinds for additional glare control. The two photo-electric cells that control the dimming system in the 5th floor test zone are located in the office of the supervisor of facilities for the organization. They are mounted in cylindrical shields so that they act as small luminance probes. They are located at the same point in the ceiling, but one is aimed at horizontal surfaces near the window and the other at horizontal surfaces near the interior wall.

A photocell was placed 2 m (7 ft) from the window at the rear edge of the desk in the office of the supervisor mentioned above, which faced parallel to the window wall (see Figure 3.1). This photocell was the only physical intrusion in the test zones. The data loggers were placed in an electrical room, so as to be unobtrusive. Measurements were recorded at 30 second intervals.

The supervisor, who asked whether he should set the window blind in any particular position for the study, was informed that he should continue to use it as he normally would.

Figure 3.4 shows global, diffuse, and 5th floor test zone task illuminances for a clear summer day (Monday, June 22, 1992), while Figure 3.5 shows 5th floor test zone task illuminances plotted with lighting power demand (in the 5th and 6th floor test zones) for the same day. The conspicuous morning variations in task illuminance in the supervisor's office are due to intermittent obstruction of direct sunlight by the slats of the venetian blind with changes in sun position. The median electric power demand in the 5th floor test zone was 50 percent of that in the 6th (non-dimming) floor test zone between 0800 and 1000, and was 73 percent of that in the 6th floor test zone between 1400 and 1600.

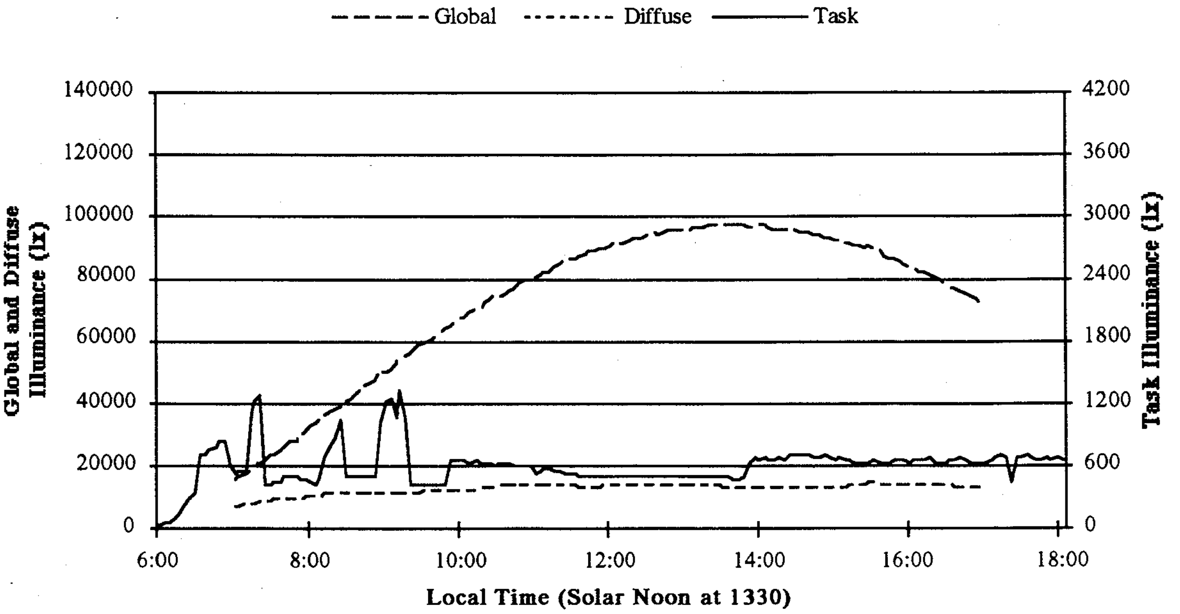


Figure 3.4 - Global, Diffuse, and Test Zone (East-Facing) Workplane Illuminances 7 ft (2 m) from the Window at Building B on Monday, June 22, 1992; Electric Lighting in Use.

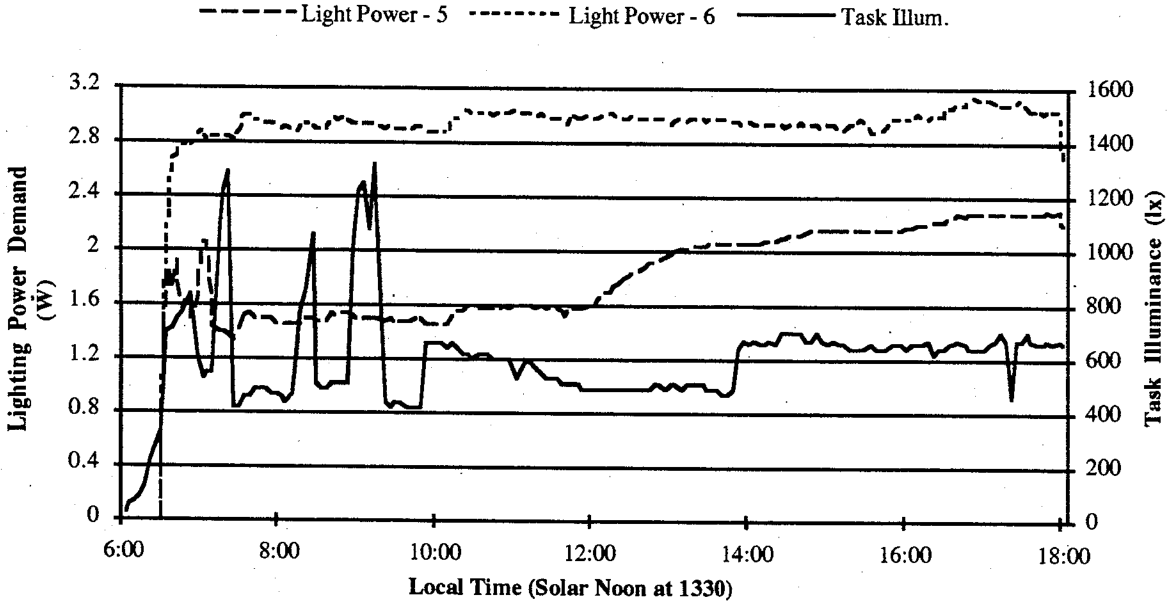


Figure 3.5 - Test Zone (East-Facing) Workplane Illuminances 7 ft (2 m) from the Window and Lighting Electric Power Demand on Monday, June 22, 1992; Electric Lighting in Use.

The lighting in the building is switched on automatically at 0600 and is reduced after 1800 unless occupants request otherwise. The standard work schedule for staff is 0800-1600 with 1200-1300 for lunch. Some staff are allowed to work flexible hours, but the organization has along history of very regimented hours of work, including the timing of coffee breaks.

Data were selected to illustrate typical patterns of illuminances and lighting power demand for a clear day. Figure 3.4 shows global, diffuse, and 5th floor test zone work plane illuminances for Monday, June 22, 1992 (a normal work day during which the ceiling-recessed dimming fluorescent systems providing general space illumination were in use), while Figure 3.5 shows 5th floor test zone work plane illuminances plotted with lighting power demand (in the 5th and 6th floor test zones) for the same day. The conspicuous morning variations in task illuminance in the supervisor's office are due to intermittent obstruction of direct sunlight by the slats of the venetian blind with changes in sun position. This contradicts Rubenstein, Ward, and Verdeber's assertion that "in any realistic building application, direct sunlight would be excluded by appropriate window treatment" [30]. The performance of the system in Building B was even poorer in terms of maintaining illuminances near the design target than the results they reported for a fully-shielded sensor and integral reset control, despite the use of dual fully-shielded photosensors. The work plane illuminance dropped to about 35 percent below the target illuminance before solar noon, and was 20 percent or more below the target illuminance for more than half the time before solar noon (measured 7 ft or 2 m from the window wall in an office 14 ft or 4.5 m deep). Because solar noon did not occur until 1330, direct sunlight was striking the facade of the test zone until that time. One of the two fully-shielded controlling photosensors was aimed near the window area. Thus, it would have received light reflected from those surfaces, as the blind slats were in a near horizontal position.

Apart from maintaining a specified minimum illuminance, dimming system are used to take advantage of available daylighting. The effectiveness of daylighting utilization will depend on interior reflectances, glazing transmittance and fenestration design (e.g., shading), and the performance of the lighting control system. For a clear summer day (Figure 3.5), the median electric power demand in the 5th floor test zone (with dimming activated) was 50 percent of that in the 6th (non-dimming) floor test zone between 0800 and 1000, and was 73 percent of that in the 6th floor test zone between 1400 and 1600. Rubenstein, Ward, and Verdeber did not report the effects of dimming on lighting power demand. They did show daylight as providing illuminances of about 400 lx (10 ft from the window wall in the small office described in the preceding paragraph) before solar noon during a clear summer day (with blind slats in a horizontal position) [31]. To quantify the daylight component of work plane illuminances, the blinds in the supervisor's office were raised over several weekends. Due to weekend use of the test zone, the electric lights were frequently switched on during Saturdays and Sundays. On Sunday, July 12, 1992, the electric lighting was not in use in the test zone. Figure 3.6 shows global, diffuse, and task illuminances. As is evident from the global and diffuse illuminances, the sky was clear in the morning and partly cloudy in the afternoon. The task illuminance (7 ft from the window wall) peaked at about 3600 lx in the morning with direct sunlight falling on the photocell (the dip near 0800 is due to obstruction of sunlight by a window mullion). The median task illuminance between 1400 and 1600 was 140 lx (solar noon occurred at 1330), about one-third the levels measured 30 percent further from the window by Rubenstein, Ward and Verdeber under comparable sky conditions (no sunlight on the facade) during their model studies, even though the model had a venetian blind on the window [32]. As in the case of Building A, the low transmittance glazing and low interior reflectances reduced the contribution of daylight to task illuminance.

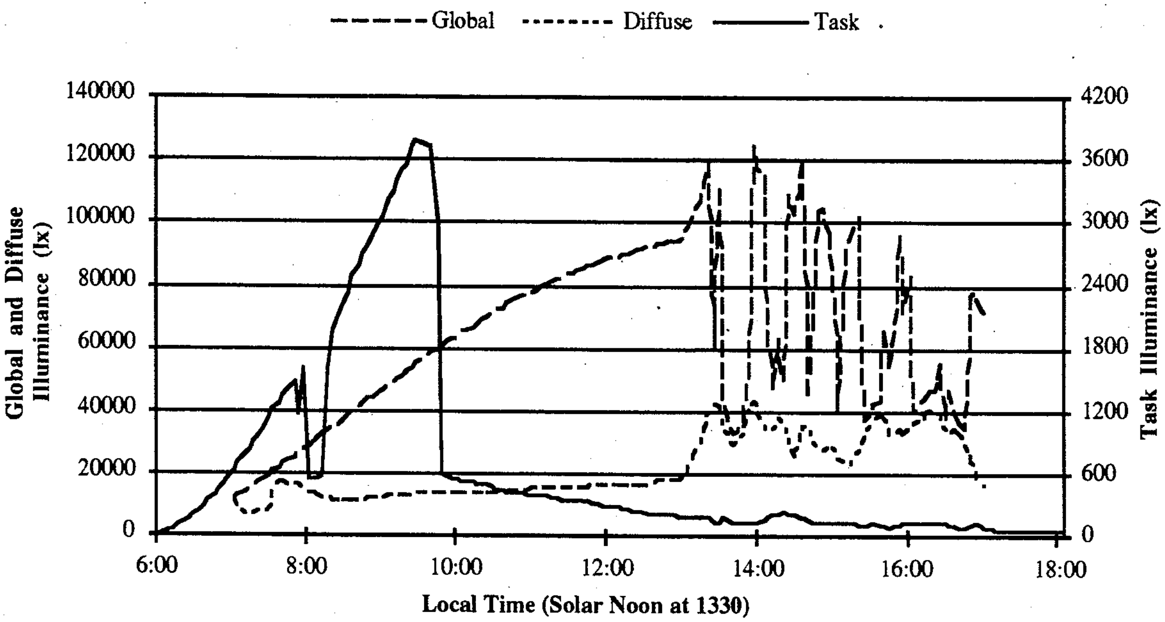


Figure 3.6 - Global, Diffuse, and Test Zone Workplane Illuminances 7 ft (2 m) from the Window at Building B on Sunday, July 12, 1992; Electric Lighting Not in Use.

A review of the data for June 22 and July 12 showed that the percentage reduction in lighting power demand was greater than the percentage contribution of daylighting to workplane illumination. On June 22, the median task illuminance between 1400 and 1600 was about 660 lx (Figure 3.5). Daylight could have accounted for no more than 21 percent of this 660 lx, given that median task illuminance on July 12, with the blinds up, was about 140 lx during this period (Figure 3.6). The fraction of lighting power demand reduction in the dimming zone (about 27 percent) is greater than the fractional daylight contribution to task illuminance. Rubenstein, Ward, and Verdeber did find considerable scatter in workplane illuminances relative to photosensor illuminances for fully-shielded photosensors.[20]

Sky conditions had a noticeable effect on lighting power demand in the test zone (Table 3.3). On clear days (June 19 and 22), the median power demand before solar noon was 30 percent less than that for a fully overcast day (June 5). Median lighting power demand lay between these extremes for partly cloudy days. When the test zone did not receive direct sunlight, sky conditions made little difference in the lighting power demand.

Table 3.3 - Lighting Power Demand for the 5th Floor Test Zone at Building B on Selected Days in June, 1992; Dimming System Activated.

Date	Before Solar Noon		After Solar Noon	
	Lighting Power Demand (kW)	Cloud Cover (in 10ths)	Lighting Power Demand (kW)	Cloud Cover (in 10ths)
Jun. 1	1.7	7	2.0	10
Jun. 2	1.9	9	2.1	not avail.
Jun. 3	1.9	8	2.0	not avail.
Jun. 5	2.2	10	2.0	8
Jun. 9	1.9	6	1.9	8
Jun. 19	1.5	0	2.0	0
Jun. 22	1.5	0	2.0	0

The power factors for the lighting circuits in this building were about 0.97, unlike the unusual results that were obtained for Building A.

Annual lighting energy use for the test zone without dimming would be 86 kWh/m^2 (8 kWh/ft^2), based on the installed lighting power demand and annual operation of 3750 hours. On June 22, the reductions in lighting power demand with the dimming system switched on were about 50 percent in the morning and 25 percent in the afternoon, or about 38 percent overall. The annual electrical use would be about 54 kWh/m^2 (5 kWh/ft^2) assuming this performance is typical. This is well above the 20 kWh/m^2 (1.9 kWh/ft^2) and 9 kWh/m^2 (0.9 kWh/ft^2) for the buildings with specially design fenestration that were reported in the literature. About 40 percent of Building B's floor area (9000 m^2 of office space) lies within 5 m of the window wall and could exploit daylight through photo-electrically controlled dimming.

One noteworthy benefit attributed to the lighting system is that the lamps have operated for 9 years, or over 30,000 hours with very few failures.

The system in Building B is better designed than that in Building A in that the zones with photo-electrically controlled dimming are within 16 ft (5 m) of the window wall, and are much smaller.

As in the case of Building A, the fenestration and glazing choices resulted in relatively low interior daylight levels.

The building operator gave a number of reasons for deactivating the photo-electrically controlled dimming system. The south side of the building is shaded by an apartment tower. At times, offices in which the controlling sensors are located receive high levels of daylight while other offices in the same control zone are in shadow. Occupants of the offices in shadow are reported to have complained about inadequate illumination, presumably due to the lights being dimmed when they are receiving relatively low levels of daylight. Another issue raised was the differential brightness of lamps where the dimming zones and interior zones are in close proximity (recall that the office partitions are glazed at the top to enhance light transfer, which also allows viewing of ceiling areas in adjacent offices). The operator reported that occupants complain, believing that something is wrong with the lighting systems. The operator also stated that he believed that the savings in cost and energy due to the dimming system were insignificant, and not worth the complaints provoked by operating the dimming system. The operator is a former employee of the company that installed the lighting control system, and was involved in the installation in the building for which he is now responsible. His position is that the concept of photoelectric control is a good one, but that it has been insufficiently developed.

Hourly cooling load data for Building B were divided according to the following criteria: 1) hours between 0900 and 1200, when the test zones (which face due east) receive direct sunlight, 2) hours between 1300 and 1600, when the test zones do not receive direct sunlight, 3) hours with the 5th floor light dimming system in operation, and 4) hours with the 5th floor lighting dimming system switched off. The hours selected were those when the normal complement of employees would be at their workstations (the organization follows a fairly rigid schedule). The first hour of normal office hours (0800-0900) was not included, in order to avoid any transient start-up effects. Lunch hours (1200-1300) were also omitted, due to occupancy fluctuations. Results are shown in Table 3.4.

Table 3.4 - Cooling requirements for the 5th and 6th floor test zones under different sky conditions and with different lighting control conditions.

5th Floor Light	Time Period	No. of hrs in Sample	Median Cooling (Watts) ± Median Absolute Deviation 5th Floor Test Zone	6th Floor Test Zone	Comment
ON	0900-1200	47	5800 ± 1200	4600 ± 1400	with sun
ON	1300-1600	47	4500 ± 400	3600 ± 1400	no sun
OFF	0900-1200	65	3600 ± 500	3600 ± 1100	with sun
OFF	1300-1600	65	3900 ± 400	2900 ± 1000	no sun

Contrary to expectations, the 5th floor cooling usage was greater after the dimming system was switched off. This may be due to differences in occupancy. The dimming system was switched off on June 23, so summer holidays may have affected usage. Regression analysis showed that no more than one-third of variations in cooling were attributable to variations in outside air temperature for either the morning or afternoon periods. Apart from occupancy, outside air temperature, and solar gain, causes of variations in cooling loads could be thermal exchanges with the interior and plenum zones and wind effects.

Because building air-handling systems at Building B are operated on Saturdays and Sundays to "flush" the building and maintain air quality, these days offered the possibility of studying cooling demands with lights switched off. Data for weekend periods were examined to identify days when the lighting systems were not in use (they are switched on for employees working on the weekend). It turned out that lights were in use most weekends. However, on July 4 and 5, the lights were off in both the 5th and 6th floor test zones, except for 0900-1100 on the 6th floor on July 5.

Data for July 4 and 5 were examined to determine the relative cooling requirements of the 5th and 6th floor test zones unoccupied and with lights off, but with the air-handling systems running. On July 4, under overcast sky until 1400 and partly cloudy sky for the rest of the day, performance of the two zones was almost identical (Figure 3.7). On July 5, under mainly sunny sky, the cooling for the 5th floor zone greatly exceeds that for the 6th floor after 1200 (Figure 3.8). A possible explanation was differential solar effects between the two east-facing test zones, although they have almost identical solar exposures (this could happen, for instance, if a thermosat in one of the zones was sitting in direct sunlight).

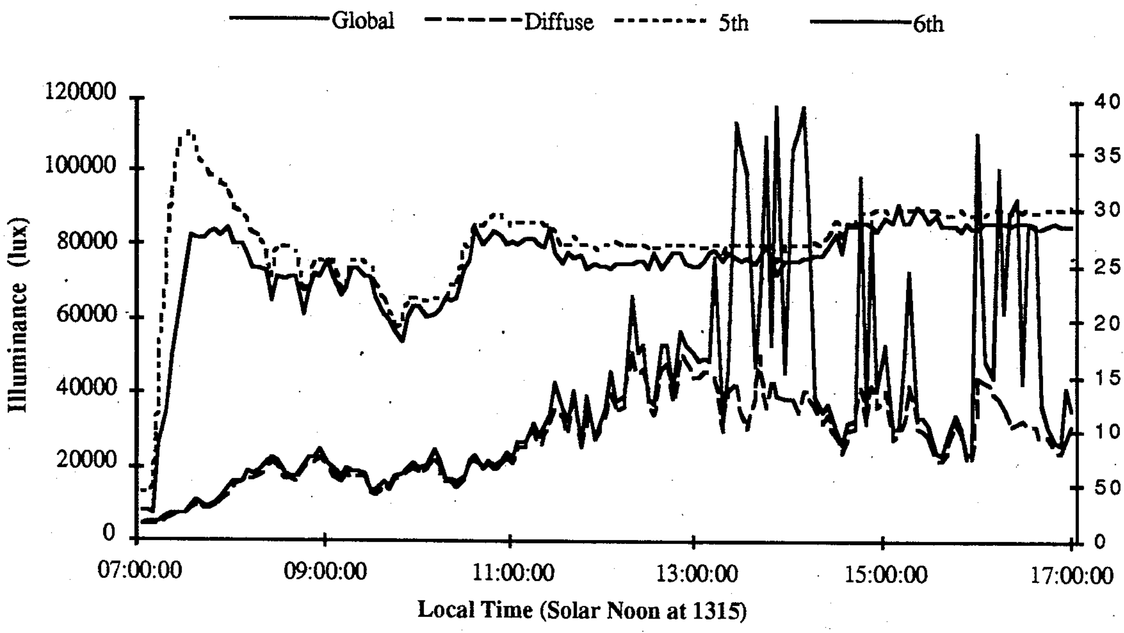


Figure 3.7 - Daylight Availability and Cooling Supplied to the 5th and 6th Floor test zones on Saturday, July 4, 1992 (lights off except for 0900-1100 for 6th).

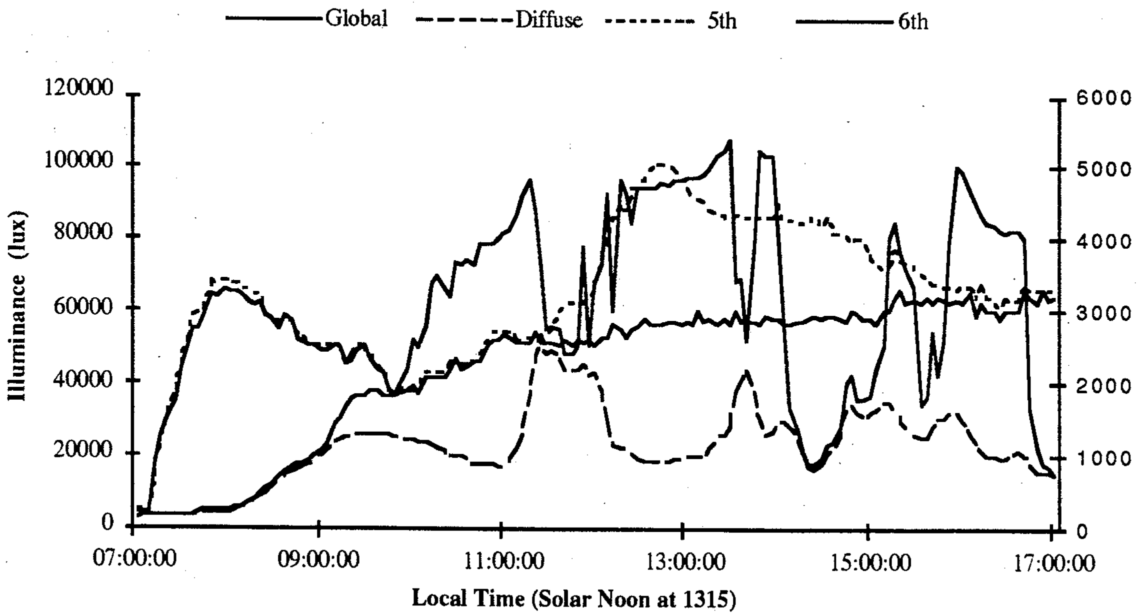


Figure 3.8 - Daylight Availability and Cooling Supplied to the 5th and 6th Floor test zones on Sunday, July 5, 1992 (lights off).

However, a review of data for other sunny weekend days shows that, even with the lights on, the cooling supplied to the two zones is very similar. It appears that either human behaviour or equipment use in the 5th floor test zone is substantially increasing the cooling supplied beyond that in the 6th floor test zone.

The differential cooling requirements of the 5th and 6th floors when unoccupied shows the importance of establishing base performance with test spaces vacant, and with office equipment and lights off if possible, although this can be difficult to accomplish in a working environment (i.e., even on weekends, the organization may need to use its spaces). This is a point that was not made in the literature on evaluation protocols.

Further studies will be conducted during the 1993 cooling season to identify the factor(s) contributing to the extra cooling requirements in the 5th floor test zone. If these can be eliminated, or a correction factor determined, then it will be possible to provide a suitably controlled assessment of the cooling effects of the dimming system.

Another noteworthy point is that, even with the spaces unoccupied and the lights switched off, the cooling requirements for the test zones are about 2500-3000 watts. The requirement for the 6th floor test zone without incident sunlight was 2900-3600 watts, so the amount attributable to lights, occupants, and equipment is about 500 watts. The power demand from equipment was estimated at 1300 watts (based on name plate ratings and actual demands indicated by the National Research Council of Canada [33]). The heat generated by occupants is about 500 watts (70 watts sensible gain for 7 occupants). The peak lighting power demand was about 3000 watts. It would appear that little of the heat from lights is ending up in the test space (i.e., much of it must be discharged into the plenum).

3.6.3 Building C

No measurements were made at this building, but the operator was interviewed. The operator reported that the dimming system had been deactivated. The primary reasons were 1) that division of the lighting system into a dimming perimeter zone and a non-dimming interior zone caused interior design and renovation problems (i.e., some spaces overlap dimming and non-dimming zones, so that lamps in the same space may differ in appearance) and 2) a belief that cost and energy savings could be better realized by use of more energy efficient systems in both perimeter and interior areas of the building.

3.6.4 Daylit High School

Figures 3.9 and 3.10 show energy use at seven Calgary High Schools, one of which was designed to exploit daylighting. The total annual energy use for the daylit school is close to the median for the other schools (Figure 3.7). However, the fraction that is electrical is higher, resulting in higher costs because electricity is a more expensive form of energy (Figure 3.8). There is a great potential for energy use reductions at the school because, although illumination levels are high enough that electrical lighting could be switched off much of the time, observations over a number of visits indicate that this is not the practice (no automatic controls are used). Similar results were found for the September-February portion of the second year of operation.

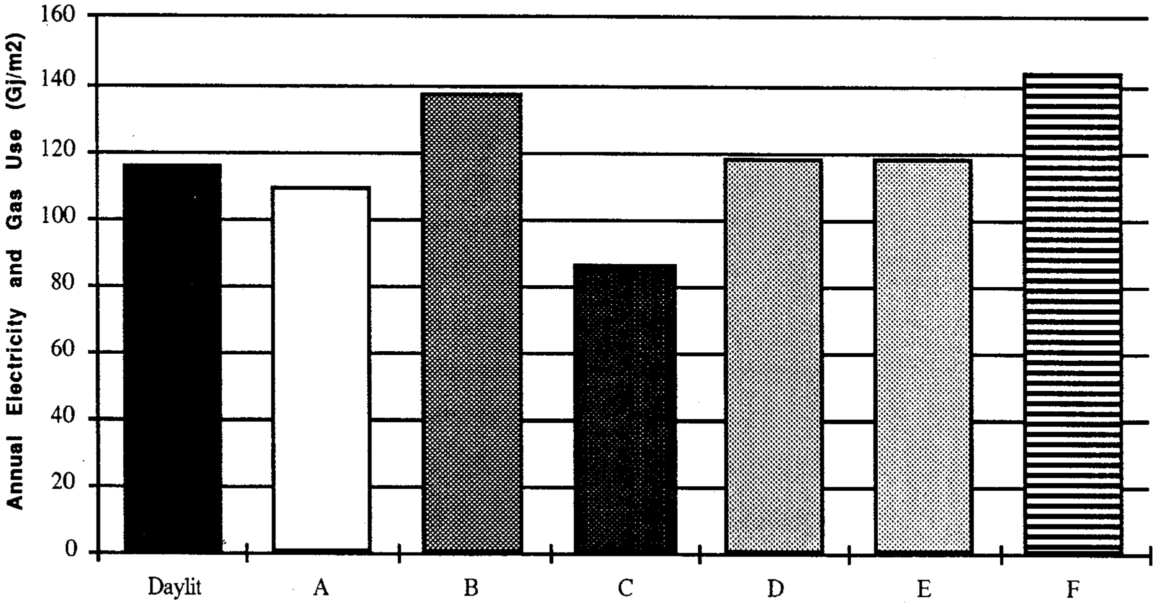


Figure 3.9 - Annual Energy Use at a Daylit High School Compared with that at Six High Schools without Special Daylighting Features.

Cooling may account for some of the higher electricity use. The school includes large areas of south-facing view glazing that is not protected by shading, which results in high levels of heat gain. This can be seen from the monthly electrical use profile for the school, which increases during the warmer months when electricity use is declining at most of the other schools (Figure 3.8). The higher cooling load is offset by a lower heating load, resulting in the near-median overall energy use. Shading can be designed in such a way that it does not interfere with daylighting; in fact, shading can be designed to enhance daylighting, so the school could have been designed for lower cooling loads while retaining the essential daylighting features.

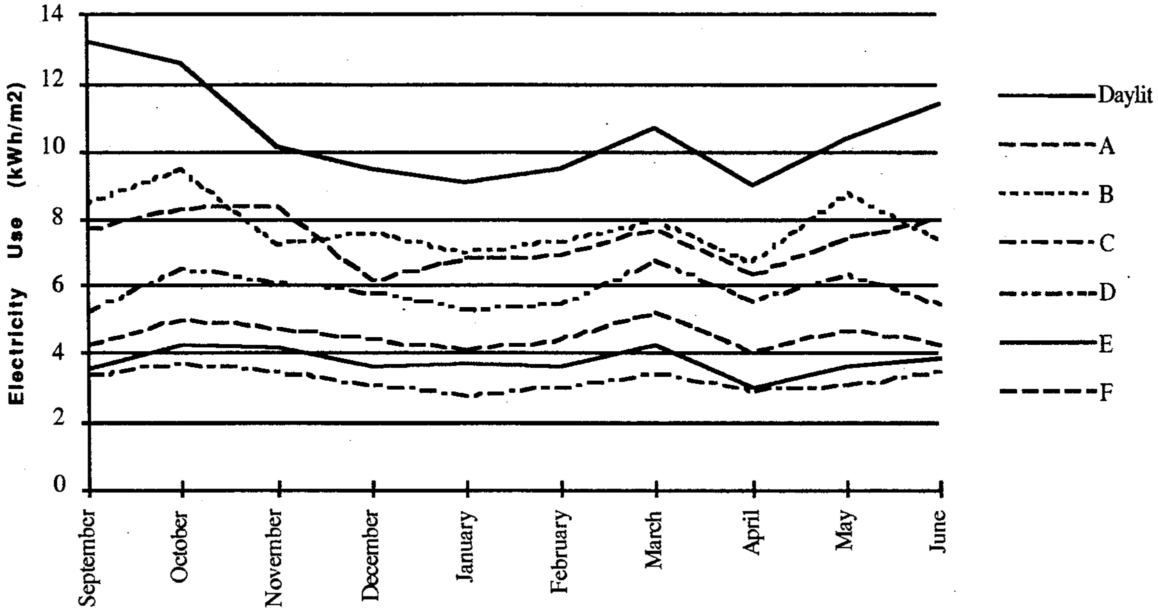


Figure 3.10 - Monthly Electricity Use at a Daylit High School Compared with that at Six High Schools without Special Daylighting Features.

Figure 3.11 shows daily electricity use plotted for each month of the 1991-92 school year. The chart shows that, while variations of 100 percent can occur between one month and another, the day-to-day variation is slight.

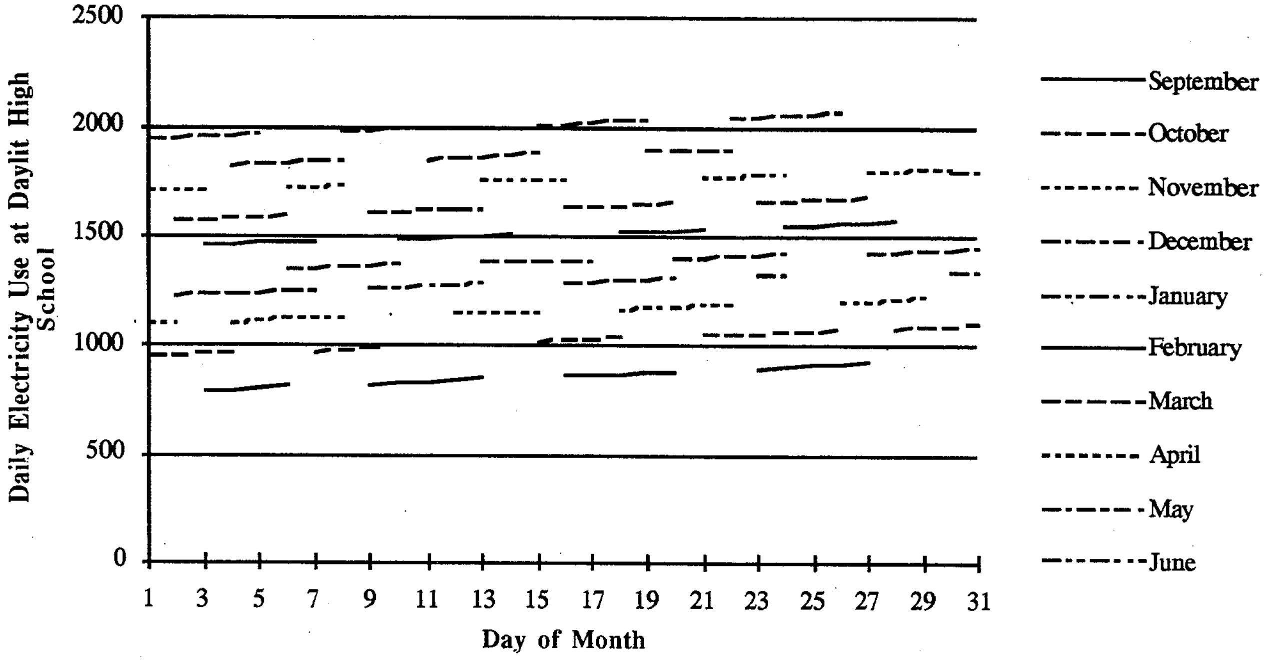


Figure 3.11 - Daily Electricity Use at a Daylit High School in Calgary for the 1991-92 School Year.

4.0 FIELD PERFORMANCE OF DESIGN TOOLS

In this part of the study, measured data was used to assess the performance of physical models and a computer simulation program in estimating the performance of daylighting systems. A method for obtaining reproducible values of the daylight factor, the daylighting performance indicator that has the longest history of use.

4.1 The Issues

4.1.1 Comparative assessment of full-scale and model photometry

In a preceding study [18], workplane illuminance measurements in scale models were compared with corresponding illuminance measurements in full-scale spaces. The accuracy of model estimates was determined for a south-facing space with five different window types (Figure 4.1). While model estimates of the sky component were generally within about 10 percent of those obtained for the full-scale space, model estimates of the internally reflected component differed by 30-50 percent from those obtained for the full-scale space under both overcast and clear skies. Except for the window with tilted venetian blinds, the model estimates of the reflected component exceeded those for the full-scale space. In the case of clear skies, the discrepancies were found to vary substantially with sun position, although, at the time of year the testing was conducted, direct sunlight did not strike any of the photocells.

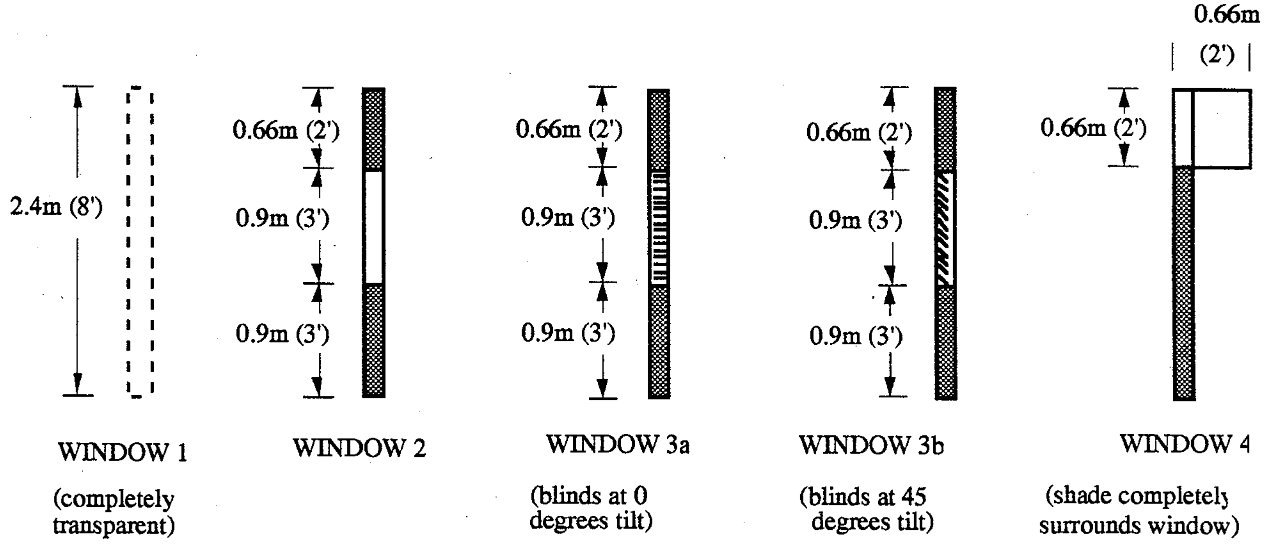


Figure 4.1 - Sections of the test windows used in the preceding study of daylighting estimation methods.

The studies described here were undertaken to better understand the over-estimates of the internally reflected component under both clear skies with sun and overcast skies.

4.1.2 Determination of the daylight factor under real overcast skies

Although the daylight factor has been the dominant and virtually unchallenged performance indicator in daylighting system design for almost 100 years [34-35], its determination by measurement has received remarkably little attention.

The daylight factor is defined as "the ratio of the daylight illumination at a given point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky. Direct sunlight is excluded for both interior and exterior values of illumination" [36]. Usually, the daylight factor is determined for the workplane, a hypothetical horizontal plane taken to be 30 in (75 cm) above the floor [37]. The definition of the daylight factor is then:

$$\text{Daylight Factor} = E_{IH} / E_{lg} \tag{4.1}$$

where E_{IH} is the illuminance on the workplane

E_{lg} is the illuminance on a horizontal outdoor surface with an unobstructed view of the sky (the global illuminance) [38]

The daylight factor was introduced so that the degree of illumination provided by alternative daylighting systems could be compared independently of fluctuations in outdoor illumination. The principle is that while the luminance of the overcast sky may increase or decrease over time, the luminance distribution of the sky vault will remain constant, as will the resulting pattern of illuminances in a daylit space.

The daylight factor has been used extensively in research and in building design. It has been used to stipulate minimum performance in building regulations [39], the enforcement of which would require its determination by measurement. Another application requiring its determination by measurement is its use in comparing the performance of daylighting systems by full-scale and model photometry under real skies when simultaneous measurements are not feasible. These applications are dependent on reasonable reproducibility of the daylight factor when determined by photometry.

Efforts have also been made to adapt the daylight factor to clear skies. As Robbins commented in 1986 [40]:

> The daylight factor method does not apply to the clear sky condition as easily as it does to the overcast sky because interior illuminance under the clear sky depends upon solar location, whereas under the overcast sky it does not. Studies applying the daylight factor method to clear sky conditions have been conducted ever since the method was first proposed over 60 years ago. Because of the predominance of the clear sky in the United States, however, the effort has been especially great in this country to refine and extend the method's application to clear skies.

This research addressed determination of the daylight factor under overcast skies, because it is under this condition that the daylight factor should be least variable.

Because of the variability of the ratio of indoor and outdoor illuminances, even under overcast skies, the term "illuminance ratio" is used to differentiate the wide range of values obtained by measurement from the ideal reproducible value of the daylight factor for a given position.

Despite the long and widespread use of the daylight factor, procedures for its determination by measurement have received relatively little attention. Neither the IESNA nor the Commonwealth Institute of Building Services Engineers (CIBSE) specifies a procedure for determination of the daylight factor from measurements [40-41]. The CIBSE *Code for Interior Lighting* refers those interested in determination of the daylight factor by measurement to Lynes, who comments on the difficulties involved [42]:

> First it is necessary to wait for an overcast sky; one may have to wait several weeks for this even in an inclement climate. If measurements have to be made far from home one must rely upon weather forecasts and still risk a fruitless journey. Even under overcast conditions, there is no assurance that the C.I.E. standard luminance pattern will prevail so one cannot hope for readings to be accurately repeatable. Since overcast skies are associated with rain and cold the measurement of outdoor illumination can be uncomfortable for observer as well as bad for instruments. The measurement of natural illumination indoors can also present problems on an overcast day since artificial lighting is likely to be in use, so daylight readings in factories or offices must be crammed into lunch breaks or week-ends when lamps can be switched off. Outdoor illumination fluctuates from moment to moment on an overcast day . . . so indoor and outdoor readings must be taken as nearly simultaneously as possible. This implies the use of two photocells, one indoors and one outside, accompanied by long leads so that the operator can take comparison readings in rapid succession. Alternatively two operators, linked by a "walkie-talkie," can read indoor and outdoor illumination simultaneously.
>
> If the outdoor cell is to be exposed to an unobstructed sky it must be placed on the roof, assuming (and this is not always so) that the roof is both accessible and unobstructed. Petherbridge and Collins have circumvented this difficulty by measuring the luminance

> of a patch of sky at an altitude of 42 degrees above the horizon, instead of measuring the outdoor illuminance, for this is the altitude at which the luminance in foot-lamberts of the C.I.E. standard overcast sky is numerically equal to the unobstructed outdoor illumination in lumens per square foot. The outdoor luminance meter may be placed outside the window (provided, of course that it opens) and avoids the need for trailing leads from floor to roof.
>
> Clearly, the field measurement of daylight factor calls for a persevering observer, and for much patience from the occupants of the building. Even so the measured values will certainly not be accurately reproducible.

Lynes does not quantify the discrepancies that may occur in field determination of the daylight factor. A review of the literature revealed only two such attempts.

The earlier of the two studies on the determination of the daylight factor from measurements was reported by Vezey, Reed, and Evans in 1954 [43]. They investigated indoor-outdoor illuminance ratios for two full-scale daylighting systems by connecting two photocells to a strip-chart recorder. Twenty recordings of the illuminances were used to calculate the daylight factor (6 for each of two positions in one space and 8 for a test position in the second space), each test period lasting from 3 to 8 hours. The test periods were spaced over the months between the solstices. The selection of data points for study was limited by the fact that their equipment took a few seconds to stabilize after each change in sky luminance. Because the sky luminance changes continually, this created significant difficulties in obtaining usable measurements.

After selecting several sub-samples of 10 sequential readings from a set of 38 observations made in February, Vezey and his colleagues concluded that "it is not necessary to make more than ten observations at a given point to ensure sufficient accuracy in arriving at the daylight factor." They defined "sufficient accuracy" as obtaining results that agree to within 10 percent of the average for the whole data set. They did not specify the interval at which the ten observations are to be made nor did they characterize the sky conditions under which the measurements were made.

More recent (1979) long-term measurements were conducted by Tregenza [44]. He measured illuminances outdoors and in models at hourly intervals during seven periods of one to two months. Four models were oriented so that each faced a cardinal direction. Illuminances were recorded simultaneously at three points in each model. He found that more than 50 percent of indoor-outdoor illuminance ratios varied by about 50 percent from the median value under overcast skies. This amount of variation is clearly beyond the 10 percent threshold employed by Vezey, Evans, and Reed. Variations of this magnitude present grave difficulties in comparing the performance of a daylighting system with a performance standard. Use of the daylight factor to compare daylighting systems under real sky conditions is even more problematic considering the combined error in the measurements. Tregenza did not suggest any procedures for obtaining reproducible values of indoor-outdoor illuminance ratios.

The lack of tested procedures for the determination of the daylight factor by measurement of illuminances has led to the use of ad hoc procedures. For instance, Murdoch, Oliver and Reed [45] used measurement periods of 30 minutes, taking measurements of E_{lg} at the beginning, mid-point, and end of each measurement period. Measurements of interior illuminances were made between the exterior measurements. If the values of E_{lg} differed by more than 10 percent, the data set was not used for determination of the daylight factor.

The standard definition of the daylight factor is valid under overcast skies, but the specification of the overcast sky has apparently not been rigorously addressed. It has been noted by Littlefair, after an extensive review of studies of the luminous efficacy of daylight, that differences between the results of different researcher might be due to different definitions of clear and overcast skies [46]. The simplest means of determining whether a sky is overcast is by visual examination. Murdoch, Oliver and Reed (see above) introduced the further measure of the stability of E_{lg} during the measurement period. Tregenza did not indicate the basis he used for classifying a sky as overcast. Navvab, Karayel, Ne'eman and Selkowitz developed a precise definition, based on extensive measurements [47]. They concluded that "sky conditions could be defined as overcast when the direct beam irradiance is less than 20 W/m^2 and the ratio of the diffuse to global irradiance is greater than 0.67." As will be seen in the following analysis, even this definition encompasses a range of conditions under which large variations in the daylight factor can occur.

Given that determination of the daylight factor in the field continues to be of interest, and that procedures proposed to date are vague, it is worthwhile determining the accuracy of approaches that have been proposed to date and learn which of these are likely to yield results with a reasonable degree of reproducibility.

Ideally, a procedure would yield results that would be reproducible within a 10 percent range. The Illuminating Engineering Society of North America, The Commonwealth Institute of Building Services Engineers, and the German Institute for Standards (Deutsches Institut für Normung) all set a 10 percent difference as the acceptable accuracy for methods for field measurement of illuminances [48]. In the case of electric illumination, a 10 percent difference in intensity is about the minimum perceptible difference that the human eye can detect [49]. A 10 percent difference from code requirements is also typically accepted by approving authorities in determining whether many design features meet quantitatively specified requirements. Thus, a 10 percent tolerance is commonly used means for making comparative judgements of the accuracy of estimation techniques in lighting.

4.1.3 Assessment of *PWClite1*

This software was developed under the auspices of Architectural and Engineering Services, Public Works Canada. It is a spreadsheet-based (macro language) program that uses data obtained through a very large number of simulations performed using the DOE2 energy analysis program developed by Lawrence Berkeley Laboratory. It is important that computer programs, as well as physical models, be validated by using field data.

4.2 Methods and Procedures

4.2.1 Comparative assessment of full-scale and model photometry

The experimental methodology followed that used in earlier studies [18, 50-51]. The accuracy of model estimates was determined by simultaneously measuring illuminances at corresponding positions in model and full-scale spaces. Measurements in spaces with near-zero reflectance interiors provided estimates of the sky component and direct sunlight. The internally reflected component was determined by subtracting these readings from illuminances measured simultaneously in higher reflectance spaces with the same geometry and fenestration.

The dimensions of the full-scale test spaces, 2.7 by 2.7 by 7.3 m (9 by 9 by 24 ft) (h·w·d), conformed with those of the test space in the last published study [18] except that the ceilings were 0.3 m (1 ft) higher (Figure 4.2). The higher ceiling simplified fabrication, being the height of the existing suspended ceiling in the commercial building in which the test spaces were fabricated.

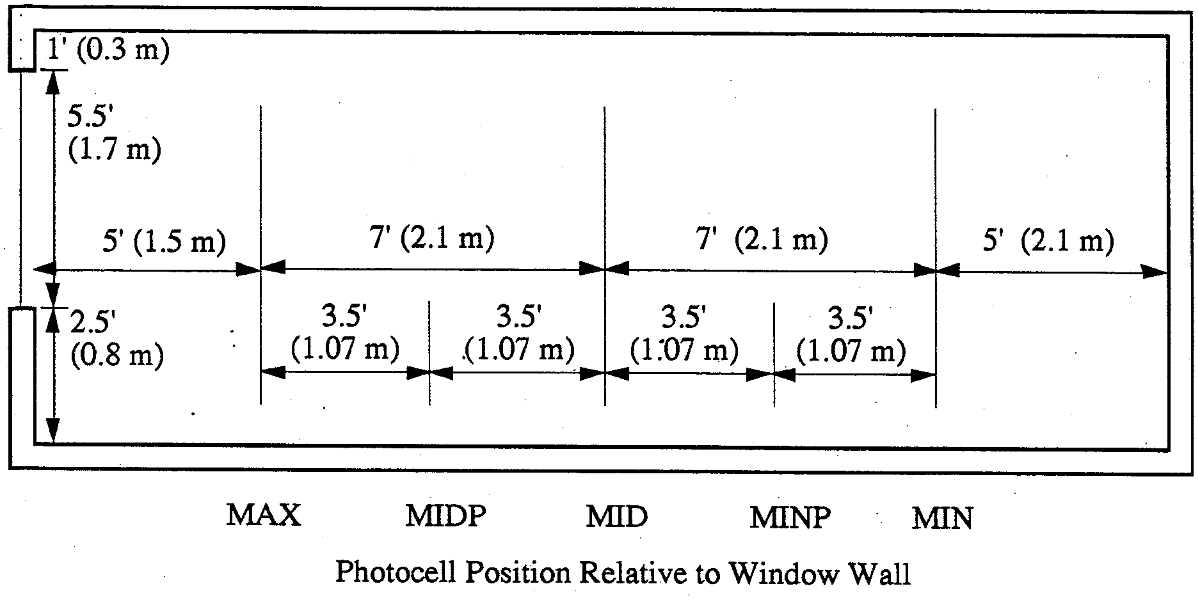


Figure 4.2 - Section of the test space, showing the placement of the sensors between the window and the rear wall.

The test spaces were located along the east facade of the fourth floor of a five-story office building in Calgary (51 degrees north latitude). This made it possible to conduct experiments with direct sunlight present in, or excluded from, the interior of the test space. The model and full-scale spaces faced the same ground plane, which had a reflectance of about 0.13. The view of the sky was free of exterior obstructions such as buildings, hills, and trees.

Location of the test spaces in a commercial building introduced additional complications to those experienced in the preceding laboratory work. The most notable of these was the substantially lower visible transmittance of the glazing, about 0.48 compared with 0.90 in the laboratory spaces. Even with high-transmittance glazing, the low light levels at the rear of the low-reflectance space had taxed the low-end measurement capabilities of the data logger used in the preceding study [18].

The window used in this study (Figure 4.2), like window 2 in the earlier study (Figure 4.1), is typical of those found in office buildings. It has an effective aperture (the product of the wall-to-window ratio and the visible transmittance) of about 0.2, compared with 0.3 for window 2. Computer simulation studies by Johnson, Sullivan, Selkowitz, Nozaki, Conner, and Arasteh showed that effective apertures of about 0.2-0.3 are optimal for daylit buildings in cold climates [52].

The window panels at this test site were only 1.2 m wide, compared with 2.7 m in the laboratory. The width of the laboratory test space was such that the test space window extended from one mullion to the next. In the full-scale test spaces fabricated in the commercial building, the windows were therefore broken by mullions. The mullions in the low- and high-reflectance spaces were not located at corresponding points because columns and partitions restricted the location of full-scale test spaces.

The full-scale spaces were created by suspending vinyl-backed canvas panels from the existing ceiling system. This provided the desired reflectances (0.05 in the low-reflectance spaces and 0.80 in the high-reflectance spaces) and an opaque enclosure. The ceiling tiles had a reflectance of about 0.80; matte black paint was used to reduce their reflectance to about 0.07 in the low-reflectance space. The remaining exposed ceiling surfaces (sprinklers, T-bar, etc.) were taped with matte black tape. Use of different floor coverings made it possible to alter the reflectance of the floors from 0.40 to 0.80.

It might be argued that the wall and ceiling reflectances used in the high-reflectance space were excessively high. However, high reflectances are important in efficiently transmitting daylight through naturally illuminated spaces. As Chauvel, Collins, Dogniaux, and Slater have shown, high reflectances near windows are also important in reducing glare in sidelit spaces [53].

The interior surfaces of the scale models were of the same materials as those used in the full-scale spaces. Both 1:12 and 1:3 scale models were used, with window mullions omitted from the 1:12 scale models to simplify construction.

Illuminances were measured at up to five positions in each of the full-scale and model spaces (Figure 2), depending on the type of data logging system being used. The photocells were placed along the centerline of the room normal to the window wall.

The spacing of the photocells between the windows and the rear walls of the test spaces was selected to correspond to the illuminance determination positions (MAX, MID, and MIN) used in the *Recommended Practice of Daylighting* [54] and to provide data for intermediate positions, labeled MIDP and MINP (Figure 4.2). Under the conditions in the preceding study [18], none of the photocells received direct sunlight. During this study, direct sunlight did strike the photocells at some times during summer mornings. The photocells received ground-reflected light only by re-reflection from interior surfaces.

Leveling of models and photocells is very important in obtaining correct readings. Errors due to tilt can be especially large at the rear of sidelit spaces. To minimize this error in the full-scale spaces, the photocells located in the rear three positions were placed in individual mounting and leveling fixtures supplied by the manufacturer to minimize this error. The photocells mounted in the model spaces were set in holes precision-drilled in the floors of the models or in custom-built holders that located the photocell surface at the workplane [55].

Illuminances (interior and exterior) were recorded at 10 s intervals using color- and cosine-corrected silicon photodiodes. The photocells were calibrated with a calibrated meter. Calibration of the photocells was spot-checked during testing, and a complete re-calibration was carried out 6 months after the initial calibration. The admissible range of input voltages was sufficient to measure illuminances of up to 130,000 lx.

Illuminance measurements had to cover a very wide range with a high degree of precision. Two types of data logging systems were used (hereafter referred to as “A” and “B”). Type A was configured to measure 40 channels simultaneously, and had greater data storage, manipulation, and display capabilities. It was limited to a nominal resolution of only 1 μv, corresponding to a 10 lx change in illumination. In practice, it was found to be capable of detecting light level changes of only about 20 lx. Type B, an 8-channel data logger, had a resolution of 0.33 μv and was found to be capable of detecting light level changes of 2 lx, allowing for greater discrimination at very low light levels. Two of these loggers were available, allowing up to 16 channels to be monitored at a time. Subsequently, a multiplexer was acquired, which allowed data to be collected for up to 38 photocells at a time.

Because the office complex in which testing was conducted included a 12-story tower to the north of the building in which the test spaces were located, the daylight availability measurement station was placed on the roof of the higher building. This provided a vantage point free of significant sky obstructions. Diffuse and global illuminances (E_{lcl} and E_{lg}) were measured with shaded and unshaded photocells. The direct component of sunlight on a horizontal plane (E_{lsh}) was calculated by subtracting measurements of the diffuse component from measurements of the global component. A correction procedure developed by LeBaron, Michalsky, and Perez [56] was used to compensate for the skylight obscured by the shadow band used to shade the diffuse illuminance photocell from direct sunlight.

4.2.2 Determination of the daylight factor under real overcast skies

Illuminance measurements were made in the full-scale test space and at the daylight availability measurement station described in subsection 4.2.1 immediately above. The illuminances obtained were used to determine the daylight factor for the space.

The floor of the test space was covered with a 0.40 reflectance fabric. The first phase of experimentation was conducted with a wall reflectance of 0.80. A second set of measurements was made with a wall reflectance of about 0.40.

Measurements were made with the photocells located at the working plane. The spacing of the photocells between the windows and the rear walls of the test spaces was selected to correspond to the illuminance determination points (MAX, MID, and MIN) used in the *Recommended Practice of Daylighting* [47] and to provide data for intermediate points (see Figure 4.2). A closer spacing was used in the rear half of the space to provide additional data at points receiving less light. The photocells received ground-reflected light only by re-reflection from interior surfaces. The ground reflectance was about 13 percent.

4.2.3 Assessment of *PWClite1*

The 5th floor test zone at Building B (see Figure 3.1) was modelled using *PWClite1*, and results of the simulation were compared with measured data.

4.3 Building and Site Descriptions

These studies were carried out in test cells in a building in the same complex as Building A. The test cell is described on page 14. The fenestration and glazing are as described for Building A on page 15.

4.4 Instrumentation and Data Collection Procedures

Daylight availability data was collected using the Doric Digitrend 245A data logger described in subsection 4.4.2. Illuminances in the low-reflectance space used in the comparisons of full-scale and model photometry were well below 20 lux in many instances due to the low transmittance of the glazing. This is the effective lower limit for the Doric logger. A Campbell Scientific 21X data logger, with a 16-bit analogue-to-digital converter and a sensitivity of 0.3 μV was found to be capable of reading illuminances, and illuminance differences, of as low as 2 lux. Therefore, the 21X logger was used in all test cell and model illuminance measurements.

The 21X has a basic capacity to measure 8 channels. A multiplexer was added so that up to 38 channels could be monitored (simultaneous measurement at 5 points in 3 high-reflectance models, a low-reflectance models, and the high- and low-reflectance full-scale required the use of 30 channels).

Licor 210S photocells were used for all lighting measurements. These were connected to 560 ohm resistors to provide the voltage inputs required by the data loggers.

Campbell Scientific supplies a *PC208* software package that allows programs to be downloaded to the logger and data uploaded. This was operated on a portable personal computer. With the system that was purchased, the memory was sufficient to store data for only 3 to 6 hours, depending on the number of channels used. The logger has very limited display capabilities, so data was transferred to personal computer on a frequent basis, and preliminary analyses were conducted immediately to assure data quality.

4.5 Data Analysis and Results

4.5.1 Comparative assessment of full-scale and model photometry

This section includes five subsections. The first discusses the measure of comparison used. The last four address: 1) discrepancies in the reflected component under clear sky with direct sun, 2) discrepancies in the reflected component under overcast skies, 3) the effects of sensor holders on model estimates under overcast skies, and 4) the effects of sensor holders on model estimates under clear skies with direct sunlight.

Method of comparison

In the earlier comparative studies [18, 50-51], estimates obtained with models were compared with full-scale values using the following formula:

$$\text{Relative Difference} = \left((\text{Val}_{FS} - \text{Val}_{M}) / \text{Val}_{FS} \right) \cdot 100\% \qquad (1)$$

where Val_{FS} was the illuminance measured at a point in the full-scale space

Val_M was the illuminance measured at a corresponding point in the model space

As was noted above, the intensity of the sky component and direct sunlight were taken to be the illuminances measured in the low-reflectance space. The reflected components were similarly compared, except that the internally reflected components were obtained by subtracting illuminances for the low-reflectance spaces from corresponding measurements for the high-reflectance spaces.

Where the sky component in the full-scale space had a value of 0 (leading to division by zero), the relative difference was taken to be 0. In the case of the type A data logger, absolute differences below 20 lx were interpreted as relative differences of 0. The type B logger allowed discrimination of absolute illuminance differences of as little as 2 lx.

Time-varying discrepancies in the reflected component under clear sky with direct sun

The first experiment was designed to reconfirm the large (30-50 percent or more) and time-varying over-estimates of the reflected component found in earlier studies under clear skies with sunlight entering the test spaces [18]. The time-series plots used to represent the results of this experiment are based on illuminances selected from the database of measurements at 240 s intervals, corresponding to a 1 degree change in sun position.

This experiment was conducted with the photocell surfaces placed just above floor level to minimize any effects caused by photocells or photocell holders. A 0.40 reflectance floor covering provided an average room reflectance of 0.70, compared with 0.80 in the preceding study. The floor reflectance is of primary importance in the first reflection of the sky component and direct sunlight during much of the time that direct sunlight enters the space. As in the earlier research, a 1:12 scale model was used.

The type A data logger allowed for simultaneous measurement at 8 positions in each of the four test spaces (two full-scale, two model). Results for the MID position are representative. A few extreme excursions of the relative differences for the sky-direct sunlight component and for the internally reflected component occurred during the measurement period (Figure 4.3). These anomalies are explained in the next paragraph. Figure 4.5 shows the relative differences after 0800 in greater detail. When direct sunlight no longer strikes the photocells, the same pattern is evident in the relative differences as was found in the earlier research. The reflected component is overestimated by about 30 to 50 percent and varies with sun position (a negative relative difference corresponds to an overestimate, since the model illuminance is subtracted from the full-scale illuminance). There does not appear to be any difference between the sky components for the model and full-scale spaces. With the sky component illuminances at 40 lx or less, a difference of 50 percent would not be distinguishable by data logging system "A." Note that the over-estimate of the reflected component recurred despite minimizing the effects of model space contents (photocells and photocell holders) and reducing the average internal reflectance.

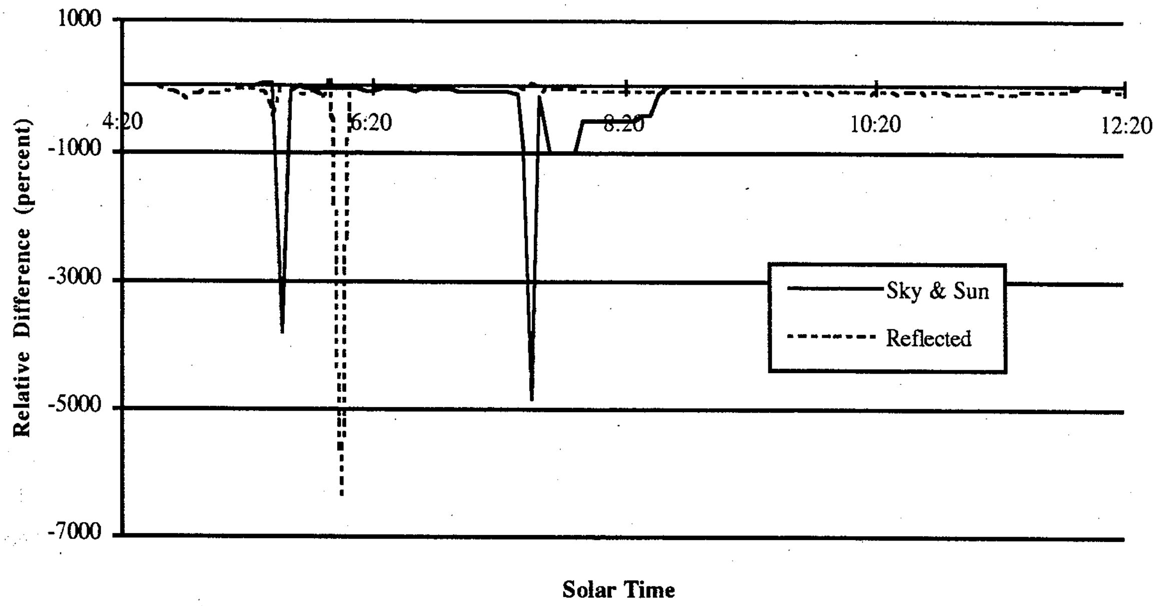


Figure 4.3 - Relative differences for the sky and internally reflected components at floor level (MID position) in 1:12 scale models; clear sky on July 23, 1991.

Figure 4.4 shows the illuminances from which the relative differences were calculated. At about 0530, the MID photocells began to receive direct sunlight, but the MID photocell in the low-reflectance full-scale space was soon shadowed by a mullion on the north side of the window. At about 0600, a mullion in the high-reflectance space briefly obstructed the photocell's view of the sun. This caused a misleading negative excursion in the reflected component determined for the full-scale space. At about 0730, there is another large excursion, as the pattern of direct sunlight moving off the photocells differed. The "shoulder" following the last peak in the low-reflectance relative difference corresponds to illuminances of 4 lx in the model and 40 lx in the full-scale space, and exemplifies some of the difficulties occurring in measurement of relatively low illuminances with the type A data logger. Data for the afternoon is not shown because the sky component under clear sky without sun was at the low-end measurement limit of the data logger.

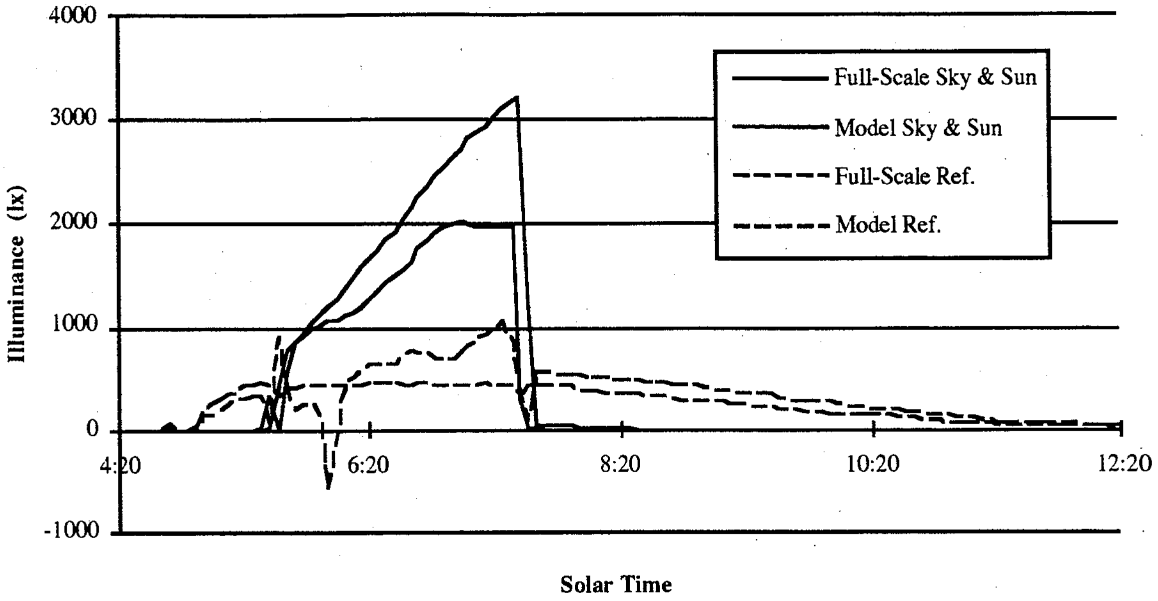


Figure 4.4 - The sky component and the internally reflected component of daylight at floor level (MID position) in 1:12 scale models; clear sky on July 23, 1991.

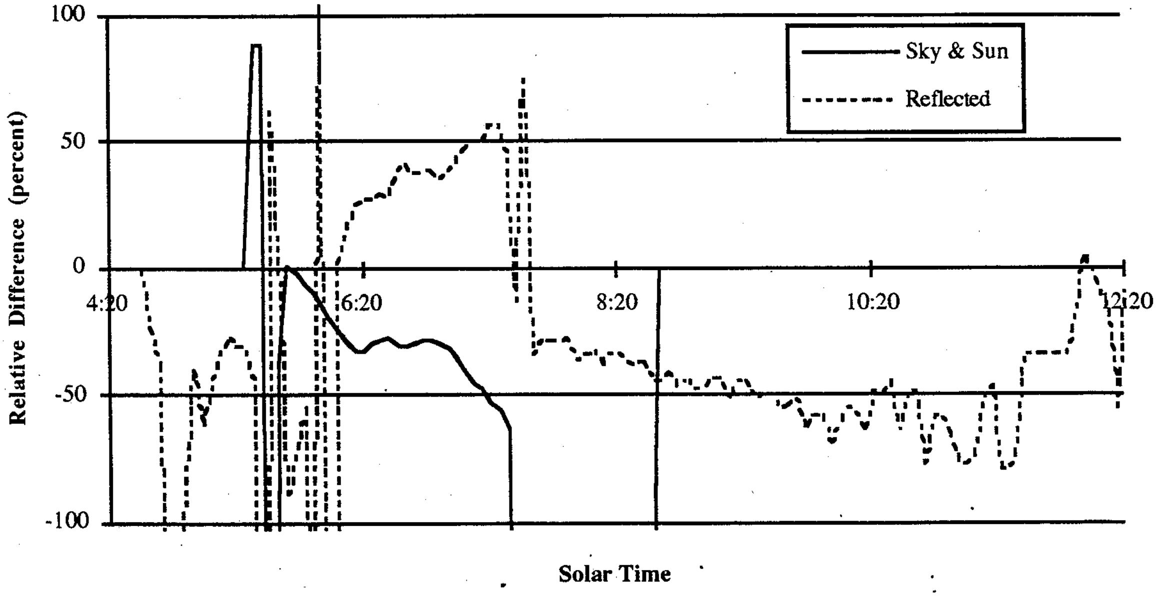


Figure 4.5 - Variations in relative differences for the sky and reflected components at floor level (MID position) in 1:12 scale models; clear sky on July 23, 1991.

Discrepancies under overcast sky with high average interior reflectance

The second experiment was designed to further explore the relationship between discrepancies in the sky component and discrepancies in the internally reflected component. In the preceding study, model estimates of the internally reflected component under overcast skies exceeded full-scale values by 30 percent. The measurements under overcast skies improved discrimination of differences between the model and full-scale readings because the sky component was higher than under clear sky without sun. The measurements were made after solar noon to ensure that direct sunlight was completely excluded from the spaces.

The relative difference was taken to be the median of the relative differences for 180 measurements made continuously at 10 s intervals (the median is the appropriate average where normality of distribution cannot be assumed) [18, 57].

As in the previous experiment, the photocell surfaces were placed just above floor level to minimize effects of sensors and sensor holders. A floor reflectance of 0.80 was used to determine whether a high average internal reflectance contributed to greater error in model measurements.

The sky and internally reflected components were determined for the full-scale space, a 1:3 scale space, and a 1:12 space. Separate low-and high-reflectance models were used in the case of the 1:12 scale space. The same 1:3 model was used in both sets of measurements, but the interior reflectances were altered as required.

Data logging system "B" was employed to better discriminate low-end illuminances. Use of the higher resolution data logger revealed discrepancies in the sky component that would not have been evident with system "A" because of the low light levels (frequently less than 10 lx) and small absolute differences being measured (frequently near 2 lx).

With the two available data loggers connected to four sensors in each space, simultaneous measurements could be made in only four spaces at a time. Therefore, simultaneous measurements were first made at the MAX, MID, MINP, and MIN positions (Figure 4.2) in the three low-reflectance spaces, and the median relative differences for the sky component were determined for the 1:12 and 1:3 models (a closer spacing was used in the rear half of the space to provide more data at points receiving less light). These median relative differences were used as factors to estimate the sky component for the models based on the sky component for the full-scale space. Simultaneous measurements were made at the same positions (MAX, MID, MINP, and MIN) in the three high-reflectance spaces and the full-scale low-reflectance space.

Figure 4.6 shows the median relative differences for the sky component and the combined sky and internally reflected component. In the case of the 1:12 model, the sky component estimate is within 10 to 20 percent of the full scale value. The combined components are well within 10 percent of the full-scale value. The internally reflected component (Figure 4.7) is also within 10 percent of the full-scale value. This tolerance should be satisfactory for test purposes, although these results are for the simplest possible space-window combinations.

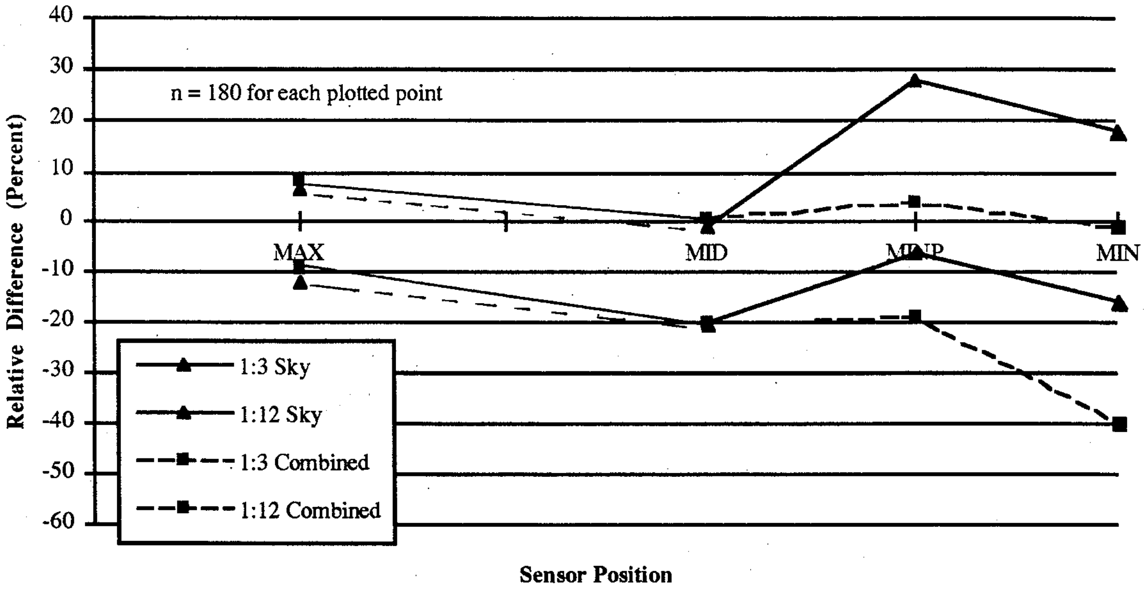


Figure 4.6 - The median relative differences for the sky component and the combined sky and reflected components of daylight at floor level in 1:3 scale and 1:12 scale models; overcast sky.

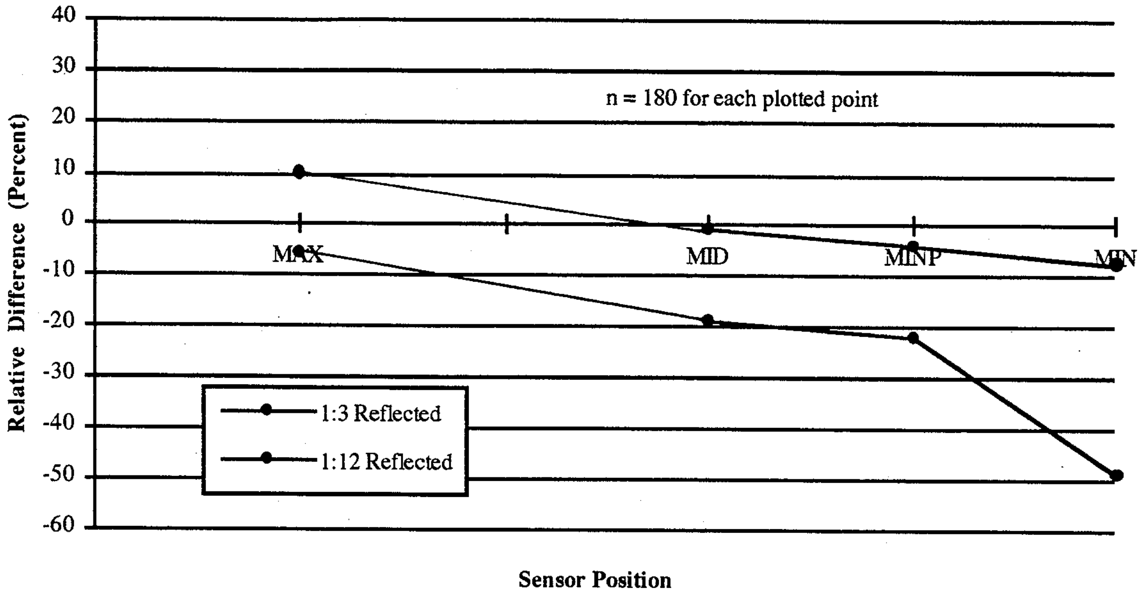


Figure 4.7 - The median relative differences for the internally reflected components of daylight at floor level in 1:3 scale and 1:12 scale models; overcast sky.

The results obtained for the 1:3 scale model were not as good. The sky component estimates were within 10 percent of the full-scale values for the front half of the space, but exhibited discrepancies of 10-20 percent in the rear half of the space. Discrepancies in the combined estimates and the internally reflected component also exceeded 10 percent by a considerable margin. In principle, the larger model should allow greater accuracy in placement of the photocells. In practice, it was more difficult to work with the larger model. It was too large to allow easy handling and too small to allow easy entry. While the model was supported on trestles to raise it to window height, it was subject to some flexing. This affected the leveling of the photocells.

The results showed that overestimates of the reflected component occurred with overestimates of the sky component, and that underestimates of the reflected component occurred with underestimates of the sky component. This is evident from the signs of the various components. The sign of the discrepancies in the combined sky and internally reflected components was consistent with the sign of the discrepancy in the sky component for both 1:12 and 1:3 scale models, as it was for the internally reflected component in the 1:3 scale model. The sign of the discrepancy in the internally reflected component in the 1:12 scale model was consistent with that of the discrepancy in the sky component for photocell positions in the front half of the space, but not in the rear half of the space. This is likely due to the large median relative difference for the sky component in the rear half of the model, a result of the very low light levels being measured and the low end measurement limits of the data logger. This effect is also evident in the median relative differences for the sky and internally reflected component in the rear half of the 1:3 scale space.

In the preceding study, overestimates of about 30 percent were found in model estimates of the internally reflected component under overcast skies. This experiment showed that, even with very high internal reflectances, accurate estimates (within 10 percent of full-scale values) of both the sky and internally reflected components can be achieved when using model photometry to predict the daylighting performance of simple spaces. It remained to determine what part the sensor holders might have played in contributing to error in the preceding research project.

Discrepancies due to photocell holders

The third experiment was designed to evaluate discrepancies caused by photocell holders. This experiment was conducted with the photocells placed at the workplane in 1:12 scale models. Floor coverings with a reflectance of 0.40 were used to bring the average space reflectance closer to typical values. Relative differences were determined for white, gray, and black photocell holders (reflectances of about 0.80, 0.40 and 0.05). The photocell holders in the full-scale space were mounted on skeletal metal supports, representing a minimal intrusion. The model photocell holders (5.5 by 5 by 60 cm or 2.25 by 2 by 24 in) (h·w·d), fabricated to locate the photocells accurately and to maintain them in a level position. These were similar to the photocell holders used in earlier research.

Measurements were made simultaneously in low-reflectance full-scale and model spaces, in the high-reflectance full-scale space, and in three high-reflectance models, each with a white, gray, or black sensor holder. Data logging system "C" was used, with sensors at the MAX, MIDP, MID, MINP, and MIN positions. This necessitated the use of a multiplexer to sample the required 30 sensors.

Measurements were made under overcast skies. The relative difference was taken to be the median of the relative differences for 180 measurements made continuously at 10 s intervals.

The relative differences for the reflected component were closest to those for the sky component with the black sensor holder in a high-reflectance model space (Figures 4.8 and 4.9 and Table 4.1). They were next closest with the gray sensor holder, and differed the most with the white sensor holders. The gray and white sensor holders evidently increased reflections significantly, because their use led to overestimates of the reflected component despite the sky component being slightly lower in the models than in the full-scale spaces.

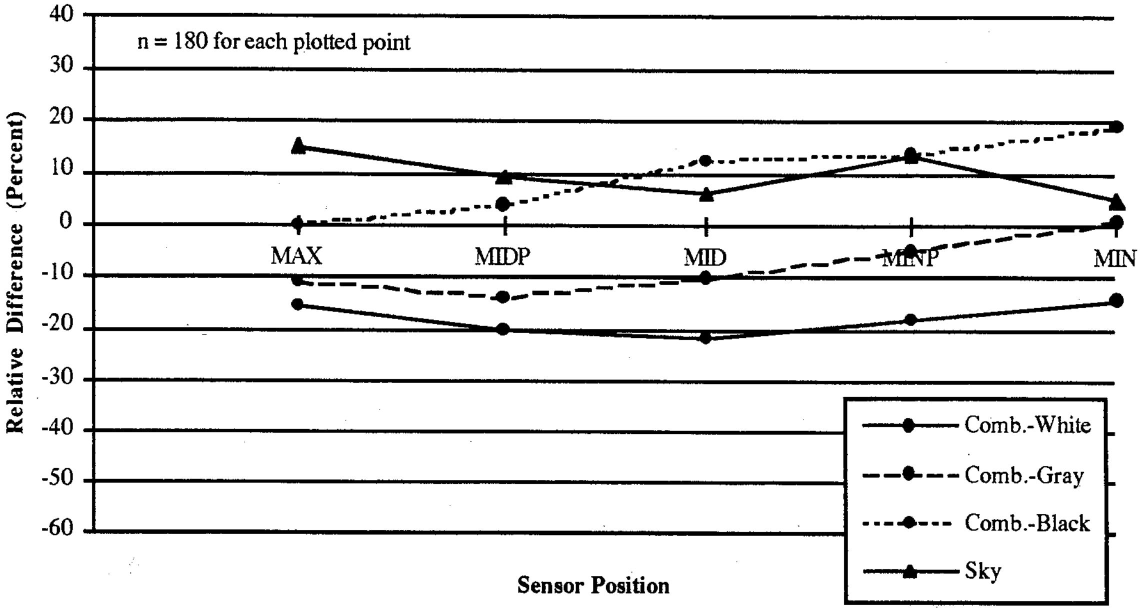


Figure 4.8 - The median relative differences for the sky component and the combined sky and internally reflected components of daylight on the working plane with white, gray and black sensor holder in the model space; overcast sky.

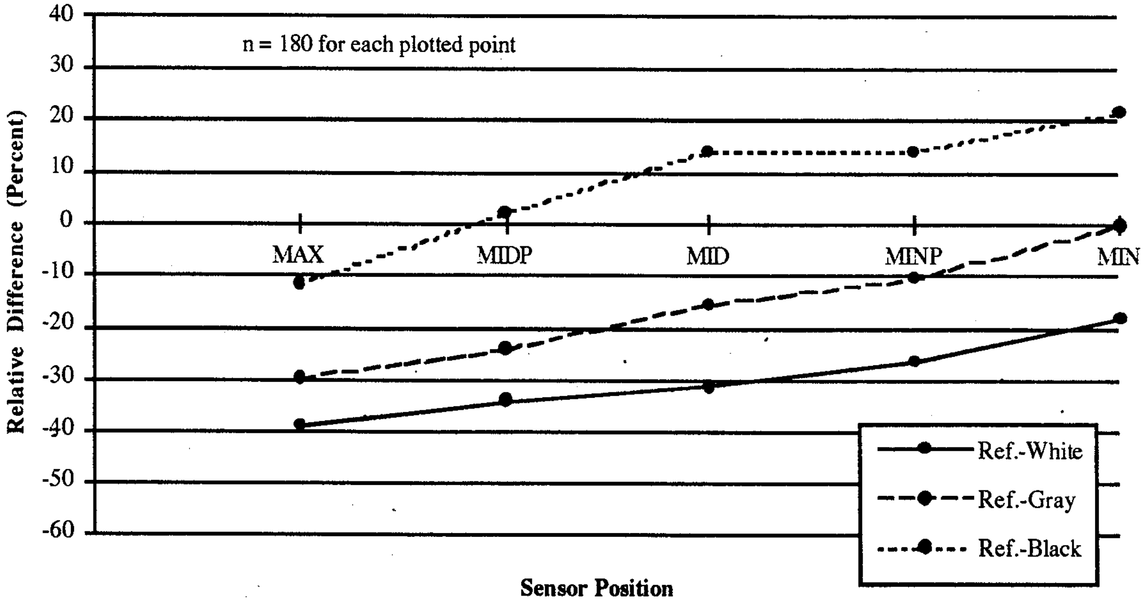


Figure 4.9 - The median relative differences for the internally reflected components of daylight on the working plane with white, gray, and black sensor holders in the model space; overcast sky.

Table 4.1 - Median relative differences for daylighting components on the workplane in 1:12 scale models (n = 180 for each point); overcast sky.

Daylight Component	MAX	MIDP	MID	MINP	MIN
Sky Component	15.0 ± 1.3	9.3 ± 2.3	6.2 ± 8.4	13.0 ± 14.3	4.9 ± 0.0
Internally Reflected Component - White Holder	-38.9 ± 2.4	-33.9 ± 2.3	-31.5 ± 2.9	-26.4 ± 3.6	-18.1 ± 3.5
Internally Reflected Component - Gray Holder	-30.1 ± 3.5	-24.2 ± 2.5	-15.6 ± 2.6	-10.5 ± 3.3	-0.2 ± 4.7
Internally Reflected Component - Black Holder	-11.7 ± 2.3	1.9 ± 1.9	13.9 ± 2.1	14.0 ± 4.4	21.8 ± 2.9
Combined Components - White Holder	-15.7 ± 0.7	-20.3 ± 0.8	-21.9 ± 1.1	-18.3 ± 2.0	-14.5 ± 2.4
Combined Components - Gray Holder	-11.1 ± 0.8	-13.9 ± 1.0	-10.3 ± 1.5	-5.0 ± 1.7	0.6 ± 4.0
Combined Components - Black Holder	-0.1 ± 0.7	3.9 ± 0.7	12.5 ± 1.2	13.7 ± 2.8	19.1 ± 2.0

Discrepancies under clear sky with sun using a black sensor holder in the high reflectance space

Measurements were then made under clear sky with direct sun with a black sensor holder in the high-reflectance model space. Measurements were made at 240 s intervals with sensors at the MAX, MIDP, MID, MINP, and MIN positions.

Because the measurement date was near the equinox, direct sun penetration of the test space was considerably less than in the earlier test under clear sky, which was conducted near the summer solstice. Figures 4.10 and 4.11 show the relative difference over time for the sky component and the internally reflected component (the large excursions of the relative difference are due to the sun being briefly obstructed by mullions in the full-scale space). Only the MAX, MID, and MIN position values are plotted to make the graphs easier to read (additional data is provided in Table 4.2). The relative difference for the internally reflected component is much closer to that for the sky component. than was the case in the earlier test under clear sky. The variation over time was also much reduced, showing the effect of high average internal reflectances combined with direct sun penetration of the test spaces.

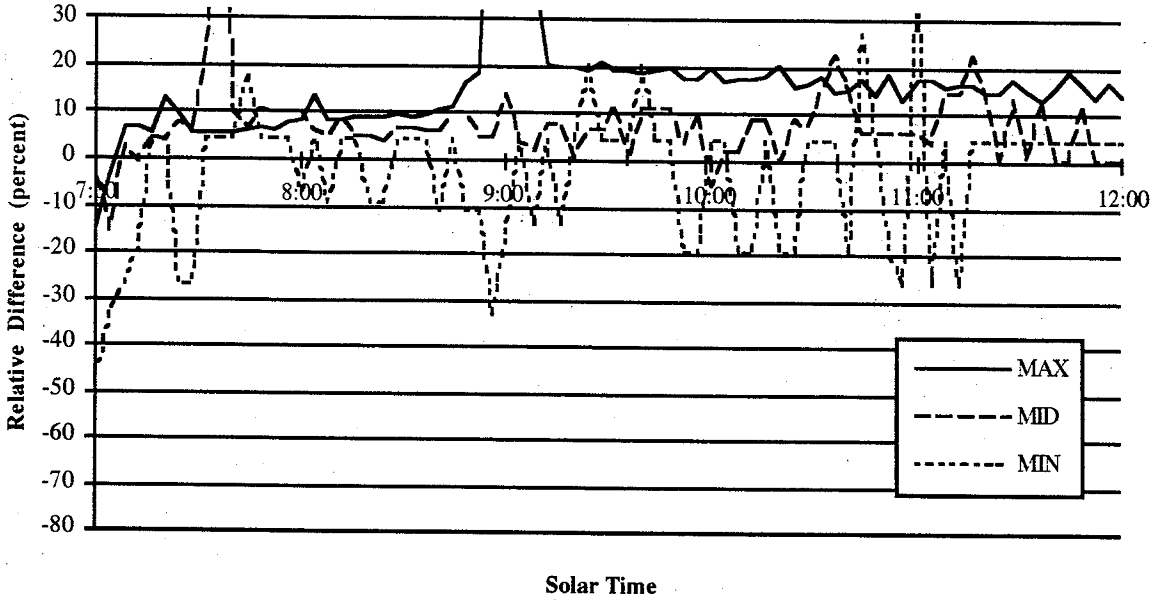


Figure 4.10 - Relative differences for the sky component and for the combined sky and internally reflected components on the working plane in 1:12 scale models with black sensor holders; clear sky on October 4, 1992.

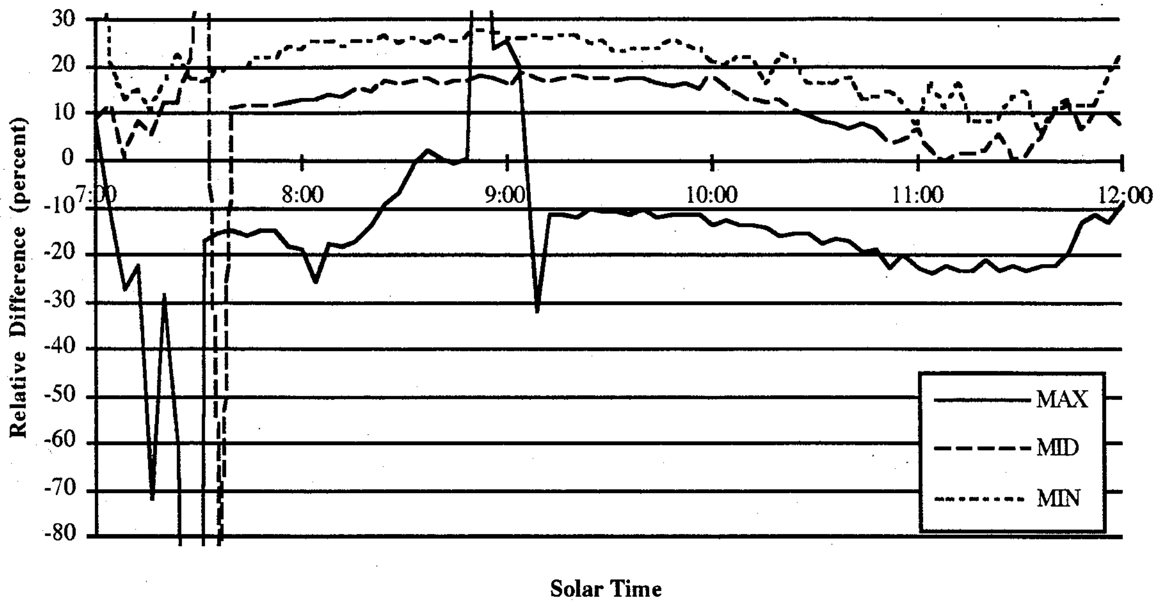


Figure 4.11 - Relative differences for the internally reflected components on the working plane in 1:12 scale models with black sensor holders; clear sky on October 4, 1992.

Table 4.2 - Median relative differences for daylighting components on the workplane in 1:12 scale models for measurements made at 4 minute intervals from 0700 to 1200 solar time (n = 75 for each point); clear sky on October 2, 1992.

Daylight Component	MAX	MIDP	MID	MINP	MIN
Sky Component	15.9 ± 3.4	11.6 ± 2.9	6.8 ± 3.8	9.4 ± 5.9	4.9 ± 0.0
Internally Reflected Component - White Holder	-39.9 ± 4.6	-32.2 ± 2.4	-28.4 ± 2.8	-18.8 ± 2.4	-12.2 ± 2.4
Internally Reflected Component - Gray Holder	-36.0 ± 7.6	-24.0 ± 6.6	-12.0 ± 5.1	-3.2 ± 4.5	-0.9 ± 3.9
Internally Reflected Component - Black Holder	-14.5 ± 4.3	-1.7 ± 4.6	12.9 ± 4.3	18.5 ± 4.3	21.9 ± 4.4
Combined Components - White Holder	-21.5 ± 5.4	-23.3 ± 8.9	-22.0 ± 13.0	-16.0 ± 14.0	-12.0 ± 10.0
Combined Components - Gray Holder	-17.0 ± 14.0	-15.0 ± 16.0	-9.0 ± 21.0	-2.0 ± 20.0	-2.0 ± 21.0
Combined Components - Black Holder	-3.0 ± 13.0	0.7 ± 4.1	12.4 ± 4.7	18.2 ± 4.7	19.4 ± 5.5

Summary

In the case of clear skies with direct sun, it can be inferred from these experiments that large, time-varying discrepancies in model estimates of the internally reflected component are due to differences in the reflection of direct sunlight. When model photometry is used in design, the combined sky and internally reflected components would normally be measured. Because of the size of the reflected component relative to the sky component in typical daylit spaces, there may be a large error (greater than 20 percent) where direct sunlight and highly reflective surfaces are involved (e.g., in beam daylighting systems).

Under ideal conditions (simple spaces and windows, correct placement of sensors, low-reflectance sensor holders), where direct sunlight does not strike the fenestration (under overcast skies or clear skies without sun), model estimates can be within 10-15 percent of values for full-scale spaces exposed to the same sky conditions. Taking into account the 4 percent light loss factor due to the mullions, the figure, estimates were within 10 percent for most measurement positions.

Photocell holders can have a marked effect on the accuracy of measurements. The additional surface areas increase interior reflections and, hence, illuminance estimates. Photocell holders should be matte black unless they are "camouflaged" as planned room contents. Likewise, care should be taken with the reflectances of other objects placed in models (e.g., model furnishings and artworks).

The experiments showed that larger models (e.g., 1:3 versus 1:12 scale) do not necessarily provide greater accuracy. They can be more difficult to work with, offsetting any gains in precision of placement and fabrication.

A logical further step in this research is to quantify the errors that occur in modeling more complex spaces. The information provided by the studies of simple spaces and windows will make it possible to determine how much of the error for more complex systems is due to simplifications that would typically be made during design and how much of the error is due to the basic error factors in model photometry.

4.5.2 Determination of the daylight factor under real overcast skies

Results of tests with high-reflectance walls

The first procedure assessed was the use of stability of E_{lg} as a means of ensuring reproducibility. Data from the afternoon of October 30, 1991 provided a satisfactory sample for investigation of the stability of the daylight factor over short periods. During the 2 hour test period, E_{lcl}/E_{lg} was greater than 0.67, except for a few readings. As was noted above, one of the two criteria used by Navvab, Karayel, Ne'eman and Selkowitz to characterize an overcast sky was that the ratio of the diffuse to global irradiance exceed 0.67. Given that the luminous efficacy of overcast skies fall within 105-120 lm/W [58], the use of illuminances should be a satisfactory substitute for irradiances. Indeed, it might be expected that the use of illuminances to determine the degree and stability of cloud cover should be more reliable for purposes of determining the daylight factor. During the first hour of the measurement period, E_{lcl}/E_{lg} varied considerably, while the ratio was stable and near 1.0 during the second hour (Figure 4.12). The illuminance ratios (E_{lH}/E_{lg}) for the MAX, MID, and MIN positions are shown in Figure 4.13. There is considerable variability (much greater than 10 percent) in the daylight factor, even using a sky that would be classified as overcast according to the criterion developed by Navvab, Karayel, Ne'eman and Selkowitz. This variability is apparent for all measurement positions, although greater variability is evident for the positions farther from the window. This is to be expected, because photocells that view a greater portion of the sky are likely to average out variations in the luminance of small areas of sky.

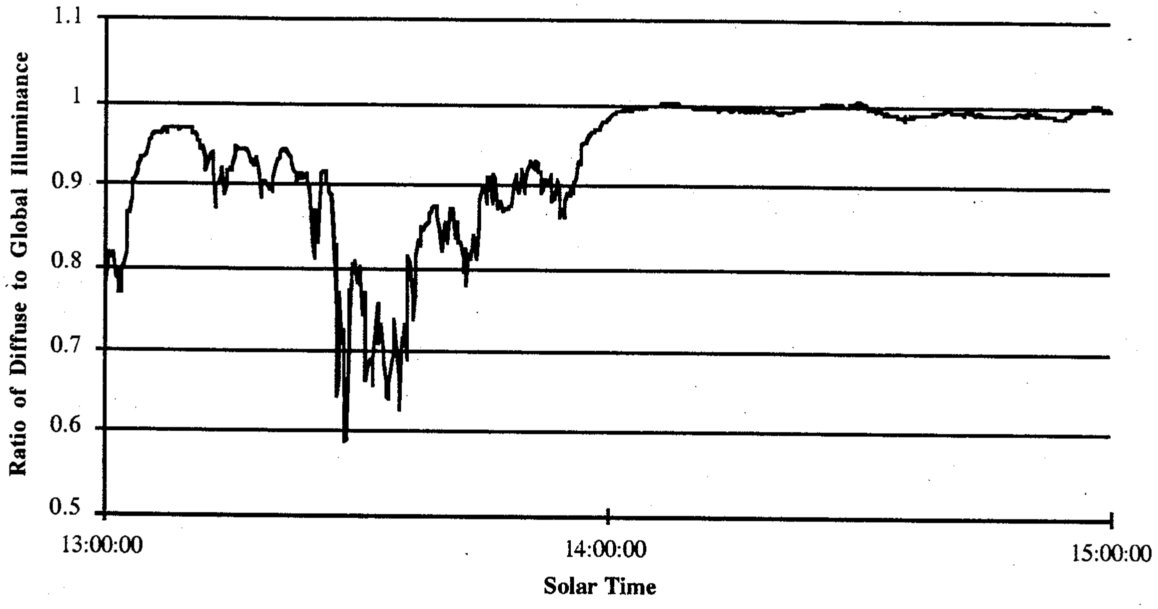


Figure 4.12 - The ratio of the diffuse to global illuminance; overcast sky on October 30, 1991.

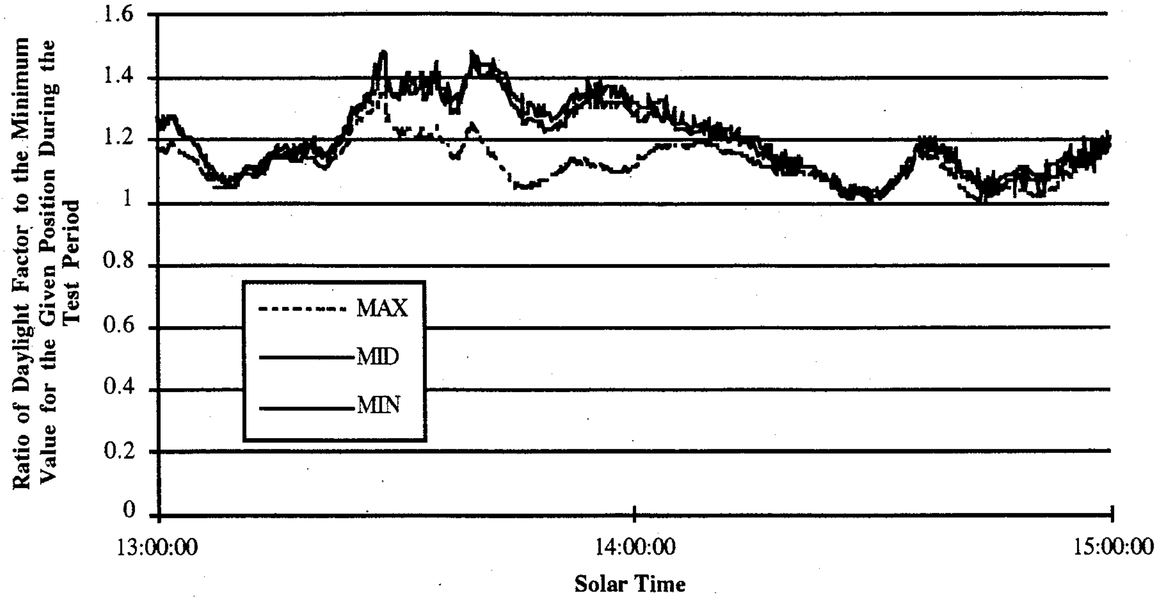


Figure 4.13 - The ratio of the instantaneous indoor-outdoor illuminance ratio to the minimum value for the test period; overcast sky on October 30, 1991.

Murdoch, Oliver and Reed's approach to defining stable overcast sky conditions was then assessed. Indoor-outdoor illuminance ratios (E_{lH}/E_{lg}) were determined for 4 intervals of 15 minutes during which the values of E_{lg} at the beginning and end of the period differed by 10 percent or less (Figure 4.14 and Table 4.3). In fact, the variations were all below 5 percent. Because the interior measurements might be made at any time within the 15 minute interval, the extreme values of the illuminance ratio were determined. The differences between the minimum and maximum values of E_{lH}/E_{lg} were generally within 10 percent for a given measurement period, but differed by more than 10 percent among measurement periods.

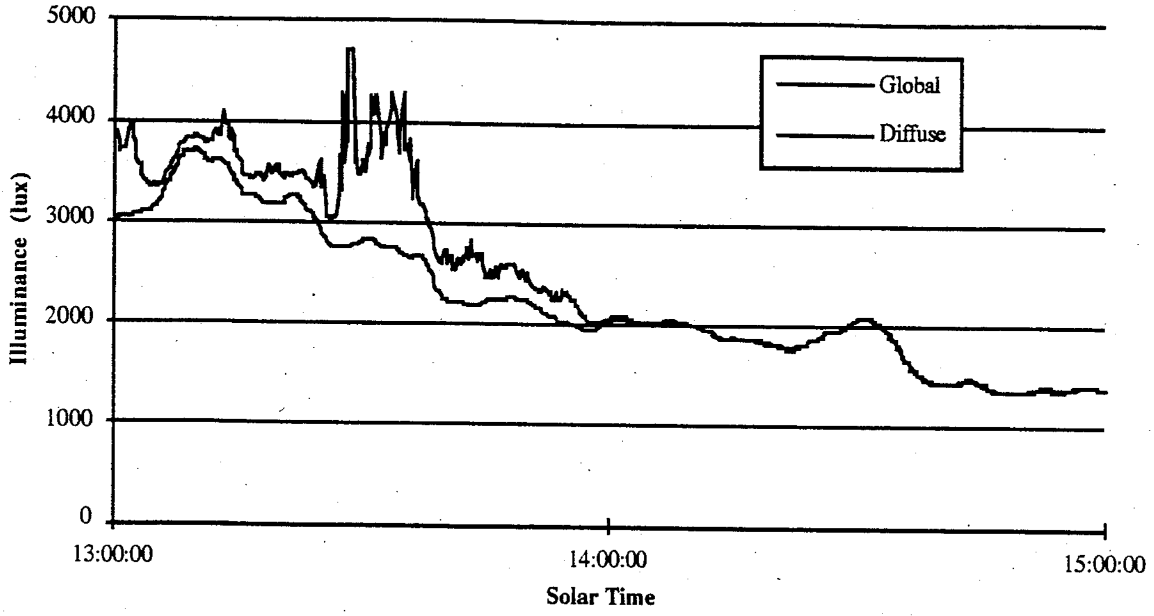


Figure 4.14 - The global and diffuse illuminances; overcast sky on October 30, 1991.

Table 4.3 - Indoor-outdoor illuminance ratios for periods of 15 minutes during which the values of E_{lg} at the beginning and end of the period differed by less than 10 percent; overcast sky on October 30, 1992.

Test period Start Time	Global Illuminance				Illuminance Ratio					
	First (lx)	Last (lx)	Mean of First & Last (lx)	Variation (%)	MAX		MID		MIN	
					Low	High	Low	High	Low	High
1300	3740	3450	3600	4.2	10.5	11.7	5.4	5.9	3.2	3.5
1400	2040	1890	1970	4.1	11.5	13.2	6.0	7.0	3.6	4.4
1415	1890	2060	1970	4.6	10.4	11.5	5.2	5.9	3.1	3.6
1445	1480	1410	1440	2.1	10.1	12.2	5.1	5.9	3.1	3.7

Lynes recommended simultaneous measurements for determination of the daylight factor. Over the four intervals of 15 minutes, the maxima and minima of ratios of simultaneously measured interior and exterior illuminances (E_{lH}/E_{lg}) differed by more than 20 percent from the mean of the extremes.

None of the procedures that were tested provided values of the daylight factor that were close to being reproducible within 10 percent, even for a high reflectance interior, which would smooth out fluctuations due to the relatively high internally reflected component.

Results of tests with low-reflectance walls

Further tests were conducted with a lower reflectance (0.40 reflectance walls) interior, providing more stringent test conditions with a lower internally reflected component. The difficulty in determining the daylight factor is evident if one compares plots of E_{lg} and E_{lH} for one interior position during an overcast period (Figure 4.15). E_{lH} at the MAX position "tracks" E_{lg}, but with variability fidelity. At times, E_{lH} is decreasing while E_{lg} is increasing (e.g., just before 11:30). The most likely explanation is nonuniformity of the real overcast sky. The luminance of the portion "seen" by the sensor at the MAX position may differ significantly from the average luminance of the entire sky vault. The effect on the daylight factor is shown in Figure 4.16, with values fluctuating between 4 and 14.

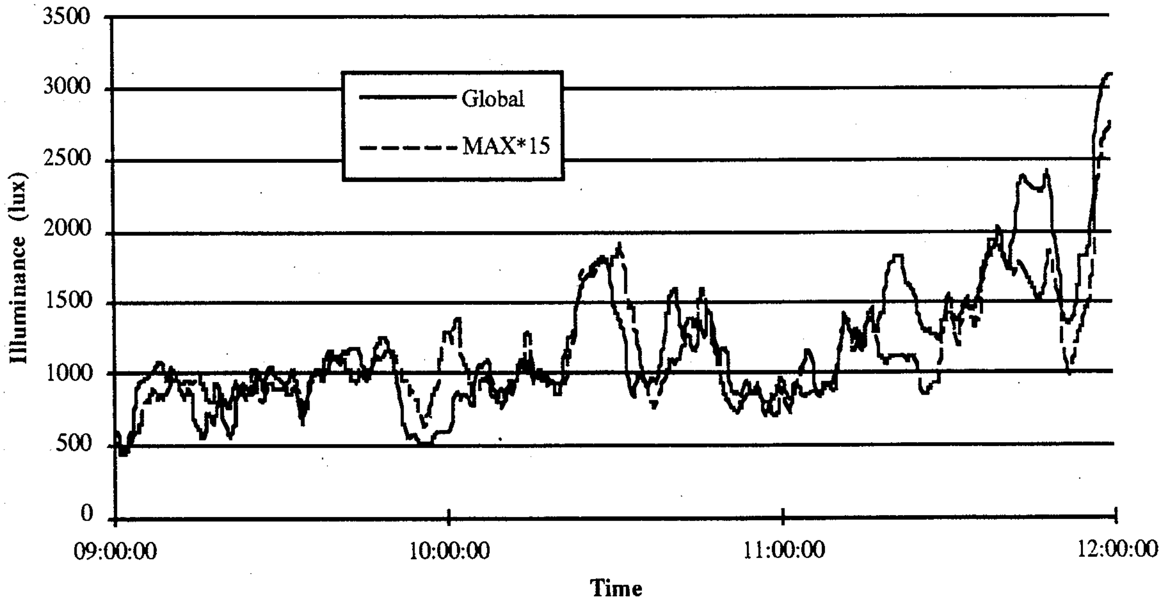


Figure 4.15 - The global illuminance and the illuminance at the MAX position; overcast sky on July 9, 1992.

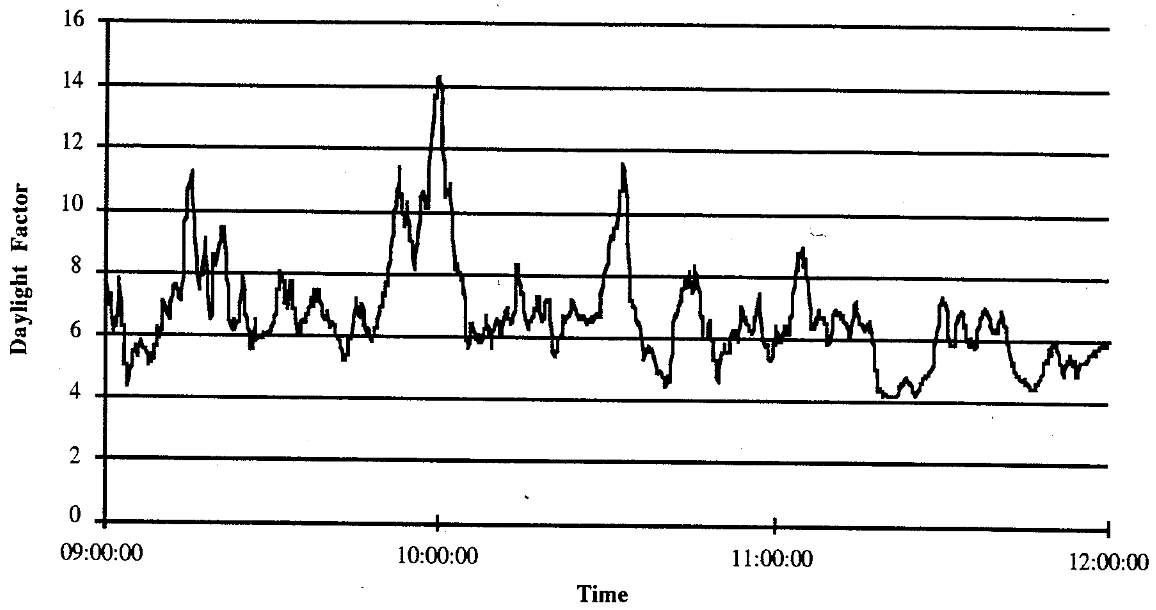


Figure 4.16 - The daylight factor at the MAX position; overcast sky on July 9, 1992.

A least squares fit technique was used to evaluate the relationship of simultaneously measured indoor (E_{lH}) and outdoor (E_{lg}) illuminances, the daylight factor being taken as the slope converted to a percentage. A one hour measurement period was selected. The analysis was first carried out for the MAX position because it was exposed to the largest solid angle of sky and, hence, was least susceptible to eccentricities in sky luminance distribution. Based on study of 33 one hour periods, during which the sky was mainly overcast ($E_{lcl} \geq 0.90\ E_{lg}$ for most of the hour), it was found that the median absolute deviation was about 10 percent of the median for 8 one hour periods during which the coefficient of determination (r^2) exceeded 0.80 (Table 4.4). A similar selection of measurements for the MID position also provided a median absolute deviation of about 10 percent (Table 4.5). The median and median absolute deviation were determined for the MIN position for the periods selected for computation of the median for the MAX position (Table 4.6). These generally had an r^2 much lower than 0.80, but showed a high degree of consistency, the median absolute deviation being within 25 percent of the median. Due to the low illuminances being measured at the MIN position (frequently 2 to 10 lx) and the 2 lx resolution of the data logger, it is likely that a significant portion of the variation in the daylight factor was due to step jumps from one value to another attributable to limitations of the measurement system.

Table 4.4 - Results of least squares fit of E_{IH} versus E_{lg} for the MAX position; 8 heavily overcast one hour periods for which r^2 exceeded 0.80.

Date	**Hour**	**Y-intercept**	**Slope**	**r^2**	**Daylight Factor (= Slope * 100%)**
June 15	1706-1806	21	0.043	0.92	4.3
June 29	1500-1600	24	0.053	0.82	5.3
July 6	0830-0930	3.4	0.058	0.90	5.8
July 6	0930-1030	10	0.055	0.90	5.5
July 6	1030-1130	32	0.048	0.80	4.8
July 6	1230-1330	9.6	0.062	0.90	6.2
July 8	0900-1000	40	0.052	0.83	5.2
July 8	1200-1300	23	0.052	0.90	5.2
				Median (n = 8)	5.2 ± 0.6

Table 4.5 - Results of least squares fit of E_{IH} versus E_{lg} for the MID position; 8 heavily overcast one hour periods for which r^2 exceeded 0.80.

Date	Hour	Y-intercept	Slope	r^2	Daylight Factor (= Slope * 100%)
June 15	1706-1806	10	0.0071	0.88	0.7
June 29	1500-1600	7.2	0.011	0.82	1.1
July 6	0830-0930	3.1	0.011	0.85	1.1
July 6	0930-1030	3.0	0.012	0.80	1.2
July 6	1230-1330	7.5	0.011	0.89	1.1
July 8	0900-1000	10	0.0096	0.87	1.0
July 8	1200-1300	8.0	0.011	0.85	1.1
				Median (n = 7)	1.1 ± 0.1

Table 4.6 - Results of least squares fit of E_{IH} versus E_{lg} for the MIN position; 8 heavily overcast one hour periods for which r^2 at the MAX and MID positions exceeded 0.80 (see Tables 4.4 and 4.5).

Date	Hour	Y-intercept	Slope	r^2	Daylight Factor (= Slope * 100%)
June 15	1706-1806	4.4	0.0029	0.73	0.3
June 29	1500-1600	4.0	0.0038	0.69	0.4
July 6	0830-0930	1.2	0.0038	0.62	0.4
July 6	0930-1030	1.4	0.0044	0.51	0.4
July 6	1030-1130	3.6	0.0043	0.42	0.4
July 6	1230-1330	33	0.0041	0.89	0.4
July 8	0900-1000	2.2	0.0037	0.80	0.4
July 8	1200-1300	4.2	0.0034	0.83	0.3
				Median (n = 8)	0.4 ± 0.1

Data was then selected from these sets to determine whether fewer measurements per hour could be used to determine the daylight factor. It was found that measurements at 1 minute and 5 minute intervals provided results similar to those obtained with 10 s intervals, provided r^2 exceeded 0.80. When the interval between selected measurements was increased to 10 minutes, it was not possible to obtain a reproducible value of the daylight factor.

Summary

A review of the literature revealed that there is little guidance on obtaining reproducible values of the daylight factor from illuminance measurements under overcast skies. It was shown that the methods that have been proposed do not provide reproducible values. Analysis of experimental data suggests that reproducible values can be obtained if the following conditions are met:

1. The indoor and outdoor illuminance measurements (E_{lH} and E_{lg}) used to calculate the daylight factor should be made simultaneously.

2. The daylight factor can be taken to be the percentage equivalent of the slope of the least squares best fit to the simultaneously measured E_{lH} and E_{lg} values at intervals of 5 minutes or less over a one hour period, provided the coefficient of determination (r^2) equals or exceeds 0.80. Increasing the number of measurements in the one hour period (i.e. shortening the interval between measurements) increases the likelihood that a satisfactory coefficient of determination will be obtained.

Further experimental studies should be undertaken to more rigorously define the conditions for obtaining reproducible values.

4.5.3 Assessment of PWClite1

There are many factors that lead to discrepancies between short-term measured values and estimates provided by simulation programs. In the case of a program like *PWClite1*, which was developed to provide a simple user interface (necessarily reducing the number of variables that can be manipulated), the real space may differ in terms of reflectances, window placement, and illuminance determination point. A serious difficulty in comparing estimates from many computer simulation programs with measured values is the fact that the computer simulation programs use mathematical models of daylighting availability and sky luminance distribution that are based on long-term measurements, while measured values may be available for only a short period of time. In some programs, such as *SUPERLITE* [59-60], the sky type may be selected (e.g. clear or cloudy) and other parameters adjusted (e.g., the overall sky luminance). The mathematical model of sky conditions cannot be manipulated in *PWClite1*. These characteristics should be born in mind in considering the following comparison.

With the dimming system in operation, lighting power demand savings on the 5th floor test zone averaged about 35 percent of the full output of 3 kW. *PWClite1* yielded estimates that the reduction in lighting power demand for the zone would be 90 percent between 0700 and 1700 in July. One cause of the discrepancy is the use of venetian blinds in the zone (the spikes in task illuminance are caused by early morning direct sunlight being periodically interrupted by the blind slats with changes in solar position.

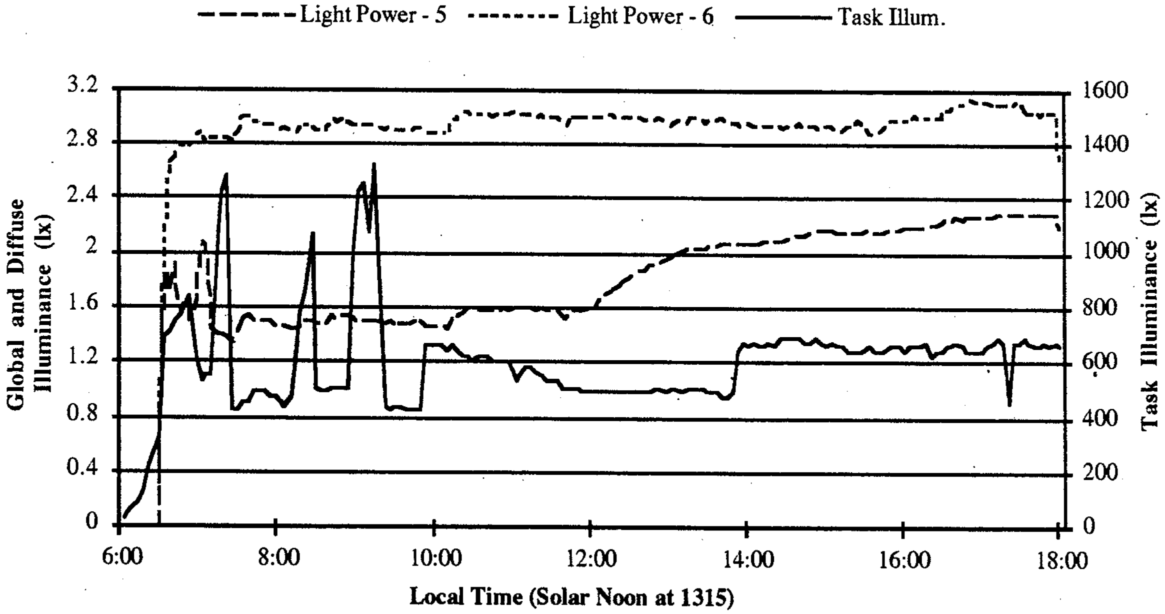


Figure 4.17 - Test Zone Task Illuminance and Lighting Electric Power Demand on June 22, 1992 (a Monday - Electric Lighting in Use).

As has been noted elsewhere, the lights were frequently in use on the weekends, complicating the measurement of daylight illuminances in the test zone. The researcher raised the venetian blinds in the office equipped with a desktop photocell on several Friday afternoons. Figure 4.18 shows task illuminances under clear sky with sun on a Sunday when the electric lights were not in use. Task illuminances range around 100 lux after solar noon (1315 local time). This is well below the 700 lux daytime illuminances estimated for July by *PWClite1*. Research to date has shown that *SUPERLITE*, used to develop the illuminance estimates in *DOE2*, which, in turn was used to develop illuminance and energy use estimates in *PWClite1*, overestimates the internally reflected component of daylight. As well, *PWClite1* estimates would be based on an average of different sky conditions, including clear and cloudy; while global illuminance is lower under cloudy skies, the sky would have a more even luminance distribution about the points of the compass. Thus, an east-facing space could receive more daylight on a cloudy day.

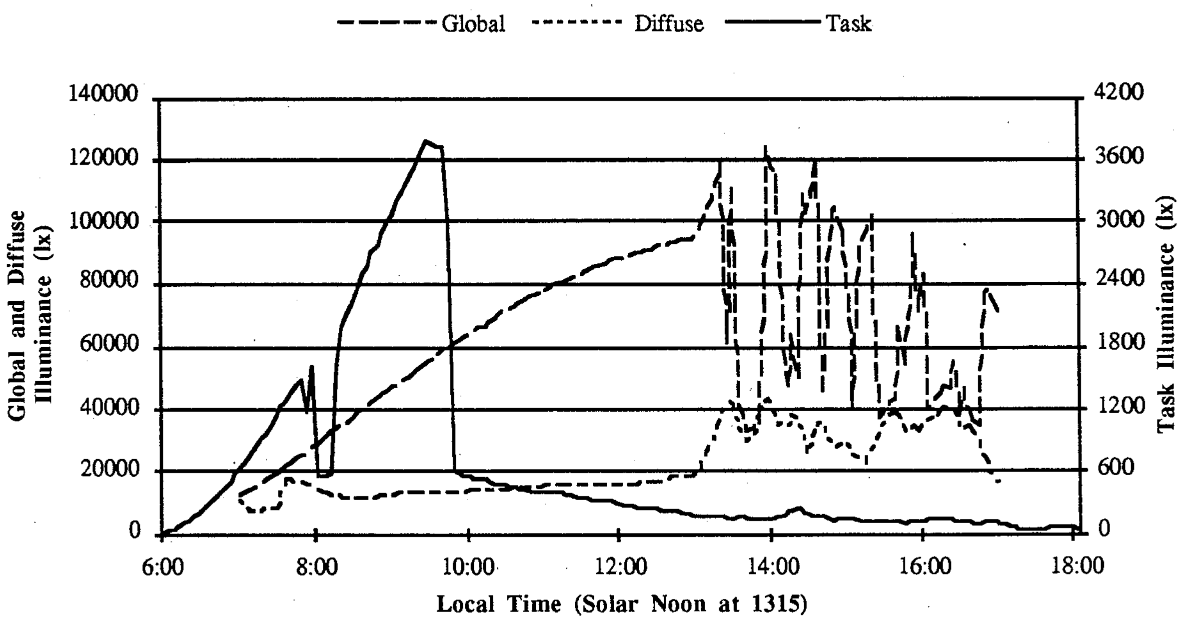


Figure 4.18 - Global, Diffuse, and Test Zone Task Illuminances at Building B on Sunday, July 12, 1992 (no electric lighting).

The validation of daylighting design tools is still in its infancy. A better basis for evaluating such tools would be to use a measured sky luminance distribution in conjunction with measured illuminances in comparative assessments of computer simulation programs. However, such equipment is costly, complex, and not widely available. To the author's knowledge, the only such studies conducted to date have used simplified (uniform) sky conditions [53].

5.0 CONCLUSIONS

Daylighting is a technology that offers great potential benefits in terms of occupant satisfaction and energy savings. The results show that further *field* research is required to ensure that is applied effectively. For instance, factors such as the partitioning of offices affects the use of such systems in practice in ways that are not indicated in computer simulation studies.

Assessment and development of lighting control systems at buildings with specially designed fenestration should be undertaken to determine the means of fully realizing the energy savings potential of daylighting. These can be usefully *supplemented* by computer simulation studies to extend the range of investigations. For instance, studies could be conducted at the daylit high school in Calgary to determine the electrical demand if daylighting were fully exploited by switching off electric lighting (the building is not equipped with automatic controls, and users often leave lights switched on). Computer simulation studies could be used to determine the impact of the large, unshaded, south-facing glass areas (not required for daylighting or view) on energy use (measured data would allow the simulation to be tested against actual performance before evaluating alternative design scenarios). Computer simulation studies, after corroboration with a working building, would also allow the energy savings to be determined for other climatic zones (e.g. Pacific, Central, Eastern).

Alternative control strategies should be investigated to determine whether approaches such as *larger* control zones and more conservative dimming strategies on facades that may be partially shadowed would offer greater actual savings (because system that are seen to dim excessively are switched off).

Control systems that allow light fixtures to be software addressable should be explored to facilitate the partitioning and re-partitioning of spaces over time so that electric lights in a given space operate in the same control group.

Currently available protocols for ergonomic assessment of illumination mainly address electric lighting. Assessment of daylighting is more complex because it is continuously, and dramatically, changing (e.g., the illuminance from direct sunlight falling on a desk may exceed 50, 000 lux, while the daylight illuminance at the same point approaches zero late in the work day during winter). Additional work is needed on protocols and performance indicators currently under development that allow for the assessment of daylight conditions.

Technology transfer is a major issue in the successful use of daylighting systems. The systems that were studied were all performing well below capability because of improper design, installation, and/or operation. Further research, development, and technology transfer efforts are required if buildings with daylighting systems are to achieve the energy savings estimated to be possible using computer simulation programs. The research should produce buildings that can be used as learning models by designers and operators so that they will have concrete examples of design features and operating procedures that work well in providing energy efficient operation and user satisfaction.

APPENDIX A

Literature Review:
Protocols for the Evaluation of Building Systems in terms of Daylighting and Energy Use

TABLE OF CONTENTS

A.1 LITERATURE REVIEW

The literature is reviewed in two groups: 1) that dealing with monitoring protocols in general and 2) that dealing with the monitoring of daylit buildings.

A.1.1 General Procedures for Monitoring Building Energy Use

Several articles on monitoring protocols were reviewed [1-9]. The most significant points are discussed below.

Under the auspices of the International Energy Agency, Lyberg and Fracastoro developed a guide for the monitoring of building energy use. In *An Overview of the Guiding Principles Concerning Design of Experiments, Instrumentation, and Measuring Techniques*, they give an overview of this guide [5]. They note some key problems in the study of energy utilization in buildings:

> Measurements on buildings in many respects differ from measurements on other engineering and physical systems. A difference between buildings and many other systems is that controlled experiments cannot be performed on buildings. This is due to the presence of [occupants] and the fact that [the] outdoor climate cannot be varied at will....
>
> Whilst laboratory techniques are available for the basic properties of building components, site measurements are needed to obtain the performance as built and as subjected to the actual climatic conditions [10].

They further comment

> If applicable, direct measurement is generally the method to be preferred. Errors are often small compared to when another data gathering technique is used. Using direct methods, it is possible to achieve a disaggregation of the end use of energy. Having a small resolution in time, the dynamic building performance can be studied. The drawback of direct measurement is the cost [11].

Three types of errors are identified by these researchers [11]:

1. the accuracy of the sensor reading (e.g. the sensor may be exposed to confounding influences, such as radiation)
2. the representativeness of the sensor position
3. sampling errors (e.g. due to reading interval)

In the case of point 1, calibration is not mentioned, but is an essential requirement for every data collection instrument.

Lyberg and Fracastoro identify three types of experimental design:

1. the test-reference design, in which the energy performance of a group of buildings is compared with that of a control group,
2. the before-after design, in which a comparison is made of energy use before and after the implementation of an energy conservation measure,
3. the on-off design, only viable with reversible conservation measures, in which energy consumption is measured during a number of repeated on-off cycles [11].

The following summary of points to consider was developed following the 1985 workshop, entitled *Field Data Acquisition for Building and Equipment Energy-Use Monitoring*, at which the Lyberg-Fracastoro paper was presented:

> ...some of the major problems associated with the selection and use of a data acquisition system [are]:
>
> 1. Planning for projects tends to be hardware-oriented
> 2. Little thought is given to data analysis and processing
> 3. No priority scheme established
> 4. Lack of redundancy in data collection
> 5. Little error analysis from a system viewpoint
> 6. Frequent modifications to data systems by advisory panels
> 7. Useful information gathered but not used for project objectives
> 8. Little or no system documentation
>
> ...resolution of these problems will require that:
>
> 1. Data analysis should be [planned] before hardware design
> 2. Critical parameters should be identified and given priority
> 3. Interdependency of parameters should be identified
> 4. On-line processing and read-out should be in simple terms
> 5. Data must be analyzed and processed regularly
> 6. Data scheme should be simple and to the point
> 7. State-of-the-art methods should be avoided
> 8. Reliability should be emphasized over accuracy
> 9. More emphasis should be placed on software needs and requirements
> 10. Documentation should be completed before data gathering commences [12]

Misuriello subsequently developed additional guidelines for building monitoring protocols. He suggests that a protocol should address [7]:

1. Statement of goals, objectives and research questions to be addressed
2. Specification of data products that meet the objectives of the project
3. Specification of an experimental design approach
4. Specification of data-analysis procedures and algorithms
5. Specification of field-monitoring data points
6. Specification of verification and quality control procedures
7. Hardware selection guidelines
8. Recording and data exchange formats

Verification and quality control can involve a number of checks, including ensuring that recorded values are:

1. within the correct range

2. have reasonable relative magnitudes

The other papers reviewed dealt with topics that were not immediately relevant to the development of a monitoring protocol for this project.

A.1.2 Case Studies - Monitoring Daylit Buildings

Very little work has been done on the monitoring of energy use in daylit buildings. Warren reports on the study of Lockheed Building 157, one of the first of the most recent generation of daylit buildings, distinguished by the use of dimming ballasts and automatic controls [13]. The researchers commented

> The integration of daylighting with electric lighting to provide ambient illumination with task lighting provided separately at each workstation is an attractive strategy for energy conservation [due to the large fraction of energy use related to electric lighting]. Energy savings come from proper control of the electric lighting system in response to available daylight. · Building level energy use measurements are generally insufficient to identify how well a building is operating. Detailed measurements of specific energy uses are needed to understand how a particular system is operating [14].

The researchers measured illuminances at 13 interior points, temperatures at 4 points, and electrical power at 7 points (all lighting circuits). Sensors were polled every minute, and the data generally saved as 15 minute averages, although 1 minute interval data was stored for some detailed investigations.

Some of the difficulties encountered in measuring illuminances are especially relevant to the development of the A-level monitoring protocol. Because the data acquisition systems used could handle only 7 channels, 4 systems were required for this study. The data loggers recorded data on cassette tapes, and the tapes were then read into a personal computer for processing. This meant that evaluation of the data that was collected was rather indirect. The resolution and data storage capabilities of the 12-bit analogue-to-digital converter used in the study required special measures to cover the range of illuminances to be studied. Scale factors, offsets, and extra resistors were required to measure the illuminances of 8, 000 lux occurring at the light shelf ceiling and 29, 000 lux occurring on the interior of the light shelf glazing.

Because the minimum dimming on the lighting system was 22 percent of full light output, the illuminance data made it possible to determine the periods during which the target illuminance of 350 lux was exceeded. The electric power data made it possible to determine the degree of dimming that was occurring. The temperature data is not discussed in the paper. Daylit availability was assessed by observation because it was not measured. Potential annual energy savings were estimated since only total electrical use and selected lighting circuits were monitored.

Andersson et al. report energy performance of two buildings designed for daylighting, a library and a church [15]. Skylighting is employed extensively in both of these buildings. Lighting is controlled manually. In the case of the library, electricity usage on each of the six lighting circuits serving the core area was matched against the illumination resulting from daylighting. Computer simulation was then used to evaluate overall energy savings. Similar procedures were used to evaluate the church.

Heap, Palmer and Hildon report on the performance of a 4-storey office building in the United Kingdom [16]. The description of the measurement method is incomplete. Energy use for lighting was assessed by an intensive monitoring program, based on the approach used by Warren at al. [13] was conducted over a period of three months (April-June). Electricity utilization was measured in 14 circuits. Five photocells were also monitored internally. Global irradiance was also monitored. Annual energy use was then estimated based on the short-term data.

A.2 The A-level Monitoring Protocol

The outline provided by Misuriello (see subsection 3.1.1 above) was adopted as a basis for the protocol.

A.2.1 Goals, objectives, and research questions

As was stated in section 1, the overall project objectives were to:

1. Assess the viability of daylighting systems in terms of technical, organizational, ergonomic and fiscal criteria, and

2. Assess the accuracy and value of currently-available daylighting design tools.

The A-level monitoring protocol was intended principally to provide information on the energy use effects and lighting power demand of the daylighting systems. It was intended that data collected in the course of monitoring also be used to assess tools for daylighting estimation. However, due to tenant concerns regarding disruptions, comparative assessments of model and full-scale photometry were carried out in test cells in unoccupied portions of one of the test sites. The advantage of this approach was that the test cells were very similar to those used in earlier research on the subject (see section 4).

The research question was to determine the effects of daylighting controls on energy utilization for lighting, heating, and cooling. The efforts reported in the literature review were limited to measurement of electricity use for lighting. Total energy use was estimated.

A.2.2 Specification of Data Products that Meet the Objectives of the Project

The following data was required:

- electricity used for lighting
- heat transferred to and from the spaces of interest
- illuminances in the spaces of interest
- daylight availability

The data was to averaged for periods of not more than 15 minutes, to be consistent with the method used by the Lawrence Berkeley Laboratory researchers. Data averaging over finer intervals would indicate whether more detailed information is useful. For instance, daylight can fluctuate extremely rapidly under partly cloudy conditions, and it might be important to know how the building systems respond to these rapid, very short-term variations. Because the position of the sun in the sky changes by 1 degree every 4 minutes, a 4-minute measurement interval (or fraction thereof) is a reasonable interval for measurement.

A.2.3 Specification of an Experimental Design Approach

The preparations for evaluation at Building A laid the foundation for studies at Building B. As is explained in the body of the report, the photo-electrically controlled dimming system at Building A was found to be improperly designed and/or installed, so A-level monitoring was never fully implemented.

Building B was a more effective installation, and detailed monitoring was carried out.

A.2.3.1 Building A

Building A is described in the body of the report. The literature review indicated that the two most significant variables in assessing building energy use are occupant behaviour and weather. The most effective experimental design for Building A therefore appeared to be "test-reference," in which simultaneous measurements are made for a test area and a control area, combined with an "on-off" approach. It was planned that simultaneous measurements, with similar operating conditions, be made to determine the comparability of occupancy effects on energy use for the test and control areas (simultaneous measurement would ensure that weather conditions were identical). One might call this "calibration" of the test area to ensure that it has a constant and identifiable relationship to the control. It would be important to determine that the changes to be detected would be greater than regularly occurring differences in performance. The continuous data collection would ensure that abnormal patterns over short periods would be detected (e.g., late night lighting usage in only one of the control or the test areas). The dimming capability could then be switched off for a test period, proposed, at this point, to be one week. Tests were to have been conducted in mid-winter, spring or fall, and mid-summer.

A.2.3.1.1 Specification of Data-analysis Procedures and Algorithms.

Establishment of a base level of performance by following the proposed experimental design was to have provided data for both simultaneous and sequential comparisons. Processing of collected data during collection would be minimized. This would have minimized the necessity of repeating experiments or "reconstructing" data should alternative analyses be desired or problems identified with data analysis procedures. For instance, determination of energy transfer from the perimeter radiation system requires measurement of the flow rate and the supply and return temperatures. The energy transfer is a function of the flow rate and the difference between the supply and return temperatures. Individual inspection of the three contributing values would better ensure that the data are correct than inspection of the energy flow determined from these values (e.g., the relationship between temperatures and between temperature and flow rate can be examined over time).

The relative difference technique, described in the body of the report (section 4), was to have been the basis of comparisons. Of course, if performance was not identical, but a regular relationship between the performance of the test and reference facilities was identified during "calibration, corrections would have been made according to this relationship prior to making comparisons.

A.2.3.1.2 Specification of Field-monitoring Data Points

The proposed field monitored data points, for each of the test and reference areas, were:

1. To determine electricity used for lighting

   Monitor a minimum of two comparable areas. Ensure that data is collected for both skies with and without sun.

   For Building A, the comparable areas would be, at a minimum, two floors, one being the test area, and the other, the reference. The dimming system is divided into three zones on each floor, so the number of points to monitor on two floors would be 2 to 6.

2. To determine heat transferred to and from the space of interest (heating).

   Perimeter radiation systems are widely used to provide heat in perimeter offices in cold weather. To assess the heat transfer from such systems, it is necessary to measure water flow, supply temperature, and return temperature) because such systems may be both variable flow and variable temperature. As a minimum, each of a north and south zone should be monitored to assess performance with and without direct solar radiation on the building envelope.

   Building A has 7 perimeter radiation zones on each floor, so it would be too costly to monitor all of them. Monitoring of north and south zones on two floors would require measurements at 12 points.

3. To determine heat transferred to and from the space of interest (cooling).

   This is the most difficult energy transfer to assess. Due to leakage through the envelope, not all air is returned, and the leakage is difficult to estimate. As a minimum, the heat removed from the test area should be determined.

In the case of Building A, the cooling requirement was to have been assessed, at a minimum, by measuring the heat transfer to the cooling coil on each of the test and reference floors. Since the building has an independent fan room for each floor, this is easily accomplished. Measurement of flow through the cooling coil and inlet and outlet temperatures requires monitoring of a total of six points for the two floors.

4. To determine illuminances in the space of interest.

   The illuminances should be measured at least one point in each of the daylighting zones. While measurement at the working plane would be the ideal choice, it might have been necessary to measure at points that would create lesser interference with building use (e.g., on the ceiling, where the dimming system sensors are located) and to establish a relationship between these values and task illuminances.

   In the case of Building A, it was proposed that illuminances be measured at two points in each of the three daylighting zones on each of the test and reference floors. This would require measurements at 12 points.

5. To determine daylight availability

   This would require, at a minimum, measurement of the global and diffuse illuminances and the zenith luminance.

The minimum number of measurement points, following this strategy would have been 35.

A.2.3.1.3 Verification and Quality Control Procedures

During initial operation of the data acquisition system, collected data would have been plotted and checked at intervals of an hour or less. Graphing of data quickly indicates any abnormalities.

Subsequently, the data collected would be verified at intervals of not greater than two days, allowing for rapid response in case of irregular values. Again, the data would be verified by plotting over daily periods, which allows rapid visual scanning.

A.2.3.1.4 Hardware Selection Guidelines

From the guidelines proposed by Courville and Fairchild,

- on-line processing and read-out should be in simple terms
- state-of-the-art methods should be avoided
- reliability should be emphasized over accuracy
- more emphasis should be placed on software needs and requirements

A.2.3.1.5 Recording and Data Exchange Formats

The data would initially have been stored in a customized compressed format used by the data acquisition software. It would then be transferred to common spreadsheet formats. This allows easy exchange among application software and minimizes custom programming.

A.2.3.2 Building B

Building B is described in section 3 of the report. Again, the "test-reference" approach, in which simultaneous measurements are made for a test area and a control area, combined with an "on-off" approach, seemed to be the best alternative (see 2.3.1).

A.2.3.2.1 Specification of Data-analysis Procedures and Algorithms.

Because of the difficulty of monitoring the perimeter radiation system, efforts were limited to study of cooling energy use.

A.2.3.2.2 Specification of Field-monitoring Data Points

The measurement locations, for each of the test and reference areas, were:

1. To determine electricity used for lighting

   Lighting power demand was measured at 2 minute intervals.

2. To determine cooling of the space of interest.

   This is the most difficult energy transfer to assess. Due to leakage through the envelope, not all air is returned, and the leakage is difficult to estimate. Thermal interactions also occur with the adjacent interior zone and the plenum.

In the case of Building B, the cooling requirement was assessed by measuring the cooling air temperatures and flow rates on each of the test and reference floors. Each zone was served by 4 variable air volume boxes. Pressure transducers were used to determine air flow. Two temperature sensors were used on each floor (the delivery temperatures were found to be the same at all points, except for minor fluctuations.

3. To determine illuminances in the space of interest.

   Illuminances throughout the test and reference zone were surveyed with a hand-held meter and found to be quite consistent. A sensor was placed at the workplane in the test zone.

4. To determine daylight availability

   Global and diffuse illuminances were measured at a station within the city.

The number of measurement points, following this strategy, was 18 (8 pressure values, 4 temperature values, 3 electrical values - one zone had two lighting circuits, 1 illuminance value in the building, and 2 illuminance values outdoors).

A.2.3.2.3 Verification and Quality Control Procedures

During initial operation of the data acquisition system, collected data was plotted and checked at intervals of an hour or less. Graphing of data quickly indicated any abnormalities, which did occur and required correction of sensor installations.

A.2.1.2.4 Hardware Selection Guidelines

See 2.1.1.4

A.2.1.2.5 Recording and Data Exchange Formats

The data was stored in a customized compressed format used by the data acquisition software. It would then be transferred to common spreadsheet formats. This allowed easy exchange among application software and minimized custom programming.

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APPENDIX B

The Vertical-to-Horizontal Illuminance Ratio:

A New Indicator of Daylighting Performance

Performance Indicators for Daylighting Systems

A serious difficulty in rating daylighting systems is the variability of light from the sky and sun. Unlike artificial sources, natural sources cannot be characterized by a single coefficient of utilization for a given space and fenestration system. This led to development of the daylight factor by 1895,[1] a performance indicator that is still widely used today. The daylight factor is defined as "the ratio of the daylight illumination at a given point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky. Direct sunlight is excluded for both interior and exterior values of illumination."[2] Usually, the daylight factor is determined for the work plane, a hypothetical horizontal plane taken to be 30 in (75 cm) above the floor.[3] The definition of the daylight factor is then:

$$\text{Daylight Factor} = E_{lH} / E_{lg} \qquad (1)$$

where E_{lH} is the illuminance on the work plane

E_{lg} is the illuminance on a horizontal outdoor surface with an unobstructed view of the sky (the global illuminance)

According to Hopkinson, Petherbridge, and Longmore, its advantages as an indicator of daylighting performance are:

- It expresses the efficiency of a room and its window(s) as a natural lighting system.
- Humans perceive relative rather than absolute luminances. The daylight factor provides a better indicator of the luminous environment experienced by humans than absolute illuminances because it expresses the amount of light in a space relative to the light that would be seen outdoors in sidelit spaces.[4]

Note that this assessment treats the daylight factor as a measure of both quantity and quality of illumination. Other researchers have endeavored to extend the use of the daylight factor as a measure of lighting quality.[5-6]

However, the daylight factor suffers from serious limitations. By definition, direct sunlight must not strike the exterior or interior points for which the daylight factor is determined.[2] Measured values have been shown to exhibit considerable variation under overcast sky condition.[7-8] It is difficult to determine and use in the case of clear skies because it changes with sun position.[9] The lighting of surfaces other than horizontal planes is critical in human perception of the adequacy of illumination; a strong case has also been made that this is especially important in evaluating lateral daylighting.[10-12] When daylighting performance is represented in terms of the daylight factor, the combined effects of daylight and electric light are difficult to quantify, because the intensity of artificial illumination is independent of the intensity of natural light.

More recently, coefficients of utilization have been developed and extended for application with daylighting systems.[13] These provide work plane illuminances for a given sky condition. Coefficients of utilization have been defined such that direct sunlight is excluded from the interior. They are subject to the limitations similar to those described above for the daylight factor in terms of determination by measurement and representation of the subjective quality of daylit spaces. Further, the space-window combinations for which coefficients of utilization have been developed are quite restricted. On the other hand, many coefficients of utilization have been developed for clear sky conditions and illuminances can be combined with those determined using coefficients of utilization for electric lighting.

The glare index for large area sources was introduced to provide information not offered by performance indicators such as the daylight factor and coefficients of utilization. This indicator is not easily determined by measurement or calculation, although research has provided some straightforward conclusions regarding glare from windows (see subsection 3 of *Results and discussion* under "Information Provided by the VH Ratio" below).[14]

The need for performance indicators "other than internal horizontal illuminance and external horizontal illuminance under overcast skies when designing for daylight" has been identified by designers involved in the development of innovative daylighting designs.[15] A review of the historical development of performance indicators for the evaluation of daylighting systems has been provided elsewhere.[16] The authors' experience in daylighting studies has suggested that illuminance ratios, in particular, the ratio of the vertical illuminance to the horizontal illuminance at a given point in a space (hereafter referred to as "the VH ratio" and "VH"), is a useful performance indicator. In Figure 1, the ratio of E_{IVS} to E_{IH} would give the VH ratio facing the window and the ratio of E_{IVN} to E_{IH} would give the value of the VH ratio facing the rear wall. The intensity of light coming from the side is in the numerator while the intensity of light coming from above is in the denominator. Thus, for dominant downlighting, values of VH will be less than 1.0, while for dominant lateral lighting, values of VH will be greater than 1.0. This paper will show the strength of the vertical to horizontal illuminance ratio as a performance indicator for daylighting systems relative to indoor-outdoor illuminance ratios. The criteria for assessing the indicators were:

1. stability over a range of sky conditions (stability meaning that those variations that do occur provide meaningful information, unlike instantaneous variations in the daylight factor when determined under overcast sky),

2. use with combined electric-daylighting systems, and

3. information provided including glare conditions, contrast conditions and spatial inter-reflections.

Methods and Procedures: General

The VH ratio was compared with the indoor-outdoor illuminance ratio used to determine the daylight factor. The latter illuminance ratio is defined by equation (1) above. This illuminance ration will be referred to as "DF." Because of the variability of the ratio of indoor and outdoor illuminances, even under overcast skies, the term "illuminance ratio" is used to differentiate the wide range of values obtained by measurement from the ideal reproducible value of the daylight factor for a given position. For purposes of comparison with the VH ratio, DF was determined under overcast, clear, and partly cloudy skies, covering and exceeding the range of conditions under which the daylight factor as well as coefficients of utilization are determined.

To make the assessment of illuminance ratios more comprehensive, the following were also determined by measurement and assessed in terms of stability (see Figure 1 for an illustration showing where E_{IVN}, E_{IVS}, and E_{IH} are measured):

$$\mathbf{VVH} = (E_{IVN} + E_{IVS}) / E_{IH} \qquad (2)$$

where E_{IH} is the illuminance on the work plane

E_{IVN} is the illuminance on a vertical, north-facing plane at the same point at which E_{IH} is determined

E_{IVS} is the illuminance on a vertical, south-facing plane at the same point at which E_{lH} is determined

$$\mathbf{VVF} = (E_{lVN} + E_{lVS}) / E_{lg} \tag{3}$$

where E_{lg} is the global illuminance

$$\mathbf{VV} = E_{lVS} / E_{lgvs} \tag{4}$$

where E_{lgvs} is the global illuminance on a vertical, south-facing plane (ground-reflected light is excluded)

$$\mathbf{VF1} = E_{lVS} / E_{lcl} \tag{5}$$

where E_{lcl} is the diffuse illuminance

$$\mathbf{VF2} = E_{lVS} / E_{lg} \tag{6}$$

The following sections will address stability of the indicator first and information provided second.

Relative stability of indoor-outdoor illuminance ratios and the VH ratio

Methods and procedures

The indicators were compared for five fenestration systems (Figure 2), primarily using data obtained by full-scale photometry under real overcast, clear, and partly cloudy skies. As will be discussed below, some data obtained by computer simulation were also used.

Two south-facing test spaces were constructed, identical except for interior reflectances of 0.05 and 0.83. The fenestration systems, the test spaces 8 x 9 x 24 ft (2.4 by 2.7 by 7.3 m) (h·w·d), and the monitoring system and procedures are discussed in detail elsewhere.[17-18] Photometric measurements were made in June and July, with a maximum sun altitude of about 71 degrees. Measurements were recorded every 10 seconds. Every 30 seconds the most recent three readings were averaged and this value was stored in a hard disk file. Daylight availability and sky conditions were recorded by measuring E_{lg} (global illuminance), E_{lcl} (diffuse illuminance), E_{lgvs} is the global illuminance on a vertical, south-facing plane (ground-reflected light excluded), and L_Z (zenith luminance). Interior illuminances (E_{lH}, E_{lVS}, and E_{lVN}) were measured at the illuminance determination points (designated MIN, MID, and MAX) used in the *Recommended Practice of Daylighting*[19] (Figure 1).

At the time of year when testing was conducted, sun angles were such that direct sun did not strike any of the measurement positions (measurement points were limited by the availability of photocells). Computer simulation[20-21] was used to compare the behavior of the selected daylighting indicators with varying penetration of direct sun (Figure 1).

Results and discussion

With south-facing fenestration, the VH ratio was determined from

$$VH = E_{lVS}/E_{lH} \quad (7)$$

While the VH ratio can be determined for any direction, this orientation (facing the window) would be subject to the greatest variations. Where the vertical and horizontal illuminance are so low as to yield meaningless values, as for window 3b in the low reflectance space, VH is taken to be zero - this indicates no directional effect and makes more sense than the results of dividing zero by zero.

The following equation was used to rate the variability of the daylighting indicators:

$$\text{variability} = 100\% \cdot \frac{(\text{median absolute deviation of VH / median VH})}{(\text{median absolute deviation of DF / median DF})} \quad (8)$$

The following data selection regimes were followed in comparing indicator stability for each sky condition:

1. overcast - all 120 illuminance values stored for a one hour period were used in comparing indicators. Two criteria were used in selecting the test data from measurements for overcast days: 1) the median ratio of E_{lcl} to E_{lg} exceeded 0.90 or greater and 2) the median absolute deviation[22] of this ratio (E_{lcl}/E_{lg}) had to be 1.5 percent or less of the median (Figure 3). The one hour comparison period was used because the skies measured seldom met the two preceding criteria for more than an hour at a time. These conditions were chosen to be most favorable to the daylight factor and to provide the most severe test for the VH ratio.

2. clear - to allow comparison over a wide range of sun positions, values were selected at four minute intervals (corresponding to a one degree change in sun position) over six hour periods ending or beginning at solar noon.

3. partly cloudy - the same value selection was used as for clear sky conditions, except that

conditions fluctuated between no interruption of the direct solar component and near overcast sky (Figure 4).

Figures 5 and 6 show VH and the DF for the partly cloudy sky represented in Figure 4. The relative stability of VH for each measurement point is obvious. These findings are consistent with those for virtually all sky conditions, window types, and measurement positions.

In the case of the high-reflectance space, the maximum variation in VH was 25 percent or less of the maximum variation in DF for 80 percent of the combinations of window type, sky condition, and measurement position which were studied (Figure 7). The maximum variation in VH was 10 percent or less of that for DF for 35 percent of the combinations tested. In the case of the low reflectance space, the maximum variation in VH was 25 percent or less of the maximum variation in DF for more than 40 percent of the combinations of window type, sky condition, and measurement position which were studied (Figure 8).

While it might appear from Figures 7 and 8 that the maximum variation in VH approached or exceeded that in DF in a few instances, this was due to the limiting 10 lx resolution of the data acquisition system. Small absolute changes in E_{lVS} and E_{lH} at levels of 0 to 100 lx produce a disproportionately larger percentage variation in VH than in DF (the levels of E_{lcl} are in the order of 2000 lx even under very dark skies, so the percent variation in the denominator of DF was not significantly affected by low-level measurement limitations).

The other performance indicators were all considerably less stable than VH, except VVH (equation 2). Detailed results for the performance indicators other than VH and DF are presented elsewhere.23 VVH is not addressed further in this paper because the human visual field covers (approximately) a hemisphere rather than a sphere (VVH incorporates the light coming from both before and behind the observer's position). VH also involves two measurements rather than three, so is easier to use.

Use of performance indicators with combined electric and daylighting systems

It will be shown that the VH ratio can be used for electric lighting systems and for integrated electric-daylighting systems.

Methods and procedures

Measurements of the VH ratio were made for a space:

1. illuminated by daylight only

2. illuminated by electric light only
3. illuminated by combined daylight and electric light

The dimensions of the test space are shown in Figure 21. It is a classroom at 51° north latitude, and is six feet deeper than the test spaces used in the other experimental work. The fenestration consists of clear double-glazing with an exterior shading system of vertical fins (Figure 21). The window wall faces southeast, and the windows may be covered with "black-out" drapes with a reflectance of about 0.8. The wall and ceiling reflectances are about 0.8, while the floor is a light gray tile with a reflectance of about 0.4, resulting in an average room surface reflectance of about 0.6.

The VH ratio was determined for the MIN, MID, and MAX positions from measurements taken under the three illumination conditions listed above. Experimental findings discussed above shown that the VH ratio does not vary substantially with sky condition as long as there is no change in the presence of direct sunlight at the point of interest. The measurements for the VH ratio with electric lighting were performed with the "black-out" drapes drawn.

Results and discussion

The VH ratio was determined for the MIN, MID, and MAX positions from measurements taken under the three illumination conditions listed above (Figure 22). As has been shown above, the VH ratio does not vary substantially as long as there is no change in the presence of direct sunlight at the point of interest. The results reported were made well after solar noon, when direct sunlight did not strike the fenestration of the test space. The measurements for the VH ratio with electric lighting were performed with the "black-out" drapes drawn.

The values of the VH ratio show that the illumination provided by daylight has a strong lateral emphasis. It may be seen that this emphasis increased with distance from the window wall, as might be expected. The VH ratios for the test classroom illuminated only by daylight lie about halfway between VH ratios for corresponding points in the low- and high-reflectance test spaces used in the variability comparisons described above.

The electric light had a downward emphasis. In fact, the VH ratio was less than 0.5, which shows the small relative magnitude of the lateral lighting. The only source of lateral illumination with conventional luminaires is reflected light. Lateral lighting contributes significantly to contrast for horizontal tasks, and hence to contrast for those tasks. It can be seen that this electric lighting system is not very effective at providing lateral illumination.

The combined systems have a fairly balanced distribution of light, although there is a slight horizontal emphasis in the half of the room nearest the window.

Information Provided by the VH Ratio

Methods and procedures

Data obtained by the measurements described above in the section on relative stability of indicators was used, as well as computer simulation.

The computer simulation programs[20-21,24] were used to calculate the glare index and the VH ratio for purposes of comparison. The space analyzed is that used to illustrate the daylighting capabilities of an energy use simulation program. It is a 10 by 20 by 30 ft (3 by 6 by 9 m) (h·w·d) space with a 3 ft (1 m) continuous window 4 ft (1.2 m) above the floor. The reflectances of the ceiling, walls and floor are 0.7, 0.5, and 0.2, respectively. The window has a direct normal visible transmittance of 0.35 with an internal reflectance of 0.15. Other conditions used in the simulation are described in the program documentation.[25]

Results and Discussion

It has been shown that the VH ratio can accommodate the presence of direct sunlight, unlike the daylight factor and current versions of coefficients of utilization. It can also be used for both electric and daylighting systems, unlike the daylight factor. It also provides a wealth of performance information, as will be shown in this section.

1. As was noted above, variations in the daylight factor across a space for a given set of conditions overstate the variability of illumination in terms of human perception.[11] VH avoids this variability where it is misleading. This is illustrated in Figures 5 and 6. VH is almost identical at the MIN and MID positions, while DF varies markedly for the same two positions. On the other hand, VH is quite different at the MAX position due to the way window 4 directs daylight into the space.

2. Figures 9 and 10 show DF and VH for five different solar altitudes as determined by computer simulation (DF was taken to be the workplane illuminance divided by the diffuse illuminance outdoors, as direct sunlight must be excluded from both exterior and interior measurement points, by definition). Although the values of DF with direct sunlight present at the interior point (marked by asterisks in Figure 9) are excluded by the standard definition, they are shown for purposes of comparison. One difficulty with values of DF that exclude direct sunlight outdoors is that the interior illuminance is being related to only part of the outdoor illumination (indeed, the less intense part). On the other hand, if DF is computed with direct sunlight indoors and outdoors, misleading values can result. For instance there is no change in the value of DF at the MIN position when the sun angle changes from 18 to 13 degrees for the example space even though the MIN position does not received

direct sunlight at the former sun angle and does receive direct sunlight at the latter sun angle. While VH is similar in some circumstances with and without direct sunlight at the point of interest, the meaning of the indicator is better understood from the types of time series plots shown in Figures 6 and Figures 18-20 (discussed below) or from comparisons of VH ratios for different parts of a space at the same point in time. If direct sunlight is excluded form both interior and exterior illuminances used to compute DF, the indicator ceases to reflect major elements of the visual experience.

3. VH gives a good indication of the directionality of light flowing into a space. This is dramatically illustrated by examining the effects of varying direct sun penetration in the low-reflectance space (Figure 11). Illumination is most laterally directed at the MIN position, and it is at this position that the VH ratios are the greatest. The directionality of light is quite similar at the MID and MAX positions (because of the solid angle of sky subtended by the photocells at these locations relative to the MIN position when there are essentially no inter-reflections in the space) except in the case where the MAX position receives direct sunlight and the MID position does not (e.g., at 30 degrees solar altitude).

Now reconsider Figure 10. The effect of the high-reflectance surfaces is to reduce the lateral directionality of the lighting, and this is reflected in VH. The effect is most noticeable at the MIN position which experienced the most exaggerated lateral illumination in the low-reflectance space.

4. The VH ratio can provide quantitative information on glare conditions because, when determined facing a window, it relates the light flowing from the window to that in the rest of the space. For instance, the values of VH in Figure 10 are half or less of those in Figure 11, indicating that glare is greatly reduced with a high-reflectance interior. In a space with perfectly diffused illumination, VH would approach 1, as it does for the MAX position with window 4.

Recent research on glare has shown that as long as the area of the windows in a daylit space exceeds two percent of the floor area of the space, the character of the glare will not change with observer position or window size.[14] This is noteworthy because glare for the smaller sources typically used in electric lighting systems is highly depended on observer position and the size of the source. The greatest influence on the glare in daylit spaces with such windows is the sky luminance. This only holds true for spaces with average interior surface reflectances of 0.4 to 0.6, but reflectances falling into this range are typical of most spaces designed for human occupation. The general evenness of the VH ratio across the high-reflectance test space (Figures 13, 15, and 17) is consistent with these recent findings regarding glare in daylit spaces.

Glare conditions, as represented by the glare index and the VH ratio, were compared by computer simulation with the test space facing north. The glare index was determined for a point on the centerline of the space normal to the window wall and 10 ft (3 m) from it. As shown by the documentation for the program with the built-in capability of determining the glare index, the most extreme values occurred with a sun altitude of 10 degrees and azimuth (measured clockwise from north) of 290 degrees.[26] Under overcast sky, it was 4.9, while under clear sky, it was 15.2 (under all other sky conditions in the example, the glare index ranged between 10.7 and 16.1). The VH ratio for the same conditions was 0.6 and 0.3 respectively. The large change in VH ratio corresponds to a large change in the glare index. This is significant because the VH ratio has been shown to be very stable when visual conditions are not changing substantially. When determined facing the window, the VH ratio for this space was 3.0 under clear sky and 2.3 under overcast sky.

5. Window type rather than sky condition dominates as a cause of difference among VH values. The effect is most noticeable in comparing VH for window 4 with VH for windows 1, 2, and 3a (Figures 13, 15, and 17). VH for the MAX position with window 4 is about half that for the other three windows because light enters near the top of the window wall. The vertical component at this position is therefore reduced with respect to the horizontal component.

The VH ratios for the low-reflectance spaces also show that window type rather than sky conditions is a greater contributor to variations (Figures 12, 14, and 16). The variations among window types are large (compared with those for the high-reflectance space) since there are no internal reflections to even out the directional effects of the side-lighting. Where there is no direct component of daylight, this is indicated by VH having a zero value (i.e., for window 3b).

The high-reflectance space approaches the qualities of an integrating sphere and reduces the directional effects of the side-lighting (compare Figures 12 and 13, 14 and 15, and 16 and 17). At the rear of the space, VH hardly varies with window type and sky condition because the internally reflected component of daylight dominates in determining the directional qualities of light. The greatest differences in VH occur at the MAX measurement position. The maximum difference between the minimum and maximum values of VH with different sky conditions is about 25 percent for windows 1 and 2 at the MAX position (clear versus partly cloudy conditions). For most other positions and window types, the maximum variation for VH with different sky conditions is 10 percent or less.

6. Variations in VH over time provide information on changing light distribution in a space. The plot for the 1 m high unshaded window shows an increasing horizontal component as the sun rises in the sky (Figure 18). Addition of horizontally set venetian blinds has pronounced effects on the admission of daylight and direct sun (Figure 19). VH is higher at all measurement points with the blinds. Throughout the morning, the blinds reflect much of the skylight to the ceiling of the space where it increase the contribution to E_{lH}. From hour 2 to hour 3, low-angle direct sun can enter the

space. As the sun rises, the blinds cut off direct sunlight and redirect it to the ceiling of the space; the effect is especially noticeable after hour 4 as the sun rises above 55 degrees solar altitude. The relative positions of the VH ratios show these changes. For instance, the VH ratio at the MIN position drops below that for the MAX position around hour 4, showing that E_{lH} is increased at MIN.

When the blinds are tilted 45 degrees (window 3b), the VH ratios become much more stable, since the direct component of daylight is eliminated. VH at the MAX position is lowest, since E_{lVS} at that position is largely determined by the luminance of the rear faces of the tilted blinds. At the MIN and MID positions, the luminance of the ceiling in the front half of the space boosts E_{lVS} more than E_{lH}.

7. Contrast potential has been defined for a space with overhead electric lights and negligible internal reflectance as[27]

$$CP = (H - V_n)/H \qquad (9)$$

where CP is the contrast potential

H illuminance on a horizontal task surface at point subtending a 25° angle to the observer

V_n illuminance on a north-facing (away from the observer) vertical surface at point subtending a 25° angle to the observer

This equation may be reformulated as

$$CP = 1 - (V_n / H) \qquad (11)$$

showing that, the VH ratio is the essential component of contrast potential.

Contrast potential is not in itself a measure of contrast. Rather, it is an indicator of the potential to create contrast based on the relative proportion of flux originating from the northern hemisphere [above the working plane] to the total flux on the horizontal. A close correlation has been shown to exist between contrast potential and contrast rendition factor for values of CP between 0.2 and 0.95. The results also show better contrast as the directionality of light becomes more horizontal (but is not in the offending zone). This is consistent with findings on contrast in daylit spaces: "...windows are particularly effective at providing high contrast environments."[28] As values of VH reflect the directionality of light, it would appear that the use of the measure could be extended to provide a measure of contrast under sidelighting as well as under overhead lighting.

To summarize earlier findings:[27]

> the illuminance-based technique is indicative of contrast potential across the entire task plane since large solid angle measurements are utilized . . . . . Large solid angle measurements present other advantages over the luminance contrast meter. With the contrast meter, a series of repetitive measurements need to be conducted for an accurate and complete assessment. With the illuminance-based technique, only one measurement is required. As contrast potential measures incident flux, and not reflected flux, it represents a measure that is independent of task type.

8. Ease of measurement

The VH ratio can be more easily determined than the daylight factor in full-scale spaces or models under real sky conditions. Because it does not vary widely with sky condition (except for extreme cases such as the sudden entry of sunlight), a survey of the VH ratio for a space can be conducted with less concern for appropriate sky conditions, elapsed measurement time, and other difficulties posed by the daylight factor and other indoor-outdoor illuminance ratios.

The VH ratio has been used in developing both sidelighting and skylighting systems for buildings as diverse as a school and a university personal computing centre. Its utility has been especially evident in dealing with designs where direct sunlight penetrates spaces of interest, in which case performance indicators such as the daylight factor are not applicable. The authors plan to address application of the VH ratio in future publications.

Conclusions

The VH ratio has been shown to be much more stable over time than the daylight factor for any real sky conditions. Its variations in space and time are much more meaningful than those of the daylight factor and other illuminance ratios; they can be interpreted to compare the daylighting qualities of alternative window systems in terms of direct sun control, the dynamic effects of sunlight on shading systems, and the interior distribution of daylight, including inter-reflections. Its absolute values can provide information on the presence or absence of direct sun, glare, contrast, and the balance of daylight illumination in a space. The VH ratio is also very simple to determine under a wide range of conditions.

Further research is needed to better determine such relationships as that between human assessment of illumination quality (e.g., glare conditions, contrast) and values of the VH ratio for various space-fenestration combinations.

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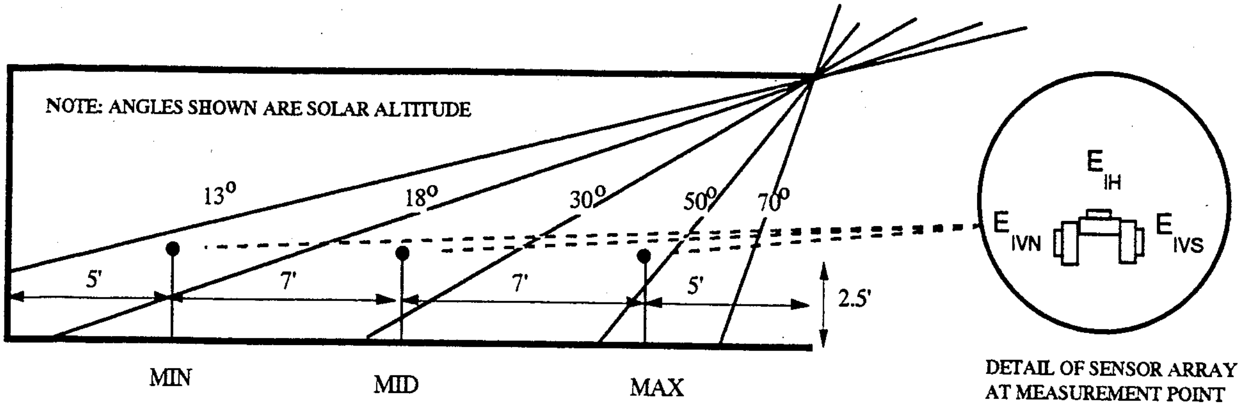

Figure 1 - Longitudinal section of the test space showing measurement positions as well as direct sunlight cutoff angles for selected solar altitudes.

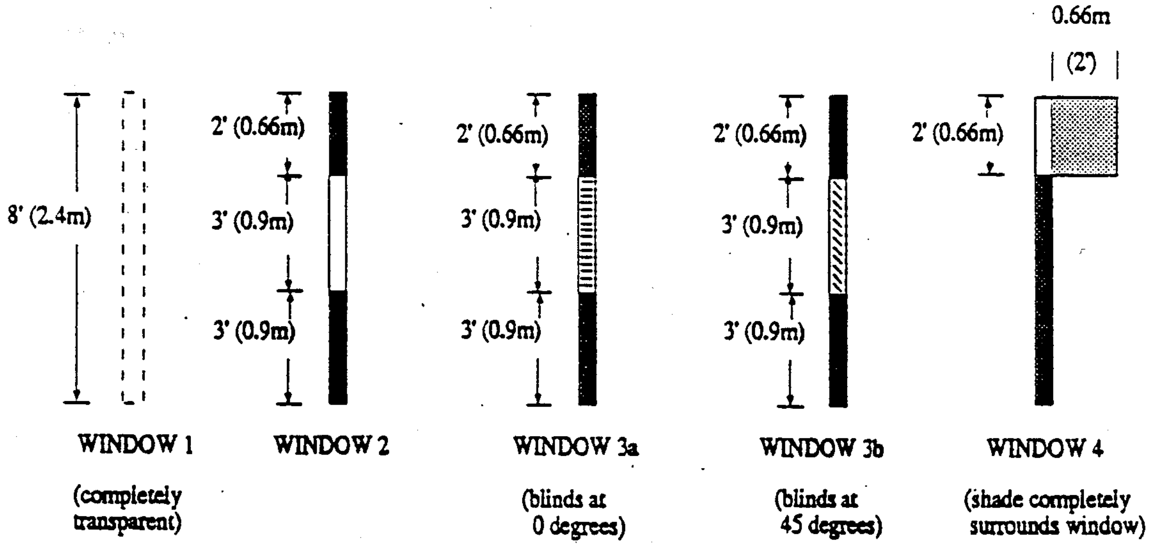

Figure 2 - The test windows.

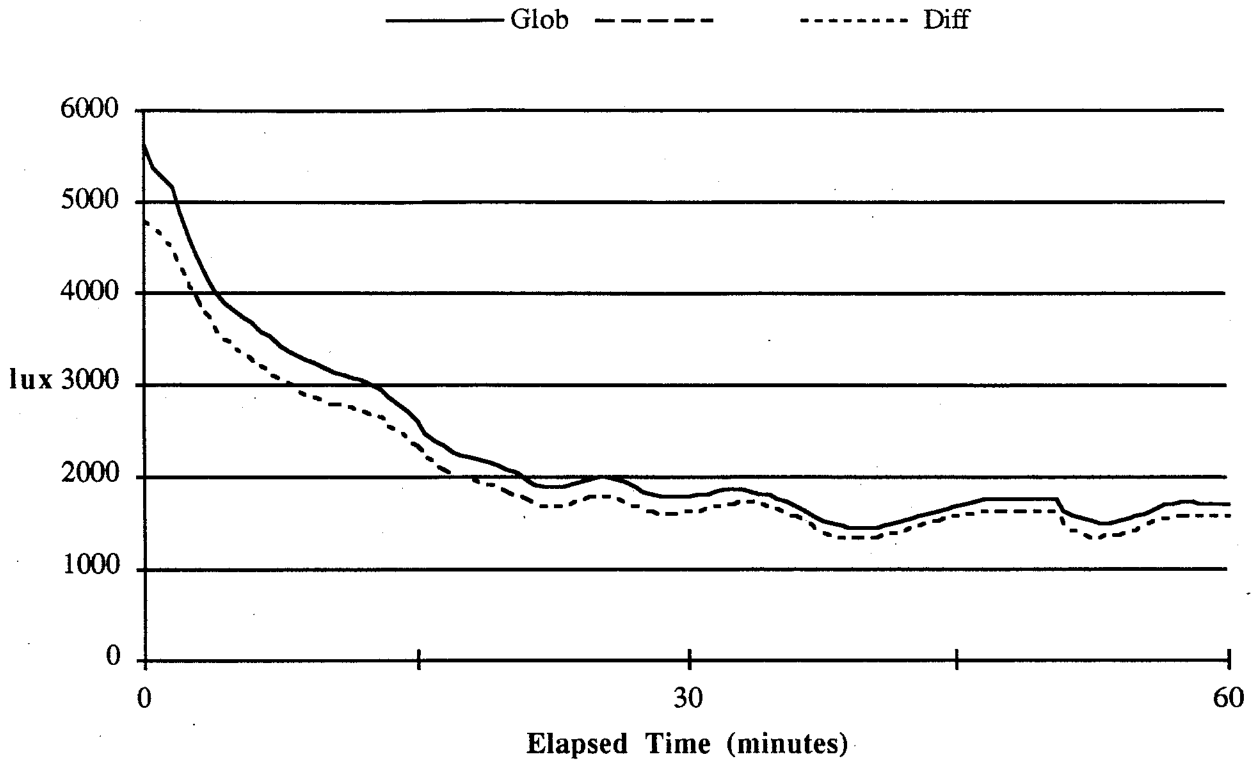

Figure 3 - Global and diffuse illuminances for a typical 1 hour overcast period used in comparing DF and VH.

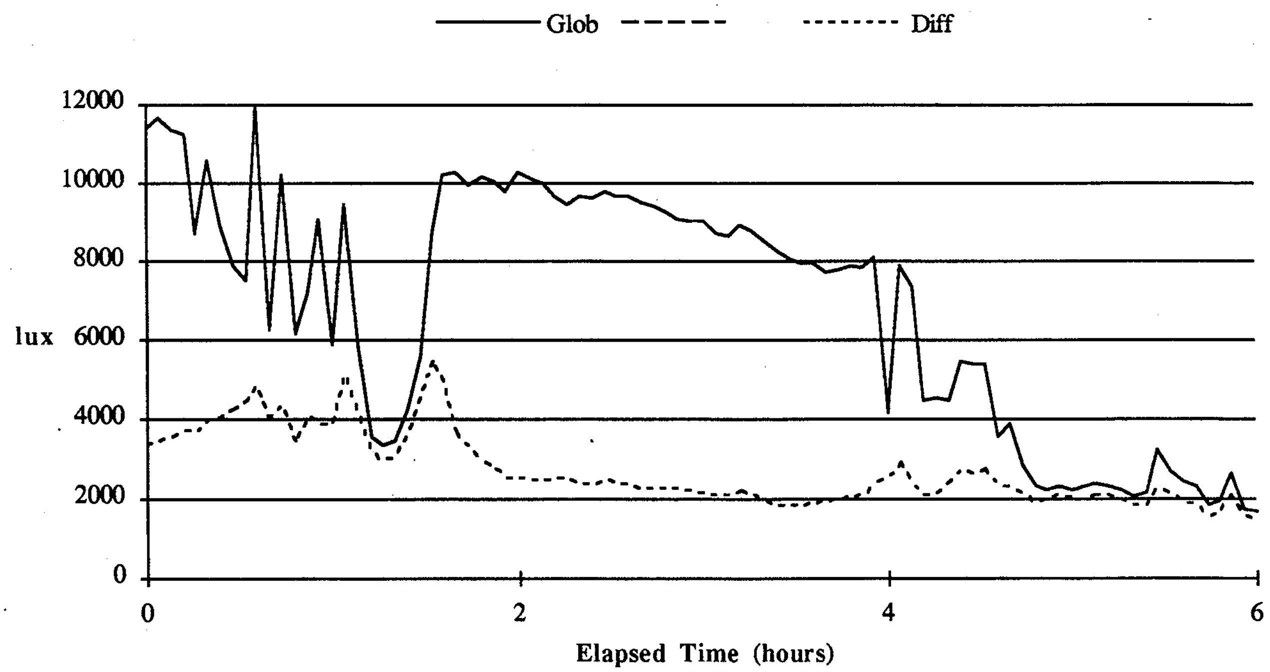

Figure 4 - Global and diffuse illuminances for a typical 6 hour partly cloudy period used in comparing DF and VH (period begins at solar noon).

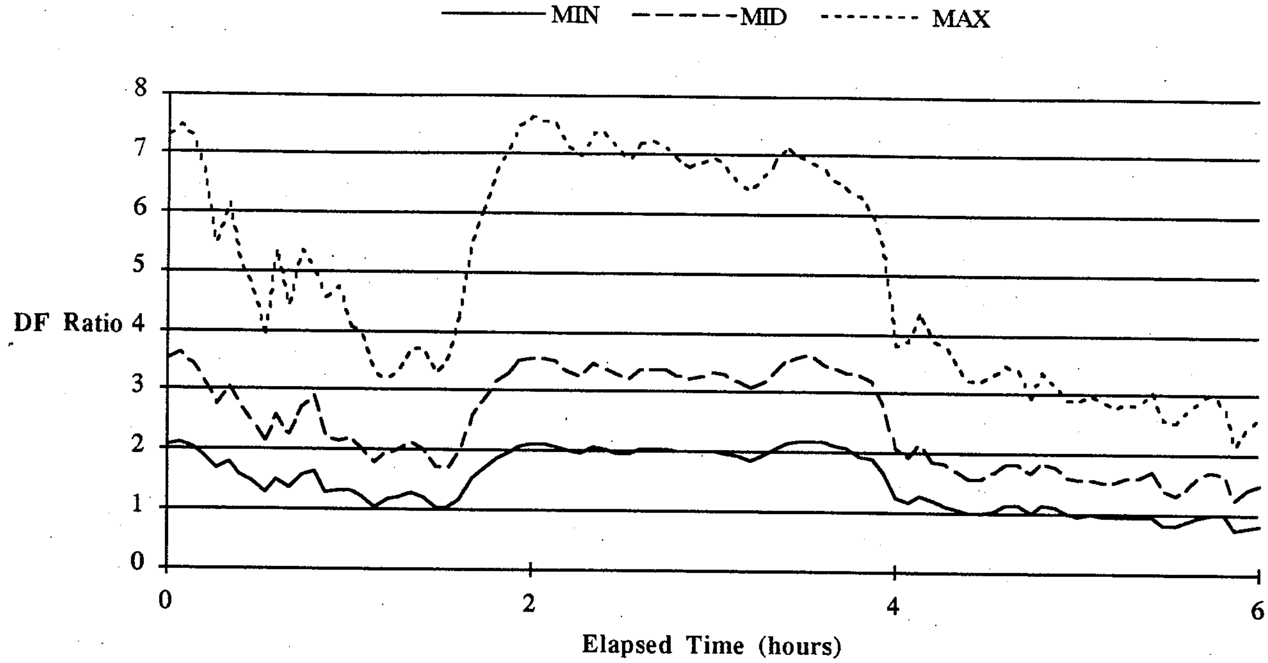

Figure 5 - DF at three measurement positions in the high-reflectance space with window 4 for the 6 hour test period under the partly cloudy sky shown in Figure 4..

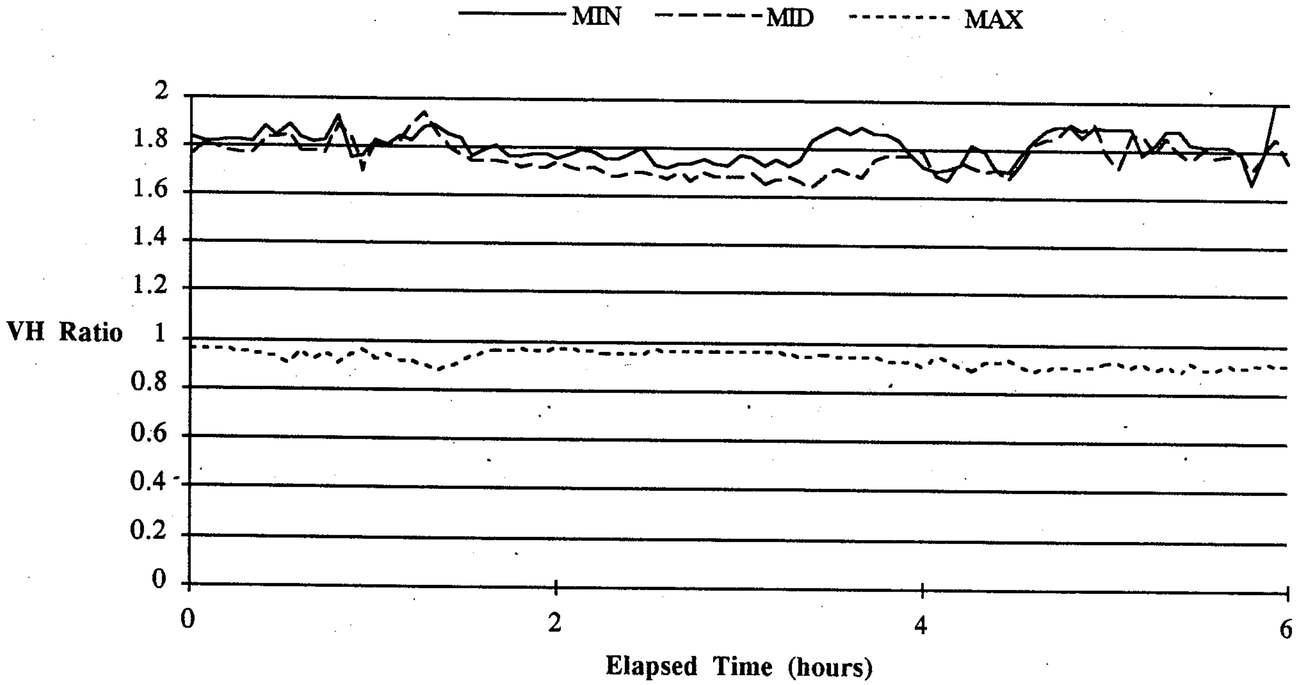

Figure 6 - VH at three measurement positions in the high-reflectance space with window 4 for the 6 hour test period under partly cloudy sky shown in Figure 4.

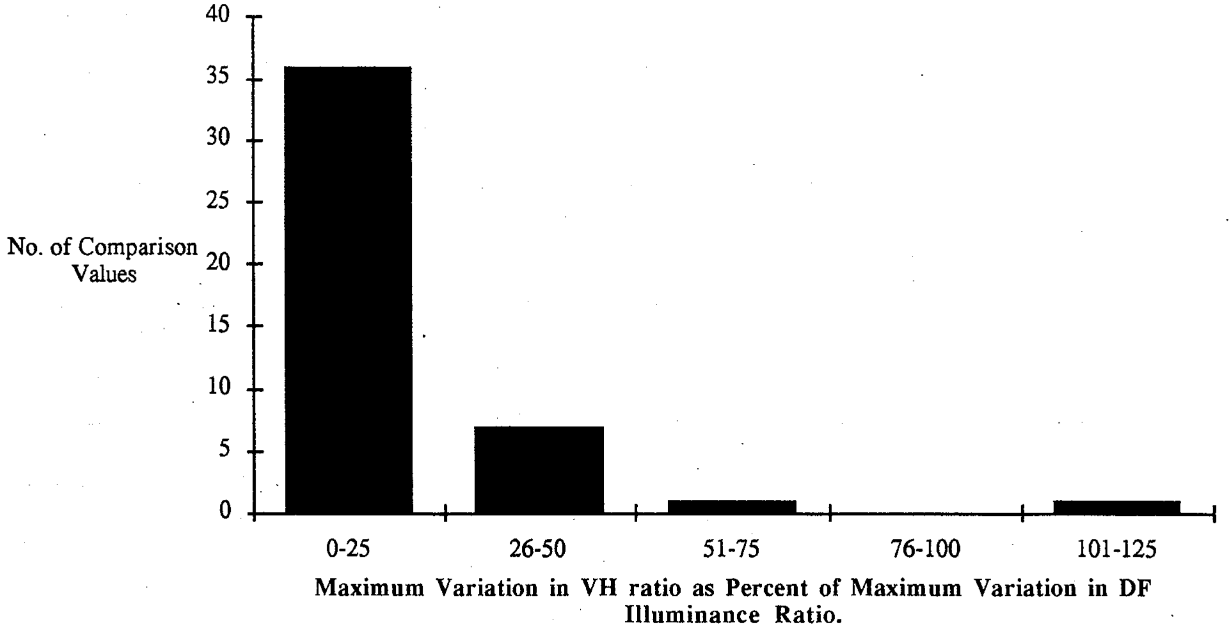

Figure 7 - Maximum variation in VH compared with maximum variation in DF for the high-reflectance space with each of the five test windows at each of the three measurement points under overcast, clear, and partly cloudy skies.

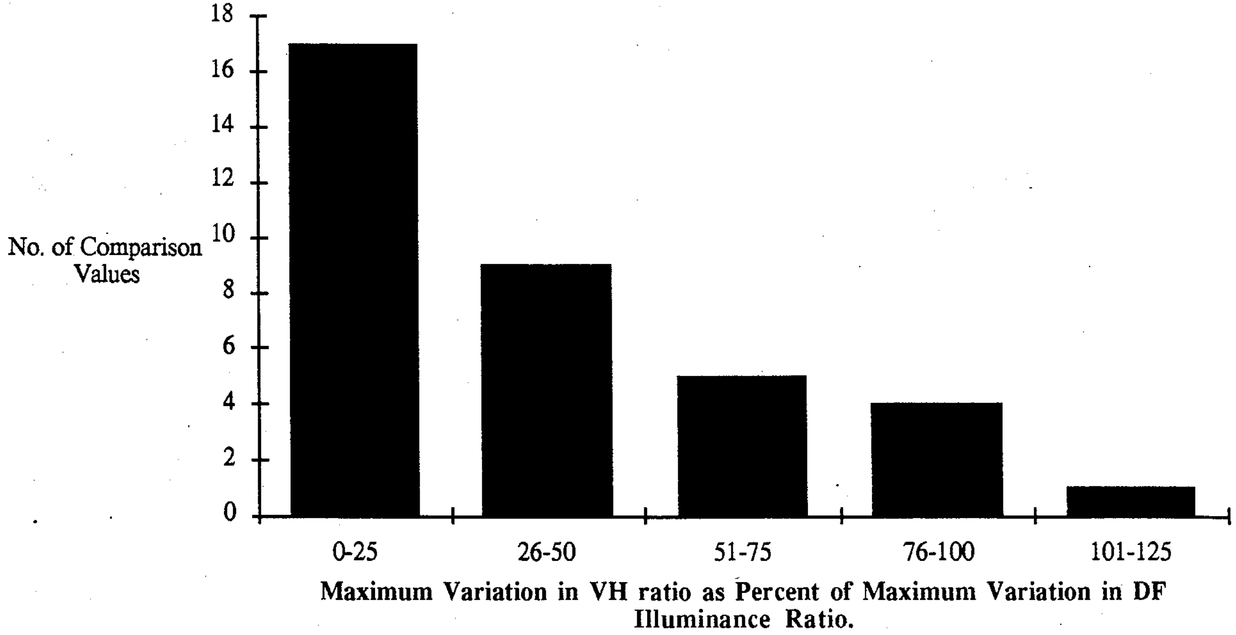

Figure 8 - Maximum variation in VH compared with maximum variation in DF for the low-reflectance space with each of the five test windows at each of the three measurement points under overcast, clear, and partly cloudy skies.

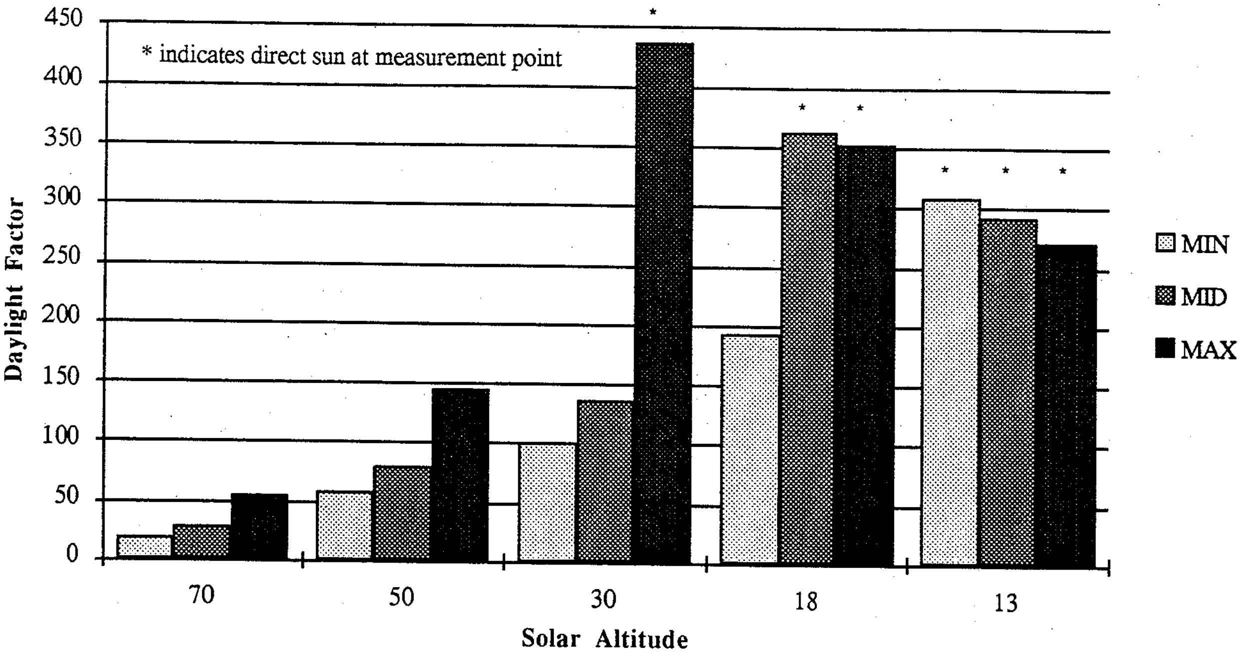

Figure 9 - DF for different solar altitudes as determined by computer simulation; high-reflectance space with window 1 at solar noon under clear sky. Direct sun on the illuminance determination position indicated by an *.

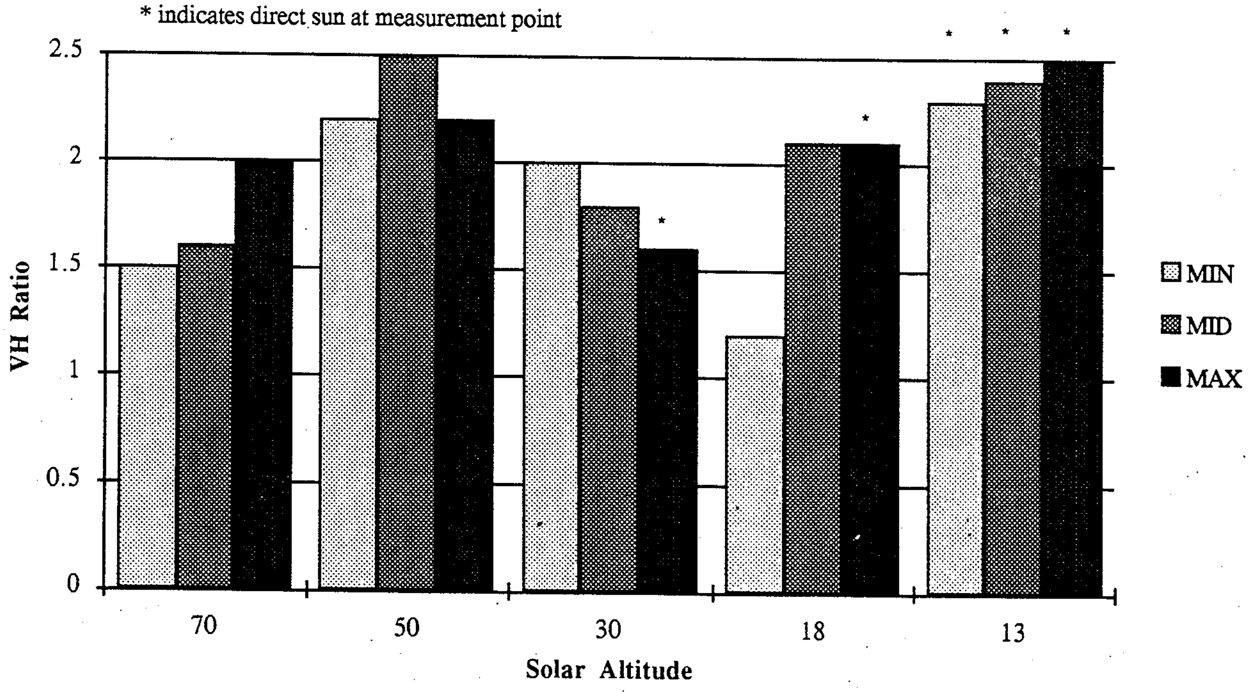

Figure 10 - VH for different solar altitudes as determined by computer simulation; for the high-reflectance space with window 1 at solar noon under clear sky. Direct sun on the illuminance determination position indicated by an *; VH illuminance ratios shown for selected positions.

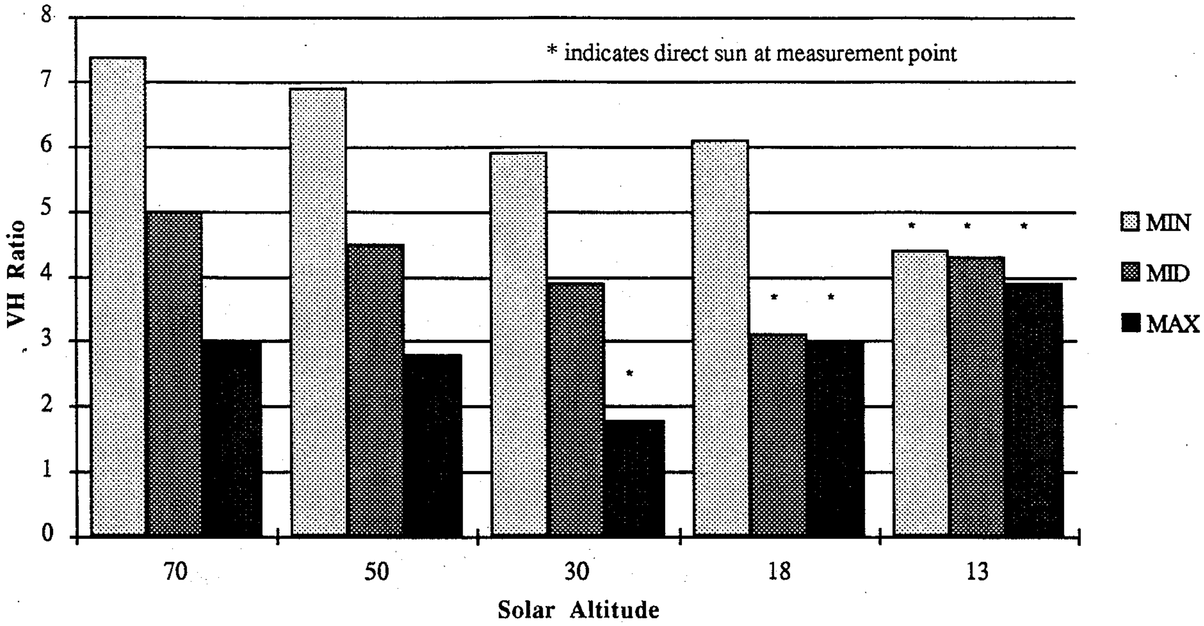

Figure 11 - VH for different solar altitudes as determined by computer simulation; for the low-reflectance space with window 1 at solar noon under clear sky. Direct sun on the illuminance determination position indicated by an *; VH illuminance ratios shown for selected positions.

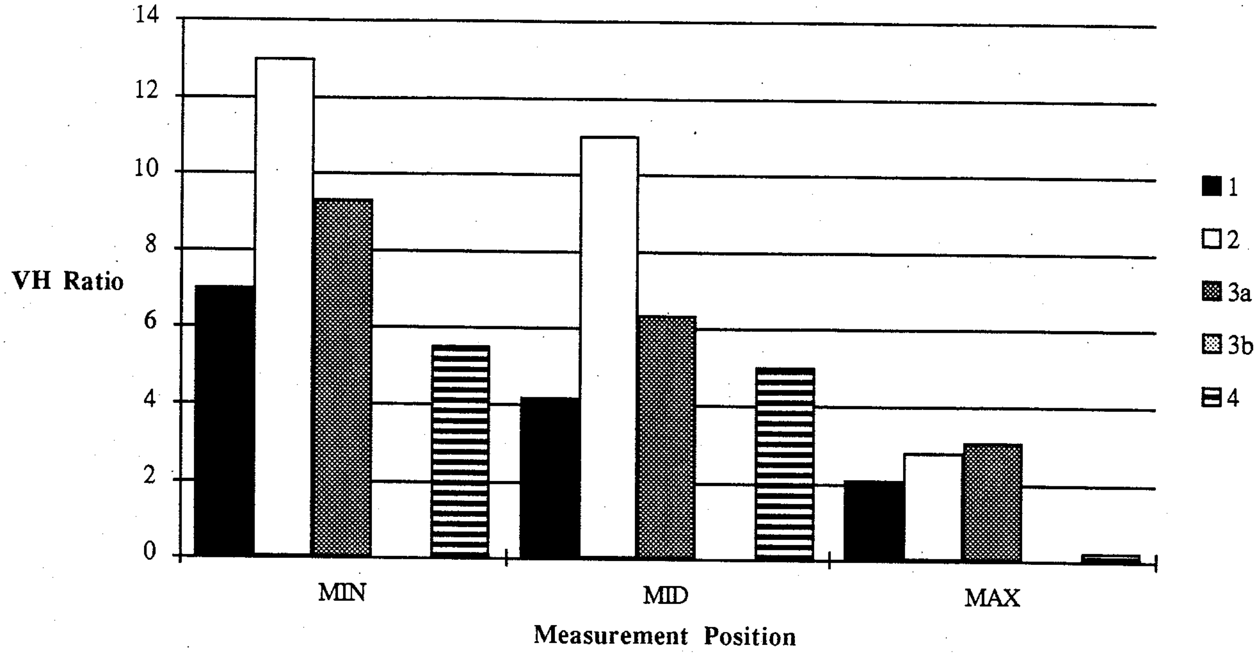

Figure 12 - VH ratios for the low-reflectance space with each of the five test windows; overcast sky.

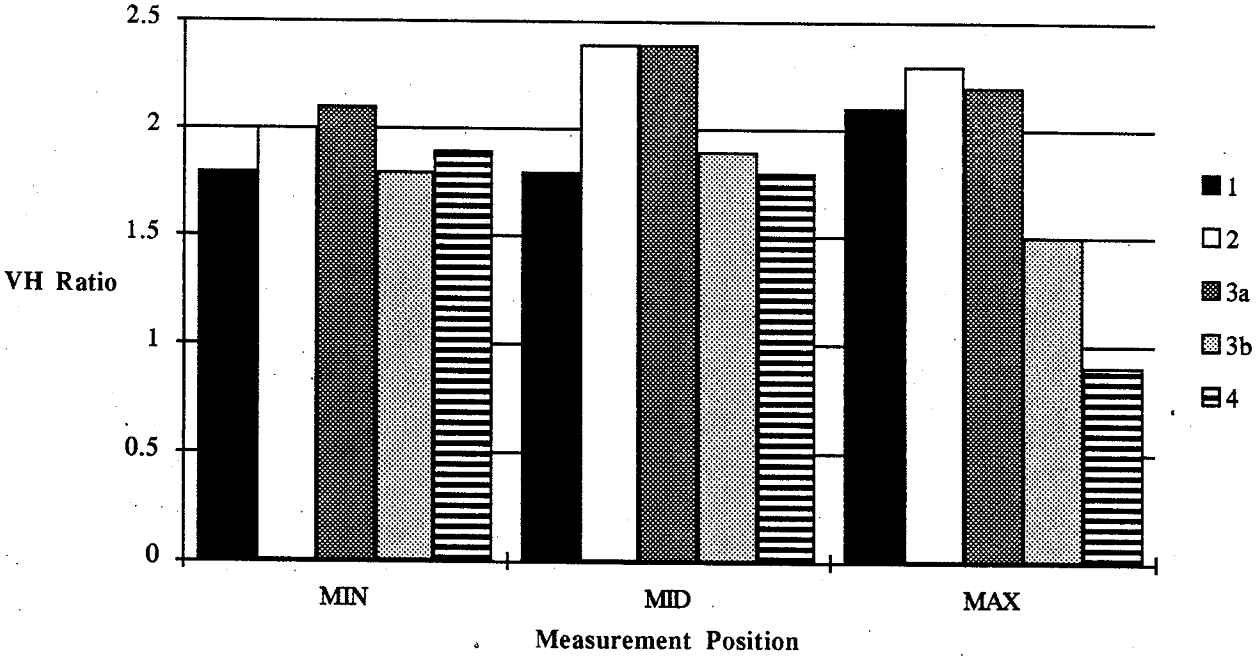

Figure 13 - VH ratios for the high-reflectance space with each of the five test windows; overcast sky.

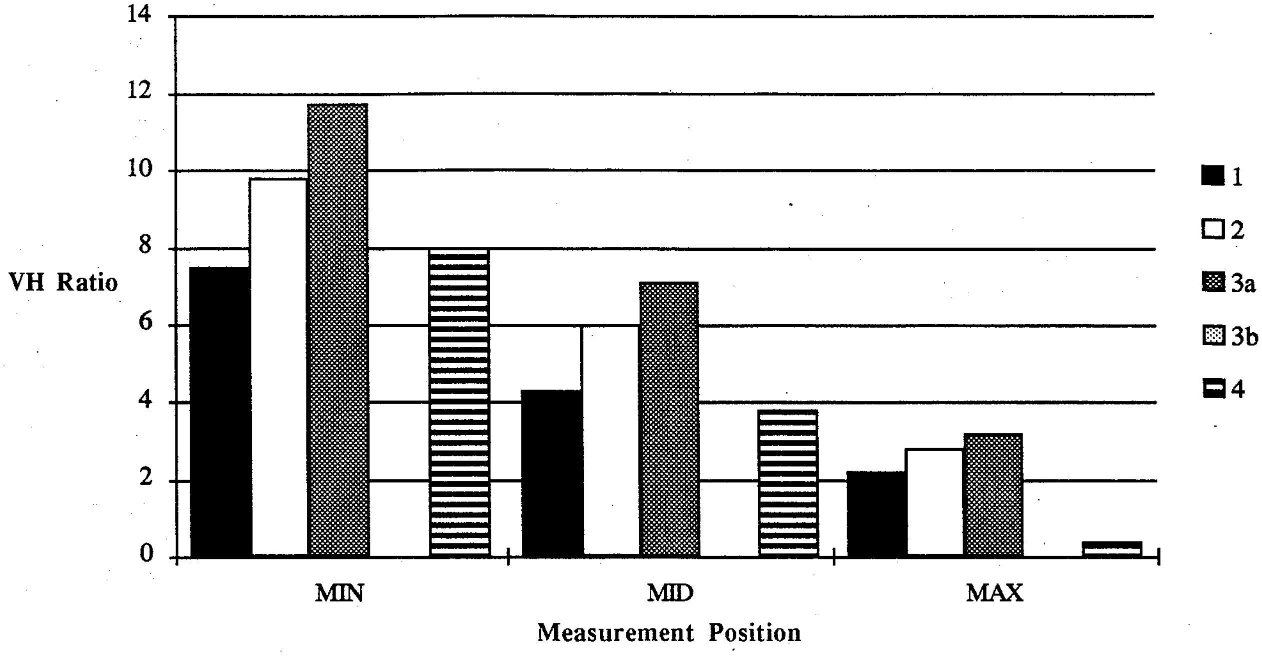

Figure 14 - VH ratios for the low-reflectance space with each of the five test windows; partly cloudy sky.

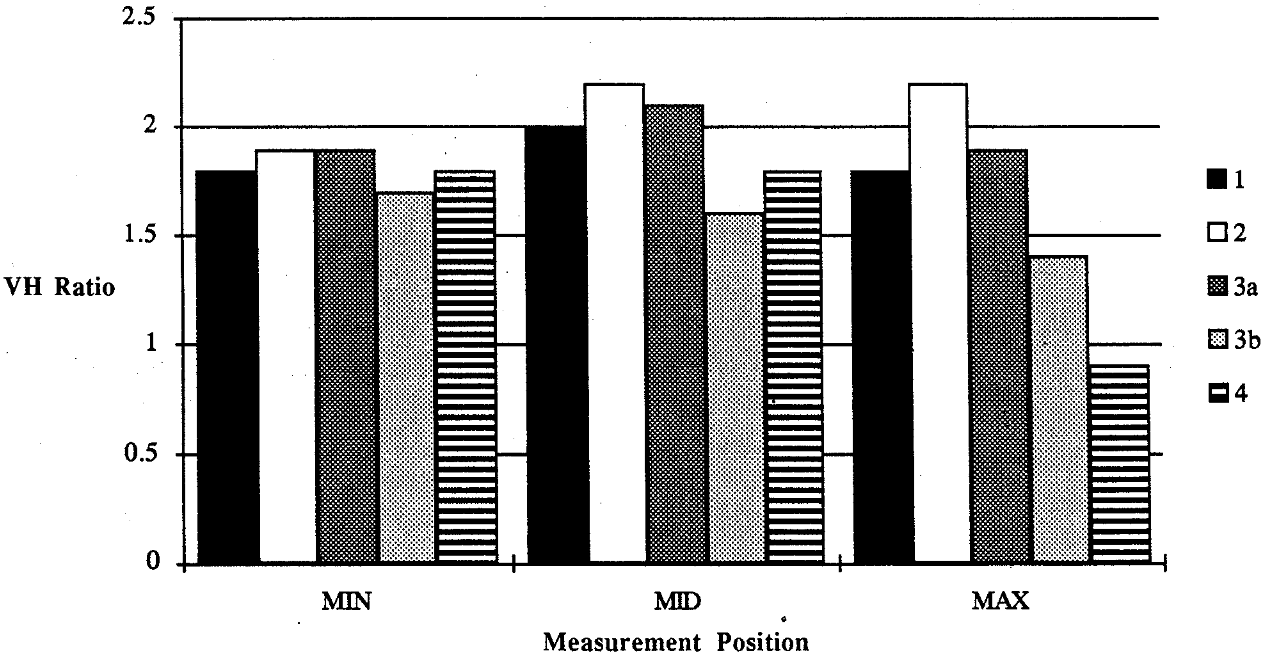

Figure 15 - VH ratios for the high-reflectance space with each of the five test windows; partly cloudy sky.

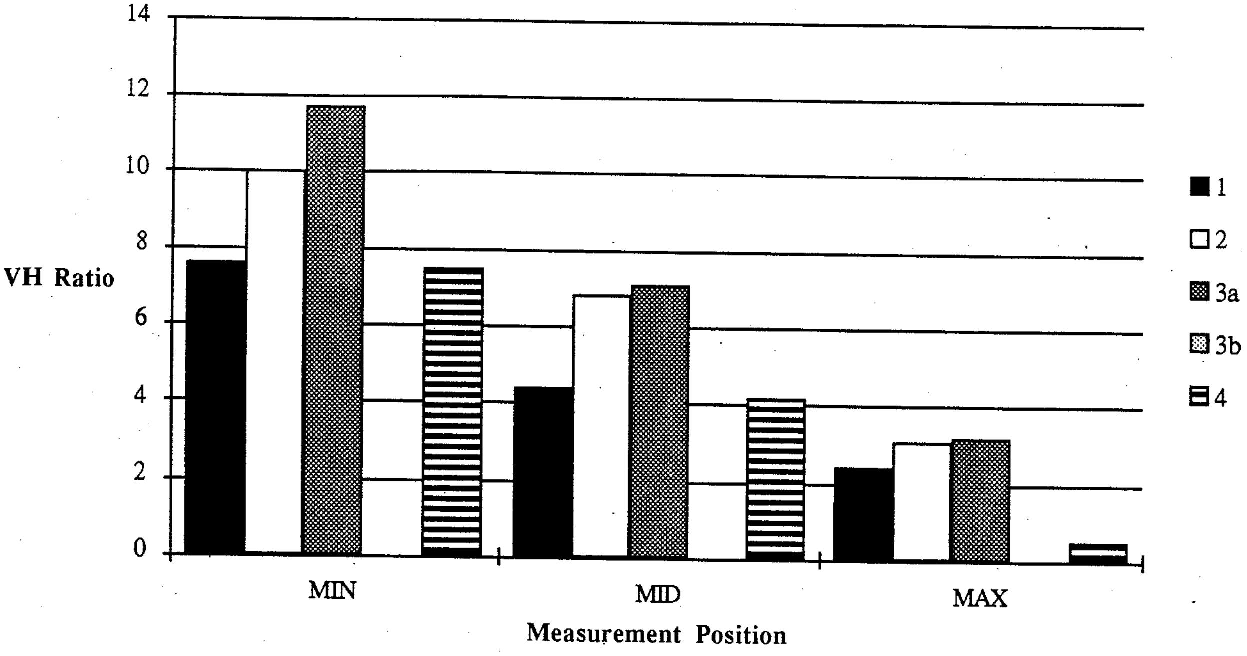

Figure 16 - VH ratios for the low-reflectance space with each of the five test windows; clear sky.

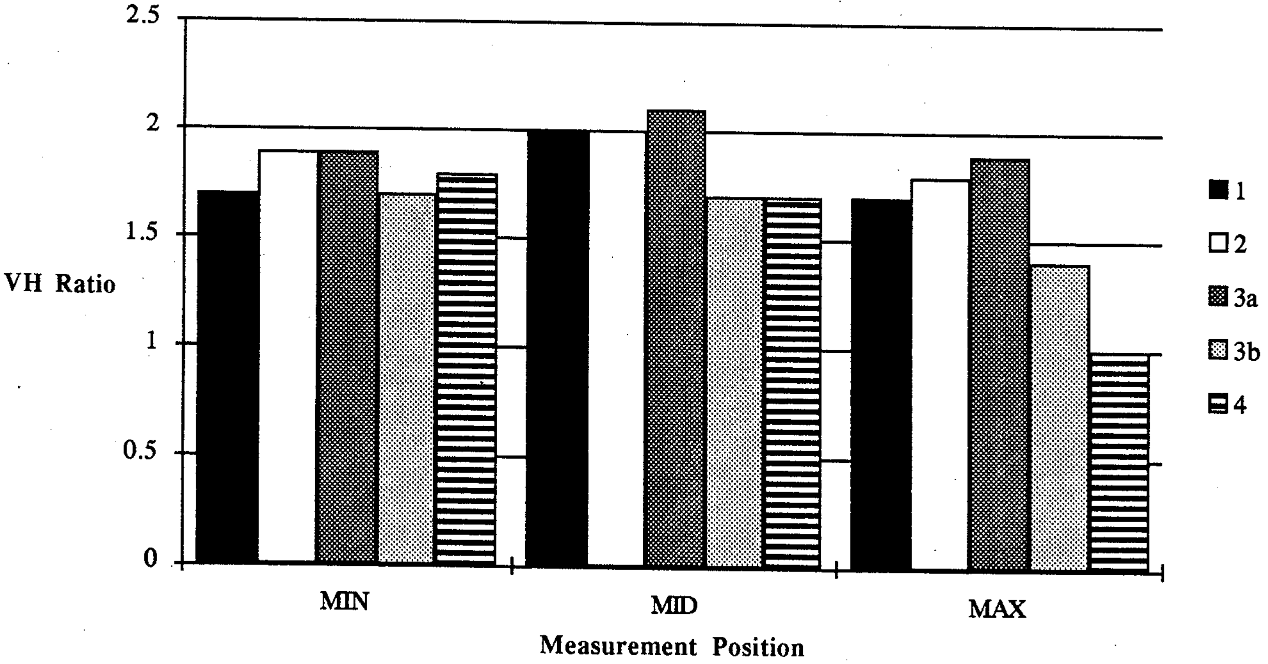

Figure 17 - VH ratios for the high-reflectance space with each of the five test windows; clear sky.

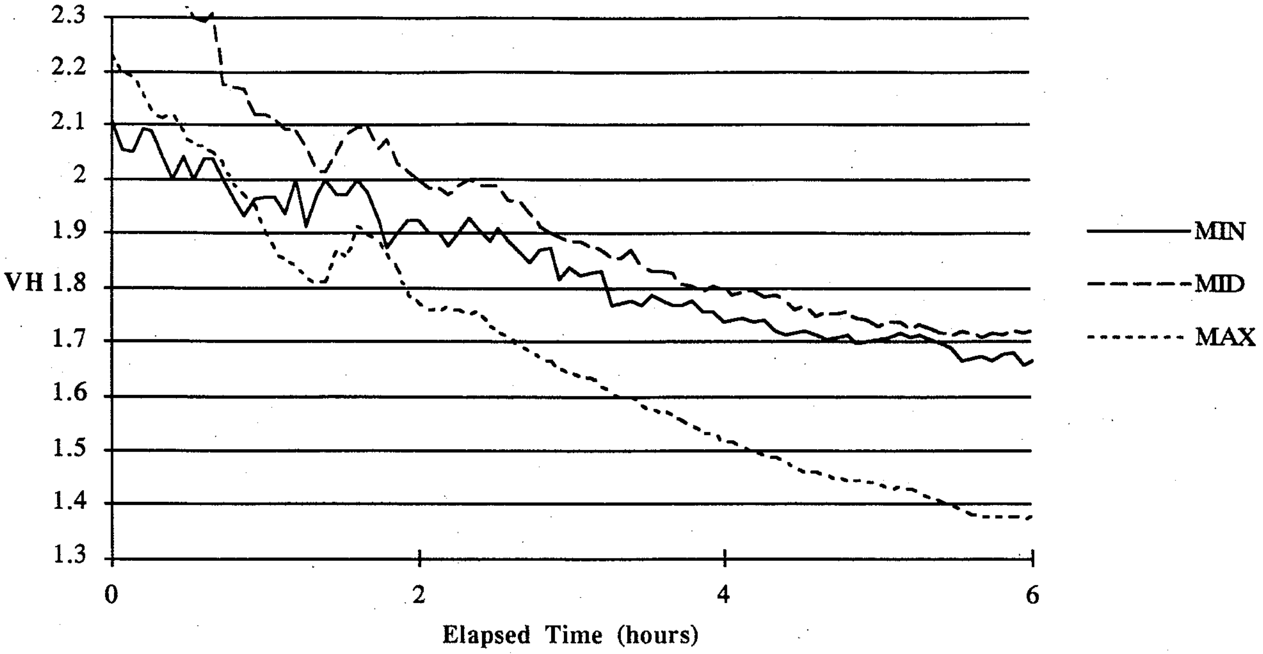

Figure 18 - VH at three measurement positions in the high-reflectance space with window 2 for a 6 hour test period under clear sky.

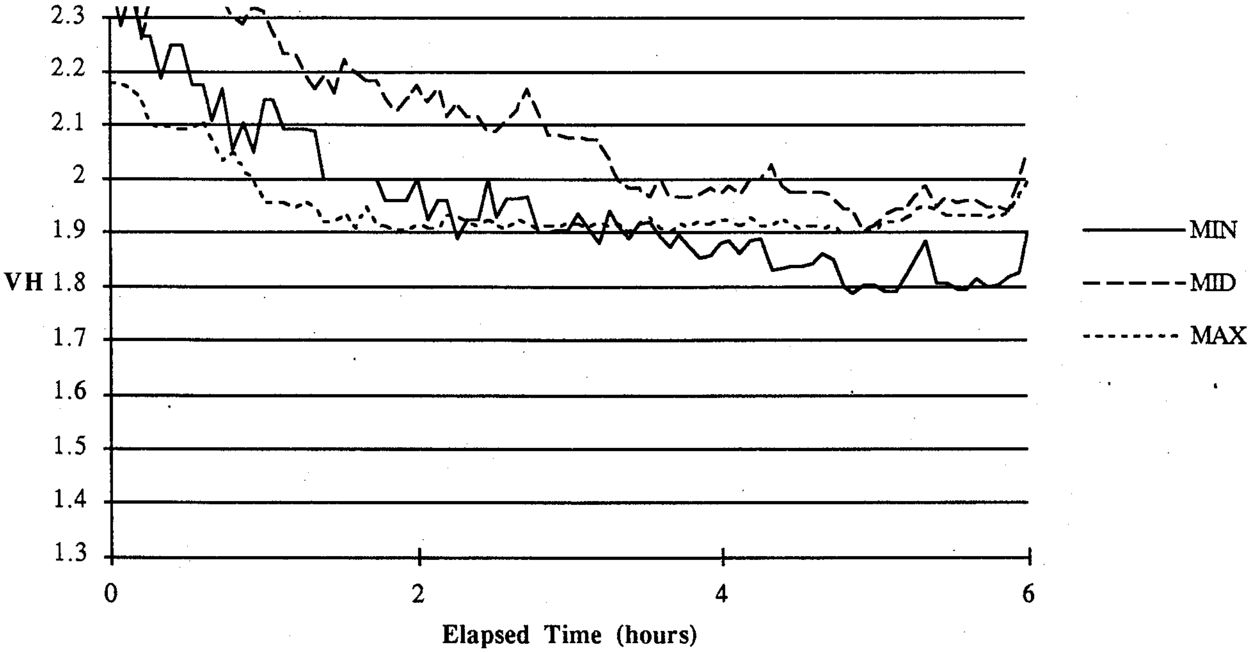

Figure 19 - VH at three measurement positions in the high-reflectance space with window 3a for a 6 hour test period under clear sky.

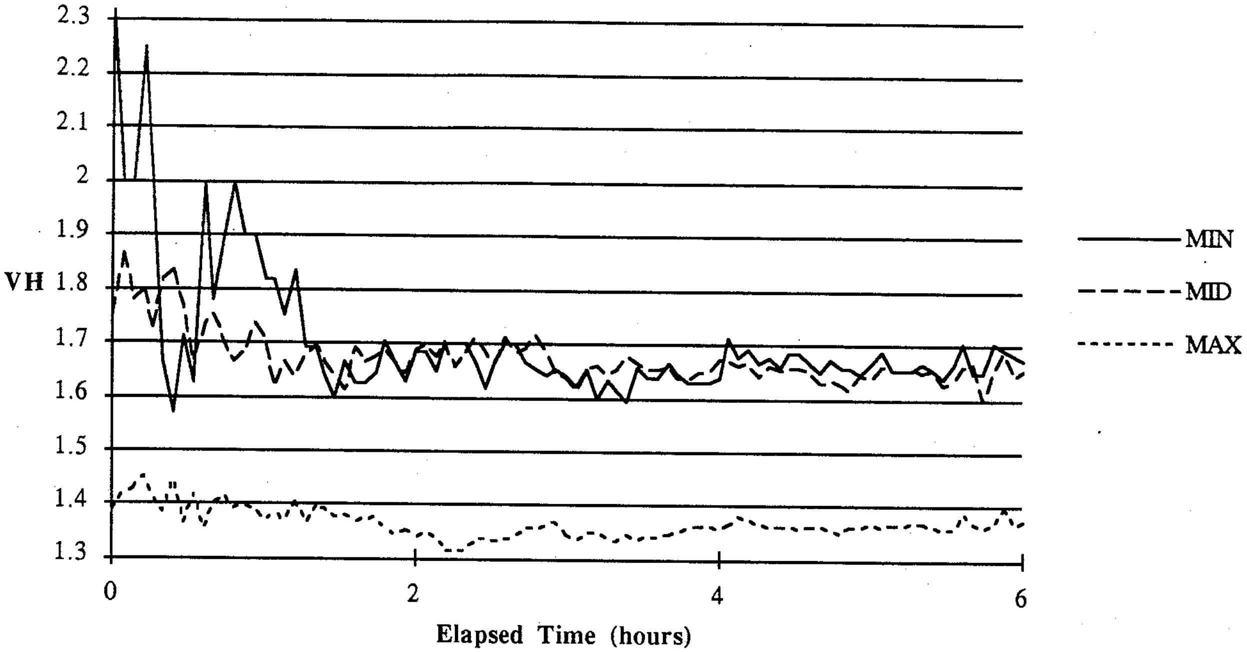

Figure 20 - VH at three measurement positions in the high-reflectance space with window 3b for a 6 hour test period under clear sky.

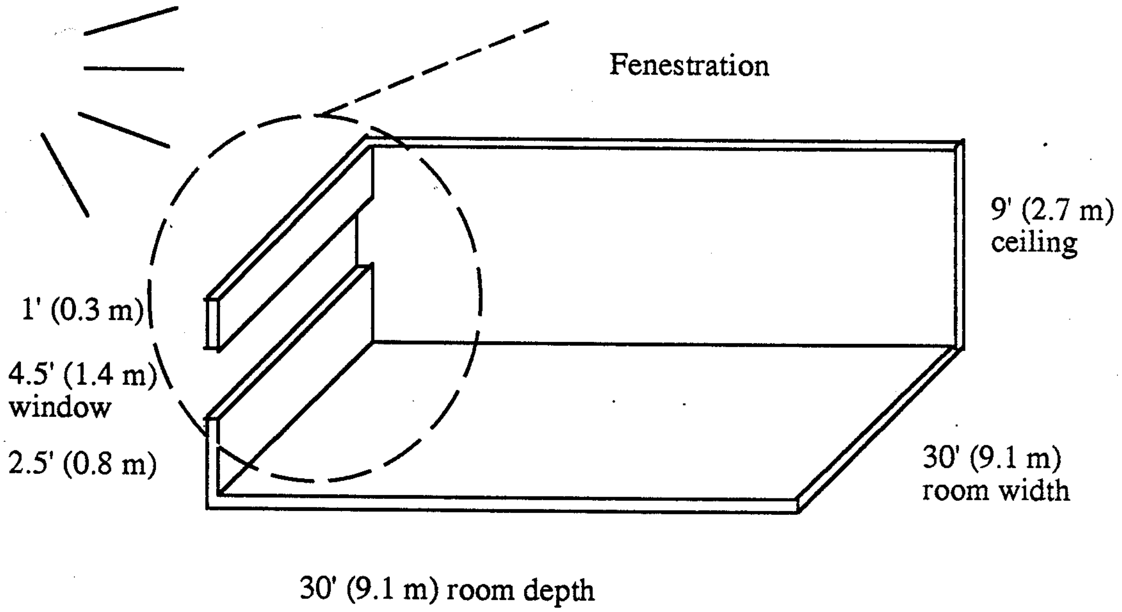

Figure 21 - Dimensions and fenestration of the room used to assess VH under electric and combined electric-daylighting systems.

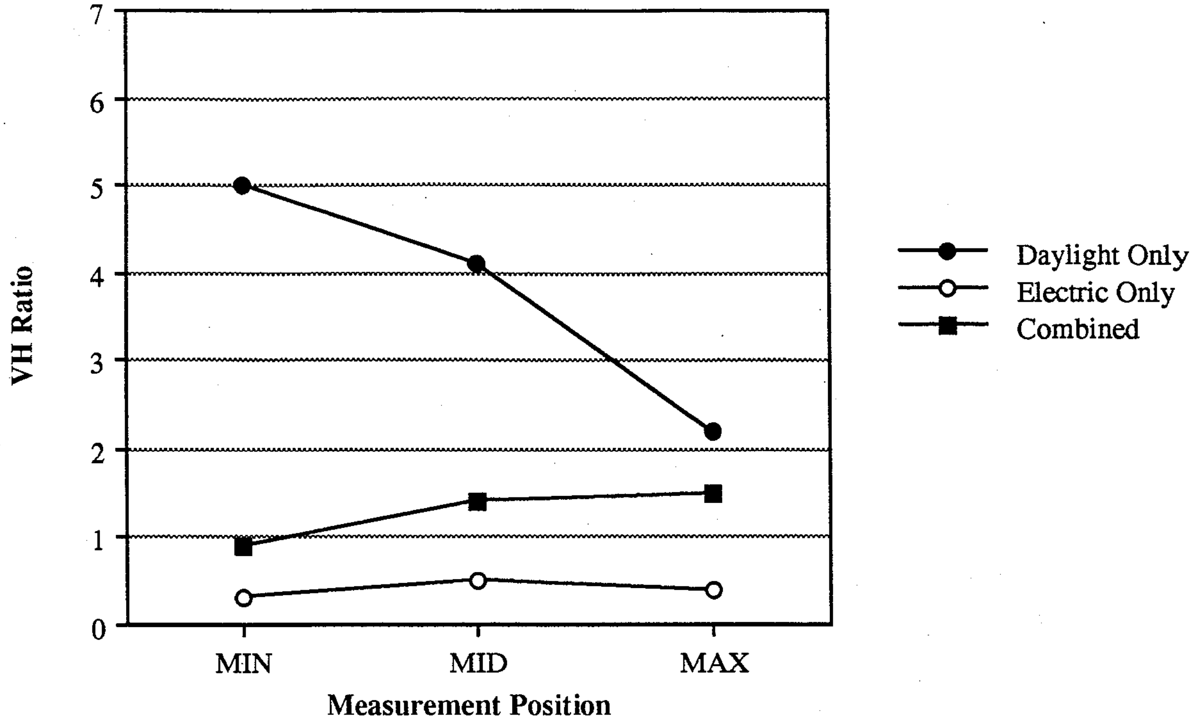

Figure 22 - VH ratios under electric and daylighting systems for the test space shown in Figure 21 with the fenestration shown in Figure 22.