FIELD ASSESSMENT OF DAYLIGHTING SYSTEMS

PREPARED FOR:

The CANMET Energy Technology Centre (CETC)
Energy Technology Branch, Energy Sector
Department of Natural Resources Canada
Ottawa, Ontario, K1A 0E4
DSS Contract No. 23440-3-9537/01-SQ
March 29, 1996

PREPARED BY:

J.A. Love, Arch. D., P. Eng.
Faculty of Environmental Design
The University of Calgary
Calgary, Alberta, T2N 1N4
Tel.: (403) 220-7428 - Fax: (403) 284-4399

SCIENTIFIC AUTHORITY:

Dr. Roger Henry
The CANMET Energy Technology Centre (CETC)
Energy Technology Branch, Energy Sector
Department of Natural Resources Canada
580 Booth Street
Ottawa, Ontario, K1A 0E4

May 21. 1996

CITATION

J. A. Love, Arch. D., P. Eng., Faculty of Environmental Design, University of Calgary, *Field Assessment of Daylighting Systems.* DSS contract No. 23440-3-9537/01-SQ. The CANMET Energy Technology Centre, Energy Technology Branch, Energy Sector, Department of Natural Resources Canada, Ottawa, Ontario, 1996, (61 pages).

Copies of this report may be obtained through the following:

The CANMET Energy Technology Centre
Energy Technology Branch, Energy Sector
Department of Natural Resources Canada
580 Booth Street, 13th Floor
Ottawa, Ontario
K1A 0E4

or

Intellectual Property and Technical Information Management (IPTIM)
Library and Documentation Services Division, CANMET
Department of Natural Resources Canada
555 Booth Street, 3rd Floor, Room 341
Ottawa, Ontario
K1A 0G1

DISCLAIMER

NOTE

Funding for this project was provided by the Federal Panel on Energy Research and Development, (PERD), Department of Natural Resources Canada.

SYNOPSIS

FIELD ASSESSMENT OF DAYLIGHTING SYSTEMS

Recently a few new Canadian buildings have been touted as "daylight buildings", designed to incorporate the best daylighting principles. From an energy efficiency point of view, the use of daylighting implies reduced electrical and cooling energy consumption by replacing some of inefficient artificial lighting with free solar lighting. Suspicion has been that energy savings are seldom realized, at least to the extent projected, and an extensive energy-use study was undertaken of two new daylit Calgary buildings. One structure was a high school and the other a university building mainly comprised of offices and classrooms. The two-storey high-school was designed with a stepped cross-section to introduce daylight at points other than the perimeter of the building. Ceilings in the university building were tilted up at the perimeter to accommodate higher windows and allow deeper daylight penetration. The windows were also equipped with a dual upper-lower blind system to allow more extensive control of daylight admission and glare.

The objectives of the study were to measure detailed energy consumption in each of the buildings, review use of daylighting and investigate opportunities for more effective exploitation of it, and use monitored data to validate daylighting simulation programs.

As suspected, daylighting was not doing much to reduce energy consumption in either building. Daylighting was used as an aesthetic quality, drawing accolades from building occupants and visitors, but not an effective energy efficiency measure. In fact, both buildings consumed more energy than other comparable buildings and as much as was typical of pre-70's levels. Surprisingly, it was learned that lighting accounted for only about ten percent of energy use (and represents the maximum that could possibly be exploited with daylighting), while energy for fans and tempering of ventilation air accounted for about fifty percent of energy used in the buildings. More efficient use of electrical lighting, increased plug loads for office equipment, and new more stringent ventilation air requirements have greatly changed the energy use patterns in these types of buildings in recent years. The net effect is usually less energy consumption but , in some instances, can lead to levels as high as in buildings constructed twenty-five years ago.

The target buildings had several factors against them in trying to exploit daylighting. Deep floor plans made it difficult to use daylight in many areas. Low fraction of lighting loads and low electricity prices in this region meant payback for elaborate dimming systems was prohibitive. In addition, better, perhaps automatic, blinds would have to be installed to reduce glare and encourage

occupants to turn off lighting when not needed. On a more positive side, in some daylit spaces of the university building, electrical lighting use was as low as has been reported in demonstration energy-efficient buildings. Finally, lighting seemed to have little effect on cooling energy requirements, probably because of the extensive free-cooling available in the Calgary climate.

Both building were modelled with DOE2 and validated with monitored data. The models proved useful to confirm energy use patterns and review impact of daylighting strategies. Simulations of the buildings with weather data for other regions of Canada confirmed that the energy-use patterns for these two particular buildings were high by standards in all locations.

SOMMAIRE

ÉVALUATION DE PROJETS D'ÉCLAIRAGE NATUREL

Récemment, on a construit au Canada quelques nouveaux immeubles dits «à éclairage naturel», conçus dans le but d'intégrer au maximum la lumière du jour. Du point de vue de l'efficacité énergétique, l'utilisation de la lumière naturelle entraîne une réduction de la consommation d'électricité et d'énergie de refroidissement, attribuable au remplacement de moyens inefficaces d'éclairage artificiel par une source gratuite, l'énergie solaire. On soupçonnait que l'éclairage naturel fourni par la lumière du jour apportait rarement des économies d'énergie, du moins dans la perspective adoptée. Une étude énergétique approfondie a donc été menée sur deux nouveaux immeubles de Calgary éclairés en lumière naturelle, une école secondaire de deux étages ainsi qu'un bâtiment universitaire composé essentiellement de bureaux et de classes. L'école secondaire a été aménagée en gradins, concept qui permet de laisser entrer la lumière du jour par des parois autres que celles qui composent sa périphérie. Dans le cas du bâtiment universitaire, les plafonds inclinés de la périphérie autorisent des fenêtres de grande hauteur, ce qui en retour laisse pénétrer la lumière du jour plus loin vers l'intérieur des étages. Les fenêtres sont équipées d'un système de stores inférieurs et supérieurs grâce auxquels on peut mieux intervenir pour contrôler la lumière et l'éblouissement.

L'étude avait pour but de mesurer en détail la consommation d'énergie de chaque bâtiment, d'analyser l'utilisation de la lumière naturelle et d'explorer les possibilités d'une exploitation plus efficace de ce principe et enfin de mettre à profit les données cueillies pour valider des programmes de simulation d'éclairage en lumière naturelle.

Comme on s'en était douté, l'éclairage naturel n'apportait de réduction importante de la consommation énergétique dans aucun des bâtiments étudiés. L'utilisation de la lumière naturelle se faisait remarquer davantage par sa qualité esthétique et par l'appréciation que les occupants et les visiteurs ont manifesté; cependant, ce système n'était pas énergétiquement efficace. En réalité, les deux bâtiments affichaient une consommation d'énergie supérieure à celle de constructions comparables; leur profil de consommation était en outre davantage apparenté à la consommation type des constructions similaires antérieures aux années soixante-dix. Étonnamment, on a appris que l'éclairage comptait pour seulement dix pour cent de la consommation totale d'énergie (maximum réalisable avec l'éclairage naturel), alors que l'énergie consacrée au fonctionnement des ventilateurs et des appareils de conditionnement d'air représentait environ quinze pour cent de l'énergie totale pour ces bâtiments. Au cours des dernières années, l'utilisation plus efficace de l'éclairage électrique, les charges électriques plus élevées de matériel de bureau et des exigences

plus rigoureuses en matière de ventilation ont beaucoup contribué à modifier les profils de consommation de ces immeubles. Au total, on a obtenu une réduction de la consommation, mais dans certains cas, la consommation peut être aussi élevée que celle d'immeubles construits il y a vingt-cinq ans.

Dans les bâtiments cibles, plusieurs facteurs jouaient contre l'exploitation de la lumière naturelle. À cause des grandes surfaces, il était difficile, dans beaucoup d'espaces, d'utiliser cette source naturelle. Avec le faible pourcentage que l'éclairage occupait dans la charge totale d'énergie et les bas tarifs d'électricité pour la région, la rentabilité qu'aurait apporté l'installation de systèmes complexes de contrôle et de gradation de l'éclairage électrique n'était plus aussi intéressante. De plus, il aurait fallu installer des stores améliorés, probablement automatiques, pour réduire l'éblouissement et encourager les occupants à éteindre l'éclairage lorsqu'ils n'en ont pas besoin. L'aspect positif de la chose, c'est que dans certains espaces du bâtiment universitaire bénéficiant d'un éclairage naturel, l'utilisation de l'énergie électrique s'est avérée aussi basse que dans des bâtiments pilotes à haute efficacité énergétique. Enfin, l'éclairage semblait avoir peu d'effet sur les besoins en énergie de refroidissement, probablement à cause de la grande possibilité de refroidissement par échange avec l'extérieur que permet le climat de la région de Calgary.

Les deux bâtiments ont fait l'objet d'une modélisation sur DOE2 et leur performance a été validée au moyen des données cueillies. Les modèles se sont révélés utiles dans la confirmation des profils de consommation et pour l'étude de stratégies faisant appel à l'éclairage naturel. Des simulations de ces bâtiments avec des données climatiques applicables aux autres régions du Canada ont confirmé que la consommation de ces derniers était élevée par rapport aux normes.

EXECUTIVE SUMMARY

The objectives of this study were to:

1. quantify the energy end uses in two buildings with fenestration designed to exploit daylighting by carrying out both frequent measurement of aggregate energy use and by detailed measurement of system level energy use in selected zones,
2. Determine the energy utilization of these buildings if efforts are made to optimize the use of the electric lighting system (i.e., taking greater advantage of opportunities for more efficient operation and exploitation of daylight available in the buildings), and
3. to use the data collected through the energy use monitoring program to validate computer simulation models of the buildings and, in turn, use the validated simulation models to estimate the performance of the designs for west coast, central Canadian and maritime climate zones.

The two Calgary buildings that were addressed in this study, Lester B. Pearson High School (14, 000 m^2 gross floor area) and the Professional Faculties Building at The University of Calgary (26, 000 m^2) were occupied in 1991 and 1993 respectively, with commissioning and other work extending into late 1994 in the case of the university building. The high school is a two-storey building and the university building is a four-storey building, both with very deep floor plates.

The simulation model, after validation with measured data, was used to estimate energy use for several Canadian locations: Halifax, Montreal, Toronto, Winnipeg, Edmonton, and Vancouver. These are cities for which Typical Meteorological Year weather data are available, data files that are representative of long term conditions. The specific energy use for the school ranged between 240 and 400 kWh/m^2 and for the university building between about 500 and 700 kWh/m^2 (Vancouver versus Winnipeg in both cases). This is in the vicinity of the 470 kWh/m^2 considered to be typical for pre-1973 office buildings, but much higher than would be expected of energy-efficient commercial buildings.

Electricity use for lighting amounted to 10 percent or less of total energy use for the high school and the university building respectively, which is a much lower fraction than has been reported in the literature. This appears to be the result of a few factors. Lighting power densities have dropped in recent construction and are continuing to decline with the increasing use of T8 fluorescent lamps and electronic ballasts. Ventilation and air circulation rates have increased due to concerns about indoor air quality, which has increased electricity used in fans and cooling, as well as natural gas use for heating of outdoor air.

It was found that the specific energy use (annual energy use in kWh/m^2) for the daylit high school was near the median for other Calgary six high schools for which energy use data were obtained. However, a much higher fraction of energy use at the daylit high school was in the form of electricity. This is also consistent with much more energy being used for fans and tempering of ventilation air in the more recently constructed building.

Lighting energy use was about 30 kWh/m^2 for the school and about 24 kWh/m^2 for the Professional Faculties Building (if night-time illumination of the 24 hour circulation system is discounted in the latter case), while values of 40-50 kWh/m^2 have been identified as typical of several energy efficient buildings. This is still above the 10-20 kWh/m^2 that has been achieved in some daylit buildings. However, the two buildings that were studied have deep floor plates and much more windowless space than most of these other projects. They also have requirements that preclude the completely open plan design used in some other deep-plan daylit buildings analyzed in the literature.

In some perimeter areas of the Professional Faculty Building, lighting energy use is in the vicinity of the 5 kWh/m^2 annually that was achieved with manual switching at the BRE Low Energy Office. This performance is commonly achieved where little or no glare is experienced from direct sunlight (e.g., in east- and north-facing spaces). In these areas, daylighting features such as high-reflectance interiors, high visible transmittances, the high window heads, and the dual upper-lower shading systems appear to be successful in providing natural lighting conditions that meet the occupants requirements. Electric lighting is used much more heavily in south-facing areas, which is consistent with other research findings on the use of electric light to offset glare from windows.

Experimental evaluation of a daylight-linked dimming system in a south-facing test area of about 60 m^2 in the Professional Faculties Building indicated that payback periods of about five years could be achieved under ideal conditions for energy saving (blinds open all the way all the time) with a marginal electricity cost of $0.08 per kWh. However, with the blinds as set by the users (almost completely closed to exclude direct sunlight), the simple payback period would be about 20 years. In Alberta payback periods are considerably longer due to lower marginal electricity costs.

At the school, staff generally seem to use electric lighting in the classrooms and other spaces even when there appears to be adequate daylight. The differences in use of electric lights in spaces that appear to be adequately daylit (i.e., relatively glare-free and adequate levels of illumination) in the two buildings indicates that a better understanding of the factors that affect switching is still needed, as this has not been extensively addressed in the literature.

Comparative tests at the school classrooms that were set up for assessment of lighting effects on cooling requirements did not show any effects of lighting on cooling.

In summary, more extensive exploitation of daylighting requires 1) the development of an alternative to current window shades or blinds that can both reduce glare and improve the distribution of daylight in perimeter spaces and 2) the development of more cost-effective lighting control strategies.

It is recommended that:

1. field trials be conducted of electric lighting control based on a "manual on-automatic (occupancy-based) off" strategy to determine the performance and cost-effectiveness of such an approach,

2. research be conducted on electric lighting control through dimming based on a more comprehensive strategy to provide combined peak shaving, daylighting-linked dimming. and light system "tuning,"

3. studies be conducted to devise shading or blind systems that admit daylight through the upper portion of windows while preventing direct sunlight from entering the upper and lower portions of windows (it would be useful to test such systems in combination with the control strategies described in 1) and 2) above), and

4. studies be conducted to determine the feasibility and cost-effectiveness of open-loop control in lobby, circulation, and similar areas.

ACKNOWLEDGEMENTS

The author thanks the Canadian Centre for Mineral and Energy Technology (CANMET) of the Department of Natural Resources Canada and Architectural and Engineering Services of the Department of Public Works Canada for their financial support. The author also thanks Dr. Roger Henry of CANMET and Dr. Ivaldo Pasini of the Department of Public Works Canada for their helpful suggestions and careful reading of the draft report.

The staff and students of Lester B. Pearson High School were very accommodating in allowing us to pursue this research in their school. Mr. Graham Dougherty of the Calgary Board of Education assisted in obtaining energy use data for several high schools. The University of Calgary Department of Physical Plant cooperated in arranging testing at the Professional Faculties Building. Graham Edmunds Architects provided drawings and other information on the designs. Ms. Anca Galasiu and Mr. Rodica Sporea assisted with the preparation of the simulation models and data collection. Mr. Marino Vardabasso assisted with the field measurements.

TABLE OF CONTENTS

SYNOPSIS

SYNOPSES

Executive Summary

LIST OF FIGURES

LIST OF TABLES

1.0 BACKGROUND, PROJECT OBJECTIVES, AND REPORT ORGANIZATION

Daylight has several attractions as a renewable resource. Firstly, the illumination is provided by the sun, so there is the possibility of reducing power requirements for electric lighting. Secondly, it displaces electricity, which is a relatively expensive form of energy (many solar technologies displace use of lower cost fuels such as natural gas, which may therefore offer less attractive payback periods). Thirdly, the ratio of the light to associated thermal energy (the "luminous efficacy") is relatively high, which is advantageous in reducing cooling loads in commercial and institutional buildings. Fluorescent lamps have efficacies of about 80 lm/W, and conventional incandescent lamps have efficacies of less than 20 lm/W (lumens per watt - the lumen is the unit of visible electromagnetic radiation, while the watts are the electrical power input or, in the case of daylight, the total associated electromagnetic energy, including ultraviolet, visible and infrared components). The luminous efficacy of diffuse daylight ranges from about 95 lm/W under overcast skies to 144 lm/W under clear skies. The luminous efficacy of direct sunlight varies from 70 lm/W for a solar altitude of 10° to 95 lm/W for a solar altitude of 60° [1]. Because many offices are equipped with windows to provide views, exploitation of daylight may be possible simply buy controlling electric lighting.

There are several challenges in exploiting daylight. One is its extreme variability in intensity and distribution across the sky, especially the direct solar component. Currently recommended levels of ambient lighting for offices with VDT's are 200-300 lux at desktop level (lux are lumens per square metre) [2]. Outdoor illumination under direct sunlight can exceed 100,000 lux. This can lead to intense glare in offices exposed to direct sunlight. Shades, venetian blinds, or other systems must be provided to exclude or regulate daylight when it produces glare. Using windows to direct daylight to interior areas beyond perimeter offices can be difficult. Illumination from daylight declines geometrically with distance from a window. A rule of thumb is that the zone of usable daylight is not greater than a distance from the perimeter equal to two times the window head height - about five metres in most commercial buildings, less if the light is obstructed by partitions. Electric lighting must be controlled, either manually or automatically, so that the illumination provided by daylight results in energy savings. The process of control introduces additional challenges in terms of strategies, performance, and costs.

While computer simulation studies have shown that use of daylighting in perimeter zones can provide significant and cost-effective energy use reductions in Canadian office buildings [3], there is little information on the field performance of daylit buildings. One of the assumptions in the computer modelling studies was ideal performance in terms of daylighting use. In other words, window blinds would only be drawn when glare exceeded a specified level, they would be opened as soon as glare dropped below that level, and electricity use reductions were linearly proportional to reductions in requirements for light from electric sources. In an earlier study of three existing office buildings with daylight-linked dimming controls in perimeter offices, it was found that the controls had been deactivated or were failing to provide significant dimming [4]. In one building, the zoning of the lighting extended from the perimeter to the core so that any dimming would have reduced illumination in offices lacking windows. In the other two, several spaces were grouped on each dimming circuit. This made it difficult to satisfy differing occupant preferences and spatial conditions (e.g., shaded versus unshaded). In all buildings, relatively low transmittance glass reduced daylight availability. These findings suggested that successful implementation of daylighting requires better understanding on the part of the building industry.

The major challenge in providing daylighting through windows rather than skylights (which are of limited usefulness in multi-storey buildings) is getting light sufficiently far into the space with reasonable uniformity and acceptable glare while providing a workable means of reducing electric lighting when illumination from daylight is adequate. The objectives of this project were to:

1. quantify the energy end uses in two buildings with fenestration designed to exploit daylighting by carrying out both frequent measurement of aggregate energy use and by detailed measurement of system level energy use in selected zones,
2. Determine the energy utilization of these buildings if efforts are made to optimize the use of the electric lighting system (i.e., taking greater advantage of opportunities for more efficient operation and exploitation of daylight available in the buildings), and
3. to use the data collected through the energy use monitoring program to validate computer simulation models of the buildings and, in turn, use the validated simulation models to estimate the performance of the designs for west coast, central Canadian and maritime climate zones.

Section 2 of this volume covers whole-building performance and energy end uses for the two buildings that were evaluated by monitoring and simulation. Section 3 covers the performance of a daylight-linked fluorescent dimming system that was retrofitted and evaluated in a test space in one of the buildings. Section 4 places the findings from this study in the context of other research on daylighting. Conclusions and recommendations are presented in Section 5.

2.0 PERFORMANCE EVALUATION FOR TWO DAYLIT BUILDINGS

This section of the report covers the building-level assessment of energy use of two buildings with special daylighting features, Lester B. Pearson High School, which is located in a low-density suburban residential area in the northeast quadrant of Calgary, and The University of Calgary's Professional Faculties Building, which is located on the university campus. Subsection 2.1 provides a description of the buildings, including photographs and drawings. Subsection 2.2 reviews the methods that were used to obtain measured energy use data, to prepare and validate the simulation models, and to carry out cooling and daylight measurements at the high school. Subsection 2.3 provides results of the assessment of energy use of the buildings. Subsection 2.4 provides information on spaces at the Professional Faculties Building that were identified as having very low electric lighting usage.

2.1 Building and Site Descriptions

2.1.1 Lester B. Pearson High School

Lester B. Pearson High School, has a gross floor area of 150, 000 ft^2 (14, 000 m^2) and a capacity of about 1200 students (Figure 2.1). It is located in Calgary, Alberta (51° north) and opened in the fall of 1991. Most of the building is made up of classrooms and spaces of equivalent size - much larger than individual offices - and divided by fixed walls. Client preferences regarding spatial adjacencies were one of the factors resulting in a very deep plan (Figure 2.2). For instance, it was desired that science classrooms be served from the same preparation-storage area. The spaces in the building are organized primarily such that those receiving direct sunlight (a major cause of glare) for most of the day (on the south side) are those in which tasks are less critical (e. g., circulation and lounge areas) or occupants are relatively free to move if lighting conditions are uncomfortable (e. g., the resource or "information" center and the student cafeteria-study area). Classrooms and technology labs are generally buffered from direct sunlight on the south side or are located to the north, where more even and less intense natural illumination is available.

A stepped section with clerestory windows was used to introduce daylight into areas further from the perimeter (Figure 2.3), and a daylit two story volume forms the nucleus of the plan (Figures 2.2 and 2.4). Windows are placed high in the walls, which is the most effective position for admitting daylight (the higher the window head the deeper the daylight penetration). The suspended ceilings are tilted up at the perimeter of the building (Figure 2.5) to further extend the window heads. Exterior light shelves are used extensively (Figure 2.6). Windows are equipped with mesh shades to control glare from direct sunlight and the sky. The shades are manually operated except for the two-story glazed south-facing reading areas, which are driven by manually-activated motors. Clear glass is used (visible transmittance of about 0.80), which allows more daylight to be admitted than tinted glass.

Average surface reflectances are high, which contributes to efficient use of both daylight and electric light, and promotes uniformity of illumination by increasing the reflected component of illumination (uniformity will normally be reduced as direct illumination becomes increasingly dominant). Most wall and ceiling areas are off-white and have reflectances of 0.70 or more. Light-colored floor tiles are also used in most spaces. Visual variety is promoted by highlighting relatively small areas (such as handrails and trim) with color. Light-colored window surrounds reduce glare [5]. Another measure taken to reduce glare was the use of two tones of paint on the perimeter wall areas of the higher spaces. A beige band of paint runs horizontally across the upper wall areas of these spaces. Being darker than the lower wall area, the effect is to reduce the brightness across the wall (the upper area, being adjacent to the window, receives much more light).

Most lighting is switched manually for cost reasons (the building was built with a conventional budget and without any special subsidies; commercial electricity rates are as low as about $0.04 per kWh, including demand charges, resulting in relatively long payback periods for many conservation measures). No daylight-linked lighting controls were installed due to the increased first costs that would have been involved.

A variable volume system is used for space conditioning, together with a perimeter hydronic heating system to meet skin losses (local temperatures typically reach -30 °C for several days in winter and the area has historically experienced about 5300 Celsius degree days of heating).

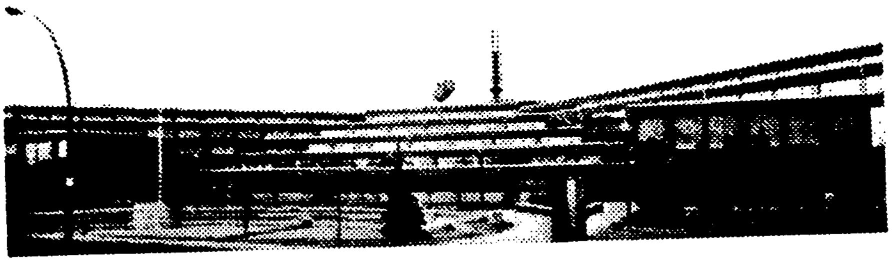

Figure 2.1 - Street facade of Lester B. Pearson High School.

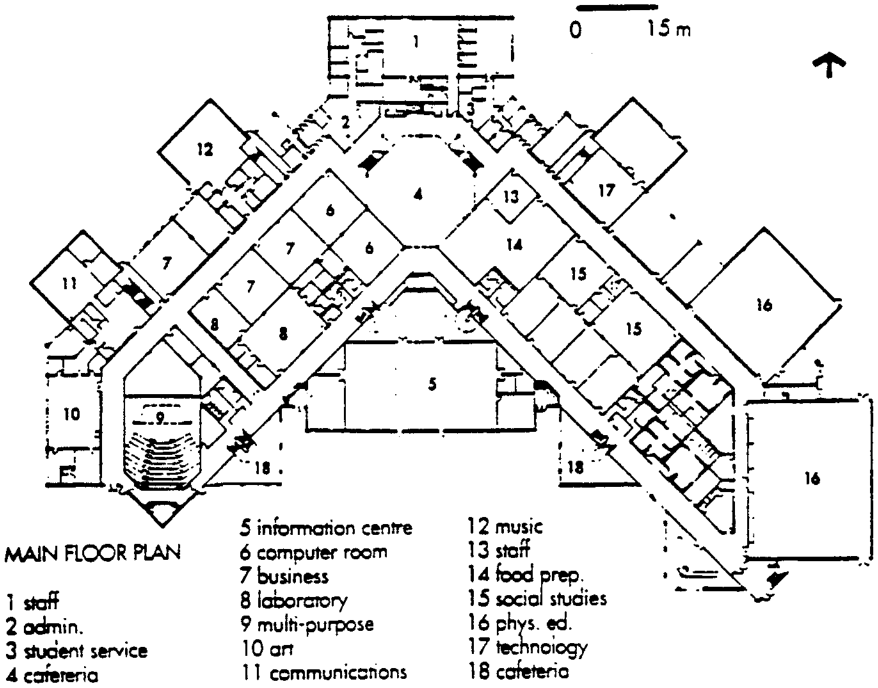

Figure 2.2 - Plan of the main floor at Lester B. Pearson High School.

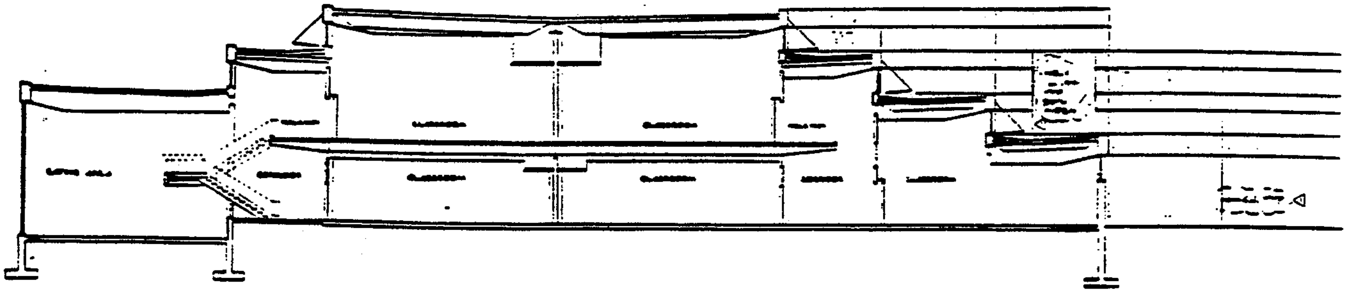

Figure 2.3 - **North-south section of Lester B. Pearson High School**

Figure 2.4 - **View of central cafeteria space at Lester B. Pearson High School.**

Figure 2.5 - View of the upper part of the two-storey main circulation volume at the high school, showing the ceiling tilted up toward the roof at the perimeter to increase the admission of daylight.

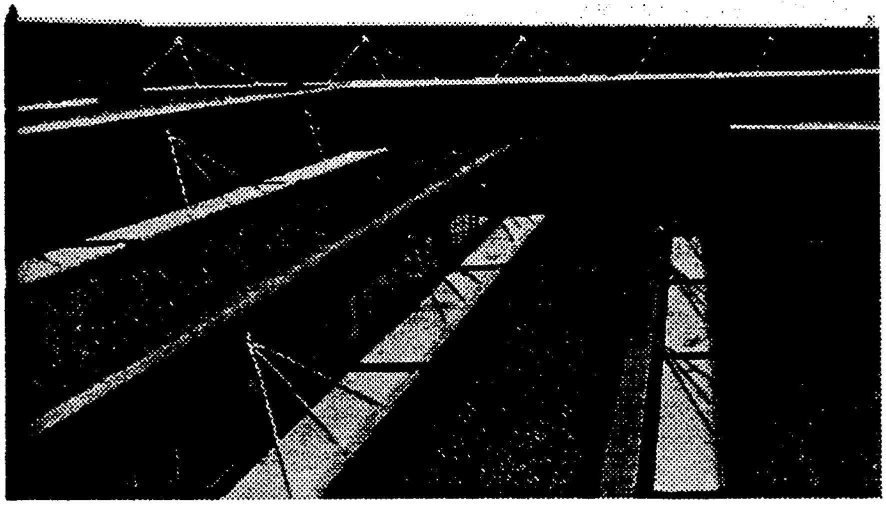

Figure 2.6 - View of typical light shelves at the high school.

2.1.2 Professional Faculties Building

The Professional Faculties Building (PFB) was occupied in November and December of 1993. It has a gross floor area of 26,000 m^2 (270,000 ft^2) on four levels. Figure 2.7 shows the passage to the central campus mall that divides the building into two blocks above grade. Figure 2.8 shows a plan of the east part of the 3rd level of this block. The organization is typical of the entire building in that most spaces along the perimeter are individual offices. Larger spaces such as classrooms and labs are generally located in core areas of the building. The University stipulated that light shelves could not be used on the project (for reasons of appearance). Light is therefore introduced through windows and a couple of light wells (see Figure 2.9).

As in Lester B. Pearson High School, the ceiling is tilted up at the perimeter of the building to maximize daylight penetration by incorporating a higher window head height (the higher the window head, the deeper the daylight penetration). A dual blind system is used so that shading of the upper (daylighting) portion of the window can be controlled separately from the lower (view) portion of the window (see Figure 2.10). The upper blind is a mesh screen, while the lower is a venetian blind. Primarily for appearance reasons (as opposed to thermal control or other reasons) glass with a slight green-blue tint (visible transmittance of about 0.75) was used, which allows more daylight to be admitted than darkly tinted glass. One of the weaknesses of the design is that a highly reflective metal window surround and specular metal blinds were used. Even with the blinds fully closed, direct sunlight on the windows results in areas of very high luminance and intense glare.

Average surface reflectances are high, which allows for more efficient use of both daylight and electric light and promotes uniformity of illumination by increasing the reflected component of illumination (uniformity will normally be reduced as direct illumination becomes increasingly dominant). Most wall and ceiling areas have reflectances of 0.70 or more. As noted above, light-coloured window surrounds reduce glare [5]. Visual variety is promoted by highlighting relatively small areas (such as handrails and trim) with accent tones. Floor tiles are also light in colour, although the carpeting in offices is darker (reflectance of about 0.30).

Sunlight admission in the light wells is controlled by automatically adjusted blinds. A few lights in circulation areas are on clocks. Otherwise, lighting controls are manual. The electric lighting in the light wells has not been used since the building was occupied (night-time illumination is provided by spill lighting from the adjacent corridors). Electric lighting in some offices can be adjusted to 4 levels - off, one lamp on per luminaire, two lamps on per luminaire, three lamps on per luminaire - with two switches. The luminaires in these offices are placed near interior walls to offset high levels of daylight at the perimeter. In other parts of the complex, the two switches in each office separately control luminaires near the perimeter and interior wall

Except for offices, there are no pairs of similar daylit spaces because most large spaces are located away from the perimeter and because of the irregular plan of the building (e.g., Figure 2.8).

The environmental control system in the PFB is unusual in that it uses a constant volume, terminal reheat air handling system with ceiling mounted radiant panels for perimeter heating. The constant volume system was selected because of a belief that it would provide better air quality than a variable air volume system.

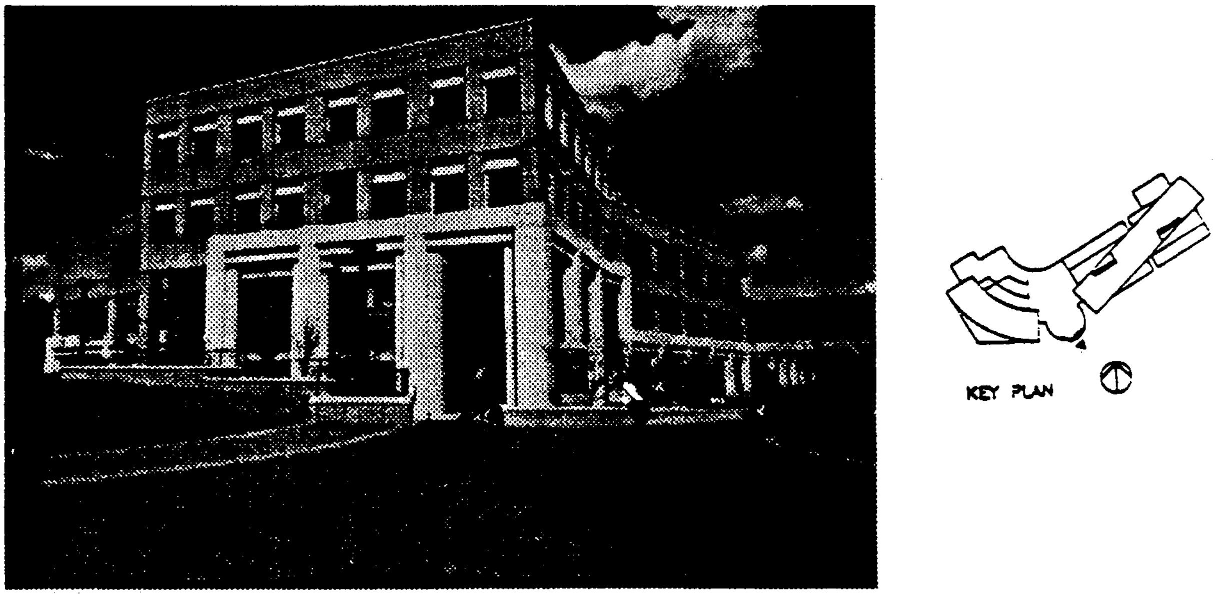

Figure 2.7 **View of the east block of the Professional Faculties Building at the gap between the east and west blocks (facing northeast) with plan of overall complex inset.**

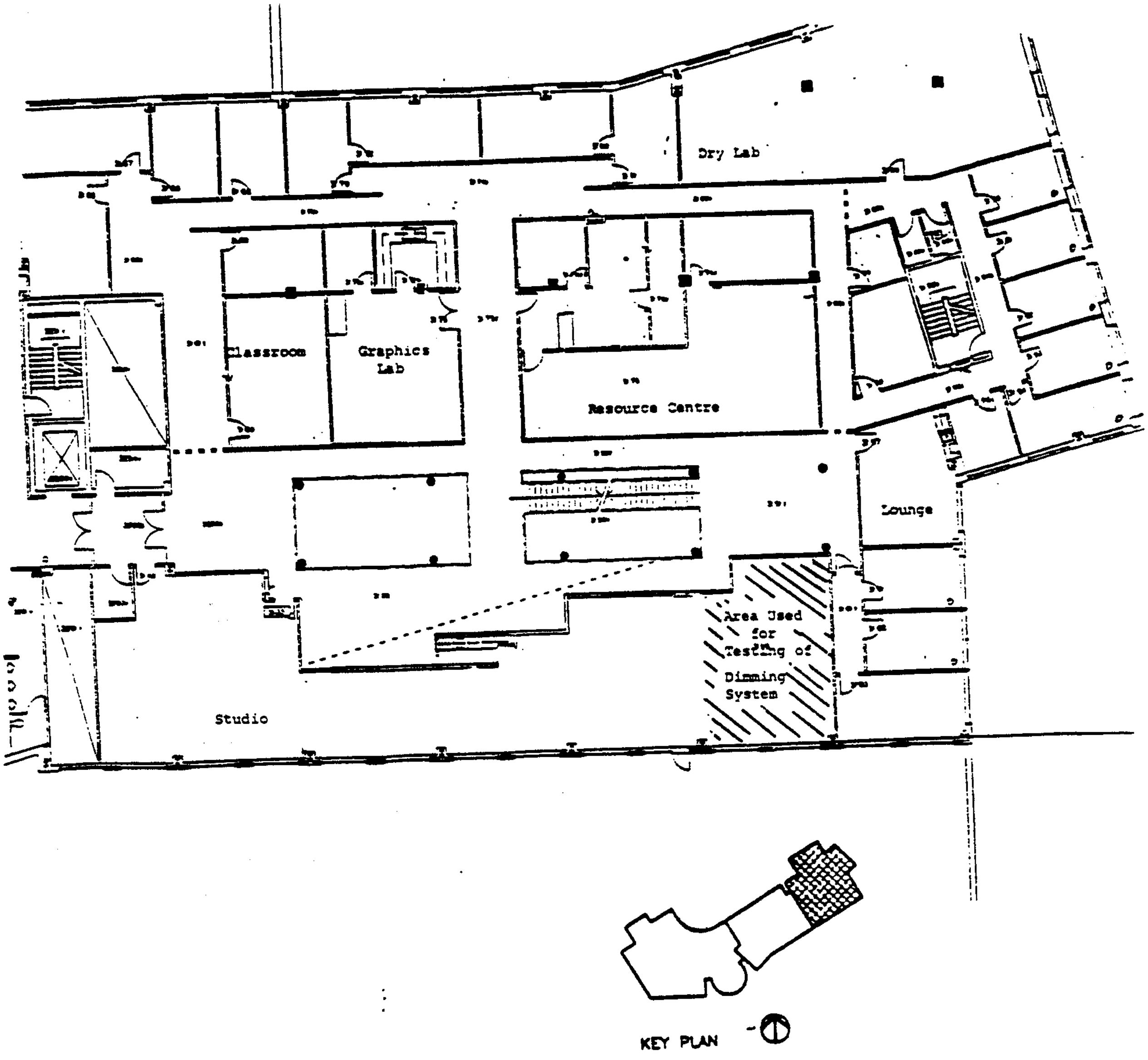

Figure 2.8 **Plan of the east area of the third level of the east block of the Professional Faculties Building.**

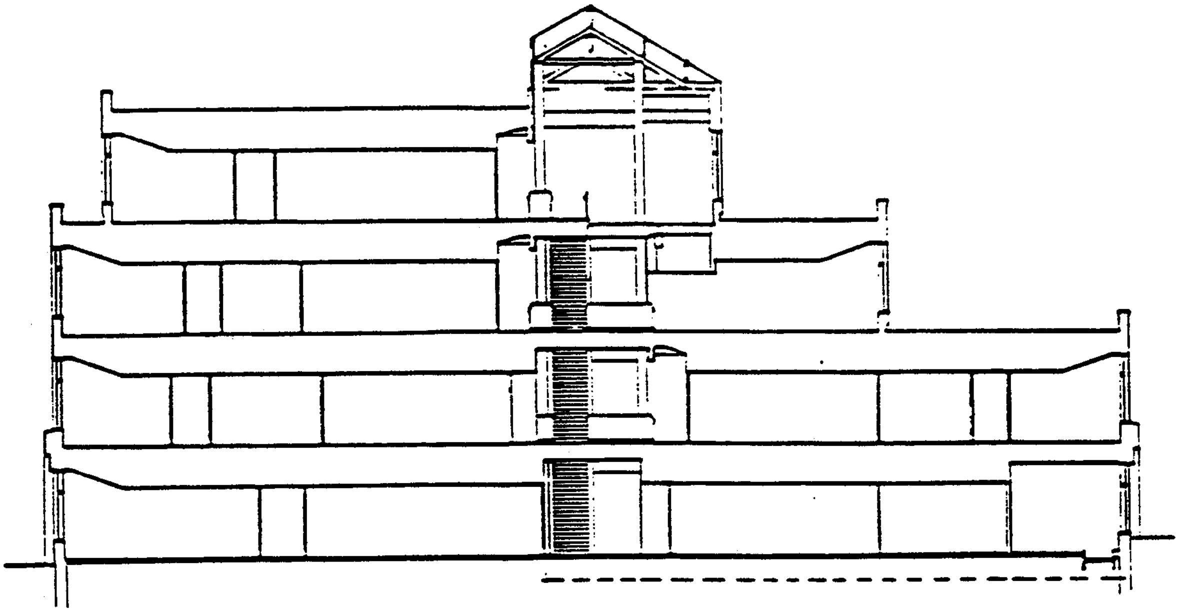

Figure 2.9 Section through the east block of the Professional Faculties Building, showing one of the light wells.

Figure 2.10 Interior view of a typical office at the Professional Faculties Building, showing the dual blind system.

2.2 Methods

The following methods were used in evaluating the performance of the two buildings being investigated:

1. monitoring of energy use and comparison with energy use for the same building type (high school),
2. monitoring of energy use and validation of computer models to allow for assessment of energy end uses and effects of climatic variations on energy use,
3. measurements to determine the daylighting characteristics of one type of classroom space, and
4. field tests and simulation studies to determine the effects of lights on cooling.

2.2.1 Methods for monitoring total building electricity and gas use

The comparative assessment of energy use for the high school on a building type basis was carried out by obtaining manually recorded meter readings accumulated daily Monday to Friday at each of seven high schools in Calgary.

To allow for detailed analysis of energy use patterns and validation of the computer simulation models, electricity use logging systems were set up at both buildings. These provided electric demand, power factor and other data at intervals of 5 minutes or less. The gas meters were read every working day at the high school. The Professional Faculties Building is supplied with chilled water and high temperature hot water by a central plant. An energy metering system was installed to record the heat transferred to and from the Professional Faculties Building, but did not provide usable measurements until September, 1994 (the building was occupied late in 1993, and correction of problems with the environmental control systems continued into the fall of 1994).

2.2.2 Methods for validation of computer simulation model - general

The size and complexity of the two buildings that were studied (14,000 and 26,000 m^2 floor area respectively) precluded a monitoring of representative spaces. To allow for a more detailed analysis of energy end uses and a greater range of studies to be conducted (e.g., effects of climate on performance), detailed energy use computer simulation models of the two buildings were created with the DOE2 program (version 2.1E). DOE2 provides an hour-by-hour simulation of energy transfer across the building envelope of the response of building systems (e.g., air-handling and hydronic systems, boilers and chillers). It is capable of modeling complex building forms and a very large number of environmental control systems.

The models were based on as-built information for the buildings, such as wall constructions, fan capacities, and installed lighting power densities. This involved extensive data gathering from drawings and in the field, and the preparation of computer code covering approximately 70 printed pages for the two simulation models. Once validated with measured building energy use data (see below), the models could be used to determine comparative performance in other parts of Canada (by using weather data for those regions) and to identify means of improving building performance by testing alternative design decisions (e.g., use of different fenestration).

DOE2 requires two basic sets of information as input: 1) the description of the thermal characteristics and systems of the building, as mentioned immediately above, and 2) hour-by-hour weather information (dry and wet bulb temperatures, wind speed and direction, station pressure, as well as global, diffuse, and direct solar radiation). Usually, the weather files used for design and research simulation studies are based on long-term average conditions. However, for purposes of validation, it is important that the weather data reflect the conditions at the time monitored data are collected.

The weather data used in the validation studies were obtained from two sources, the International Daylight Measurement Program Station at The University of Calgary (in the case of solar radiation data) and the University weather station. These data are archived on a minute-by-minute basis, so hourly averages were computed to prepare, for 1994, an hour-by-hour data base of weather conditions. The format used for the weather data was WYEC2, the revised Weather Year for Energy Calculations format. Measured data used in the simulation included direct, global and diffuse solar radiation, dry and wet bulb temperatures (the latter calculated for measurements of relative humidity), wind speed and direction, and station pressure.

Electricity use data from the building monitoring systems were selected for 24-hour periods falling in different seasons so that load components (e.g., magnitude and schedules for lighting, plug loads, fans) could be verified. The main factor to be adjusted was equipment loads. It was found that the amount of electrical equipment in use at any given time was much less than the sum of the nameplate ratings on all the equipment.

Likewise, measurements of thermal energy use were used to verify computer estimates.

2.2.3 Methods for validation of computer simulation model - high school

Figure 2.11 shows measured and simulated power demand for a typical 24 hour period used in validating the model of Lester B. Pearson High School. Note that the simulation model could have been programmed to provided a closer match for this particular day, but this would have resulted in greater disparities in load profiles in other seasons. The overall objective of the validation was to obtain a good match on an annual basis. Figure 2.12 shows measured and simulated electrical energy use on a monthly basis for 1994. Figure 2.13 shows measured and simulated natural gas use for 1994.

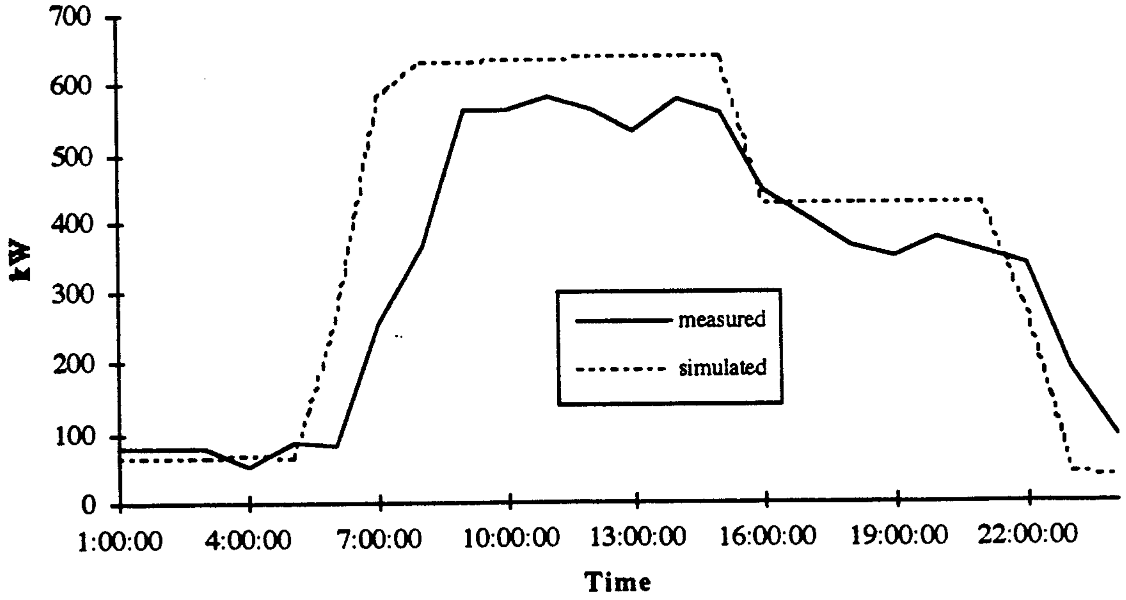

Figure 2.11 **Measured and simulated electricity demand for Lester B. Pearson High School, Monday, October 3, 1994.**

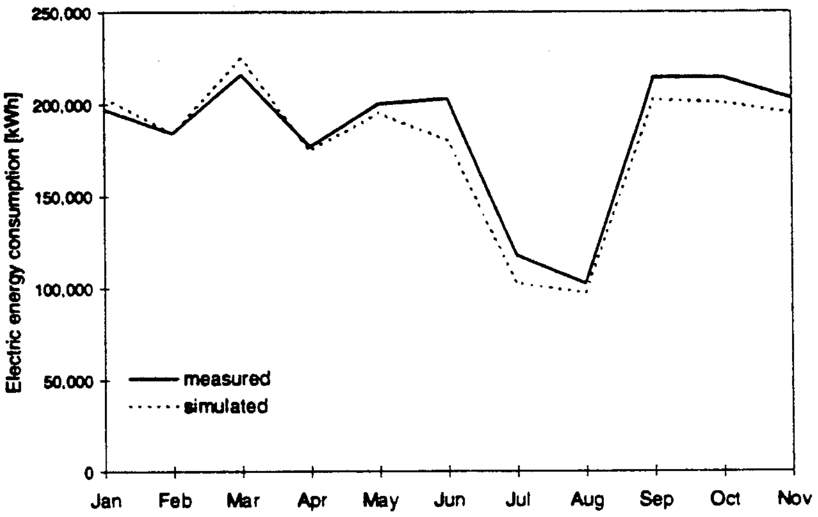

Figure 2.12 Measured and simulated electricity use for Lester B. Pearson High School, 1994.

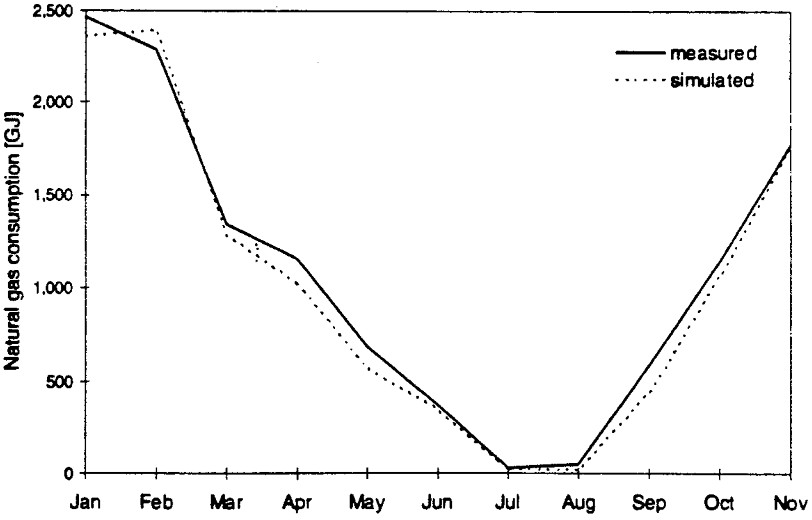

Figure 2.13 Measured and simulated natural gas use for Lester B. Pearson High School, 1994.

2.2.4 Methods for validation of computer simulation model - PFB

Using the same process as that described above for Lester B. Pearson High School, the computer simulation model was adjusted to match the measured performance of the building. Thermal energy data were not available until September of 1994, as was mentioned above. The system for monitoring electric demand was put into operation in July. Figure 2.14 shows measured and simulated electric demand for October 18, 1994. Figure 2.15 shows measured and simulated electrical energy use on a monthly basis. Figure 2.16 shows measured and simulated thermal energy use for the fall of 1994.

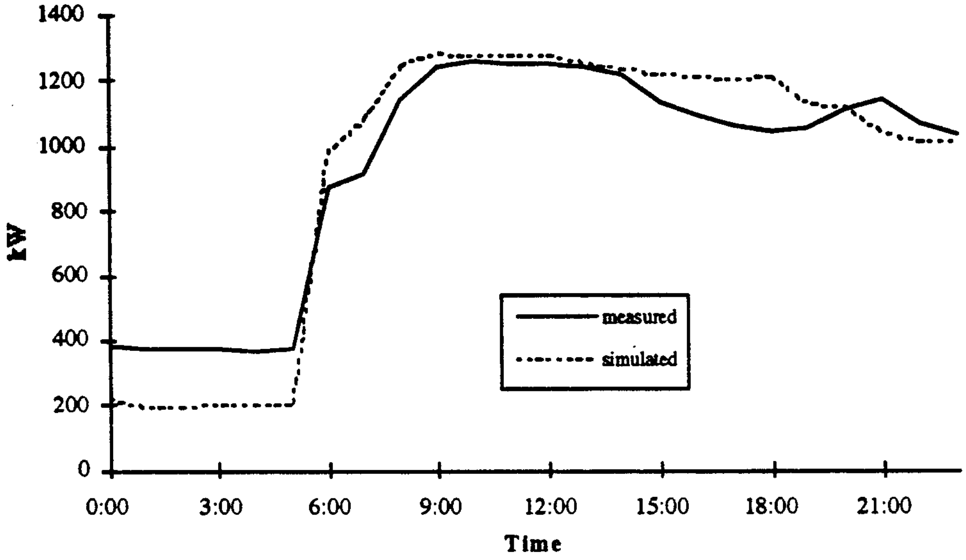

Figure 2.14 **Measured and simulated electric demand for the Professional Faculties Building, Tuesday, October 18, 1994.**

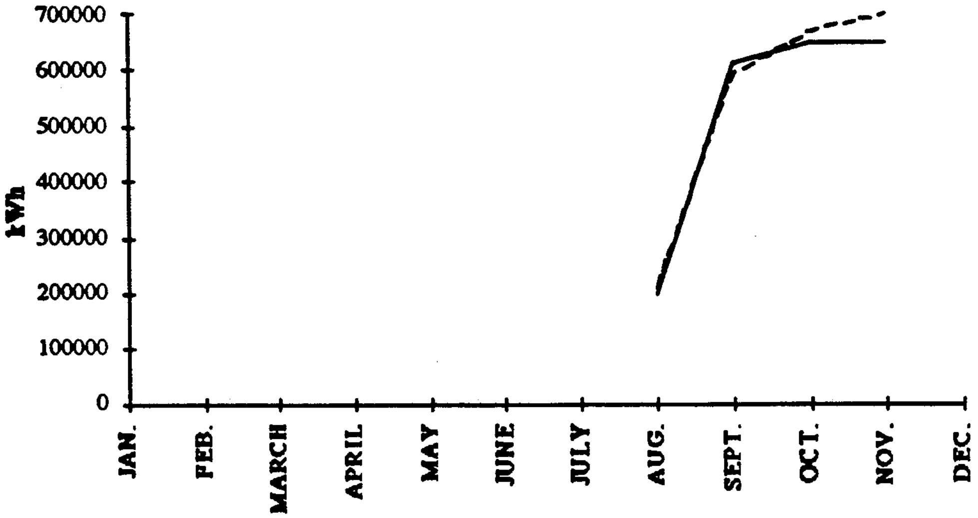

Figure 2.15 Measured and simulated electricity use for the Professional Faculties Building, 1994.

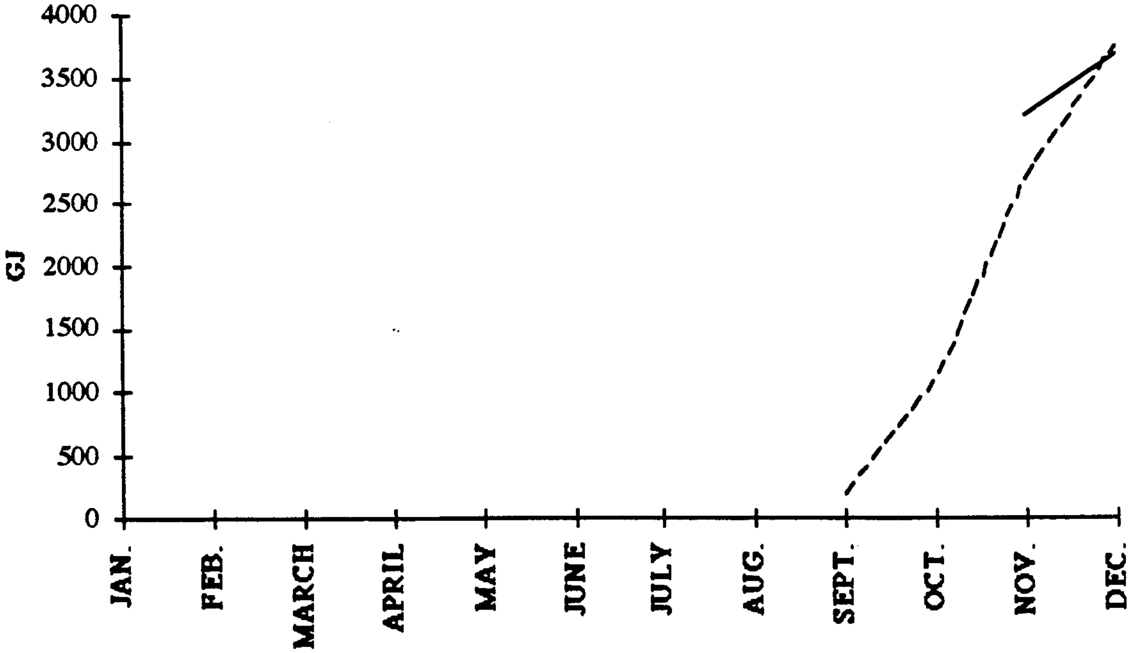

Figure 2.16 Measured and simulated natural gas use at the Professional Faculties Building, 1994.

2.2.5 Methods for simulation studies

The validated models were run with "Typical Meteorological Year" weather files for selected Canadian locations. Solar radiation measurements have been made at The University of Calgary's daylight measurement station only since the fall of 1993, while longer term solar radiation data are available for some other sites (usually provincial capitals, such as Edmonton). The long term data provide a more reliable basis for assessing performance under typical conditions.

2.2.6 Methods for interior daylight measurements

A rail was set up at work plane height (75 cm above the floor) along the centre line of one of the classrooms during the summer months when it was not in use. Calibrated photocells were mounted on the rail and connected to a data logger so that daylight levels could be monitored over the course of several days.

2.2.7 Methods for cooling studies

Two mirror-image classrooms on the second level of the school were selected to determine the effects of lighting on cooling requirements. A check of the air-handling systems revealed that one of the variable air volume boxes was connected to a thermostat in another space. This was rectified. The building management control system was programmed to allow delivery temperatures and air flows to the two spaces to be logged. The use of the two spaces allowed for both before-after and test-reference assessment of cooling impacts. Conditions were allowed to stabilize (e.g., lights either all on or all off, space vacant) in the classrooms for periods of 20-30 minutes and lights were switched to determine the effects on cooling. In a variable air volume system, air flow will increase as cooling loads increase and decrease as cooling loads decrease. On-off switching of all the lights in a space should highlight any effect of heat from electric lights on cooling. Measurements at the test spaces were supplemented by analysis with the simulation model for the school.

2.3 Assessment of Energy Performance of the Daylit Buildings

Subsection 2.3.1 addresses energy use of the daylit high school relative to six other schools for which energy use data were obtained. Subsection

2.3.1 Comparison of performance with other high schools

Specific energy use is based on the floor area of buildings, but this can be misleading in the case of double volume spaces. The floor area of Lester B. Pearson High School is about 14,000m^2; however, the energy management group at the Calgary Board of Education uses 17,600 m^2 to correct for the large number of double volume spaces.

Figure 2.17 shows specific energy use for seven Calgary high schools for September, 1991 through August, 1992. The daylit school is at the median, with a specific energy use of about 300 kWh/m^2. For the 1994 calendar year, specific energy use was about 350 kWh/m^2. This was due to higher natural gas use (approximately 230 kWh/m^2 versus 180 kWh/m^2). There were 8 percent more degree days during the latter period. The specific annual energy use is in the neighbourhood of ASHRAE-IES Standard 90.1 guidelines, which would allow for about 320 kWh/m^2. Natural gas use (Figure 2.18) accounts for just under 60 percent of total energy use at the daylit school, unlike the other schools at which it accounts for 70 to 85 percent of total energy use at the schools. It follows that electricity use accounts for a much higher fraction of energy use at the daylit school. In the analysis of simulation results (below), the breakdown of energy end uses will be addressed. Figure 2.19 shows the specific electricity use for each of the high schools.

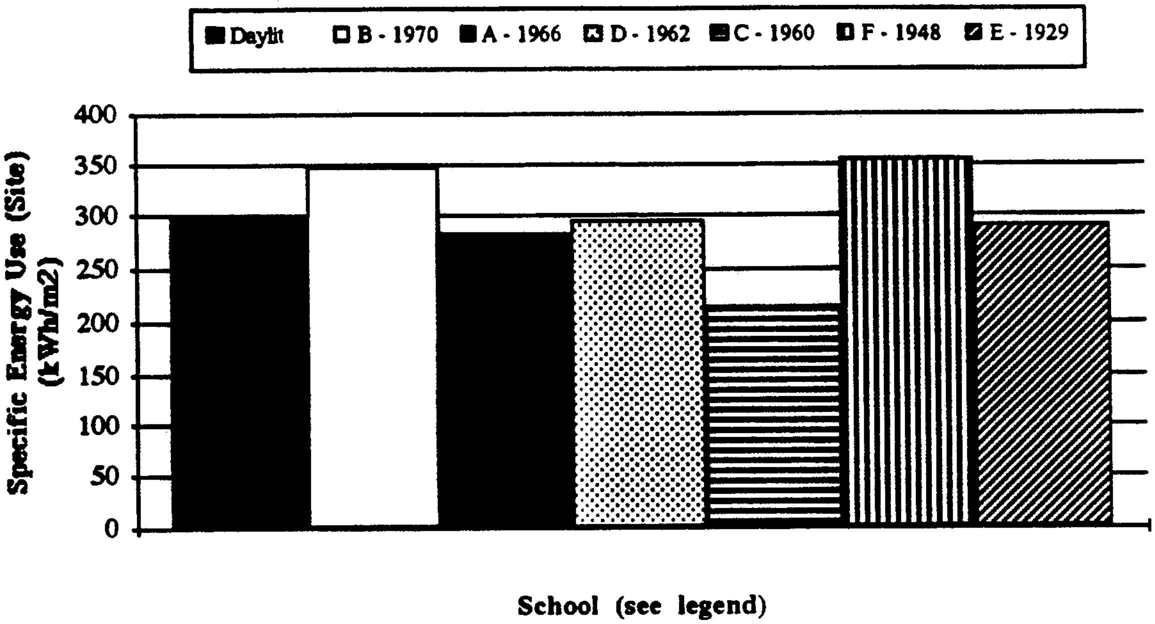

Figure 2.17 Specific energy use for seven Calgary high schools (September, 1991-August, 1992).

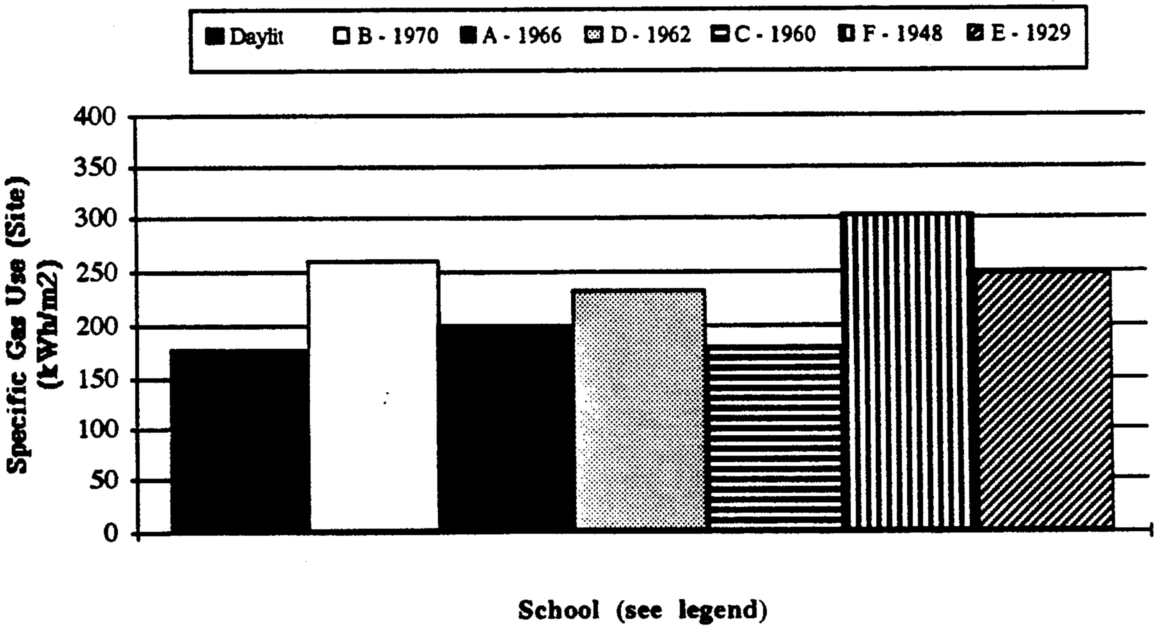

Figure 2.18 Specific electricity use for seven Calgary high schools (September, 1991-August, 1992).

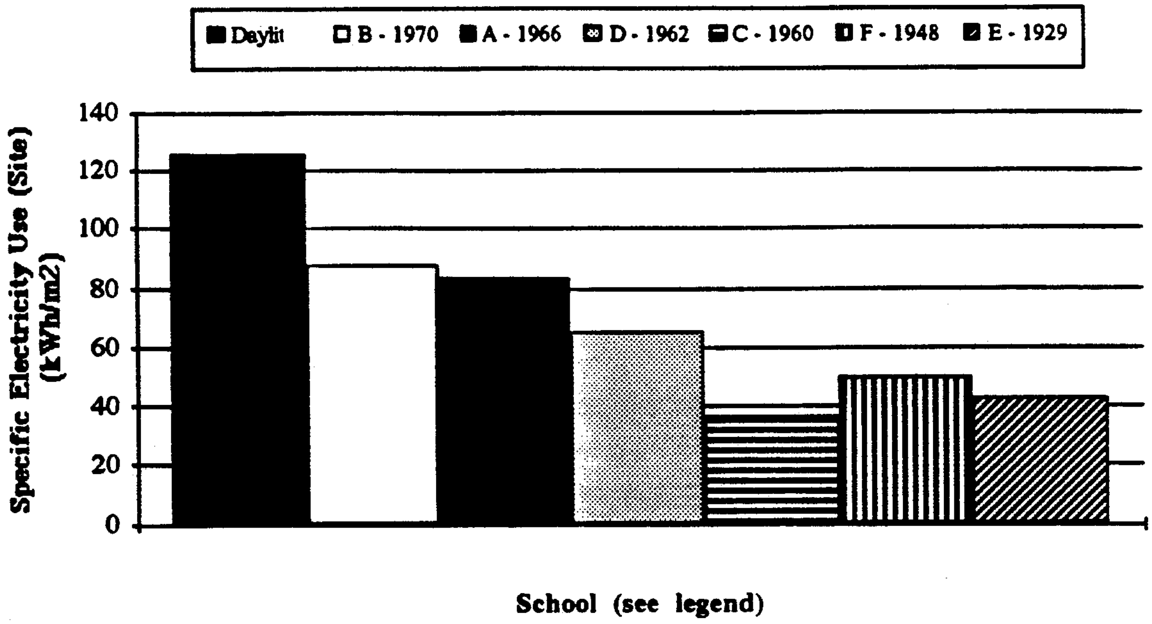

Figure 2.19 Specific energy use for seven Calgary high schools (September, 1991-August, 1992).

2.3.2 Lester B. Pearson High School - results for Alberta conditions

Table 2.1 shows energy end use calculated for Lester B. Pearson High School with representative annual weather data for Edmonton. Edmonton was chosen as representative for Alberta because, as noted above, it is the closest site to Calgary for which standard weather data for energy simulation are available. The mean annual temperature for Edmonton is about 2.7 °C compared with about 3.9 °C for Calgary, so Edmonton has an additional 400 Celsius degree days of heating (about 10 percent more than Calgary).

It is evident that lights account for a much smaller proportion of energy end use (about 7 percent) than is reported in the literature. For instance, Caudill Rowlett and Scott [6], based on a sample of 1600 commercial buildings, estimated typical energy use for lighting for schools to be about 40 percent of total energy use. The simulation for Edmonton showed the dominant energy end uses to be space heating (65 percent of site energy use) and operation of ventilation fans (11 percent of energy use). Much of the space heating requirement is to temper air being introduced to the building. Ventilation rates have increased substantially since ASHRAE increased recommended rates to 7 to 10 l/s (15 to 20 cfm) per person from 2.3 l/s (5 cfm) for classrooms, offices and similar spaces (ASHRAE Standard 62-89 versus ASHRAE Standard 62-81) [7-8].

A sensitivity analysis (based on elimination of ventilation) indicated that more than 60 percent of heating energy use is attributable to tempering of ventilation air. More than 30 percent of electricity use is attributable to operation of fans. In total, air-handling accounts for about 50 percent of site energy use. Lighting accounts for about 20 percent of electricity use, 7 percent of site energy use and about 12 percent of source energy use.

Table 2.1 Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Edmonton.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                  WEATHER FILE- EDMONTON TMY
---------------------------------------------------------------------------------------------


                                 ENERGY TYPE:  ELECTRICITY  NATURAL-GAS
                                 UNITS: MBTU

                              CATEGORY OF USE
                              ---------------

                                  AREA LIGHTS       1511.6          0.0

                                 MISC EQUIPMT       1311.0          0.0

                                   SPACE HEAT        737.0      14162.2

                                   SPACE COOL        575.3          0.0

                                  HEAT REJECT        625.4          0.0

                                 PUMPS & MISC        297.0          0.0

                                    VENT FANS       2422.4          0.0

                                 DOMHOT WATER          0.0        239.2
                                               ----------   ----------

                                        TOTAL       7479.7      14401.4
```

2.3.3 Lester B. Pearson High School - results for other Canadian locations

Tables 2.2-2.6 show energy end use for Lester B. Pearson High School for locations across Canada. Results are summarized in Figure 2.20. Total electricity use differed by only about 10 percent from the lowest value (Vancouver) to the highest (Toronto). Natural gas use varied by almost 70 percent from the lowest (Vancouver) to the highest (Winnipeg). Specific energy use ranged from about 240 kWh/m^2 for Vancouver, to about 400 kWh/m^2 for Winnipeg. Even in the former case, lights accounted for only about 10 percent of site energy use and about 15 percent of source energy.

The dominant loads in all cases were space heating (both control of perimeter losses and tempering of ventilation air), accounting for about 50 percent of total energy use in most cities, and the operation of fans for ventilation, accounting for about 20 percent of total energy use and about 30 percent of electricity use.

2.3.4 Lester B. Pearson High School - daylighting potential

Lighting electricity use at the high school accounted for about 20 percent of total electricity use in all of the locations for which simulations were conducted (the lighting power density is about 20 W/m^2). This is about 30 kWh/m^2, which is less than half the 80 kWh/m^2 that would be incurred if this lighting power density were operated 3750 hours per year. However, much of the load is in classrooms, which are operated only about 1400 hours (0830-1530, Monday to Friday) during the regular school year. Observation and discussions with school staff indicate that electric lighting is commonly used when spaces are occupied, even when illumination from daylight is adequate.

The simulation model was used to investigate the potential savings if daylight were more fully utilized. If electric lighting was switched off in spaces with adequate daylighting during working hours, the electricity use could be reduced to about of 20 kWh/m^2 overall.

Table 2.2 **Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Halifax.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                 WEATHER FILE- HALIFAX  TMY
-------------------------------------------------------------------------------------------

                                 ENERGY TYPE:   ELECTRICITY   NATURAL-GAS
                                 UNITS: MBTU

                              CATEGORY OF USE
                              ---------------

                                  AREA LIGHTS        1511.6           0.0

                                 MISC EQUIPMT        1311.0           0.0

                                   SPACE HEAT         629.2       10584.8

                                   SPACE COOL         850.5           0.0

                                  HEAT REJECT         765.4           0.0

                                 PUMPS & MISC         478.8           0.0

                                    VENT FANS        2267.3           0.0

                                 DOMHOT WATER           0.0         239.2
                                                 ----------    ----------

                                        TOTAL        7813.7       10824.0
```

Table 2.3 **Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Montreal.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- MONTREAL  TMY
-------------------------------------------------------------------------------------------

                                 ENERGY TYPE:   ELECTRICITY   NATURAL-GAS
                                 UNITS: MBTU

                              CATEGORY OF USE
                              ---------------

                                  AREA LIGHTS        1511.6           0.0

                                 MISC EQUIPMT        1311.0           0.0

                                   SPACE HEAT         644.0       12183.1

                                   SPACE COOL        1090.1           0.0

                                  HEAT REJECT         784.6           0.0

                                 PUMPS & MISC         642.1           0.0

                                    VENT FANS        2399.4           0.0

                                 DOMHOT WATER           0.0         239.2
                                                 ----------    ----------

                                        TOTAL        8382.7       12422.3
```

Table 2.4 Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Toronto.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- TORONTO  TMY
-------------------------------------------------------------------------------------------

                                   ENERGY TYPE:  ELECTRICITY  NATURAL-GAS
                                   UNITS: MBTU

                                CATEGORY OF USE
                                ---------------

                                    AREA LIGHTS       1511.6          0.0

                                   MISC EQUIPMT       1311.0          0.0

                                     SPACE HEAT        607.0      10736.9

                                     SPACE COOL        929.9          0.0

                                    HEAT REJECT        768.0          0.0

                                   PUMPS & MISC        501.5          0.0

                                      VENT FANS       2386.9          0.0

                                   DOMHOT WATER          0.0        239.2
                                                  ----------   ----------

                                          TOTAL       8015.8      10976.1
```

Table 2.5 Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Winnipeg.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- WINNIPEG TMY
-------------------------------------------------------------------------------------------

                                   ENERGY TYPE:  ELECTRICITY  NATURAL-GAS
                                   UNITS: MBTU

                                CATEGORY OF USE
                                ---------------

                                    AREA LIGHTS       1511.6          0.0

                                   MISC EQUIPMT       1311.0          0.0

                                     SPACE HEAT        762.6      15671.7

                                     SPACE COOL        775.3          0.0

                                    HEAT REJECT        675.0          0.0

                                   PUMPS & MISC        453.4          0.0

                                      VENT FANS       2403.4          0.0

                                   DOMHOT WATER          0.0        239.2
                                                  ----------   ----------

                                          TOTAL       7892.3      15910.9
```

Table 2.6 **Simulated electricity use for Lester B. Pearson High School, Typical Meteorological Year at Vancouver.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY              WEATHER FILE- VANCOUVER TMY
-------------------------------------------------------------------------------------------

                                   ENERGY TYPE:  ELECTRICITY   NATURAL-GAS
                                   UNITS: MBTU

                                CATEGORY OF USE
                                ---------------

                                    AREA LIGHTS       1511.6           0.0

                                   MISC EQUIPMT       1311.0           0.0

                                     SPACE HEAT        452.2        6332.1

                                     SPACE COOL        711.2           0.0

                                    HEAT REJECT        836.4           0.0

                                   PUMPS & MISC        287.8           0.0

                                      VENT FANS       2529.1           0.0

                                   DOMHOT WATER          0.0         239.2
                                                  ----------    ----------

                                          TOTAL       7639.4        6571.4
```

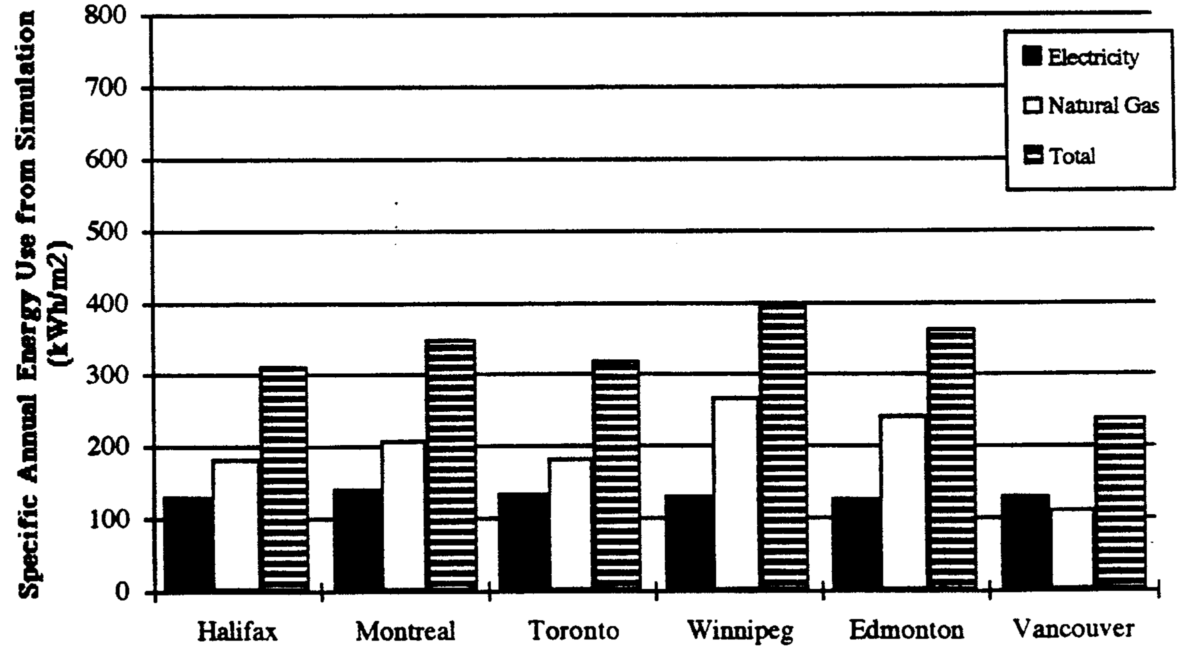

Figure 2.20 **Specific energy use for Lester B. Pearson High School for different Canadian locations; determined by simulation.**

2.3.5 Lester B. Pearson High School - daylighting performance in a selected space

Measurements made in a classroom facing north-west in early August, 1993 show that the uniformity of illumination from daylight is excellent (Figure 2.21) (measurements were made during the summer when the photocells could be left in a classroom for several days to allow continuous logging). Illuminances were measured along the centreline of the classroom at equal intervals from the window wall to the rear wall). This classroom has a stepped section with a clerestory at the midpoint. Illuminance levels rise sharply later in the day as sunlight swings onto the northwest facade of the school.

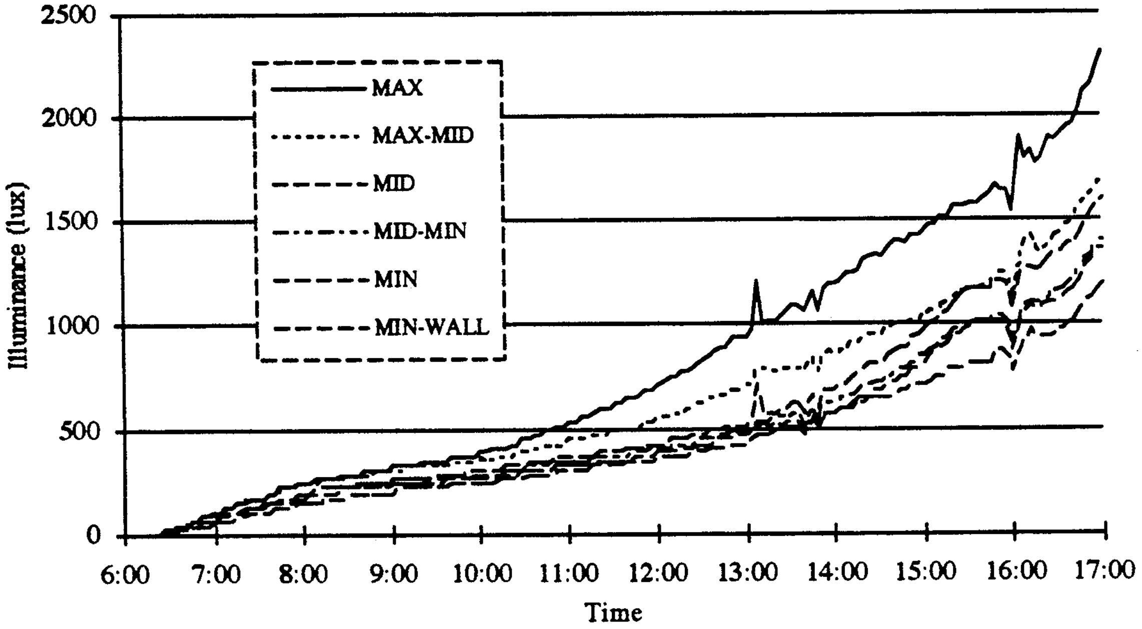

Figure 2.21 Illumination from daylight in a north-facing classroom at Lester B. Pearson High School, August 5, 1994.

2.3.6 Lester B. Pearson High School - effects of lighting on cooling

Test were conducted in September of 1994. No changes in air flow rates were found as a result of switching the lights on or off in the test spaces.

A simulation was run for the school with the Edmonton Typical Meteorological Year and the light scheduling programmed so that building operation would be simulated without lights for the year (Table 2.7). Energy use under these conditions represents the boundary for improvements that could be achieved through daylighting. Cooling energy use was about 13 percent lower, fan energy use about 5 percent lower, and total energy use was about 18 percent lower with electric lighting use eliminated. However, this extreme scenario is not attainable in practice since many spaces (e.g., interior classrooms on the lower level) require electric lighting when occupied and because of night-time uses.

Table 2.7 **Simulated electricity use for Lester B. Pearson High School - no electric lighting, Typical Meteorological Year at Edmonton.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- EDMONTON TMY
-------------------------------------------------------------------------------------------

                            ENERGY TYPE:  ELECTRICITY   NATURAL-GAS
                            UNITS: MBTU

                         CATEGORY OF USE
                         ---------------

                            MISC EQUIPMT       1311.0           0.0

                              SPACE HEAT        680.4       12253.9

                              SPACE COOL        499.5           0.0

                             HEAT REJECT        653.0           0.0

                            PUMPS & MISC        236.0           0.0

                               VENT FANS       2294.2           0.0

                            DOMHOT WATER          0.0         239.2
                                           ----------    ----------

                                   TOTAL       5679.0       12493.1
```

2.3.7 Professional Faculties Building - results for Alberta conditions

As with the high school, electricity use for lighting accounted for a small fraction of total energy use - about 3 percent (Table 2.8) - and 16 percent of total electricity use. Natural gas for space heating accounted for about 62 percent of total site energy use and electricity for ventilation fans accounted for about 21 percent of total site energy use.

Table 2.8 Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Edmonton.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                 WEATHER FILE- EDMONTON TMY
---------------------------------------------------------------------------------------------

                                      ENERGY TYPE:   ELECTRICITY   NATURAL-GAS
                                      UNITS: MBTU

                                    CATEGORY OF USE
                                    ---------------

                                         AREA LIGHTS        3861.0           0.0

                                        MISC EQUIPMT        2663.6           0.0

                                          SPACE HEAT        3582.9       38136.8

                                          SPACE COOL         365.9           0.0

                                         HEAT REJECT          58.1           0.0

                                         PUMPS & MISC        374.2           0.0

                                           VENT FANS       13715.2           0.0
                                                        ----------    ----------

                                               TOTAL       24620.9       38136.8
```

The specific site electricity use for lighting at The Professional Faculties Building is about 44 kWh/m^2, compared with about 32 kWh/m^2 for the High School (the lighting power density at the Professional Faculties Building is about 17 W/m^2, compared with about 20 W/m^2 at the school). It is important to allow for the fact that the lighting is in use many more hours per day in much of the university building. It has a high fraction of circulation space (about 20 percent) to accommodate the 24-hour indoor circulation system that links university buildings. If operated 3750 hours per annum instead of 8760 hours perannum, the reduction in lighting energy use would be about 430,000 kWh. This, averaged over the entire floor area of the building, would account for about 16 kWh/m^2. The remaining approximately 24 kWh/m^2 makes the building relatively energy efficient in terms of lighting energy use.

2.3.8 Professional Faculties Building - results for other Canadian locations

Tables 2.9-2.13 show energy end use for the Professional Faculties Building for locations across Canada. Figure 2.22 provides a summary of specific energy use by resource for these locations. Total electricity use differed by only about 7 percent from the lowest value (Vancouver) to the highest (Winnipeg). Natural gas use varied by about 75 percent from the lowest (Vancouver) to the highest (Winnipeg). Specific energy use ranged from about 520 kWh/m^2 for Vancouver, to about 730 kWh/m^2 for Winnipeg. Even in the former case, lights accounted for only about 8 percent of site energy use and about 12 percent of source energy.

The dominant loads in all cases were space heating (both control of perimeter losses and tempering of ventilation air), accounting for about 50-60 percent of total energy use, and the operation of fans for ventilation, accounting for about 20-30 percent of total energy use and about 55-59 percent of electricity use, depending on location.

2.3.9 Professional Faculties Building - daylighting potential

A much smaller fraction of the floor area of the Professional Faculties Building is exposed to daylight than is the case for the high school (e. g., see Figure 2.8). There core areas also experience long hours of electric lighting operation because circulation areas are illuminated 24 hours per day. In many perimeters areas, electric lighting use is already low, or is used to offset glare effects of direct sunlight. Therefore, daylighting could not provide substantial further reductions in lighting electricity use.

Table 2.9 **Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Halifax.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY              WEATHER FILE- HALIFAX  TMY
-----------------------------------------------------------------------------------------

                                ENERGY TYPE:  ELECTRICITY  NATURAL-GAS
                                UNITS: MBTU

                             CATEGORY OF USE
                             ---------------

                                AREA LIGHTS      3861.0          0.0

                               MISC EQUIPMT      2663.6          0.0

                                 SPACE HEAT      2823.6      29517.7

                                 SPACE COOL       500.5          0.0

                                HEAT REJECT        85.1          0.0

                               PUMPS & MISC       374.2          0.0

                                  VENT FANS     13715.2          0.0
                                             ----------   ----------

                                      TOTAL     24023.2      29517.7
```

Table 2.10 **Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Montreal.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY             WEATHER FILE- MONTREAL  TMY
-----------------------------------------------------------------------------------------

                                ENERGY TYPE:  ELECTRICITY  NATURAL-GAS
                                UNITS: MBTU

                             CATEGORY OF USE
                             ---------------

                                AREA LIGHTS      3861.0          0.0

                               MISC EQUIPMT      2663.6          0.0

                                 SPACE HEAT      3080.1      32811.0

                                 SPACE COOL       677.5          0.0

                                HEAT REJECT       121.0          0.0

                               PUMPS & MISC       465.6          0.0

                                  VENT FANS     13715.2          0.0
                                             ----------   ----------

                                      TOTAL     24584.0      32811.0
```

Table 2.11 Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Toronto.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- TORONTO  TMY
--------------------------------------------------------------------------------------------


                          ENERGY TYPE:  ELECTRICITY   NATURAL-GAS
                          UNITS: MBTU

                       CATEGORY OF USE
                       ---------------

                           AREA LIGHTS      3861.0           0.0

                          MISC EQUIPMT      2663.6           0.0

                            SPACE HEAT      2803.3       29558.2

                            SPACE COOL       724.1           0.0

                           HEAT REJECT       125.6           0.0

                          PUMPS & MISC       406.3           0.0

                             VENT FANS     13715.2           0.0
                                        ----------    ----------

                                 TOTAL     24299.2       29558.2
```

Table 2.12 Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Winnipeg.

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                WEATHER FILE- WINNIPEG TMY
--------------------------------------------------------------------------------------------


                          ENERGY TYPE:  ELECTRICITY   NATURAL-GAS
                          UNITS: MBTU

                       CATEGORY OF USE
                       ---------------

                           AREA LIGHTS      3861.0           0.0

                          MISC EQUIPMT      2663.6           0.0

                            SPACE HEAT      3708.9       40003.4

                            SPACE COOL       461.3           0.0

                           HEAT REJECT        75.5           0.0

                          PUMPS & MISC       444.7           0.0

                             VENT FANS     13715.1           0.0
                                        ----------    ----------

                                 TOTAL     24930.1       40003.4
```

Table 2.13 **Simulated electricity use for Professional Faculties Building, Typical Meteorological Year at Vancouver.**

```
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY               WEATHER FILE- VANCOUVER TMY
-------------------------------------------------------------------------------------------


                               ENERGY TYPE:  ELECTRICITY   NATURAL-GAS
                               UNITS: MBTU

                            CATEGORY OF USE
                            ---------------

                                AREA LIGHTS       3861.0           0.0

                               MISC EQUIPMT       2663.6           0.0

                                 SPACE HEAT       2180.3       22843.7

                                 SPACE COOL        495.7           0.0

                                HEAT REJECT         77.2           0.0

                               PUMPS & MISC        302.9           0.0

                                  VENT FANS      13715.2           0.0
                                              ----------    ----------

                                      TOTAL      23296.0       22843.7
```

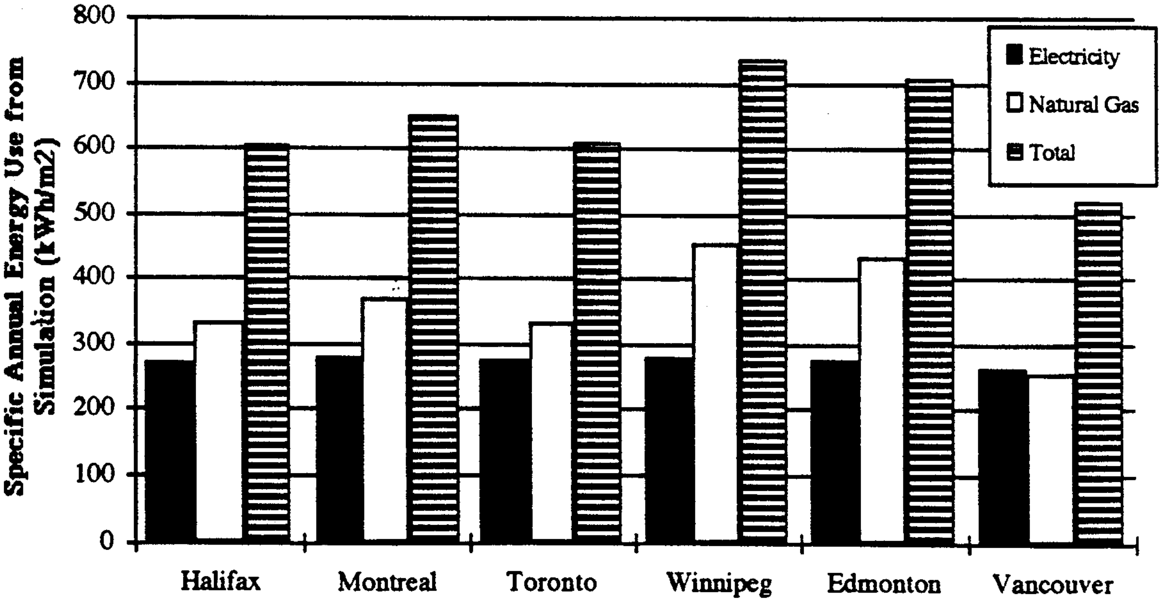

Figure 2.22 **Specific energy use for Professional Faculties Building for different Canadian locations; determined by simulation.**

2.4 Daylit Spaces with High Energy Savings

Observations were made during the 1994-95 academic year of electric lighting use in selected areas of the Professional Faculties Building. Three types of spaces were identified where electric lighting was seldom used in the daytime:

1) east-facing and north-facing private offices on third level of the building, with electric lights controlled by the four level manual switching described above
2) an open plan studio area on the fourth level of the building, with ambient electric lighting controlled by on-off manual switches
3) a daylit corridor on the main level of the building, in which an automatic control (on-off) had been installed.

These spaces were all located so that they received relatively little direct sunlight during the day. It was noted that in both private offices and multi-occupant spaces on the south side of the Professional Faculties Building, shades were usually covering most or all of the window areas and the electric lights were typically switched on the daytime. While, the upper window shades were of a mesh type that admitted some diffuse light when drawn, it is believed that occupants switched the electric lights on to counteract the effects of glare rather than to raise workplane illuminances. This is notably supported by the fact that occupants of the fourth level studio area listed above seldom switched lights on (less than 5 percent of working hours) despite the fact that illuminances at the centre of the studio area were about 60 lux in the daytime. The difference in the spaces was that the 4th level studio space was buffered from direct sunlight by a large light well with blinds that were automatically adjusted to exclude direct sunlight.

To allow comparison with projects reported in the literature [9], 3750 hours of operation are used as a basis for computing annual energy use for lighting. This amounts to about 14 hours of lighting use per working day (based on 22 working days per month).

2.4.1 East- and north-facing private offices

It is estimated that electric light is used less than 5 percent of hours between 0900 and 1700 in most of these private offices (Figure 2.10), which are equipped with four level manual switching. The lighting power density (ambient) is about 17 W/m^2. The electric lighting use is then less than the 5 kWh/m^2 reported for a low-energy office in the United Kingdom that made very successful use of daylighting [10-11].

As noted above, the fact that these offices are exposed to little direct sunlight is believed to be a key factor in daylighting use. Other contributing factors are 1) the high visible transmittance of the glazing, which allows use of a relatively high fraction of the available daylight, 2) light interior surfaces and window surrounds, which reduce apparent sky luminance and glare and increase uniformity of illumination, and 3) high window heads, which allow for relatively deep daylight penetration.

2.4.2 Open plan studio area

It is estimated that electric light is used less than 5 percent of hours between 0900 and 1700 in the open plan studio area in winter and between 0700 and 1900 in summer. The lighting power density (ambient) is about 17 W/m^2 and the installed ambient lighting load for the space is about 5 kW (of which about 1 kW is lighting permanently wired on in adjacent circulation areas). Almost every workstation is equipped with one or two task lamps. For 3750 hours of operation, the reduction in ambient lighting energy use due to daylighting is estimated at 65 percent. This would give an annual electrical use of 22 kWh/m^2, which is very efficient. As noted above, the fact that this space is shielded from direct sunlight is believed to be a key factor in daylighting use. The space received daylight from both the north and south sides, which improves uniformity and reduces glare. Other contributing factors are the window and space design characteristics that were noted above for the private offices.

Figure 2.23 - View of open plan studio area.

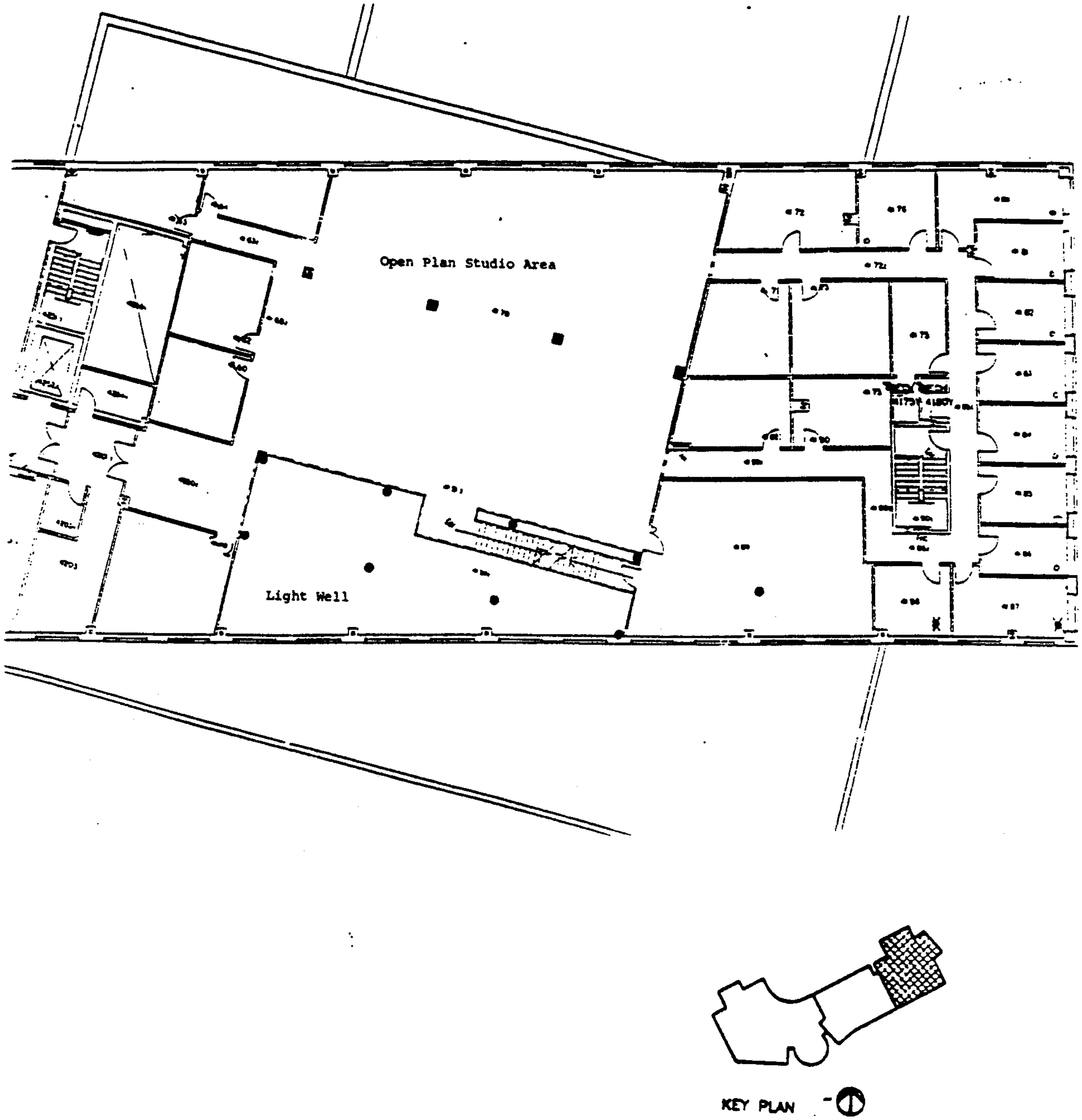

Figure 2.24 - Plan of fourth floor of Professional Faculties Building showing the open plan studio area.

2.4.3 Corridor

It is estimated that electric light is used less than 5 percent of hours between 0900 and 1700 in the corridor. The lighting power density (ambient) is about 17 W/m^2 and installed lighting capacity is about 5 kW. For 3750 hours of operation, the reduction in lighting energy use is conservatively estimated at 50 percent. However, the corridor is, in reality, illuminated on a round-the-clock basis. Daylighting is estimated to displace electric lighting about 3400 hours of the 8760 in a year, providing about 40 percent of the continuous illumination requirement. The annual energy and dollar savings are about 17,000 kWh and $700.

Figure 2.25 - View of daylit corridor at the Professional Faculties Building.

3.0 PERFORMANCE OF SELECTED DAYLIGHT-LINKED DIMMING SYSTEMS

3.1 Test Space Description and Method

A south-facing area was chosen to test the dimming system because this orientation is most vulnerable to direct glare from sunshine (most hours of exposure during working hours) and represents the most critical test for glare control. An third level open-plan area of the Professional Faculties Building (see Figures 2.8 and 3.1) was partitioned to isolate it from lighting conditions in adjacent open plans areas (for a section of the window wall, showing the split window and dual blind system see Figure 3.2). The test area continued to be used as a working studio area furnished with drafting tables, layout tables, and lockers. Light levels were monitored at several points in the space (designated by the small squares; the ones with x's are at the top of 1.3 m high partitions, while the others are at the workplane). The space

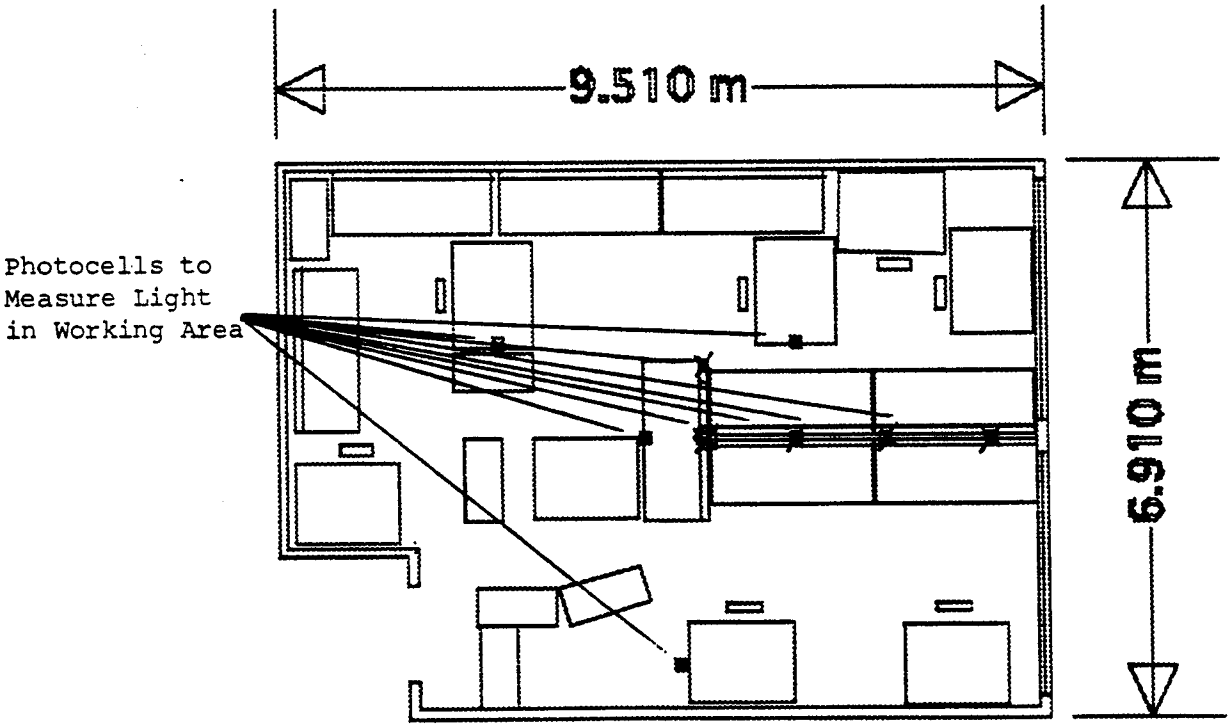

Figure 3.1 **Plan of dimming test area at the Professional Faculties Building.**

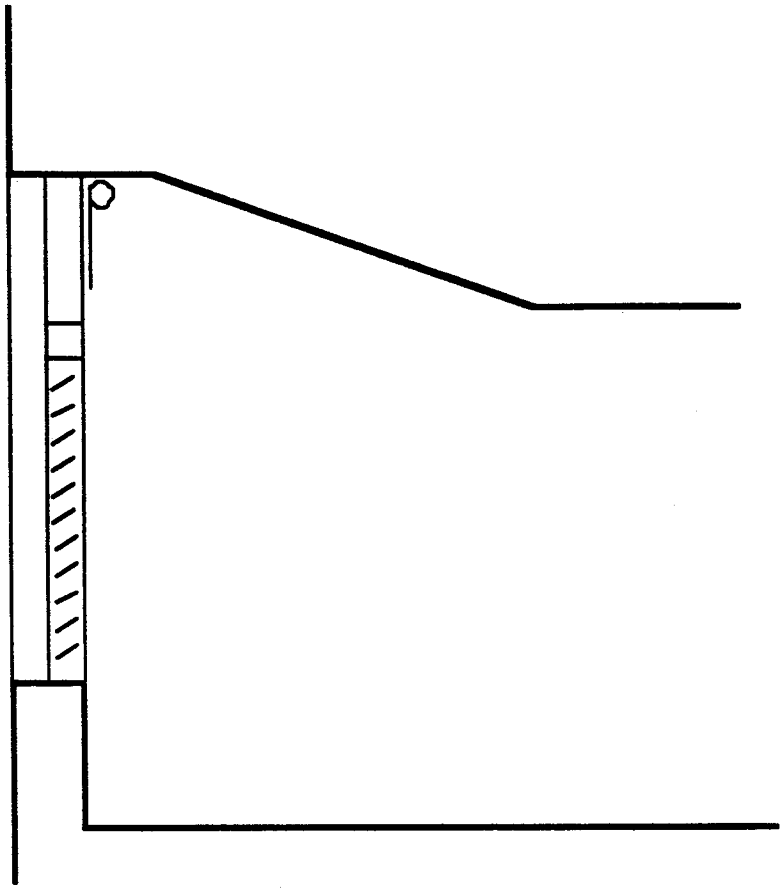

Figure 3.2 **Section of window wall in dimming test area at the Professional Faculties Building.**

is illuminated by 9 two-lamp luminaires, which were retrofitted with solid state dimming ballasts. The choice of ballasts was limited by the fact that the lighting circuit operates at 347 volts, which is common in Alberta, but uncommon in North America as a whole. These were isolated on a separate circuit, monitored by a logging system. This provided continuous recording of electricity use, including electric demand and power factor. The dimming ballasts were connected to commercial sensing and control units designed to detect the level of ambient light at the workplane (located on the ceiling near the centre of the space -see circle near centre of plan) and to reduce the electric light output in response to the amount of available daylight. The control detectors were located about 4 m from the window wall.

The first control system (referred to as Control System A) was supposed to be adjustable by night-time calibration to provide workplane illuminances between 70 and 700 lux. However, it was found that the lowest setting was about 580 lux and the highest 750. The second control system (referred to as Control System B) allowed workplane illuminances to be adjusted between 200 and 500 lux.

The first detector was calibrated to provide 580 lux at the workplane. In response to complaints by the occupants, the level was increased to 700 lux when the second detector was installed. This is noteworthy, because ambient levels in much of the open plan drawing areas discussed in 2.4.2 were typically between 200 and 300 lux. It is believed that the desire for higher light levels was to offset the glare from the windows (even with the blinds drawn, or mostly drawn) in the south-facing dimming test area rather than because of task requirements, which were similar.

3.2 Results of daylight-linked dimming tests

Figure 3.3 shows the light level measured at the ceiling by a photocell mounted in the manufacturer's housing for the detector for Control System A, along with the workplane illuminance measured near the centre of the test space and the lighting power demand (clear winter day, blinds raised).

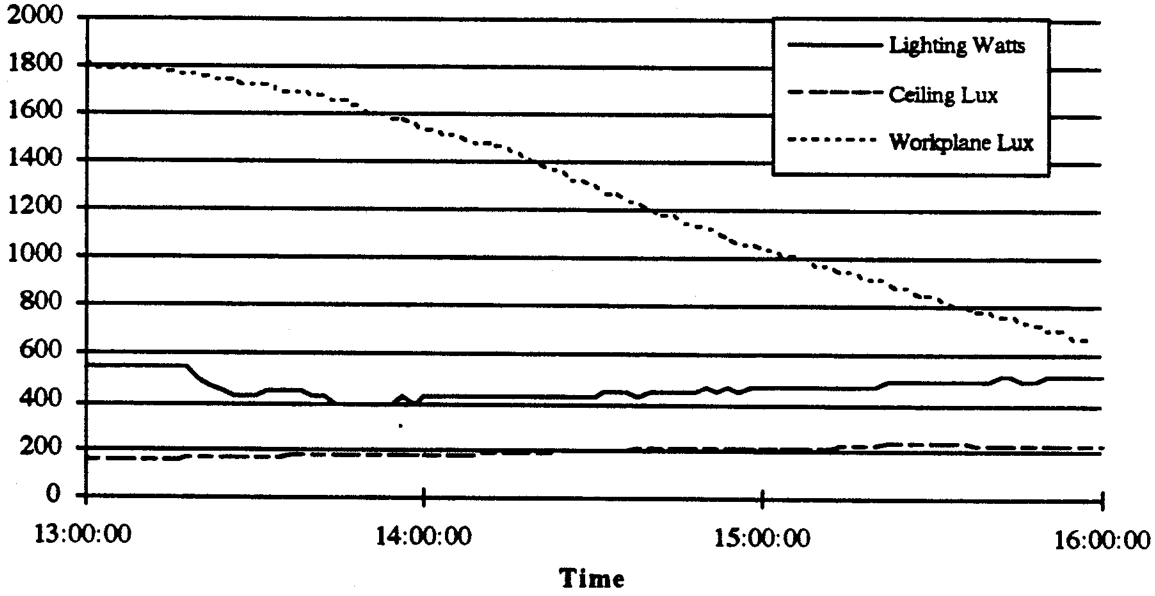

Figure 3.3 **Light levels and lighting power demand in the dimming test area on January 6, 1995.**

Figure 3.4 shows the degree of dimming for the test area for a clear summer day with the blinds as set by the occupants. The usual setting over several months was to have the mesh shades (above) and the venetian blinds (below) fully lowered, with the blind slats horizontal on the left side (facing the window) and closed on the right side. The ballast used has a minimum power demand of about 20 percent of the maximum power demand, which is attained near the middle of the day. The peak around 1000 is due to obstruction of the sun by a 14 storey building to the south.

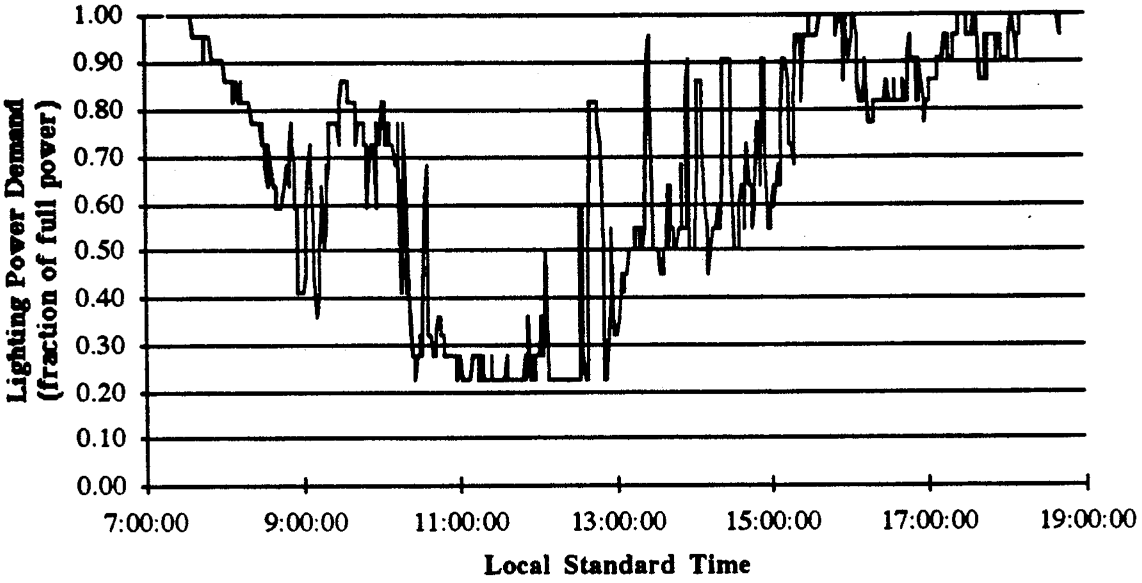

Figure 3.4 Lighting power demand for a mainly clear summer day with blinds as set by the occupants.

If the dimming ballasts operated at minimum power for 12 hours per day, 365 days per year, the energy savings would be about 4400 hours * (1-0.20) * 550 W or about 2000 kWh for the test space. At $0.04 per kWh, the marginal rate paid by the university (including demand charges), the dollar saving would be about $80 per annum. The cost of the installation is about $900 ($450 for 9 ballasts, $80 for the control unit, and $300 for installation), so the simple payback is about 11 years. At a marginal electrical rate of $0.08, this would be reduced to about 5 years.

However, the average lighting power reduction, even on a mainly clear day in summer with all shades raised, is about 65 percent between 0700 and 1900. In this case the simple payback period would be about 14 years (or 7 years at $0.08/kWh). With the blinds as set by the participants, the average lighting power reduction for a mainly clear day in summer is about 23 percent between 0700 and 1900 (for reference, the reduction would be 37 percent between 0800 and 1700). Under these conditions the payback period would be about 45 years.

In terms of daylight exploitation, the chief obstacle in these south side spaces is the lack of a system that provides adequate glare control while admitting daylight. Possible solutions would include use of a baffle system on the upper window areas instead of the mesh screens.

In terms of cost-benefit, the high cost of dimming ballasts is a serious obstacle to cost effectiveness.

4.0 FINDINGS IN RELATION TO OTHER RESEARCH ON DAYLIGHTING

In this section, some factors affecting the energy-saving potential of daylighting are discussed. A review of the findings from monitoring studies of buildings with special daylighting features is provided. These findings are used to place the results of this study in perspective.

4.1 User Preferences Regarding Illumination Levels in Daylit Offices

Successful implementation of lighting and lighting control strategies requires accommodation of user requirements. As was noted in the introduction, earlier studies have found that controlling electric lights multiple offices or workstations based on a daylight control signal from a single detector is problematic because preferences and requirements vary from occupant to occupant (e.g., a manager who spends a high percentage of time in meetings may not be distracted by sunlight, while it can be a major problem for an analyst working on a computer a few offices away). Research in Finland and the Netherlands has shown that occupants of sidelit offices preferred higher levels of electric lighting as exterior illumination from daylight increased. This is consistent with findings regarding glare - increasing interior light levels as exterior light levels increase reduce the contrast between indoors and outdoors, which, in turn, reduces glare [5]. However, it is inconsistent with the usual approach taken in the design of daylighting controls, which assumes that increased outdoor illumination from daylight increases interior light levels and decreases requirements for electric lighting. Research currently underway by this author shows that the assumption may be valid when fenestration and shading are designed so that daylight is well-distributed, which reduces glare from the window.

4.2 Energy-saving Potential and Cost-effectiveness of Daylighting

Apart from factors usually considered in calculating daylighting levels (e. g., window size, glass transmittance), others have been found to be very important in terms of energy savings from daylighting, including:

1. installed lighting power density,
2. opportunities for energy savings through use of occupancy detectors
3. lighting control system use and performance, and
4. occupant use of shades.

These factors will be reviewed in this subsection.

4.2.1 Trends in lighting power densities

A key factor in determining the energy-saving potential and cost-effectiveness of daylighting is the amount of electricity used for lighting. The lower the lighting electricity use per unit floor area, the lower the potential savings from daylighting and the lower the value of the dollar savings to offset any additional expenses associated with daylighting.

New technologies are allowing substantial reductions in lighting electricity use. Until recently, a lighting power density (installed lighting power per unit floor area) of 22 W/m^2 was considered to be energy-efficient. A building drawing a steady 22 W/m^2 for lighting would use about 80 kWh/m^2 for 3750 annual hours of operation (about 12 hours per day, 6 days per week) or about 57 kWh/m^2 for 2600 annual hours of operation. Designers are now satisfying office illumination requirements with lighting power densities of about 12 W/m^2, equivalent to about 45 kWh/m^2 for 3750 annual hours of operation or about 31 kWh/m^2 for 2600 annual hours of operation.

One technology combination allowing more efficient lighting is the smaller diameter fluorescent lamp together with the electronic ballast (ballasts are devices required to operate fluorescent lamps; they regulate voltage and current for starting and regular operation). Electronic ballasts require much less power than magnetic ballasts for the same functions. The smaller lamps, known as T8 lamps, are one inch in diameter (lamp diameters are commonly rated in eighths of an inch), compared with the one and a half inch diameter T12 lamps that are still widely used in Canada. The smaller diameter lamps are made with coatings that are more efficient in terms of light production; the smaller diameter contributes to cost-effective use of these coatings. A lamp-ballast system with two 40 watt lamps (the combination typically used in fluorescent fixtures in commercial and institutional settings) with a pre-1990 magnetic ballast would draw about 96 watts. Two T8 lamps with an electronic ballast can produce almost as much light using about 60 watts of electricity. Further, the light output of T8 lamps diminishes much less over time than the light output of T12 lamps, reducing the need for initial over-design of illumination levels. The result of the new technology is a substantial reduction in the electric lighting use to be displaced.

4.2.2 Occupancy-related control

Another consideration in the potential for daylighting application is the use of occupancy controls, which can further reduce the potential electricity savings. Recent studies have shown that workers are out of their offices 30-70 percent of the time during working hours [10-13]. Due to time delays on occupancy control systems, only about 80 percent of the potential savings would be realized with automatic controls. The reductions in lighting electricity use would then be about 30 percent, which is consistent with the Power Adjustment Factor for occupancy detectors that is provided in the ASHRAE-IES standard for energy efficient design [14]. The combination of occupancy controls and reduced lighting power density would reduce annual lighting electricity use that could potentially be displaced by daylighting to less than 31 kWh/m^2 for 3750 annual hours of operation or about 22 kWh/m^2 for 2600 annual hours of operation.

4.2.3 Lighting control systems

Some dimming ballasts, including both core-coil and solid state ballasts, can be adjusted to a minimum of 20-30 percent of full power output, even when daylight fully meets illumination requirements. Dimming electronic ballasts are available in two types - low-voltage-control input and high-voltage-control input. The low-voltage-control input ballasts are most common. An experimental study found that the high-voltage-input ballasts were more effective at dimming over the full range of possible power output. It has also been found that in certain areas in control ranges, varying the control signal had no effect on the light output [15]. Because of the cost of automatic controls, lighting for several offices or workstations is frequently regulated by a single controller. This often leads to deactivation of the system, due to differing user requirements and characteristics.

Field studies have shown that manual switching can result in lower lighting electricity use than automatic switching because users will, in many cases, not switch on electric lights until illumination from daylight is well below that at which automatic systems would be programmed to activate the electric lights [16]. This seems to be dependent on the provision of relatively glare-free daylighting. However, once switched on, the lights are generally left on until the end of the day.

4.2.4 Occupant use of shades

Window blinds affect daylighting in two ways. Firstly, because the upper part of the window contributes the most to illumination at points further from the window wall , and because most blinds are lowered from the top of the window head, blinds can greatly reduce the admission of daylight when they are lowered to exclude direct sunlight. Secondly, blinds can affect the signals received by detectors used in daylight-linked fluorescent dimming systems. Light redirected to the ceiling by blind slats may contribute to a misleading indication of light of the workplane. In larger spaces with dimming systems controlled by a single detector, differential use of blinds may lead to excessive (in terms of energy efficiency) or inadequate illumination. The former can occur if blinds exclude daylight near the detector when natural illumination is adequate to supplement electric sources [17]. The latter can occur if blinds are drawn in areas away from the detector to control glare [4, 18]. It has been found that most occupants of offices with window blinds have preferred settings that vary little with daily and seasonal conditions. It appears that this preferred blind setting is based on the exclusion of direct sunlight [19-20]. Thus, use of typical window blinds usually results in significant reductions in the daylight admitted through fenestration

Monitoring of daylight-linked fluorescent dimming systems in offices and other spaces with simple windows has revealed annual electricity use reductions of about 30 percent for sidelighting systems [13, 17, 21]. This is less than might be expected based on calculations; a chief cause of lower than expected savings is occupant use of shades to exclude direct sunlight.

4.2.5 Summary

The lighting energy reduction potential of a daylighting system will be a function of

1) the installed lighting power density (the lower the lighting power density, the less electricity will be saved by daylight-linked control systems),
2) the actual hours of lighting requirement (allowing for occupancy-based control),
3) control system use and performance, and
4) occupant use of adjustable shades.

Projections of lighting electricity savings from daylighting based on 22 W/m^2 installed lighting power density, no use of occupancy controls, linear daylight-linked fluorescent dimming, and ideal occupant behaviour in using shades for glare control might suggest a potential lighting electricity displacement of about 60 kWh/m^2 from 80 kWh/m^2. However, use of more efficient lighting together with occupancy detectors would reduce lighting electricity use in many offices to about 31 kWh/m^2 for 3750 annual hours of operation or about 22 kWh/m^2 for 2600 annual hours of operation. Some field studies have shown that this can be reduced about 30 percent through daylight-linked fluorescent dimming in perimeter offices, allowing for occupant use of shades and the characteristics of automatic control systems.

It appears that financial justification of systems to provide automatic daylighting control through dimming in individual offices may require consideration in terms of other control functions. At $0.08/kWh, the value of the annual energy savings from daylighting for 3750 hours of operation would be worth about $12 per annum for a 15 m^2 office with occupancy control (i.e., using about 31 kWh/m^2 per annum). With dimming ballasts currently costing about $20 more than non-dimming electronic ballasts and a detector-controller costing about $50, the payback for dimming control in a private office would be more than 8 years if based on daylighting savings alone (in warmer climates reductions in lighting electricity use can be accompanied by substantial reductions in energy use for cooling [22], which can add to the cost-effectiveness of lighting controls). However, dimming ballasts and the control systems that detect illumination levels for purposes of daylighting control may be used to achieve other savings. If dimming ballasts are used for purposes of load shedding to reduce peak demand, the financial savings from this measure alone may be sufficient to justify the cost of the dimming ballasts. Electric lighting systems are typically designed to provide illuminance levels about 20-30 percent in excess of the design target in order to allow for losses over time. These losses include depreciation of light output as lamps age (about 7 percent over the life of a T8 fluorescent lamp), losses due to the accumulation of dirt on room and luminaire lens surfaces, and losses due to the aging of the luminaire lens. The latter two types of losses are estimated in rather gross terms. The adjustment of illumination levels possible with the daylighting control system can allow for "tuning" of illumination to design targets - power supplied to the lamps would automatically increase to offset losses due to aging of lamp and lens and the accumulation of dirt.

Another possibility is to provide occupancy controls together with manual on-off switching on an individual office or workstation basis. Research has shown that the switching decision in an office with the lights off is typically made on entering a space (as long as the light switch is conveniently located near the door). However, once switched on, lights are typically left on until there is a major break in activity (e.g., lunch or the end of the work day). Use of occupancy controls would force a user to make a switching decision after each prolonged absence from an office or workstation. This approach has the advantage of allowing the user to decide whether lighting conditions are adequate rather than assigning control to an automatic system.

These considerations suggest that increased use of daylighting as an energy conservation strategy is contingent upon:

1. the development of less expensive electronic dimming ballasts (with full-range linear dimming) and controls, the application of controls in a more comprehensive manner, and/or the use of less expensive control strategies (such as automatic occupancy-based extinction of lights combined with manual activation), and

2. the development of more effective blind or shade systems for distributing daylighting in perimeter spaces while screening direct sunlight .

4.3 Reported results for monitored buildings

The BRE (Building Research Establishment of the United Kingdom) low-energy office, occupied in 1981, is a shallow plan three-storey 2000 m^2 office building (mainly private offices ranged along a double-loaded corridor) with a lighting power density of 7.7 W/m^2 providing 350 lux on the work plane [10]. Annual energy use for lighting is about 5 kWh/m^2. This was achieved with manual switching after the automatic switching controls were disconnected because difficulties arose with occupants being unable to "over-ride the lighting controls (e.g., if staff worked overtime)" [11]. A system of automatically deployed awnings was used to exclude direct sunlight on facades where such protection was required. Monitoring showed that offices are unoccupied about 50 percent of the time during working hours.

Performance of a photoelectric dimming system in a 56, 000 m^2 office building in the San Francisco area (38° north latitude) was reported in 1986 [9]. The structure had five floors, with a floor plate extending 28 m from the exterior to the atrium. The design incorporated radical design features such as a floor-to-ceiling height varying from 4.5 m at the perimeter to about 3 m at the center of the floor plate and light shelves to increase daylight penetration and shade lower window areas. The interior spaces were organized on an open plan basis in combination with the unusually high ceiling to increase daylight penetration beyond the perimeter. Services were clustered at the east and west ends of the building, again to keep the office areas free of interior walls.

It was concluded that:

- the architectural features of the building were providing in excess of 350 lux (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

- 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 even 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

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

Andersson et al. conducted extensive field measurements and simulation studies on two small skylit projects (also in the United States), a library (at about 36° north) of 1200 m^2, of which the core area of 520 m^2 was evaluated, and a church class and meeting room addition (location not identified) of 420 m^2 [16]. The buildings were equipped with manual controls. The annual lighting energy use was 9 kWh/m^2 for the core area of the library and 21 kWh/m^2 for the church addition. Total annual energy use was 65 kWh/m^2 and 62 kWh/m^2 respectively (the buildings were equipped with heat pump systems). Through scale model and computer simulation studies the relative performance of daylight-linked automatic controls was assessed. For the library core area, it was estimated that lighting energy use would have been about 300 percent greater with on-off controls and about 100 percent greater with dimming controls. In the case of the church addition, it was estimated that lighting energy use would have been about 30 percent greater with on-off controls and 100 percent greater with dimming controls. The explanation is that "occupants keep the lights off the great majority of the time that daylighting provides illumination above accepted standards, and much of the time when illumination is below, even substantially below, those standards." However, it was noted, in the case of the library, that once lights were turned on, they were usually left on for the rest of the day, regardless of the amount of available daylight.

Heap et al. reported the performance of another dimming system in the 3000 m^2 South Staffordshire Water Company building (an office) near Birmingham, UK (52.5^o north latitude) was reported [23]. It is a four story structure, with a floor plate extending 7.5 to 11 m from the perimeter to the core, and a photo-electrically controlled dimming zone 5 to 7 m deep. The building has a 10 ft (3 m) 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 investigators 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, with 9 kWh/m^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 lux with uniformity of 0.8

The electricity use in the dimming zones would be about 11 kWh/m^2 if extrapolated to the 3750 hours of annual operation used to estimate consumption in the San Francisco study.

The BRE low energy office appears to be near the limit of substituting daylight for electric light, with a specific site electricity use of about 5 kWh/m^2 for lighting. However, this is a very shallow plan building. In the case of a toplit library, a value as low as 9 kWh/m^2 was achieved, and this was matched by the sidelit dimming zones of an office building in the UK with special daylighting features.

4.4 Findings for the buildings studied in relation to other research results

The validated simulation models for the buildings studied were used to estimate energy use for several Canadian locations: Halifax, Montreal, Toronto, Winnipeg, Edmonton, and Vancouver. The specific energy use for the school ranged between 240 and 400 kWh/m^2 and for the university building between about 500 and 700 kWh/m^2 (Vancouver versus Winnipeg). This is in the vicinity of the 470 kWh/m^2 cited as typical for pre-1973 office buildings [24], but much higher than the approximately 300 kWh/m^2 that might be expected for a building meeting the current ASHRAE-IES recommendations for energy efficient design.

It was found that the specific energy use (annual energy use in kWh/m^2) for the daylit high school was near the median for the other six high schools for which energy use data were obtained. A much higher fraction of energy use at the daylit high school was in the form of electricity. However, the daylit high school was built subsequent to the adoption of much higher recommended ventilation rates (40 l/s versus the earlier 10 l/s) by the American Society of Heating, Refrigerating and Air-conditioning Engineers. Indeed, use of electricity for ventilation fans and related energy use for tempering of ventilation air was found to be the single largest component of energy end use.

Electricity use for lighting amounted to 6 and 3 percent of total energy use for the high school and the university building respectively, which is a much lower fraction than has been reported in the literature [6]. This appears to be a result of a few factors. Heating requirements appear to have a major effect on energy use (note the results for Vancouver versus Winnipeg). This has a double impact with the high ventilation rates used in the two buildings that were studied, due to the tempering of air for ventilation. As well, lighting power densities have dropped in recent construction and are continuing to decline.

Lighting energy use was about 30 kWh/m^2 for the school and about 40 kWh/m^2 for the Professional Faculties Building, while Ternoey identified values of 40-50 kWh/m^2 as typical of several energy efficient designs [25]. This is still above the 10-20 kWh/m^2 that has been achieved in some daylit buildings [9-11]. However, the two buildings that were studied include much more interior space than most of these other projects and have requirements that preclude completely open plan design. At 14,000 and 26,000 m^2 floor area, they are also much larger than most completed daylit buildings for which energy use assessments have been performed.

Experimental evaluation of a daylight-linked dimming system in a south-facing test area of about 60 m^2 in the Professional Faculties Building provided results consistent with findings of other studies that daylighting controls provide reductions of about 30 percent annually in lighting energy use in sidelit spaces (see section 4.1). Use of shades to reduce glare from sunlight appears to be the chief contributing factor in energy savings being less than projected by simulations. Another factor is that many electronic ballasts cannot currently reduce power below 20 percent of full output, regardless of the ambient light level.

In some perimeter areas of the Professional Faculties Building, lighting energy use is in the vicinity of the 5 kWh/m^2 annually that was achieved at the BRE Low Energy Office (also with manual switching). This performance is commonly achieved where little or no glare is experienced from direct sunlight (e.g., in east- and north-facing spaces). In these areas, daylighting features such as high-reflectance interiors, high visible transmittances, the high window heads, and the dual upper-lower shading systems appear to be successful in providing natural lighting conditions that meet the occupants' requirements. Electric lighting is used much more heavily in south-facing areas, which is consistent with observations on reduction of glare from windows (illumination from the electric lighting is used to reduce glare) [5].

At the school, staff generally seem to use electric lighting in the classrooms and other spaces, even when there appears to be adequate daylight. The differences in use of electric lights in spaces that appear to be adequately daylit (i.e., relatively glare-free and adequate levels of illumination) in the two buildings indicates that a better understanding of the factors that affect switching is still needed, as this has not been extensively addressed in the literature [26-29]. It may be that teacher use the switching of lights to signal that class is in session. One teacher reported that she switched the electric lighting off when administering tests because of the reduced noise from lights.

Comparative tests at the school classrooms that were set up for assessment of lighting effects on cooling requirements did not show any effects of lighting on cooling. This is thought to be due to the ventilation rates in the building in combination with the relatively cool, dry climate of Calgary.

A primary conclusions from this study is that, to achieve significant energy savings with either automatic or manual controls, glare must be controlled. To do this, direct sunlight must be excluded from task areas. Reducing illumination gradients in sidelit spaces reduces sky glare from windows, which, while still less extreme than glare from direct sunlight, can lead to higher use of electric lighting. The high window heads achieved by tilting the ceiling system up at the perimeter of the Professional Faculties Building, along with the other measures described in subsection 2.1.2, appear to have been successful in satisfying users in offices on facades receiving little or no direct sunlight. The mesh shades used on the upper window areas do not seem to provide the best combination of preventing glare while admitting daylight. A baffle or slat system might be more effective.

Another conclusion is that ventilation requirements in newer buildings account for a much higher fraction of annual energy use and lighting requirements a much lower fraction than has been reported in the literature.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Findings with Respect to Study Objectives

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

1. quantify the energy end uses in two buildings with fenestration designed to exploit daylighting by carrying out both frequent measurement of aggregate energy use and by detailed measurement of system level energy use in selected zones,
2. Determine the energy utilization of these buildings if efforts are made to optimize the use of the electric lighting system (i.e., taking greater advantage of opportunities for more efficient operation and exploitation of daylight available in the buildings), and
3. to use the data collected through the energy use monitoring program to validate computer simulation models of the buildings and, in turn, use the validated simulation models to estimate the performance of the designs for west coast, central Canadian and maritime climate zones.

With respect to objective 3, the simulation models were created and validated. They were used to address objectives 1 and 2. It was found that electrical energy use would vary little from one part of the country to another, but natural gas energy would vary by more than 65 percent from the warmest area (Vancouver) to the coldest area (Winnipeg) for which simulations were conducted.

With respect to objective 1, it was found that the two buildings had higher energy use per unit floor area than would be expected for very energy efficient buildings. A major contributing factor was high levels of energy use related to ventilation (operation of fans and tempering of supply air). In the case of the university building, this is due in part to its extended hours of operation; circulation areas are publicly accessible 24 hours per day. Lighting energy use was found to amount to 10 percent or less of total energy use, about 30 kWh/m^2 for the school and 40 kWh/m^2 for the Professional Faculties Building. If circulation areas in the PFB were only operated 3750 hours per annum instead of around the clock, the PFB lighting electricity use would be about 24 kWh/m^2. This is a much lower fraction than reported in the literature for commercial buildings.

Some spaces in the Professional Faculties Building had a lighting electricity use that was comparable to the most efficient of the spaces reported in the literature - 5 kWh/m^2 or less annually. These spaces were equipped with manual switching. The key to their success appears to be the exclusion of direct sunlight from task areas (they were either private offices on facades receiving little or no daylight, or multi-occupant spaces with buffer spaces to exclude direct sunlight).

Comparative tests at the school classrooms that were set up for assessment of lighting effects on cooling requirements did not show any effects of lighting on cooling. This contradicts findings by other researchers that lighting has a substantial effect on cooling requirements. A likely explanation is the high ventilation rates in the buildings combined with Calgary's relatively low temperatures and humidity. The resulting cooling effect offsets heat gains from lighting.

With respect to objective 2, it was estimated that more extensive exploitation of available daylighting at the school could reduce lighting electricity use from about 32 kWh/m^2 to about 20 kWh/m^2. This is comparable to levels achieved at Lockheed Building 157 in the San Francisco area, another deep-plan sidelit building, although the hours of operation are much less at the school. The savings are limited due to the requirement for electric lighting in interior lower-level classrooms and other spaces lacking adequate daylighting (e.g., the gymnasia). It was concluded that large further reductions could not be obtained at the Professional Faculties building because a relatively small fraction of the plan is exposed to daylight, because daylight is already extensively used as primary light source in some perimeter spaces, and because, in other perimeter areas, the electric lights are used to counteract glare due to direct sunlight.

Tests in a space in the Professional Faculties Building that was retrofitted with dimming ballasts and a daylight-sensing controller showed lighting electricity use reductions of 30 percent or less. This space was on the south-facing facade of the building, and occupant use of shades to exclude direct sunlight also greatly reduced the admission of daylight. This finding is consistent with those by other researchers for offices with conventional blind systems.

5.2 Cost-Effective Application of Daylighting and Further Research

Conventional blind and shade systems are generally effective in excluding direct sunlight and allowing users to reduce glare from daylight, but they are ineffective at meeting this requirement while providing good distribution of daylight. They obstruct the top part of the window, which plays a key role in admitting daylight to the parts of a space furthest from the window. Illumination of areas furthest from the window is important in reducing glare and allowing occupants to more fully utilize daylight (when interior exterior contrasts are high, electric lighting is often used to correct the imbalance). Research is needed to develop low-cost and practical shades that are better for exploiting daylight, regardless of the electric lighting control strategy.

The cost-effectiveness of daylighting is highly dependent on the annual electricity use per unit floor area (the lower the use the lower the potential savings) and the cost and performance of the lighting system components. Potential energy savings from, and the cost-effectiveness of, daylight-linked fluorescent dimming systems are still limited by nonlinear performance of dimming electronic ballasts and by the costs of the ballasts (those purchased for the study were about $50 each). If offices are equipped with very efficiently designed electric lighting (12 W/m^2 or less installed lighting power density) and occupancy detectors, the potential energy savings from daylighting is about 10 kWh/m^2 annually (see above). For a typical private office of about 15 m^2 floor area, the dollar value of the energy savings is about $12.00 per annum at $0.08 per kWh. The payback for the extra cost of automatic controls and dimming ballasts would therefore be at least 8 years.

It may be possible to increase the cost-effectiveness of daylighting systems by using their characteristics to achieve other savings. For instance, if dimming ballasts are used to reduce peak electric demand through load-shedding, this may offset the costs of the ballasts. If the detector used to sense the illumination level in the space and to adjust light output to reduce excess capacity provided to offset deterioration of illumination over time (due to aging of lamps and lenses and accumulation of dirt), this may reduce the cost of daylight-linked dimming to a smaller marginal cost. Research should be conducted to assess this approach. The author is currently working with a private Canadian company to develop and field-test a control system with these capabilities.

The potential savings for occupancy detectors is also about 10 kWh/m^2 annually, but can be achieved with non-dimming ballasts, which are much less expensive, and can be realized in both perimeter and core spaces. A strategy for cost-effective daylighting in this situation would appear to be the use of occupancy-controlled deactivation and manual activation. The user would decide on the acceptability of illumination from daylighting on entering the space and would make the switching decision accordingly. The goal would be to keep the cost of control low enough to avoid zoning of lighting controls to encompass several offices on a single circuit. Research is needed to better understand switching behaviour in daylit offices. The author is currently conducting research on this subject.

Automatic control of electric lights should be cost-effective in areas such as lobbies and corridors where on-off switching systems would be acceptable. These are areas where pedestrian traffic could reduce savings from occupancy detectors. As well, the design illuminances are lower, so there is the potential for more hours of electric lighting displacement. It may be possible to use an open-loop approach to lighting control. This is the approach used in the corridor in the Professional Faculties Building that is discussed in detail in subsection 2.4.3. Rather than using a system that senses the light levels in the controlled space, lights are controlled based on outdoor illumination levels. A constant or formula can be developed to specify the conditions under which the electric lights can be switched off. This can be programmed into the building control system for each lighting circuit to be controlled. A single detector could be used to control several zones. This could provide acceptable performance in non-task areas.

Top-lit areas also offer opportunities for more cost-effective exploitation of daylighting. In northern areas with relatively low-sun angles, glare control is relatively easy for toplighting systems due to reduced sun penetration of skylight wells. The relatively uniform illumination provided by many toplighting systems also means that fewer control detectors can be used in the space.

5.3 Technology Transfer

One of the objectives of the research was to improve the state of knowledge related to daylighting application. A paper on the school was presented at the 1995 annual conference of the Illuminating Engineering Society. As well, the research findings are being used in preparing the update of the Illuminating Engineering Society's *Recommended Practice of Daylighting*. As noted in the above subsection, the author is currently working with the implementation of some of the findings in a commercial lighting control system.

5.4 Summary

It is recommended that:

1. field trials be conducted of electric lighting control based on a "manual on-automatic (occupancy-based) off" strategy to determine the performance and cost-effectiveness of such an approach,

2. research be conducted on electric lighting control based on a more comprehensive strategy to provide combined peak shaving, daylighting-linked dimming, and light system "tuning,"

3. studies be conducted to devise shading or blind systems that admit daylight through the upper portion of windows while preventing direct sunlight from entering the upper and lower portions of windows (it would be useful to test such systems in combination with the control strategy described in 1) above), and

4. studies be conducted to determine the feasibility and cost-effectiveness of open-loop control in lobby, circulation, and similar areas.

The overall conclusion of this study is that daylighting can contribute significantly to building energy efficiency if less expensive means of implementation can be found, including both more cost-effective and user-responsive control strategies and better systems for admitting daylight while controlling glare. However, it appears that ventilation of recently constructed buildings accounts for much more of building energy use on both proportional and absolute bases than has been reported in the literature.

REFERENCES

1. Littlefair, P. J. 1988. Measurements of the luminous effiacy of daylight. *Lighting Research and Technology* Vol. 20 (3): 177-188.

2. IESNA 1989. IES Recommended Practice for Lighting Offices Containing Computer Visdual Display Terminals. RP-24. New York: Illuminating Engineering Society of North America.

3. Johnson, C. A., R. W. Besant, and G. J. Schoenau. 1989. "Energy-economic trade-off studies recommended to enhance the use of daylighting in large office buildings in Canada," *Renewables: A Clean Energy Solution*. Ottawa: Solar Energy Society of Canada: 25-31

4. Love, J. A. 1989. *Field assessment of daylighting systems and design tools*. Report submitted to Architectural and Engineering Services, Public Works Canada, March 1993.

5. Chauvel, P., J. B. Collins, R. Dogniaux, and A. I. Slater. 1982. "Glare from Windows: Current Views of the Problem," *Lighting Research and Technology*,14 (1) : 31-46.

6. Caudill Rowlett and Scott, reported in Ternoey, S., Bickle, L., Robbins, C., Busch, R. and McCord, K. *The design of energy responsive commercial buildings*. New York: John Wiley & Sons. 28.

7. ASHRAE 1989. Standard 62-1989. *Ventilation for acceptable indoor air quality*. Atlanta: American Society of Heating Refrigerating and Air-Conditioning Engineers.

8. ASHRAE 1981. Standard 62-1981. *Ventilation for acceptable indoor air quality*. Atlanta: American Society of Heating Refrigerating and Air-Conditioning Engineers.

9. Warren, M., Selkowitz, S., Morse, O., Benton, C., and Jewell, J. E. 1986. "Lighting system performance in an innovative daylighted structure: an instrumented study," in Zdepski and McCluney (eds.) *Proceedings of the 1986 International Daylighting Conference*, McLean, VA (1508 Emerson Ave): 1986 International Daylighting Conference Organizing Committee: 215-221.

10. Crisp, V. H. C.; Fisk, D. J., and Salvidge, A. C. 1984. *The BRE low-energy office* Garston, Watford, UK: Building Research Establishment, Department of the Environment.

11. John, R. W. and Salvidge, A. C. 1986. *The BRE low-energy office - five years on* Garston, Watford, UK: Building Research Establishment, Department of the Environment.

12. Newsham, G., Mahdavi, A., and Beausoleil-Morrison, I. Lightswitch: a stochastic model for predicting office lighting energy consumption. *Proceedings of Right Light Three: the Third European Conference on Energy-Efficient*. Vol. 1 - Published papers. Newcastle upon Tyne, UK: Northern Electric. 59-66.

13. Opdal, K. and Brekke, B. 1995. Energy Saving in Daylighting by Utilization of Daylight. Proceedings of Right Light Three: the Third European Conference on Energy-Efficient. Vol. 1 - Published papers. Newcastle upon Tyne, UK: Northern Electric. 67-74

14. ASHRAE. 1989. "Energy efficient design of new buildings except new low-rise residential buildings", *ASHRAE/IES Standard 90.1-1989*. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers.

15. Buddenberg, A. 1995. The performance of components used in daylighitng and lumen maintenance control systems. Proceedings of the Third European Conference on Energy-Efficient Lighting. Newcastle upon Tyne, UK: Northern Electric. 279-285.

16. Andersson, B.; Adegran, M; Wenster, T; Place, W; Kammerud, R.; and Albrand, P. 1987. "Effects of daylighting options on the energy performance of two existing passive commercial buildings," *Building and Environment*, Vol. 22 (1): 3-12.

17. Floyd, D. and D. S. Parker 1995. Field commissioning of a daylight-dimming system. *Proceedings of Right Light Three: the Third European Conference on Energy-Efficient*. Vol. 1 - Published papers. Newcastle upon Tyne, UK: Northern Electric. 83-89..

18. Bordass, W.; T. Heasman; A. Leaman; and M. J. Perry 1994. Daylight use in open-plan offices: the opportunities and the fantasies. Proceedings of National Lighting Conference and Daylighting Colloquium. Cambridge, UK: Robinson College. 243-256..

19. Rubin, A. I.; B. L. Collins and R. L. Tibbott 1978. Window blinds as a potential energy saver. NBS Building Science Series 70. Washington, DC: Institute for Applied Technology, National Bureau of Standards (now the National Institute for Standards and Technology, Gaithersburg, MD).

20. Rea, M.S. 1984. Window blind occlusion: a pilot study. Building and Environment 19 (no. 2): 133-137.

21. Schrum, S. and D. Floyd. Daylight dimming and energy savings: the effects of window orientation and blinds. Report No. FSEC-CR-791-95. Cape Canaveral, FA: Florida Solar Energy Centre March, 1995.

22. Treado, S.J., and J.W. Bean. "Experimental evaluation of lighting/HVAC interaction". Proceedings of the 1990 Annual Meeting of the ASHRAE, St. Louis, MO, USA. ASHRAE Transactions pt.2 ASHRAE, Atlanta , GA, USA. 773-779.

23. Heap, L. J., Palmer, J., and Hildon, A. 1988. "Redistributed daylight - a performance assessment," *Proceedings of National Lighting Conference and Daylighting Colloquium*, Cambridge, UK: Robinson College: 248.

24. Ternoey, S., Bickle, L., Robbins, C., Busch, R. and McCord, K. *The design of energy responsive commercial buildings*. New York: John Wiley & Sons. 112.

25. Ternoey.

26. Hunt, D. R. G. 1979. The use of artificial lighting in relation to daylight levels and occupancy. *Building and Environment*, Vol. 14 : 21-33.

27. Hunt, D. R. G. 1980. Predicting artificial lighting use - a method based upon observed patterns of behaviour. *Building and Environment*, Vol. 12 (No. 1): 8-14.

28. Levy, A.W. 1978. "Pattern of lighting use in a large open office," Building Research Note 129, Ottawa: National Research Council of Canada.

29. Levy, A.W. 1978. "Pattern of lighting use in a school classroom," Building Research Note 132, Ottawa: National Research Council of Canada.