Energy Conservation Using Scotopically Enhanced Fluorescent Lighting In An Office Environment

Prepared For:

Building Technologies Program
Office of Energy Efficiency & Renewable Energy
U.S. Department of Energy

March 2004

Prepared By:

AFTERIMAGE + SPACE
5950 Doyle St. #4
Emeryville, CA 94608

DISCLAIMER

COPIES OF THIS REPORT

Electronic (PDF) copies of this report are available to the public from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Tel: 1.800.553.6847
www.ntis.gov

BUILDING TECHNOLOGIES PROGRAM

U.S. department of Energy
www.eren.doe.gov/buildings/documents/

FORWARD

Scotopically enhanced lighting studies have been ongoing by the U.S. Department of Energy since 1990. While the theoretical energy savings potential of this lighting method has been clearly established prior to this study, user acceptance remained unknown. Because this method requires both a shift in color spectrum and a reduction in traditional lighting level measurements, occupant acceptance under these altered conditions presents a potential critical market barrier to the use of this method in applied practice.

This study, co-sponsored by the U.S. Department of Energy, the Pacific Gas & Electric Company, and the University of California, investigates the use of a previously derived design method in a field application to determine the acceptability and energy savings potential of scotopically enhanced lighting when used at reduced lighting levels.

This study was managed by AfterImage + Space. Brian Liebel was the principal investigator and primary author of this report. He is a registered professional electrical engineer in California and is Lighting Certified with 20 years of specialized experience in lighting research, design, and applications. Rita Lee, co-author and chief editor for this report, assisted with the occupant surveys and overall results analysis. She is a registered architect in California and is a LEED Accredited Professional with 15 years of specialized experience in commercial interior architecture.

COMMENTS

The Department is interested in receiving input on the material presented in the report. If you have suggestions of better data sources and/or comments on the finding presented in this report, please submit your feedback to Dr. James R. Brodrick at the following address:

James R. Brodrick, Ph.D.
Program Manager – Lighting Research & Development
EE-2J / Forrestal Building
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585

ACKNOWLEDGMENTS

The authors would like to acknowledge the valuable support, guidance, and input offered in the preparation of this report. James R. Brodrick, Ph.D., of the U.S. Department of Energy, Building Technologies Program provided oversight of the assignment, helping to shape the approach, execution, and documentation. The authors are also grateful to the following list of experts for their respective contributions, guidance, and review, which proved invaluable in conducting this study.

Contributer:	Affiliation:
Sam Berman, Ph.D.	AfterImage + Space
Dick Brecher	16500
Jim Chace	Pacific Gas & Electric Company
Marc Fountain, Ph.D.	AfterImage + Space
Phil Hall	16500
Michael Keleman	University of California, Office of the President
Linda Lonay	AfterImage + Space
Robert Marcial	Pacific Gas & Electric Company
Maric Munn	University of California, Office of the President
Ed Petrow	Lincoln Technical Services
Tom Preston	Sun Industries
Jerry Sasser	General Electric Company
Brooks Sheifer	Sun Industries
Ken Shelley	Tridonics
Sean Villa-Carlos	University of California, Office of the President
Stan Walerczyk	Sun Industries
Guido Walther	Tridonics

TABLE OF CONTENTS

TABLES

FIGURES

..

SYMBOLS AND NOMENCLATURE

In addition to the industry recognized symbols, there are several other symbols and nomenclature that are specific to the study of scotopically enhanced lighting. Symbols used in this report include:

Lighting Metrics, Abbreviations, and Symbols:

E	Illuminance
EPE	Eye Position Illuminance
VEE	Visually Effective Illuminance
ℓm	Lumens
VE*ℓm*	Visually Effective Lumens

Subscripts (apply to any of the above Lighting Metric symbols):

E_{HP}	Horizontal Illuminance, as measured photopically
E_{HS}	Horizontal Illuminance, as measured scotopically
E_{VP}	Vertical Illuminance, as measured photopically
E_{VS}	Vertical Illuminance, as measured scotopically
$E_{(1)}$	Subscript (1) denotes light source #1 (reference source)
$E_{(2)}$	Subscript (2) denotes light source #2 (source being compared to the ref. source).

Other Measurement Symbols and Abbreviations:

S/P	Scotopic/Photopic ratio; applies to lamp lumens or measured illuminance values
$(S/P)^X$	S/P ratio, raised to the power "x", where "x" is an empirically derived exponent specific to a visual task.
W	Watts
ℓm/W	Lumens per Watt
VE*ℓm*/W	Visually Effective Lumens per Watt
LPD	Lighting Power Density, as measured in watts of lighting power per square foot of building area being illuminated.
m, m^2	meter, or square meter
ft, ft^2	feet, or square feet
CRI	Color Rendering Index
CCT	Correlated Color Temperature
BEF	Ballast Efficacy Factor

Other Abbreviations:

UCOP	University of California, Office of the President
PG&E	Pacific Gas & Electric Company
DOE	U.S. Department of Energy
AI+S	AfterImage + Space (Principal Investigator and Author)

EXECUTIVE SUMMARY

This study was conducted in a recently built and occupied office building (University of California Office of the President, UCOP) to determine whether the energy savings benefits of scotopically enhanced fluorescent lighting[1] can be achieved while maintaining user acceptability.

The pre-existing lighting in the test building employed the traditional and widely used 3500 Kelvin (K) lamps with a mix of 2 levels of Color Rendering Index (CRI) values of 75 and 85. For this study, two nearly identical floors of the office building were retrofit with new lamps and dimming ballasts to compare differences in light level, energy and user acceptance. Each floor was approximately 30,000 square feet in area, and consisted of open areas with office cubicles as well as private offices. There were approximately 60 offices of each type per floor. The open office area lighting consisted of pendant indirect luminaires, while the private office lighting consisted of recessed parabolic direct luminaires.

In this study, one floor was re-lamped with new 3500 Kelvin (K) lamps (reference lamp) and the other with new 5000K lamps (scotopically enhanced). Both new lamp types had a CRI of 86. Electronic dimming ballasts were installed in the existing luminaires on both floors to adjust the light levels. The floor with 3500K lamps (835) had the lighting levels adjusted to approximately the same light level that existed prior to re-lamping. The lighting levels in the offices on the floor with the 5000K lamps (850) were set at approximately 20% lower light levels than the floor with the 835 lamps.[2] Open office area occupants were not able to modify their light level, while private offices were outfitted with computer software controls that allowed the individual occupants to adjust the light level at their own discretion. Occupants on both floors were surveyed to determine differences in occupant acceptance between the 835 and 850 lamps.

For open office areas, the following conclusions were made:

1. There was no statistically significant difference in occupant acceptance of the 850 lamp as compared to 835 lamp under the conditions of having the 850 lighting system illuminances reduced approximately 20% below that of the 835 lighting system.
2. The energy savings potential due to the spectral effect of the 850 lamp, as a scotopically enhanced light source, ranges between 17-24% when compared to the <u>835</u> lamp. By extension, the energy savings potential due to the spectral effect of the 850 lamp ranges between 22-30% when compared to the <u>735</u> lamp.
3. The previously derived illuminance-based design method for scotopically enhanced lighting proved to be an adequate predictor of light level reduction and energy savings potential in an open office application, based on the tasks being performed.

For private offices, there was no statistically significant difference in occupant acceptance of the 850 lamps compared to the 835 lamps. However, no conclusive results were obtained in the private offices for light level and energy savings potential due to the unforeseen circumstances of the insignificant number of occupied non-daylit private offices, the confounding variables of daylight in perimeter offices, and the confounding variable introduced by a computer interface occupant control system that was nearly universally unused by private office occupants.

[1] Scotopically enhanced lighting is white light with a higher bluish content generally achieved by adjustment of the spectrum to produce a higher correlated color temperature. Lamps with this property are readily commercially available at approximately the same cost as other more traditionally used lamps.

[2] The light level reduction of the 850 lamps was set at 20% to test a previously derived predictive design method.

1 INTRODUCTION

Previous research sponsored by the U.S. Department of Energy has determined that light sources with more energy in the blue wavelengths that match the rod sensitivity (scotopic content) provide higher levels of brightness perception[1] and higher levels of visual acuity[2]. With this premise, it is possible to reduce lighting levels using scotopically enhanced lighting while maintaining equal visual effect. Thus, using scotopically enhanced lighting in commercial office buildings may possibly provide significant energy savings throughout the United States.

1.1 TECHNICAL BACKGROUND

Currently, lighting measurements use weighting functions that are based solely on the spectral sensitivity of the cone photoreceptors (photopic response) of the eye[3]. This spectral sensitivity has its peak value in the yellow-green region of the color spectrum. Recent past research has shown, however, that the photopic function does not adequately describe the visual response to light, and that current lighting measurements must be supplemented with the scotopic response in order to describe how lighting affects pupil size and brightness perception.[1,4] The scotopic response peaks in the blue-green region of the color spectrum.

Scotopically Enhanced Lighting is lighting that has more blue in the spectrum, typically characterized by higher correlated color temperatures. This lighting has been shown to provide better visual acuity and enhanced brightness perception as compared to more standard lighting operating at the same photopic light level. It is also noted that scotopically enhanced lamps produce a light spectrum more closely resembling daylight than most lamps used in office spaces today.

The light output of lamps (Lumens) and the correlating measure of lighting efficiency (Efficacy, or Lumens per Watt) are based solely on the photopic weighting function[3]. Phosphors of fluorescent lamps are mixed specifically to try to make lamps of equal wattage and operating characteristics have approximately the same photopic lumen output, so that the overall lamp efficacy is generally the same regardless of lamp color. An 85 CRI, normal output T8 lamp, for example, will have approximately the same lumen and efficacy values for 3000K, 3500K, 4100K, and 5000K correlated color temperatures.

Scotopically enhanced lighting research suggests that certain lamps containing more blue in the spectrum will be more visually efficient than lamps with less scotopic content, even if they have the same (photopic) lumen and efficacy values. The use of scotopically enhanced lighting can therefore be used at lower energy levels while maintaining equal vision, or visual effectiveness. The functioning factor used in scotopically enhanced lighting is called the S/P ratio, which evaluates the spectrum of any lamp on the basis of the Scotopic function in comparison to the Photopic function. This ratio is independent of lighting levels for fluorescent lamps, and can be provided by lamp manufacturers for any light source that they manufacture. For most fluorescent and HID lamps the S/P values vary between 0.8 and 2.5, with the higher values representing lamps with more blue in their spectrum.

---

1 Berman, S.M., Jewett, D.J., Fein, G., Saika, G., and Ashford, F. 1990. "*Photopic luminance does not always predict perceived room brightness.*". Lighting Research Technology, 22(1): 37-41.

2 Berman, S.M., Fein, G.; Jewett, D.L.; Benson, B. R.; Law, T.M. and Myers, A.W. 1996. "*Luminance controlled pupil size affects word reading accuracy*". JIES, 25(1): 51-59.

Berman S.M., Fein, G.; Jewett, D.L., and Ashford, F., 1993. "*Luminance controlled pupil size affects Landolt C test performance*". JIES, 22(2):150-165.

3 The IESNA Lighting Handbook, Reference & Application, 9th edition, IESNA, New York, New York, 2000.

4 Berman, S.M., Jewett, D.L, Benson, B.R., and Law, T.M. 1997. *"Despite different wall colors, vertical scotopic illuminance predicts pupil size*" . J.IES 26 (2): 59-68.

Previous research also indicates that the visual effectiveness of the scotopic enhancement vary with the task[1]. Brightness perception, for instance, is more a cooperative function between rods and cones, and therefore the S/P ratio is not weighted as heavily as compared to when evaluating visual acuity for self-illuminated tasks, such as working at the computer[2]. *Table 1.1*, below, summarizes a Design Method model for scotopically enhanced lighting based on previous research. It shows examples of how the lumen ratings of lamps can be modified for specific tasks using the S/P ratio:

TABLE 1.1: DESIGN METHOD - Visually Effective Lumens and Efficacies Using The S/P Ratio

LAMP TYPE	Photopic Lumen Rating P* (lumens)	Photopic Lumen Per Watts (ℓm/W)	S/P Ratio (S/P)* (ratio)	Visually Effective Measurements based on Brightness Perception** $P(S/P)^{0.5}$ VE ℓm (VE ℓm/W)	Visually Effective Measurements based on Visual Acuity for Paper Reading** $P(S/P)^{0.78}$ VE ℓm(VE ℓm/W)	Visually Effective Measurements based on Visual Acuity for Computer Tasks** P(S/P) VE ℓm(VE ℓm/W)
735	2800	87.5	1.40	3313 (103.5)	3640 (113.8)	3920 (122.5)
835	2950	92.2	1.50	3613 (112.9)	4047 (126.5)	4425 (138.3)
850	2800	87.5	2.0	3960 (132.6)	4808 (161.0)	5600 (187.5)

** Lumen values and S/P ratios in the table above are for normal output 32 watt T8 lamps, from the General Electric Lighting website, gelighting.com. Lumen ratings are initial Lumens.*

*** Exponents were empirically derived from illuminance measurements taken vertically at the viewing eye position.*

The most common lamp used in office lighting applications is the 735 lamp (3500K color temperature and CRI of 78), based on national sales of T8 fluorescent lamps. However, 835 lamps (also 3500K color temperature, but with a CRI of 86) are also used in offices, and generally provide higher light output and have better lumen maintenance. In addition, there are perceived benefits of better color rendering when using higher CRI lamps. *Table 1.1* illustrates how the scotopically enhanced 850 lamp (5000K color temperature and CRI of 86) provides significant energy savings potential, as measured by the different Visually Effective Lumens per Watt (VE ℓm/W), when compared to either the 735 or 835 lamp. The percentage of potential energy savings are illustrated in *Table 1.2*.

TABLE 1.2: Percentage of Potential Energy Savings
Using Visually Effective Lumen Ratings, comparing the 850 Lamp to the 835 and 735 Lamps

	Lamp Type	% Energy Savings based on Brightness Perception	% Energy Savings based on Visual Acuity for Paper Reading	% Energy Savings based on Visual Acuity for Computer Tasks
Predicted Energy Savings Using the 850 lamp when compared to:	735	16%	24%	30%
	835	9%	16%	21%

Tables 1.1 and *1.2* show that the scotopic weighting function is solely responsible for maximizing visual effectiveness for computer tasks. For all tasks noted, there are potentially significant energy savings benefits to using the Design Method that includes the scotopic content of lamps. Specifically, the 850 scotopically enhanced lamp demonstrates potential energy savings ranging from 9 to 21% as compared to the 835 lamp, and 16 to 30% as compared to the 735 lamp.

1 Berman, S.M., Fein, G., Jewett, D.L., Saika, G. and Ashford, F., 1992. *"Spectral Determinants of Steady-State Pupil Size with Full Field of View"*, JIES, 21(2): 3-13.

2 Berman, S.M., Fein, G.; Jewett, D.L.; Benson, B. R.; Law, T.M. and Myers, A.W. 1996. "*Luminance controlled pupil size affects word reading accuracy*". JIES, 25(1): 51-59.

1.2 STUDY APPROACH

Scotopically enhanced lighting has been used in several facilities with general overall success[1]. However, skepticism exists in the lighting community based on beliefs that building occupants prefer warm-colored light and will not accept lighting that has more blue content in a real working environment. Effective energy savings will result only when occupants accept scotopically enhanced light at a reduced lighting level. Therefore, the primary objective of this study was to test whether the predictions of the scotopic Design Method model could be used in an operating facility without affecting user acceptance.

The scotopically enhanced lighting Design Method predicts maximum light level reduction and energy savings based on the specific tasks of paper reading and computer use. This study therefore tests the light level reduction predictions in an office environment, consistent with these tasks. Given that office buildings are ranked as the highest consumer of lighting electricity use in the commercial sector[2] and the significant savings potential of this method, a thorough field study investigation of the use of scotopically enhanced lighting in an office building is seen as an important step towards energy conservation in buildings throughout the United States.

1.3 BENEFITS TO UNITED STATES ELECTRICITY CONSUMERS AND LIGHTING COMMUNITY

There are three primary benefits derived from this project:

1. This study benefits the commercial lighting sector by having addressed the largest known barrier to implementing scotopically enhanced lighting through an objective study that investigates user acceptance at a lower energy level. If scotopically enhanced lighting is determined to be acceptable by users, then this lighting method can be reliably promoted as a viable approach to saving energy in office buildings throughout the United States.
2. The knowledge and experience gained by using this lighting strategy in a large-scale building with measured results provides evidence as to whether the Design Method model can reliably be used in lighting practice for energy efficient lighting design.
3. This demonstration provides an analysis of the potential to reduce initial and operating costs of lighting systems below what is generally installed in office building applications.

[1] For some examples see Berman ,S.M. 2000: "*The coming revolution in lighting practice*". Energy Users News Oct, 25,10, pg. 23-25. In addition, PG&E has successfully retrofit approximately 300,000 square feet of their existing office buildings with 850 lamps set at lowered photopic lighting levels.

[2] Navigant Consulting, Inc. for U.S. Department of Energy, Sept. 2002. *U.S. Lighting Market Characterization Volume 1: National Lighting Inventory and Energy Consumption Estimate*.

2 PROTOCOL OF THE UCOP STUDY

The University of California Office of the President (UCOP) study compares the lighting of two nearly identical floors to determine the acceptability and energy savings potential of scotopically enhanced lighting. The project sponsors, including the University of California (host site), Pacific Gas & Electric Company (local utility) and the U.S. Department of Energy (Federal Government), shared the common goal of investigating the potential benefits of scotopically enhanced lighting through a formal study that could potentially provide the foundation for energy savings throughout the UC system, the state of California, and the United States at large.

2.1 PROJECT BACKGROUND

In December 2001, the University of California contacted the Pacific Gas and Electric Company (PG&E) for assistance in designing energy-saving lighting at the Office of the President building. The University proposed using the building as a testing ground for new lighting technologies to develop standards for University-owned buildings. AfterImage + Space (AI+S), the lighting consultant to PG&E's Pacific Energy Center, and a DOE contractor surveyed the building and prepared an initial proposal for the University in January 2002. Upon review of the work scope with UCOP and PG&E, AI+S subsequently proposed merging the UCOP project with a scotopically enhanced lighting research study that was concurrently being developed for the U.S. Department of Energy (DOE). An agreement was completed in March 2001 in which PG&E, DOE, and UCOP agreed to cooperate in a field study to demonstrate the benefits of scotopically enhanced lighting, using two floors of the UCOP building.

2.2 STUDY OBJECTIVES

2.2.1 Primary Objectives of this study

1. Evaluate user acceptability of scotopically enhanced fluorescent lighting in an actual operating office environment.
2. Evaluate the measurement of light level reduction with scotopically enhanced lighting that does not significantly affect user acceptance.
3. Evaluate, through careful measurement, the energy consumption, thus establishing the energy savings potential of scotopically enhanced lighting.
4. Evaluate the existing Design Method model of predicting energy savings when using scotopically enhanced lighting.

2.2.2 Secondary Objectives of this study

1. The building being studied was built in 2000 by a design/build contractor and was designed to meet California Title 24 Energy Standards. As is typical of many buildings, the approach used was to provide as much light as possible while still meeting the Standard. A secondary objective of this study is to evaluate whether energy could have been initially saved at the beginning of the building's life by simply installing a more energy efficient system based on better lighting design practice.
2. This project uses the DALI (Digitally Addressable Lighting Interface) fluorescent dimming system to monitor energy consumption and dim the lamps. This dimming system has the capability of providing both energy savings and peak load reduction and is new to the lighting industry. A secondary objective of the study is to test this system in a large-scale application.

2.3 DESCRIPTION OF PROJECT SITE

The project site consists of two floors within the University of California Office of the President, an 11-story building in downtown Oakland. The building was built 4 years prior to this study in accordance with California Title 24 energy efficiency standards.

Figure 2A: Project Site – Exterior Views

View From The West	View From The North-West

The floors that were compared in the study are the 10th Floor and the 11th Floor, with occupants on both floors performing similar tasks. Both floors have private offices (perimeter and interior) with recessed 2'x4' parabolic fixtures and open office areas with pendant indirect fixtures.

Figure 2B: Project Site – Floor Plans

10TH FLOOR	11TH FLOOR
Open Offices: 55 Private Offices: 61	Open Offices: 65 Private Offices: 58

2.4 LIGHTING SYSTEMS DESIGN AND PROTOCOL OF STUDY

The two floors selected were chosen primarily on the basis of the similarities in floor plans and types of work being performed. Lighting modifications consisted of retrofitting existing luminaires with new lamps and dimming ballasts without affecting the optical systems of the fixtures; no luminaires were replaced or optically altered.

Prior to the launch of the project protocol, each floor was retrofitted identically, with the installations following the same installation schedule. Therefore, the only variable between the two floors was the lamp color. This was done so that any predictable difference in the Hawthorne effect[1] between floors would be nullified.

2.4.1 Lighting System Design Components

2.4.1.1 *Lamps*

The existing building standard lamps had a correlated color temperature of 3500K. Some of the lamps had an 85 CRI (835), while others had a 75 CRI (735). All the existing lamps were removed and replaced for this study. This study compared 835 lamps with 850 lamps to ensure that neither lamp had an advantage over the other lamp due to better color rendering characteristics.

2.4.1.2 *Ballasts*

New DALI addressable dimming ballasts were installed on the two floors. The dimming ballasts have digital network data communications for controlling and monitoring the lighting level and energy consumption.

2.4.1.3 *Central Control System*

The new control system consisted of a centralized panel that gathered all the dimming ballast wiring and allowed for the individual control and monitoring of each ballast. A central computer was used to tie the panels on each of the floors together and to collect the data for the energy monitoring each night. The system did not affect the existing occupancy sensor ON/OFF functionality that existed throughout the building.

2.4.2 10th Floor Offices

New dimming ballasts were installed in all luminaires, then cleaned and re-lamped with **850** four-foot T8 lamps.

2.4.3 11th Floor Offices

New dimming ballasts were installed in all luminaires, then cleaned and re-lamped with **835** four-foot T8 lamps.

2.4.4 Modification Descriptions Per Room Type of Both Floors

2.4.4.1 *Private Offices*

Private office lighting consisted of 2′ x 4′ 3-lamp parabolic luminaires with T8 lamps. The existing fixtures had standard output instant start electronic ballasts. The retrofit required new sockets for the dimming ballasts and installation of dimming ballasts and new lamps. No reflectors, de-lamping, or other changes were made in order to ensure that the lighting distribution did not change within the spaces.

A single wallbox occupancy sensor provided on/off control for the fixtures in private offices, and the luminaires were not 2-level switched. These occupancy sensors were kept intact and operational. The retrofit added the ability of controlling lighting levels by the private office occupants through a computer software program installed on their computers that was tied to the lighting control system.

---

[1] Mayo, E. (1933) THE HUMAN PROBLEMS OF AN INDUSTRIAL CIVILIZATION (New York: MacMillan) ch.3.

2.4.4.2 *Open Office Areas*

Open office area lighting consisted of multiple rows of linear 2-lamp indirect pendant luminaires with T8 lamps spaced 10 feet on center. The existing building had standard output instant start electronic ballasts. These luminaires did not require new sockets for the dimming ballasts. As with the private offices, the lamps and ballasts were changed without any modifications to the optics of the luminaires.

Open offices were controlled by large-area ceiling mounted occupancy sensors. No modifications were made to this control system, and open office area occupants had no control of their lighting level.

2.4.4.3 *Other Spaces*

Other spaces were provided with new lamps that match the color characteristics of the open plan office lamps to ensure consistency within each floor. Some of the spaces were also provided with dimming ballasts for adjustability (conference rooms) and for light level consistency with adjacent office spaces (copy rooms).

2.5 SYSTEM INSTALLATION

2.5.1 Pre-Installation

2.5.1.1 *Design Process*

- Design standards and preliminary plans were developed for the project using the building's lighting electrical plans provided by UCOP. These plans included the scope of work and control system diagrams.
- The building was surveyed for lamp and ballast count, and design documentation was completed, including room-by-room modification lists and drawings showing the zoning and control schemes.
- The finalized design was presented to UCOP for review and approval.

2.5.1.2 *Notification*

- UCOP emailed an informational bulletin to the building occupants with notification that work was to be performed on the lighting system.
- The occupants were informed that the changes were to test a new lighting control system, and that the work would take several weeks to complete.

2.5.2 Installation

2.5.2.1 *Ballast Installation*

- The installation of the dimming ballasts occurred on a floor-by-floor basis, starting with the 10th floor.
- Lamps were not changed at this stage. Each floor took approximately 3 weeks to install the ballasts, due to the wiring of the control system and the coordination with the existing facilities to minimize disruption. Crews worked only at night with 10-hour shifts.

2.5.2.2 *Control System*

- The control system for the addressable dimming ballasts was configured and tested.
- This process took approximately 10 weeks and included several iterations with software trials to develop a fully functioning system for both addressing and dimming the ballasts and acquiring accurate monitoring data from the ballasts.

2.5.2.3 *Lamp Installation and Commissioning*

- After the control system was tested and ready for use, the new lamps were installed on the two floors and the control system was commissioned over a weekend. The commissioning team was instructed to commission the system as follows:

  Open Offices:

  11th Floor, Open Offices: *35 fc*. (set to match measured pre-study lighting level)
  10th Floor, Open Offices: *28 fc*. (20% below 11th floor)

  Private Offices:

  11th floor, Private Offices: *66% of full lighting level*
  10th Floor, Private Offices: *53% of full lighting level* (20% below 11th floor)

- The lighting system commissioning team was instructed to set the 10th floor lighting levels 20% below the 11th floor levels, with the 11th floor serving as the baseline for the study. This was based on the Design Method model when comparing 850 and 835 lamps, using the Visually Effective Lumen Ratings based on visual acuity for paper reading.[1] The commissioning team set the light levels using horizontal illuminance measurements at 30" above finish floor (desk height).
- The open office lighting level was set to match the measured light levels that existed prior to the study on the 11th floor
- Private office light level settings were based on observations that most offices used 2/3 of their lamps in the existing 2 x 4 parabolic fixtures. Since the private office occupants could control their lighting levels via their computers, the selection of the (66% of full) lighting level was deemed acceptable as a starting point.

2.5.2.4 *Notification*

- The building occupants were notified immediately following the weekend installation that the lighting system had been updated with a new control system, and that they would be surveyed in two weeks subsequent to the installation for their feedback.
- Occupants in the private offices were informed of the new control system capabilities and were given written instructions for its use.
- Occupants were not informed of the difference in the lamp color between the two floors.

2.6 STUDY IMPLEMENTATION

2.6.1 General Parameters

- Information gathered in this study was divided into open office areas and private offices. The data was then analyzed by comparing results between the 11th floor (reference lamp) and the 10th floor (scotopically enhanced lamp) for each of the two office types.

2.6.2 Light Level Measurement and Analysis

- Horizontal illuminance measurements were taken in each of the open office cubicles and private offices on both floors, using a light meter capable of measuring both scotopic and photopic illuminance.
- Vertical illuminance measurements were taken at the viewing eye position were measured in open office areas.[2]
- Lighting measurements were taken at night.
- Light measurements were correlated with occupant surveys and mapped to discern trends by location and/or user group. Only light levels measured in offices for which there were completed occupant surveys were used in the data analysis.

[1] It is noted here that the light level reduction of 20% between the 835 to 850 lamps are not equal to predicted energy savings of 16%, shown in Table 1.2, due to the increased efficacy of the 835 lamp. Refer to equations E7 and E9 in Appendix E.

[2] Complications in private offices made it unnecessary to take vertical measurements in the private offices. Refer to Appendix C for discussion on the private offices.

2.6.3 Energy Measurement And Analysis

- The lighting control system computer polled each individual DALI ballast every five minutes. The data delivered to the computer consisted of a DALI bit number, which correlates to a DALI percentage dim value. There were approximately 1,000 ballasts total.
- The daily data (approximately 300,000 lines per day) were downloaded every night to a daily spreadsheet file. Through a customized batch routine developed by AI+S, the raw data was converted to power measurements at each 5 minute interval, and the data was organized into groups according to ballast location.
- The conversion values from DALI bit numbers to power input varies with each specific ballast type, i.e.1-lamp ballasts have a different load than 2-lamp ballasts given the same DALI bit number. Corroboration of manufacturer-supplied values to actual power consumption was determined through in-house testing see *(Appendix D)* and through actual field measurements using data logging equipment on three circuits per floor.
- Scotopically enhanced lighting is a load reduction technique and has no effect on the time value of energy consumption. No attempts were made to alter the time of use in this study. Therefore, the percent power reduction can be translated directly to percent energy savings, and are used interchangeably in the body of this report.

2.6.4 Occupant Acceptance Survey

2.6.4.1 *Lighting and Occupant Satisfaction Survey*

- A survey consisting of ten questions on user satisfaction with the overhead lighting system and one question on the overall rating of the overhead rating of the lighting system were administered to both private office and open area occupants. These questions were Likert scaled questions, adapted from previous lighting studies.[1] The subjective response scale was from 1 to 7, ranging from very strong disagreement to very strong agreement on statements pertaining to the perceptions of the overhead lighting.
- Results from these surveys were tabulated to compare the rankings of each question on the lighting system between the 10th floor and the 11th floor occupants. Results for open areas were compared independently from the private offices.

2.6.4.2 *Lighting Controls Survey*

- A series of questions regarding the use of the computer-interface lighting control system in the private offices were administered to private office occupants.
- These questions were developed to assess occupant use and satisfaction with the installed system, and to determine if the preset light levels in the private offices were satisfactory for the occupants.

2.6.4.3 *Occupant Comments*

- Occupants were afforded the opportunity to provide additional comments on the lighting system.

2.6.4.4 *Basis of the Survey Questions and Analysis*

- This study focuses on user acceptance only, and made no attempt at determining preference.
- On the assumption that the 835 lamp is acceptable to most office workers, the goal of this study was to determine whether significant differences in acceptance would occur under the scotopically enhanced 850 lamp under otherwise identical lighting conditions.

[1] Eklund N.H. and Boyce, P.R. (1996). "The development of a reliable valid, and simple office lighting survey." Journal of the Illuminating Engineering Society, 25-40.

Eklund, N.H., Boyce, P.R., and Simpson, S.N. (2000). "Lighting and sustained performance." Journal of the Illuminating Engineering Society, Winter 2000, 116-130.

2.6.4.5 *Questionnaire and Survey Administration and Analysis*

- Three web enabled questionnaires were administered to the office occupants (one pre- and two post-installation). The response rate from building occupants when using this approach never exceeded 35%, which was not sufficient for a full analysis of the results.
- One of the post-installation questionnaires provided sufficient indication of the need for adjustments of the lighting levels in the open areas. These adjustments were consequently made and retained for the remainder of the study.
- In order to achieve statistically significant results, a personal interview survey was conducted over a three-day period in December. The overall response to this survey was 79% for open office areas and 66% for private offices. The results from this survey are the basis for the findings and conclusions contained within this report.
- The survey results were collected and analyzed to determine what differences in occupant satisfaction existed between the floor using the 835 lamp and the floor using the 850 lamp. The statistical testing consisted of t-tests comparing the resultant means of the two floors.

3 RESULTS OF THE UCOP STUDY

The results of the UCOP study conclude that office occupants accept the use of the 850 scotopically enhanced lamp at reduced light levels consistent with the previously derived Design Method. These conclusions are based on results obtained in the open office areas. Findings from the private offices were deemed inconclusive due to the confounding variables of daylight exposure and the computer interface control system (see Appendix C). This section therefore details the factual findings and derived conclusions for the open office areas only.

3.1 FINDINGS

This section summarizes the measurements and factual findings pertinent to the study objectives for the open office areas.

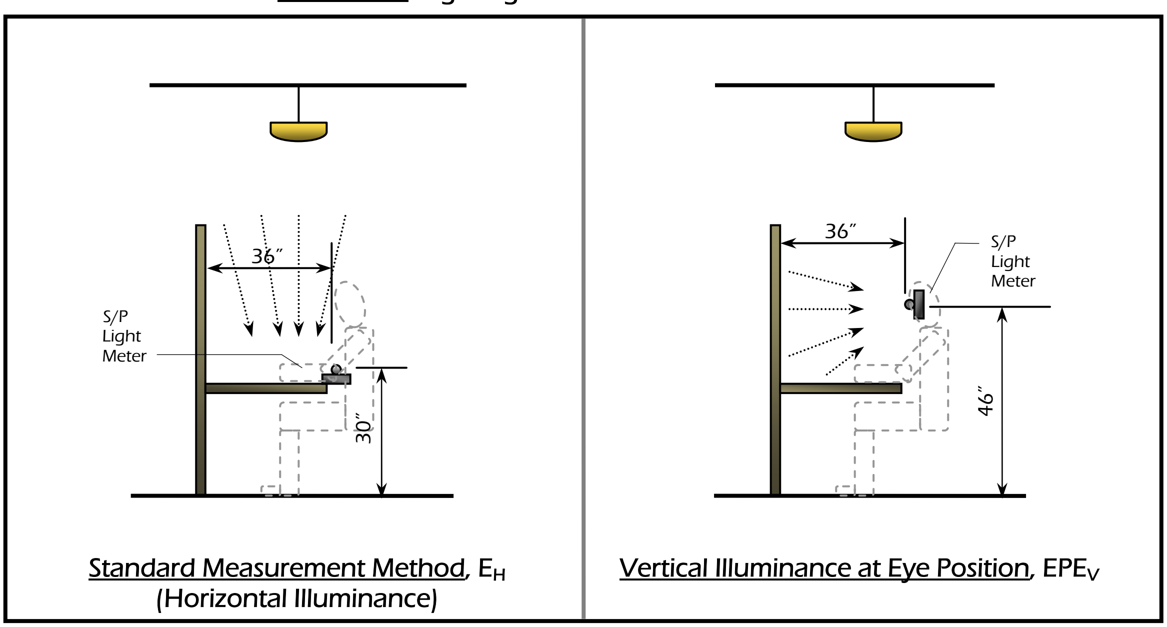
3.1.1 Open Office Lighting Measurement Findings

The open office areas were illuminated with linear 2-lamp indirect pendant luminaires. The office cubicles varied in size and had the same warm tan/gray patterned fabric finish on each floor. Each cubicle had one section of desk surface without overhead storage compartments or supplemental task lighting, which provided a consistent location within the cubicles for taking measurements.

Measurements of horizontal and vertical illuminance at the viewing eye position were taken in the open office areas to get averages for the two floors, using a newly developed S/P light meter on a tripod. This light meter, manufactured by Solar Inc. model #PMA2100, has two photocells, one calibrated to the photopic response curve and the other calibrated to the scotopic response curve.

Only the offices of respondents to the survey questionnaire were measured. 33 open area cubicles were measured on the 10th floor and 33 on the 11th. These measurements were taken at night. Horizontal illuminance was measured at 30 inches above the floor (standard desk height). Vertical illuminance was measured at 46 inches above the floor (viewing eye position). Both measurements were taken 36" away from and perpendicular to the office cubicle partition. *Figure 3A*, below, illustrates the horizontal and vertical illuminance lighting measurement methods.

FIGURE 3A: Lighting Measurement Methods



Note: The Vertical Illuminance at Eye Position, EPE_V, is introduced here as a metric that will be used for analysis and comparison with previous scotopic lighting research, all of which uses vertical illuminance, as measured at the viewing eye position, as a basis for its findings.

Tables 3.1 and 3.2 summarize the lighting measurement findings from the Open Office Areas.

TABLE 3.1: Measured Horizontal Photopic Illuminance, E_{HP}[1]

Floor	Lamp	Measured S/P Ratio	Open Office Horizontal Illuminance E_{HP}	
11th	835	1.40	390 lux	n= 33 min=228 max=513 se = 9.3
10th	850	1.86	322 lux	n= 33 min=214 max=459 se = 12.7
Measured Percent Reduction of Horizontal Photopic Illuminance with the 850 lamp			*17. 5%*	

TABLE 3.2: Measured Eye Position Vertical Photopic Illuminance, EPE_{VP}[2]

Floor	Lamp	S/P Ratio	Open Office Illuminance EPE_{VP}	
11th	835	1.37	219 lux	n= 33 min=119 max=279 se = 7.5
10th	850	1.81	168 lux	n= 33 min=108 max=263 se = 7.1
Measured Percent Reduction of Eye Position Vertical Illuminance with the 850 lamp			*23 .1%*	

[1] Values are Mean averages of Horizontal Photopic Illuminance as measured in lux units at 30" above finished floor. "se" refers to standard error.

[2] Values are Mean averages of Eye Position Vertical Photopic Illuminance as measured in lux units at 46" above finished floor. "se" refers to standard error.

3.1.2 Open Office Power Measurement Findings

Open office area measurements were taken by polling all ballasts within the open office areas on each floor. No attempt was made to segregate specific ballasts, since all lighting was set at identical levels throughout each floor and all ballasts were operating at a constant output level throughout the day.

Prior to the study, calibration testing was performed on the ballasts to ensure software-generated values matched electrically metered values. In addition, data logging equipment was used on three circuits per floor to validate the field test results from the ballast software. The savings are therefore considered as clear, accurate, and definite as the measurements allow. The monitored results are shown in *Figure 3B* below.

FIGURE 3B: Measured Power Consumption of Open Office Areas

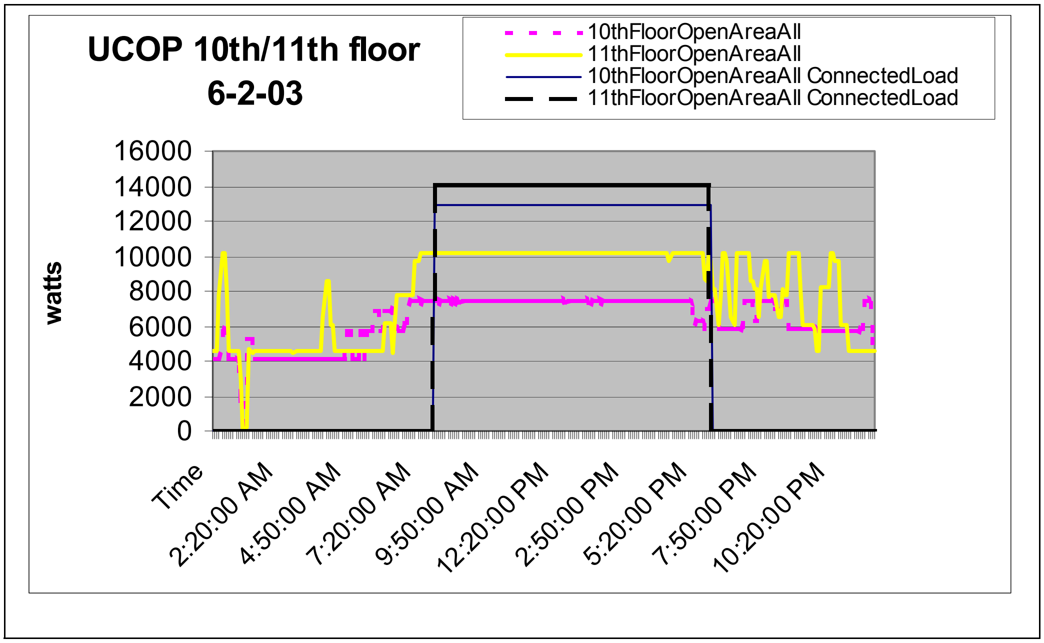


Figure 3B shows the daily pattern of power usage for a typical day. The measurements demonstrate that the 11th floor (reference lamp) has a measured load of 10kW, while the 10th floor (scotopically enhanced lamp) has a measured load of 7.5kW. In order to normalize for the differences in pre-existing connected loads, the pre-existing connected load was calculated (based on all ballasts at full-on) and are superimposed on *Figure 3B*. These values are 14kW for the 11th floor and 13kW for the 10th floor.

A summary of energy savings for the open office areas are presented in *Table 3.3* below:

TABLE 3.3: Measured Power Reduction between Reference Lamp and Scotopically Enhanced Lamp

Floor	Lamp	Connected (Full-On) kWh*	Measured (Dimmed) kWh*	Measured Load / Connected Load %	% Energy Savings from 11th Floor to 10th Floor
11th	835	140	100	71.4%	19.2%
10th	850	130	75	57.7%	

** Assumes constant load for a 10-hour day.*

The measured reduction in power, as a percentage of full load, is 19.2% using the 850 lamp, as compared to the 835 lamp.

3.1.3 Open Office Occupant Survey Findings

A survey was administered to the 10th and 11th floor occupants by four individuals over a period of three days. The survey had a total overall response rate of 79% for open office cubicles.

TABLE 3.4: Survey Response Rate for Survey – Open Office Areas

Office Type	Total Existing Offices	Total Occupied Offices	Total Occupied Offices Surveyed	Percent of Occupied Offices Surveyed
11th Floor Open	65	46	34	74%
10th Floor Open	55	43	36	84%
Totals for Open Offices	**120**	**89**	**70**	**79%**

Survey exclusions and final sample count: From all the surveys taken in the open office area, those declaring full or partial colorblindness were excluded from the results. The final sample count for the open office area is illustrated in *Table 3.5*.

TABLE 3.5: Final Sample Count for Open Office Areas

Floor	No. of Occupants Surveyed	No. of Occupants with Color Vision Deficiency	No. of Occupants Included in Sample Count
11th	34	0	34
10th	36	2	34

The purpose of the occupant surveys was to assess the acceptability of the lighting systems on each floor. The occupant survey consisted of ten Likert Scale questions on occupant perceptions of lighting. See *Table 3.7* for occupant perception results *and Figure 3C* for the Likert Scale values. Additionally, there was one question on *Overall Rating* of the lighting system, see *Table 3.6.* For complete survey results and occupant comments, refer to *Appendix A*.

TABLE 3.6: *Overall Rating* Results By Floor - Open Offices

Scale Value: *Terrible(1) Bad(2) Poor(3) Neutral(4) Fair(5) Good(6) Great(7)*	Mean Value *10th Floor*	Mean Value *11th Floor*
Overall, how would you rate the current overhead lighting?	**4.7**	**4.8**

- *Table 3.6* illustrates that, on the question of *Overall Rating*, the mean values of both floors were *neutral* to *fair* . There was no statistically significant difference between the two floors.

FIGURE 3C: Likert Scale Used For Occupant Survey Questions

Scale Values	Disagree Very Strongly	Disagree Fairly Strongly	Disagree Slightly	Neutral	Agree Slightly	Agree Fairly Strongly	Agree Very Strongly
	1	2	3	4	5	6	7

TABLE 3.7: *Survey Results: Occupants' Perceptions of the Lighting* - Open Offices

Survey Statement	Mean Value *10th Floor*	Mean Value *11th Floor*
The lighting level is set at my preferred level for the work that I do.	3.9	4.3
The overhead lighting makes it difficult for me to read printed materials	3.6	3.4
The overhead lighting makes the colors in the room appear natural	4.5	4.4
I rely on my task lighting for performing my visual tasks comfortably	4.7	5.3
The overhead lighting is acceptable.	4.2	4.5
This overhead lighting is too dim for the work that I do.	3.7	3.5
The overhead lighting allows me to see comfortably.	4.3	4.9
This overhead lighting makes it difficult to read my computer screen	3.4	2.9
The overhead lighting is pleasant to work under.	4.1	4.1
The new lighting levels are too high for the work that I do.	2.5	2.9

- *Table 3.7* illustrates nearly equivalent values of acceptance for the lighting between the two floors. There is no statistically significant difference in occupant acceptability of the lighting system between the two floors (for all tests: p=0.05, Fishers F-Test two-tailed), based on the 10 Likert scaled questions on occupant satisfaction.

3.1.4 Open Office Light Level Correlation Study

Results from the survey questions pertaining to light level, measured horizontal illuminance values, and locations of non-operating lamps were mapped onto the floor plans according to the cubicle space number and luminaire locations. There were several lamps that were removed by occupants, and occupants' comments alerted the interviewers that this had an impact on their responses to the survey. This correlation study was therefore performed to determine:

- if there were any correlations between measured light levels and occupant opinions on whether the light levels were "too dim" or "too high"; or
- if there were any specific areas within each floor where the lighting levels were deemed "too dim" or "too high" that may have introduced a bias into the overall comparison between floors; or
- if there were any undo bias introduced into the overall rankings of light levels resulting from lamps that were either removed or otherwise non-operational at the time of the survey.

Correlation Findings:

1. No correlations could be determined between measured light levels and occupant survey ratings for the light levels, based on descriptors of light levels being "too dim" or "too high" on either floor.
2. There were no distinct areas on either floor in which there appeared to be a confluence of opinions between occupants located close to each other as to whether the lighting levels were "too dim" or "too high".
3. There were more non-operational lamps on the 10th floor (14 total) than the 11th floor (10 total). There were no correlations drawn between occupant opinions on light levels being "too dim" or "too high" and the locations in the open office areas where lamps were non-operational.

3.2 CONCLUSIONS OF UCOP STUDY – PRIMARY OBJECTIVES

This section provides conclusions and supporting analysis drawn from the Findings presented in *Section 3.1* pertaining to the primary objectives, outlined in *Section 2.2.1.* Supplemental background information is also referred to and detailed in the *Appendices*, as necessary.

Objective 1: Evaluate user acceptability of scotopically enhanced fluorescent lighting in an actual operating office environment.

Conclusion: **There is no significant difference in user acceptability between the 850 lamp, when used at reduced light levels, and the more commonly used 835 lamp.**

Objective 2: Evaluate the measurement of light level reduction with scotopically enhanced lighting that does not significantly affect user acceptance.

Conclusion: **The use of the 850 lamp, as a scotopically enhanced light source, can be used at reduced light levels ranging between17-24% below that of the 835 lamp without affecting user acceptance.**

Objective 3: Evaluate, through careful measurement, the energy consumption, thus establishing the energy savings potential of scotopically enhanced lighting.

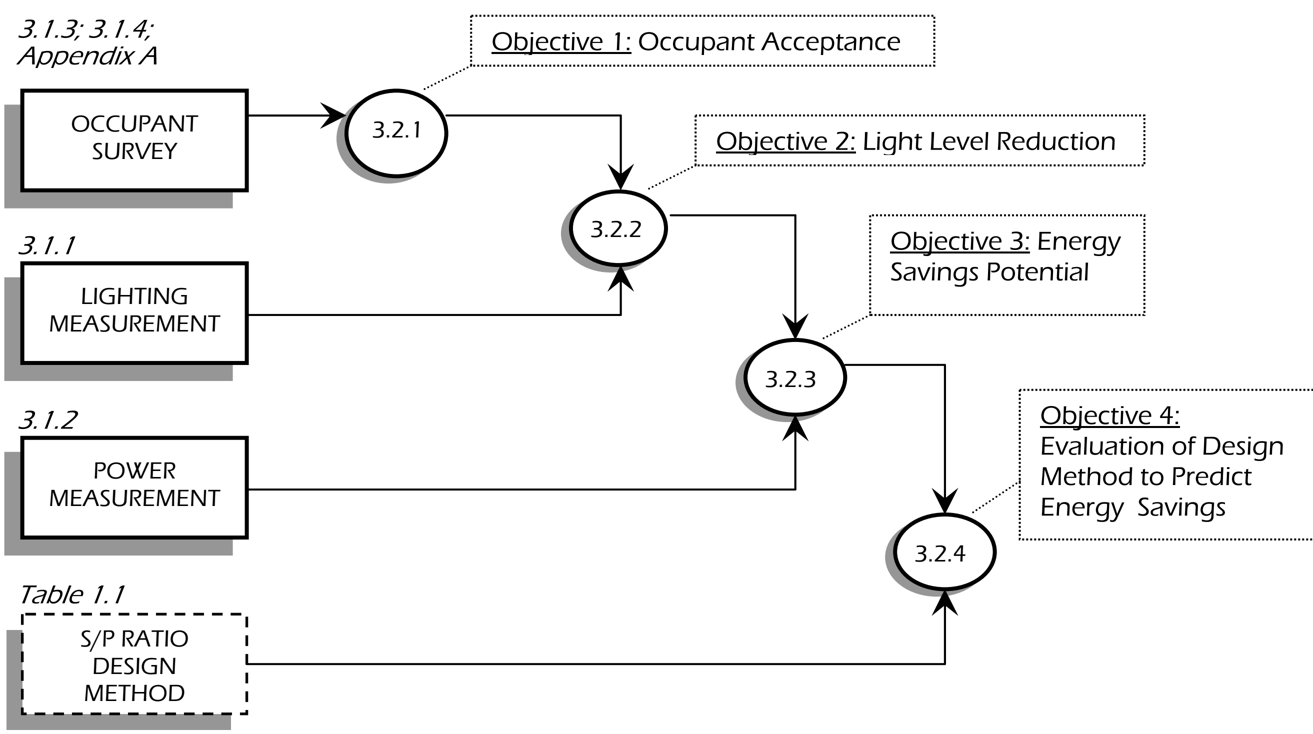
Conclusion: **The energy savings potential due to the spectral effect of the scotopically enhanced 850 lamp ranges between 17-24% when compared to the 835 lamp. By extension, the energy savings potential of the 850 lamp ranges between 22-30% when compared to the 735 lamp.**

Objective 4: Evaluate the existing Design Method model of predicting energy savings when using scotopically enhanced lighting.

Conclusion: **The existing Design Method provides a reliable model for predicting light level differences and energy savings potential.**

These conclusions are specific to the study conditions of open office areas using neutral colored partitions, and indirect lighting.

FIGURE 3D: Illustration of the Analysis Process Noting the Reference Sections used in the Study



3.2.1 User Acceptance

It is concluded that:

There is no significant difference in user acceptability between the 850 lamp when used at reduced light levels, and the more commonly used 835 lamp.

This conclusion is supported by the following:

3.2.1.1 *User Satisfaction Findings:*

There are no statistically significant differences in the responses to any of the individual 10 Likert questions on user satisfaction between office occupants working under the 850 lamp and office occupants working under the 835 lamp. See *Table 3.7.*

3.2.1.2 *Overall Rating Findings:*

On the question of overall rating, office occupants working under the 850 scotopically enhanced lamps ranked the lighting nearly identically to the ranking given by office occupants working under the 835 lamps. The overall ranking was between "neutral" and "fair" for both lamps. See *Table 3.6.*

3.2.1.3 *Light Level Correlation Study Findings:*

The study compared office workers in open office areas with similar configurations, orientations, and fabric finish. There were no correlations found on either floor indicating the introduction of a bias due to illuminance levels or lamp removal on either floor. See *Section 3.1.4*

3.2.1.4 *User Comments:*

Comments varied on each floor, with slightly more comments on the scotopically enhanced floor pertaining to the noticeable change in lamp color. However, this did not appear to affect the outcome of overall acceptance. See *Appendix A.3.*

3.2.2 Light Level Reduction

It is concluded that:

The use of the 850 lamp, as a scotopically enhanced light source, can be used at reduced light levels of 17-24% below that of the 835 lamp in open offices with indirect lighting without affecting user acceptance.

This conclusion is supported by the following[1]:

3.2.2.1 *S/P Ratio Measurements:*

Values for the S/P ratio for the 850 and 835 lamps were measured and compared to catalog values:

TABLE 3.8: Comparison of Catalog S/P values to measured S/P values

<table>
<tr><th rowspan="2">Floor</th><th rowspan="2">Lamp</th><th colspan="2">Catalog Values</th><th colspan="2">Measured EPE$_V$ Values</th><th colspan="2">Measured E$_H$ Values</th></tr>
<tr><th>S/P Ratio</th><th>$\frac{(S/P)_{850}}{(S/P)_{835}}$</th><th>S/P Ratio</th><th>$\frac{(S/P)_{850}}{(S/P)_{835}}$</th><th>S/P Ratio</th><th>$\frac{(S/P)_{850}}{(S/P)_{835}}$</th></tr>
<tr><td>10th</td><td>835</td><td>1.5</td><td rowspan="2">1.33</td><td>1.37</td><td rowspan="2">1.32</td><td>1.40</td><td rowspan="2">1.33</td></tr>
<tr><td>11th</td><td>850</td><td>2.0</td><td>1.81</td><td>1.86</td></tr>
</table>

This table demonstrates that the ratio of (S/P) values between the 850 lamp and the 835 lamp is consistent between catalog and measured values. This shows that even though the (S/P) values for each lamp were reduced due to the environmental conditions of the space (predominantly, by the influence of the partition surfaces), the ratio of (S/P) values is essentially unaffected. This is important to evaluate, since it is only the ratio of the (S/P) values that are used in the calculations (see Appendix E).

[1] This section provides conclusions derived from the findings in Section 3.1 and the Analysis Methods and Calculations in Appendix E.

3.2.2.2 *Measured Illuminance Analysis*:

Two lighting measurements were taken at each open office cubicle as described in Section 3.1.1. While the vertical illuminance at the eye (EPE) is the benchmark measurement used in previous scotopic research, horizontal illuminance measurements are used more predominantly in lighting practice. Measurement analysis of both sets are illustrated in *Table 3.9*.

TABLE 3.9: Summary of Measured Percent Light Reduction

	Vertical Analysis (EPE_{VP})			Horizontal Analysis (E_{HP})		
	11th Floor (835) Mean	10th Floor (850) Mean	Percent Light Reduction	11th Floor (835) Mean	10th Floor (850) Mean	Percent Light Reduction
Average (Mean)	219 lux	168 lux	23.1%	390 lux	322 lux	17.5%

The predictive Design Method is based on eye position illuminance only. However, this study makes no conclusions as to the basis of user acceptance, which may include factors of both eye position illuminance and the horizontal illuminance. Therefore, the light level differences must include the range of values based on the premise that the equal acceptance of the lighting could have been based on wither horizontal illuminance, eye position vertical illuminance, or some combination of both measurements. The range of values based on the actual measurements is therefore 17.5%-23.1%.

3.2.2.3 *Statistical Analysis Testing:*

A statistical analysis was performed (contingency analysis, p=.05) to determine whether the measured values of illuminance on the floor with the 835 lamps, when multiplied by various $(S/P)^X$ Design Method factors, were within the range of statistical significance of the values measured on the floor with the 850 lamps. The range of exponential values tested and the resulting percentage light level reduction results are shown in *Table 3.10*.

TABLE 3.10: Comparing Deisgn Method Predictions to Measured Light Levels

Basis of Exponent Tested	Exponent	Statistically Valid?	Resulting % Light Reduction
Design Method, Brightness Task	.5	N	
Measured Average E_{HP}*	.68	Y	17.2%
Design Method, Paper Reading Task	.78	Y	19.5%
Measured EPE_{VP}	.96	Y	23.4%
Design Method, Computer Task	1.0	Y	24.2%

*Note: The Design Method has been derived using EPE_{VP} only. The exponent value of .68 was derived from the 17.5% light level reduction from horizontal measurements, and was used to test whether this light level reduction value fell within the statistical range using the Design Method.

The statistical tests were performed to test the range of measured values against predicted results. The range of values of light reduction is 17-24% when comparing the 835 lamp to the 850 lamp.

3.2.2.4 *Occupant Response to Light Levels*

The occupant survey metrics did not demonstrate statistically significant results on three statements concerning light level (too dim, too bright, set at preferred level). There appeared, however, to be slight shifts toward light levels being perceived as dimmer on the floor with the 850 lamps, and occupant comments were consistent with these survey results. Exceeding the 24% maximum light level reduction may result in dissatisfaction with lighting levels, due to the perception that the lighting may be too dim. Conversely, there were slightly more non-operational lamps on the 10th floor resulting from occupants removing or twisting lamps out of their sockets than on the 11th floor. These lamp removals correlated with occupant comments of the lighting being "too bright". Installation of the 850 lamps may therefore result in more user complaints of the lighting being too bright if light levels are not reduced by the minimum finding of 17%.

3.2.3 Energy Savings Potential

It is concluded that:

The energy savings potential due to the spectral effect of the 850 lamp, as a scotopically enhanced light source, ranges between 17-24% when compared to the 835 lamp. By extension, the energy savings potential of the 850 lamp ranges between 22-30% when compared to the 735 lamp.

This conclusion is supported by the following:

3.2.3.1 *Power Measurement / Light Level Reduction Analysis:*

The measured energy savings between the floor illuminated with the 835 lamp and the floor illuminated with the 850 lamp was 19.2%. The calculated value using the Design Method and the mean values of EPE_{VP} between floors is 19.3%. These values indicate a high level of correlation, on the other hand, it was discovered during the course of the data analysis that the dimming ballasts used in the study do not have a direct correlation between "percent dimmed" and "percent power" (refer to *Additional Findings Section 4.2*).

A direct analysis of the potential energy savings would assume equivalent lamp efficacies and ballast factors for each lamp. Therefore, the potential energy savings due to the spectral effects of scotopically enhanced lighting are equivalent to the light level reduction, which range from 17-24% when comparing the 835 lamp to the 850 lamp.

3.2.3.2 *Extension of Findings:*

The energy savings potential of scotopically enhanced lighting based on equal lamp/ballast system efficacies are determined by the ratios of S/P values and the exponential factor "x". While the lamps used in this study were the 850 and the 835 lamps for consistency in Color Rendering Index, an extension of the analysis is desirable to find the potential energy savings when comparing the 850 lamp to the more predominantly used 735 lamp. *Table 3.11* illustrates this analysis.

<u>TABLE 3.11</u>: Summary of Potential Energy Savings from Spectral Effect, Comparing the 850 Lamp to the 835 and 735 Lamps

	Catalog S/P Value	850 Catalog S/P Value	Ratio of S/P Values	Minimum Reduced LightLevel (x=.68)	Maximum Reduced Light Level (x=1.0)
835	1.5	2.0	1.33	17%	24%
735	1.4	2.0	1.43	22%	30%

3.2.3.3 *Qualifications of This Study:*

Lighting measurements in this study were made in open offices using indirect lighting with uniform distribution throughout the space and neutral colored finishes. It is therefore a valid approximation to use the measured light level differences and derived (S/P) exponential factors as a proxy for energy savings potential under the presumption of equivalent lamp/ballast system efficacies. This may not be valid if the lighting distribution were uneven or if the surface finishes were highly absorptive in the scotopic region, which could adversely affect the resultant S/P ratios.

It is also noted that the open office areas had task lighting available in all office cubicles. This study only addresses the overhead lighting. Occupant responses to the surveys indicate that both floors used task lighting at approximately the same level, and it is unknown whether any additional task lighting loads were added to either floor as a result of the study protocol. Based on occupant surveys and comments, (see *Appendix A*) it appears that any differences in task lighting use would be consistent between the two floors.

3.2.4 Evaluation Of Existing Design Model

It is concluded that:

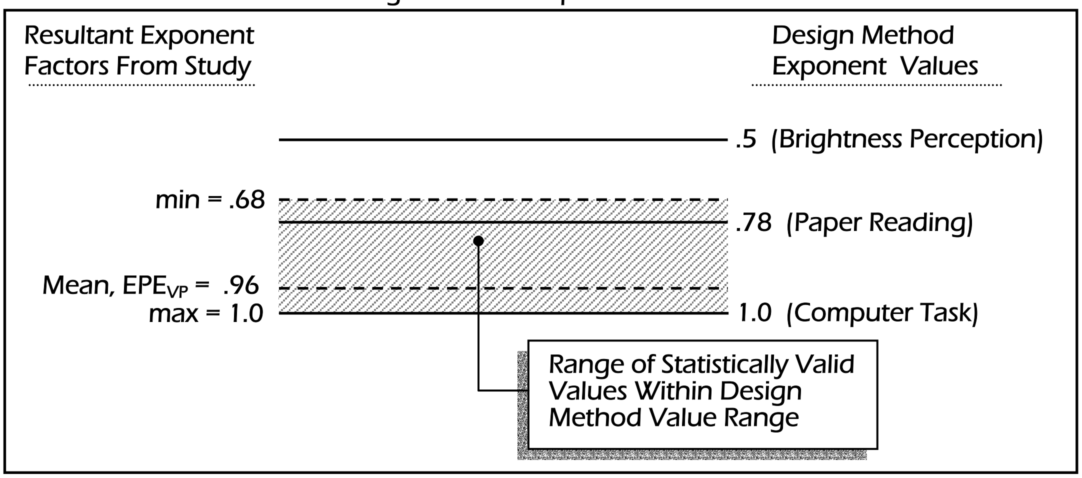
The existing Design Method provides an adequate model for predicting light level reduction and energy savings potential in an open office application.

The conclusion is supported by the following:

3.2.4.1 *Comparison of Measured Values to Design Method Values*

The Design Method S/P exponent factors are derived values for specific tasks, as measured vertically at the position of the viewing eye. A comparison of the statistically valid study resultant S/P exponent factor values to the Design Method S/P exponent values is provided in *Figure 3E*.

FIGURE 3E : Comparison of Study Exponent Values to Design Method Exponent Values



3.2.4.2 *Task Consistency:*

The Design Method is based on visually efficient equivalents for specific tasks. The tasks performed in open office areas are consistent with tasks identified in previous research, mainly paper reading and computer tasks. This study's conclusions indicate that the use of either derived exponent value (.78 for paper reading or 1.0 for computer) can be used when comparing 835 and 850 lamps without adversely affecting user acceptance. Furthermore, indications from user surveys and comments indicate that this range yields some perceptions of decreased brightness perception, which is consistent with results that would be predicted from the Design Method (Equal Brightness Perception Exponent is .5, lower than the measured results).

3.2.4.3 *Computer Task Analysis:*

The Design Method concludes that the maximum benefit of scotopically enhanced lighting is achieved when using the method for self-illuminated tasks such as working on the computer. In this study, 98% of survey respondents claimed to spend more than one-half of their time working on the computer.

Horizontal measurements of illuminance have no relevance in evaluating lighting for computer tasks. Correlation between this study and the Design Method can therefore be performed comparing measured Vertical Eye Position Illuminance values to the Design Method. The (S/P) exponent value based on the measured mean value of Vertical Eye Position Illuminance is .96, which is very close to the Design Method exponent value of 1.0. It is therefore concluded that the use of the exponent 1.0, as measured vertically at the eye position, can be used in open offices with high levels of computer use without having a statistically significant adverse effect on user acceptance.

3.3 CONCLUSIONS OF UCOP STUDY – SECONDARY OBJECTIVES

This section provides conclusions and supporting analysis drawn from the *Findings* presented in *Section 3.1* pertaining to the secondary objectives, outlined in *Section 2.2.2*. Supplemental background information is also referred to and detailed in the *Appendices* as necessary.

3.3.1 Comparison To Building Designed Lighting Levels

Objective 1: The building being studied was in 2000 by a design/build contractor and was designed to meet California Title 24 Energy Standards. As is typical of many buildings, the approach used was to provide as much light as possible while still meeting the Standard. A secondary objective of this study is to evaluate whether energy could have been initially saved at the beginning of the building's life by simply installing a more energy efficient system based on better lighting design practice.

Conclusion: **The use of dimming ballasts throughout the open offices with indirect lighting demonstrate a 28% reduction from the connected load using 835 lamps and a 42% reduction using 850 lamps.**

The conclusion stated above is derived from the values shown in *Table 3.3*. The resulting Lighting Power Densities (LPD's) are illustrated in *Table 3.12* below:

TABLE 3.12: Building Design LPD Compared to Study LPD's

Floor	Basis of Measurement	LPD
Both	Connected Load (As designed)	1.4
11th	Monitored Load, 835 Lamps, dimmed to equal average of pre-study illuminance values.	1.0
10th	Monitored Load, 850 Lamps, dimmed to equal visually efficient illuminance values of the 11th floor.	0.8

As can be seen from this table, significant energy savings can be achieved through the use of scotopically enhanced lighting in conjunction with lowered light levels overall. It is noted that, prior to this study, many lamps had been removed by occupants, and that the largest complaints from occupants was that the lighting was "too bright." However, further analysis would be required to ascertain whether the resultant LPD values would be acceptable in open offices under differing conditions, i.e. parabolic lighting installations and/or higher or darker furniture partition systems.

3.3.2 DALI System Analysis

Objective 2: This project uses the DALI (Digitally addressable Lighting Interface) fluorescent dimming system to monitor energy consumption and dim the lamps. This dimming system has the capability of providing both energy savings and peak load reduction and is new to the lighting industry. A secondary objective of the study is to test this system in a large-scale application.

Conclusion: **The DALI system tested in this study provided the necessary functionality. However, the overriding complications of non-integrated occupancy sensors, study protocol parameters, and inadequate monitoring software prevented an adequate test of the effectiveness of the DALI system.**

A detailed discussion of the DALI system is presented below:

A. *Commissioning*. The DALI system proved to be particularly difficult to commission in this study, taking 10 weeks of evening work for approximately 60,000 square feet of office space. The extraordinary circumstances in this particular research study contributed significant difficulty to the commissioning process, and the commissioning of a DALI system in a more traditional application is unknown. These extraordinary circumstances include:

- Interfacing with non-DALI, ON/OFF occupancy sensors in each private office and in the open offices.

- Commissioning an existing facility at night only, with extreme care to leave all lighting conditions the same as they were every morning after work was performed prior to the launch of the study.
- Compensation for commissioning ballasts for which lamps had been intentionally taken out by users (the commissioning team had to install the lamps, commission the ballast, and then uninstall each of these lamps).

B. *Dimming Functionality*. The dimming functionality of the DALI system proved effective.

C. *System Operation Ease of Use*. The system requires a computer specialist to operate and administer passwords and to change pre-programmed lighting levels.

D. *Private Office User Interface*. The use of the computer interface in the private offices could not be evaluated due to complications arising from the use of pre-existing non-DALI occupancy sensors (see *Appendix C*).

E. *Outcome Predictability*. Light level reductions did not track power reductions as predicted by the system manufacturer data (see *Section 4.2.3*).

F. *Energy Monitoring*. While the data collected proved to be accurate, the monitoring software version available at the time of this study required considerable refinement and customization in order to extract pertinent power and energy results. It is unknown whether improvements have been made at the time of this printing.

3.4 NOTES ON SURVEY RESULTS

3.4.1 Assessment of Acceptance

The assessment of equal acceptance was based on the evaluation of the results of the survey questions and comments. In addition to the individual testing of statistical significance between each of the survey questions, it is noted that the mean values for all questions were generally in the “neutral” range, with no overriding negative results in the mean values on either floor. This is significant from the point of view that while occupants exhibited no hesitation in expressing their views (see comments, Appendix A.3), their overall acceptance of the lighting was similar under both the 835 and 850 lamps.

3.4.2 Survey Sensitivity

It is recognized that absolute levels of subjective response are difficult to unequivocally state with this sample size. However, definitive conclusions were seen in the private offices as to the non-use of the computer software lighting control system, which demonstrate the survey capability to accurately detect occupant dissatisfaction. The survey is therefore considered sufficiently sensitive for the purposes of this study.

4 DISCUSSION & ADDITIONAL FINDINGS OF THE UCOP STUDY

The findings and conclusions in *Section 3* are based on the specific lighting and environmental conditions of the UCOP study, and are confined to results pertinent to the study objectives. In this Section, extrapolations of the UCOP findings and conclusions are made to extend the results to current lamp technologies and related applications. Additionally, there were significant additional findings in this study that, while not relevant to the study objectives, are of interest to the study sponsors and the lighting community at large.

4.1 DISCUSSION OF UCOP STUDY

4.1.1 Design Methodology

This study indicates that the Design Method value of 1.0, while statistically valid in this study, may be too aggressive for a generalized approach due to user observations of "dimness". These perceptions did not adversely affect the overall acceptance, however, it is also observed that 98% of all occupants surveyed spend more than 50% of their time working on computers.

A more generalized approach would therefore propose that:

1. For open offices where the predominant task is working on computers, and task lighting is available, the exponent of 1.0 can be used, however,
2. For open offices where paper reading is predominant, and/or task lighting is not available, the exponent of .78 should be used.

As stated in previous Sections, this applies to interior spaces where the color palette is essentially neutral, and may not apply to spaces where saturated colors adversely affect the resultant S/P ratio of the measured illuminance.

4.1.2 Extension Of Findings To Current Fluorescent Lamp Technologies

Since the time that the study was implemented, new fluorescent lamp technologies have been developed that increase lamp efficacies. The new lamps are generically referred to as "Super T8" lamps and are limited to T8 lamps with 85 CRI("80 series" lamps). There have been no increases in lamp efficacies for the "70 series" lamps.

Lamp manufacturers have confirmed that the highest volume T8 lamp for office spaces is the 735 lamp. Extending the findings from the UCOP study to include the newer, higher efficacy 850 lamps, we see that there are additional energy savings to be gained:

<u>TABLE 4.1</u>: Potential Energy Savings of 850 T8 Lamps As Compared to 835 T8 Lamps

				Potential Energy Savings of:			
Lamp				Standard 850		"Super" 850	
	Rated Initial Lumens			2800		3050	
		Efficacy		87.5		95.3	
			S/P	2.0		2.0	
				x=.78	x=1.0	x=.78	x=1.0
735	2800	87.5	1.4	**24 %**	**30 %**	**30 %**	**36 %**
835	2950	92.2	1.5	16 %	21 %	23 %	27 %
"Super" 835	3100	96.9	1.5			19 %	24 %

As can be seen from the *Table 4.1*, the increases in energy efficiency of the "Super T8" lamps provides an additional 6% energy savings benefit when comparing the 850 lamp to the 735 lamp, with the savings ranging from 30%-36%.

It is noted that these differences assume equal ballast technologies and lumen maintenance of lamps. Other fluorescent lamp comparisons can be performed using mean lumen values and lamp/ballast system efficacies. For example, the potential energy savings when comparing the "Super T8" 850 lamp and electronic ballasts to 34 Watt T12 cool white and 34 Watt T12 warm white lamps with energy saving magnetic ballasts are 40% and 54%, respectively, using the .78 exponent value. According to one lamp manufacturer, T12 lamps represent approximately 50% of the lamp sales in office buildings. The incremental difference in energy savings that the scotopic content provides may therefore increase the deployment of other energy saving technologies such as T8 lamps and electronic ballasts.

4.1.3 Extension Of Findings To Other Light Sources

The studies on scotopically enhanced lighting have primarily been done with T8 fluorescent lamps. However, the foundation of the Design Method is the S/P ratio, which can be measured and applied using any light source. While an exhaustive study of comparative analysis is beyond the scope of this document, one theoretical example is provided below:

TABLE 4.2: Comparison of 850 "Super T8" Fluorescent Lamp to Standard High Pressure Sodium Lamp

Lamp	Mean Lumens	Input Watts (incl. ballast)	System Efficacy (lm/W)	S/P Ratio	Calculated Energy Savings Potential x=.78
LU400	45,000	457	98.5	.62	56%
"Super T8" 850	2,870	32	89.7	2.0	

Note that the above analysis used the mean lumen values and system wattages (lamp with ballast) to compare the overall system efficacies, which is necessary when evaluating different source types. A complete analysis would also require luminaire photometrics. As a hypothetical example, this calculation assumes identical photometrics, and the .78 Paper Reading exponent is used as a possible recommendation for use in warehouses, mail handling facilities, and other industrial facilities where high pressure sodium installations have been installed. The energy savings potential of the 850 lamp as a replacement for high pressure sodium due to the scotopic enhancement is significant. Other benefits of this replacement, such as reduction of lamp operating hours due to the elimination of warm-up and restrike times, would add to the scotopically enhanced lighting energy savings.

4.1.4 Extension of Findings to Other Lighting Methods

The findings of this study are specific to indirect lighting in open office areas with neutral colored partitions. Given the same environment, it is reasonable to extend the Design Method to other lighting distributions such as direct lensed and parabolic luminaries, as long as the implementation of the Design Method does not increase the luminance of the luminaire. This very important consideration in best illustrated by example: Given a 3-lamp parabolic luminaire, it may be proposed to de-lamp to 2 lamps, add a reflector, and slightly bump up the ballast factor of the 2 lamps. This approach, however, results in lower general lighting levels (as desired) but increased luminaire luminance, and the end result is increased glare. (The authors note that this is based on an actual test case, not a hypothetical conjecture). Therefore, any application of this method in office spaces requires uniform light level reductions in both ambient illuminance and luminaire/ceiling luminance.

4.1.5 Extension Of Findings To Private Offices

This study was inconclusive regarding energy savings for private offices. However, based on the fact that there were no statistically significant differences in user acceptance overall for private offices, (similar to open office areas, see *Appendix B.3*), it can be concluded that the 850 lamp is acceptable for use in private offices.

The energy savings potential in private offices is unknown. Indications from previous work lead toward a more conservative approach, (i.e. using a lower exponent value), possibly due to the increased importance of surface brightness perception in enclosed spaces. There is also a pronounced effect that furniture systems have in absorbing light in private offices (higher shelving systems, limited light distribution, and possibly darker finishes). Further studies are required to verify this hypothesis to determine the energy savings potential in private offices.

4.1.6 Extension Of Findings To Other Building Types

Scotopically enhanced lighting is best suited to applications where visual acuity is an important consideration. It can therefore be considered for schools, medical facilities, laboratories, manufacturing facilities, warehousing, and large-scale retail spaces at the .78 exponent value. At the 1.0 exponent values (computer use), the method may be considered for use in call centers, computer programming areas, computer graphics areas, and other spaces where the use of visual display terminals are predominate. Scotopically enhanced lighting may not be acceptable in hospitality applications such as restaurants, hotels, or high-end retail applications due to the industry perceived preferences for warm colors, though no studies have been performed in these applications.

4.2 ADDITIONAL FINDINGS FROM UCOP STUDY

4.2.1 Color Adaptation Period

Occupants notice the color appearance of scotopically enhanced lighting and an adaptation period is required for many individuals. Comments made during and after the field study by the building manager are consistent with other projects managed by the authors regarding the time it takes to get used to the lighting. It appears that three weeks is the time required for most occupants to fully adapt to the new scotopically enhanced 850 light source.

4.2.2 Differences between Vertical and Horizontal Illuminance Measurements

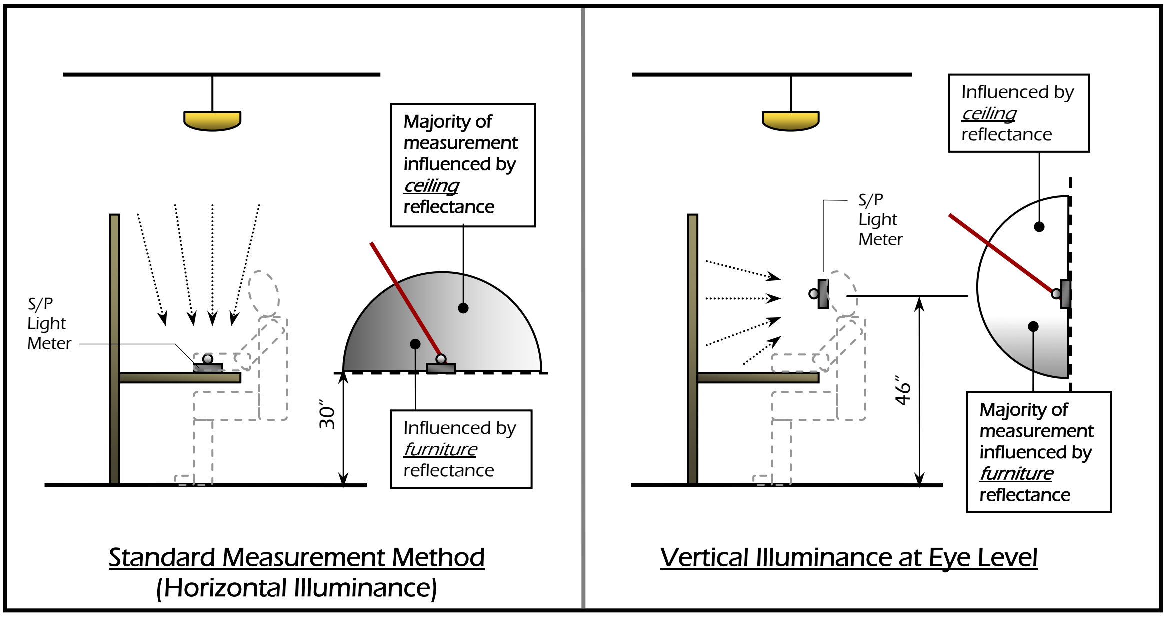
Tables 3.1 and 3.2 illustrate differences between measured horizontal and eye position vertical illuminances, measured S/P ratios, and the resulting differences in percentage light reduction. These values are summarized in *Table 4.3.*

TABLE 4.3: Open Office Area Lighting Measurements:
Horizontal vs. Eye Position Vertical Photopic Illuminance and S/P Ratios

Floor	Horizontal Illuminance E_{HP}	Measured S/P Ratio	Vertical Illuminance EPE_{VP}	Measured S/P Ratio
11^{th}	390	1.40	219	1.37
10^{th}	322	1.86	168	1.81
% Reduction	*17.5 %*		*23.1 %*	

Table 4.3 shows that although the horizontal photopic illuminance is reduced 17.5 %, the vertical photopic illuminance is reduced 23.1%. This difference is most likely explained by the pronounced effect that the office cubicle furniture has in relation to the position of the viewing eye, where the vertical illuminance measurements were taken. The furniture has a warm-toned fabric that apparently absorbs slightly more of the light energy from the scotopically enhanced lighting on the 10^{th} floor. This effect is not as pronounced when measurements are taken in the horizontal plane because the field of view of the sensor is more affected by the ceiling than the office furniture, as is illustrated in *Figure 4A*:

FIGURE 4A: Lighting Measurement Methods



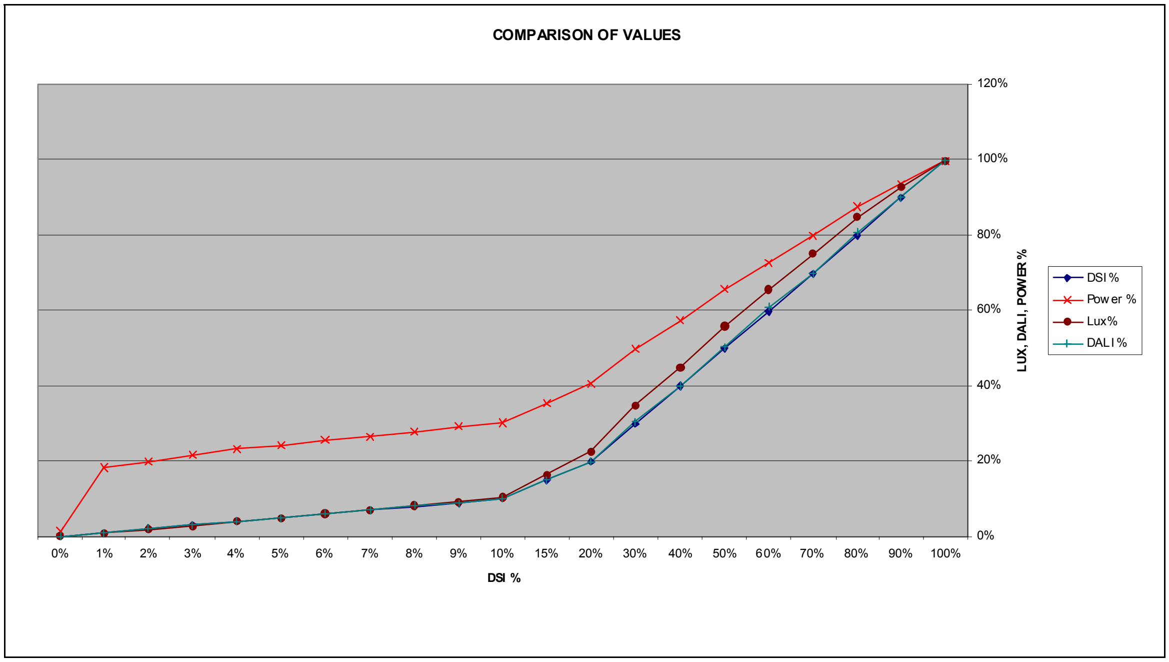
Previous research makes conclusions based on eye position vertical illuminance only, and this study's conclusions are consistent with the previously derived Design Method approach. In fact, the study conclusions as to the validity of the Design Method cannot be made by analysis of horizontal illumination measurements alone. The implications are that eye position illumination measurements are necessary when considering visual efficiency.

The surface finishes in the proximity of the eye position and the differences in the percentage light reduction between horizontal illuminance and vertical eye position illuminance demonstrate that there may be more pronounced differences under the conditions of different light distributions, surface colors or surface reflectance properties. Further studies are required to determine the relevance of horizontal illuminance measurements and the effect of surface absorption properties as this pertains to general applications and the existing Design Method.

4.2.3 Dimming Ballast Light Level to Power Input Relationship

It was discovered through the monitoring of the ballasts that there is a significant difference between the percentage power reduction and the percentage light reduction. The level of this discrepancy was not known until the lighting level and power measurements were analyzed. Further investigation indicates that these differences appear to exist in other fluorescent dimming ballasts, however, the extent that this problem is recognized and/or acknowledged in the industry is unknown. As shown in *Figure 4B*, the percent light output drops off faster than the percent power as the lamp is dimmed.

FIGURE 4B: Comparison of Light Output and Power Values



Values in the *Figure 4B* are provided by Tridonics. DSI% and DALI% are electronic command protocols, and are designed to track light level reductions or Lux%. The key differences to note are between Lux% and Power %. The following *Table 4.4* summarizes monitored DALI% values and the predicted light level and power percentage values compared to measured values:

TABLE 4.4: Comparison of Average Percent Differences in Control Settings, Lighting Level Difference and Power Reduction

Office Type	System Control Setting Monitored Values (Percent DALI of full setting)	Predicted Lighting Level Reductions (Percent illuminance of full setting)	Measured Illuminance, E_{HP}	Measured Illuminance EPE_{VP}	Predicted Percent Power = measured Percent Power (of full setting)
11th floor Open	64.5%	66.5%	390	219	71.4%
10th floor Open	43%	45.5%	322	168	57.7%
% Reduction	33%	32%	17.5 %	23.1%	19.2%

The predicted values listed in this table are taken from information provided by the ballast manufacturer. Discussions with Tridonics indicates that the differences in lighting level as compared to power in actual installations are difficult to predict due to unknown circumstances of ballast temperature, lamp temperature, and lamp variability.

This table demonstrates that while the monitored power values of the ballast percentages tracks within a range of measured actual light level values, the measured light level differences are considerably different from those that would be predicted based on manufacturer information. This discrepancy presented an unforeseen problem in data gathering and energy analysis.

A cursory review of other electronic ballasts also reveals that dimming electronic ballasts are generally not as efficient as the predominant instant start ON/OFF electronic ballasts, even at full light output. As observed above, the differences in efficiency amplify as light levels are reduced. *Table 4.5* illustrates this for a T8 ballast comparison.

TABLE 4.5: BEF Values for 2-Lamp T8 Electronic Ballasts

Ballast Factor or Dimmed Level	Instant Start Electronic Ballast	Dimming Electronic Ballast
1.0	1.5	1.43
.88	1.5	1.39
.77	1.5	1.34

In summary, it is clear that the overall efficiency of dimming ballasts continues to decrease as the lighting levels are dimmed, and that the overall efficiencies are difficult to predict. This has direct consequences to the energy efficiency of any lighting system using dimming ballasts, the impact of which was unknown prior to conducting this research.

4.2.4 S/P Ratio Measurements

It was discovered that there are discrepancies in the values and methods used to determine the S/P ratio of lamps and in metering equipment. These discrepancies appear to be the result of some manufacturers using incorrect normalization factors for the scotopic luminous efficiency function in their measurement equipment. Written standards may be necessary to ensure consistency of S/P measurements, which is critical to the successful implementation of this lighting method.

4.2.5 Energy Consumption Of Failed Occupancy Sensors

The power monitoring of the lighting systems provided evidence of occupancy sensor failure in the open office areas. These sensors were failing to turn the lighting off at night, resulting in a constant load of approximately 4,500 watts on each floor being consumed each night and on weekends. The approximate annual energy cost of these two floors is 46,000 kwh (based on 10 hours per night on weekdays and 24 hours/day on weekends, which allows for cleaning hours). The annual cost, using a rate of $.10/kwh, would therefore be $4,600.00. It is not known to what extent this problem exists on other floors.

5 STATUS OF SCOTOPICALLY ENHANCED LIGHTING

The findings of the UCOP study add to the body of previous work performed by others in their field of scotopically enhanced lighting. This section provides a snapshot of what is known, unknown, and potential steps that could be made to further understand , refine, and implement scotopically enhanced lighting in commercial applications.

5.1 SUMMARY OF FINDINGS ON SCOTOPICALLY ENHANCED LGIHTING

1. Previous studies have concluded:
   - Given two light sources with different spectral distributions and equal photopic illuminance measurements, the eye's pupil size will be smaller under the source that has more energy in the wavelengths contained within the scotopic region. Smaller pupil size results in better visual acuity and increased depth-of-field.
   - Industry standard lighting measurements, as defined by the photopic luminous efficiency function, are not accurate predictors of pupil size (and hence, visual acuity) or brightness perception. The scotopic luminous efficiency function provides a more accurate predictor of these two important visual responses.
   - There are mathematical models for predicting visual equivalences between two light sources of different spectral distribution, using a ratio of the Scotopic (S) to Photopic (P) content of the lamps (the S/P ratio). These models demonstrate that light measurements based on spectra are Task Dependent.
2. This study concludes that:
   - A scotopically enhanced lamp with a Correlated Color Temperature (CCT) of 5000K and a Color Rendering Index (CRI) of 85 has been tested in office applications and has been considered just as acceptable as the more commonly use lamp with a CCT of 3500K and CRI of 85 by building occupants, with approximately 20% measured decrease in (photopic) illuminance. This resulting light level percentage difference can be directly translated into energy savings. The results of this research conclude that the mathematical model can be used in practice.

<u>Energy Ramifications</u>:

The above findings are significant. Projections of National Total Energy Savings using scotopically enhanced lighting are .45 Quads, based on the assumption of 20% average energy savings throughout the commercial sectors where fluorescent lighting is currently used. However, the savings may be higher when considering two specific and common lighting installations:

- The 20% energy savings are obtainable when comparing like-for-like technologies, i.e. both systems are T8 and electronic ballasted. A large portion of the United States fluorescent lighting inventory is still using T12 lamps and magnetic ballasts, due primarily to low energy costs. It is highly probable that the incremental savings resulting from the added benefit of scotopically enhanced lighting will cost-justify changing lighting systems in these installations, which will could result in 45% energy savings for these applications.
- Where commercial and industrial applications use high-pressure sodium lamps, the energy savings will generally be over 50%. These installations are not included in the estimate.

<u>Additional Findings</u>:

Additional discoveries have been made during the course of this research and past studies that affect energy savings and user acceptance:

a) Horizontal photopic illuminance measurements are not sufficient in describing the visual response to lighting. Eye position illuminance measurements are better predictors of pupil size and brightness perception, and are therefore necessary when considering the visual effectiveness of a lighting system.

b) Lighting that has indirect lighting distribution may be more visually effective than sharply directional recessed downlighting (typical of fluorescent parabolic luminaires). This expectation is based on the higher levels of vertical illumination at the eye that generally result from indirect lighting distributions. Indirect lighting may therefore provide an energy efficiency benefit that is amplified with scotopically enhanced lighting.

c) Using scotopically enhanced lighting requires a balance of lamp image brightness to ambient light levels in order to ensure balance and minimize glare from the lamps. This issue is particularly important in spaces where computer use is high and the lighting fixtures are parabolic louver luminaires. In spaces using this common luminaire type, dimming or reduced-output ballasts are required to reduce the bulb wall brightness to maintain visual comfort. The contrast ratio for visual comfort based on S/P ratios is unknown.

d) The interaction of lighting color with room surface colors affects the color perception of the space. In one installation (not UCOP), occupants complained that the space appeared too "blue", resulting in non-acceptance of the lighting. This was an isolated case where the wall color was a "cool white" color. While additional energy savings can be obtained through the use of lamps with higher S/P ratios (and thus higher color temperatures) than the 5000K lamps that have been tested, higher S/P lamps may not be accepted due to the appearance of spaces. These perceptions might be overcome through compensatory color changes of surface properties, as in shifting surface colors toward warmer colors to compensate for the "cooler" colored light. The balance between the color of light received into the eye and the acceptance of the color of spaces under higher scotopic enhancement is unknown.

e) The normalization of the scotopic luminous efficiency functions has been found to be inconsistent between manufacturers. This is a fundamental component of the S/P ratio, and therefore must be correct for measurement and calibration. Standardization is necessary within the industry to solidify this method.

f) There appears to be discrepancies between the power input percentage and the light output percentage in dimming ballasts that are not well documented or understood. The energy ramifications of this discrepancy need clarification for accurate predictions of energy savings.

5.2 REMAINING BARRIERS

1. While the energy savings potential of scotopically enhanced lighting has been established, the economics of the installation have not been. DOE and PG&E research in scotopically enhanced lighting have thus far used dimming ballasts, which costs more than other non-dimming methods. Further economic studies are required to determine more cost effective methods of implementing scotopically enhanced lighting that do not require dimming ballasts.
2. Lamp manufacturers have been hesitant to promote this method, largely due to concerns on user acceptance that have been addressed in this study. Economic incentives for consumer use and/or product development of scotopically enhanced lighting may promote manufacturer interest. Further studies should also encourage participation of key leaders in the manufacturing sector, so they can participate fully and realize the market potential of scotopically enhanced lighting.
3. Lighting practitioners are reticent to use scotopically enhanced lighting due to the fear of lawsuits, since the method is not sanctioned by any authority. A design method, sanctioned by a recognized authority, is required that encompasses the means by which architects, lighting designers, electrical engineers, lighting suppliers, and lighting contractors can promote and implement scotopically enhanced lighting.
4. Professionals in architecture, lighting design, and electrical engineering disciplines are not generally aware of this Design Method. There are no publications describing the method beyond articles and technical papers that have been presented in limited-publication trade journals.

5.3 RECOMMENDED FUTURE RESEARCH

The present body of knowledge concludes that scotopically enhanced lighting will provide the benefits of energy savings with better visual acuity, and that the 850 fluorescent lamps are acceptable in office applications.

There are potentially greater energy savings and higher levels of user acceptance to be gained through the use of indirect lighting, color compensation for room surfaces, higher S/P ratio lamps, and better understandings of proper measurement methods.

The barriers to implementing scotopically enhanced lighting on a wide-scale basis are largely market based. These barriers can be overcome through research efforts that encourage participation from utilities and manufacturers, and result in a published, sanctioned, and marketed design method.

1. These findings show the use of 850 lamps as a viable choice for lighting interior office spaces, and that the S/P lighting method can provide a reliable prediction for energy savings. However, the field study does not provide good economic data for installation costs of such systems because this study used a research-oriented system that is more costly than that required for a standard installation. More work is needed to determine typical installation costs.
2. Given that scotopically enhanced lighting requires no new technology or product development, the immediate needs of an energy efficiency program may be best met by the development of a prescriptive incentive program that encompasses the economics of a variety of scotopically enhanced lighting installations. The development of such an incentive program can add significant information to the field of scotopically enhanced lighting and provide the necessary incentive for more active manufacturer participation. The resulting incentive programs could provide the needed stimulus for building owners to change their lighting systems in the same way that the T8 lamp and electronic ballast changed the lighting systems throughout the 1990's.
3. Further research is required to determine the projected energy savings in enclosed private offices.
4. Further research is required to test the Design Method in other market sectors, such as retail and warehouse applications, for acceptance, energy savings, and economics.
5. This study demonstrates the acceptance of the 5000K, 85 CRI fluorescent lamp. Further research is required to test the acceptance and energy savings potential of lamps with higher S/P ratios.
6. One of the largest remaining market barriers to large-scale implementation of scotopically enhanced lighting is the lack of a sanctioned design method. Identified studies to be performed include more comprehensive studies on the interaction of light color on vertical surfaces and brightness perceptions; indirect lighting energy saving potential; and determining the proper method for design and analysis, i.e. using vertical illuminance at the eye versus using horizontal illuminance at the task.
7. It is desirable to investigate and evaluate the discrepancy between percentage power reduction and percentage light reduction over the dimming range for dimming ballasts. It is also essential, if DALI control systems are used in the future, to influence at least one manufacturer to build metering capabilities into their hardware and software that are optimized for the type of energy analysis required to meet energy efficiency program development requirements.
8. It is necessary to develop a Standard for the measurement and publication methods for the S/P ratio in order to have reliable information that can be used in design.

6 APPENDICES

A. OPEN OFFICE SURVEY AND RESULTS

Appendix A.1: Occupant Survey of Open Offices

Appendix A.2: Survey Results of Open Office Occupants

Appendix A.3: Occupants' Comments from Survey of Open Offices

B. PRIVATE OFFICE SURVEY AND RESULTS

Appendix B.1: Occupant Survey for Private Offices;, Survey Results; Occupant Comments

Appendix B.2: Survey Results of Private Office Occupants

Appendix B.3: Occupants' Comments from Survey of Private Offices

C. ANALYSIS OF PRIVATE OFFICES

Appendix C.1: Analysis of Private Offices

D. WimDim CALIBRATION

Appendix D.1: WinDim Calibration Process

Appendix D.2: WinDim Calibration Raw Data

E. ANALYSIS METHOD AND CALCULATIONS

Appendix E.1: Analysis Method and Calculations

6.1 APPENDIX A.1: OCCUPANT SURVEY FOR OPEN OFFICES

INTRODUCTION: **Surveyor:________________**

We are conducting this survey to get your feedback on the OVERHEAD lighting system that was changed earlier this year. Your answers are confidential and wil be evaluated to see whether the newly installed system has improved.

Were you working on this floor at the time the lighting was changed in March?

☐ Yes ☐ No

Do you spend half or more of your time working on the computer?

☐ ☐ No

Do you use your Task Lighting?

☐ Undercabinet Task Lights ☐ Yes ☐ No

☐ Table Lamps ☐ Yes ☐ No

☐ Floor Lamps ☐ Yes ☐ No

LIGHTING QUALITY QUESTIONS

Please answer the following questions based on how ou feel about the overhead lighting in your workspace. Please use the 7-point rating scale we have given you to indicate your level of agreement with each of the statements.

Please refer to the first line, SCALE No. 1	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
The lighting level is set at my preferred level for the work that I do.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting makes it difficult for me to read printed materials.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting makes colors in the room appear natural.	❑	❑	❑	❑	❑	❑	❑
I rely on my task lighting for performing my visual tasks comfortably.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting is acceptable.	* ❑ *	* ❑ *	❑	❑	❑	❑	❑
The overhead lighting level is too dim for the work that I do.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting allows me to see comfortably.	* ❑ *	* ❑ *	❑	❑	❑	❑	❑
The overhead lighting makes it difficult to read my computer screen.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting is pleasant to work under.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting level is too high for the work that I do.	❑	❑	❑	❑	❑	❑	❑

Please refer to the third line, SCALE No. 2	Terrible	Bad	Poor	Neutral	Fair	Good	Great
Overall, how would you rate the overhead lighting?	* ❑ *	* ❑ *	❑	❑	❑	❑	❑

Please refer to the third line, SCALE No. 3	Much Worse	Worse	Slightly Worse	About the Same	Slightly Better	Better	Much Better
If you can remember, how would you compare this lighting to the lighting that was here before the system was changed?	* ❑ *	* ❑ *	❑	❑	❑	❑	❑

COMMENTS:

____

Would you mind if we asked: *(Optional)*

Is your age

☐ Under 50 ☐ Over 50

To your knowledge, do you have colorblindness:

☐ Yes ☐ No

SCALE No. 1 : For Overhead Lighting Questions

Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly

SCALE No. 2 : For Overall Rating Question

Terrible	Bad	Poor	Neutral	Fair	Good	Great

SCALE No. 3 : For Question Comparing NewLighting to Previous Lighting

Much worse	Worse	Slightly worse	About the same	Slightly better	Better	Much Better

6.2 APPENDIX A.2: SURVEY RESULTS OF OPEN OFFICE OCCUPANTS

Feelings About Overhead Lighting

	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
Scale Value	1	2	3	4	5	6	7

Survey Questions:	*Mean Value* 10th Floor open area	n	*Mean Value* 11th Floor open area	n
The lighting level is set at my preferred level for the work that I do.	3.9	(33)	4.3	(34)
The overhead lighting makes it difficult for me to read printed materials	3.6	(34)	3.4	(34)
The overhead lighting makes the colors in the room appear natural	4.5	(34)	4.4	(34)
I rely on my task lighting for performing my visual tasks comfortably	4.7	(23)	5.3	(24)
The overhead lighting is acceptable.	4.2	(34)	4.5	(34)
This overhead lighting is too dim for the work that I do.	3.7	(34)	3.5	(34)
The overhead lighting allows me to see comfortably.	4.3	(34)	4.9	(34)
This overhead lighting makes it difficult to read my computer screen	3.4	(34)	2.9	(34)
The overhead lighting is pleasant to work under.	4.1	(34)	4.1	(34)
The new lighting levels are too high for the work that I do.	2.5	(34)	2.9	(34)

Overall Rating of the Lighting

	Terrible	Bad	Poor	Neutral	Fair	Good	Great
Scale Value	1	2	3	4	5	6	7

Survey Question:	*Mean Value* 10th Floor	*Mean Value* 11th Floor
Overall, how would you rate the current overhead lighting?	4.7 (n=34)	4.8 (n=34)

New Lighting Compared to Previous Lighting

	Much Worse	Worse	Slightly Worse	About the Same	Slightly Better	Better	Much Better
Scale Value	1	2	3	4	5	6	7

Survey Question:	*Mean Value* 10th Floor	*Mean Value* 11th Floor
If you can remember, how would you compare this lighting to the lighting that was here before the system was changed?	4.2 (n=34)	4.4 (n=34)

Demographics (Age)

Breakdown by Floor	Under 50	Over 50	Total:
10th Floor Open Offices	11	13	24
11th Floor Open Offices	9	15	24
Total:	20	28	48

6.3 APPENDIX A.3: OCCUPANTS' COMMENTS FROM SURVEY OF OPEN OFFICES

<u>Occupants' Comments: 10th Floor Open Offices</u>:

- *"The lights seem to automatically dim now and then for a few minutes at a time; very distracting."*
- *"Mess occurred during construction 3 times."*
- *"Lamps in fixture above have been out for months. Needs lights to be brighter, especially under shelves."*
- *"Turn off more lights, especially where there are no desks."*
- *"Lighting was brighter before. Would like to have dimming controls."*
- *"No adverse affects: headaches, eye strain."*
- *"Was difficult to get used to at first – headaches when working on computer. Now I'm used to it."*
- *"It was hard to get used to. Didn't seem natural. Took about a few weeks."*
- *"Lighting casts a gray pallor – depressingly gray."*
- *"A little too gray. Transition was difficult. About 3 weeks to get used to."*
- *"Bit 'foggy'."*
- *"Doesn't really affect my work on computer." If he needs more light, he uses task lighting.*
- *"Never used task lighting before new lighting was installed."*
- *"Task lighting is imperative."*
- *"I have trouble reading under this light comfortable because it's too dim."*
- *"Early morning and later in evening is more difficult to see – too dim. Daylight helps."*
- *"Too dim and not adjustable."*
- *"Lighting is not bright enough."*
- *"Too dark – feels sleepy when she reads."*
- *High glare in her face when she uses computer, so she removed the lamps.*
- *"At first I liked the change. Then, removed lights in 2 fixtures because too bright. Much better now."*
- *New lights are too bright – removed lamps from 2 fixtures.*
- *Lighting feels more natural.*
- *"Like it for the overall atmosphere."*
- *"Fixtures seem hung too low."*
- *"Improvement is that there is no glare on computer screen."*
- *"Less glare."*
- *"Has perception that overhead lighting is better: indirect, no glare."*
- *"Vision felt blurry after lighting was changed. Blurriness would last for 2 hours. Did not have vision problem with previous system."*
- *"Eyes hurt less at end of day with new lighting – less strained."*
- *Difficult to read print, so he needs to turn on undercabinet lights. Undercabinet lighting is essential or else he gets eye strain.*
- *"Lighting is dim – makes everything look blue. Looks fake. Lighting before was brighter and more yellow-toned."*
- *"Quality of light is depressing, cold quality, blue."*

Occupants' Comments: 11th Floor Open Offices:

- *Wants individual controls.*
- *"Would like to see more natural light."*
- *"Would rather have incandescent."*
- *"Studies have shown fluorescent lighting is unhealthy, 'harsh'." Doesn't care much about.*
- *Fluorescent lighting is uncomfortable for her eyes. "Too bright, noisy, it hums." Next to window.*
- *Previous system: several lamps were out. No lamps have been out with new system - great improvement.*
- *Does not like fluorescent lighting.*
- *Don't use fluorescent task lighting - sees bulb.*
- *"No Natural light."*
- *"Would prefer more natural lighting."*
- *Noticed difference.*
- *"Generally satisfied - a little."*
- *"Indirect is good."*
- *Has daylight in space. Prefers natural light.*
- *"Lighting is okay." Has a lot of windows by space.*
- *Needs higher levels for paper tasks.*
- *Likes undercabinet task lighting – "not so glaring."*
- *"Lighting appears muted." Payroll- does detailed work with figures, so needs additional task lighting.*
- *Still needs task lighting.*
- *"Lighting is too dim." Fixtures are not directly over her work surface.*
- *"Lights turn off automatically sometimes."*
- *"Sometimes lights dim out for a minute or 2 at a time – a couple times a week."*
- *Light feels too bright for computer work. Wants to wear a visor because lights are directly over computer. Prefers task lighting for print work, but doesn't use her task lights because it's already bright enough.*
- *Prefers lights turned down.*
- *"Light glares and lights up the ceiling more than down."*
- *She would like it dimmer.*
- *Prefers lighting on 10th floor – seems softer or not as bright.*
- *"Lighting is too bright. Need to soften brightness."*
- *Finds it pleasant, likes indirect lighting. Likes Diffuse.*
- *Feels eye strain under this light.*
- *Hasn't noticed difference.*
- *"Furniture too white."*
- *"Lighting is comfortable – seems brighter than before, which is good."*

6.4 APPENDIX B.1: OCCUPANT SURVEY FOR PRIVATE OFFICES

INTRODUCTION: **Surveyor:________________**

We are conducting this survey to get your feedback on the OVERHEAD lighting system that was changed earlier this year. Your answers are confidential and wil be evaluated to see whether the newly installed system has improved.

DO YOU USE YOUR OVERHEAD LIGHTING? ❑ Yes ❑ No Why not? ________________________

Were you working on this floor at the time the lighting was changed in March?
☐ Yes ☐ No

Do you spend half or more of your time working on the computer?
☐ ☐

Do you use your Task Lighting?

☐ Undercabinet Task Lights	☐ Yes	☐ No
☐ Table Lamps	☐ Yes	☐ No
☐ Floor Lamps	☐ Yes	☐ No

P.O. Walls:
____ Window Walls
____ Blank Walls (<50%)
____ Covered Walls (>50%)

Office Type:
❑ Perimeter P.O
❑ Interior P.O
___ # of Fixtures

LIGHTING QUALITY QUESTIONS

Please answer the followng questions based on how ou feel about the overhead lighting in your workspace. Please use the 7-point rating scale we have given you to indicate your level of agreement with each of the statements.

Please refer to the first line, SCALE No. 1	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
The lighting level is set at my preferred level for the work that I do.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting makes it difficult for me to read printed materials.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting makes colors in the room appear natural.	❑	❑	❑	❑	❑	❑	❑
I rely on my task lighting for performing my visual tasks comfortably.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting is acceptable.	* ❑ *	* ❑ *	❑	❑	❑	❑	❑
The overhead lighting level is too dim for the work that I do.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting allows me to see comfortably.	* ❑ *	* ❑ *	❑	❑	❑	❑	❑
The overhead lighting makes it difficult to read my computer screen.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting is pleasant to work under.	❑	❑	❑	❑	❑	❑	❑
The overhead lighting level is too high for the work that I do.	❑	❑	❑	❑	❑	❑	❑

Please refer to the third line, SCALE No. 2	Terrible	Bad	Poor	Neutral	Fair	Good	Great
Overall, how would you rate the overhead lighting?	* ❑ *	* ❑ *	❑	❑	❑	❑	❑

Please refer to the third line, SCALE No. 3	Much Worse	Worse	Slightly Worse	About the Same	Slightly better	Better	Much Better
If you can remember, how would you compare this lighting to the lighting that was here before the system was changed?	* ❑ *	* ❑ *	❑	❑	❑	❑	❑

PRIVATE OFFICE LIGHTING CONTROLS

Were you aware that you can change your overhead lighting levels through your computer?

❑ Yes ❑ No

Please refer to the first line, SCALE No. 1	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
I like the ability to change my lighting level.	❑	❑	❑	❑	❑	❑	❑
The lighting controls are easy to use.	❑	❑	❑	❑	❑	❑	❑
I change my lighting level depending on what type of work I am doing.	❑	❑	❑	❑	❑	❑	❑
I like to have higher lighting levels when working on the computer.	❑	❑	❑	❑	❑	❑	❑

When do you change your lighting settings using your computer?

❑ Never
❑ Once per day when I enter the room
❑ Every time I enter the room
❑ Throughout the day when I am in the room

Have you changed the preset levels using the wrench tool?

❑ Yes ❑ No

If the control were a wall dimmer, would you use it more?

❑ Yes ❑ No ❑ Not Sure

When I first enter my room and the lights turn on, the lighting is:

❑ Just Right ❑ Too Dim ❑ Too Bright

Would you like to have your light levels adjusted to a different level for when you first enter your room?

❑ Yes **(If yes, to what level?)** _____________ ❑ No

COMMENTS:

Would you mind if we asked: *(Optional)*

Is your age

☐ Under 50 ☐ Over 50

To your knowledge, do you have colorblindness:

☐ Yes ☐ No

SCALE No. 1 : For Overhead Lighting Questions

Disagree very strongly	**Disagree fairly strongly**	**Disagree slightly**	**Neutral**	**Agree slightly**	**Agree fairly strongly**	**Agree very strongly**

SCALE No. 2 : For Overall Rating Question

Terrible	**Bad**	**Poor**	**Neutral**	**Fair**	**Good**	**Great**

SCALE No. 3 : For Question Comparing New Lighting to Previous Lighting

Much Worse	**Worse**	**Slightly Worse**	**About the Same**	**Slightly Better**	**Better**	**Much Better**

6.5 APPENDIX B.2: SURVEY RESULTS OF PRIVATE OFFICE OCCUPANTS

Lighting Quality: Feelings About Overhead Lighting

	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
Scale Value	1	2	3	4	5	6	7

Survey Questions	*Mean Value* 10th Floor private offices	n	*Mean Value* 11th Floor private offices	n
The lighting level is set at my preferred level for the work that I do.	5.0	(29)	5.4	(29)
The overhead lighting makes it difficult for me to read printed materials	3.2	(29)	2.0	(24)
The overhead lighting makes the colors in the room appear natural	4.3	(27)	4.6	(24)
I rely on my task lighting for performing my visual tasks comfortably	4.5	(10)	4.9	(8)
The overhead lighting is acceptable.	5.0	(29)	5.4	(24)
This overhead lighting is too dim for the work that I do.	3.0	(29)	2.3	(24)
The overhead lighting allows me to see comfortably.	5.0	(29)	5.5	(24)
This overhead lighting makes it difficult to read my computer screen	2.7	(27)	2.5	(24)
The overhead lighting is pleasant to work under.	4.3	(28)	4.6	(24)
The new lighting levels are too high for the work that I do.	2.7	(29)	2.3	(24)

Overall Rating of the Lighting

	Terrible	Bad	Poor	Neutral	Fair	Good	Great
Scale Value	1	2	3	4	5	6	7

Survey Question:	*Mean Value* 10th Floor	*Mean Value* 11th Floor
Overall, how would you rate the current overhead lighting?	5.1 (n=29)	5.5 (n=24)

New Lighting Compared to Previous Lighting

	Much Worse	Worse	Slightly Worse	About the Same	Slightly Better	Better	Much Better
Scale Value	1	2	3	4	5	6	7

Survey Question:	*Mean Value* 10th Floor	*Mean Value* 11th Floor
If you can remember, how would you compare this lighting to the lighting that was here before the system was changed?	4.7 (n=26)	4.4 (n=19)

Private Office Lighting Controls

	Disagree very strongly	Disagree fairly strongly	Disagree slightly	Neutral	Agree slightly	Agree fairly strongly	Agree very strongly
Scale Value	1	2	3	4	5	6	7

Survey Questions:	*Mean Value* 10th Floor private offices	n	*Mean Value* 11th Floor private offices	n
I like the ability to change my lighting level	4.7	(15)	5.4	(19)
The lighting controls are easy to use	4.1	(12)	4.4	(18)
I change my lighting level depending on what type of work I am doing	3.3	(11)	2.9	(19)
I like to have higher levels when working on the computer	2.9	(10)	3.1	(20)

	Never	Once per day when I enter the room	Every time I enter the room	Throughout the day when I am in the room
Scale Value	1	2	3	4

Survey Question:	*Mean Value* 10th Floor private offices	n	*Mean Value* 11th Floor private offices	n
When do you change your lighting settings using the computer?	1.3	(22)	1.7	(18)

	Yes	No
Scale Value	1	2

Survey Questions:	*Mean Value* 10th Floor private offices	n	*Mean Value* 11th Floor private offices	n
Have you changed the preset levels using the wrench tool?	1.6	(26)	1.8	(21)
If the control were a wall dimmer, would you use it more?	1.4	(26)	1.6	(20)

	Too Dim	Just Right	Too Bright
Scale Value	1	2	3

Survey Question:	*Mean Value* 10th Floor private offices	n	*Mean Value* 11th Floor private offices	n
When I first enter my room and the lights turn on, the lighting is:	1.3	(28)	1.6	(23)

<u>Demographics (Age)</u>

Breakdown by Floor	Under 50	Over 50	Total:
10^{th} Floor Private Offices	19	11	30
11^{th} Floor Private Offices	19	12	31
Total:	38	23	61

6.6 APPENDIX B.3: OCCUPANTS' COMMENTS FROM SURVEY OF PRIVATE OFFICES

<u>Occupants' Comments: 10th Floor Private Offices</u>:

- *"Communication with workers sucked."*
- *"I don't think about the lights."*
- *"Bad building, badly designed lighting, bad furniture, switching problem, single switch."*
- *"I don't even notice whether it's on or not. Sometimes I switch it off when I leave."*
- *A stigmatism.*
- *"Fix heater, then I'll care. I think it's amusing that we're spending so much effort on the lighting."*
- *"Show me how to control lighting." (Was not aware of ability to control lighting.)*
- *"Light is good for what I do. I played with it first, but not now."*
- *"Lighting is fine."*
- *"I use the window for light."*
- *"I have daylight, so I use the lights very occasionally at night. Then it's fine."*
- *Likes dark. Uses daylight.*
- *"Changing controls doesn't seem to change level much. I raise the blinds instead."*
- *"Motion sensor is inconvenient - turns off too soon."*
- *"It drives me crazy when the occupancy sensor shuts the light off when I'm here. Is mine on a shorter fuse?"*
- *"Motion sensor is good economically, but controls are inconvenient to use."*
- *"Wonderful, but inconvenient to use, complicated."*
- *"I notice the other yellow floor. I like the blue light."*
- *"When it was first changed, could really tell the difference. Noticed change in lobby color. Have adapted; glare is gone."*
- *"I don't like fluorescent lights, but this is much better."*
- *"Whole floor seems depressing."*
- *"Morgue lighting in the open areas. Depressing at first."*
- *Likes under cabinet task light.*
- *"Bluer than before."*
- *"Don't like overhead lights."*
- *"Annoying when I leave the room, the lights go off and revert to preset level, which is too bright. Why can't it come back on at the level where I set it?"*
- *"Bad vision, contacts, lots of eye problems. I want it brighter."*
- *"Lighting level seems dark. Seems lighter on other floors."*
- *"I'm on a deadline, I don't want to do the survey, just write down that I hate the color."*
- *"Could be brighter, but I open the shade so don't adjust it, show me how."*
- *"Prefer daylight; overhead lighting causes glare on my computer screen."*
- *"Don't like how quickly the lighting goes off. Occupancy sensor isn't as sensitive as it used to be and it ramps up rather than lowering. Lights turn on all the way (up)."*
- *"Very strange at first when it was changed. Seems unnecessary, cloudy and stormy, depressing. Most people okay now."*
- *"Your shirt is vibrating! No daylight! "*
- *"Motion sensor is inconvenient - turns off too soon."*

- *"Noticed color but now adapted."*
- *"Difficulty reading glossy material."*
- *"Controls make all the difference in the world."*
- *"Don't like difference between my office and outside area - too dim in outside office area."*
- *"Controls crashed my computer."*
- *"Easier to read with my desk lamps."*
- *"Control is slow. I always have to adjust it down when I return to my office."*
- *"Was way too dark, had it set to 100%. I want it brighter still."*
- *"These lamps suck. I hate the color hue."*
- *"Easy to change lighting on computer, but (wall) dimmer would be nice."*
- *"Don't like fluorescent lights."*

<u>Occupants' Comments: 11th Floor Private Offices</u>:

- *"Fluorescent lighting results in stinging eyes."*
- *<u>Complaints from open office occupants (to mgr)</u>: "They can't adjust their light level - this created animosity and people felt they didn't get the perks the private office occupants did."*
- *"Don't like fluorescent lights."*
- *"Instead of a dimmer switch, if there were a computer utility for the control, instead of hogging the entire window."*
- *Doesn't pay attention to lighting – doesn't think about it, so it must be okay.*
- *Hates fluorescent lighting - increases eye strain, gives headaches, etc., flickering.*
- *Knows a lot of people that like it, but she's just not interested.*
- *He has had to use the overhead lighting when darkness comes early in winter, and he doesn't like the fluorescent lighting.*
- *Suggestion for change/improvement: do away w/ password – it's too much to remember all the different passwords they have.*
- *"The lighting system was an absolute waste of money."*
- *Doesn't think about the lights. No comments.*
- *Has been fairly satisfied with change– hasn't affected him.*
- *Hugely pleased with lighting system – when they were bright, she got headaches working under those lights for 8 hrs/ day. She used to have to do things to the overhead lighting to reduce the light level.*
- *"Windows really help."*
- *Has never used the overhead lighting system – only uses natural light. Only uses the overhead lighting during the late afternoons in winter, and then she uses on/off only.*
- *She wanted to change the period the lights stay on before she has to re-new the motion sensor. Even a mouse click on the computer screen would be better than getting up and going over to create motion or hitting the switch.*
- *<u>Complaints from private office occupants (to mgr)</u>: "Switches run on motion sensor located far from where person sits- they have to devise some method of perpetually creating motion to keep their lights on (waving their arms around, putting a fan w/ a ribbon in front of sensor)."*
- *"You have to go out of your way to bring up the computer menu. Having to find it makes it a disincentive to use – inconvenient."*
- *"The controls could be more convenient."*

- *"IE interface is clunky. It doesn't work with Netscape and he uses Netscape, so it's not convenient. He has to open IE."*
- *"Nuisance to use control system. Dimmer would be much better."*
- *"Lighting controls – didn't want it; doesn't use it' could care less' it was a waste of money. Would certainly use controls if it were on a wall dimmer."*
- *"Couldn't find control icon on screen. Controls were initially difficult to use, gave up."*
- *Tried to use controls once, but lost interest after she couldn't remember user name.*
- *Doesn't like the additional computer-controlled functions – it's inconvenient. Would be much more convenient with a wall dimmer.*
- *"A little clunky and inconvenient to go thru computer, pulling up IE, entering password, dealing w/ the scales. Disincentive to using it."*
- *Likes the ability to adjust the light levels because he's on a perimeter office and the outside, natural light changes according to seasons. Uses blinds, but in morning, sun glare stripes run vertically across his computer screen and he has to have blinds completely closed to screen. No glare from overhead lights in those cases.*
- *"Controls make all the difference in the world." Otherwise, likes the lighting controls.*
- *He adjusts his overhead lgihting according to the light outside his window – when it gets dark around 4 or 5, that's when he adjusts the overhead lighting.*
- *Doesn't like fluorescent lighting, period – will probably leave the lighting off most of the time, anyway. Doesn't like the glare.*
- *He uses window blinds for lighting controls and uses 2 table task lights.*
- *Every time the lights go off (motion sensor), she has to get them back on and they come on too bright, so she has to reset the lighting settings.*
- *Would like to NOT have to wave her arms so much to trigger occupancy sensor. Sensor is opposite from where she sits at her desk.*
- *Control system was disabled. Computer controls easy, just didn't work for a period of time, gave up.*
- *Nice that survey is being conducted to follow up.*
- *In general, she doesn't like fluorescent lighting – too much glare/aesthetically displeasing, too cold.*
- *Lighting controls easy to use, but doesn't due to Netscape/Explorer. Doesn't think to use controls.*
- *"Problem is lack of task lighting."*
- *"Task lighting more relaxing and more conducive to productivity."*
- *Has lighting set @ 100%. 80% is too dark. Initial lighting was worse - too low.*
- *Disconnected 2 lamps – too much glare.*
- *Prefers separate controls for each light fixture.*

6.7 APPENDIX C.1: ANALYSIS OF PRIVATE OFFICES

Data collection and analyses of the private offices included the same level of effort as those in the open office areas, including the Lighting Measurement Analysis, the Power Measurement Analysis, and the Occupant Survey. However, the information retrieved yielded inconclusive results. This Appendix documents the confounding variables that were discovered in the private offices, and how these confounding variables affected the outcome of the study.

1. Occupant Surveys:
   a. Daylight Influence: Only three (3) 11th floor interior private office occupants and six (6) 11th floor interior private office occupants were surveyed. This was partially due to the unanticipated low number of interior offices that were actually occupied and the fact that many of the occupied interior private offices had only part-time occupants.

TABLE 6C.1: Survey Response Rate for Survey - Private Offices

Private Office Type	Total Existing Offices	Total Occupied Offices	Total Occupied Offices Surveyed	Percent of Occupied Offices Surveyed
11th Interior	14	7	5	69%
11th Perimeter	44	41	28	
11th Flr. Totals	**58**	**48**	**33**	
10th Interior	15	10	6	64%
10th Perimeter	46	45	29	
10th Flr. Totals	**61**	**55**	**35**	
Totals for Private Offices	119	103	68	66%

Survey exclusions and final sample count: From the total surveys taken in private offices, those declaring full or partial colorblindness were excluded from the survey results. Additionally, a number of respondents definitively declared that they never used the overhead lighting, and were therefore also excluded from the results. The final sample count for the private offices is illustrated in *Table 6C.2*.

TABLE 6C.2: Final Survey Count for Private Offices

Private Office Type	No. of Occupants Surveyed	No. of Occupants with Color Vision Deficiency	No. of Occupants That Never Use Overhead Lighting	No, of Occupants Included in Sample Count
11th Interior	5	0	2	3
11th Perimeter	28	3	4	21
11th Flr. Totals	**33**	**3**	**6**	**24**
10th Interior	6	0	0	6
10th Perimeter	29	1	4	24
10th Flr. Totals	**35**	**1**	**4**	**30**
Totals For All Private Offices	**68**	**4**	**10**	**51**

The overriding impact is that over 80% of the private office survey respondents occupy private offices on the perimeter of the building, which are exposed to a large amount of daylight. It was noted by all four interviewers that the influence of daylight appeared to have a significant affect on occupants' responses to the surveys, and many of the comments seen in Appendix B indicate this response. The influence of daylight, and the preponderance of daylight in offices among the private offices in the survey is therefore considered a confounding variable.

b. <u>Control System Influence</u>: Private office occupants were given control of their lighting level through a computer interface. The intention of the study was to determine if, in the aggregate, there were noticeable differences in light levels and resulting energy usage between private office occupants using the scotopically enhanced lighting and private office occupants using the reference lamps. However, the occupant surveys revealed that the lighting control system was rarely used, and considered too complicated, too inconvenient, or both:

- The control system did not interface with the existing wall mounted occupancy sensors. Occupants could change their light levels only after they had: 1) entered the room and energized the lighting via the occupancy sensor; 2) turned on their computers and logged onto the main network, and 3) logged onto the lighting computer program via a separate computer interface and password.
- Upon leaving the room, the occupancy sensor turned the lights off, and the light level that the occupant had previously set as their preference through the computer interface was not retained. Re-activation of the lights upon re-entering the room would turn the lights to a predetermined "Power ON" setting. The occupant would then be required to re-establish connection to the lighting software computer interface to adjust the lighting level back to their preferred light level.
- The "Power ON" setting is pre-programmed in the centralized computer and could not be changed by the occupants – they were required to call the building computer supervisor to change this level.

The preponderance of control system complaints from private office occupants resulting from the complications noted above and listed as complaints in the survey comments (see Appendix B) constitutes a confounding variable that affected the results of the occupant survey.

2. <u>Light Level Measurement and Analysis:</u> The research team envisioned that the use of the dimming controls by occupants in the private offices would provide insight into user preferences of light level. A valid comparison of user preference of lighting levels could therefore have been made between the private offices using the scotopically enhanced lighting as compared to those using the reference lamp. However, the confounding variable of daylight clearly influenced occupant *need or desire* to adjust lighting levels, and the control system complications directly affected occupant *ability* to adjust light levels, as noted in item 1 above. Therefore, light level measurements in private offices were not reliable indicators of user preference, and any comparison of light level measurements between the two floors is not valid for the purpose of analysis in this study.

3. <u>Power Measurement and Analysis</u>: Power measurements were tracked for the private offices throughout the study. However, for the reasons stated in Items 1 and 2 above, the power values that were measured do not necessarily correlate to user preferences are therefore invalid due to the confounding variables of daylight and the difficulties encountered with the control system.

6.8 APPENDIX D.1: WINDIM CALIBRATION PROCESS

The UCOP study required that DALI controlled ballasts provide accurate power consumption data to justify energy savings calculations. It was found that factory-issued calibration software did not provide accurate power consumption values. Alternate calibrations were prepared and verified by as part of this study.

Background:

The Windimnet software program used for this project (from Tridonic, Inc) provides control and monitoring functions for DALI ballasts. Prior to this project, the monitoring and logging functions were rudimentary. In order to improve the monitoring functions, Tridonic developed new software modules and calibration data files. This Appendix describes an independent calibration process to determine whether the Windimnet software produces accurate stored values of power consumed by a DALI system. If so, the factory-issued calibration tables could be recommended, if not, alternative calibration tables would be necessary.

Technical Architecture:

The Windimnet system is a server-based system that reads and writes parameters to ballasts connected via Ethernet loop. In order to determine how far below full power a ballast on the loop is dimmed, Windimnet polls the ballast and retrieves a bit (between 0 and 255) representing the dimmed level of the ballast. To compute power and/or energy consumed by the ballast, Windimnet looks up a coefficient in a table that corresponds to the bit collected. That coefficient (an un-scaled point on the dimming for that ballast powered at a specific voltage) is then multiplied by the full scale power in order to compute the power consumed and that value is stored in a database. Tridonic claims that Windimnet cannot poll ballasts and store the values in a database more rapidly than at 5 minute intervals – this has not been tested.

Approach:

To test the two types of T-8 DALI ballasts available, 1-L and 2-L, a test setup with 2 1-L ballasts and 3 2-L ballasts was built using ballasts and software provided by Tridonic.

To measure power consumed, a Fluke meter was used in series mode to measure AC current and an AEC microdatalogger was used with a 5 amp current transducer to measure AC current. The Fluke was independently used to measure and record AC voltage. In each case power was calculated as VxA.

Original Test Values

The first set of measurements was done using the off-the-shelf software as delivered. Current was recorded at intervals of 10% dimming from 100% of full power down to 10% of full power. The points 0.1% of full power (fully dimmed) and 0% of full power (software-controlled 'off' but physically wired into the circuit) were also tested.

The *Figure 6D.1* below shows the power consumed by all five ballasts in the demo setup. Note that the Fluke and MDL track each other well and WinDim substantially under predicted the power consumed.

FIGURE 6D.1

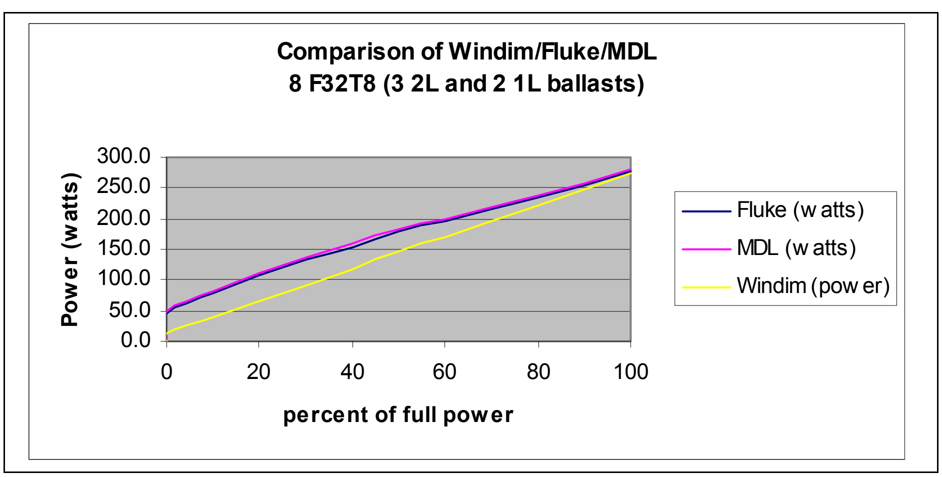


Figure 6D.2 shows the power consumed by a single 1L ballast in the demo setup. Note that the Fluke and the MDL track each other well and the Windim substantially under predicts the power consumed.

FIGURE 6D.2

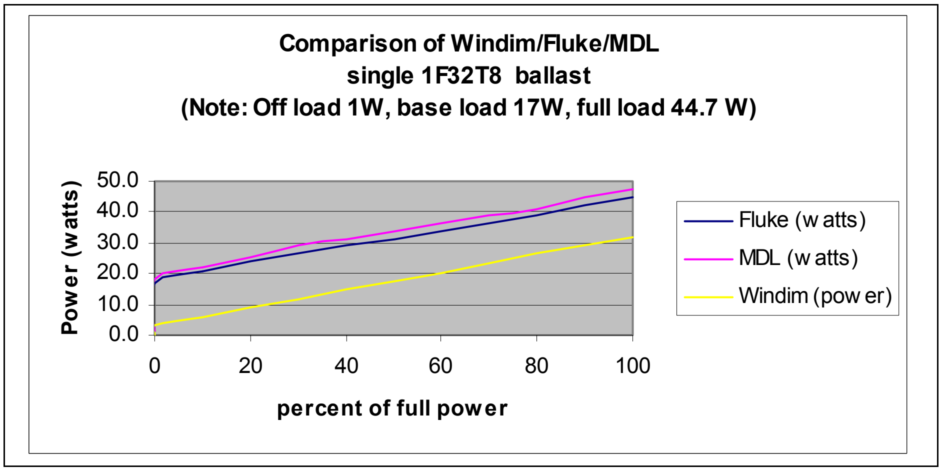
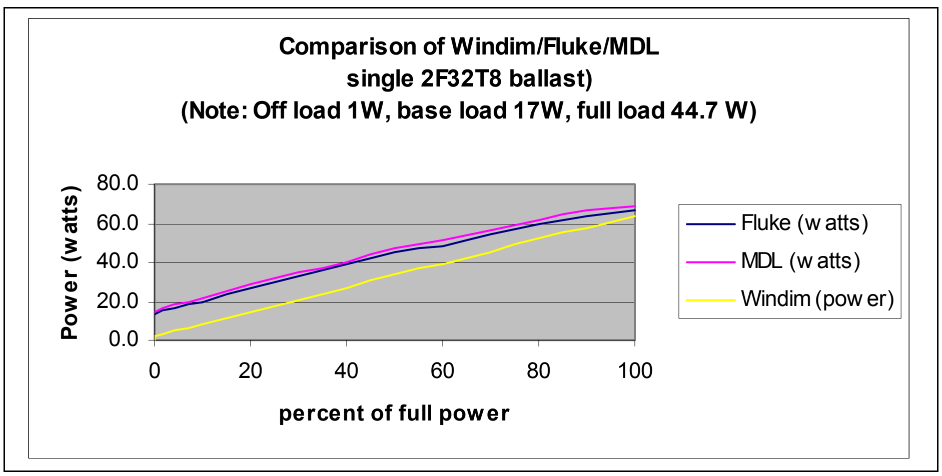


Figure 6D.3 shows the power consumed by a single 2L ballast in the demo setup. Note that the Fluke and the MDL track each other well and Windim substantially under predicts the power consumed.

FIGURE 6D.3



These data were forwarded to the Tridonic factory and it was then disclosed that the power curves for the ballasts in our demo system had not been developed yet. The data were collected using 'standard' i.e. theoretical power curves that were not related to actual performance. Some time later, Tridonic provided new power curves and the measurements were repeated using the same apparatus.

Software Results:

Figure 6D.4 shows the power consumed by all five ballasts in the demo setup. Note that all three track together over most of the range.

FIGURE 6D.4

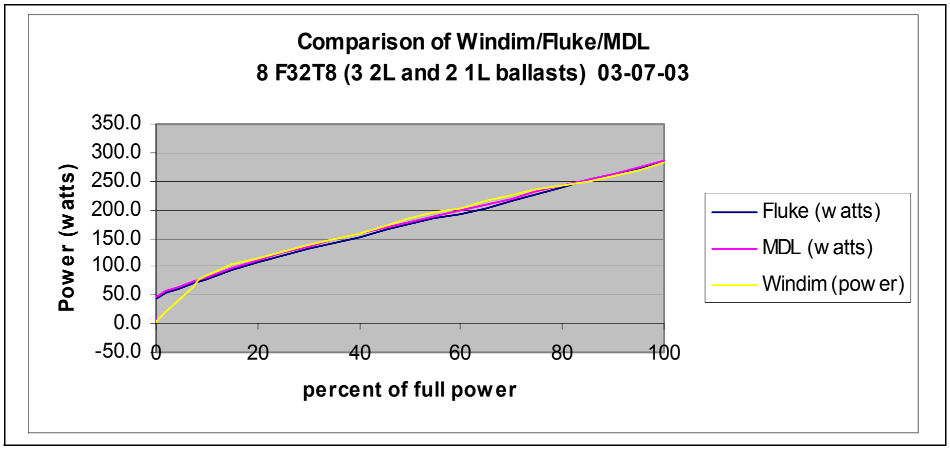


Figure 6D.5 shows the power consumed by a single 1L ballast in the demo setup. Note that there is still a discrepancy between the measured data and Windim.

FIGURE 6D.5

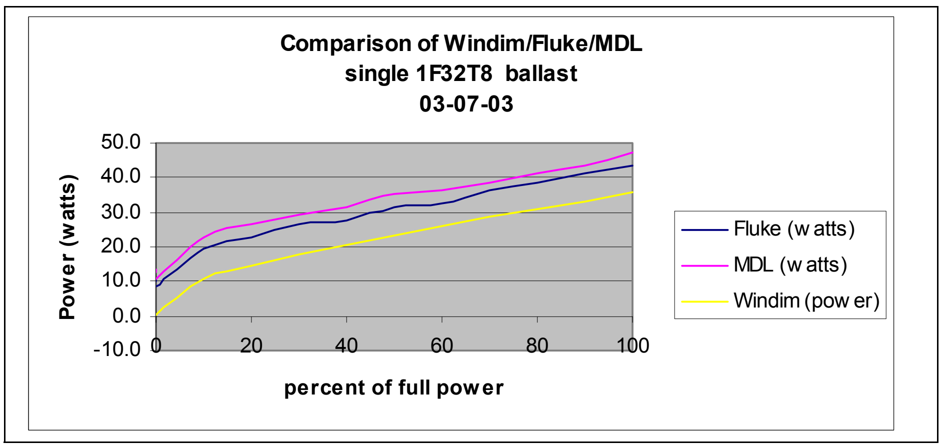
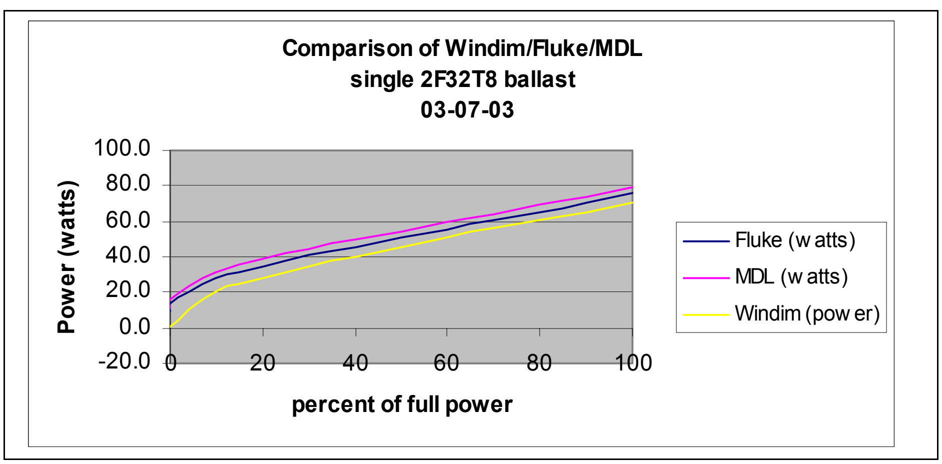


Figure 6D.6 shows the power consumed by a single 2L ballast in the demo setup. Note that there is still a discrepancy between the measured data and Windim.

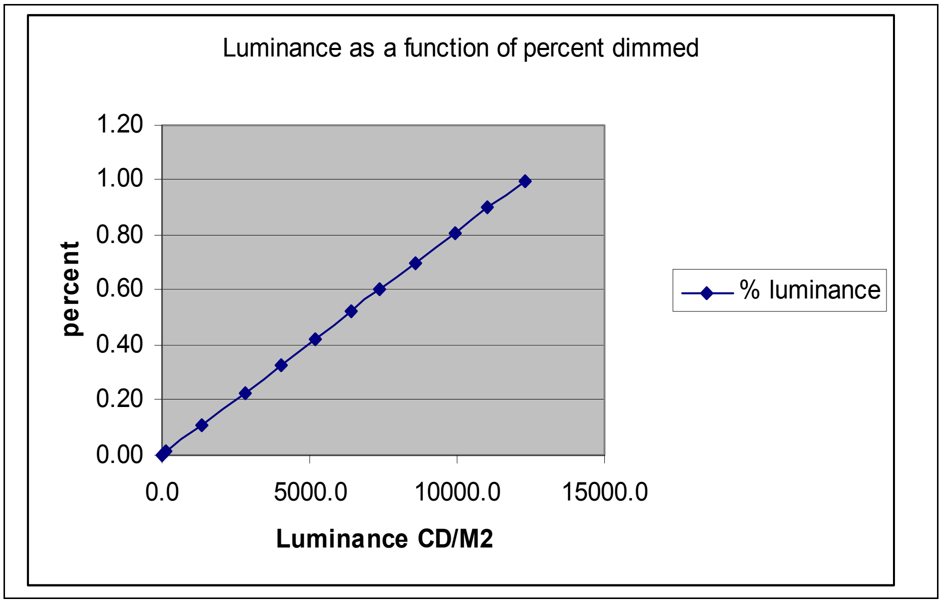
FIGURE 6D.6



Measurements were also taken of the luminance of the lamp at each dimmed level. Measurements were taken on the absolute center of the lamp (vertically and horizontally) using a Minolta Luminance meter on a tripod.

Figure 6D.7 shows the lamp luminance as a function of percent dimmed.
Note the linearity of the data.

FIGURE 6D.7



Conclusions:

The revised power curves appear to track well against measured data for aggregate quantities of ballasts. Isolating individual ballasts for independent measurement proved difficult. Even when off, the ballasts consume some extrapolating from our data, it's between 1 and 3 watts per ballast. Using Tridonic numbers, the value should be 0.5 W per ballast. Since the aggregate values were deemed to be accurate throughout most of the dimming range, the values from the Tridonic ballasts and the WimDim software were deemed adequate for evaluating power consumption in this study.

6.9 APPENDIX D.2: WINDIM CALIBRATION RAW DATA

<u>TABLE 6D.1</u>: Original Test Values

Full Board of 5 ballasts 3 2F32T8 and 2 1F32T8					**Old**
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)
0.05	0.05	0	6.0	6.0	0
0.38	0.41	0.1	45.9	49.6	13.8
0.65	0.68	10	78.6	82.2	40
0.89	0.92	20	107.6	111.2	66.3
1.1	1.14	30	133.0	137.8	92.4
1.28	1.31	40	154.8	158.4	116.8
1.47	1.51	50	177.7	182.6	145.3
1.61	1.65	60	194.6	199.5	168.5
1.79	1.82	70	216.4	220.0	196
1.95	1.98	80	235.8	239.4	222.5
2.1	2.13	90	253.9	257.5	246.5
2.3	2.32	100	278.1	280.5	273.3
Voltage	120.9				
1F32T8					
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)
0.01	0.01	0	1.2	1.2	0.0
0.14	0.15	0.1	16.9	18.1	3.3
0.17	0.18	10	20.6	21.8	6.1
0.2	0.21	20	24.2	25.4	9.0
0.22	0.24	30	26.6	29.0	11.9
0.24	0.26	40	29.0	31.4	14.7
0.26	0.28	50	31.4	33.9	17.8
0.28	0.3	60	33.9	36.3	20.4
0.3	0.32	70	36.3	38.7	23.4
0.32	0.34	80	38.7	41.1	26.4
0.35	0.37	90	42.3	44.7	29.0
0.37	0.39	100	44.7	47.2	32.0
Voltage	120.9				
2F32T8					
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)
0.01	0.01	0	1.2	1.2	0.0
0.11	0.12	0.1	13.3	14.5	2.3
0.16	0.18	10	19.3	21.8	8.4
0.22	0.24	20	26.6	29.0	14.6
0.27	0.29	30	32.6	35.1	20.9
0.32	0.33	40	38.7	39.9	26.7
0.37	0.39	50	44.7	47.2	33.5
0.4	0.42	60	48.4	50.8	39.0
0.45	0.47	70	54.4	56.8	45.6
0.49	0.51	80	59.2	61.7	51.9
0.53	0.55	90	64.1	66.5	57.6
0.55	0.57	100	66.5	68.9	64.0
Voltage	120.9				

TABLE 6D.2: Revised Software Results

Full Board of 5 ballasts 3 2F32T8 and 2 1F32T8							
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)	percent delta	
0.05	0.05	0	6.0	6.0	2.8	-54%	
0.37	0.4	0.1	44.7	48.4	2.8	-94%	
0.63	0.67	10	76.2	81.0	84.04	4%	
0.88	0.91	20	106.4	110.0	114.06	4%	
1.09	1.12	30	131.8	135.4	139.85	3%	
1.26	1.3	40	152.3	157.2	159.69	2%	
1.46	1.49	50	176.5	180.1	184.36	2%	
1.6	1.63	60	193.4	197.1	203.2	3%	
1.79	1.82	70	216.4	220.0	224.63	2%	
1.99	2.01	80	240.6	243.0	242.97	0%	
2.16	2.18	90	261.1	263.6	259.86	-1%	
2.35	2.37	100	284.1	286.5	283.2	-1%	
Voltage	120.9						
1F32T8							
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)	Luminance (cd/M2)	% luminance
0.09	0.11	0	10.9	13.3	0.5	0.69	0.00
0.07	0.09	0.1	8.5	10.9	0.5	137.2	0.01
0.16	0.19	10	19.3	23.0	10.8	1361.0	0.11
0.19	0.22	20	23.0	26.6	14.6	2863.0	0.23
0.22	0.24	30	26.6	29.0	17.9	4223.0	0.35
0.23	0.26	40	27.8	31.4	20.4	5390.0	0.44
0.26	0.29	50	31.4	35.1	23.5	6705.0	0.55
0.27	0.3	60	32.6	36.3	25.9	7739.0	0.63
0.3	0.32	70	36.3	38.7	28.6	8968.0	0.73
0.32	0.34	80	38.7	41.1	30.9	10020.0	0.82
0.34	0.36	90	41.1	43.5	33.0	11080.0	0.91
0.36	0.39	100	43.5	47.2	36.0	12240.0	1.00
Voltage	120.9						
2F32T8							
Fluke (amps)	MDL (amps)	Percent of full power	Fluke (watts)	MDL (watts)	Windim (power)	Luminance (cd/M2)	% luminance
0.08	0.1	0	9.7	12.1	0.6	0.0	0.00
0.11	0.13	0.1	13.3	15.7	0.6	137.5	0.01
0.23	0.26	10	27.8	31.4	20.8	1352.0	0.11
0.29	0.32	20	35.1	38.7	28.3	2789.0	0.23
0.34	0.37	30	41.1	44.7	34.7	4049.0	0.33
0.38	0.41	40	45.9	49.6	39.7	5163.0	0.42
0.42	0.45	50	50.8	54.4	45.8	6418.0	0.52
0.46	0.49	60	55.6	59.2	50.5	7397.0	0.60
0.5	0.53	70	60.5	64.1	55.8	8605.0	0.70
0.54	0.57	80	65.3	68.9	60.3	9947.0	0.81
0.58	0.61	90	70.1	73.7	64.6	11030.0	0.90
0.63	0.66	100	76.2	79.8	70.4	12280.0	1.00
Voltage	120.9						

6.10 APPENDIX E.1: ANALYSIS METHOD AND CALCULATIONS

The basis of light measurement and analysis when considering the spectral effects of scotopically enhanced lighting relies on the concept of equal visual efficiency when performing specific tasks. This Appendix provides the basic formulas and analysis methods used in this study.

6.10.1 Light Measurement Analysis

The basis of light measurement analysis when considering the spectral efficacy of scotopic content relies on the premise of equivalent visual effectiveness as expressed in the following equation:

$$\text{Equation (E1) : } VEE_{(source2)} = VEE_{(source\ 2)}$$

Visual effectiveness is based on the relationship of the scotopic to photopic content of the light source and the effect that the spectral composition has on the visual system for specific visual tasks. This relationship is described as:

$$\text{Equation (E2) : } E_{P(1)} \times (S/P)^{x}_{(1)} = E_{P(2)} \times (S/P)^{x}_{(2)}$$

The exponential factor "x" must be equal on both sides of this equation, and represents a derived relationship between photopic and scotopic visual response to a specific visual task or perceptual response. To date, exponential values have been derived for brightness perception, paper reading tasks, and self-illuminated tasks. All previously derived values were based on vertical illuminance measurements taken at the position of the viewing eye. The equation simplifies to the following form:

$$\text{Equation (E3): } \frac{E_{P(1)}}{E_{P(2)}} = \left(\frac{(S/P)_{(2)}}{(S/P)_{(1)}} \right)^{x}$$

and

$$\text{Equation (E4): } E_{P(2)} = \frac{E_{P(1)}}{\left(\frac{(S/P)_{(2)}}{(S/P)_{(1)}} \right)^{x}}$$

It is also noted that, given an identical lighting installation (lamp type, luminaire placement, luminaire photometric distribution, and identical space being illuminated), the above equations can be used to directly compare the Visually Efficient Lumens of lamps, i.e. substitution can be made using lumen values of lamps for E.

6.10.2 Calculation of Exponent "x":

The following equation is used to compare measured values of illuminance to previously determined exponents:

$$\text{Equation (E5): } x = \frac{\mathrm{Log}\left(\frac{E_{P(1)}}{E_{P(2)}} \right)}{\mathrm{Log}\left(\frac{(S/P)_{2}}{(S/P)_{1}} \right)}$$

6.10.3 Calculation Of Percent Light Reduction:

The general equation for percentage reduction in light level between light source 1 and light source 2 is:

Equation (E6): $$\% \text{ Light reduction} = \left(\frac{E_{(1)} - E_{(2)}}{E_{(1)}} \right) \times 100$$

For Visually Effective lighting analysis, Equation E4 can be used to derive the following equation:

Equation (E7): $$\% \text{ Light reduction} = \left\{ 1 - \left(\frac{(S/P)_{(2)}}{(S/P)_{(1)}} \right)^x \right\} \times 100$$

The above mathematical relationship isolates the S/P ratios of the two light sources and the exponent "x" as the only variables necessary for determining the percent of light level reduction for equal visual effectiveness for a given task. This relationship does not require the introduction of measured illuminance, rated lamp lumens, or lamp efficacies, and applies as long as all other design parameters are identical in the comparison.

6.10.4 Calculation Of Percent Power Reduction:

When comparing light sources for overall efficiency, lumens per watt are used. The general equation for percentage in power reduction between two sources is:

Equation (E8): $$\% \text{ power reduction} = \left\{ \frac{\dfrac{lm_{(1)}}{(lm/W)_{(1)}} - \dfrac{lm_{(2)}}{(lm/W)_{(2)}}}{\dfrac{lm_{(1)}}{(lm/W)_{(1)}}} \right\} \times 100$$

For Visually Effective lighting analysis, Equation E4 can be used by substituting lumens for illuminance. The resulting equation is:

Equation (E9): $$\% \text{ power reduction} = \left\{ 1 - \left(\frac{(S/P)_{(1)}}{(S/P)_{(2)}} \right)^x \left(\frac{(lm_P/W)_{(1)}}{(lm_P/W)_{(2)}} \right) \right\} \times 100$$

6.10.5 Statistical Testing of Results:

A statistical test was performed to test the validity of the light level resultant value range, comparing the 11th floor photopic measurements and the Design Method calculations to the measured values on the 10th floor. The statistical test was a contingency analysis using the means of the logs, and the test parameter of p=.05.

Test range of values:

Equation (E10): $$\log EPE_{VP(1)} - x \log \left(\frac{(S/P)_{(2)}}{(S/P)_{(1)}} \right)$$

Compared to range of values:

$$\log EPE_{VP(2)}$$

Values for x that were tested included .5, .78, and 1.0 (theoretical values) and .68, which was derived from the measured mean value of light level differences for E_{HP}. Refer to Section 3.2.2.3.