Spectrally Enhanced Lighting Program Implementation for Energy Savings:

Economics Validation Study

Prepared by
AfterImage + Space

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

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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:

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EXECUTIVE SUMMARY

The history of Spectrally Enhanced Lighting begins in the 1990's with the scientific discovery of previously unknown visual responses to lighting based on the spectral content of a light source. The principal findings are well-established and the associated energy savings potential in commercial buildings is significant, averaging 25% when compared to conventional lighting systems. In spite of the known benefits, Spectrally Enhanced Lighting has not been widely applied by the lighting community due to uncertainties about occupant acceptance of the lamp color and the lack of demonstrated economic benefit. This study addresses these concerns and concludes that retrofitting existing lighting systems with Spectrally Enhanced Lighting in office buildings is both cost effective and regarded equally to conventionally used lamps by building occupants.

This 3-building field study is an extension of the 2004 field study, "Energy Conservation Using Scotopically Enhanced Fluorescent Lighting in an Office Environment", dated March 2004. The 2004 study demonstrated that applying Spectrally Enhanced Lighting through the Visual Effectiveness Method achieved the predicted energy savings as well as occupant acceptance of Spectrally Enhanced lamps. Because the 2004 study was a proof-of-concept demonstration project, the lighting was only changed on 2 floors of a 10 floor building and dimming ballasts were used so that possible occupant concerns could be addressed using lighting controls. In the current study, the Visual Effectiveness Method is applied to fully retrofit three office buildings with Spectrally Enhanced Lighting and fixed output electronic ballasts. Pre- and post-retrofit lighting measurements are taken to validate the Visual Effectiveness calculations, and occupant satisfaction is determined through pre- and post retrofit online surveys of the building occupants. Power consumption of the overhead lighting system and task lighting usage are continuously monitored to determine the energy savings.

The measured energy savings associated with installing Spectrally Enhanced Lighting were between 19% and 27%, depending on the pre-existing lamp spectrum, and occupant satisfaction for the Spectrally Enhanced Lighting retrofits was maintained in all three buildings. The normalized economic analysis (using electricity costs typical for California) show that the installation costs for Spectrally Enhanced Lighting retrofits are no greater than non-Spectrally Enhanced Lighting retrofits, making the 19%-27% associated energy savings a no-cost added benefit when compared to non-SEL retrofit installations. For new construction, Spectrally Enhanced Lighting provides both initial cost reduction and long-term energy savings benefits. When comparing Spectrally Enhanced Lighting to otherwise equal lighting retrofit installations or lighting for new construction, therefore, Spectrally Enhanced Lighting provides an immediate economic benefit for the commercial office building sector.

For buildings that were not considering a lighting retrofit and still have T12 lamps, Spectrally Enhanced Lighting can provide a 1.4 year payback when considering the life-cycle annual savings associated with the SEL retrofit. A 3.5 year payback is obtainable for buildings with existing T8 lamps. A simple payback analysis that does not consider the benefits derived over the life of the system shows the payback periods to be 2.7 years when retrofitting pre-existing T12 lamps and magnetic ballasts, and 7.1 years for T8 lamp to T8 lamp retrofits with similar pre- and post-retrofit ballast technologies. Taken together, these results suggest that incentives may be required to produce changes in markets where either electricity costs remain lower than average or short-term perspectives drive retrofit decisions. However, where electricity costs are higher than average or longer-term (life-cycle) benefits drive retrofit decision-making, the economic case for using the Spectrally Enhanced Lighting method are firmly demonstrated by this study.

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1.0 INTRODUCTION

In 2004, the US Department of Energy initiated the Spectrally Enhanced Lighting Program – Implementation for Energy Savings (SELPIES) program. The SELPIES program has three principal elements; Economics Validation, Design Method Validation, and Lighting Equipment Standards. This report describes the findings of the Economics Validation portion of the SELPIES program, the major objective of which is to assess the cost effectiveness of retrofitting common office lighting systems with Spectrally Enhanced Lighting using fixed output electronic ballasts.

1.1. BACKGROUND

Conventional commercial interior lighting practice in the United States generally recommends lamps with Correlated Color Temperatures (CCT) of 3000K to 4100K. Spectrally Enhanced Lighting is a design method that capitalizes on naturally occurring gains in visual efficiency as a consequence of the spectral content of higher CCT light sources. These gains can be translated directly into improved energy efficiency by employing lamps with higher CCT and Color Rendering Index (CRI), such as the 5000K, 80-85 CRI (850) lamps utilized in this study. The 850 lamps are readily available from major lamp manufacturers without cost penalty.

A theoretical energy-savings potential of 25% through the use of Spectrally Enhanced Lighting was established during the 1990's with US Department of Energy supported studies. Empirically derived Visual Effectiveness formulas (See Appendix B) demonstrate how this method could provide significant energy savings on a national basis. The widespread implementation of Spectrally Enhanced Lighting, however, has been hindered by the lighting community's concern that the color appearance of the higher CCT lamps would not be acceptable in the workplace. This specific concern was addressed in a 2004 DOE-sponsored field study[1] which found equal acceptance of the 850 Spectrally Enhanced Lighting at 20% lower light levels when compared to a nearly identical space with the more commonly used 3500K, 85 CRI (835) lamps.

The greatest potential for widespread implementation of Spectrally Enhanced Lighting is in lighting retrofits, which is largely economics-driven. Spectrally Enhanced Lighting retrofits promise roughly the same level of energy savings as the highly popular1990's conversions from T12 lamps with magnetic ballasts to T8 lamps with electronic ballasts, and is theoretically just as easy to implement through standard lamp/ballast replacements. The present study evaluates the economics of retrofitting three typical office buildings with spectrally enhanced lamps and fixed output electronic ballasts.

The economics of these installations is considered a critical step toward implementation of Spectrally Enhanced Lighting. The resulting values of installed cost per square foot, lighting power densities, energy savings, payback, and rate of return on investment are the criteria for many energy-efficiency improvement projects, and are often used as benchmark criteria for reaching specific energy-savings objectives. Specifically, the economics of implementing the Spectrally Enhanced Lighting method will provide substantive information for federal, state and utility agencies interested in promoting energy-saving technologies.

1.2. STUDY OBJECTIVES

1.2.1. Primary Objective of this study

The primary objective of this study is to demonstrate both the cost effectiveness and energy savings resulting from retrofitting typical fluorescent office lighting systems with Spectrally Enhanced Lighting. Three buildings were retrofitted with the following tasks performed in each building to support the above objective.

1 AfterImage + Space, 2004; "Energy Conservation Using Scotopically Enhanced Fluorescent Lighting in an Office Environment"

- Pre- and post-retrofit light levels were measured to determine changes in the illuminance resulting from the Spectrally Enhanced Lighting system retrofit.
- The demand load and energy consumption by the overhead lighting systems were continuously monitored to measure the energy savings from the retrofits.
- Task lighting usage in office cubicles was monitored to determine if the lowered illumination levels under Spectrally Enhanced Lighting resulted in higher use of task lighting.
- The installed costs of the Spectrally Enhanced Lighting systems were provided by the contractors and these retrofits were evaluated using life-cycle cost-benefit analyses.

1.2.2. Secondary Objectives of this study

The secondary objective of the study is to further confirm related findings from previous studies, i.e.:

- Confirm occupant acceptance of Spectrally Enhanced Lighting at reduced illumination levels by comparing ratings of satisfaction with the lighting system between the pre- and post-retrofit lighting conditions.
- Confirm the use of Visual Effectiveness formulas for various lamps and fixed output ballast combinations as the means for determining resultant lighting levels and energy savings.

1.3. STUDY APPROACH

This study provides a common basis for economic comparison by virtue of retrofitting three buildings that have similar luminaire type and occupancy. The variables are therefore limited to the lamp/ballast combinations within the buildings (pre- and post-retrofit), which allow for a cross-referenced data set for comparison of results. Objective measurements of illuminance, overhead lighting power and task lighting usage, as well as subjective responses through occupant surveys are administered by an independent third party (Pacific Northwest National Laboratory, PNNL), and installation costs are provided by the retrofit contractors. Each building owner independently hired their own lighting retrofit contractor through their normal contracting mechanisms.

The three office buildings retrofitted in the study are all fully operational and are located in California. Each building contains a blend of private and open offices, the majority of which are located in interior (non-daylit) zones. The predominant luminaire type in all buildings is a 3-lamp recessed parabolic luminaire. New lamps and ballasts were provided by one of the three co-sponsoring manufacturers as an integrated system to each building. All of the products used in this project are cataloged products readily available to lighting installers throughout the United States.

The design approach for the retrofits includes the following guidelines:

- The method used to select the retrofit lamps and ballasts is the Visual Effectiveness Method described in Appendix B. This approach utilizes the photopic lumen ratings and S/P values[2] of the lamps, and the Ballast Factors (BF)[3] of the ballasts.
- Pre-retrofit lighting levels forms the baseline illumination for each building. Light levels are not arbitrarily reduced to save energy but specifically reduced according to the design retrofit solution that maintains the pre-retrofit Visual Effectiveness levels within each building.

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2 The quantity S/P is the ratio of scotopic to photopic output of a light source, as determined by the scotopic and photopic sensitivity functions, respectively. The S/P value is independent of light level and serves as the proxy for relative lamp bluishness. Lamps that have a higher CCT will have higher S/P values.

3 The ballast factor is the fractional factor applied to the rated lumens of a lamp when used in combination with the specific ballast being used, as compared to the rated lumen output of the same lamp being driven by a reference ballast whose ballast factor is 1.00.

- The correlated color temperature of all retrofit lamps is 5000K with color rendering index of 80-85, (850). The choice of the 850 retrofit lamp is based on the previously demonstrated acceptance of this lamp in office lighting applications under the conditions of designed reduced illuminance. All retrofit lamps are T8 lamps, with varying wattages based on maintaining the Visual Effectiveness in each building.
- Readily available fixed output electronic ballasts are used in each building for the lighting retrofits. The ballasts with specific ballast factors were chosen to match with the retrofit lamps to produce the calculated design total lumen output for the particular retrofit system.
- The retrofits are not limited to the office spaces, but include bathrooms, entryways, conference rooms, and circulation and support spaces.

This approach provides a comprehensive and practical approach to lighting retrofits using typical lighting retrofit installations. The study aims to provide a multi-layered approach using different lamp/ballast combinations while maintaining variety and redundancy by having three similar buildings retrofitted. The varieties of products demonstrate different ways of using the Visual Effectiveness formulas, while the redundancy provides a higher level of confidence in the energy analysis, economics, and occupant satisfaction ratings.

All three of the major lamp manufacturers lended support to this project through lamp and ballast donations. In two of the buildings, the retrofits utilized programmed start ballasts with lower-than-normal ballast factors to achieve the reduction in lumen outputs, and these installations occurred in buildings with pre-existing instant start ballasts. These installations required additional equipment and labor due to the change in wiring associated with changing from instant start to programmed start ballasts, which would normally have been avoided in an unrestricted retrofit application (as opposed to the experimental conditions of this study) by using retrofit instant start ballasts to maintain the existing wiring. To compensate for this factor, the cost inputs were normalized in the economic analysis using a method described in Appendix D. This allowed the buildings to be analytically compared to each other on the same basis and also be more representative of how such retrofits would actually be carried out in office buildings.

1.4. BENEFITS TO THE UNITED STATES ELECTRICITY CONSUMERS AND LIGHTING COMMUNITY

This study provides a comprehensive evaluation of Spectrally Enhanced Lighting as an energy-saving technique for retrofitting lighting systems. The principal benefit to United States electricity consumers is to have definitive and reliable results for evaluating the cost-effectiveness of retrofitting lighting systems using Spectrally Enhanced Lighting. The lighting community also benefits by having a set of full-scale lighting retrofits documented which successfully implement Spectrally Enhanced Lighting using standard lighting equipment. Government and utility companies benefit through the knowledge gained in this study that could be used to formulate energy-saving incentive programs. On a national basis the total energy savings potential is estimated at 0.84 Quads annually.

2.0 SELPIES ECONOMICS VALIDATION STUDY – PROTOCOL AND DESIGN PARAMETERS

This section describes the general protocol and schedule for the installations as well as the design parameters used for the lighting retrofits. For more detailed protocol that provides the step-by-step procedure, see Appendix A.

2.1. PROJECT BACKGROUND

2.1.1. Building Selection

AfterImage + Space, the principal investigator for the SELPIES Economics Validation Study, searched for three occupied office buildings to be retrofitted with Spectrally Enhanced Lighting. These buildings would be used as case studies to demonstrate the energy savings and cost effectiveness of simple lamp-ballast retrofits. The criteria for the buildings were as follows:

- Building Size: 50,000 – 100,000 square feet
- Building Occupancy: Minimum 100 full-time office employees
- Office Types: A mixture of open and private offices
- Predominant Luminaire Type: 3-lamp, 2′ x 4′ recessed 18 cell parabolic luminaires in acoustic tile ceilings
- Daylight Penetration: At least 2/3 of the offices must be in areas where daylight is not a major influence on the illumination.
- Several buildings were surveyed as candidates for the study. The three office buildings selected include one utility owned building, one civilian federal building, and one military federal building. All buildings are located in California.

2.2. PROJECT PROTOCOL

2.2.1. General:

2.2.1.1. *Protocol Design:*

- The protocol design was established by the principal investigator and reviewed by PNNL. The independent review by PNNL included a review by their subcontracted and recognized expert in lighting and human factors and also an internal review board to ensure that the design met guidelines for studies involving human subjects.
- The protocol design is structured to replicate, as close as possible, a typical lighting retrofit installation. The premise for the work is to ensure building owners that they can implement this method using standard methods without risk; therefore, contractors were free to use their standard methods and means of installation, and building owners used their established methods for communicating with their staff.
- The study remained as unobtrusive to building occupants as possible. Measurements and installation of monitoring equipment were performed during non-occupied hours. The installation of the lighting retrofits followed typical installation procedures in that all work was performed at night and cleaned up by the following morning. Occupant surveys were administered online, and were designed to take approximately 5 minutes to complete.
- Building occupants were informed that the lighting retrofits would take place, but were not informed that the color of the lamps would be changed as part of the retrofit. No information about the use of Spectrally Enhanced Lighting was provided to the occupants, although building management was fully informed. Persons with knowledge of the specific nature of the retrofits were not included in the occupant surveys.

2.2.1.2. *Retrofit Lighting Equipment Selection:*

- Initial building surveys were performed by the principal investigator to establish the retrofit lamp and ballast requirements. The selection of equipment used in the retrofits was done by first assessing the theoretical post-retrofit photopic lumen output desired using the Visual Effectiveness calculations (see Appendix B), and then conferring with the lamp and ballast manufacturers to decide on the actual equipment that would most closely produce the desired results.

2.2.1.3. *Contractor Selection*

- The building owners of the three selected buildings were required to engage the services of lighting retrofit contractors to install the systems that were specified by the principal investigator. The contracting procedure varied with the building owners, resulting in slightly different start points in the calendar year for one of the buildings.
- The retrofit contractors were selected at large. In Building A, the building owner used a contractor with whom they had an existing contract, Building B used a public bid process, and Building C used the local utility to serve as the primary contractor, under which a lighting retrofit company was subcontracted.

2.2.1.4. *Monitoring and Measurement*

- PNNL was retained by the DOE under a separate contract to monitor the lighting levels, power consumption of the overhead lighting systems, task lighting usage, and occupant surveys. The specific guidelines for the measurement techniques were established in meetings between AI+S and PNNL prior to any of the installations. The findings of the PNNL measurements and monitoring are summarized in this report. For a detailed report on the procedures and findings, see document PNNL-15784.

2.2.1.5. *Retrofit Contractor Scope of Work:*

- The following summarizes the Scope of Work performed in each of the three buildings:
    1. The overhead lighting systems with 4' fluorescent lamps in all spaces throughout the building were retrofitted to 850 T8 fluorescent lamps.
    2. Lighting modifications to the overhead lighting systems in offices consisted of retrofitting luminaires with new lamps and ballasts without affecting the optical systems of the fixtures; no luminaires were replaced, removed, relocated, de-lamped or optically altered.
    3. Task lighting in the office work areas were also retrofitted to 850 lamps, however, the ballasts for the task lighting were not changed.
    4. In the rare case where unusual or incidental lamps (i.e. not 4' T8 lamps) were encountered and no equivalent 850 lamps were available, 841 lamps were used (the cases where this occurred were in non-office spaces within the building) .
    5. No modifications were made to the lighting control system.

2.2.2. Schedule:

2.2.2.1. *Timeline:*

- Each retrofit contractor followed a similar construction schedule to ensure that the timing between installations and occupant surveys and lighting measurements was consistent for the three buildings. The following schedule describes the general procedure followed for all buildings; however, slight variations in timing and/or process were necessary due to site conditions[4].

4 For more information on the schedules for each building, refer to PNNL report No. PNNL 15784, "Field Evaluation of the Spectrally Enhanced Lighting Program: Implementation for Energy Savings (SELPIES)", April 18, 2006

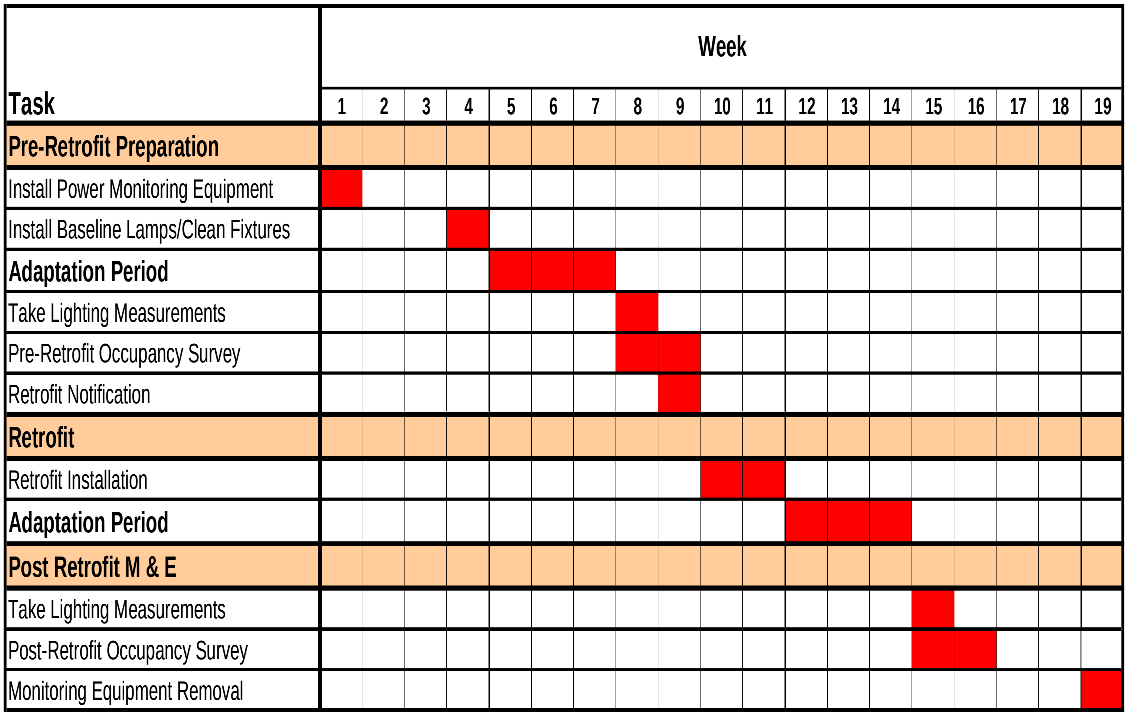

Figure 2-1: Protocol Schedule used in Lighting Retrofits

2.2.2.2. *Project Schedule Highlights:*

- PNNL installed the monitoring equipment three weeks prior to the beginning of the protocol to ensure proper operation of the equipment.
- The baseline lamp installation included replacing all existing lamps with new lamps of the same type that existed in the building. This ensured that all pre-retrofit lamps were of the same color and age, which is necessary for proper comparison with the 850 lamp retrofit installation.
- The period between the baseline lamp installation and the Spectrally Enhanced Lighting retrofit were identical to the post-retrofit schedule whereby occupants were allowed a 3-week adaptation period prior to being given an online occupant survey to assess their satisfaction with the lighting system. Building occupants had 2 weeks to respond to both the pre-retrofit and post-retrofit survey.
- The overhead lighting system power and task lighting usage were monitored throughout the study.
- Pre- and post-retrofit lighting measurements were taken during the period when the occupant survey was being administered.

2.3. DESCRIPTION OF PROJECT SITES & LIGHTING SYSTEMS

2.3.1. Overview of Buildings: Pre-retrofit Lighting Conditions

2.3.1.1. *Overview*

The following table provides relevant information on the buildings used in the study and includes their pre-retrofit lighting systems:

Table 2-1:Overview of Buildings and Pre-retrofit Lighting Systems

	Building A	Building B	Building C
BUILDING DESCRIPTION			
Location	Santa Rosa, CA	Vallejo, CA	Oxnard, CA
Area (sq. ft.)	57,000	119,000	67,000
No. of full-time employees	179	279	209
Open office area cubicles	140	260	176
Private offices	39	19	33
Average ceiling height	11'-0"	9'-6"	9'-0"
PRE-RETROFIT LIGHTING SYSTEM			
Predominant Luminaire	Recessed 18 cell 3-lamp parabolic	Recessed 18 cell 3-lamp parabolic	Recessed 18 cell 3-lamp parabolic
Existing Lamp Type	F34 T12	F32 T8	F32 T8
Existing Lamp Color	735	730	741
Existing Ballast Type	Magnetic Energy Savings, circa 1986	Electronic Instant Start, circa 1999	Electronic Instant Start, circa 1997

- Notes on Table 2-1:

1. The predominant luminaire type in all three buildings was a three-lamp, 18 cell parabolic luminaire installed in acoustic tile ceilings, which provides a stable reference for comparison in the economics of installing new lamps and ballasts as a retrofit strategy (all luminaires are similar and undergo the same lamp/ballast change-out only, with no reflectors).
2. Building A had T12 lamps and magnetic ballasts, while Buildings B and C had T8 lamps with electronic ballasts. The differences in lamp and ballast technologies allow this study to analyze the economics of both T12 and T8 retrofits.
3. The baseline fluorescent lamps in each of the buildings had different Correlated Color Temperatures (CCT's) from each other. The variation in lamp color characteristics allows this study to analyze the use of the Visual Effectiveness formulas using the various S/P values of different lamps within the buildings. Of particular interest is Building B, where the change from the pre-retrofit condition of 730 lamps to 850 lamps has not previously been tested, and would possibly be a more difficult transition for the employees due to the more significant shift in color appearance.

2.3.2. Lighting System Retrofit Designs

2.3.2.1. *General Considerations:*

- The premise for designing the lighting retrofits is to maintain the same level of Visual Effective Illuminance (VEE) for the task of reading of paper or hardcopy. The general formula chosen for this is based on maintaining equal Visual Effectiveness for the reading of printed material and is determined by equality of the factor $P(S/P)^{.78}$, where P is the relevant photopic quantity (See Appendix B). Because the luminaire distribution, locations, and quantities remain unchanged, the photopic lamp lumen values will translate proportionally to illuminance values; photopic lamp lumens are therefore used in these equations.
- The total post-retrofit photopic lumen output is determined by the product of the rated lumens of the post-retrofit lamp multiplied by the ballast factor of the post-retrofit ballast. The choice of post-retrofit rated lamp lumens and ballast factors can be traded off to achieve the desired total lumen output. Different combinations of lamp-ballast pairs were chosen for the 3 test buildings to achieve 3 different perspectives.
- The equipment selected was based on optimized total lumen output to match the Visual Effectiveness formulas and did not consider the exact nature of the pre-existing internal wiring of the luminaires. This was done to achieve the stated purpose and to exclude any bias toward an economic advantage. It is noted here however, that the pre-existing internal wiring of the luminaires plays a very important role in the economics of retrofitting lighting systems and should be considered at the earliest stages of retrofit design.

2.3.2.2. *Data and Calculations: Selection of Lighting Retrofit Systems*

The following table provides the input data and resultant calculated values used for predicting the change in photopic illuminance between pre and post retrofit. Lamp, ballast, and S/P values were provided by the manufacturers, which are the bases of the predicted retrofit values in Table 2-2:

Table 2-2: Pre-retrofit Lighting Systems and Calculated Changes in Illumination Levels (for the retrofit) Based on Visual Effectiveness Calculations

	Building A	Building B	Building C
PRE-RETROFIT LAMPS AND BALLASTS			
Lamp	F34T12/SPEC35/RS/EW	F32T8/SP30/ECO	FO32/741/ECO
Nominal Lamp Wattage	34	32	32
Lamp Color	735	730	741
Rated Photopic Lumens (P)	2800	2800	2800
Ballast Factor (BF)	0.88	0.88	0.88
Lumen Output (P x BF)	2464	2464	2464
S/P Ratio	1.32	1.30	1.56
Visually Effective Lumens (P x BF) x (S/P).78	3060	3024	3486
POST-RETROFIT LAMPS AND BALLASTS			
Lamp	F32T8/ADV850/XEW	F32T8/XL/SPX50/HLEC	FO30/850XP/SS/ECO
Nominal Lamp Wattage	25	32	30
Lamp Color	850	850	850
Rated Photopic Lumens (P)	2400	3000	2800
Ballast Factor (BF)	0.77	0.60	0.71
Lumen Output (P x BF)	1848	1800	1988
S/P Ratio	1.87	2.00	1.85
Visually Effective Lumens $(P \times BF) \times (S/P)^{.78}$	3011	3091	3212
PREDICTED CHANGES IN LIGHT LEVELS			
Target Light Level Reduction **(Equation B-2)**	24%	29%	12%
Predicted Increase in S/P Ratio	***0.55***	***0.70***	***0.29***
Predicted Change In Photopic Lumens (Post - Retrofit - Pre-Retrofit Values)	***-25.0%***	***-26.9%***	***-19.3%***
Predicted Change in Visual Effectiveness (Post - Retrofit - Pre-Retrofit Values)	***-1.6%***	***2.2%***	***-7.8%***

- Notes on Table 2-2:
  1. The calculations show that the predicted Visual Effectiveness obtained with the available lamp/ballast combinations is within 8% of the pre-retrofit conditions in all cases. This spread is within the confidence levels obtained in the empirical determination of visual effectiveness. The exponent in the Visual Effectiveness formula has a standard error of 0.03 and the differences are all within 2 standard errors of the exponent.
  2. The calculations are not dependent on the pre-retrofit lighting level. The premise of the study was to maintain the same level of Visual Effectiveness as the pre-retrofit condition, whatever value that might have been.

3. The selection of lamp/ballast combinations are all predicated on the color of the pre-retrofit lamps. The largest reduction in post retrofit photopic illuminance based on the Visual Effectiveness Calculations are with 730 baseline lamp (Building B), which has the lowest S/P value, while the highest baseline S/P value lamp (741, Building C) shows the smallest predicted change in photopic illuminance.
4. Building A's baseline 735 T12 lamp and Building B's baseline 730 T8 lamp have unexpectedly similar S/P values (within .02 of each other, according to manufacturer data). This may be a function of differences in T12/T8 technologies, manufacturer phosphor mixes, or differences in manufacturer tolerances in S/P value measurements.
5. The published value for the particular 850 lamp in Building B (2.0) is significantly higher than that of Building A (1.87) or Building C (1.85).

- The systems used in the lighting retrofits to achieve the equal visual effectiveness described in the Table 2-2 are different for each of the three buildings:
  1. Building A: 25 Watt, low-wattage T8 lamps and normal low ballast factor ballasts (BF=.77). This system utilizes the lowest wattage T8 lamp currently available on the market in combination with high-efficiency instant start electronic ballasts that have a commonly used ballast factor of .77.
  2. Building B: "Super" 32 watt T8 lamp and very low ballast factor ballasts (BF=.60). This system uses the extra-efficient, high-lumen version of the more commonly used 32 Watt T8 lamp (as compared to a reduced-wattage lamp) and reduces energy and photopic light output through the use of a recently developed ultra-low ballast factor programmed start ballast.
  3. Building C: 30 Watt, slightly lower than regular wattage T8 lamps and slightly lower than regular low ballast factor ballasts (BF=.71). The approach used here is between that of Building A and Building B, avoiding extra-low wattage lamps or extra-low ballast factor ballasts. Instead, this system uses a more common reduced-wattage lamp and a programmed start ballast with slightly lower than usual low ballast factor.

2.3.2.3. *Data and Calculations: Predicted Energy Savings*

- Table 2-2 provides a calculation for light level reduction based on equal Visual Effectiveness. Under the conditions of using identical ballast technologies, as might be done in an analysis for new construction, the predicted reductions in photopic light levels could translate directly to predicted energy savings.
- For lighting retrofits, the energy savings calculations must be predicated on the pre- and post-retrofit ballast technologies matched with the specific lamps being driven by the ballasts. Table 2-3 below shows the data and calculated values used for predicting the energy savings and Lighting Power Densities of the proposed lighting retrofits. The data in the Table were provided by the manufacturers for each specific post-retrofit lamp/ballast combination, and pre-retrofit system values were taken from manufacturer catalogs and nameplates from pre-existing ballasts.

Table 2-3: Lighting Retrofit Predicted Energy Savings

	Building A	Building B	Building C
Average Fixture density (sq. ft. per luminaire)	78	89	71
PRE-RETROFIT LIGHTING ENERGY CALCULATIONS			
Lamp	F34T12/SPEC35/RS/EW	F32T8/SP30/ECO	FO32/741/ECO
Nominal Lamp Wattage	34	32	32
Ballast	Magnetic R.S.	Electronic I.S.	Electronic I.S.
Ballast Configuration	(1) 2-lamp and (1) 1-lamp ballast per luminaire	(1) 4-lamp and (1) 2-lamp ballast per pair of luminaires	(1) 4-lamp and (1) 2-lamp ballast per pair of luminaires
Ballast Wattages	2-lamp = 72 1-lamp = 43	4-lamp = 114 2-lamp = 59	4-lamp = 112 2-lamp = 58
Wattage per Luminaire	115	86.5	85
Lighting Power Density (Watts/sq. ft.)	1.47	0.97	1.20
POST-RETROFIT LIGHTING ENERGY CALCULATIONS			
Lamp	F32T8/ADV850/XEW	F32T8/XL/SPX50/HLEC	FO30/850XP/SS/ECO
Nominal Lamp Wattage	25	32	30
Ballast Manufacturer	Advance Optanium	GE Lighting Ultrastart	Sylvania PSX
Ballast Technology	Electronic Instant Start	Electronic Programmed Start	Electronic Programmed Start
Ballast Configuration	(1) 3-lamp ballast per luminaire	(3) 2-lamp ballasts per pair of luminaires	(3) 2-lamp ballasts per pair of luminaires
Ballast Wattages	3-lamp = 56	2-lamp = 44	2-lamp = 43
Ballast per Luminaire	1	1.5	1.5
Wattage per Luminaire	57	66	64.5
Lighting Power Density (Watts/sq. ft.)	0.73	0.74	0.91
PREDICTED ENERGY SAVINGS			
Predicted Percentage Reduction in Energy	**50%**	**24%**	**24%**

- Notes on Table 2-3:
  1. Building A, with pre-retrofit T12 lamps and magnetic ballasts, shows a predicted 50% energy savings.
  2. Buildings B and C, with pre-retrofit T8 lamps and electronic ballasts, show a predicted 24% energy savings.

2.3.2.4. *Percentage Contributions to Predicted Energy Savings from Spectrally Enhanced Lighting vs. Lamp/Ballast Technologies*

- If the lamp/ballast combinations had equal ballast efficiencies, the Visual Effectiveness Calculations for photopic light level reductions would also predict the energy savings. In specific retrofit scenarios, however, the pre- and post-retrofit ballasts have differing ballast characteristics. It is therefore of interest to analyze the percentage of predicted energy savings derived from the spectral properties of the lamps as compared to the lamp/ballast system efficiency, as rated by the photopic properties of the lamps:

Table 2-4: Energy Savings Calculations: Percentage Energy Savings Derived from Spectrally Enhanced Lighting Compared to Ballast Efficiency

	Building A	Building B	Building C
ENERGY SAVINGS FROM SEL COMPARED TO BALLAST EFFICIENCY			
Total Predicted Energy Savings (Table 2-3)	***50%***	***24%***	***24%***
Predicted Energy Savings Attibutable to SEL (Based on Photopic Lumens (Table 2-2)	*25%*	*27%*	*19%*
Predicted Energy Savings Attibutable to Ballast Technology Change	*25%*	*-3%*	*5%*

- Notes on Table 2-4:

1. Building A: There is an equal contribution to energy savings from the Spectrally Enhanced Lighting to the change in ballast technology. This demonstrates that the Spectrally Enhanced Lighting benefit, when changing from 735 lamps to 850 lamps, is predicted to be equivalent to the change from T12/magnetic ballasts to T8/electronic ballasts.
2. Building B: The pre-retrofit electronic instant start ballasts in Building B were installed in 1999, and are therefore already energy efficient. The new ballasts are programmed start, and have an extremely low ballast factor. For these reasons, the actual efficiency of the ballast system is not as high as the pre-retrofit system, however, the reduction in overall power consumption is still predicted to be 24% due to the reduction in lighting allowed under the Visual Effectiveness calculations.
3. Building C: The pre-retrofit electronic instant start ballasts were installed in 1997 and are 5% less efficient than the newly installed programmed start ballasts. The calculations predict that 80% of the energy savings will come from Spectrally Enhanced Lighting and 20% will come from increases in ballast efficiency.

2.4. STUDY IMPLEMENTATION

All three buildings started and completed the process of following the protocol in late summer/early fall of 2005. Building A was the first to start the process, followed by the concurrent installations in Buildings B and C. Building owner representatives complied with the design teams' request not to inform building occupants about the nature of Spectrally Enhanced Lighting to avoid potential bias. In addition, the principal investigator and monitoring team were kept appraised of any issues related to product or contractor performance, occupant questions, and unsolicited responses from occupants and visitors to their facilities regarding the lighting installations. The projects, once initiated, went generally as expected without interruption.

3.0 RESULTS OF SELPIES ECONOMICS VALIDATION STUDY

This Section summarizes the results of this study and is divided into two parts. The first part includes the results of the independent monitoring performed by PNNL and analysis of these findings by the principal investigator, details of which are in Appendix C. Part 2 includes a detailed discussion of the economic analysis, the details of which are in Appendix D.

3.1. FINDINGS BY PNNL

This section summarizes the PNNL findings, compares them with the predictive calculations in Section 2, and uses these results in the Economics Evaluation in Section 3.2.

3.1.1. Summary of Results

3.1.1.1. *Lighting Measurements:*

- The Illuminance measurements taken by PNNL were used to assess how close the predicted lighting measurements in Section 2 were to actual measurements, and to examine if correlations exist between light level measurements and the other measures of overhead lighting power, task lighting usage, and occupant satisfaction. The following summarizes the findings:

  1. Building A: All lighting measurements were consistent with predicted illuminance and S/P values. Thus the general expectation is no change in task lighting use or occupant satisfaction.
  2. Building B: The measured horizontal photopic illuminance was consistent with the predicted illuminance reduction. However, the measured S/P value was more than 0.10 lower than the manufacturer data used in the predictive calculations. The measured lower S/P value significantly affected the actual post-retrofit horizontal Visual Effective illuminance values, which became10 percentage points below prediction. Thus there is the possibility of increased use in task lighting to compensate for the lowered Visual Effectiveness in Building B.
  3. Building C: All horizontal lighting measurements are consistent with predicted illuminance and S/P ratios. However, there remains an anomaly in the vertical photopic illuminance measurements that result in increases from the predicted Vertical VEE. While the horizontal measured photopic illuminance was reduced 15% (close to the 19% predicted reduction), the measured vertical photopic illuminance was reduced by only 9%. This measurement is not readily explainable; however, the likely outcome of this would be no change in occupant satisfaction, and possibly a decrease in the use of task lighting due to a possible advantage in having higher levels of visual acuity.

3.1.1.2. *Overhead Lighting Power and Energy Measurements*

- The post-retrofit measured connected loads for the three buildings were within 5% of the predicted loads. The measured loads of lighting circuits indicated a consistent shift towards higher power consumption than manufacturer listings (3.6% to 4.8%). The manufacturers have suggested that the differences between catalog values and field conditions may be due to differences in voltage and/or temperature.
- Lighting Power Densities are determined from the luminaire spacing and lamp/ballast system efficiencies. The highest LPD is found in Building C (.91 w/sq.ft.), which had the highest density of luminaires per square foot and programmed start ballasts. The other two systems, which are more representative of common parabolic luminaire spacings in office buildings, resulted in .79 Watts per square foot, a value 21% below the current ASHRAE 90.1 Standard.

3.1.1.3. *Task Lighting Usage*

- There was no statistically significant difference between pre- and post-retrofit task lighting usage in any of the buildings. This finding from the monitored task lighting usage provides significant evidence that properly applied Spectrally Enhanced 850 lamp can be used at reduced photopic illumination levels in office work environments without risk of increasing task lighting use.
- Further analysis of the data across all 3 buildings shows a potentially significant correlation between task lighting usage and the Visually Effective Illuminance metrics (VEE). Furthermore the same analysis shows no correlation between task lighting usage and photopic illuminance measurements. Specifically, the lowered Visual Effectiveness illumination levels in Building B resulting from lower than expected S/P values showed the only increase in task lighting usage, whereas the buildings that maintained their levels of Visually Effective illuminance had slight decreases in task lighting usage. While the shifts in task lighting usage within each building were not statistically significant, the correlations of task lighting usage resulting from varying Visual Effectiveness measurements has high statistical strength, as it considers 3 unrelated buildings under two conditions in each building (See Appendix C). The correlation between task lighting usage and Visual Effectiveness illumination measurements provides evidence that people make decisions on lighting based on the principals of the Visual Effectiveness Method rather than on photopic measurements alone.

3.1.1.4. *Occupant Ratings of Satisfaction with the Lighting*

- The findings from the Occupant Ratings of Satisfaction with the Lighting survey provide significant evidence that spectrally enhanced 850 lamps can be used at reduced photopic illumination levels in office work environments without risk of decreasing occupant satisfaction. This demonstrates that the color appearance of 850 lamps is just as acceptable to other more commonly used fluorescent tri-phosphor lamps when used under the conditions of equal Visual Effectiveness.

3.1.2. Conclusions Derived from PNNL Measurements and Evaluation

- The conclusions from the independent monitoring and evaluation are consistent with the Visual Effectiveness Method as it predicts light levels, energy savings, task lighting usage and occupant satisfaction.
- The PNNL findings validate previous studies on occupant acceptance of the 850 lamps in office lighting applications and demonstrate that Spectrally Enhanced Lighting can be used without risk of occupant rejection under the conditions of reduced illumination levels that were based on Visual Effectiveness calculations.

3.2. ECONOMIC ANALYSIS

3.2.1. Introduction

- The analysis employed in the current study calculates the economics of changing lamps and ballasts from the pre-retrofit condition to the Spectrally Enhanced Lighting installation. Large areas of open and private offices were included in the study so that the analysis included a representative portion of the building. The number and types of luminaires within the area of study were counted along with their associated cost of materials and labor for the retrofit installation that were provided by the installing contractor. This analysis limits the actual cost of the retrofit under study without including additional costs incurred by the project, such as the task lighting and other luminaire changes from which there was no energy benefit.

- The economic analysis used in this study follows the recommendations for Life Cycle Cost Benefit Analysis (LCCBA) found in the Illuminating Engineering Society of North America Handbook, Chapter 25. The analysis includes benefits derived from lighting maintenance improvements, primarily derived from increases in lamp life. The analysis does not factor in reductions in air conditioning load and uses average blended commercial electric utility rates in California.
- Costs are normalized to ensure that the three buildings are compared on the same basis. The normalization of material costs, labor costs, energy rates, annual hours of operation, projected system life, the cost of money etc. are described in the detailed analysis in <u>Appendix D</u>.

3.2.2. Factors Affecting Economic Analyses

3.2.2.1. *Installation Factors for each Building*

- Each building had a unique set of circumstances that required some additional level of attention by the installing contractor. While the building lighting equipment surveys were performed by each of the contractors, the actual conditions of the site required modification to the original designed system in either wiring technique or types/numbers of ballasts. These unique conditions are described below.
- Building A:

  1. The Pre-retrofit conditions of Building A were 1986 era recessed parabolic luminaires with T12 lamps and magnetic ballasts that had never been retrofitted since the original installation. The 11'-0" ceiling height allowed for changing the pre-retrofit inboard/outboard switching to alternating "checkerboard" switching in the open office areas, which made it possible for the contractor to use single 3-lamp ballasts in each luminaire.
  2. In the private offices, the inboard/outboard switching was maintained using (1) 2-lamp and (1) 1-lamp ballast per luminaire (this was more cost-effective than trying to install new wiring "whips", and there were proportionally fewer private offices).
  3. Factors that increased pricing included the higher-than normal 11'-0" ceiling and the labor time for retrofitting the luminaires themselves. The contractor informed us that the ballasts were unusually difficult to change due to a somewhat complicated and antiquated ballast channel design. This complication added approximately 10 minutes of man-hour labor to each luminaire that was retrofitted.
  4. The technology change from rapid start T12 to instant start electronic ballasts is common and was not considered a factor in this installation.

- Building B:

  1. The Pre-retrofit conditions of Building B included 1999 era instant start electronic ballasts and T8 lamps. Most luminaires were inboard/outboard switched using a 4+2 configuration (for every pair of luminaires, the outboard lamps were controlled by a 4-lamp ballast while the inboard lamps were controlled by a 2-lamp ballast). Luminaires that did not come as a pair contained single 3-lamp ballasts..
  2. The pre-retrofit ballasts were 1999 era electronic instant start ballasts. The luminaires had shunted lamp sockets, which is typical for instant start ballasted luminaires. The new ballasts are programmed start ballasts, which necessitated installing new sockets and more wires than the pre-retrofit system had between luminaires. This necessitated the purchase and installation of new wiring "whips" between luminaires, which added significant materials and labor costs to the installation of the retrofit.

3. Building occupants provided several comments on the pre-existing occupancy sensors that control most of the lighting in the building. These were not addressed in the retrofit, however, it is likely that the extended life obtained through the use of the programmed start ballasts may have more of a positive impact than is accounted for in the economic analysis.

- Building C:

1. The Pre-retrofit conditions of Building C were similar to Building B. The pre-retrofit system included 1997 era instant start electronic ballasts wired inboard/outboard with a 4+2 ballast configuration.
2. In some areas of the retrofit, the installing contractor repaired problems in switching that were caused by the 1997 retrofit contractor, which added some cost to the project.
3. The ballast retrofit changed the instant start ballasts to programmed start ballasts, which necessitated installing new lamp sockets and using more wires than the pre-retrofit system had between luminaires. These factors significantly affected the economics of this retrofit, both in materials and labor costs.

- Summary:

1. The installation in Building A is representative of common lighting retrofits in the lighting industry and can be used as a fair gauge for analysis.
2. The lighting retrofits in Buildings B and C included unforeseen additional costs due to the selection of the programmed start ballasts as replacements for the instant start ballasts. These costs have been normalized in the economics analysis, as described in Appendix D.

3.2.3. Lighting Retrofit Analysis

3.2.3.1. *Scope of Study:*

- Each building was analyzed to define the area used to assess the economics of the lighting retrofits. The areas chosen for the study included combinations of open and private offices and circulation areas within the office areas building to ensure that the cost and energy savings impact was properly proportioned and representative of the building. The areas did not include bathrooms, storage rooms, support spaces and other spaces that did not have the fluorescent retrofits specific to this study installed.
- The installing contractors provided installed costs and component costs on a per luminaire basis. The numbers of luminaires within the areas under study were counted and the energy analysis was performed on a Watts per Luminaire basis. Having the total watts and the area in which the luminaires are installed as basic metrics, the analysis conclusions are presented in the format of cost per Luminaire, cost per square foot, and Lighting Power Density (LPD, Watts per sq. ft.). The "per unit" and "per square foot" method enables easily transferable information to building owners, utilities, and governmental agencies.

3.2.3.2. *Analysis Summary*

- The Following Table summarizes the Retrofit Lighting Analysis:

Table 3-1: Lighting Retrofit Analysis

Lighting Retrofit Economics	**Building A**	**Building B**	**Building C**
SUMMARY OF ECONOMIC ANALYSIS			
Total Installed cost for the area	$25,210	$56,049	$32,354
Annual Savings from Retrofit	$17,921	$15,557	$9,276
Payback Including Life-Cycle Annual Savings	1.41	3.60	3.49
Rate of Return	71%	28%	29%

Notes on Table 3-1:

1. The payback including life-cycle annual savings for changing from T12 lamps with magnetic ballasts to spectrally enhanced T8 with electronic ballasts is 1.4 years.
2. The payback including life-cycle annual savings for changing existing T8 lamps and electronic ballasts to new spectrally enhanced T8 lamps with electronic ballasts is approximately 3.5 years. This analysis presumes that the retrofit uses the same electronic ballast technology as in the existing installation, i.e. existing instant start ballasts are replaced with new instant start ballasts.

- The normalization process in Appendix D demonstrates highly consistent results between the three buildings: the installation costs per luminaire range from approximately $59.00 to $68.00, with the largest factor being that of the labor rate charged for installation. The material costs per luminaire ranged between $26 and $32 per luminaire.

4.0 DISCUSSION & ADDITIONAL FINDINGS OF THE SELPIES STUDY

4.1. CONCLUSIONS OF SELPIES ECONOMICS VALIDATION STUDY

4.1.1. Primary Objectives - Conclusions

4.1.1.1. *Cost-Effectiveness of Spectrally Enhanced Lighting Retrofits*

- The energy savings of Spectrally Enhanced Lighting range from 19 to 27%, depending on the spectral characteristics of the pre-retrofit lighting. These energy savings represent a no-cost benefit for new construction and in comparison to non-SEL lighting retrofits that are otherwise equal in their design.
- When compared to the no-action alternative, i.e. the base case is leave the building as it is, the resulting payback including life-cycle annual savings for Spectrally Enhanced Lighting retrofits (using California energy costs) are 1.4 years when changing from T12 lamps with magnetic ballasts to T8 lamps with electronic ballasts. The payback including life-cycle annual savings for changing out existing T8/electronic ballast systems with new spectrally enhanced lighting systems have been calculated to be 3.5 years.
- When compared to the no-action alternative, i.e. the base case is leave the building as it is, the resulting simple payback, (which considers only the energy savings benefit) for lighting retrofits with 850 Spectrally Enhanced Lighting have been calculated to be 2.7 years when changing from T12 lamps with magnetic ballasts to T8 lamps with electronic ballasts. The simple payback for changing out existing T8/electronic ballast systems with new spectrally enhanced lighting systems have been calculated to be 7.2 years.
- Taken together, these results suggest that incentives may be required to produce changes in markets where either electricity costs remain lower than average or short-term perspectives drive retrofit decisions. However, where electricity costs are higher than average or longer-term (life-cycle) benefits drive retrofit decision-making, the economic case for using the Spectrally Enhanced Lighting method are clearly demonstrated by this study.

4.1.2. Secondary Objectives - Conclusions

4.1.2.1. *Occupant Satisfaction with Spectrally Enhanced Lighting Retrofits*

- This study provides conclusive evidence that the Visual Effectiveness Method with 850 lamps can be used as an energy efficient lighting retrofit technique that provides equal building occupant satisfaction as compared to that of more conventional lighting installations.

4.1.2.2. *Usefulness of the Visual Effectiveness Formulas*

- The Visual Effectiveness calculations were utilized in this study and proved to be an effective means of predicting both light levels and energy savings. Furthermore the acceptance of the equal Visual Effectiveness concept was confirmed through the lack of any change in task lighting usage or occupant concerns over the amount of light, even though the photopic illuminance levels were reduced.

4.2. DISCUSSION OF THE SELPIES ECONOMICS VALIDATION STUDY

4.2.1. Discussion on Conclusions

4.2.1.1. *Energy Savings and Economics*

- The study concludes that the use of Spectrally Enhanced Lighting and the Visual Effectiveness formulae provide a cost effective means of retrofitting lighting installations. The premise of these savings is that the naturally-occurring visual efficiencies of increased brightness perception and visual acuity resulting from higher color temperature lighting can be transferred into energy efficiency by utilizing using commonplace lamps and ballasts paired to provide equal visual effectiveness. These energy savings range from 19% to 27%, depending on the spectrum of the pre-retrofit lamps.
- Properly designed Spectrally Enhanced lighting systems will generally reduce initial costs in new construction, due to the added efficiencies of the lamps, which will result in fewer lighting components. The combination of reduced initial costs and long-term energy-saving benefits provide a compelling case for considering using Spectrally Enhanced Lighting in new construction.
- For commercial buildings that have committed to performing lighting retrofits, the incremental costs for installing Spectrally Enhanced Lighting are minimal or non-existent. Therefore, in comparison to other lighting retrofit measures, Spectrally Enhanced Lighting provides a no-cost added benefit of 19%-27% energy savings.
- The economics of the T12 lamps/magnetic ballasts have been well known for nearly 20 years. However, the driving motivator for making this change has been the cost of energy, and T12 lamps with magnetic ballasts are still prevalent in low-cost utility rate areas due to the poor paybacks from low energy costs. This method demonstrates how the savings from T12 to T8 systems nearly doubles to 46% when combined with the use of Spectrally Enhanced Lighting.

4.2.1.2. *Occupant Satisfaction*

- This study provides significant validation that the 850 Spectrally Enhanced lamp can be used in office lighting conditions without compromising occupant satisfaction. In all the ratings of occupant satisfaction between the three buildings, no single indicator of occupant satisfaction declined.
- The premise that lighting levels can be reduced using the Visual Effectiveness formulas without affecting occupant satisfaction has been demonstrated through these three buildings. Since the pre-retrofit ambient lighting levels are at the upper end of the IESNA recommendations, it remains for further study as to whether the same result would apply if the pre-retrofit conditions were at the lower lighting levels of 20-30 photopic footcandles.

4.2.2. Recommendations for Using Spectrally Enhanced Lighting in Retrofit Applications

4.2.2.1. *Pre-retrofit Conditions*

- The understanding of the pre-retrofit conditions played a critical role in these retrofits. As a guideline for future retrofits using Spectrally Enhanced Lighting, the lighting practitioner is advised to determine the following pre-retrofit conditions in order to optimize the energy savings and economic benefit:

  1. Existing lamp type: Determine the lumen output, wattage, technology, and S/P value.
  2. Ballast Type: Determine the input wattage, start type, and internal wiring.
  3. Luminaire switching and between-luminaire wiring: Determine whether there is tandem wiring, quantify the number of tandem wires between luminaires, and assess whether 2-level switching is desired or required by the owner and/or codes. In addition, determine whether de-lamping can be performed.

4. Once all of the above parameters are determined, the lamp and ballast equipment should be evaluated using the most cost-effective solutions. This does not mean to imply the least-cost equipment solutions, but rather the investigation should be made as to the type of lamp/ballast combination that best fits the installation to minimize labor costs while providing the maximum energy benefit.

4.2.2.2. *Illuminance Level Reductions*

- The use of Spectrally Enhanced Lighting and the Visual Effectiveness Method results in photopic illuminance level reductions. The method used in the current study maintains pre- and post-retrofit visual effectiveness by using the Visual Effectiveness Method, and no effort was made to arbitrarily reduce the illuminance levels. However, it could be argued that additional energy savings could be gained through further reductions in illuminance. If a building owner and lighting practitioner agree that the general lighting levels can be reduced, a new target illuminance could be assumed, and the visual effectiveness formulas applied to the new reduced illuminance targets.
- The photopic illuminance level in these buildings fell within IESNA recommendations.
- Additional Findings From the SELPIES Economics Validation Study

4.2.3. Correlation Between Task Lighting Usage and Visual Effectiveness Metrics

A significant indication of a correlation between the use of task lighting and the Visual Effectiveness Metrics was unexpectedly discovered through analyzing the data. This finding is described in Appendix C, however is worthy of mention as an additional finding in the body of this report.

Lighting practitioners would generally expect that task lighting usage would increase as photopic illuminance is reduced; however, this study finds no such relationship. Instead, task lighting usage appears to be a function of the Visual Effective Illuminance as determined using the S/P values of the lamps and the paper reading exponent of .78. This result is consistent with the Visual Effectiveness Method, since task lighting is generally tied to paper reading tasks.

- Previous concerns expressed by lighting practitioners have been that the differences in visual improvement provided by Spectrally Enhanced Lighting are too small to make a difference; however, the significant correlation between the Visual Effectiveness metric $P*(S/P)^{.78}$ and task lighting usage provides an objective indication that office workers do make selections of lighting based on the visual effectiveness formulas rather than photopic illuminance. The evidence found in this study is compelling, since the statistical strength is from three separate and unrelated buildings, in both pre- and post-retrofit conditions. However, further studies are advocated to further study this correlation.

4.3. SUMMATION

This field study of three buildings retrofitted with Spectrally Enhanced Lighting demonstrates that using the Visual Effectiveness Method combined with 850 fluorescent lamps results in reduced lighting energy consumption while maintaining occupant satisfaction. For new construction and buildings that have already committed to performing lighting retrofits, Spectrally Enhanced Lighting provides an immediate energy saving benefit at no additional cost. For buildings that would otherwise stay with their status quo lighting systems, the economics depend on assumptions used to model various outcomes, and incentives may or may not be necessary to compel retrofits using the Spectrally Enhanced Lighting method.

For states that have urgent energy saving needs, the results are very compelling. The study shows energy savings of 19% - 27% from the Spectrally Enhanced Lighting component of the retrofit. This is made further significant in that these energy savings are concomitant with permanent peak load reductions. The compelling conclusion of these results is to utilize the findings of this study to develop regional targeted approaches to implementing Spectrally Enhanced Lighting.

APPENDIX A -PROTOCOL FOR BUILDING RETROFITS

Each of the three buildings followed the same protocol with variations in actual schedule dates. The overall schedule for each of the buildings covered a 16-week timeframe beginning with the installation of the measuring and monitoring equipment and ending with the completion of the post-retrofit occupancy survey. While there were small variations between the buildings, the building owners followed the planned schedule.

The following describes the overall protocol used for the three buildings:

A1.0 Pre-Retrofit

A1.1. Pre-Retrofit Design Process

- The principal investigator surveyed candidate buildings to determine the suitability of the building for the study. Once the building was confirmed as suitable, the building owners were informed of the study protocol and for the need to have the schedule and monitoring tightly controlled. The building owners then signed a letter of understanding agreeing to the study protocol.
- The principal investigator reviewed the pre-retrofit lighting equipment to determine possible solutions for retrofitting the lighting systems. The principal investigator worked with the lamp/ballast manufacturers to determine the possible lamp/ballast combinations for each of the particular buildings assigned to them. The lamp/ballast combination was based on the Visual Effectiveness calculations and the available products from the manufacturers.
- Each building owner selected their own contractor. The contractors were provided with the general lighting solution requirements and then performed a typical lighting audit to determine the lamp and ballast counts. The audits included both overhead and task lighting. All lamps and ballasts were ordered based on the counts taken by the installing contractors or building owner.

A1.2. Overhead Lighting Power and Task Lighting Usage Monitoring Equipment Installation

- Prior to the Pre-retrofit Lighting Baseline, the overhead lighting and task lighting metering and monitoring equipment was installed by PNNL. This equipment operated for the duration of the project.

A1.3. Pre-Retrofit Lighting Baseline

- Five weeks prior to the retrofit, the contractor cleaned and re-lamped all overhead luminaires to establish a baseline lighting condition. The baseline lamps were of identical wattage and color to the existing lamps. This work was done at night or over the weekend, simulating re-lamping as part of normal building maintenance.
- If lamps were missing in the existing luminaires, the contractors were instructed not to install new lamps, i.e. the lighting was to stay the same as the existing condition throughout the project. The premise was that some of the lamps were intentionally removed by building occupants and adding new lamps could cause negative reactions on the part of those occupants.

A1.4. Light Measurements

- PNNL took pre-retrofit lighting measurements in designated occupied office spaces that are representative of typical lighting conditions:
- Measurements were taken at nighttime with task lighting turned off.
- The specific positions where light measurements were taken were dimensioned on drawings to ensure that the post-retrofit lighting measurements are taken at the same locations.

- The Pre-retrofit lighting measurements were taken approximately at the same time as the Pre-Retrofit Occupant Survey to correlate illuminance measurements with occupant satisfaction ratings.

A1.5. Pre-Retrofit Occupant Survey

- PNNL administered Pre-Retrofit Occupant Surveys to building occupants approximately 3 weeks after the Baseline cleaning and relamping was complete. The survey questions were taken from the *Indoor Environmental Quality Survey*, created by the Center for the Built Environment at UC Berkeley.
- An email announcement was delivered to all full-time employees requesting their participation. The announcement informed occupants that a lighting retrofit would be performed and that the purpose of the survey was to evaluate the employees' perceptions of the pre-retrofit lighting system, and that it would take approximately 5 minutes to complete.
- Occupants were given one week to answer the survey, after which a following one-week grace period was extended with additional requests to complete the survey. After two weeks, the survey was considered complete and no further surveys were allowed into the statistical data.

A1.6. Lighting Retrofit Notification

- One week prior to the lighting retrofit, building occupants were notified that a lighting contractor would be re-lamping the building during non-working hours.
- The notification informed the occupants of the lighting retrofit schedule and that they would be asked to respond to an online survey three weeks after the retrofit was completed. The notification did not describe the change in lamp color or illuminance level to avoid potential bias.

A2.0 Retrofit Installation

A2.1. Lamp/Ballast Installation

- The installation of the lamps and ballasts were performed on a sequencing schedule approved by the building owner. Crews typically worked 10-hour shifts at night. The retrofit schedule varied with the different buildings based on the size of the building and the size of the crew working on the facility.

A2.2. Cost Analysis

- The contractors monitored their installation costs for their respective building and provided a breakdown of material and labor costs. Labor costs tracked man-hours for the different types of installations that were in the design with the costs for retrofitting the overhead lighting in the offices areas separated from other non-office area lighting.

A3.0 Post-Retrofit Monitoring and Evaluation

A3.1. Overhead Lighting Power and Task Lighting Usage Monitoring

- PNNL continued to monitor the overhead lighting power consumption and task lighting usage for a period of approximately two months after the retrofit was complete.

A3.2. Light Measurements

- PNNL took lighting measurements at the same locations and under the same conditions as performed in the Pre-Retrofit phase. The lighting measurements were taken approximately at the same time as the Post-Retrofit Occupant Survey to correlate illuminance measurements with occupant satisfaction ratings.

A3.3. Post-Retrofit Occupant Survey

- PNNL administered Post-Retrofit Occupant Surveys three weeks after the retrofit was complete. This survey was used to check for changes in ratings of satisfaction with the lighting system from the Pre-Retrofit Occupant Survey, using a within-subjects paired results analysis.
- As with the Pre-Retrofit Occupant Survey, occupants were given one week to answer the survey, after which a following one-week grace period was extended with additional requests to complete the survey. After two weeks, the survey was considered complete and no further surveys were allowed into the statistical data.

A3.4. Measurement and Evaluation

- Once the Post-Retrofit Occupant Surveys were completed, all data was collected and compiled by PNNL. Once the data was taken and confirmed, the measuring and monitoring equipment was removed from the site.
- Contractors provided the economic data of actual man-hours, labor rates, and purchased materials used in their projects to AI+S. For the prices of the donated lamps and ballasts, the contractors provided materials costs that they would have charged for the equipment by getting quotes from distributors and applying their standard mark-ups. Similarly, the participating manufacturers provided their generally quoted suggested contractor pricing for their products.

APPENDIX B -– LIGHTING CALCULATIONS AND METHODS

B1.0 Technical Background

Spectrally Enhanced Lighting is lighting that contains relatively more bluish content in its visible spectrum and is typically characterized by higher correlated color temperatures. Spectrally Enhanced Lighting research concludes that lamps with these properties will be more visually efficient than warmer colored lamps with the same (photopic) lumen rating and efficacy values. The factor used in determining Visual Effectiveness is the S/P value, which evaluates the spectrum of any lamp on the basis of the Scotopic function in comparison to the Photopic function. This research also concludes that visual effectiveness based on spectral enhancement will vary with the task[5]. For instance, the S/P value is not weighted as heavily in evaluating brightness perception as it is for visual acuity for self-illuminated (i.e. computer) tasks[6]. Appendix Table B-1 illustrates the Visual Effectiveness Method lighting calculations using the S/P values and rated lumens of common T8 fluorescent lamps:

Appendix Table B-1: Visual Effectiveness Lighting Calculations - Lumens and Efficacies for Fluorescent Lamps

Lamp Type	Photopic Lumen Rating P* (lumens)	Photopic Lumen Per Watts (lm/W)	S/P Value (S/P)* (value)	Visually Effective Measurements: Brightness Perception** $P(S/P)^{0.5}$ VEL (VEL/W)	Visually Effective Measurements: Visual Acuity for Paper Reading** $P(S/P)^{0.78}$ VEL (VEL/W)	Visually Effective Measurements: Visual Acuity for Computer Tasks** P(S/P) VEL (VEL/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 values in Table 1 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 in laboratory studies[5] from illuminance measurements taken vertically at the viewing eye position.

The Visual Effectiveness (VE) calculations used in Table 1-1 demonstrate how the S/P value can be used to determine the Visual Effective Lumens (VEL) of a light source. The 850 lamp shown in the above table clearly has the highest VEL and Visually Effective Lumens per Watt (VEL/W), whereas normal photometric measurements would indicate that this lamp would not be as efficient as the other two sources in the table (735 and 835 lamps). The same Visual Effectiveness formulas can be applied to other photometric measures; when used with illuminance, for example, the incident S/P value and illuminance at a point are used to determine the Visual Effective Illuminance (VEE).

B2.0 Energy Saving Ramifications:

The increase in light source efficacies shown in Appendix Table B-1 directly translate into energy savings, assuming all other factors are equal (temperature, ballast factor and efficiency, voltage, etc.). When using VE calculations, the impact of spectrum and the impact of technology as measured through the ballast efficiency are blended when assessing energy savings. The first step in this procedure is to determine the potential energy savings of the lamp choices based on the lumen output change resulting from applying the VE method.

5 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.

6 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.

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 85) are also used in offices, and generally provide higher photopic lumen ratings output and have better lumen maintenance. In addition, there are perceived benefits of better color rendering when using higher CRI lamps. Appendix Table B-1 above illustrates how the 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 is illustrated in Appendix Table B-2.

Appendix Table B-2: Percentage of Potential Energy Savings Using Visually Effective Lumen Ratings, Comparing the 850 Lamp to the 735 and 835 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%

Appendix Table B-1 and Appendix Table B-2 show that the scotopic weighting factor is maximal when applied to the visual effectiveness for computer tasks. For all tasks noted, there are potentially significant energy savings benefits to using Spectrally Enhanced Lighting. Specifically, the 850 Spectrally 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. For office spaces, the Visual Acuity for Paper Reading exponent of .78 is generally used, as it is presumed that most office workers engage in some form of paper reading tasks during the day. The use of more aggressive values based on computer tasks is applicable for a computer-only environment and if applied indiscriminately might result in a negative impact on the ability to read paper tasks.

B3.0 Design Parameters and Calculations

The designs for the lighting retrofits in the current study are based on the following criteria:

- The baseline illuminance level is a measured value using the pre-retrofit lamp/ballast system and new lamps. Since there is no change in luminaire distribution, location, or quantity, the change in illuminance varies only as a function of the total lumen output of the lamp/ballast system within the luminaires; the study therefore uses the rated lumens of the pre-retrofit lamps and ballast factor of the pre-retrofit ballast, as provided by lamp and ballast manufacturer(s) respectively, as the basic input of the calculations.
- The designs for the lighting retrofits utilize the Visual Effectiveness formula for Visual Acuity for Paper Reading (.78 exponent).   The use of the Visual Acuity for Reading exponent results in lighting levels that ensure equal visual acuity for reading paper tasks, even though the photopic illuminance is reduced.
- This study therefore uses the lumen ratings and S/P value of the pre-retrofit lamps, and compares it to the lumen rating and S/P value of the post-retrofit 850 lamp to determine the proposed reduction in photopic light level for each of the buildings.

The general form of the Visual Effectiveness formula for lighting retrofits therefore has the following relationship between pre- and post photopic illuminance $E_{(pre)}$ and $E_{(post)}$ and pre- and post-retrofit S/P values $(S/P)_{(pre)}$ and $(S/P)_{(post)}$:

Equation B-1: $$E_{(pre)} \times \left(S/P\right)_{(pre)}^{.78} = E_{(post)} \times \left(S/P\right)_{(post)}^{.78}$$

The simplified expression for the targeted percentage light level reduction is therefore:

$$\textit{Equation B-2: \% Light Level Reduction} = \left\{1 - \left(\frac{\left(S/P\right)_{(pre)}}{\left(S/P\right)_{(post)}}\right)^{.78}\right\} \times 100$$

The illuminance values in Equation B-1 will be proportional to the product of the catalog rated lamp lumens (P) and the ballast factor (BF). In lighting retrofits where only the lamps and ballasts will be replaced without change in fixture configuration or geometry this proportionality factor will be the same for the pre- and post-retrofit conditions[7]:

$$\textit{Equation B-3:}\ P_{(pre)} \times BF_{(pre)} \times \left(S/P\right)^{.78}_{(pre)} = P_{(post)} \times BF_{(post)} \times \left(S/P\right)^{.78}_{(post)}$$

When evaluating possibilities for lamp/ballast lighting retrofits, the pre-retrofit photopic lumen ratings and ballast factors are known, as are the pre- and post-retrofit S/P values. The variables for the new system design are the post-retrofit rated lamp lumens and ballast factor. Generally, lamp choices are evaluated first for their operational characteristics and/or best-fit light output. Once the post-retrofit lamp is selected and the rated post-retrofit lumen ratings known, the optimal ballast factor is determined by the following equation:

$$\textit{Equation B-4:}\ BF_{(post)} = BF_{(pre)} \times \frac{P_{(pre)}}{P_{(post)}} \times \left(\frac{\left(S/P\right)_{(pre)}}{\left(S/P\right)_{(post)}}\right)^{.78}$$

Equation B-4 shows how the ballast factor and rated lamp lumens must combine in order to achieve equal visual effectiveness. Specific choices of these quantities will depend on the most economical or available combination that comes closest to satisfying Equation B-4.

The targeted values for light level reductions were used to determine options for the lighting retrofit. By using manufacturer's data for Rated Lumens and S/P values, the lighting designer can choose various lamp/ballast combinations to attain roughly equal visual efficiencies. The criteria used for selecting the technologies used in this study were:

1. All products to be available as standard products;
2. The selection of the specific lamp and ballast combinations were based on conversations with the participating manufacturers;
3. The equipment selected to be approved by the building owners.

7 Equation B-3 and Equation B-4 assumes that since there are no changes in the lighting distribution of the fixture, i.e. the luminaire distribution and efficiencies of the pre- and post-retrofit conditions will be identical. While it is acknowledged that there may be slight changes in luminaire distribution and efficiency associated with the T12 to T8 lamp conversion, these are not considered to be significant for the purposes of evaluating the retrofits proposed here.

APPENDIX C - PNNL FINDINGS AND ANALYSIS

C1.0 Introduction:

The Pacific Northwest National Laboratory (PNNL) was retained by the US Department of Energy to monitor light levels, energy savings, and task lighting usage, and to survey occupants for their satisfaction with the lighting systems in each of the three buildings included in this study. PNNL also performed statistical analyses of the collected data.

This section summarizes the most pertinent data and provides an analysis and discussion on the PNNL findings. The PNNL report with the full findings is entitled *Field Evaluation of the Spectrally Enhanced Lighting Program: Implementation: Implementation for Energy Savings (SELPIES)"* and is documented as PNNL-15784.

The measurements taken by PNNL include the following:

1. Lighting Measurements: Both photopic and scotopic illuminance measurements were taken. Horizontal illuminance was measured at desk height and vertical illuminance was measured at eye position looking toward the partition walls. These measurements were taken after the baseline lamp installation and after the lighting retrofits, during the same time periods as the pre- and post-retrofit occupancy surveys. Lighting measurements were taken at night to determine the actual change in light level due to the lighting retrofits without the influence of daylight.
2. Power and Energy Monitoring: Continuous monitoring of the overhead lighting systems at the electrical panels was performed throughout the duration of the study. In addition, selected lighting circuits that contained only luminaires that were retrofit were tested to verify the pre- and post-retrofit power values and thus the luminaire power savings.
3. Task Lighting Usage Monitoring: Pre- and post-retrofit task lighting was monitored throughout the duration of the field study to assess whether the reductions in photopic illuminance would be offset by the users through increased use in their task lighting.
4. Occupant Ratings of Satisfaction with the Lighting: Pre- and post-retrofit online surveys were administered to all full-time workers in each of the buildings to assess changes in occupant satisfaction with the lighting system resulting from the change to Spectrally Enhanced Lighting under the conditions of reduced (photopic) illuminance.

C2.0 Lighting Measurements:

C2.1. <u>Method:</u>

- Measurements by PNNL include horizontal illumination measurements at desk height and vertical illumination measurements at eye height in sitting position, looking at the partitions or walls within the office. The horizontal measurements are considered the most reliable to assess photopic light level reduction in the space, while vertical illumination at the eye is considered when analyzing occupant reactions to the lighting conditions in the space.
- The equipment used for taking light level measurements had Scotopic and Photopic measurement capability. These measurements provide the resultant pre- and post-retrofit S/P values based on the actual conditions within the office spaces.
- The combination of measured horizontal photopic illuminance, combined with the S/P values, can be used to determine the actual visual effectiveness level of the installed retrofit lighting installation. The comparison of these resultant values to predicted values based on catalog values (Section 2) provides an assortment of evaluations as to the reliability of predictions and may also provide additional insight to occupant responses to the lighting conditions within the space.

C2.2. Data Summary:

Lighting measurements taken by PNNL are summarized in the following tables:

Appendix Table C-1: Summary of PNNL Measurements – Illuminance and S/P Values

PNNL Measurements Analysis	Units	Bldg. A	Bldg. B	Bldg. C
LIGHTING MEASUREMENTS				
HORIZONTAL MEASUREMENTS				
Horizontal Photopic Illuminance				
Mean Before Retrofit	Lux	461.75	468.37	558.20
Mean After Retrofit	Lux	370.45	321.29	474.09
Statistical Difference	Lux	-92.00	-147.00	-84.00
Confidence Interval on Difference	+ Lux	14.00	18.00	15.00
Percent Difference	%	-20%	-31%	-15%
Horizontal Scotopic Illuminance				
Mean Before Retrofit	Lux	595.95	596.22	886.98
Mean After Retrofit	Lux	671.65	596.20	901.75
Statistical Difference	Lux	76.00	0.00	0.00
Confidence Interval on Difference	+ Lux	22.00	NA	NA
Percent Difference	%	13%	0%	0%
Horizontal S/P Ratio				
S/P Before Retrofit	Num	1.29	1.27	1.59
S/P After Retrofit	Num	1.81	1.86	1.90
Difference in S/P Ratio	Num	0.52	0.59	0.31
Confidence Interval on Difference	+ Num	0.03	0.02	0.02
VERTICAL MEASUREMENTS				
Vertical Photopic Illuminance				
Mean Before Retrofit	Lux	168.45	151.84	165.38
Mean After Retrofit	Lux	126.35	104.86	150.75
Statistical Difference	Lux	-42.00	-47.00	-15.00
Confidence Interval on Difference	+ Lux	13.00	10.00	12.00
Percent Difference	%	-25%	-31%	-9%
Vertical Scotopic Illuminance				
Mean Before Retrofit	Lux	212.95	191.45	256.11
Mean After Retrofit	Lux	218.05	189.51	276.77
Statistical Difference	Lux	0.00	0.00	0.00
Confidence Interval on Difference	+ Lux	NA	NA	NA
Percent Difference	%	0%	0%	0%
Vertical S/P Ratio				
S/P Before Retrofit	Num	1.26	1.26	1.54
S/P After Retrofit	Num	1.73	1.81	1.83
Difference in S/P Ratio	Num	0.47	0.55	0.29
Confidence Interval on Difference	+ Num	0.02	0.02	0.04

C2.3. Discussion:

- The measured illumination and S/P values are used to evaluate differences between measured values and predicted values and possible correlations between measured lighting values, measured energy consumption values, task lighting usage, and occupant surveys.
- Note that all post-retrofit photopic illuminance measurements fall within IESNA recommendations for office lighting.

C2.4. Illumination Measurement Analysis:

- The results in Appendix Table C-1 are compared to the Section 2 predicted photopic illuminance reductions as given in Appendix Table C-2:

Appendix Table C-2: Illumination Measurement Analysis: Compares predicted photopic illuminance changes to measured photopic illuminances

Illumination Measurement Analysis	**Bldg. A**	**Bldg. B**	**Bldg. C**
Predicted Change In Photopic Lumens (Table 2-2)	***-25%***	***-27%***	***-19%***
Percentage Change in Horizontal Photopic Illuminance as measured	-20%	-31%	-15%
Percentage Change in Vertical Photopic Illuminance as measured	-25%	-31%	-9%

- Notes on Appendix Table C-2:

1. The predicted changes in photopic illuminance described in Section 2 of this report were based on the assumption that the reduced lumen output of the lamps would translate directly to reduced illuminance measurements. This assumption is valid since neither the quantities of lamps nor the luminaire distribution were changed in the retrofit. Due to the predominance of direct lighting distribution from the recessed parabolic luminaires, it is assumed that the predictions of the change in illuminance would translate more directly to the horizontal measurements than the vertical measurements.
2. The predicted and measured mean percent reductions in horizontal photopic illuminance are within 6% of each other, which is 2 standard errors. Buildings A and C had higher mean illuminance values than predicted, while Building B had lower values than predicted but all within 2 standard errors.
3. The changes in horizontal illuminance measurements as compared to vertical illuminance measurements are not completely consistent. In Building A, vertical photopic illuminance measurements showed a larger reduction than the horizontal measurements, while in Building B they were similar, and in Building C, the horizontal photopic illuminance measurements showed a larger reduction than the vertical measurements. For all 3 buildings, the vertical illuminance changes were within one standard error of the predicted value.

C2.5. S/P Value Analysis:

- The results in Appendix Table C-1 are compared to the Section 2 predicted S/P values, as provided by lamp manufacturers, in Appendix Table C-3:

Appendix Table C-3: S/P Value Measurement Analysis: Compares predicted S/P value changes based on manufacturers' data to measured S/P values

S/P Value Analysis	**Bldg. A**	**Bldg. B**	**Bldg. C**
Pre-Retrofit S/P Ratios (Based on Mean Values)			
Pre-Retrofit S/P - Manufacturer's Data	***1.32***	***1.30***	***1.56***
Pre-Retrofit S/P - Horizontal	1.29	1.27	1.59
Pre-Retrofit S/P - Vertical	1.26	1.26	1.54
Post-Retrofit S/P Ratios (Based on Mean Values)			
Post-Retrofit S/P - Manufacturer's Data	***1.87***	***2.00***	***1.85***
Post-Retrofit S/P - Horizontal	1.81	1.86	1.90
Post-Retrofit S/P - Vertical	1.73	1.81	1.83
S/P Ratio Shift			
Predicted Increase in S/P Value	***0.55***	***0.70***	***0.29***
Increase in Horizontally Measured S/P Value	0.52	0.59	0.31
Increase in Vertically Measured S/P Value	0.47	0.55	0.29

- Notes on Appendix Table C-3:

1. Measured S/P values are expected to be different from manufacturer's values once lamps are introduced into a space since the color characteristics of the lighting within a space are affected by surface colors such as walls and partition systems.
2. The measured mean vertical S/P values are lower than the mean horizontally measured S/P value for all 3 buildings. The reduction in S/P value from the horizontal measure to the vertical measure is .08 in Building A, .05 in Building B, and .07 in Building C. These shifts show a general trend of lower S/P values when measured at eye position as compared to the horizontal S/P value measurements. This shift in S/P values is consistent with the neutral, but slightly warmer colored partitions in the buildings.
3. The measurements of the horizontal S/P Value show varying differences when compared to the manufacturer data: In Building A the mean S/P Value is .06 less than the manufacturer's data, Building B measurements are .14 less than manufacturer's data, and Building C is .05 higher than manufacturer's data. The difference between the manufacturer's data and the measured levels in Building B seems disproportionate given that the neutral colors of the space would not be expected to create such a difference.

C2.6. Visual Effectiveness Analysis:

- The results in Appendix Table C-1 are used to calculate Visual Effective Illuminance (VEE) values, and compares them to predicted values (Section 2). The following Appendix Table C-4 summarizes these calculations:

Appendix Table C-4: Visual Effectiveness Analysis. Compares predicted Visual Effective Illuminances (VEE) changes to calculated values based on measured photopic illuminance and S/P values

Visual Effectiveness Analysis	**Bldg. A**	**Bldg. B**	**Bldg. C**
Predicted Change in Visual Effectiveness (Table 2-2, Catalog Values, Post-Retrofit - Pre-Retrofit)	***-1.6%***	***2.2%***	***-7.8%***
Visual Effectiveness Calculations - Horizontal VEE (Based on Measured Means)			
Pre-Retrofit Mean Horizontal VEE	563.21	564.36	801.46
Post-Retrofit Mean Horizontal VEE	588.46	521.34	782.15
Standard Error, Horizontal VEE	+/- 4.5%	+/- 6%	+/- 4.5%
Change in Mean Horizontal VEE	4.5%	-7.6%	-2.4%
Difference, Measured Values - Predicted Value	6.1%	-9.8%	5.4%
Visual Effectiveness Calculations - Vertical VEE (Based on Measured Means)			
Pre-Retrofit Mean Vertical VEE	201.73	181.83	231.61
Post-Retrofit Mean Vertical VEE	193.75	166.57	241.53
Standard Error , Vertical VEE	+/-11%	+/- 10.5%	+/- 9.5%
Change in Mean Vertical VEE	-4.0%	-8.4%	4.3%
Difference, Measured Values - Predicted Value	-2.4%	-10.6%	12.1%

- Notes on Appendix Table C-4:

  1. The predicted Visual Effective Illuminance (VEE) calculations use manufacturer rated lumen output and S/P values as the basis for the lamps/ballasts combinations used in the lighting retrofits. The measured values of the horizontal photopic illuminance and horizontal S/P value are used to calculate the Horizontal VEE; likewise, the measured values of the vertical photopic illuminance and vertical S/P value are used to calculate the Vertical VEE.

  2. The horizontal measurements are used to test how close the predicted changes in VEE are to the measured conditions. Buildings A and C show that the measured values indicate a slight increase over the predicted VEE that are consistent within one standard error as discussed in connection with Table 2-2. Building B shows a nearly 10 percentage point mean reduction from what was predicted, which is slightly larger at about 1.3 standard errors. This shift is still small enough that there should not be any implications on occupant satisfaction or task lighting use.

  3. The vertical measurements may provide insight into occupant satisfaction ratings. Building A calculations are very consistent with the predicted Vertical VEE, while the calculations for Building B are 10.6% mean percentage points lower than the predicted Vertical VEE and the calculations for Building C are 12.1 percentage points higher than the predicted Vertical VEE. These differences are slightly larger than one standard error and should not influence occupant satisfaction and/or task lighting usage.

C2.7. Conclusions:

- Measured post-retrofit illuminance measurements are close to predicted values and validate the use of the Visually Effectiveness design method. There are 2 slight differences between predicted and mean measured illuminance values:
  1. Building B mean Visually Effectiveness Illumination values were lower than predicted, but still within one standard error. This resulted from having a lower measured mean S/P value than expected when compared to manufacturer provided data.
  2. Building C had higher than predicted vertical illuminance measurements in mean values, but still remained within one standard error. The larger standard error in this case is due to the larger scatter in measured vertical illuminance values which in turn is related to the differences in surface colors.

C3.0 Overhead Lighting Power and Energy Measurements

C3.1. Method:

- The PNNL Report includes the continuous measurement of pre- and post- retrofit energy use connected load measurements. The ensuing analysis uses values the connected load measurements only, since these values are considered by PNNL to be the most reliable for predicting annual energy savings. The direct translation from changes in connected load to energy savings is appropriate in this case, since changes were made in the retrofits that would have changed the time element of the energy equation, Energy = Power x Time. Furthermore, the direct comparison of connected load on a per-lamp or per-luminaire basis provides a basic check on assumptions and calculations made based on manufacturer-supplied information.

C3.2. Data Summary:

The overhead lighting system connected load measurements taken by PNNL are summarized in the following table:

Appendix Table C-5: Summary of PNNL Measurements –
Overhead Lighting Connected Load Measurements

PNNL Measurements Analysis	Units	Bldg. A	Bldg. B	Bldg. C
OVERHEAD LIGHTING POWER AND ENERGY MEASUREMENTS				
Connected Load Measurements				
Load Reduction	%	45.6%	19.8%	20.5%
Pre-Retrofit Load (Watts/tube)	W/tube	37.7	29.08	27.11
Post-Retrofit Load (Watts/tube)	W/tube	20.5	23.32	21.56

C3.3. Discussion

- *Percentage Change in Connected Load:* The following Appendix Table C-6 compares the calculated values of overall energy savings, based on the manufacturer data described in Section 2 to the measured connected load reductions in Appendix Table C-5:

Appendix Table C-6: Comparison of Calculated Changes in Connected Load Based on Manufacturer's Data to Measured Changes in Connected Load

Connected Load Analysis: Mfgr. Data vs. Measured % Change	**Bldg. A**	**Bldg. B**	**Bldg. C**
Predicted Percentage Reduction in Energy (Table 2-3)	***50%***	***24%***	***24%***
Measured Percentage Change	45.6%	19.8%	20.5%
Difference in Percentage Change (Measured - Predicted)	-4.8%	-3.9%	-3.6%

- Notes on Appendix Table C-6:
  1. The measured reduction in connected load was lower than predicted in all three buildings. The difference between the predicted levels and the measured values falls within a narrow range of between 3.6% and 4.8%.
  2. The differences between calculated values and measured values may be due to temperature and/or voltage differences between actual field measurements and equipment tested under laboratory conditions. A review of actual differences on a Watts-per-luminaire basis provides some insight into the actual shifts from predictions that occurred in the field.

C3.4. Wattage per Luminaire Analysis:

- The following Table compares the calculated wattage per luminaire, based on manufacturer's data, to the measured connected load per luminaire:

Appendix Table C-7: Comparison of Calculated Watts per Luminaire Based on Manufacturer Data to Measured Watts per Luminaire

Connected Load Analysis - per Luminaire	**Bldg. A**	**Bldg. B**	**Bldg. C**
Pre-Retrofit Load Connected Load			
Watts/Luminaire (per mfgr data)	115.0	86.5	85.0
Measured Watts/Luminaire*	113.1	87.2	81.3
Percentage Difference (mfgr to measured values)	-1.7%	0.9%	-4.3%
Post-Retrofit Connected Load			
Watts/Luminaire (per mfgr data)	57.0	66.0	64.5
Measured Watts/Luminaire*	61.5	70.0	64.7
Percentage Difference (mfgr to measured values)	7.9%	6.0%	0.3%

Measured Watts/Luminare = 3 x Watts/Tube, as reported by PNNL, Appendix A.

- Notes on Appendix Table C-7:
  1. The measured wattage per luminaires for the pre-retrofit lamp/ballast combinations are very close to manufacturer's published data for Buildings A and B, while the pre-retrofit measurement of Building C was 4.3% lower than expected.
  2. The measured wattage per luminaire for the post-retrofit lamp/ballast combinations were off by 7.9% and 6.0% for Buildings A and B, respectively, while the Building C measured wattage per luminaire was nearly identical to the manufacturer's data (0.3% difference).

C3.5. Lighting Power Density Analysis:

- Lighting Power Densities (LPD) are used as a means of assessing the power consumption of lighting within a building. The use of the LPD metric is widespread and an important consideration in lighting design:

  1. LPD's are used throughout the United States in energy conservation standards to limit the amount of power used for lighting buildings, based on the building types and currently available energy-efficient lighting technologies.
  2. Utility company energy conservation incentives often utilize LPD's as a basis for determining the amount of incentive they provide to commercial customers.
  3. Newly enacted federal laws allowing tax deductions for installing energy conserving equipment in buildings use LPD's as the basis for the deduction.

- For these reasons, it is desirable to determine the pre- and post-retrofit Lighting Power Densities of the three buildings. The following table shows the extension of the measured findings of watts per luminaire to Lighting Power Density (Watts per sq. ft.):

Appendix Table C-8: Pre- and Post- Retrofit Predicted and Measured Lighting Power Densities

Connected Load Analysis: Lighting Power Density (LPD)	**Bldg. A**	**Bldg. B**	**Bldg. C**
Average sq. ft. / Luminaire	***78***	***89***	***71***
Pre-Retrofit LPD			
Pre-Retrofit Calculated LPD (Table 2-3)	1.47	0.97	1.20
Calculated LPD based on Measured Conn. Load	1.45	0.98	1.15
Post-Retrofit LPD			
Post-Retrofit Calculated LPD (Table 2-3)	0.73	0.74	0.91
Calculated LPD based on Measured Conn. Load	0.79	0.79	0.91

- Notes on Appendix Table C-8:

  1. The resultant Lighting Power Densities for Buildings A and B are quite similar at .79 Watts per sq. ft. measured. These end up with the same LPD in spite of different luminaire densities due to the relative efficiencies of the lamp/ballast system; while Building A had a higher luminaire density than Building B, the relative lamp/ballast system efficiency due to the instant start ballast technology was higher and the end resulting LPD was identical.
  2. Building C has a higher LPD than Buildings A and B due to the increased luminaire density within the building. A contributing factor, when compared to Building A, is the slightly higher connected load per luminaire due to the slightly less efficient programmed start ballast technology.
  3. Buildings A and B show a slightly higher than predicted LPD due to the differences in the per-luminaire Wattage described in Appendix Table C-7.

C3.6. <u>Conclusions:</u>

- The post-retrofit measured connected load was within 5% of the predicted post-retrofit load for all three buildings. The measured loads of lighting circuits indicated a consistent shift towards higher power consumption than manufacturer listings (3.6% to 4.8%). The manufacturers have suggested that the differences between catalog values and field conditions may be due to differences in voltage and/or temperature.

- Lighting Power Densities are determined from luminaire spacing and lamp/ballast system efficiencies. The highest LPD is found in Building C (.91), which had the highest density of luminaires per square foot. The other two systems, which are more representative of common parabolic luminaire spacings in office buildings, resulted in .79 Watts per square foot, which is 21% below the current ASHRAE 90.1 Standard.

C4.0 Task Lighting Usage

C4.1. Method:

- Task lighting usage was monitored in all three buildings through local data loggers that sensed the fixed output status of undercabinet task lights in selected open office cubicles. Questions on the use of task lighting were also included in the online occupant survey. This provides an objective measurement and a subjective response to the question of task lighting usage, and allows a comparison of the results.

C4.2. Data Summary:

Task lighting usage measurements taken by PNNL are summarized in the following tables:

Appendix Table C-9: Summary of PNNL Measurements – Task Lighting Usage

PNNL Measurements Analysis	Units	Bldg. A	Bldg. B	Bldg. C
TASK LIGHTING USAGE				
Task Lighting Measurements				
Number of workstations monitored	Num	39	37	98
Pre-retrofit Mean Task Lighting Usage	%	23.5%	21.7%	14.1%
Post-retrofit Mean Task Lighting Usage	%	19.6%	24.4%	12.6%
Statistically Significant Change?	Yes/No	N	N	N
Self-Reported Through Occupant Survey				
Number reporting increased use	Num	3	12	8
Number reporting decreased use	Num	2	7	7
Number reporting no change	Num	17	61	43
Total number of survey respondents	Num	22	80	58
Statistical Significant Change?	Yes/No	N	N	N

C4.3. Discussion:

- Task lighting usage is an important consideration when assessing the overall effectiveness of lighting retrofits. The concern may be that when photopic light levels from overhead lighting systems are reduced, occupants may make up for the reduced ambient photopic illumination by turning on their localized task lighting more often. If this occurred, it would have a negative impact on the energy savings for the building.
- There is no statistically significant change in the task lighting usage in any of the three buildings.
- In Buildings A and C, there was a slight decrease in task lighting usage; in Building B, there was a slight increase in task lighting usage. The increase in task lighting usage in Building B, although not statistically significant, is consistent with expectations resulting from the slightly lowered mean values of both horizontal and vertical VEE (- 7.6% and -8.4%, respectively).

C4.4. Task Lighting Usage Analysis

- The lack of any significant change in task lighting usage indicates that the use of the Visual Effectiveness formulas can be used without risk of increase in the use of task lighting, even with reduced photopic illuminance values.

- The slight increase in task lighting usage in Building B triggered a compelling question, since it is also the only building that had a resultant decrease in the measured mean horizontal Visual Effectiveness. An analysis was therefore performed to investigate the possible correlation between task light usage and the illuminance coming from overhead lighting. For this analysis, we compare the percentage of task lighting usage in 6 different scenarios using mean values from all three buildings in both pre- and post-retrofit conditions:

Appendix Table C-10: Correlations between Lighting Measurements and Task Lighting Usage

	Task Lighting Usage (%)		Hor. VEE		Vert. VEE		Hor. E		Vert. E	
Bldg	%	Rank	VEE_H	Rank	VEE_V	Rank	E_H	Rank	E_V	Rank
B_2	24.4	1	521	1	167	1	321	1	105	1
A_1	23.5	2	563	2	201	4	461	3	168	6
B_1	21.7	3	564	3	181	2	468	4	152	4
A_2	19.6	4	588	4	194	3	370	2	126	2
C_1	14.1	5	801	6	232	5	558	6	165	5
C_2	12.6	6	782	5	242	6	474	5	151	3

Appendix Table C-10 shows that the ranking of task lighting usage, from highest to lowest, follows most closely the ranking of VEE_H, from lowest to highest; in fact, the correlations follow the trend throughout nearly all the values, with the single exception at the highest end of measured VEE_H values that are only 2% different from each other. A graph showing the relationship of task lighting usage to illuminance measurements is shown below:

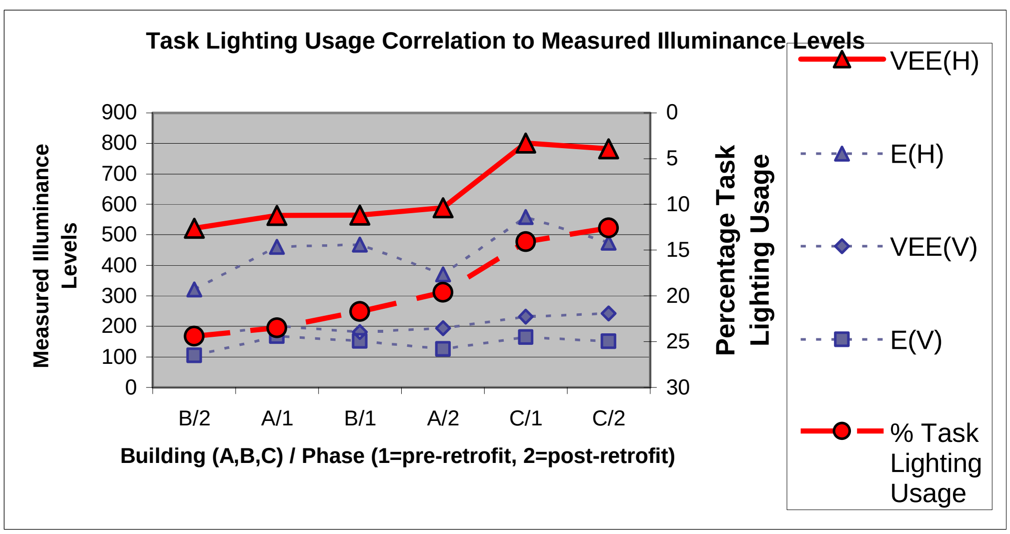

Figure C-1: Relationship of Task Lighting Usage to Illuminance Measurements from Overhead Lighting Systems.

As can be seen in Figure C-1, task lighting usage tracks quite closely with VEE_H as compared to any other lighting measurement, including horizontal photopic illuminance measurements. By plotting the percent task lighting usage against the lighting measurements, we find a very high correlation between the Visual Effectiveness measurements and essentially no correlation with the photopic measurements:

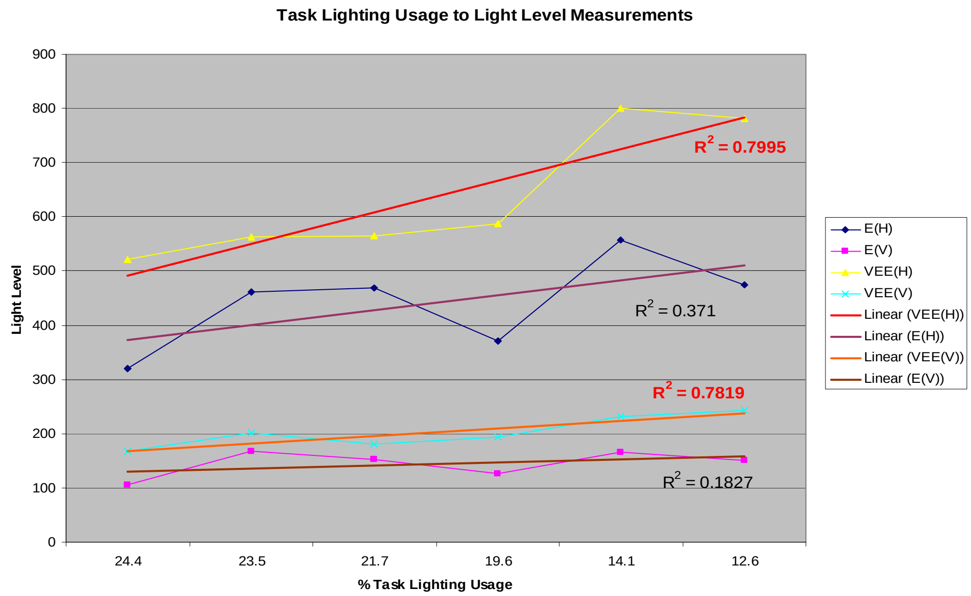

Figure C-2: Correlation between task lighting usage and four measurements of illuminance

C4.5. Conclusions:

There were no statistically significant differences in task lighting usage between the pre- and post-retrofit conditions within the three buildings when each building was considered separately. However, when reviewing the various illuminance measurements across all 3 buildings, the study results show significant correlation between task lighting usage and the mean lighting measurements of Visually Effective Illuminance values $VEE_{H,}$ and VEE_V, with virtually no correlation to photopic illuminance measurements. This trend towards using more task lighting as the Visually Effective Illuminance decreases is based on data from three different buildings under two different lighting conditions in each building. This follows the theories of Spectrally Enhanced Lighting, since the VEE values were predicated on the basis of the visual task of Reading Paper, and task lighting in these offices consisted of undercabinet lighting for use in reading paper tasks. Further study of this effect should be considered.

C5.0 Occupant Ratings of Satisfaction with the Lighting System

C5.1. Method:

- An online survey was issued to all full-time occupants to assess their levels of satisfaction with the lighting before and after the lighting retrofit to clearly establish differences in occupants' ratings of satisfaction with the lighting between the pre- and post-retrofit lighting conditions. The survey was administered by PNNL as an online survey, with the assistance of the building operations and IT personnel.
- The occupant survey used questions taken from the Center for the Built Environment Occupant Indoor Environmental Quality Survey. The survey instrument uses a 7-point scaling system, ranging from negative to positive. There are three questions related to occupant satisfaction with lighting in the survey:

  1. How satisfied are you with the light level in your workspace?
  2. How satisfied are you with your visual comfort under this lighting?
  3. Overall, does the lighting quality enhance or interfere with your ability to get your job done?

- These questions were asked, along with other information on age, gender, type of computer monitor, and other non-lighting questions, three weeks after the baseline lamp installation and three weeks after the retrofit installation. The survey therefore asked the same questions to the same people after the same adaptation period from when the two different lamps were installed in each building.
- The statistical analysis only uses paired results where the difference between the pre- and post-retrofit responses for each question were evaluated on a per-person basis, and the results of the shifts in responses from pre-to post-retrofit, per person, were analyzed for statistical significance.

C5.2. Data Summary:

Occupant ratings of satisfaction with the lighting systems were determined by an online survey instrument administered by PNNL. The results are in the following table:

Appendix Table C-11: Summary of PNNL Measurements – Occupant Ratings of Satisfaction with the Lighting

PNNL Measurements Analysis	Units	Bldg. A	Bldg. B	Bldg. C
OCCUPANT SATISFACTION SURVEY RESPONSES				
Question: How satisfied are you with the light level in your workspace? 1=Very Dissatisfied, 7=Very Satisfied				
Mean Before	Rank	5.15	5.24	5.49
Mean After	Rank	5.23	5.26	5.56
Statistically Different?	Yes/No	N	N	N
Question: How satisfied are you with your visual comfort under this lighting? 1=Very Dissatisfied, 7=Very Satisfied				
Mean Before	Rank	4.9	5.04	5.29
Mean After	Rank	5.1	5.06	5.48
Statistically Different?	Yes/No	N	N	N
Question: Overall, does the lighting quality enhance or interfere with your ability to get your job done? 1=Inteferes, 7=Enhances				
Mean Before	Rank	4.62	4.88	5.26
Mean After	Rank	5.03	5.03	5.28
Statistically Different?	Yes/No	Y	N	N
Statistics on Surveys				
No. of full-time staff surveyed	Num	143	256	186
No. of full-time workers responding to pre-retrofit and post-retrofit surveys	Num	63	145	88
Percentage of full-time workers responding to pre-retrofit and post-retrofit surveys	%	44%	57%	46%
Statistical difference between age groups?	Yes/No	N	N	N
Statistical difference between genders?	Yes/No	N	N	Y

C5.3. Discussion

- The science behind Spectrally Enhanced Lighting emphasizes that the use of Visual Effectiveness formulas result in lower levels of (photopic) illumination, and therefore reduced energy use, without risk of reducing visual performance. With this premise, the remaining risk to building owners is the occupant rejection of the spectrally enhanced light source.

- It has been widely speculated by members in the lighting industry that Spectrally Enhanced Lighting would not be acceptable to building occupants due to the color of the lamps, especially under the conditions of reduced illuminance. This study clearly shows that for the three buildings tested, there were no decreases in occupant ratings of satisfaction when the lighting was changed to the 850 Spectrally Enhanced lamp under the conditions of reduced photopic illuminance; all ratings of satisfaction increased with the use of the Spectrally Enhanced Lighting, although only one of them to a statistically significant level (Question 3, Building A).
- The study found no statistically significant differences in occupant responses to the questions among age groups or gender, with one exception. Males in Building C had statistically higher ratings of satisfaction with the post-retrofit lighting levels (Question 1) than females.

C5.4. Analysis:

- There are no statistically significant differences between pre- and post-retrofit survey results, nor are there any apparent trends in these data.

C5.5. Conclusions:

- These three buildings demonstrate that the 850 lamp can confidently be used in commercial office buildings under the conditions of reduced photopic illuminance through the use of the Visual Effectiveness formulas without risk of a loss in occupant satisfaction with the lighting.

APPENDIX D - ECONOMIC ANALYSIS DETAILS

This Appendix presents the economic analyses of the three buildings. The economic analysis evaluates the cost of the retrofits on a per-luminaire and per-square-foot basis without including the non-energy saving additional costs encumbered in the project such as task lighting and miscellaneous luminaires.

D1.0 Method:

D1.1. Data Collected:

- All material and labor costs used in the analysis are fully-burdened costs, i.e. they are the total costs incurred by the building owner. The following information was provided by the installing contractors for the purpose of this analysis:
  1. Materials Costs: Includes the lamp and ballast costs on a per unit basis, as well as incidental materials costs, where applicable.
  2. Labor Costs: Includes the Contractor man-hour rate per luminaire and the fully burdened hourly labor rate. The rate used is a weighted average based on actual hours expended by labor, supervisor, and administrative personnel.
  3. Total project cost, which essentially consists of the bill paid by the building owner at the end of the project.
  4. Breakout of Abnormal Costs: For buildings B and C, costs that were incurred due to specifics on the retrofit that would not ordinarily have been encountered were separated out for normalizing the data.
- The lamps and ballasts were donated to the project, and were therefore not actual costs to the building owners. The costs of lamps and ballasts were provided by two sources; the manufacturers' estimated price through general distribution, and the Contractors' prices that they obtained by asking their distributor what the cost would have been, if they would have bought the lamps and ballasts as part of the project.

D1.2. Analysis Methods:

- The analysis based on the IESNA Life Cycle Cost Benefit Analysis, as described in Chapter 25 of the IESNA Handbook, Ninth Edition. The analysis does not, however, include potential air conditioning savings from the reduction in lighting loads or factors for first costs of HVAC equipment since this is a retrofit application. The analysis assumes that the base case would be to leave the pre-retrofit lighting installation as-is; therefore the economics analysis simplifies to the initial cost of the retrofit and the annual cost differences in energy and operating costs.
- All buildings are analyzed using the same fundamental criteria as follows:
  1. Life of System = 20 years
  2. Opportunity or Interest Rate = 7%
  3. Annual Insurance Cost = 1.5%
  4. Annual Property Tax = 5%
  5. Energy Rate = $0.15 per kWh
  6. Annual Operating Hours = 3350
  7. Sales tax = 8.25%

  These costs represent typical values for privately owned commercial buildings in California. While not necessarily the actual costs for each of the buildings, these values are used for all buildings so that the comparisons are done using equal economic values.

- Actual costs have been normalized for Buildings B and C, due to the added costs incurred by these buildings made necessary to accommodate the retrofit ballasts used in the study. These costs would not normally have been encountered under normal retrofit installation practice. The following describes the normalization process:

  1. The retrofit lamp/ballast combinations used in Buildings B and C included the use of programmed start ballasts. These ballasts were used to balance the light output of the retrofit lamps in order to achieve a targeted resultant lumen output from the lamp/ballast system. What was not known at the inception of the retrofit, however, was that the existing ballasts were instant-start ballasts wired in a tandem-wired configuration that maintained 2-level switching through a 4 + 2 configuration (one luminaire has both a 4-lamp ballast and a 2-lamp ballast, the tandem luminaire did not have any ballasts).

  2. Retrofitting luminaires with existing 4+2 instant start ballast configurations to programmed start ballasts significantly affected the installation costs for buildings B and C, as outlined below:

     - The number of wires between the luminaires were significantly increased, requiring new wiring between the luminaires;

     - The number of ballasts were increased to maintain the switching and simplify the installation; instead of having two ballasts per pair of luminaires, there were three ballasts per pair of luminaires installed for most luminaires;

     - The sockets in the luminaires had to be replaced;

     - The additional time for the above installation and rewiring was estimated by both Building B and Building C contractors to be 15 minutes per luminaire.

  3. Under a normal lighting retrofit scenario, the unforeseen condition of this additional work would have been rectified by changing strategies and using similar technologies to Building A. Instead of using programmed start ballasts that significantly increased the initial costs, the lighting retrofit contractor would have installed a lower ballast factor extra-efficient instant start ballast with a reduced wattage lamp, balanced to get the same light outputs as were targeted in this study. Therefore, the normalizations used in the economic analysis take this into account and work under the presumption that existing instant start ballast installations would be retrofit with new instant start ballasts as a more economically viable approach.

  4. It is acknowledged that the use of programmed start ballasts generally add a benefit to building owners by extending the lamp life, especially when the building uses occupancy sensors for lighting controls. The normalization used here does not diminish this known added value; rather, it acknowledges the importance of the first-cost of installation as a major driver in lighting retrofit installations. Given the actual building wiring configuration, the lighting contractors agree that they would have used a different solution than that used in this study for economic reasons.

D2.0 Data and Analysis:

D2.1. Introduction

The Lighting Retrofit Analysis concentrates on the economics of the specific lamp/ballast retrofit without including the costs incurred from changing lamps in the task lighting or other luminaires in the building that did not necessarily result in energy savings. This analysis provides the cost effectiveness of the retrofit on a per-luminaire basis, which is likely to be of interest to utility companies, governmental agencies, and building owners to assess the value of these retrofits as stand-alone energy conservation measures.

D2.2. Area Used in the Analysis:

- The building plans were reviewed and areas of combined open and private offices were used in this analysis. The analysis covers the majority of the office spaces in the building to cover the overhead lighting system retrofit over as large an area as possible to reasonably represent the office area lighting retrofit. The areas were added up, as were the luminaire counts inside of these areas, to determine the approximate luminaire and lighting power densities of the office spaces.

D2.3. Analysis

- Appendix Table D-2 provides the summary of installation costs while Appendix Table D-3, Appendix Table D-4, and Appendix Table D-5 provide the details of the lighting retrofit analysis for the three buildings. The following table summarizes these into simple payback and Life-Cycle Cost-Benefit Analysis (LCCBA) Payback:

Appendix Table D-1: Summary of Payback Analysis

Lighting Retrofit Economics	Building A	Building B	Building C
SUMMARY OF ECONOMIC ANALYSIS			
Simple Payback (Energy Savings Only)			
Total Installed cost for the area	$25,210	$56,049	$32,354
Annual Savings from Retrofit (Energy Only)	$9,438	$7,996	$4,501
Payback	2.67	7.01	7.19
Rate of Return	37%	14%	14%
Payback Including Life-Cycle Annual Savings			
Total Installed cost for the area	$25,210	$56,049	$32,354
Annual Savings from Retrofit	$17,921	$15,557	$9,276
Payback (years)	1.41	3.60	3.49
Rate of Return	71%	28%	29%

- Notes on Appendix Table D-1:

  1. Simple Payback, while used by many, does not properly account for the inherent advantages of installing new equipment that has longer life, and in general, better performance. These factors are taken into consideration with the LCCBA calculations which show significantly improved payback periods.

  2. Taken together, these results suggest that incentives may be required to produce changes in markets where either electricity costs remain lower than average or short-term perspectives drive retrofit decisions. However, where electricity costs are higher than average or longer-term (life-cycle) benefits drive retrofit decision-making, the economic case for using the Spectrally Enhanced Lighting method are clearly demonstrated in this table.

- Notes on Appendix Table D-2:

  1. The normalized installed cost per retrofit luminaire is fairly consistent between the three buildings. The range is from $58.98 to $68.21, with an average cost of $62.27 per luminaire.

  2. The normalized installed cost per square foot is partially a function of the luminaire density (luminaires per square foot). The range is from $0.67 to $.87 per square foot, with an average of $0.79 per square foot. In reviewing this cost with the installing contractors, the normalized cost for these installations are consistent with generally accepted norms for lighting retrofit costs in the geographic regions being served.

3. Both Building B and Building C have the normalization for materials and labor calculated into the Table. While Building A retrofit contractors reported that the installation times were longer than normal due to the unique construction of the luminaires and the ceiling heights, no normalization factors were applied to the economic analysis of this building on the presumption that this field condition was not rectifiable as a matter of equipment selection as were Buildings B and C.

D3.0 Discussion

D3.1. General Considerations:

- The economics of these retrofits are performed using energy and labor rates unique to California. While the energy rates are high relative to other regions in the United States, it is reasonable to assume that lower energy rate regions generally have lower labor rates as well. Therefore, lower installation costs and lower energy savings are conjectured to balance out in many regions, yielding similar payback results. Lighting practitioners are encouraged to use the Table format found here to calculate results based on the labor and energy rates specific to their projects.
- The analysis does not take into account the additional benefit that might be derived for buildings owners by capitalizing on the currently available tax deduction for installation of energy saving equipment. For office spaces, this benefit could be substantial, as it allows for deducting the entire amount of equipment installation, up to $0.60 per square foot, if the LPD is at or below .75 Watts per square foot. In these retrofit installations, Buildings A and B came very close to this value, and would have been able to deduct $0.59 per square foot of the installed cost, had they been privately owned companies. Note that Building A's total installed cost was $0.87 per square foot, and Building B's total installed cost was $0.67 per square foot.
- This study was limited by the use of parabolic luminaires in which no de-lamping was allowed. For other luminaire types, such as lensed luminaires, the energy savings are likely much greater since de-lamping becomes a very good option in these cases. Alternatively, there are many forms of retrofits possible for parabolic luminaires that allow for de-lamping, but were not entertained in the study due to the need to maintain the existing optics in order to minimize variables that might affect the occupant satisfaction portion of the study.
- Through discussions with several retrofit contractors including those in this study and others that perform this work regularly, it appears that the normal time taken to retrofit these types of luminaires is approximately 20 minutes when there is no re-wiring necessary. When re-wiring is necessary, the time can vary from 30 to 45 minutes, as witnessed in the installations for Buildings B and C.
- Taken in its entirety, the conditions of this study result in a slightly conservative approach to evaluating the economics for lighting retrofit installations.

D3.2. T12 to T8 Retrofit Analysis:

- The economic analysis of these buildings demonstrate that the T12 to T8 conversion retrofits are extremely compelling and that short term paybacks are easily obtainable when combining the spectral contributions of Spectrally Enhanced Lighting with the equipment efficiencies of replacing magnetic ballasts with electronic ballasts.
- The study concludes that roughly half the 46% energy savings through this retrofit strategy are derived from the use of the Visual Effectiveness Method and Spectrally Enhanced Lighting and that the combined long-term benefits result in a 1.4 year payback.

D3.3. T8 to T8 Retrofit Analysis:

- The economic analysis of these buildings demonstrate that retrofitting existing T8 lamps with electronic ballast to new T8/electronic ballast systems result in 19% - 27% energy savings, depending on the pre-retrofit lamp color specifications. The payback for these installations is highly dependent on the specific lamp/ballast combination used for the retrofit since this affects material cost, wiring costs, labor costs, and the energy savings.

- The normalized payback including life-cycle annual savings of 3.5 years for the T8 to T8 retrofits is quite good for many building owners and applications. This value would be decreased considerably if the project could take advantage of the currently available tax incentive. However, if the building owner has short-term economic criteria, the simple payback calculations suggest that this solution is not as economically viable.

D3.4. Extrapolation to Other Lighting Installations

- The economics shown in the tables are for the specific installation of parabolic retrofit lighting limited to a lamp-for-lamp replacement and presumes the base case to be that of a building for which no lighting retrofit is being considered. This presumption in the economic analysis presents the most conservative case in evaluating the economics of Spectrally Enhanced Lighting. Alternative lighting applications and the potential economic benefits are described below:

    1. *What would be the projected economics if de-lamping was an option?* Because the energy savings and lighting level reductions are equal with Spectrally Enhanced Lighting (assuming the same lamp and ballast technologies), de-lamping becomes quite attractive with systems that can be retrofit in this manner without affecting the luminaire optics. In this case, the quantities of lamps and ballasts are generally reduced, and energy savings are compounded by using more efficient lamp/ballast systems. For example, when retrofitting from a 3-lamp to a 2-lamp configuration, the Spectrally Enhanced benefit of 25% and the additional efficiency of a 3rd generation high-lumen 850 T8 lamp can easily provide equal visual effectiveness over 700-series lamps by de-lamping one lamp, resulting in 33% peak load reduction and energy savings. The Spectrally Enhanced Lighting benefit often times allows for de-lamping in installations that would otherwise not be able to use this retrofit strategy, due to the inherently high initial savings attributable to the spectral effect of the 850 lamp.

    2. *What are the projected economics of the case where a building owner is already considering a lighting retrofit?* In this case, the base case in the economic analysis would be an impending retrofit installation. The difference in initial costs between a non-Spectrally Enhanced lighting retrofit and a Spectrally Enhanced Lighting retrofit are minimal, or in favor of the SEL retrofit in the case where de-lamping is possible. The additional energy savings of 19%-27% through Spectrally Enhanced Lighting are therefore acquired through no additional cost, or perhaps at a reduced cost. The payback in this scenario is therefore immediate and the Rate of Return is infinite.

    3. *What are the economics of installing Spectrally Enhanced Lighting in new construction?* The maximum advantage of Spectrally Enhanced Lighting can be found in new construction, where the Visual Effectiveness calculations can be used to determine alternate lighting approaches that will reduce the lamp/ballast counts in proportion to the photopic light level reductions allowed by the compensatory spectral effects. In this case, the initial cost will be reduced through fewer components (lamps, ballasts, or luminaires), energy savings are immediate, and compliance with energy codes is substantially easier.

- The scenarios in lighting design are numerous and beyond the scope of this report. However, the findings of this report support the use of Spectrally Enhanced Lighting as a design method, and the initial cost of implementing this method are typically no higher than other lighting designs. In comparison to a pre-destined lighting installation, therefore, the general economic conclusion is that the 19%-27% energy savings associated with Spectrally Enhanced Lighting are a no-cost benefit, yielding an immediate payback when compared to otherwise identical non-Spectrally Enhanced lighting installations.

D4.0 Conclusions

The economic analysis demonstrates that the retrofit of existing lighting systems through the use of Spectrally Enhanced Lighting is a viable and potentially profitable venture for many commercial buildings. Specifically, the installation costs of installing Spectrally Enhanced are no higher than other forms of lighting retrofits, making the incremental energy savings of 19%-27% a no-cost benefit to commercial office building tenants and/or building owners who are already considering retrofitting their lighting. For buildings that were not considering a lighting retrofit and still have T12 lamps, Spectrally Enhanced Lighting can provide a 71% Rate of Return on their investment over the life of the system, and a 30% Rate of Return is obtainable for buildings with existing T8 lamps. Finally, for new construction, Spectrally Enhanced Lighting provides a design tool that will reduce the initial construction costs and provide peak load reductions and long-term energy savings for the building owner/tenant.

Appendix Table D-2: Lighting Retrofit Analysis: Summary of Installation Costs

Lighting Retrofit Economics	**Building A**	**Building B**	**Building C**
OFFICE AREA DESCRIPTION			
Area under study	28,417	81,879	38,629
Number of Retrofit Luminaires	364	924	539
Luminaire Density (sq. ft. per Luminaire)	78	89	72
INSTALLATION COSTS - MATERIALS COST			
Materials Costs			
Lamp costs per luminaire	$8.25	$13.50	$8.25
Ballast cost per luminaire	$15.50	$26.09	$31.36
Added wiring cost per luminaire	$0.00	$7.52	$0.00
Materials cost per luminaire	*$23.75*	*$47.11*	*$39.61*
Tax	8.25%	8.25%	8.25%
Total materials cost per luminaire	*$25.71*	*$51.00*	*$42.88*
Labor Costs			
Man hours per luminaire	0.50	0.75	0.75
Labor Rates	$85.00	$55.35	$65.45
Labor cost, per luminaire	*$42.50*	*$41.51*	*$49.09*
Summary of Actual Project Cost			
Total cost for the area	$24,828	$85,478	$49,570
Total installed cost per luminaire	$68.21	$92.51	$91.97
Total installed cost per sq. ft.	$0.87	$1.04	$1.28
NORMALIZATION			
Materials Cost Reductions			
Ballast cost per luminaire	$0.00	-$10.09	-$15.36
Added wiring cost per luminaire	$0.00	-$7.52	$0.00
Materials cost Reduction per luminaire	*$0.00*	*-$17.61*	*-$15.36*
Tax	8.25%	8.25%	8.25%
Total Materials Cost Reduction per luminaire	*$0.00*	*-$19.06*	*-$16.63*
Labor Cost Reduction			
Man hours per luminaire	0.00	-0.25	-0.25
Labor Rates	$85.00	$55.35	$65.45
Total Labor Cost Reduction, per luminaire	*$0.00*	*-$13.84*	*-$16.36*
Total Normalization Reduction			
Normalized Materials Cost per Luminaire	$25.71	$31.93	$26.25
Normalized Labor Cost per Luminaire	$42.50	$27.68	$32.73
Normalized Total Cost per luminaire	$68.21	$59.61	$58.98
Normalized Total Cost for Analysis	$24,828	$55,078	$31,788
Normalized cost per sq. ft.	$0.87	$0.67	$0.82

Appendix Table D-3: Lighting Retrofit Analysis, Building A

LIFE-CYCLE COST-BENEFIT ANALYSIS - BUILDING A		
System Description	**EXISTING**	**RETROFIT**
Initial Costs		
Lighting System: Initial installed cost	$0	$24,828
System Material Costs	$0	$9,358
System Labor Costs	$0	$15,470
Lamp Disposal *Cost ea.* $ 0.35	$0	$382
Total installed cost	$0	$25,210
Installed cost per square foot	***$0.00***	$0.89
Total Installed Cost	**$0**	**$25,210**
Annual Energy Costs		
Total power used by lighting system (kW)	41.2	22.4
Power density (W/sq.ft.)	1.45	0.79
annual operating hours	3350	3350
annual energy use (kWh)	137,914	74,993
cost of energy	$0.15	$0.15
Annual Lighting System Energy Costs	**$20,687**	**$11,249**
Other Annual Operating Costs		
Cost of lamps annually (Spot Relamping)	$2,077	$1,839
cost of lamp	$1.00	$2.75
per lamp disposal cost	$0.35	$0.35
cost of installation/lamp	$15	$15
Cost of ballast replacement	$14,070	$2,423
cost per ballast	$15	$15.50
ballast life (yrs)	10	15
Luminaire washing cost	$211.70	$169.36
no. of cleanings/yr	0.12	0.09
cost per luminaire (labor)	$5	$5
Annual insurance cost	$0	$378
percent of initial cost	1.5%	1.5%
Annual property tax cost	$0	$1,261
percent of initial cost	5.0%	5.0%
Subtotal, annual maintenance costs (incl. tax)	$13,087	$4,856
owners income tax rate	20%	20%
Income tax effect of depreciation	$0	($252)
system economic life	20	20
annual depreciation	$0	$1,261
Other Annual Operating Costs	**$13,087**	**$4,604**
Total, Annual Operating Costs	**$33,774**	**$15,853**
Retrofit Installation Costs	**$25,210**	
Annual Savings from Retrofit	**$17,921**	
Payback Including Life-Cycle Annual Savings	**1.41**	
Rate of Return	**71.1%**	

Appendix Table D-4: Lighting Retrofit Analysis, Building B

LIFE-CYCLE COST BENEFIT ANALYSIS - BUILDING B		
Initial Costs		
Lighting System: Initial installed cost	$0	$55,078
System Material Costs	$0	$29,507
System Labor Costs	$0	$25,572
Lamp Disposal *Cost ea.* $ 0.35	$0	$970
Total installed cost	$0	$56,049
Installed cost per square foot	**$0.00**	$0.68
Total Installed Cost	**$0**	**$56,049**
Annual Energy Costs		
Total power used by lighting system (kW)	80.6	64.7
Power density (W/sq.ft.)	0.98	0.79
annual operating hours	3350	3349
annual energy use (kWh)	269,919	216,613
cost of energy	$0.15	$0.15
Annual Lighting System Energy Costs	**$40,488**	**$32,492**
Other Annual Operating Costs		
Cost of lamps annually (Spot Relamping)	$5,272	$6,354
cost of lamp	$1.00	$4.50
per lamp disposal cost	$0.35	$0.35
cost of installation/lamp	$15	$15
Cost of ballast replacement	$17,858	$6,348
cost per ballast	$15	$16.00
ballast life (yrs)	10	15
Luminaire washing cost	$537.40	$533.53
no. of cleanings/yr	0.12	0.12
cost per luminaire (labor)	$5	$5
Annual insurance cost	$0	$841
percent of initial cost	1.5%	1.5%
Annual property tax cost	$0	$841
percent of initial cost	1.5%	1.5%
Subtotal, annual maintenance costs (incl. tax)	$18,934	$11,934
owners income tax rate	20%	20%
Income tax effect of depreciation	$0	($560)
system economic life	20	20
annual depreciation	$0	$2,802
Other Annual Operating Costs	**$18,934**	**$11,373**
Total, Annual Operating Costs	**$59,422**	**$43,865**
Retrofit Installation Costs	**$56,049**	
Annual Savings from Retrofit	**$15,557**	
Payback Including Life-Cycle Annual Savings	**3.6**	
Rate of Return	**27.8%**	

Appendix Table D-5: Lighting Retrofit Analysis, Building C

LIFE-CYCLE COST-BENEFIT ANALYSIS - BUILDING C			
Initial Costs			
Lighting System: Initial installed cost		$0	$31,788
System Material Costs		$0	$14,149
System Labor Costs		$0	$17,639
Lamp Disposal	*Cost ea.* $ 0.35	$0	$566
Total installed cost		$0	$32,354
Installed cost per square foot		**$0.00**	$0.84
	Total Installed Cost	**$0**	**$32,354**
Annual Energy Costs			
Total power used by lighting system (kW)		43.8	34.9
Power density (W/sq.ft.)		1.13	0.90
annual operating hours	*(from worksheet)*	3350	3349
annual energy use (kWh)		146,799	116,791
cost of energy		$0.15	$0.15
	Annual Lighting System Energy Costs	**$22,020**	**$17,519**
Other Annual Operating Costs			
Cost of lamps annually (Spot Relamping)		$3,075	$3,267
cost of lamp		$1.00	$2.75
per lamp disposal cost		$0.35	$0.35
cost of installation/lamp		$15	$15
Cost of ballast replacement		$10,417	$3,703
cost per ballast		$15	$16.00
ballast life (yrs)		10	15
Luminaire washing cost		$313.48	$300.85
no. of cleanings/yr		0.12	0.11
cost per luminaire (labor)		$5	$5
Annual insurance cost		$0	$485
percent of initial cost		1.5%	1.5%
Annual property tax cost		$0	$485
percent of initial cost		1.5%	1.5%
Subtotal, annual maintenance costs (incl. tax)		$11,045	$6,593
owners income tax rate		20%	20%
Income tax effect of depreciation		$0	($324)
system economic life		20	20
annual depreciation		$0	$1,618
	Other Annual Operating Costs	**$11,045**	**$6,270**
	Total, Annual Operating Costs	**$33,065**	**$23,788**
Retrofit Installation Costs		**$32,354**	
Annual Savings from Retrofit		**$9,276**	
Payback Including Life-Cycle Annual Savings		**3.5**	
Rate of Return		**28.7%**	

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