PIER Lighting Research Program

California Energy Commission
Contract # 500-01-041

Complementary Research Review

Deliverable 6.3.4b

May 26, 2004

Submitted To:
Accounting Office, MS-2
California Energy Commission
1516 Ninth Street, 1st Floor
Sacramento, California 95814

Submitted By:
Architectural Energy Corporation
2540 Frontier Avenue, Suite 201
Boulder, Colorado 80301

Prepared By:
Heschong Mahone Group Inc.

Table of Contents

Contact Information:

Heschong Mahone Group Inc.
11626 Fair Oaks Blvd. #302
Fair Oaks, CA 95628
(916) 962-7001
dmahone@h-m-g.com
Subcontract Project Manager:
Douglas Mahone

Architectural Energy Corporation
2540 Frontier Avenue
Boulder, CO 80301
(303) 444-4149
jporter@archenergy.com
AEC Program Director:
Judie Porter

Complementary Lighting Research Review
Project 6.3 Lighting R&D/Codes Scoping Study

Executive Summary

Context

This report provides a discussion of the research context around each of the PIER Lighting Research Program (LRP) projects. This context includes prior and ongoing research that compares the general approach taken by each PIER project with other possible approaches, research that suggests specific improvements that could be made to prototype products, and research that suggests future directions for a specific project either within or beyond the LRP. Awareness of parallel efforts and applications creates opportunities to contact other researchers and manufacturers that are involved with these same technologies to leverage each other's efforts.

Structure of this research review

For each project, the discussion has been broken up into two main sections: "general research issues" and "issues specific to the LRP project". The former sections contain discussions of the major ongoing research issues relevant to each project, and of what further research may be needed to better understand the issues; the latter sections contain details of specific research findings or research needs that should influence the development of that project.

Typically, the analysis of each LRP project contains some or all of these elements:

- Accurately characterizing the base case conditions of the technology that the LRP products would replace. This characterization includes:
    - The current and projected quantity or market share of products installed in California buildings.
    - Key features of the base case technologies including visibility cost, energy consumption, longevity, maintenance and ease of integrating into current building construction practices.
    - Market research on what people like about the product and what they would like improved.
    - Human behavior. This includes frequency of use of areas and lighting, need for wayfinding and security, and the biological impacts of lighting.
- Adequately describing the key features of the proposed technology in terms of visibility, cost, energy consumption, cost-effectiveness, longevity, maintenance, and ease of integrating into current building construction practices.
- Accounting for human factors: frequency of use, user acceptance, and biological impacts.

- Market research on user acceptance of unique features of the product and what they would pay for the product.
- Awareness of pros and cons of other competing technology, although since manufacturers' development work is confidential, it is often not possible to find information on products that are under development.
- Specifically for codes and standards, pertinent issues include: likely energy savings, cost-effectiveness, current favorability of codes toward the product, the level of market maturity, and competition.

Summary of Research Findings and Recommendations

The following list is not exhaustive; it summarizes the most important or relevant findings and recommendations for each project. For details, refer to the main body of the report.

2.1 Light Emitting Diode (LED) Luminaires for Exterior, Porch and Perimeter Lighting

- The Color Rendering Index (CRI) commonly used to describe the color quality of lamps, does not seem to describe narrow-band (monochromatic) sources such as LEDs very well, and is under review by CIE. Until this review is complete, product developers should always visually assess the color quality of LEDs under various conditions, rather than relying on the CRI.
- The features, performance, and aesthetics required of outdoor luminaires by homeowners are not well understood, due to the fragmented nature of the residential outdoor fixture market. For instance, it is not known whether homeowners buy outdoor luminaires primarily to provide light for wayfinding, or for security, or for aesthetic reasons. It is not known whether homeowners will see a need for 'standby' lighting. Research including focus groups and surveys may help to ensure market success for the prototype fixtures.

2.2 LED Task Light Utilizing New Materials to Reduce Thermal Stress on High Brightness LEDs

- The development of new materials, manufacturing methods, and designs in the LED market is very fast-paced.
- The performance and service life of the prototype task light could be improved by increasing the rate of convective air flow over the LED heat sinks and the fixture body. Every additional degree of temperature reduction will improve both the efficacy and life of the LED source.

2.3 LED Low Profile Fixtures

- The efficacy of the prototype fixture is lower than that of currently available fixtures using incandescent lamps.
- The efficiency of the first prototype luminaire was limited by the design of the reflector.

- The efficacy of commercially-available LEDs is expected to continue to increase rapidly; the efficiency of the fixture will increase in the same proportion.
- It may be possible to use the experience gained in project 5.1 to develop a bi-level elevator luminaire that takes advantage of the increased life and increased efficiency of LEDs at low output levels.

3.1 Retrofit Fluorescent Dimming with Integrated Lighting Controls

- The controls infrastructure developed within this project allows a wide range of possible control algorithms to be used. Commercially-available systems tend to use only a narrow range of options, but research shows that options common outside the United States (such as switching the fixtures on at the same level they were set to when switched off) can result in significant energy savings. Research indicates that certain features are appreciated by occupants and these could be designed into the control algorithm.
- The prototype system allows luminaires to be controlled in small groups with no additional wiring. The use of small control groups (1, 2, or 3 luminaires) has been shown to further increase energy savings and improve occupant satisfaction compared to the use of larger control groups.
- The economic viability of the system may not be as good as reported in the technology transfer plan, and vary significantly between one building and another. The challenge may be to find existing buildings with high energy consumption that are undergoing lighting retrofits in which the prototype control system can be installed cheaply.
- Triac-based control systems are being developed that may provide competition to the prototype system. However, this system may offer advantages in terms of power quality, and it might be worthwhile to quantify the power quality impacts of both systems.

3.2 Energy Efficient Load Shedding Technology

- Lighting load shedding may be the cheapest per-kW option available to utilities who wish to expand their load shedding capability, so widespread adoption is possible.
- Each year, lighting load shedding might create between 1 and 3MW of sheddable load in California. This is only a few tenths of a percent of the total sheddable load in the state, but since the annual contribution of lighting load shedding would increment over time, the eventual contribution could be 10% or more, assuming 10% market penetration by load shedding ballast systems.
- The LRC has performed a series of experiments that suggest that office occupants are unlikely to object to the use of lighting load shedding, as long as they are informed about the ecological and societal reasons for it, and as long as it occurs infrequently. It should be noted that conventional daylight-linked lighting control systems function in much the same way, and that well-commissioned daylight-linked systems are well accepted by occupants.
- One pilot study is being performed in an office building owned by a utility company. This pilot will be valuable in terms of trialing the functionality of the system, but real-

world trials will be required to demonstrate the persistence of participation in any load shedding program.

3.3 Classroom Photocell and Control System

- The effect of daylight and electric light distributions on the wellbeing and performance of students and teachers in classrooms is not well understood. For instance, it may be important to maintain electric light levels on the 'teaching wall' when the classroom is daylit, to retain the visual focus of students. Monitoring of installed systems may lead to a better understanding of the key determinants of success for a lighting control system, and this project presents a good opportunity to carry out this monitoring, since the functioning and responses of the system are well understood. Any monitoring should take into account the widest possible range of variables, including non-lighting features of the classroom. Post-occupancy assessments of photocontrol systems in sidelit spaces will be conducted by Heschong Mahone Group during 2004 to inform the 2008 Title 24 standard.
- The target illuminance level for the photosensor of 500 lux used in this project is on the higher range of what is required by students or teachers per codes and standards such as those set by IESNA and CIE. If the system works successfully at 500 lux, it could be tested at lower target light levels in order to further reduce energy use.
- The photocell used in this project may be overly susceptible to upward specular reflections of sunlight that lead the sensor to set inappropriately low electric light levels. Simple design changes to the photocell may reduce the probability of this occurring.
- The ability to easily manually override a lighting control system greatly increases the chance that users will accept and continue to use the system. The override features of the system have been intelligently addressed by the design team, and should be considered and tested in detail before the final commercialized system is ready for manufacture. Reasons and triggers for occupant override are not well understood.
- The installation and commissioning of lighting control systems is often not carried out well by contractors. An opportunity exists within this project to work with other controls manufacturers to develop standard design, installation, and commissioning procedures for their systems. A guide to these procedures could be produced for use in schools, and could be used as a template for other similar guides for other building types.

4.1 Hotel and Institutional Bathroom Lighting Project

- It might be possible to achieve significant market success as well as progress in codes and standards if the project team is able to demonstrate experimentally that this system provides adequate light for wayfinding and orientation, specifically for the demographic groups likely to live in varying types of institutions.
- Title 24 2005 does not provide incentives for the use of energy-saving control systems in hotel and motel bathrooms, and may require an inappropriately short delay time for the motion sensor; this could be changed for the 2008 edition.

- The color of the LEDs chosen for the bathroom fixture may have a minimal effect on the degree of circadian disruption caused to hotel guests based on recent information from the Lighting Research Center.

4.2 Energy Star Residential Fixture Project

- If this project is successful, research data suggests that it might be fruitful for a future project to address improved designs for energy-efficient *outdoor* residential lighting.
- The features, performance, and aesthetics required of both indoor and outdoor luminaires by homeowners are not well understood, due to the fragmented nature of the residential fixture market. For instance, it is not known whether homeowners buy indoor luminaires primarily to provide task lighting, or for general illumination, or for aesthetic reasons. Research including focus groups and surveys may help to ensure market success for the prototype fixtures.

4.3. Development of Energy Efficient Retrofit/Remodel Alternatives to Incandescent Downlights

- There may be minimal safety concerns regarding the use of twin-lamp ballasts in residential fixtures. When one of the lamps controlled by the twin-lamp ballast burns out, the other lamp will also be powered OFF. In the absence of consistent labeling that identifies which lamps are wired in tandem, the user may be confused as to why replacing one of the lamps does not fix the problem, and may be tempted to tinker with the fixture electronics.
- The thermal performance of residential indoor luminaires varies widely, and ballast case temperatures sometimes exceed manufacturers' recommendations and may lead to early ballast failure. No standardized thermal test procedure exists for residential luminaires; a standard thermal test might usefully be adopted into the ENERGY STAR® requirements. Pacific Northwest National Laboratories have conducted extensive thermal testing and have developed fixture design guidelines that could be adopted more widely.
- Thermal testing of the fixture has been carried out, but the test fixture did not include a gasket or caulking between the fixture and the sheetrock, as required by Title 24 2005. The fixture should be tested with a gasket in place as a final check on thermal performance.
- The light distribution of the fixture is optimized for the cut-off requirements of office lighting rather than residential lighting. Other reflector options might increase the acceptance (both short-term and long-term) of CFL luminaires by homeowners. The persistence of residential hardwired (bi-pin) CFL fixtures is not known.

4.4 Portable Office Lighting Systems

- Portable office lighting systems represent a very large opportunity for energy saving, compared with ceiling-based lighting. This potential is not recognized by Title 24 which does not address the use of portable fixtures. It might be justifiable to include a Power Adjustment Factor in Title 24 2008 to recognize this potential energy savings. Portable systems also offer benefits to occupants by increasing the degree of control and the autonomy that occupants feel over their environment.

- The photometrics and aesthetics of the fixture in real office environments have already been considered by the design team, but will require close attention to ensure successful commercialization. It appears to be photometrically possible to use portable fixtures in offices with standard-height ceilings.
- The experience of companies already attempting to market similar products in the United States should be leveraged by the design team. Patent checks should be carried out.

4.5 Integrated Classroom Lighting System

- This system offers a wide range of non-energy benefits that have not yet been incorporated into the marketing plan for the system. These are described in full below.
- As with project 3.3, this project offers a valuable opportunity to investigate whether alternative strategies for photocontrol (such as using photocells pointed at the teaching wall, or multiple photocells) offer benefits in terms of perceived lighting quality or energy saving.
- This system fulfils the power density and control requirements for the forthcoming 2005 edition of the Title 24 standards, and offers a variety of usability features that go beyond Title 24 recommendations and may increase the robustness and utility of the system. Nevertheless, the system may not achieve lower energy consumption than classrooms that have only bi-level manual switching, since research indicates that those classrooms already have comparatively low energy consumption. Monitored data will be required in order to demonstrate savings.
- Existing commercially-available wiring and cabling technologies and systems should be leveraged to reduce the installation cost of the packaged system. Design advice and installation, and commissioning guidelines will be an integral part of the marketing success of the system.
- A factory-commissioned photocell should not be relied upon to control the luminaires, since classroom geometry, surface reflectances, and daylight distributions change from one classroom to another and may change during construction. Some type of on-site commissioning will always be required. The LRC's self-commissioning photocell may be useful in this context.
- Classrooms are often well daylit and are occupied during afternoon peak times, so they present an opportunity to reduce peak electrical lighting loads. The value to electrical utilities of daylight-linked control systems in classrooms should be investigated as a major benefit of this system.

5.1 Bi-Level Stairwell Fixture Performance

- Code changes in Title 24, such as Power Adjustment Factors might help to create a market for this type of fixture. Although the fixture is cost effective in the long term, the price may be too high to make the fixture attractive to specifiers without additional incentives. Since the fixture itself is not inherently costly to manufacture, its price can be expected to decline rapidly as the market for it expands. Research on the reliability of motion sensors and detailed monitoring of the energy savings from the system will be required to justify a code change. Motion sensor reliability is particularly important because failed motion sensors may result in dangerously low light levels for visually impaired people.

- It is not clear whether the bi-level fixture will have a detrimental effect on lamp life; it is possible that the fixture will actually extend lamp life, but monitoring of several lamp-ballast combinations is recommended.
- The NFPA 1 fire code requires "fail-safe" operation of motion sensors, but there is currently no detailed description of what fail-safe means. It may be possible to incorporate a definition into the forthcoming California fire code.
- The NFPA 1 fire code also requires minimum 15-minute duration for illumination timers. It's possible that this would have a significant impact on the achieved energy savings, but it should be possible to estimate the magnitude of this effect by analyzing the usage data from stairways monitored by the project team. The possibility of exempting bi-level fixtures from the 15-minute requirement in the forthcoming California fire code could be investigated.
- Photometric calculations should be performed to ensure that, for typical stairwell geometries, the light distribution from the fixture would allow it to meet the requirement of NFPA 1 that the failure of any single fixture should not result in an illuminance less than 2.2 lux in any designated area, while the stairs are lit to a design illuminance of 108 lux. This failure-mode requirement may be particularly problematic in retrofit applications where the stairwell design illuminance is only required to be 10.8 lux.
- At this point in time, the California Building Standards Commission (CBSC) has not yet decided on whether to adopt the new NFPA 1 standard that would increase stairwell light levels ten-fold. On one hand, the new standard would render a bi-level stairwell fixture more cost effective, as there would be greater energy consumption and greater energy savings. On the other hand, the combination of the new standard with the bi-level fixtures would consume more energy than lighting to the existing standard with no controls. The CBSC should check that the NFPA 1 standard is based on peer-reviewed research showing a significant increase in fire safety before adopting a standard that would result in increased energy use.

5.2 Evaluations of Electronic Ballasts and Related Controls for HID Lighting Systems

- The results reported in the Performance Characterization report (deliverable 5.2.1a) seem broadly to agree with figures quoted by manufacturers. This shows both that LBNL's testing facility is well calibrated, and that the figures quoted at least by major manufacturers can generally be relied upon for accuracy. The accuracy of manufacturers' data is further corroborated by their participation in the NVLAP laboratory accreditation program.

5.3 Low Glare Outdoor Retrofit Luminaire

- There appears to be a significant potential for both energy and cost savings through the use of twin lamp fixtures along roads and other areas in which "curfew" dimming is possible. Future research could investigate this possibility.

- There are currently few performance goals set for the prototype fixture. Goals for semi-cylindrical or vertical illuminance, for veiling glare, and for sky glow would be appropriate. The goal of achieving 5 lux at a range of 40-45' from a 15' mounting height seems to be incompatible with the goal of limiting veiling glare.
- The proposed fixture is not dissimilar in photometric terms to stadium or parking lot floodlights, so it may not be possible to improve significantly on the photometric performance of existing fixtures of that type.
- The approach to photometric analysis used in this project could be adapted to analyze the ideal spacings and mounting heights of full cut-off streetlights, which are often used with excessive spacings and overly powerful lamps, which leads to high levels of sky glow and glare.

5.4 DALI Lighting Control Device Standard Development

- The DALI protocol seems to offer a unique opportunity to reduce the design cost, installation and commissioning cost, and the failure rate of lighting control systems. DALI already allows specifiers the freedom to use ballasts from a variety of manufacturers and to be sure that any DALI-compliant ballast will function properly within a DALI system. This project will expand the DALI protocol, and allow specifiers the freedom to use control system modules such as motion sensors and photosensors from a variety of manufacturers.
- It is possible to conduct automatic testing and monitoring of emergency lighting using the lamp error feedback signals already incorporated into DALI. Several manufacturers already offer systems with this functionality, using their own proprietary protocols. This or a future project could attempt to develop standard protocols for automatic testing and monitoring of emergency lighting.

Sources of Research Data

Several approaches were used to gather a broad range of research and corroborating information relevant to the LRP projects. Examples of each type of source are given below:

Published Research

Academic Journals and Conference Papers

1. International Journal of Lighting Research and Technology 2000-2004 (www.lrtjournal.com)
2. Proceedings of the CIE 25th Session, San Diego
3. Proceedings of the IESNA Conference, Salt Lake City, 2002
4. Journal of the IESNA (2000-2004)
5. Journal of Light and Visual Environment 2002-2004 (http://www.jstage.jst.go.jp/browse/jlve/-char/en)

Reports and Studies Published by Institutions

1. Institute for Research in Construction, of the National Research Council of Canada (http://irc.nrc-cnrc.gc.ca/irccontents.html)
2. Florida Solar Energy Center (http://www.fsec.ucf.edu/)
3. Lawrence Berkeley National Laboratory (www.lbl.gov)
4. Lighting Research Center, Rensselaer Polytechnic Institute (www.lrc.rpi.edu)
5. The Building Research Establishment (www.bre.co.uk)
6. Research Group for Inclusive Environments (http://www.rdg.ac.uk/ie/)

Product Information from Manufacturers

1. LED manufacturers
2. Ballast manufacturers
3. Luminaire manufacturers
4. Lighting controls manufacturers

Interviews and discussions

1. Members of the LRP Technical Advisory Group and LRP project team leaders.
2. Experts including lighting designers, manufacturers, code specialists.
3. Online discussion groups.

Complementary Research Review

2.1 Light Emitting Diode (LED) Luminaires for Exterior, Porch and Perimeter Lighting

Erik Page and Michael Siminovitch, California Lighting Technology Center

Outdoor, porch, and perimeter luminaires seem to be an excellent short-term prospect for the use of LED lamps, although the residential market for fixtures of this type is poorly understood, is not friendly to premium pricing, and is dominated by very traditional, low-risk products. It might be risky for a manufacturer to begin to produce an LED fixture without a pilot program to test consumer response.

Title 24 and other standards based on bare-lamp efficacy or fixture efficiency (including Luminaire Efficiency Rating) may be treating LEDs unfairly for applications where light must be closely controlled and directed on to small target areas.

The color quality of LEDs is an important issue and is the subject of ongoing research.

General Research Issues

There are a number of ways in which LEDs are difficult to quantify using the metrics typically used for incandescent, fluorescent, and metal halide lamps, although it should be stressed that there is no fundamental difference in photometry between LEDs and other light sources. The two main difficulties are described below:

LED Efficacy

With the hybrid fixtures and the concrete mount LED pathlight, it is questionable whether the performance of these LED fixtures is good enough 'on paper' to fulfill the "high efficacy" requirements of Title 24 2005, since Title 24 requires a lamp efficacy of 40lm/W, and LEDs a present provide only around 25lm/W. The requirement for a minimum bare-lamp efficacy favors omnidirectional lamps such as CFLs that have high bare lamp efficacies but lower application efficacies (because a reflector is required that typically reduces efficacy by 20-60%).

Alternative methods of quantifying luminaire efficiency, such as the Luminaire Efficiency Rating (LER[1]) might be more equitable because they *do* account for reflector losses, but they do not capture the ability of LEDs to project lumens toward a particular target. The ability of point sources such as tungsten halogen lamps and LEDs to project lumens efficiently toward a target is generally not recognized by luminaire efficiency metrics, and this is a major barrier to the use of potentially efficient fixtures. One solution would be to define "application efficacy", i.e. the number of lumens that arrive at a target, divided by the power consumed by the fixture. There is at present no standard measure of application efficacy, except for the "cone diagrams" for spotlights that give the diameter of the pool of light at various distances from the fixture and the average illuminance within this pool of light. Application efficacy would have to be calculated differently for each application.

LED Color Rendering

Color rendering is an important issue; the poor color rendering of CFL lamps (despite CRI values in excess of 80) is widely regarded as a contributory factor to their low acceptance in the residential market (differences in chromaticity are also believed to be a factor[2]). LED luminaires intended for the residential market should therefore pay very close attention to the color quality of the light sources used, and not rely on CRI as a guide.

LEDs are sometimes not optimized to score well on the color rendering index (CRI), so their CRI values vary widely. Many LED manufacturers do not give figures for CRI, but Lumileds (for instance) produces 'warm white" LEDs with CRI values between 70 and 90, and a paper by Shakir and Narendran[3] quotes measured CRI values as low as 48 and as high as 80. Triphosphor fluorescent lamps typically score between 80 and 85, incandescents score 100 by definition since they are one of the standards by which other lamps are judged.

CRI is intended as a measure of how accurately a light source allows the colors of illuminated surfaces to be judged, but it is a very simple system and, although very widely used, has not been extensively tested against subjective judgments of overall color quality. CRI may also not be suitable as an indicator of other quantities such as 'colorfulness' which may be equally important as color accuracy in many applications. Shakir and Narendran found that LEDs with low CRI values were judged to be more colorful than LEDs and other light sources with higher CRI values. A similar effect can be seen with neodymium-doped incandescent lamps such as GE's 'Reveal' which has a lower CRI value than a regular incandescent lamp but is often judged to produce more vibrant color.

Although there has been no conclusive evidence[4] of the shortcomings of CRI, there is widespread skepticism among the research community about its usefulness, and further research is ongoing. The CIE published a document in 1997 establishing a set of standards for LED photometry[5]. These standards are under continuing review by CIE committees TC2-45 *Measurement of LEDs - Revision of CIE 127* and TC2-46 *CIE/ISO standards on LED intensity measurements*. Some of this research work is being carried out at NIST[6].

Issues specific to the LRP projects

As described in the November 2003 deliverable report "Matrix of New Concepts", this project investigated several different possibilities for incorporating LEDs into residential luminaires, under three broad headings:

- Hybrid LED/Incandescent Security Fixture
- Concrete Mount LED Pathlight
- Photovoltaic LED Pathway Lighting

Another possible application is buried ("in-grade" or "in-ground") luminaires. Lighting designers often want to use these luminaires for architectural emphasis or to enhance wayfinding, but the heat generated by the halogen lamps usually used in small buried luminaires means that the temperature of the top glass of the luminaire can become dangerously high[a]. Halogen lamps are usually limited to 50W or sometimes 75W for this reason, and several highly-priced buried luminaires are available with additional insulation between the lamp and the top glass. LEDs could provide significantly more light without creating high temperatures, and could potentially offer the same performance at lower cost.

Hybrid LED/Incandescent Security Fixture

The suitability of this fixture for the residential market is predicated on the assumption that homeowners will accept the fixture as long as the LED provides "illumination…sufficient to provide coverage to the wall and ground area adjacent to and under the fixture." This is a photometric rather than an aesthetic requirement, and it assumes that the purpose of the luminaire is to provide functional illumination (for

[a] Neither UL 1598 section 14 nor NEC section 410 contains guidelines about the maximum allowable temperature of the top glass. Other regulations may exist. European regulations require top glass temperature to be limited to between 65°C and 80°C.

security or wayfinding) of the ground and the wall, rather than to contribute to the night-time appearance of the building.

The reasons why homeowners buy porch lights and other exterior fixtures are not well understood, and it seems likely that their requirements include both functional and aesthetic criteria. No research has been conducted in this area, although the area of commercial outdoor lighting is much better understood[b]. Furthermore, since residential outdoor fixtures are rarely sold directly by the manufacturer, manufacturers have only a second-hand understanding of homeowners' reasons for buying these fixtures, or their reasons for either keeping them, returning them to the store, or disposing of them. Consequently there is little understanding of the market for residential outdoor fixtures even among key market actors.

Some basic research into the key aesthetic and performance criteria that homeowners look for would clarify whether the appearance and the photometry of the current LED unit are appropriate, or whether a different design would make this fixture better suited to its target market. The aesthetics of the fixture are already being seen as a key determinant of its success - one of the recommendations from the April, 2004 PAC meeting was to have a shroud over the LEDs to block direct view of the light source, while allowing illumination of the wall surface or walkway as intended.

The 2005 California Title 24 standards (section 150(k)6) require that outdoor porch or façade based lighting for residential buildings should either have a high-efficacy lamp source (pin-based CFL) or have both motion sensing and daylight sensing integrated into the product. LEDs do not meet the requirement for high efficacy lamps, so the LED porch light fixture would need to incorporate a daylight sensor that would turn all the lights off (including the LED) during daylight hours and a motion sensor for turning off the lights during unoccupied periods of night. A clarification is being sought from the Commission on whether the low wattage LEDs would be exempt from the motion sensing requirement at night.

Photovoltaic LED Pathway Lighting

Anecdotal evidence suggests that the performance of current commercially available solar pathway lighting is poor. Many customers who have purchased these products express disappointment with the amount of light they produce. No research could be found on the light output or the duration of output of solar pathway lights, except for one paper from 1996[c] concerning low pressure sodium luminaires with lead-acid and lead-antimony batteries, which are different to the batteries used in smaller residential fixtures.

[b] Eley Associates, *Outdoor Lighting Research: California Outdoor Lighting Standards*, report prepared for the California Energy Commission, June 2002. Retreived from http://www.energy.ca.gov/outdoor_lighting/documents/2002-06-18_workshop/2002-06-06_ELEY_REPORT.PDF on 5/3/04

[c] *Photovoltaic Lighting System Performance*, S. Harrington and T. Hund, Sandia National Laboratory, 1996. 8 pp. Available from the National Technical Information Service (NTIS), NTIS Order No. DE96010527.

There is a dearth of knowledge surrounding these fixtures: their actual performance and their target performance are unquantified, and the effect of daily charging and discharging on battery life is unknown and likely detrimental. A push-to-make switch could be used to prevent cycling on evenings during which the fixture is not being used. Some effort may be required to overcome consumer skepticism about these products as a result of the poor performance of existing systems.

Concrete Mount LED Pathlight

Bollards are considered by Underwriters' Laboratory to be "damp location" luminaires (http://www.ul.com/regulators/ode/0803.pdf), and a luminaire mounted in a concrete slab in direct contact with the earth is classed as a "wet location" luminaire. Since LEDs do not require a lamp base, and do not require high starting voltages, they may offer easier and cheaper compliance with UL requirements for damp and wet locations than other lamp types.

Concrete bollards with cast-in fixture housings are made by at least the following companies, who could be considered as manufacturing partners:

- King Lighting
- Lumec
- Architectural Area Lighting
- Stonelight
- Architectural Landscape Lighting

2.2 LED Task Light Utilizing New Materials to Reduce Thermal Stress on High Brightness LEDs

Steve Johnson, Lawrence Berkeley National Laboratory

Thermal stress is the critical factor in LED fixture design, and the nascent condition of the LED fixture market means that there has as yet been little standardization of conductive or convective methods of removing heat from LED fixtures. One LED manufacturer, Lumileds, is trying to adopt a systems approach to ensuring that electrical, electronic, and optical components from different manufacturers can be brought together to produce fixtures that are optically, thermally, and photometrically viable.

General Research Issues

LED Thermal and Optical Performance

Research to improve the thermal and optical performance of LEDs is being undertaken by many manufacturers – not only LED manufacturers, but companies that manufacture printed circuit boards, conductive glues, and other electronic components. Since these technologies are under intense development, third-party programs to quantify LED performance (such as the LRC's NLPIP program) are at a very early and tentative stage, and are somewhat dependent on the ongoing activities of two CIE committees on LED photometry (see section 2.1).

Some recent developments with relevance to this project are listed below:

- The "Lamina" product from Lamina Ceramics[7] allows LEDs to be mounted directly to an engineered metal core without sub-mounts, in order to reduce the thermal impedance of the mounting.
- IRC Electronics has developed a method for printing thick-film circuits directly on to aluminum heatsinks[8], allowing 42% lower thermal impedance than previous methods.
- StockerYale Canada has developed a means of mounting LEDs into a reflective recess in the printed circuit board, which may improve the light distribution and therefore the system efficiency of LED systems. This system is called Chip-On-Board Reflective Array (COBRA)[9].
- Research on improvements to high-brightness LED technology that will allow less heat to be generated by the p-n junction is being done by K.L.Wang at the University of California Los Angeles. Wang published a paper in conjunction with Chinese and German researchers in June 2003 on the properties of tunnel-regenerated multiactive-region LEDs[10].

LED Optical Safety

Some LEDs emitting blue light (including white LEDs) have been found *not* to meet the "eye-safe" requirements of IEC standard 60825-1-2001. This could pose a problem for the use of LED task lights, since the adjustability of the task light might allow prolonged direct viewing of the LEDs by children or possibly by adults.

Researchers appear to believe that blue LEDs are not unsafe for direct viewing, but the CIE recently established a new technical committee (TC 6-55) to review the safety criteria and underlying assumptions of both IEC 60825-1-2001 and CIE S009/E:2002. A brief paper summarizing this issue was presented at the CIE Conference in San Diego, 2003[11].

Issues specific to the LRP project

The efficacy and the service life of LEDs improve continuously as their operating temperature is reduced, so the conduction and convection of heat away from LEDs is a major determinant of their performance. Product data from Lumileds[12] indicates that adequate heat dissipation for a 5W LED can be achieved using a 1.5" square, 1.3" deep aluminum heat sink in free air. If four 5W LEDs were used (producing light output similar to a 35W MR16 lamp or a 13W biax CFL), four 1.5" square heat sinks would be required, which would fit easily within the same volume currently occupied by the luminaire housing.

The current design of the task lamp incorporates a small vent in the top of the lamp housing that allows some convective cooling. The report on the first prototype task light reported that the temperature of the air inside the luminaire was 45° C after 30 minutes of operation. The report did not give a temperature for the luminaire housing. The air temperature inside open fluorescent luminaires is typically 25-35°C, which suggests that it may be possible to reduce the air temperature inside the prototype fixture by improving airflow over the heat sinks.

Heat sinks and cooling methods for computers and other electronic devices are highly developed; research papers and product data on the design of heat sinks are available online, and may be a useful source of design ideas.

2.3 LED Low Profile Fixtures

Nadarajah Narendran, Lighting Research Center

The accurate beam control and small size of LEDs suggest that they may be suitable for a variety of applications in which space is limited. The combination of LEDs with novel reflectors and other optical devices may create new aesthetic possibilities, which may increase the rate of acceptance of LEDs into the commercial market. At this time, however, the high cost of LEDs and the uncertainty surrounding the possible benefits and drawbacks of their use means that manufacturers are reluctant to risk development money on novel fixture types. The LRC's prototype fixture may help to expand the range of luminaire options considered by manufacturers' R&D staff.

General Research Issues

The general research issues identified in section 2.1 and section 2.2 also apply to this section.

Issues specific to the LRP project

We were not able to identify any commercially-available technologies that would improve the performance or marketability of this fixture, but since photometric information about competitive incandescent fixtures is available, we performed a photometric comparison that shows that the prototype fixture is currently around three times less efficient than best practice. This difference is due mainly to unavoidable light loss in the reflector arrangement.

We understand that the LRC has designed an alternative LED fixture that uses the LEDs in a direct arrangement, and avoids the reflector losses incurred with the initial prototype. They are working toward a target of 16-20 lm/W for the new fixture.

Fixture Efficiency

The Technology Transfer Plan (deliverable 2.3.7) claims that the low-profile LED fixture is 20% more efficient than the base case. However, the base case chosen for comparison (50W mains voltage internally-reflectorized R30 lamp) is not commonly used in new elevators. A more appropriate base case for comparison is current MR-16 lamps, which have a similar recess depth and similar photometric distribution to the prototype low-profile fixture, and are commonly used in elevators.

Tungsten halogen lamps are widely available with infra-red reflective ("IRC") coatings on the lamp capsule that reflect heat back on to the filament, reducing radiative heat loss and thereby improving the performance of the lamp. Elevator manufacturers looking for higher-performance lighting would appraise the upgrade to IRC lamps as a less expensive alternative to LEDs.

Photometric data available on the Osram website shows that their Halostar 50W VWFL IRC lamp (product number 48870) delivers an average of 160 lux at a range of 3m inside a 30 degree cone, which translates to an application efficiency of 30 lm/W. Similarly Philips reports 1180 lumens from its 45 Watt MasterLine® ES IRC MRC16, which translates to 26 lm/W. Current best practice for low-profile elevator lighting can therefore be benchmarked at around 25 lm/W. These figures incorporate reflector losses and luminaire losses (since no luminaire is required) but not transformer losses.

The low-profile LED luminaire has not been photometrically tested, and no details are given in the report of the basis for the photometric comparison, but an approximate assumption would be that current LEDs produce 25 lm/W, and that the reflector used in the LED fixture is 40% efficient. Using these assumptions, the fixture might be expected to produce around 10 lm/W. So with current LED technology, the low-profile fixture's efficiency is only one-third as good as current incandescent technology. Recently, the efficiency of commercially available LEDs has been approximately doubling every 2-3 years, so the performance gap can be expected to close over time if, as expected, LED efficiency continues to rise. Cost may remain an issue in the commercialization of LEDs for a number of years.

It may be possible to use the experience gained in LRP project 5.1 to develop an elevator luminaire that dims to a low level when the elevator is unoccupied; this would take advantage of a unique feature of LEDs - their increased life and increased efficacy at low output levels. There is a comparable gain in life for incandescent lamps, but their efficacy drops rather than improves when they are operated at low levels.

3.1 Retrofit Fluorescent Dimming with Integrated Lighting Controls

Francis Rubinstein, Lawrence Berkeley National Laboratory

Theoretical calculations of energy savings from daylight linking and motion sensors are a common topic of research, but comparatively few studies of achieved energy savings in the field have been conducted. Those studies that are available back up the predictions of lighting energy use made in the Technology Transfer Plan (deliverable 3.1.7).

A few studies have been published that estimate baseline lighting energy use when only simple light switches are used. Predictions of lighting energy savings from the proposed system should be based on these studies if the integrated control system is intended for widespread use. Using this method, the predicted lighting energy savings are lower than those quoted in the Technology Transfer Plan, this suggests that the integrated control system should, at least initially, be selectively targeted toward buildings that currently have high lighting energy use, rather than sold as an option for all office building retrofits.

General Research Issues

Estimated Savings from Dimming Ballasts and Controls

A study by Moore et al.[13] measured average lighting loads during working hours in 14 office spaces in which various lighting control systems had been operating for a number of years. Five of the buildings studied by Moore et al. had lighting control systems with manual dimming and scheduled off-switching similar to the system proposed in LRP project 3.1; in these buildings the simple (unweighted) average lighting load was 54% of full load. Two of the buildings studied by Moore et al. had daylight linking in addition to manual dimming and scheduled off-switching; in these buildings the simple average lighting load was 37%. In this context, the 50% lighting load assumed by the researchers in project 3.1 seems reasonable.

However, to calculate the payback period for the control system, the anticipated lighting load should be compared with an estimate of the base-case lighting load, which will be less than 100%. Again, comparatively few studies of base-case lighting loads have been conducted.

A recent study by Mahone et al.[14] analyzed manual switching patterns in open offices and private offices that had no lighting control systems, and varying levels of access to daylight. Private office lighting loads averaged 55% during peak times (2:00-4:00p.m.), and the average load during all periods when the offices were occupied was 53%. The second figure is an upper bound for the average lighting load during "working hours". Open office lighting loads averaged 72% at peak times. Mahone et al. did not collect occupancy data for open offices, so no upper bound figure is available. It could reasonably be assumed that 72% is an upper bound, since many other research papers have shown that lights in open offices are almost never switched off during the day, and are seldom switched on except first thing in the morning or after lunch (before the peak period).

In the Technology Transfer Plan (deliverable 3.1.7) energy savings from the proposed system are quoted relative to a base case in which lights are switched on 100% of the time. We would recommend that these figures be revised to accommodate the likelihood that in most offices, lights will not be used at full capacity. Using 72% average load as the base case, the energy savings in open plan offices from the proposed control system are around half the values estimated in the Technology Transfer plan. Using 55% average load as the base case, the proposed control system saves hardly any energy at all. All the figures quoted above are subject to a fairly high degree of error, especially since they are derived from studies conducted in different countries, and there is a great deal of variability between offices – in some offices, lights are actually used at or near full capacity.

Ways of Quoting Lighting Energy Use

Measuring the average lighting load during working hours is a slightly arbitrary way to quantify lighting energy consumption, and is subject to a high degree of error caused by different researchers' assumptions about when "working hours" occur. A more useful measure would be the average lighting load taken over an entire year, including weekends and night-time periods. An entire year of measurement is required because, as Moore et al. found, lighting loads can vary very significantly from summer to winter. A full-year average also allows different lighting control strategies to be directly compared, for instance a system that performs a timed sweep of the building's lighting at 8:00p.m would save almost no energy during "working hours".

Issues Specific to the LRP Project

Control Algorithms

The technologies developed in this project lend themselves to a variety of possible control algorithms. One algorithm that is not commonly used in the United States, but has been found to yield high levels of energy saving, is one in which the luminaires switch on at the same dimming level at which they were previously switched off. Moore et al. (ibid.) found that systems that reset at the previous off-level (reset systems) had an average power consumption of 42% of full load during hours of occupation, whereas those with pre-set switch-on levels typically had power consumptions close to the pre-set level (i.e., the control systems turned the lights on at, say, 80%, and the occupants did not take the trouble to adjust the lights up or down from the pre-set level). Pre-set systems had a much lower variance from the average than the reset systems did, indicating that occupants used the switches less frequently. Conventional wall switches appear to be a good basis for an automatic control system, offering a combination of amenity, intelligibility robustness. Control systems in which luminaires are zoned in small groups of 1 or 2 luminaires encourage a sense of ownership and therefore reduce the potential for conflict between occupants over who should control the lights. The absence of conflict encourages occupants to use the control system and therefore reduce energy consumption.[15,16.] The control algorithm should therefore allow luminaires to be controlled individually or in small groups.

Fontoynont[17] found in a survey of unsolicited responses that an automatic daylight-linked system with easy manual override may be the 'ideal' lighting control system for an open office, from the point of view of user acceptance. Fontoynont's finding that users generally added a low level of artificial lighting to their workplace (around 300 lux) is consistent with the findings of Moore et al. Fontoynont gives extensive tables of desirable and undesirable features of lighting control systems that could be a useful discussion tool in the further development of the LBNL retrofit dimming system.

Cost of System

LBNL's estimates of the electricity costs avoided by this system assume that the system reduces energy use by around 50% of installed load during hours of occupancy. The analysis above suggests that energy savings during hours of occupancy are unlikely to be as high as 50% in the majority of buildings, although the system may also reduce energy use during non-occupied periods (but this cannot be taken for granted).

Consequently, to achieve widespread economic viability, the installed cost of the system would have to be toward to low end of LBNL's target of $1-2 per square foot. The Technology Transfer Plan (deliverable 3.1.7) suggests using RS Means electrical cost data to estimate the installation cost of the system. RS Means provides the following estimates that include the cost of materials and labor:

Replacement ballasts	
2-lamp dimmable ballast	$126
1-lamp dimmable ballast	$97
Momentary action light switch (20A)	$51
Junction box (4" square, including cover)	$29
Photocontrol (or motion sensor)	$150

Assuming that one three-lamp luminaire illuminates 100 square feet of space, that the decoder box costs $50 and that the costs of the ancillary equipment are divided between 6 luminaires, the installation cost per square foot would be $2.69 per square foot. This figure assumes that the material cost of the ballasts would be no higher than the cost of conventional dimming ballasts, so the installed cost is likely to be higher than the figure quoted, unless 3-lamp ballasts are used.

If the installed cost of the system is at or around this value, then (as mentioned above) the challenge in marketing the integrated control system will be to find buildings that currently have high energy consumption, and in which retrofits can be carried out comparatively cheaply.

Competitive Systems

Industry sources indicate that three major ballast manufacturers intend to have new low-cost retrofittable "triac" dimming ballasts on the market within one year. These ballasts will take their power from existing mains wiring controlled by a rotary wall switch, and will convert this "chopped-up" 60Hz wave form into high frequency power that can run a fluorescent lamp. The performance of these systems cannot be predicted, but they are unlikely to seriously compromise lamp life, otherwise large brand-name manufacturers would not be releasing them. However, the power quality issues raised by the use of rotary wall switches are quite serious, and it is not known to what extent the ballast manufacturers have considered this, and what remedial products or guidelines they might provide.

3.2 Energy Efficient Load Shedding Technology

Andy Bierman, Lighting Research Center

Widespread use of lighting load shedding may be highly attractive to utilities, many of which have already used up many of the most obvious, industrial opportunities for load shedding and are now looking for additional "negawatts" from other sources. The estimated cost per kW of lighting load shedding compares favorably with that of other sources, although the administrative cost remains a large unknown.

The LRC has performed a series of experiments in this PIER program that suggest that office occupants are unlikely to object to the use of lighting load shedding in the short term, as long as the lights are not dimmed much more than 30% and they are informed about the ecological and societal reasons for it, and as long as it occurs infrequently.

The largest unknown factor is whether office occupants and managers will accept lighting load shedding in the long-term. Research carried out by the LRC suggests that office occupants may not even notice the reduction in light levels from lighting load shedding (especially in daylit spaces), and that if they do notice it, they're unlikely to object to it. Office managers remain an unknown quantity – they may object to the hassle and overhead costs of the system, but large-scale pilot studies (one of which is already planned for summer 2004 and funded by NYSERDA) will help to determine the likelihood of acceptance by office management.

General Research Issues

Acceptability to Office Occupants and Managers

LRC's studies into the noticeablility and acceptability of reductions in office light levels are an important contribution not only to this project but to the literature on vision, specifically the role of memory and elapsed time in people's judgments of light levels. For the purpose of this project, these studies now need to be followed up with a study of the long-term acceptability of lighting load shedding systems, to check that the incentives offered are sufficient to retain participants, and that there are no reasons why participants should drop out of load shedding programs.

Occupants' perceptions of the environmental, societal, and cost benefits of load shedding were found to be an important factor in the acceptability of the system, so the long-term study would have to be a real installation responding to real signals sent out by a utility. To evaluate the marketability of lighting load shedding, the study should focus on the overhead costs and degree of administrative and personal inconvenience caused to the staff and management of the company in which the system is installed. There are a number of companies that manufacture load-shedding systems for industrial and residential applications; these companies might be eager to participate in a pilot study that could open up a new market, and would certainly provide added perspective on the market potential, costs, and barriers to further development. The LRC is in talks with utilities that may sponsor pilot lighting load shedding programs.

Since existing load shedding technologies (for various electrical systems, not only lighting) are not currently used in office spaces, there is no existing research or market data on how well load shedding systems are accepted by office occupants. However, participants in domestic load shedding programs have a very high drop-out rate[22]. Although there is no reason to think that lighting load shedding programs would suffer from similarly high drop-out rates, this must be proven by the project team before utilities will be willing to establish a large-scale program.

The ballast manufacturing partner should easily be able to identify from their order book one or more suitable new-build buildings into which a prototype system could be installed.

Effectiveness of Lighting Load Shedding Relative to Daylight Linked Systems

As mentioned above in Section 3.1, daylight-linked dimming systems typically reduce lighting energy use by around 2/3rds in open-plan offices. This means that they are twice as effective at shedding peak load as the proposed load shedding system. The capital cost and the maintenance costs associated with daylight linked dimming systems are higher than for the proposed load shedding system, but the payback for the customer is also higher because their electricity use is reduced throughout the year rather than just during peak periods. The satisfaction of specifiers with daylight-linked dimming systems is typically high[18], although post-occupancy surveys have revealed shortcomings in design and commissioning that should be addressed by manufacturers and by standards bodies[16].

Lighting load-shedding should not be seen as a competitor with daylight linking – rather, these two technologies are appropriate in different types of building: in many existing buildings there is not enough daylight to make daylight linking an economically viable option, whereas in new buildings, good daylighting should always be a determining factor in architectural decisions, and daylight-linked systems should always be installed in daylit areas. Therefore, there should be little crossover between the markets for these different systems. There would be no sense in using a daylight-linked system that also incorporated lighting load shedding.

Furthermore, these two technologies serve different purposes from the point of view of utilities: daylight linking reduces annual energy consumption and also "passively" reduces peak load, whereas lighting load shedding gives utilities a useful and predictable tool for additional "active" control of peak loads.

Issues Specific to the LRP Project

Magnitude of Achievable Peak Load Reduction

We have assumed that the only potential market for a load shedding ballast or device is the new construction or lighting retrofit markets, i.e. that the cost of installing any load shedding device is prohibitive except if installed as part of a new lighting system. This means that the load shedding technology could be incorporated into a standard high-frequency ballast, which is a cheaper option than using a separate module both in terms of cost to the manufacturer and installation cost. We have assumed that the target markets are offices, schools, and government buildings.

	Office space	**Schools, educational and government**
Estimated new construction in CA 2003 (M ft^2)[19]	19.4	27.8
Percentage of this space that is owner-	75%	96%

occupied[20] (including government-owned)		
Estimated percentage of luminaires that can be fitted with load shed ballasts[d]	75%	75%
Percentage of load shed by each luminaire	33%	33%
Proportion of lamps switched on at time of peak load[14]	55%	47%
Lighting power density (W/ft^2)[21]	1.1	1.2
Estimated eventual percentage market penetration	10%	10%
Total potential annual peak load reduction in CA, new buildings	218 kW	373 kW
Total potential annual peak load reduction in CA, retrofits (estimated)[e]	218 kW	373 kW
Total potential annual peak load reduction in CA	**436 kW**	**746 kW**

A survey by the Peak Load Management Alliance found that the average peak load reduction program had 148 MW of load that could potentially be shed. We could not find figures for the total capacity of load shedding programs in California, or a target figure for how much load should ideally be shed in the state, but both these figures would be much higher than 148MW. Compared with the figure of 148MW, the annual contribution of lighting load shedding (approx. 1.2MW, see table above) is only 0.8%, but this figure would compound every year, so after ten years the contribution of lighting to the whole would be 8%.

Capital Cost per kW of Potential Peak Load Reduction

One significant difference between the load shedding ballast and conventional utility load shedding programs is the high capital cost of the ballast and its associated control infrastructure. Typically, utility load shedding programs incur almost no capital cost except the relatively low cost of additional communications infrastructure such as pagers and modems. These costs are low because the number of kW controlled by each communication device is high; this is not the case with the load shed ballast. Existing load shedding systems often rely on staff at the client's building to manually switch loads, or at least they allow a manual override of the load shedding request. The

[d] Some luminaires may be of a type not compatible with load shedding, for instance those containing HID lamps, incandescents, and unusual fluorescents for which load shed ballasts may not be available.

[e] In the absence of data for the retrofit market, it has been assumed that the retrofit market in CA is approximately the same size as the new build market. In many states, the retrofit market would be much larger than the new build market, but the pace of population growth in CA, the availability of land, and the lack of planning regulations make new building a proportionally larger part of the market. Figures compiled by the LRC estimate the CA retrofit market to be 2-3 times as large as the figures given above.

proposed lighting load shed system would require no human intervention, so the situation is wholly different.

The target incremental cost of $9 per ballast used by the project team was based on an analysis of rebates likely to be available for load shedding ballasts, and the likely incentive payments from utilities for participation in load-shedding programs.

Table 1 Capital cost per kW of potential peak load reduction

Average incremental cost per ballast[f]	$9[g]
Ballast cost per kW, assuming a 32W T8 lamp	$281

Annual Cost per kW of Potential Peak Load Reduction

The mean annual cost per kW of potential peak load reduction in existing utility programs is around $85[22] (see Table 2). This cost includes the incentive payments to participants as well as the administrative costs of the program.

To provide lighting load shedding customers with a simple three-year payback, the utility must provide annual incentive payments of $94 per kW ($281÷3), and the utility must also bear the administrative cost of running the program. This indicates that the cost of lighting load shedding may be competitive with the cost of existing load shedding programs.

Additionally, the marginal cost (the cost of adding the next kW of potential load reduction) of existing programs may be close to the maximum recorded cost, $878 per kW. This is corroborated by the large difference between the mean and median costs, which suggests that a significant number of kW cost significantly more than $85 per year. Therefore the cost of adding further kW to existing load shedding programs may be much more than the cost of lighting load shedding. Utilities have found it difficult to both retain participants and recruit new participants for load shedding programs, so lighting load shedding may be one of the few options for future expansion of load shedding programs.

The administrative cost per kW for the load shedding ballast is unknown. Because a single transmitter (pager, webserver, cellphone) could be used to send out a common signal to many different load shedding systems, the annual cost per kW may be small. Furthermore there would be a single standard contract for all participants. Conversely, because the peak load reduction per site is so small (6.4 kW for a building with 200 luminaires, compared to an average of over 3000 kW per site in existing load shedding programs[22]), the administrative cost incurred may be higher than for existing programs.

Table 2 Annual costs per kW of potential peak load reduction - utility programs

---

[f] This cost includes the cost of the controls infrastructure required to control the device

[g] The figure of $9 incremental cost was used as the target manufacturing cost to achieve 10% market penetration, based on an analysis of utility incentives available to customers.

Mean annual cost per kW	$85
Median annual cost per kW	$29
Maximum annual cost per kW	$878

Table 3 Annual costs per kW of potential peak load reduction – load shed ballast programs

Capital cost per kW (see Table 1)	$281
Annual cost per kW assuming a simple 3-year payback	$94

3.3 Classroom Photocell and Control System

Doug Paton and Dorene Maniccia, The Watt Stopper

There has been limited research into teachers' assessments of the performance of different photosensor types and control algorithms in classrooms. This project may create an opportunity to conduct this type of research in the context of a photosensor system whose photometric performance and characteristics are well understood.

This system appears to offer the potential for significant energy savings, and there are several possible ways to further improve the performance and acceptance of the system.

General Research Issues

Light Distributions

Student performance in schools has been shown to be strongly influenced by visual conditions[23], especially by daylighting but also by electric lighting. However, as was found by a recent comprehensive review: "in general, we have a poor understanding of daylight quality in schools, and a poor understanding of the relationships between the quantity and quality of daylighting."[24]

Although daylight is generally beneficial to the classroom environment, it can sometimes be detrimental; and although it's possible to draw general conclusions about which distributions of daylight are helpful and which are not, these distributions have not yet been accurately characterized or quantified. The effect on student performance, task visibility, or student attention caused by adding electric lighting to daylighting is, of course, unknown.

A recent study of office lighting found that horizontal illuminance on the desktop was not only a poor predictor of the visual quality of the room as a whole, but also a poor predictor of occupants' satisfaction with their desktop illuminance.[25] One study found that the lighting preferences of college students in a library were well approximated by a measure of the directionality of light.[26] Clearly, there are more important factors determining the acceptability of visual conditions than the desktop illuminance.

However, in keeping with established practice for photosensor design, the performance goals for the photosensor in this project are predicated on the assumption that it will always be necessary and desirable to add electric lighting if the horizontal illuminance on students' desks falls below 500 lux. Conversely, this could be described as the assumption that it will always be acceptable to dim electric lighting toward zero when the illuminance from daylight reaches 500 lux.

Monitoring of Installed Systems

To test the assumptions mentioned above has not been within the scope of this project, since the project's goal is to develop a reliable, effective packaged system for widespread use in classrooms rather than to question basic assumptions about the purpose and nature of control systems. Nevertheless, in the course of future monitoring of this system there will be opportunities to ask basic questions about whether teachers and students feel that the system creates good visual conditions, and whether any shortcomings could be better addressed by using a fundamentally different control algorithm, by mounting the sensor in a different position or pointing it at a different target, or by using more than one sensor. The interaction between daylighting, electric lighting, and blinds is of course a very important aspect of successful classroom control.

Surprising, these basic questions don't seem to have been addressed by other researchers who have monitored systems in the field, so this represents an important research opportunity.

Appropriateness of Daylight Control

It seems certain that the strategy of daylight linking (combined with a time clock or occupant sensor) is the best approach for achieving energy savings in schools. Several studies have shown that although occupants frequently switch lights on when daylight levels are low (for instance in the morning), they don't switch them off when daylight levels become sufficient to light the room.[27,28] Because school classrooms are occupied early in the morning, it will be common for lights to be switched on in the morning and not to be switched off during the rest of the day even if daylight levels become sufficient. Although one study has shown that teachers are slightly more conscientious in their switching behavior than other types of occupants[29], the difference is not very great.

Illuminance Levels

The use of the comparatively high value of 500 lux as the target illuminance seems unnecessary, given evidence from vision research, and 500 lux is at the high end of the range of designed illuminance levels typically recommended for use in buildings.

Studies of visual performance and the models of visual performance derived from those studies[30] show that visual performance of adults on typical high-contrast paper-based tasks increases with task illuminance up to around 300 lux, after which it does not increase further. Some design guides recommend that 500 lux may be preferred for particularly difficult or protracted visual tasks, neither of which are likely to occur in schools. Furthermore the illuminance levels required by children are lower than those required by adults whose eyes are less sensitive to light due to various processes of aging including macular degeneration, increasing opacity of the lens and cornea, and reduced accommodation (range of focus).

Consequently, 300 lux would be a more suitable target illuminance level, and lower levels would almost certainly not create problems. However, it's likely that such low levels of daylight would occur at the beginning and the end of the day, when daylight distributions become highly non-uniform due to the low angle of incident sunlight; this would result in significant detection errors for any photocontrol system mounted, as is the case in this project, inside the building. The level of 500 lux seems to have been chosen in order to maximize the robustness of the system and to minimize the occurrence of errors, rather than in order to optimize either visual conditions or energy use. If the system performs adequately at a 500 lux target level, it could be tested at lower levels to further reduce energy use.

Issues Particular to the LRP Project

Specular Reflections

The photocell used in the project has a white housing and a partially diffusing cover over the photodiode, both of which make the photocell sensitive to upward reflections of direct sunlight, for instance from specularly reflective desks, window frames, floor materials, and any other specular materials found in schools. Specular reflections would cause the photocell to reduce light levels far below 500 lux. The simulation report (deliverable 3.3.5a) does not directly address the issue of specular reflections of sunlight; it assumes that because the nominal angle of acceptance of the photocell is 55 degrees, specular reflections from outside this angle would not influence the sensor. This assumption may not be true, and it would be simple to check the response of the sensor, to ensure that no unexpected responses occur.

The photocell could easily be modified to mitigate the effect of specular reflections, for instance by adding an asymmetric shield, by painting the area around the photodiode a dark color, or by adjusting the field of view to point at internal walls rather than the floor – this approach has been used successfully by commercial photosensor manufacturers.

Accuracy as a Design Goal

As mentioned above, the design goal in this project is to maintain a certain level of illuminance on students' desk surfaces, but this may not be the most important metric for the satisfaction of teachers or students with the lighting system. However, the research work conducted in this project is concerned with maintaining a constant illuminance and does not question this underlying assumption.

Since it cannot be assumed that if the photocontrol system meets its design goals as set, that it will create acceptable classroom conditions, a series of monitored field studies will be necessary before the system can be deemed ready for widespread use. Future monitoring should not concentrate only on "accuracy" defined as the measurement of horizontal illuminance, but on as many other variables and measures of teacher satisfaction as can be identified.

Occupant Override

It is important that occupants (teachers, in this case) can easily override and adjust the output of any lighting control system, since the alternative is that they will decommission the system. The section concerning "occupant control" in the Performance Specification (deliverable 3.3.5a and 3.3.6c) briefly describes a wall switch with up/down and on/off controls, but doesn't indicate how long the override would last. In a school with set changeover times for classroom usage, it might be possible for maintenance staff to pre-set a series of time points at which manual overrides would revert to automatic settings.

There is no existing research that indicates an ideal duration for manual overrides, although a good and wide-ranging discussion of desirable control system features can be found in a paper by Escuyer and Fontoynont[17]. The stipulation that a future system could include a wall switch that "provides a visual indication of the override status" is highly desirable; this is a feature that many specialist lighting designers and engineers want to include in their systems.

Lighting control systems are often seen as unpredictable and impossible to control. Therefore the suggestion that the system could include one or more arcane methods to "defeat the common tactic of taping over the photocell to defeat the dimming control" is an outdated approach that frames the relationship between the control system and the occupants as an adversarial battle of wits, and is likely to exacerbate dissatisfaction with the system, and lead to permanent rather than temporary decommissioning.

The triggers for occupant override are not well understood, and since occupant override is the ultimate limiting factor not only for energy savings but for market acceptance of lighting control systems, research in this area is urgently needed.

Commissioning and Achieved Energy Savings

The opportunity to develop a clear, simple, and structured commissioning and design process in conjunction with other lighting controls manufacturers should be taken. Failures in commissioning have been shown to be a major contributor to long-term underperformance and non-acceptance of control systems; a survey of daylight-linked lighting controls in a sample of 46 buildings conducted by Heschong Mahone Group[31] found that only 24 out of 46 of photosensor systems were working in the way intended by their designers. All of the systems installed in school classrooms were functioning but teachers were regularly turning off lights before they were automatically turned off by the photocontrol system. Dimming systems were found to be more likely to be fully functional than switching or step-dimming systems. These results are typical of findings in other surveys; they suggest that long-term field trials in a variety of classroom types are likely to be necessary, and also that there is a deep-seated problem with poorly chosen photosensor locations, poor installation, and commissioning. The HMG survey found in 18 of the 25 sites with non-functioning or poorly functioning photocontrols that the problems had existed since installation and had not been rectified.

A consensual standard describing common design practices along with standardized installation and commissioning procedures could be written, perhaps in conjunction with third parties such as a the California Commissioning Collaborative, New Buildings Institute, Collaborative for High Performance Schools, or the Lighting Controls Association.

When the classroom photocell and control system is installed in classrooms, the achieved energy consumption can be compared with the figure predicted by the Lightswitch Wizard[32] software written by researchers at the Institute for Research in Construction of National Research Canada.

4.1 Hotel and Institutional Bathroom Lighting Project

Michael Siminovitch, Lawrence Berkeley National Laboratory

This project is based on sound research into the energy use of hotel bathroom fixtures, and offers very definite opportunities for energy saving. There is the possibility for the luminaire to be further refined, and for its performance as a wayfinding system for healthcare and other institutions to be investigated.

General Research Issues

Performance Specifications for Night Lighting

Requirements for night lighting in hospitals and other institutions vary significantly from one area to another, and also vary significantly in their performance specifications. For instance in Germany, night lighting is often provided by uplighting; whereas in the UK, uplighting is discouraged on the grounds that it might trigger a psychological condition known as phantasmagoria[33]. Elsewhere, low-level lighting systems that concentrate light on the floor around obstructions are preferred. The effectiveness of different lighting systems at facilitating wayfinding is not well documented, especially among seniors who suffer from age-related visual impairments. Consequently, like many lighting guidelines, recommendations for night lighting are based on informed hunches rather than measured performance data.

The potential market for this night light system includes hospitals and similar institutions, and it might be possible to achieve significant market success as well as progress in codes and standards if the project team is able to demonstrate experimentally that this system provides adequate light for wayfinding and orientation, specifically for the demographic groups likely to live in those institutions. The yellowing of the macula (a region of the retina) common among seniors suggests that light sources that contain a significant amount of yellow light might be the most efficient choice, but the effect of such spectra on glare and color rendering would need to be taken into account. Several research projects conducted on the visual performance of visually impaired subjects have been carried out the Research Group for Inclusive Environments[h] at the University of Reading, UK, and may be of interest.

[h] www.rdg.ac.uk/ie/index.htm

Issues Particular to the LRP project

Title 24 2005

Despite being non-residential buildings, hotels and motels currently are granted an exception within Title 24 (in section 130(b)) such that they need only comply with the residential lighting requirements (section 150(k).

Section 3 of 150(k) requires that bathroom lighting must be high efficacy *or* must be controlled by a motion sensor with automatic off. Consequently, hotel builders may put fluorescent fixtures in bathrooms but may not be willing to support the additional cost of motion sensors. Guaranteed incentives, assured replacement contracts, or a comprehensive outreach program may help to persuade builders to install the fixtures developed by this project. Alternatively, cooperation with industry bodies such as the International Hotel and Restaurant Association or with specific hotel chains might be helpful. The IH-RA supports a program of seminars and provides a variety of publications to inform its members about useful technologies.

Section 150(k) requires that motion sensors comply with section 119(d), which requires that motion sensors "shall be capable of automatically turning off all the lights…no more than 30 minutes after the area has been vacated". The research conducted for this project showed that a 30-minute delay would save only slightly more energy than a 60-minute delay, and it would run the risk of annoying occupants by switching the lights off while they're taking a bath. So while the 60-minute setting is preferable, in order to make the fixture compliant with the letter of Title 24, it should have the option of being set to a 30-minute delay (note that the wording of section 119(d) requires only that the fixture be *capable* of having a 30-minute delay, not that a 30-minute delay must actually be used in practice). If it can be demonstrated that bathroom occupant sensors with time delays greater than 30 minutes and less than 60 minutes are significantly less likely to be disabled, this could form the basis of a code change proposal to Title 24.

The requirements for hotels could be amended for the 2008 edition of Title 24, or alternatively the exclusion for hotel lighting in 130(b) could be removed. As Title 24 becomes more detailed in its treatment of specific space, it may be worth incorporating a table showing preferred motion sensor time delays in various types of space.

4.2 Energy Star Residential Fixture Project

Janet Leishman, Applied Proactive Technologies

General Research Issues

There seem to be no general research issues surrounding this project.

Issues Particular to the LRP project

The proposal put to manufacturers in this project asked for either table lamps or floor lamp prototypes; all four of the eventual prototypes were table lamps, presumably partly because of the lesser development cost and financial risk involved with smaller fixtures, and because a wide range of dedicated CFL and other fluorescent torchiere fixtures are already available.

A report into the California residential lighting market in 1997[34] supports this concentration on table lamps; it surveyed 683 California homes and monitored the annual energy use of 2600 fixtures. The average California household was found to have 4.3 table lamps and 0.9 floor lamps, while non-portable fixtures were more prevalent, with an average of 9.5 ceiling fixtures and 5.0 wall-mounted fixtures per household. There were only 0.5 outdoor fixtures per household. Table lamps accounted for 13% of statewide residential lighting energy use, while floor lamps accounted for 5%. Outdoor lighting accounted for 15% of energy use.

A similar report conducted in 200 homes in Tacoma in 1995[35] found that table lamps accounted for 11% of energy use, floor lamps for 6%, and outdoor lighting for 9%.

Both these reports suggest that, if this project proves successful, it might be fruitful for a future project to address improved designs for energy-efficient outdoor lighting although, as mentioned in Section 2.1, the features and performance that residential buyers look for in outdoor fixtures are not well understood, and a foray into the residential outdoor lighting market would have to be preceded by a study into the purposes to which these fixtures are put.

4.3. Development of Energy Efficient Retrofit/Remodel Alternatives to Incandescent Downlights

Michael Siminovitch, Lawrence Berkeley National Laboratory

The fixture developed in this project has already been favorably received by builders in a number of pilot projects, and has been refined according to their feedback. Questions remain over the safety impact of twin-lamp ballasts in homes, and over the performance and life of airtight fixtures in enclosed ceilings. The way that CFL installations are designed by builders, and the opinions of homebuyers toward CFLs (both before and after purchase) remain largely unknown.

General Research Issues

Ballast Shut-down

All twin-lamp ballasts shut down both lamps in the event that either of the lamps fails. Brief discussions with manufacturers have indicated that it is not possible to produce twin-lamp ballast that does not exhibit this behavior, unless the “twin” lamp ballast is simply two single ballasts in one housing. Homeowners will not be aware of this feature of twin-lamp ballasts, and may assume that since neither lamp works, the ballast itself is faulty. This may lead them to attempt to replace the ballast – a piece of equipment with which they are not familiar, and which therefore creates an increased risk of electrocution. It may be prudent to ensure that the ballast carries a warning sticker describing that both lamps are shut down in the event of failure, and describing a safe procedure for replacing the ballast itself in the event of failure. The Energy Star labeling requirements could be amended to include this provision. The potential risks of twin-lamp ballasts to homeowners should be investigated as part of the Title 24 development process, since Title 24 2005 mandates the use of fluorescent fixtures.

Insulation-Contact Airtight (IC-AT) Fixtures in Title 24

Title 24 2005 requires that residential recessed cans be rated for contact with insulation (IC), rated as airtight (AT), and sealed for airtightness between the fixture housing and the ceiling, using either a gasket or caulking[36]. Since caulking requires extra work by the contractor on site, it's anticipated that airtight fixtures will become the norm. Since the volume of air above residential ceilings can be very low, the potential for heat build-up is high, and will be increased by the use of airtight fixtures. There is already anecdotal concern from a number of utility incentive programs that the rate of return of residential CFL fixtures is higher than expected, and that heat may be a problem.

There is no standard thermal testing procedure for residential luminaires. The ASTM E283 procedure tests the amount of air leakage through the fixture body, not between the fixture and the sheetrock, but this is only a leakage test, not a thermal test. It might be cost-effective for the ENERGY STAR® fixture requirements to incorporate thermal testing along with the other types of testing required, since thermal tests (especially for surface mounted fixtures) would likely flag fixtures in which early ballast failure and subsequent costly return of fixtures is likely. A standardized thermal test procedure would have to stipulate the type of ceiling, the depth of insulation, the air volume and air temperature of both the conditioned space below and the unconditioned space above the ceiling, as well as a detailed experimental procedure.

The prototype fixture developed in this project has been extensively heat tested in a mocked-up attic with an air temperature of 70°C, while covered with insulation. The ballast case reached around 70°C after 4-6 hours of use, compared to the ballast manufacturer's limit of 90°C. The thermal performance of the fixture is very good, partially because some rules of thumb developed by Pacific Northwest National Laboratory[37] in regard to ballast positioning and other luminaire features and properties have been followed.

The fixture tested did not incorporate a gasket to ensure airtightness between the fixture and the sheetrock, but the research team believes that heat loss from air leakage does not significantly affect ballast temperature. Nevertheless, we believe that an additional thermal test of the luminaire should be performed with the airtight seal in place, to provide confirmation of the fixture's performance, to benchmark its performance against other fixtures, and to provide more information on the heat loss modes of CFL can luminaires.

Issues Particular to the LRP project

Installed Power Density

Several dozen prototype fixtures have already been installed in real homes. In several cases, the power density of fixtures installed into kitchens was in excess of 2 W/ft^2, whereas a power density of 1 W/ft^2 from high efficacy fixtures can easily provide enough light for domestic use. It can be expected that power density will vary widely not only from one builder to another but from one house to another, but at such high power densities, incandescent lights could provide an adequate level of illumination, which means that despite being "energy efficient", the fluorescent fixtures are in some cases not actually reducing energy use compared with the baseline condition.

The final decision about how many fixtures to use and where to locate them is often made on site under time pressure, so "rules of thumb" written on an instruction sheet in the box containing the fixtures may help builders to make better decisions. A simple indication of how many fixtures (or how many watts) are required per hundred square feet might be helpful. Some simple post-installation monitoring of the installed wattage of fixtures should be carried out.

Reflector Options and Homebuyer Perceptions

The reflector used in the fixture is a low-end commercial spun aluminum reflector, with a deep recess, narrow aperture and consequent low efficiency, which may contribute to very high power densities. Fixtures of this type were developed for the control of reflections in office computer screens, and so may not be the best choice for residential use. The control of reflections requires that the luminaires have sharp cut-off angles and do not emit light beyond 60-70 degrees from the vertical; this light distribution means that the ceiling and the tops of the walls are not lit, creating an impression of gloom. The narrow light distribution from each fixture increases shadowing on faces and on the work surface - other reflector designs would alleviate these problems and would yield higher efficiencies.

Conversely, the metallic finish of the fixtures matches the metallic finish found on high-end kitchen appliances, and may be popular with builders and buyers for that reason. In general, while builders and realtors may believe that they have a good understanding of what buyers want from a home; their views are likely to be influenced by their own prejudices, so it may be worthwhile on behalf of the wider cause of energy-efficiency to conduct a more objective survey of the perceptions and behavior of potential homebuyers.

4.4 Portable Office Lighting Systems

Michael Siminovitch, Lawrence Berkeley National Laboratory

Portable lighting systems for offices represent a very large opportunity for energy saving, which may not yet be fully recognized by Title 24. Portable systems also offer benefits to occupants and managers by increasing the degree of control and autonomy that occupants feel over their environment.

The marketing of these fixtures, especially into commercial speculative office space, remains a very high hurdle. It may be beneficial to work with particular office developers or with development industry bodies to attempt to gain acceptance for this type of fixture. Government agencies may be a good first step.

General Research Issues

Title 24

The Technology Transfer Plan (deliverable 4.4.4) states that “No new codes are necessary for implementation of this product”. However, although energy codes may allow a wide variety of lighting solutions, they are almost never neutral in their effect on the market for different types of lighting system. The requirements of Title 24 2005 are in one way supportive of portable lighting systems, because portable systems effectively benefit from an additional power density allowance of 0.2W per square foot: Section 146 states:

> *If the actual watts of portable lighting are not known at the time of permitting, the actual lighting power for portable and integral lighting shall be determined using either A or B following…*
>
> *A. in office areas greater than 250 square feet…0.2 watts per square foot*
>
> *B. in offices of 250 square feet and less, no additional task lighting power will be required in the calculation of actual lighting power.*

This power density allowance makes compliance with Title 24 easier for portable lighting than for ceiling-mounted lighting, and compliance with the 2005 version of Title 24 is somewhat onerous; power density requirements have become tightened to the point where compliance is difficult without the use of either high-efficiency suspended direct-indirect luminaires, or of Lighting Power Adjustment Factors (table 146A). Currently Table 146A does not provide an adjustment factor specifically for task lighting, although existing research demonstrates a beneficial effect of fixture “ownership” on energy consumption (see section 3.1), and suggests that the next revision of Title 24 could justifiably include an allowance for task lighting.

Effect of Motion Sensors on Energy Use

When motion sensors are installed, they cause two competing effects on energy use. Firstly, they tend to reduce energy use by switching off lamps when they judge the space to be unoccupied, but conversely they tend to make occupants less likely to manually switch their own lights off, because occupants come to rely on the motion sensor to perform that function. Pigg, Eilers and Reed[38] found that the second of these effects caused a reduction in expected savings by 30%; Floyd, Parker and Sherwin[39] found in one case study that lighting energy use actually increased after the installation of motion sensors in a building that previously only had manual switching. Since the high degree of ownership felt by occupants toward their floor fixtures is likely to result in conscientious manual switching behavior, it shouldn’t be taken for granted that an integrated motion sensor will result in further energy savings in this case.

Issues Particular to the LRP Project

Uniformity

Giving users control over their own lighting raises the concern that light levels across the space will be highly non-uniform and result in an unattractive appearance and visual discomfort that will lead to rejection of the concept of portable lighting. Typically, floor lamps with a strong indirect component are used in spaces with high ceilings, and this extra height acts to increase the uniformity of light. To attempt to light a space with a conventional-height ceiling with floor lamps might require prismatic or similar optics to increase the throw of the uplight component. A large-scale installation would be required to test the performance of the fixture in this respect. As an indicative value, commercial suspended luminaires using T8 and T5 lamps can achieve minimum recommended suspension distances of around 350mm (14") using prismatic optics. The performance of CFL lamps in this respect will not be as high as that of T8 or T5 lamps.

Comparison with Existing Systems

Several manufacturers have been attempting to market similar systems in the United States for a number of years. European manufacturers offer particularly advanced systems that enjoy a small but profitable market share in continental Europe, and in some cases these systems are available to United States buyers. Waldmann offers four families of portable CFL floor fixtures that have adjustable motion sensors incorporated into the luminaire head, to allow for variations in the position of the luminaire relative to the occupant. These luminaires have dimmable lamps controllable by a switch in the fixture stem. All four families have complementary wall-mounted fixtures and desk lamps that share key aesthetic and maintenance features. Zumtobel Staff offers three similarly integrated families of portable CFL floor fixtures with integrated motion sensors and photocells; these fixtures can be controlled via a power line carrier control system to provide a fully integrated office lighting system. All these luminaires have similar modern styling to the fixture developed in Task 4.4.

The experience of these companies in trying to market portable fixtures in the United States will be valuable to the project team, and the remaining items on the technology transfer plan could be carried out in consultation with them:

- Assuring product value to customers
- Motivating lighting designers/specifiers, and other key actors
- Educating and motivating buyers

Zumtobel Staff's experience with marketing the "LaTrave" range of suspended direct-indirect fixtures might be particularly helpful, since these attempted to reconcile the conflicting demands of individual control for users and the architect's desire for uniform lighting for the whole space through a concept named "Balanced Lighting". Similarly the United States manufacturer Ledalite offers the Ergolite series light fixtures that are suspended direct-indirect fixtures providing motion, daylight and load shedding controls as well as individual user control. The ambient uplighting component is maintained at a steady level throughout the space, and the downlighting component is controlled by the individual users, thus avoiding uneven illumination.

Currently available portable fixtures retail for many times the $150-$250 target range for the LRP luminaire, and are aimed at a few high-end office and architectural applications in which high prices can be tolerated. The possibility of expanding the market for these fixtures into the middle ground of office lighting would be an interesting area of discussion.

The "barn door" option suggested for the portable luminaire is similar to the "X-Ceiling" range of luminaires manufactured by Louis Poulson, so a check for patents should be carried out.

4.5 Integrated Classroom Lighting System

Terry Clark, Finelite, Inc.

The current intention seems to be to market this system based mainly on its impact on energy consumption, but the research sources listed below suggest that a marketing approach based on the non-energy benefits may be more successful, especially in the context of schools.

The system incorporates several features that reflect best-practice advice from California High Performance Schools (CHPS) and others, such as a separate lighting mode for audio/video presentations, a manual switch that allows teachers to force the system into the full-on mode for a set period of time, ,and the capability to use several motion sensors in a single space. The system also incorporates features designed to reduce the potential for installation and commissioning errors, such as RJ45 cabling and (potentially) self-commissioning photosensors. Installation and commissioning shortcomings are increasingly acknowledged as a major barrier to the success of lighting control systems[31]. Future monitoring of installed integrated classroom light systems will show whether or not these features are successful.

General Research Issues

Non-Energy Benefits of the Integrated Classroom Lighting System

The Technology Transfer Plan (deliverable 4.5.4b) states that the integrated classroom lighting system will increase the rate of student learning. This conclusion in misleading, since improved student learning has only been linked to certain types of daylighting[23], rather than to electric lighting; the report packages daylighting and electric lighting together to give the impression that the electric lighting system will improve student learning. Literature describing the Integrated Classroom Lighting System should not make this claim.

Although no specific evidence exists that student learning is improved under direct-indirect electric lighting compared with conventional direct lighting, it can be argued on the basis of existing research that student learning is likely to be positively affected, for several reasons. Firstly, models of human visual response (particularly glare, spatial frequency response, and adaptation) suggest that the degree of visual disturbance and visual stress is likely to be reduced by the more even light distribution typically provided by suspended direct-indirect fixtures. Although it should be noted that most people do not experience significant visual disturbance and stress under conventional direct fixtures; people who suffer from migraine, visually induced epilepsy, and seasonal affective disorder may benefit from direct-indirect lighting.

Secondly, the provision of dimming controls or bi-level switching controls enhances the teacher's ability to control mood and activity in the classroom, for instance to calm young children who are over-stimulated. This increased degree of control can be expected to aid the teaching and therefore the learning process. This effect was noted anecdotally by researchers at Heschong Mahone Group[40]. Special needs students may benefit especially from this feature.

Thirdly, a study by Fleischer[41] found that the relative proportion of uplight and downlight in an office environment produced changes in the psychological affective states of occupants. Keeping the horizontal illuminance constant, an increase in the proportion of uplight produced a small decrease in psychological arousal level, which in turn might increase people's willingness to tackle "reluctance-oriented" (as opposed to "pleasure-oriented") tasks such as those often performed by office workers and students. A decrease in arousal might also have a beneficial effect on stress levels and particular benefits for special needs students.

Fourthly, research evidence from acousticians shows that young children's ability to hear in noisy environments is not as good as that of older children and adults[42,43]. Since hearing depends to a great extent on lip-reading (even for children with normal hearing), good modeling of the facial features of the teacher and other children is important for learning. A study at the Centre for Inclusive Environments, University of Reading, UK[44], showed that hearing-impaired subjects find lip-reading easier when the speaker is lit by uplights than by downlights. A combination of uplight and downlight may be a more optimal combination. In the study, daylight was preferred to artificial light in all cases.

Additionally, the system incorporates an audio/video (A/V) mode that reduces light levels throughout the classroom but maintains a focus of light on the teacher and whiteboard. This lighting mode improves the utility of the classroom in line with recommendations from CHPS[45] (although CHPS recommends dimming ballasts, which have been avoided in this project because their cost is seen as a potential barrier to the adoption of the integrated classroom lighting system. In some senses the ICLS goes beyond the CHPS requirements, since CHPS only requires manual control for classrooms likely to be used for A/V, whereas the ICLS provides a preset A/V mode called up by a dedicated switch).

The non-energy benefits of the proposed system are potentially a much more powerful argument than the energy benefits.

Energy Benefits of the Integrated Classroom Lighting System

The Integrated Classroom Lighting system can achieve a very low level of installed power density, coming close to the minimum value of W/sq ft currently achievable by a suspended direct-indirect lighting system. However, the Technology Transfer report is inconsistent in its analysis of the baseline lighting conditions to which the proposed system is compared. The report quotes 30-50% savings, presumably compared to the 1.4 W/sq ft allowed by Title 24 2001 (note that the requirement tightens to 1.2 W/sq ft for Title 24 2005), but it's possible to exceed Title 24 by the same amount using conventional recessed luminaires, and achieve the same illuminance on desk surfaces. Both types of luminaire can achieve lighting power densities of around 0.9 W/sq ft with acceptable uniformity of desktop illuminance, though of course suspended luminaires distribute the light more equally between the floor, walls and ceiling. Data from several manufacturers shows that fixtures with recessed lenses or parabolic louvers have coefficients of utilization comparable with suspended direct-indirect systems, typically in the range of 60-80% in classroom-sized spaces. The proposed system therefore does not provide any benefits over conventional technology in terms of installed power or efficiency.

To judge whether the Integrated Classroom Lighting System provides benefits in terms of the lighting energy load in use (rather than installed load), monitored data from the installed systems will have to be analyzed over the long term. A suitable baseline for comparison is provided by a study carried out by Heschong Mahone Group[14], which found that in classrooms with bi-level switching but no other means of control, lighting loads averaged 47% of installed load during peak times. Since the average installed load in the classrooms tested was 1.5 W/sq ft, this equates to a load in use of 0.71 W/sq ft, which is actually less than the estimated load for the proposed system. The proposed system would have to achieve average loads significantly lower than this to justify its increased cost over conventional systems. More importantly, the average annualized lighting load (over the entire year, 24 hours per day, 365 days per year) was 19% (0.29 W/sq ft). The proposed system would also have to improve on this figure. The HMG study also estimated the potential saving from motion sensors: the average classroom was unoccupied with its lights turned on for 1.2 hours per day. This would represent about a 15% maximum possible saving from motion sensors. It may be difficult to justify added system cost if the energy savings achieved in use are not higher than 15%.

Peak Load Reduction through Daylight Linking

In addition to reducing annualized energy consumption, the Integrated Classroom Lighting System offers an opportunity to significantly reduce peak lighting load. As mentioned above, classroom lighting energy use during peak times has been measured at 47%, but since most classrooms are well daylit, and daylight is abundantly available at times of peak electrical load, it should be possible to reduce this figure close to zero by using daylight-linked lighting controls. The financial value to utilities of this peak load reduction may outweigh the value of annualized energy savings; as mentioned in Section 3.2, the average cost to utilities of peak load reduction is $85 per kW, and since daylight controls should offer a saving of 53% of installed load compared to baseline conditions, this equates to $40 per year per classroom.

Issues Particular to the LRP project

Cost of the System

The cost of the system is hard to estimate, partially because information on the installation cost of suspended fixtures in not available in the industry-standard RS Means cost data tables. However, RS Means estimates the installed cost (materials plus labor, including lamps and mounting hardware) for a 2'x 4' recessed troffer luminaire to be $129, which would equate to $1.61 per square foot if the luminaires were placed in a standard 10'x 8' grid (no citation is given for the higher value of $2.86 per square foot given in the Technology Transfer Plan). The figure of $1.61 seems high because it assumes 1.5 hours of labor per fixture, which would be excessive for a modern pre-wired lay-in fixture. It seems unlikely that a suspended system could be installed as cheaply, since rather than simply being laid into an existing grid, the luminaires must be connected together and through-wired on site - a process which typically requires at least two contractors to work on the lighting installation simultaneously.

Achieving a low cost is partially dependent on incorporating plug and play low voltage connectors and structured cabling to minimize installation time. The Technology Transfer Plan states that "these products do not exist today", but several ballast manufacturers already produce products that incorporate RJ11 sockets that allow sensors or control system network wires to be plugged in very simply, and these should be leveraged. Factory-produced structured cabling systems for luminaire power are also available from several manufacturers, and could be adapted for use in this system.

Factory calibration of daylight sensors is an ambitious goal, since the response of a ceiling-mounted sensor is dependent on the reflectance of the objects in its field of view, and this may not be known at design time, and may change during construction. Therefore, while approximate factory calibration may be possible, some commissioning of photocells on site will always be necessary to accommodate the varying proximity of different photocells to windows, daylit walls, or to particularly high-reflectance or low-reflectance surfaces, and to accommodate differences in classroom geometry. The LRC's self-commissioning photosensor[46] may be useful in this context.

Since commissioning is such a critical factor in the success of photocell installations[31], simple sequential instructions for commissioning should be part of the package delivered to site.

Photocell Choice and Placement

As discussed above in section 3.3, the assumption that the goal of daylight-linked lighting controls should be to maintain a constant level of desktop illuminance has not been tested by research either in the field or in the lab. The use of photocells in novel locations or with novel angles of acceptance, or the use of multiple photocells, is an under-researched opportunity to improve the suitability of photocontrols specifically for classroom lighting

5.1 BI-Level Stairwell Fixture Performance

Francis Rubinstein, Lawrence Berkeley National Laboratory and Cylette Willis, International Facility Management Association

There are a number of regulatory factors that might work against the successful introduction of this fixture; research is required to justify code changes that would kick start the market for bi-level stairwell fixtures, since energy savings alone may not be enough to justify the increased capital cost. Questions over lamp life remain to be resolved.

General Research Issues

Reliability of Motion Sensors

Motion sensors do not have a reputation for perfect reliability, and the potential for a sensor to fail and cause illuminance levels to drop to around 10 lux during periods of normal stairwell use is a serious concern. People with normal vision should not find a sudden change from, say, 500 lux to 10 lux too problematic, but in cases where people are moving from a very brightly lit (perhaps daylit) space into a stairwell lit to 10 lux, or in the case of people with visual impairments, this sudden change may cause temporary blindness that results in an accident. Research on the visual abilities of visually impaired people in the built environment is limited, but some research into the suitability of the 10 lux figure for people with the more common visual impairments such as macular degeneration, cataract, glaucoma, diabetic retinopathy, etc. may be warranted. Around 2% of the population are blind or partially sighted, and another 2% have other visual problems that cannot be rectified by corrective lenses.

No research into the reliability of the various types of motion sensors in different applications in the field seems to have been conducted. A study into the reliability of sensors would seem to be a prerequisite for the development of code requirements that mandate their use.

Occupant Use of Stairwells

If the use of bi-level fixtures discourages occupants from using the stairs and leads to increased use of elevators, the energy savings from reduced lighting use will be overwhelmed by the very much larger energy use of the elevator motors. Field studies should monitor the frequency with which both the stairs and the elevators in the test building are used.

Definition of Fail-safe

The 2003 revision of the National Fire Protection Agency's Uniform Fire Code (NFPA 1) requires that "switch controllers are equipped for fail-safe operation". The Watt Stopper is currently redesigning the ultrasonic motion sensor in the LaMar fixture to ensure that the lamps remain in (or switch in to) the high mode should a typical failure occur. NFPA 1 does not define what "fail-safe" means, but a simple definition is that the lamps should revert to the "safe" (high) state when the signal from the sensor to the ballast (or controller) is lost. This situation is complicated when the controller is integrated into the sensor, and in that situation the ballasts should revert to the safe state when the signal from the controller is lost. In any electronic system there are a host of failure modes from short circuits, failed power supplies, failed components, and loose connections. Responsible manufacturers will try to identify the most common failure modes, but a standard for fail-safe operation might be difficult to write and enforce.

Title 24

Title 24 currently allows a Lighting Power Adjustment Factor of between 0.15 and 0.25 for the use of an "occupant sensor controlled multi-level switching or dimming system that reduces lighting power at least 50% when no persons are present", but this can only be claimed for hotel and motel hallways, storage stack areas and library stacks, i.e. not for stairwells. On the basis of proven energy savings, a separate control credit for stairwells could be proposed for the 2008 revision of Title 24. This factor could be dependent on whichever factor(s) are proved to be the best predictors of energy savings (numbers of stories, type of building, etc.) for a particular building.

Alternatively, a mandatory requirement or a Power Adjustment Factor for bi-level control in stairwells could be introduced.

Delay Time for Dimming to Low Output State

The 2003 revision of the National Fire Protection Agency's Uniform Fire Code (NFPA 1) requires that "illumination timers are set for a minimum 15 minute duration". It seems possible that such a long delay could negate some of the energy savings that could accrue from the use of a bi-level stairwell fixture, although initial results from monitoring of buildings on the Berkeley campus indicates that a 15 minute delay would make only a small difference[47]. If further analysis of the results suggests that a 15 minute delay might impact savings, it might be possible to submit a proposal to reduce the required delay time prior to the revision of the California Uniform Fire Code. It might also be necessary to investigate whether the effects of smoke, heat, or sprinkler systems would cause the bi-level fixture to turn off the lights while the building is being evacuated. Proposed changes to the California Uniform Fire Code must be submitted by August 2, 2004.

Issues Particular to the LRP project

Effect of Dimming on Lamp Life

The effect of dimming on lamp life is generally not well understood. There are a large number of different ballast characteristics that can influence lamp life, and these ballast characteristics interact to produce a very complex situation. Although some studies have been carried out into the effect of dimming on lamp life, none of these address the particular situation found with the bi-level stairwell fixture, that is: frequent dimming between a very low output state and the full output state, with daily off-switching. Expert opinion seems to be that some ballasts are very good at maintaining the right cathode current during dimmed operation, whereas others are very poor. The better ballasts can extend lamp life significantly beyond the standard 20,000 hours in continuous dimmed operation, but the poorer ballasts can reduce it by a similar amount.

Although this is a complex technological problem, a simple practical solution would be to run a test sample of luminaires with a variety of different ballasts to determine which ballast offers the best reliability with this particular product under typical operating conditions. The interactions between the ballast and the lamp are very complex, especially at low output, so it's highly likely that one or two particular combinations of lamp and ballast might significantly outperform others.

Venues for Field Trials

Before California code requirements are changed to encourage or mandate the widespread use of motion sensors in stairwells, a large scale field trial in buildings owned by a large government client like the General Services Administration should be feasible. This would answer a number of outstanding research and development questions, and would establish the market and reduce the cost of bi-level stairwell fixtures prior to widespread commercial introduction. A large scale field trial in California multifamily housing units would also be desirable; this should be possible through one of the many incentive programs that exist for multifamily buildings. The multifamily housing market has only a few market actors so might be a good initial market for the LaMar fixture.

Results obtained by the LRC[48] showed that the LaMar OccuSmart fixture achieved 53% energy savings in a high-rise residential building, and 60% savings in a commercial office building, so both building types seem to offer promising ground for large-scale trials.

Illuminance Requirements

The 2003 revision of the National Fire Protection Agency's Uniform Fire Code (NFPA 1) requires that "the failure of any single lighting unit [should] not result in an illumination level of less than 0.2 Ft-candles (2.2 lux) in any designated area". This requirement presumably refers to the high output condition rather than to the low output condition. It is not clear how "designated area" is defined; but a sensible definition might include the centerline or center point of the treads and landings.

Although NFPA 1 has not yet been adopted into the California Uniform Fire Code, photometric calculations should be performed to ensure that, for typical stairwell geometries, the light distribution from the fixture would allow it to meet the requirement of NFPA 1 that the failure of any single fixture should not result in an illuminance less than 2.2 lux in any designated area while the stairs are lit to a design illuminance of 108 lux. This failure-mode requirement may be particularly problematic in retrofit applications where the stairwell design illuminance is only required to be 10.8 lux.

It may be possible to optimize the photometry of the fixture to account for the single-fixture failure requirement, in anticipation of the adoption of NFPA requirements into the California Uniform Fire Code.

At this point in time, the California Building Standards Commission has not yet decided on whether to adopt the new NFPA 1 standard that would increase stairwell light levels ten-fold. On one hand, the new standard would render a bi-level stairwell fixture more cost effective, as there would be greater energy consumption and greater energy savings. On the other hand, the combination of the new standard with the bi-level fixtures would consume more energy than lighting to the existing standard with no controls. The CBSC should check that the NFPA 1 standard is based on peer-reviewed research showing a significant increase in fire safety before adopting a standard that would result in increased energy use.

5.2 Evaluations of Electronic Ballasts and Related Controls for HID Lighting Systems

Steve Johnson, Lawrence Berkeley National Laboratory

The results reported in the Performance Characterization report (deliverable 5.2.1a) seem broadly to agree with figures quoted by manufacturers. This shows both that LBNL's testing facility is well calibrated, and that the figures quoted at least by major manufacturers can generally be relied upon for accuracy. Having established this, future enquiries into the performance of lighting technologies could make more extensive use of manufacturers' data.

General Research Issues

The fact that manufacturers' data seem to be accurate may be due in part to the participation of many manufacturers in the National Voluntary Laboratory Accreditation Program (NVLAP) run by the National Institute of Standards and Technology. The NVLAP is essentially a quality control procedure for testing laboratories[49] that requires traceability of calibration standards, structured internal audits, rigorous management procedures, regular cross-testing between different laboratories, and a formal complaint procedure in cases of error. Since the major lamp manufacturers are very large and resourceful companies, and the differences in performance between their products are small, it can be assumed that falsifications or errors on the part of one manufacturer would be quickly challenged by others.

Manufacturers that run laboratories accredited by NVLAP include:

- Cooper Lighting - Metalux Research Laboratories,
- Lithonia Testing Laboratories
- Litetronics International
- Philips Lighting Corporate Calibration & Standards Laboratory
- OSRAM SYLVANIA, Applications & Measurements Laboratory
- Daybrite Lighting (Genlyte Thomas Group) Photometric Laboratory
- GE Consumer & Industrial - Lighting Product Testing
- Westinghouse Light Bulb Test Lab
- Hubbell Lighting Photometric Laboratory

It's interesting to note that no LED manufacturers currently run NVLAP accredited laboratories, except in as much as Philips is the parent company of LumiLeds, and OSRAM or OSRAM Opto Semiconductor. The rapid rate of development of LED products may make formalized testing uneconomic at present; when the LED market becomes more mature, it can be expected to use the same testing procedures as are currently used for other lamp types. However, it may take several years to mature, and in the meantime it may be prudent to verify manufacturers' performance claims every so often. A check on LED manufacturers' claims about lamp life led to a partial retrenchment in the LED market in 2001.

Issues Particular to the LRP project

Market for Low Wattage CMH Lamps in California

The Building Efficiency Assessment study[50] found that non-halogen incandescent spotlights outnumbered halogens by more than 4:1 in new retail construction in California during the period of the study (1997-1999). A new BEA study is about to be released, and can be expected to show a shift in the market toward 12V halogen fixtures. Increased use of 12V halogen would be good news, but although 12V fixtures are roughly twice as efficient as non-halogen incandescents, they are still less than half as efficient as metal halides. Ceramic metal halide (CMH) lamps, especially self-ballasted lamps, represent a major potential for energy saving in retail applications.

The BEA study showed that almost all incandescent lamps used in retail are between 40 and 100W. These could be replaced with CMH lamps between 10W and 39W to achieve significant energy savings, but this project has not evaluated lamps of less than 39W. Since the performance of metal halide lamps is highly dependent on the distribution of heat within the discharge tube, these lamps may vary in performance more than those of higher wattages. Very low wattage metal halide lamps might be an excellent subject for an expanded study of metal halide lamp performance; GE's self-ballasted "brite-spot" 39W lamp is commercially available and might be an interesting subject for study because of its high neon content. The experience of lighting designers (especially in Europe) of using very low wattage lamps might be a useful source of anecdotal evidence. In the United States, very low wattage metal halide lamps are used mainly in specialist applications such as bicycle lights, and medical and dental fixtures.

5.3 Low Glare Outdoor Retrofit Luminaire

Steve Johnson, Lawrence Berkeley National Laboratory

Given the poor performance of typical wall pack luminaires, this project presents an opportunity for some energy savings, and for major improvements in sky glow and light trespass. The challenge to the development team will be to improve on the photometric performance of high-end commercially available fixtures, and to develop performance metrics based on horizontal illuminance, vertical illuminance, and veiling glare that can be used as criteria for the performance of future competitive fixtures.

General Research Issues

Curfew Dimming

Both LBNL's report on outdoor lighting design criteria (deliverable 5.3.1b and c) and a previous report by Eley Associates[51] deal with the idea of 'curfew dimming' to reduce the energy use of parking lot lighting during the hours of the night when the parking lot is unlikely to be used. Firstly, the idea of curfew hours is counter to the main functions of pedestrian lighting, which are to provide sufficient light for face recognition, to enhance the pedestrian's sense of security, and to provide sufficient light for CCTV systems to record viable images. Reducing the level of light at precisely those times at which pedestrians will feel most vulnerable seems to be precisely the wrong approach. The minimum level of light for these purposes should be determined, and used as the minimum illuminance at all times of night. In parking lots, there is no need to provide more light than this, since vehicle speeds are low enough for headlights to provide ample forward illumination.

Lighting to Reduce the Fear of Crime

The effect of lighting on actual levels of crime has been the subject of extensive debate. Several studies by Painter have shown benefits, but these results are hotly contested especially by the astronomical community[52]. However, consensus exists that lighting reduces the fear of crime among pedestrians. This is also an energy issue because people are more likely to walk or cycle at night with adequate lighting and a reduced fear of crime instead of using their cars for short trips. People are also more likely to frequent downtown areas, which in turn encourages the development of more sustainable communities.

Caminada and van Bommel[53] devised experiments based on the observation that people tend to feel safer when there is enough ambient light to recognize faces of others nearby. They found that semi-cylindrical illuminance is a better indicator than other measures, such as vertical plane illuminance, for defining the face recognition distance. The cylinder axis remains vertical. The azimuth of the axial plane can be in either of two orientations, as appropriate: one parallel to the street length and the other normal to it. For face recognition at 4 m and 10 m, the semi-cylindrical illuminance needs to be 0.8 and 2.7 lux respectively, provided there are no sources of excessive glare present. At 4 m, an alert person was thought able to take evasive or defensive action if a threat were perceived. The 10 m distance was considered to provide a greater margin for comfort. Caminada and van Bommel's work provides an empirical quantitative basis for lighting as a means to reduce fear that could be used in the development of standards.

Sky Glow and Light Trespass

Wallpacks throw light back on to the wall around the fixture. This light can be beneficial in reducing glare and adding to the ambient light level, but if it's poorly distributed or excessively bright it may fulfill no useful function, and simply contribute to sky glow and light trespass. For wallpacks, even a full cut-off fixture may not be optimized to reduce sky glow. A performance metric for the light thrown on to the wall might be an important component of this project, and a contribution to the ongoing debate on light pollution and light quality.

Streetlight and Parking Lot Fixture Spacing

Full cut-off fixtures require closer spacings than non cut-off fixtures to achieve uniform light levels over a roadway or parking lot. It appears that many municipalities are trying to use cut-off fixtures on the same spacings as non cut-off fixtures, and have to overlight to achieve minimum illuminance values between fixtures. The resulting effect is an increase in sky glow. The approach taken by the team in this project has been to analyze the photometry of existing commercially available fixtures as a starting-point for a performance specification. A similar approach to streetlight spacing recommendations would lead to a rationalization in current practice, and a reduction in sky glow for new installations.

Issues Particular to the LRP project

Photometrics

The proposed fixture is intended to project light 40-45' across a parking area from a mounting height of 15', while also shining light down the wall on which it's mounted. The photometric distribution required to achieve this is the same as the photometric distribution used by stadium floodlights, i.e. a very high intensity at 45-65° from the downward vertical, along with some light shining back behind the fixture, with full cut-off above horizontal. Some existing asymmetric flat-glass parking-lot fixtures have the type of distribution that would be ideal for the proposed wallpack fixture.

This analysis poses two questions: firstly, since stadium floodlights are a lucrative niche in the lighting market that has been filled with high performance, optically optimized fixtures from a variety of manufacturers, it is possible to significantly improve on the performance of those fixtures?

Secondly, are stadium floodlights that produce very high levels of glare a good choice of fixture for illuminating a parking lot? To achieve the performance specification of 5 lux at a range of 45' from a 15' mounting height, the fixture would have to produce an intensity of 3600cd at 71° from nadir. Assuming that the apparent area of the fixture is around $0.15m^2$ at that angle, this requires a luminance of $24{,}000cd/m^2$, which is about the same as a bare fluorescent lamp. This amount of glare might actually reduce visibility levels below what they would have been under ambient urban light levels. An upper limit on the luminance of the fixture should be determined on the basis of veiling glare.

Veiling Glare as a Performance Metric

Veiling glare is certainly a suitable metric to measure the performance of a parking lot lighting system. The proposed fixture, which shines light on the adjacent wall as well as across the parking lot, may perform well under this metric. The full disability glare metric takes into account the ambient vertical illuminance level as well as the vertical illuminance from the glare source, and this ambient level would have to be taken into account to fully quantify the benefits of the proposed fixture. Several commercially available lighting design software packages can perform veiling glare calculations for roadway lighting purposes according to IESNA document ANSI/RP-8-83, and this method could easily be adapted to parking lot luminaires. The development of a criterion for disability or veiling glare for California parking lots would be a simple matter, and could be combined with the Caminada and Van Bommel's criterion for semi-cylindrical illuminance described above.

The IESNA's Design Guide "Lighting for Automatic Teller Machines"[54] is a useful source of information that could be referenced in a performance specification for the proposed luminaire.

Discomfort Glare

Discomfort glare is not really defined for outdoor lighting installations, since it was developed only for indoor use. It would be interesting to correlate readings from a new type of ocular stress monitor[55] with figures for veiling glare from a wallpack fixture, to see whether ocular stress is well predicted by veiling glare, or whether some other metric of visual discomfort for outdoor lighting might be useful.

5.4 DALI Lighting Control Device Standard Development

Dave Peterson, The Watt Stopper

There seems to be no research data relevant to this project. General research issues relevant to lighting control systems are mentioned in sections 3.1, 3.2, 3.3, and 4.4.

References

[1] National Electrical Manufacturers Association, *LE5: Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires*. Retrieved from www.nema.org/DocUploads/5F6AA4C9-12A2-4653-9E5FF107E52B716D//le5for~1.pdf on 6/1/04.

[2] Lighting Research Center, Increasing the Market Acceptance of Screwbase Compact Fluorescent Lamps, Report submitted to US Environmental Protection Agency, September 2003. Retrieved from http://www.lrc.rpi.edu/programs/lightingTransformation/colorroundtable/pdf/MarketAcceptanceOfCFLsFinal.PDF on 5/20/04

[3] Shakir, I, Narendran, N, *White LEDs in Landscape Lighting Application*, retrieved from http://www.lrc.rpi.edu/programs/solidstate/pdf/evaluatingWhiteLEDs.pdf on 2/5/04

[4] An attempt was made to demonstrate the shortcomings of CRI in a paper by Deng and Narendran (Deng, L, Narendran, N, *Color Rendering Properties of LED Light Sources*, retrieved from http://www.lrc.rpi.edu/programs/solidstate/pdf/CRIForLED.pdf on 5/3/04) but in this study the environment surrounding the test apparatus was not sufficiently well controlled to allow the results to be extrapolated to other situations.

[5] Measurement of LEDs, CIE 127-1997. ISBN 3 900 734 84 4

[6] http://physics.nist.gov/Divisions/Div844/facilities/photo/Projects/led_photometry.htm

[7] www.mouser.com/catalog/617/48.pdf. Retrieved on 5/4/04.

[8] Press release, *New IRC Resistor-On-Aluminum Technology Drives Performance For Automotive Applications*, retrieved from www.irctt.com/templates/whats_new_print.cfm?id=82 on 5/4/04

[9] http://www.stockeryale.com/i/leds/intro.htm. Retrieved on 5/4/04

[10] X. Guo, G. Shen, Y. Ji,et al., *Thermal property of tunnel-regenerated multiactive-region light-emitting diodes*, Applied Physics Letters 82(25) pp.4417-4419. 23 June 2003. Retrieved from www.ee.ucla.edu/faculty/papers/klwang_APL_23jun03.pdf

[11] Sliney and Tajnai, *Direct Viewing of LEDs and the Photobiological Safety Standard*, Proceedings of the 25th Session of the CIE, pp.D6-48-51. 2003

[12] *Application Brief AB05: Thermal Design Using Luxeon Power Sources*, Lumileds Lighting US LLC, San Jose, CA. August 2003. Retrieved from www.lumileds.com/pdfs/protected/AB05.PDF

[13] Moore, T, Carter, D, Slater, A, *A Qualitative Study of Occupant Controlled Office Lighting*, Lighting Research and Technology 35(4). 2003. pp. 297-313.

[14] Mahone, D, Chappell, C, Howlett, O, Dohrmann, D, Rubenstein, F, *Effectiveness of Bi-Level Switching in Offices, Retail Space and Classrooms*, Forthcoming in IES Journal.

[15] Moore, T, Carter, D, Slater, A, Conflict and Control, the Use of Addressable Lighting in Open Plan Office Space. CIBSE Conference 2000, Dublin, Ireland.

[16] Bordass, B, Heasman, T, Leaman, A, Perry, M, Daylight Use in Open-Plan Offices: The Opportunities and the Fantasies. CIBSE Lighting Conference 1994, Cambridge, UK.

[17] Escuyer S, Fontoynont M. Lighting controls: a field study of office workers' reactions. Lighting Research and Technology, June 2001, vol. 33, no. 02, pp. 77-96

[18] Architectural Energy Corporation, Application Research, Report submitted to California Energy Commission as deliverable 5.4.1 of the PIER Lighting Research Program. Retrieved from http://www.archenergy.com/lrp/team/deliverables/deliverable_5.4.1a-dControl_Needs_Appl_Research_final.pdf on 5/21/04

[19] NRNC Market Characterization Report, Qtr 1-2, 2003, Prepared for Richard Pulliam, Southern California Edison Co., August 2003, Quantum Consulting Inc., Berkeley, CA, p.2-4

[20] 1999 Commercial Buildings Energy Consumption Survey (CBECS) Table B13, retrieved from http://www.eia.doe.gov/emeu/cbecs/pdf/allbc.pdf on 2/4/2004

[21] California Energy Commission, *2005 Building Energy Efficiency Standards ("Title 24") Table 146-B*, California Energy Commission, Sacramento, CA

[22] Peak Load Management Alliance, Final Results of the EEI / PLMA 2002 Demand Response Benchmarking Survey, retrieved from http://www.peaklma.com/files/public/DRSurvey2002FinalReport0503.doc on 2/4/2004

[23] Heschong Mahone Group, Daylighting in Schools: An Investigation into the Relationship between Daylighting and Human Performance, submitted to Pacific Gas and Electric Company, August 1999. retrieved from http://www.pge.com/003_save_energy/003c_edu_train/pec/daylight/di_pubs/SchoolDetailed820App.PDF on 5/12/04

[24] Wu, W, Ng, E, A review of the development of daylighting in schools, Lighting Res. Technol. 35(2), 2003. 111-124

[25] Moore, T, Carter, DJ, Slater, AI, User attitudes toward occupant controlled office lighting, Lighting Res. Technol. 34(3), 2002. 207-219

[26] Parpairi, Baker, Steemers, Compagnon, *The Luminance Differences Index: A New Indicator Of User Preferences In Daylit Spaces*. Lighting Res. Technol. 34(1). 2002. pp.53-68

[27] Hunt, *Predicting Artificial Lighting Use - A Method Based Upon Observed Patterns Of Behaviour.* Lighting Res. Technol. 12(l) 7-14 (1980)

[28] Hunt, *The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy*. Building and Environment, Vol. 14, pp. 21-33. 1979.

[29] Mahone, D, Chappell, C, Howlett, O, Dohrmann, D, Rubinstein, F, *Effectiveness of bi-level switching in offices, retail space and classrooms*. Forthcoming in IES Journal

[30] Rea, Ouelette, *Relative Visual Performance: A Basis For Application*. Lighting Res. Technol. 23(3), 135-144. (1991).

[31] Heschong Mahone Group. Photocontrol System Field Study. Submitted to Southern California Edison Co, Irwindale, CA. October 2003.

[32] www.buildwiz.com/lightswitch/

[33] Chartered Institution of Building Services Engineers, *Code for Lighting*, CIBSE, London, 2002

[34] Heschong Mahone Group, *California Baseline Lighting Efficiency Technology Report*, submitted to California Energy Commission, September 1999 P-400 0098

[35] Mills, E, Siminovitch, M, Page, E, Sardinsky, R, *Dedicated Compact Fluorescent Fixtures: The Next Generation For Residential Lighting.* Proceedings of the 3rd European Conference on Energy-Efficient Lighting, June 1995. Newcastle-upon-Tyne, UK. Retrieved from http://eetd.lbl.gov/emills/PUBS/PDF/gonio.pdf on 5-13-04.

[36] California Energy Commission, *2005 Building Energy Efficiency Standards ("Title 24") Section 150(k)5*, California Energy Commission, Sacramento, CA

[37] McCullough, J. Personal Communication, May 2004

[38] Pigg, S, Eilers, M, Reed, J, Behavioral Aspects of Lighting and Occupancy Sensors in Private Offices: A Case Study of a University Office Building. Proceeding of the ACEEE Summer Study, 1996, pp.8.161-8.170.

[39] Floyd, D, Parker, D, Sherwin, J, Measured Field Performance and Energy Savings of Occupancy Sensors: Three Case Studies. Florida Solar Energy Center internal report FSEC-PF309. August 1996. Retrieved from http://www.fsec.ucf.edu/bldg/pubs/pf309/index.htm on 5/14/04

[40] Heschong, L, personal communication May 2004.

[41] Fleischer, S, *Effect of Brightness Distribution and Light Colours on Office Staff*, Ph.D. Thesis, Institute of Hygiene and Applied Psychology, Zurich, Switzerland. 1998.

[42] Soli, S, Sullivan, J, *Factors Affecting Children's Speech Communication in Classrooms*. Journal of the Acoustical Society of America, 101:S3070. 1997

[43] Johnson, C, *Children's Phoneme Identification in Reverberation and Noise*. Journal of Speech, Language and Hearing Research, 43, 144-157. 2000

[44] Research Group for Inclusive Environments, *Project Crystal Website*, http://www.rdg.ac.uk/ie/research/crystal/index.htm Retrieved on 5-14-04

[45] California High Performance Schools, *CHPS Best Practices Manual 2002*, Retrieved from www.chps.net on 6/22/04

[46] Lighting Research Center, *Self-Commissioning Photosensor*, Retrieved from http://www.lrc.rpi.edu/programs/lightingTransformation/improvedPhotosensors/pdf/selfCommisioningPhotosensor.pdf on 6/2/04

[47] Rubinstein, F, personal communication June 2004.

[48] Lighting Research Center, Field Test DELTA Snapshots: Staircase Lighting, March 2004. Retrieved from http://www.lrc.rpi.edu/programs/DELTA/pdf/DELTAsnapshotStaircaseLighting.pdf on 6/3/04

[49] White, V, Alderman, D, Faison, C (editors), National Voluntary Laboratory Accreditation Program Procedures Requirements and General Requirements (NIST Handbook 150). July 2001. National Institute of Standards and Technology, Gaithersburg, MD. Retrieved from http://ts.nist.gov/ts/htdocs/210/214/docs/final-hb150-2001.pdf on 5/17/04

[50] RLW Analytics, *Final Report - 1999-2001 Building Efficiency Assessment (bea) Study: An Evaluation of the Savings By Design Program*, Report submitted to Southern California Edison, April 2003. Retrieved from www.calmac.org on 6/1/04

[51] Eley Associates, *Outdoor Lighting Research*. Submitted to California Energy Commission June 2002

[52] Clark, B, *Outdoor Lighting And Crime, Part 1: Little Or No Benefit*. Published on the website of the Astronomical Society of Victoria, November 2002. Retrieved from http://www.asv.org.au on 5/17/04.

[53] Caminada, J, Van Bommel, W, *Residential area lighting. Engineering Report 43*, Lighting Design and Engineering Centre. Eindhoven, The Netherlands: NV Philips Gloeilampenfabrieken. 1980.

[54] Illuminating Engineering Society of North America, *Lighting for Automatic Teller Machines (DG-9-97)*. IES, New York, NY. 1997.

[55] Murray, I, Plainis, S, Carden, C, *The ocular stress monitor: a new device for measuring discomfort glare.* Lighting Res. Technol. 34(3), 2002. pp. 231-240.