Integrating Daylighting and Electrical Lighting for Premium Efficiency and Performance

Gary Epstein[1]
Brian McCowan[2]
Daniel Birleanu[3]

[1]President, Energy & Resource Solutions, Inc., Phone: 978-521-2550 x 225, Fax: 978-521-4588. E-mail: gepstein@ers-inc.com
[2]Director, Energy & Resource Solutions, Inc., Phone: 978-521-2550 x 301, Fax: 978-521-4588. E-mail: bmccowan@ers-inc.com
[3]Project Manager, Energy & Resource Solutions, Inc., Phone: 978-521-2550 x 265, Fax: 978-521-4588. E-mail: dbirleanu@ers-inc.com

1. INTRODUCTION

Many geographical areas of the United States are experiencing an unprecedented increase in the construction of new schools and renovation of existing schools. The growth of the student age population and the fairly uniform deterioration of schools built during the school building boom of the 1960's, have coincided with a robust economy and healthy tax base to promote the current school construction boom.

This dramatic increase in construction of new public school facilities challenges lighting designers to develop lighting systems that are cost effective, offer premium efficiency, and provide the high quality lighting demanded for modern educational environments, while meeting new building energy codes. The lighting design approach presented in this paper allows high color rendering, low glare, premium efficiency lighting and energy codes to work together to provide optimal lighting performance.

Energy codes, typically a subsection of the building code, are gaining acceptance in a growing number of jurisdictions. Requirements for maximum connected lighting loads for space types and sizes (lighting power density) and the mandatory application of advanced automatic lighting controls are typically included in contemporary energy codes. Innovative methods for complying with, and improving upon, aggressive energy codes while providing premium quality lighting are presented in this paper. It is the strong belief of the authors that code compliance establishes the minimum performance levels to which new schools should be designed, and that proficient lighting designers should set their goals well beyond the requirements of these codes.

Working closely with DesignLights™ Consortium (DLC), Massachusetts Electric, and Narragansett Electric, Energy & Resource Solutions, Inc. (**ERS**) has developed and implemented techniques that ensure optimum levels of lighting performance and energy efficiency. Incorporating premium performance fixtures with new lamp/ballast technologies ensures low-glare, high color rendering, and energy efficient lighting. Automatic occupancy controls, daylight harvesting systems, and DDC lighting control panels complete the systems approach to lighting design.

Approaches and technologies discussed include: daylight enhanced education; color rendering and lighting level interaction; premium T-8 lighting systems; T-5 lighting systems; modern athletic facility lighting; task lighting; multi-purpose spaces with multi-level lighting; line and low voltage lighting control systems; integrated occupancy/daylight control systems; and individually addressable ballasts.

1.1 Design Lights Consortium (DLC)

The DLC is a regional collaboration promoting lighting quality, comfort, and efficiency. As part of its mission, DLC promotes the implementation of improved design practices in all parts of the commercial lighting market. Coordinated by the Northeast Energy Efficiency Partnership (NEEP), the DLC brings together regional utilities and other interested parties to implement energy-efficient and high quality lighting in commercial buildings throughout the Northeast. Although the DLC efforts seek to include property management firms, large retail chains, and others, it is in the area of public school lighting design that the DLC has made the most significant impact.

In New England, major utility companies such as Massachusetts Electric, Narragansett Electric, NSTAR, and Western Massachusetts Electric have sponsored pilot projects that promote premium efficiency and premium quality school lighting designs. Rather than rely on their standard conservation incentive programs, these utility companies have worked with the DLC to pay conservation incentives only when the lighting designs improve upon applicable energy codes. In this way, the codes and the utility programs work perfectly together, with the code providing the minimum performance base, and the DLC/utility program providing the incentive to design beyond that minimum.

Working closely with the DLC and the above mentioned utility companies, **ERS** has designed lighting for several school projects, and has reviewed and upgraded lighting designs for over fifty school projects, many of which have now been completed. The techniques described in the following sections are proven and have been successfully demonstrated in several public and private school projects.

2. LIGHTING ISSUES IN THE EDUCATIONAL ENVIRONMENT

Quality lighting is not simply the delivery of adequate illumination (measured in foot candles) to the work area. Numerous factors are involved in the design of premium quality and efficient lighting systems. Two of these factors are closely associated, sharing a symbiotic relationship: glare and uniformity.

2.1 Lighting Glare

Both direct and reflected glare are significant problems in educational environments. Direct overhead glare is caused by excessive brightness at the light fixtures themselves. Reflected glare is a problem when lighting brightness is reflected off working surfaces such as white paper or computer screens. Glare induced shadows cast on task surfaces further impair effective visual perception.

Improperly designed and controlled daylighting is also a dramatic cause of disability glare in classroom environments. Ironically, daylight can be both the best ally and worst enemy of proper lighting in schools.

2.2 Lighting Uniformity

Proper lighting uniformity not only assures that each student and their instructors receive their “fair share” of light, but that the resulting lack of lighting “hot spots” prevents glare from becoming a hindrance.

Typical “standard practice” classroom lighting does not provide uniform lighting levels as prismatic and parabolic fixtures provide lighting levels that are higher than necessary directly below fixtures in an effort to provide reasonable levels between fixture rows and at room corners.

2.3 Wall Illumination

Years ago, it was common for virtually all classroom work to be conducted on a front wall-mounted blackboard. A look at any modern classroom will reveal most, if not all, wall surfaces being utilized for display of classroom projects. Illumination of these wall-mounted displays is extremely important. Additionally, illuminating walls adds to the overall brightness of the room. Wall illumination is severely limited by the use of deep cell parabolic fixtures that are commonly used to provide low-glare lighting.

2.4 Lighting Levels

When discussing lighting levels, the focus is usually on a lack of adequate illumination. In contrast, we have found the majority of classrooms designed during the last twenty years are over-lit, and many professionals continue to design classrooms with lighting levels that are higher than necessary.

Recent studies have suggested that accurate color rendering promotes proper visual acuity (Heschong Mahone Group 1999; Berman 1992, 1996), allowing lower illumination levels. Designers, however, continue to ignore color rendering as a critical element in the delivery of proper lighting levels.

Multi-level switching can provide additional lighting for particular tasks, rather than designing the general lighting for the most demanding tasks encountered.

Because the eyes ability to gather in light decreases with age, the illumination levels required by students and teachers can vary greatly. Visual performance for instructors is at least as important as it is for students, so it is typical for classroom lighting to be designed to provide lighting levels required by staff members at retirement age. The design of classroom lighting that provides additional illumination only at the teaching station should be considered for all classrooms.

2.5 Color Rendering and Temperature

As previously stated, the accurate rendering of colors is an integral part of providing adequate and comfortable lighting levels. Accurate color rendering provides the visual contrast needed to perform accurate work. Years ago, nearly all classroom work was done in black and white. This is, of course, no longer true.

Often confused with color rendering, color temperature is the actual color of the light source (lamp, in this case) as it appears to the human eye. The color temperature has long been considered a matter of personal taste. Recently the idea has been promoted that visual acuity is enhanced when color rendering and color temperature are selected together as a relational unit (New Buildings Institute 2000). Numerous "studies" sponsored by lamp suppliers, have suggested that visual acuity is enhance under certain color temperatures. The color temperature typically recommended by these studies is in the "daylight" range (around 5000K), and/or "full spectrum" lamps. In reviewing these studies, it is revealed that scientific methods have not been fully utilized, and too many variables cloud the picture. Independent, scientific study is needed on this issue.

3. ENERGY CODES AND SCHOOL LIGHTING

During the past several years, there has been a considerable effort to introduce more aggressive building energy codes that address all building energy systems, including lighting. There are several design techniques and technologies that allow adequate lighting levels with code compliant designs.

Energy codes being implemented throughout the United States typically include maximum connected lighting loads (lighting power density) for various space types, and requirements that certain areas have all of their lighting controlled automatically (excluding emergency lighting).

3.1 Lighting Power Density

With the rapid advancement of lighting technology, it is fortunate that energy codes tend to not require specific lighting technologies. Whereas utility incentive programs might require specific lamp and ballast technologies, energy codes are rooted in lighting performance. This approach allows the innovation of new lighting technologies without the hindrance of codes.

Most codes place the lighting power density threshold for schools at 1.5 watts/sqft foot for the total of all interior spaces. Additionally most codes allow the individual space types to be calculated separately. For example, lighting power density for classrooms and offices is typically 1.6 and 1.3 watts/sq ft, respectively.

Although there is much concern in the architectural/engineering communities about these lighting power density levels, they are easily reached and improved upon.

3.2 Automatic Lighting Controls

A common misconception is that energy codes require occupancy sensors in virtually all spaces. This is not the case, as again the writers of energy codes have specified levels of performance rather than specific equipment.

Current energy codes basically require that automatic controls be used to turn-off lighting at the end of the normal work/school day. This task can and many times should be done by automatic occupancy sensing. However, timer based scheduling controls can also provide this function. When timer based scheduling controls are used to satisfy this code requirement, local control (in the same room as the lights being controlled) must also be provided. This local control can be a manual switch.

3.3 Energy Conservation Codes are not Design Tools

By their very nature, building codes define the minimum standard to which buildings should be designed. Especially pertaining to lighting power density levels, many designers are making the mistake of assuming that the code writers intended to imply that matching the specified lighting power density levels will result in the appropriate lighting levels. At a recent school design review meeting, ERS was presented with this comment from the project architect, “There won’t be enough light; the density is only 1.1 and the code calls for 1.6.”

The maximum lighting power density levels identified in the code assume “average or below average” fixture efficiencies, lamps of average efficacy, high ceilings, low room surface reflectivity, and an abundance of light absorbing furnishings. When rooms and lighting systems are designed with energy efficiency and visual performance as a priority, lighting power density codes are bettered by a large margin.

3.4 FLUORESCENT LAMP SELECTION FOR PREMIUM EFFICIENCY AND QUALITY

3.4.1 T-8 Lamps. Although T-5 technologies have recently been making inroads, there is no doubt that T-8 lamps are the mainstay of efficient lighting design for most spaces encountered in schools. Because T-8 lamps, as a generic item, have been heavily promoted for energy conscious lighting design, an assumption that all T-8 lamps are essentially the same is prevalent. Standard T-8 lamps are termed 70 (or 700) series lamps because they offer color renderings in the 70’s. 80 (or 800) series lamps offer color rendering in the 80’s along with 20% greater mean lumen output. 90 series offer even better color rendering, but they do so at the expense of lumen output, and should be considered only for spaces where color rendering is the overriding criterion. Table 1.1 illustrates the performance characteristics of various fluorescent lamps.

Light Source	Lamp Type	Efficacy Lumens/watt	Lumen Maintenance	Avg. Life Hours	CRI
Fluorescent	T-12 Cool White - EE	62.2	87%	20,000	62
	T-8 80 Series Lamp	101.7	95%	20,000	86
	T-8 90 Series Lamp	62	93%	20,000	95
	T-5	98.6	97%	16,000	85
	T-5 HO	100	97%	16,000	85

Table 1. Comparison of Selected Fluorescent Lamp Types

Newly introduced T-8 lamps offer both reduced and increased lumen outputs. Additionally T-8 dedicated lamp/ballast systems are now reaching the market that offer improved efficacy and longer lamp life.

3.4.2 T-5 Lamps. These 5/8” diameter lengths were developed in Europe for the European market. As such, they are presently available in metric lengths only. However, many U.S.

lighting fixture manufacturers are producing fixtures for these lamps because of their unique characteristics. The small diameter tubes not only allow for slim fixture designs, but the narrow tubes allow fixtures to be designed with improved optic control. This control is particularly useful when light needs to be projected farther than typically encountered in a normal classroom or office. T-5 lamps do have a few disadvantages that designers should be aware of:

- T-5 lamps are rated for full output at 100° F, and as such do not generate full lumen output until they reach that ambient temperature.
- T-5 lamps not yet available in low mercury versions, presenting difficult disposal issues.
- T-5 lamps are more expensive than T-8 lamps.
- T-5 lamps tend to have a shorter life than T-8 lamps. Although some manufacturers now rate them the same, many manufacturers rate T-5 lamps as having a 25% shorter operational life.
- Ballast options for T-5 lamps are not yet as extensive as they are for T-8 lamps.

3.4.3 Biax Lamps. Often referred to as a type of "compact fluorescent" lamp, biax lamps offer very good efficacy and color rendering, typically matching 80 series T-8 lamps. Two foot biax lamps are a good choice for 2'x2' fixtures, but they are significantly more expensive than linear fluorescent lamps.

3.5 SELECTING LAMPS

3.51. Recessed Fluorescent Parabolic Fixtures. Parabolic fixtures, although less efficient than their prismatic counterparts, offer dramatic reductions in certain types of glare. Given proper fixture/computer terminal placement, disability glare encountered when looking across a room is reduced, as is reflected glare on computer screens. However, glare reflected off paper or other light surfaces can actually be increased with parabolic fixtures when the working surface is directly below the fixture because the working surface is directly exposed to bare lamps.

Parabolic fixtures, especially deep-cell versions, have a significant drawback for classroom lighting as the same "cut-off" feature that controls glare, also prevents light from reaching the walls. Illuminating walls is extremely important in classrooms, both for class-work display and the overall feeling of brightness in the room.

3.5.2 Surface Mounted Fixtures. Before T-bar suspended ceilings became common, surface mounted fluorescent fixtures were used extensively for school lighting. Most were inefficient, and even those with louvers offered minimal glare control. The introduction of T-5 lamps has encouraged lighting fixture designers to develop new low profile surface mounted fixtures with improved glare control. While presently not the best choice for classroom or office lighting, the new generation of surface mounted fixtures are improving rapidly.

3.5.3 Fluorescent Wall Washing Fixtures. As previously stated, illumination of walls is an important element of classroom lighting design. When recessed glare control fixtures such as deep cell parabolic fixtures are used, it is often necessary to incorporated wall washing fixtures into the design. Because incandescent wall washers have been so popular, it is easy to think of fluorescent wall washing fixtures as being of the compact fluorescent variety. Many fixture manufacturers offer linear parabolic louvered wall washing fixtures that do an efficient job of illuminating the walls. Classroom lighting designs that include both standard distribution, and wall washing parabolic fixtures can provide uniform, low-glare, efficient lighting.

3.5.4 Pendant Direct/Indirect. Given the current state of lighting technology, pendant mounted direct/indirect lighting offers the best compromise between efficiency, glare reduction, lighting uniformity, wall illumination, and aesthetics. Lighting glare is directly linked to the brightness of the surface that is projecting the light. A bare lamp is, of course, a major culprit, as is a small refractive or reflective surface. Pendant direct/indirect fixtures, to a variable degree, shield room occupants from direct view of the lamps, and use the largest possible reflective surface (the room's ceiling) for light distribution. This approach provides a very uniform and glare-free distribution of light.

Direct/Indirect fixtures are available with a variety of distribution patterns. Typical direct/indirect components range from 50% to 80% indirect lighting. Provided good available ceiling reflectivity (80% or better), fixtures with an 80% indirect component will offer excellent glare reduction with sufficient lighting levels at lighting power density levels well below those required by today's most stringent codes. When ceiling surfaces are less than ideal, or when added "punch" is needed directly underneath the fixtures, 50/50% direct/indirect fixtures will perform well, but with increased glare and a drop in uniformity.

Lighting designers should be cautious when specifying this type of fixture for areas with limited ceiling heights. Ceiling heights of less than 9' 6'' typically do not allow the fixture to be suspended far enough below the ceiling to allow for proper light distribution. Suspending fixtures closer than 18" from the ceiling reduces the effective surface area of the reflector (ceiling), increasing glare and reducing uniformity.

3.5.5 Pendant Fully Indirect Fixtures. If direct/indirect fixtures offer good classroom and office lighting performance, wouldn't 100% indirect fixtures perform even better? Our experience tells us that this question can confidently be answered, "No." It is possible to demonstrate that "theoretically" 100% indirect fixtures can outperform direct/indirect fixtures. However it is often said of engineers that, "they attempt to prove that what works in the field, can actually work in theory." Countless field installations of 100% indirect fixtures in classrooms have shown that instructors and students feel that the lighting levels are inadequate and that the room is dull and lifeless. A recent school project that ERS reviewed included the installation of pendant mounted 100% indirect fixtures in classrooms. The fixtures had replaced recessed troffers, and the instructors felt that lighting levels and "brightness" had been reduced. Using illumination meters, the design firm demonstrated that lighting levels had actually increased by 20%. This demonstration did little to impress the teaching staff, and what could have been a successful project, instead resulted in a dissatisfied customer.

3.5.6 Recessed Direct/Indirect Fixtures. One other fixture style has prompted significant controversy. Recessed direct/indirect fixtures are particularly popular where they can replace recessed troffers, and where sufficient ceiling heights do not allow the proper utilization of pendant direct/indirect fixtures. They have often been promoted as offering all the advantages of pendant mounted direct/indirect fixtures. They do not offer all of the advantages, as their illumination is delivered from a relatively small reflective surface rather than from an expansive ceiling. However, comparing these fixtures with pendant fixtures is unfair. Instead they should be compared with recessed parabolic fixtures, as they are best utilized under similar conditions. When compared to parabolic fixtures, they offer similar efficiency levels and similar overall glare reduction. They do not offer the extreme cut-off of deep cell parabolic fixtures, meaning that glare reduction is not as significant at some angles, on the other hand, walls are better illuminated and uniformity is improved.

3.6 DESIGNING FOR DAYLIGHT

Natural daylight has the potential for supplying the highest quality lighting for the educational environment. The performance of all artificial lighting is measured against daylight, as daylight is considered to offer the ultimate in its ability to render colors and provide contrast. Daylight "brings the outdoors indoors" providing an attractive and interesting environment. The lively changes in brightness and color gives building interiors visual interest that cannot be obtained with artificial lighting. In addition, daylighting can offer significantly reduced electrical consumption for lighting, even if the connected lighting load (lighting power density) remains essentially unchanged.

As pleasing as natural daylight can be, if it is not properly incorporated into the design, it can supply lighting problems to rival the poorest designed artificial lighting system. Step outside on a sunny day and attempt to read the newspaper in direct sunlight, without benefit of sunglasses, to experience the discomfort that can be associated with daylighting. Without careful design, direct and indirect glare can be severe. Various techniques to diffuse daylight and deliver it to the working environment are effectively used to provide high performance lighting. Glazing materials that diffuse the light are one option, but the proper use of clerestories, skylights, and monitors are often a more effective strategy. Many architects designing with daylighting incorporate features that ensure that room occupants will never be in the direct line of sight of the sun's rays, using reflective building surfaces to evenly provide diffuse, non-glare lighting.

3.6.1 Automatic Controls for Daylight. Many of the most dramatic buildings being designed today incorporate natural daylight as a featured design element. One of the most famous day-lit buildings of recent vintage is the new Denver International Airport. A recent visit by ERS revealed that the daylighting was indeed dramatic and comfortable. However, all of the artificial electrical lighting was on during the middle of a sunny day. A subsequent discussion with the lighting system architect revealed, "I was responsible for designing the architectural daylighting, the electrical engineering firm was responsible for the lighting controls. I don't think they ever got installed."

Schools also often suffer this fate. At a minimum, daylight harvesting controls that will turn off unneeded lighting when sufficient daylighting is available should be incorporated. More sophisticated controls that provide daylight dimming with dimmable electronic ballasts provide improved energy savings and a more comfortable environment. One strategy that can work well in classrooms is the use of daylight harvesting controls only for the row of fixtures that is near glazing. Combination occupancy and daylight harvesting sensors are becoming commonplace, but it should be noted that daylight and occupancy sensors do not always share the same location needs.

3.6.2 Controls for Occupancy Sensing. Many previous efforts have discussed the subject of occupancy sensing for schools. For this reason, this paper will not go into the basics of this subject. However, a few points should be emphasized concerning the use of occupancy sensing in schools.

1. The type of occupancy sensing technology should be carefully considered. Passive infrared sensors cannot "see" around corners or past other obstructions. Classrooms that incorporate movable display boards and other obstructions should not rely on passive infrared detection. Ultrasonic sensors can suffer from false triggering as sound waves are bounced off walls and other objects, requiring careful adjustment of sensor sensitivity. Additionally, ultrasonic sensor can be triggered by nearby HVAC registers. Dual technology sensors incorporating both ultrasonic and passive infrared technologies may be the best solution for larger classrooms where the limited sensing capabilities of single technology units can allow lighting to go off while the area is occupied.
2. All types of sensors must be "commissioned." Many contractors simply install the sensors with the factory default (or random) setting and "walk away." Dissatisfaction with poorly adjusted sensors often leads to a large percentage of sensors being disabled. Lighting designers should arrange to have all sensors "commissioned" before spaces are occupied. Some utility incentive programs, as well as some energy codes, now require this commissioning.
3. Newly developed "adaptive" sensors should be considered. These sensors incorporate circuitry that records and "remembers" room occupancy patterns. As patterns develop and/or change, the sensor automatically adjusts the time delay set-point to maximize energy savings.

3.6.3 Ballasts for Automatic Controlled Lighting Fixtures. Automatic lighting controls, both occupancy and daylight based, can be significant savers of electrical energy. However, the on/off cycling of lighting is hard on fluorescent lamps, reducing lamp life. Most T-8 lamps are nominally rated at 20,000 hours, however with instant start ballasts, they are typically rated at 15,000 hours. The majority of electronic ballasts on the market are of the instant start type. The deleterious effect on lamp life is magnified when lighting controls cycle the lamps more than might be typically encountered. Rapid start ballasts do not share this problem, but rapid start ballasts use more energy because they send a constant "warming" current to the lamp electrodes. "Programmed start" ballasts strike a balance between these two technologies, using a starting procedure that is almost as fast as "instant-start" yet is easy on the lamp electrodes, extending lamp life.

3.6.4 Athletic Facility Lighting. The lighting of gymnasiums and other athletic facilities can be a significant energy consumer for any school. Athletic facilities tend to use more energy than their "fair share" for a variety of reasons:

- Increasing demand on athletic facilities creates long operating hours. Evening, weekend, and summer usage often creates operating hours 50 to 100% greater than classroom operational hours.
- Typically, the lighting is metal halide (or another HID source). The long warm-up time encourages staff to turn on the lighting in the morning and leave it on all day, often

spanning long unoccupied time periods. During spring and fall, when many physical education classes are held outdoors, gymnasium lighting is often on all day, illuminating not a single activity.

- Especially at the high school and collegiate level, lighting levels are designed for sanctioned competitive events. With the inflexibility of HID lighting, most other activities are over illuminated.

Two strategies have been incorporated in the DesignLightsTM Schools Initiative Program to reduce the consumption of athletic facility lighting.

1. 350-Watt Pulse-Start High/Low Dimming – This system is typically designed as a one-for-one replacement for 400-watt metal halide lighting. Operating on the high setting the fixtures deliver 95-100% of the lighting supplied by comparable 400-watt metal halide. On the low setting the wattage is reduced by 50% while the lumen levels are reduced by 60%. Occupancy sensing, or automatic scheduling, controls the high/low function. Daylighting controls may also be utilized for the high/low function. Additionally the system can be manually overridden to the low setting to allow for reduced lighting levels for gym classes, assemblies, and cleaning.
2. Multi-Lamp Fluorescent High Bay Lighting – The advent of smaller diameter tubes for fluorescent lighting has allowed fluorescent fixtures to be designed with improved ability to project light. Because fluorescent lighting does not have the long warm-up time associated with HID lighting, fluorescent lighting can be turned off when gymnasiums are not in use during the day. Upon occupancy, the lighting can be operating at full output within a matter of seconds. These systems utilize 6-8 lamps per fixture, with each pair of lamps operated by an electronic ballast. By delivering an individual "hot" lead to each ballast, the fixture can be operated on 2, 4, 6, or 8 lamps, allowing for fine control over lighting levels and enhanced energy savings. Again, both occupancy sensing and daylight sensing can be used to control the individual circuits.

4. Case Studies

4.1 Quabbin Regional School District Support Facilities

This 8,000 square foot project belongs to a regional school facility in central Massachusetts and was recently completed. ERS worked with Coldham Architects and Massachusetts Electric in the design of the lighting system for this facility. The architects designed the daylighting system, while ERS designed the artificial lighting and controls. A joint effort integrated these systems. This project is particularly noteworthy in that it incorporates architecturally integrated daylighting along with three types of automatic lighting controls to provide the ultimate in high performance lighting. The project features:

- Architecturally integrated daylighting.
- Architectural features that eliminate daylight glare.
- Low glare pendant and surface mount fluorescent fixtures.
- Dimming ballasts with ambient light sensors where appropriate.
- Daylight harvesting sensors for on/off control where appropriate.
- Ceiling and wall mounted occupancy sensors.

The project achieves the highest levels of energy efficiency, easily improving upon all applicable energy codes. Table 2 illustrates this design's energy performance advantages.

Mass. Code Allowable Power Density (W/ft^2)	1.3
Calculated Base Global Power Density (W/ft^2)	1.28
Proposed Global Power Density (W/ft^2)	**0.77**
Base Design Connected Lighting Load (kW)	9.54
Proposed Design Connected Lighting Load (kW)	5.734
kW Saved:	**3.806**
Average Annual Operating Hours	3,000
Estimated Rate	$0.0884
Annual kWH Saved Lighting Only	11,418
Annual kWH Saved Lighting Controls Only	3,023
Total Annual kWH Saved Lighting & Controls	**14,441**
Annual Savings in Dollars:	**$1,277**

Table 2. Quabbin Regional School District Support Facilities Summary Data

4.1.1 Architecturally Integrated Daylighting To receive maximum benefit from daylighting, the daylighting systems must be an integrated part of the architectural design. Coldham Architects designed this building with the daylighting system as the principal lighting system. After modeling the design using "Radiance" daylighting design software, the designers built a scale model of the design with interchangeable roof systems. Using a specially designed outdoor "daylight modeling stand" (Coldham 2001) that allows building orientation to the sun to be manipulated on all planes, the building was modeled with several different roof integrated daylight schemes. Monitors, clerestory, and ridgeline skylights were all considered. Ridgeline skylights were chosen as they provide the best combination of daylight contribution and glare reduction. Figure 1 illustrates the installed roof system.

Figure 1. **Quabbin Project – Integrated Ridgeline Skylighting**

To maximize the performance of the daylighting system, all ceiling surfaces were kept to a minimum reflectance of 85%, while wall surfaces are calculated at an average reflectivity above 60%. Skylight, window, overhangs, and other architectural elements were carefully designed to reduce and/or eliminate glare.

4.1.2 Bringing Light Into Interior Core Spaces. Most daylighting designs utilize daylighting for the illumination of perimeter spaces only. This project was designed with an interior false roof with strategically placed glazing. The glazing on the false roof, allows daylight to penetrate from the skylights into the interior spaces. These spaces are used for tasks that require less glare control (storage, filing, and small conference rooms) than designed for perimeter offices. Photo1-2 illustrates the interior roof system.

Figure 2. **Quabbin Project – Interior Roof System**

4.1.3 Lighting Fixture Selection. Because the daylighting system is the primary lighting source for the project, electrical lighting was kept to a minimum. However, the quality of the electrical lighting system was not compromised, as the artificial lighting should provide even, low-glare lighting, when needed. As can be seen in the above photographs, pendant mounted direct/indirect fixtures were used to supply lighting to all areas with ceiling heights greater than 9'. Surface mounted direct/indirect fixtures were utilized for areas with ceiling heights of less than 9'. With the exception of storage rooms, all lamps are hidden from direct view.

T-8 lamps with a color temperature of 4100K, and color rendering of 86 were chosen as the best compromise between matching natural daylight and providing "warmth."

4.1.4 Lighting Controls. To take full advantage of the daylighting system and occupancy patterns, several different lighting controls were incorporated.

1. Daylight Harvesting with Dimming Ballasts – For larger areas with significant connected load (group training classroom, and open office/training areas) daylight sensors adjust ballast

output from 10-100% of rated lamp output. The sensors are adjusted to begin increasing ballast output when illumination values drop below 45 F.C. at the work surfaces.

2. On/Off Daylight Harvesting – The small offices have a connected lighting load of only 60 watts. For these areas, the daylight sensors turn on the lights when daylight illumination drops below 55 F.C. The artificial lighting is designed to provide 40-45 F.C., but by supplementing the lighting at 55 F.C., the change from natural to artificial lighting is made less intrusive. Because of the excellent architectural design, artificial lighting is kept off during most of the typical workday.
3. Manual On/Automatic Off Occupancy Sensing – Most occupancy sensors feature automatic on and off of the lighting. With such a system, artificial lighting is often turned on when the occupant might have otherwise not chosen to turn on their lighting. A post installation interview with the building occupants revealed that many choose to leave lights off, even when both occupancy and daylight sensors are calling for them to be "on". It is important that automatic lighting controls do not defeat the energy conservation habits of motivated employees.

4.2 Metropolitan Career and Training Center

This Rhode Island facility will be a school for special needs students that are following a career based education path. The facility is designed with movable walls for a flexible teaching environment. The flexible design presents lighting design challenges, as differing lighting levels may be needed, and the incorporation of automatic lighting controls becomes problematic. The lighting design includes:

- Pendant mounted direct/indirect fixtures with "twist-loc" connectors and removable pendants to allow for the movement of modular walls.
- Multi-level switching allowing for three lighting levels for each educational space.
- Zoned lighting control circuits allow each lighting fixture module to be connected to any local zone for occupancy control.
- Daylight harvesting for all perimeter spaces.
- Multi-lamp fluorescent high bay lighting for two gymnasiums.

4.2.1 Energy Code Issues. As of the date of this paper, the State of Rhode Island has not adopted an energy conservation code. However, it is the intention of the state to do so by January 1, 2003. In order to establish a benchmark for the base system for this project, the Massachusetts Energy Code (Chapter 13 of the Building Code) was utilized as the most likely model for the upcoming Rhode Island code. Energy savings for this project were calculated by comparing the proposed design with a theoretical base design complying with the Massachusetts Energy Code.

4.2.2 Open Plan Classrooms and Lighting Issues. The classroom areas for this project are designed as large open areas with movable partitions. The partitions are rigid structures that are intended to be moved only once a semester to conform to current educational needs. It is indeed a challenge to design an efficient lighting system that allows for the moving of walls. Without an innovative plan, unneeded lighting fixtures will be illuminated following changes in the classrooms layouts.

To eliminate this problem, the lighting system for many areas consists of 8’ lengths of pendant mounted direct indirect fixtures. Removable aircraft cable hangers will be used for suspension, allowing the fixtures to be temporarily removed during wall rearrangements. Areas with limited ceiling heights will receive recessed direct/indirect fixtures with multi-level switching capabilities. The line voltage electrical connection will be made with twist-loc connectors, more commonly used for industrial lighting. Low voltage control wiring will feature snap in connectors similar to phone/data connectors. Manual overrides for the lighting controls can be connected and activated on each movable wall section as required.

4.2.3 Daylighting. Although this project does not include the architecturally integrated approach of the Quabbin project, significant perimeter daylighting is provided through vertical “vision” glass incorporating glare control blinds. Modular daylighting controls will be included for all perimeter spaces. The daylighting controls can be re-circuited as walls are moved.

4.2.4 Occupancy Controls. Perhaps more challenging than lighting fixture layouts is the design of occupancy controls for large areas with movable walls. Passive infrared sensors with adjustable sensitivity are to be installed so that there maximum coverage areas overlap by about 20%. They will be zoned to control only the lighting in their coverage area, and sensitivity will be adjusted during commissioning to ensure that unneeded lighting is not activated. Like the daylight controls, the occupancy sensors are designed to be re-circuited and readjusted when walls are moved.

4.2.5 Usage. However, during spring, fall, and summer (this is a year-round facility) it is typical for gym classes to be held outdoors, and gymnasiums become glorified passageways to outdoor athletic fields. The project is designed with alternative paths to outdoor facilities, allowing more design flexibility. Traditional HID lighting of gymnasiums does not allow for the turning on and off of the lighting during the day, because of long warm-up times. For this project, multi-lamp fluorescent high-bay fixtures have been chosen for the gymnasium. Zoned occupancy sensors will control these fixtures, additional manual controls will allow for the selection of differing lighting levels depending on the activity scheduled.

The advantages of multi-lamp fluorescent lighting for gymnasiums include:

- Instant on/off
- Occupancy sensor compatibility
- Multi-level lighting (typically 2, 4, 6, and 8 lamp)
- No lamp flicker with electronic ballasts
- Improved color rendering
- Better vertical illumination, allowing better visual ball tracking

Project Floor Area (Sq. Ft.)	108,172	Base Design Demand (kW)	142.41
Average Operating Hours	3600	Proposed Design Demand (kW)	116.90
Code Allowed Lighting Power Density (W/sf)	1.5		
Base Design Lighting Power Density	1.32	**Demand Savings (kW)**	**25.51**
Proposed Design Lighting Power Density	**1.08**	**Annual kWH Savings**	**91,822**

Base Design Estimated Cost	$130,911
Proposed Design Estimated Cost	$233,413
Incremental Cost of Improved Design	**$102,502**

Table 3. Metropolitan Career & Training Center Summary Data

kW Controlled	77.7	Base Design Estimated Cost	$ -
Average kW Savings - Peak Periods	25%	Proposed Design Estimated Cost	$56,705
kW Savings - Peak Periods	19.4	Incremental Cost of Improved Design	$56,705
Annual kWH Savings	85,337		

Table 4. Metropolitan Career & Training Center - Controls Summary Data

5. CONCLUSION

Sophisticated architectural design techniques, along with innovative lighting fixture, and automatic control designs, allow modern school projects to be illuminated to a much higher quality level. This level of quality can be reached at electrical energy demand and consumption levels far below what has traditionally been utilized for schools and at levels far below those promoted by the most aggressive energy conservation codes.

By keeping codes performance based, rather than technology based, codes will continue to encourage innovative thinkers to develop new strategies and technologies to further enhance the educational environment.

6. REFERENCES

Heschong Mahone Group. 1999. *Daylighting in Schools.* Pacific Gas & Electric.

Berman, S.M. 1992. *Energy Efficiency Consequences of Scotopic Sensitivity.* Journal of the Illuminating Engineering Society.

Berman, S.M. 1996. *Essay by Invitation; Task Modified Lumens.* Lighting Design and Application, November 1996.

----------. 2000. *The IESNA Lighting Handbook, 9th Addition*. The Illuminating Engineering Society of North America.

----------. 2001. *Advanced Lighting Guidelines*. New Buildings Institute.

Coldham, Bruce. 2001. *Constructing a Daylighting Model*. www.coldhamarchitects.com.