Experimental and Simulation Evaluation of Alternative Interior and Exterior Lighting Solution for Virginia Tech

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Abstract

According to the U.S. Department of Energy, the energy consumption for lighting is estimated to be about 22% of the total electricity generated in the U.S for the year 2001. With the very poor conversion of electrical energy to visible radiation there is an immediate need to adopt new and efficient lighting solutions.

Virginia Tech with its own commitment to reduce energy consumption is continuously looking and experimenting with the latest and most efficient lighting solutions for the interiors and exteriors of buildings on its campus. This study seeks to evaluate the performance of selected exterior and interior lighting solutions through experimental and simulation means.

A proposed exterior lighting solution, for the “Hokie” light, the most common outdoor lamp fixture on campus, was monitored and evaluated under control settings in the Environmental Systems Laboratory at Virginia Tech. Options for improving the performance of the Hokie light and reducing the uplight were experimentally tested and analyzed. Use of a non-perforated aluminum LiteLid® was selected as the most promising and cost effective solution after analyzing the performance of a variety of options.

For general interior lighting, the feasibility of using advanced lighting methods such as Light Emitting Diodes (LEDs) was explored and analyzed. The performance of LEDs was experimentally compared with the existing fluorescent lamps. Performances of the fluorescent and LED lamps were analyzed for selected parameters such as the quality, color and quantity of the light. The annual energy consumption and utility cost of a representative building on the Virginia Tech campus with existing fluorescent lamps and the proposed LED lamps was estimated using E-Quest simulation software. The building chosen for this purpose was the newly constructed Institute for Critical Technology and Applied Science (ICTAS). Low lumen output of the LED lamps and burnout due to heat dissipation and poor color rendition index (CRI) of the LED lamps makes them unviable for interior applications at this time.

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I have no words to express my gratitude to my friend, brother, mentor to Abhinav Sharma whose absence I will feel all throughout my life. The void he has left will never be filled. Without him the dream of Masters from Virginia Tech could have never been realized. I dedicate my work to Abhinav.

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Chapter 1 Introduction

Being one of the premier research universities in the United States, Virginia Tech is committed to being a leader for reducing energy usage in institutional buildings. Virginia Tech aims to maximize energy efficiency, and comply with the energy conservation requirements as per its latest Design and Construction Standards.

Virginia Tech Energy Conservation Standards (2006) describes the following:

> In order to incorporate sustainable design solutions in new construction and renovation projects, Virginia Tech has joined the US Green Building Council (USGBC) and fully supports the principles of the *LEED (Leadership in Energy and Environmental Design) Building Rating System.* The pursuit of high performance green buildings that are energy efficient and environmentally sensitive will help to lower operating and energy costs, improve employee productivity, promote improved learning, and enhance the health and well-being of the students, faculty and staff at Virginia Tech. (p. 8)

Virginia Tech desires to reduce energy use through improved system performance including lighting. Toward this goal the administration supports the investigation of alternative interior and exterior lighting solutions. This research is a direct response to this goal to improve the light distribution of the "Hokie" light and determine the cost/benefit of general LED lighting on campus. This thesis presents the findings for the study of 1) the Hokie light and 2) application of LED lamps.

1-1 Hokie Light

The "Hokie" light is the outdoor lighting fixture that is widely used on the campus of Virginia Tech. Hokie lights are located in the parking areas, walkways, parks and roadways of campus. Much like "Hokie" stone they are also a part of Virginia Tech architectural standards.

1-1-1 Background

The major components of the Hokie light include the following:

- The Pole - The pole style has been used at Virginia Tech for about 80 years. The materials have changed significantly over this time as the poles were originally cast iron. Fiberglass was used for a time and today the poles are aluminum, although many cast iron poles remain. The poles are 10 feet tall and an antique brown in color.

Figure 1-1-1a The Hokie light pole (Photo by author, 2008)

- The Lamp – The lamps used in the Hokie light were originally incandescent, then mercury vapor lamps were used. Currently high-pressure sodium are the most commonly used lamps (see Figure 1-1-1b).

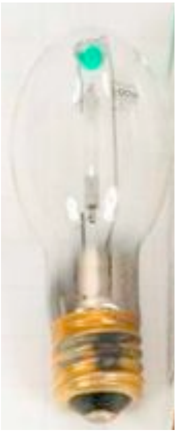


Figure 1-1-1b Philips Alto 100W HPS lamp (Photo by author, 2008)

- Finial –The finial is the topmost part of the globe and currently is made of cast aluminum.

- Globe –

  There are two types of globes in use on the Virginia Tech campus

  (a) Old Globe - The old globe was made of polycarbonate. The problem with this was that it yellowed over time and thus delivered less light to the ambient environment. It is still in use in some locations such as College Avenue. This globe was estimated to have 60% uplight as per product literature.

  (b) Current Globe – For the past four years, to improve lighting performance from the globe and to reduce the replacement and maintenance costs, Virginia Tech has been using the Lundy 424 globe from Spectrus. This globe is used for all the Hokie Lights on campus except for the old globes on College Avenue. The globe may be classified as a medium, non-cutoff or semi-cutoff fixture depending upon lamp type and lamp center location. Refer to Section 2-1-4 for the definition of medium, non-cutoff and semi-cutoff fixtures.

Figure 1-1-1c The Hokie light luminaire (Photo by author, 2008)

The material of the globe is a clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80°Centigrade or 176° Fahrenheit for optimum performance. This will be a factor in selecting among alternative options for this study.

The Globe has two components – a) prismatic top and b) refractor bottom element.

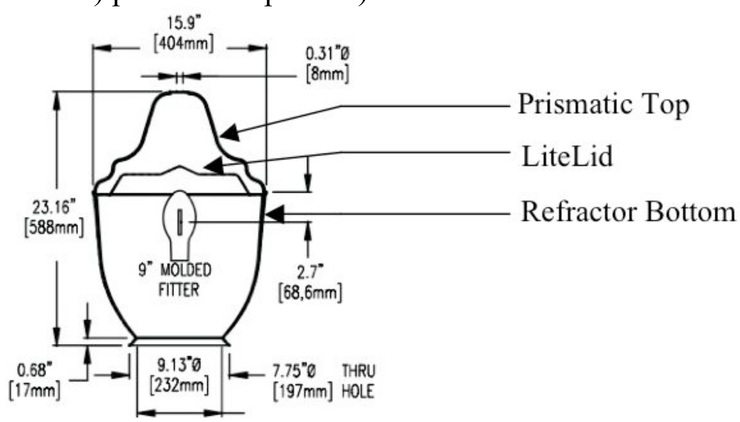


Figure 1-1-1d The Hokie light luminaire schematic section (Lexalite International Corporation, 2009)

The assembled refractor bottom and prismatic top are 15.9" in diameter and 23.16" high. Both the refractor and prismatic top are polycarbonate. The globe has a cast metal post-top fitter and a socket base.

As per the product literature, the uplight from the current globe is 14%.

Accessories

LiteLid®- LiteLids are patented, aluminum reflectors which fit between the top and bottom components of the globe. These components are used to reduce the percentage of uplight. Currently, perforated LiteLid®s are most often used. The perforated LiteLid® is used so that the heat generated inside the globe can be effectively dissipated.

Other accessories used in Hokie Light include:

Stainless Steel Clamp Band- This is used for attachment of the top.

Neck Ring- that protects the fitter from the metal screws.

1-1-2 Problem Statement

Virginia Tech has set a high priority for making the campus sustainable in terms of energy demand and consumption. Much effort is being directed towards this agenda. The university community has started looking for opportunities for energy conservation in and around the campus buildings.

One such area that is under scrutiny is the Hokie light. The current problem with the Hokie light is that it throws a high percentage of light upward. As a result much electrical energy is wasted in lighting the sky. As per the product literature the uplight is 14% of the total light output by the lamp. One of the objectives of this research was to reduce the percentage of uplight from 14% to below 5% while redistributing the light downward. Once achieving this, it is believed that not only will the quality of light falling on the roadways and pathways be increased but the solution would also be eligible for points in the U.S. Green Building Council's LEED-EB (Version-2) building rating system. Therefore a series of experiments were undertaken to evaluate the photometric light distribution of several Hokie light alteration strategies in an effort to identify the most cost effective solution.

1-1-3 Test Hypothesis

Using experimental procedures the Hokie light retrofit strategy that minimizes uplight and best redistributes the light downward will be determined.

1-1-4 Goals and Objectives

To determine the best solution to decrease the uplight from Hokie light to meet the LEED–EB criteria, the following objectives were met.

Objectives

- To replace the perforated LiteLid® with a non-perforated aluminum sheet inside the Hokie light and then determine the change in light distribution.
- To paint the tip of the 100W HPS bulb with Quartz-Coat 845-Silver paint by Aremco Company and determine the change in light distribution.
- To paint the inside of the prismatic top of the Hokie light with CP 2010 reflective paint from Aremco Company and determine the change in light distribution.
- To add a strip of aluminum foil to the outer part of the Hokie light near the steel clamp and determine the change in light distribution.
- To determine the effect on inside temperature and heat build up of the Hokie light globe in all the above-mentioned options.

1-1-5 Important assumptions and limitations

- The lamp light distribution was assumed to be symmetrical about the vertical axis. Therefore only one half of the candlepower distribution curve was experimentally measured.
- The amount of light received by the photometers was assumed to only be coming from the lamp inside the Hokie Light. The surroundings near the experimental set up were painted black to minimize the room reflection.
- An industrial method of determining the candlepower distribution curve was not adopted because of the complexity and cost of the set up required and time and budget constraints for the research. The method used was assumed to be a reasonable approximation of the standard protocol.

With the commitment to reduce energy usage and implement programs that are friendly to the environment, Virginia Tech seeks to utilize energy efficient light fixtures for university buildings. One such initiative is to investigate the use of LEDs in the interiors of campus buildings. Currently LEDs are used only in lighted exit signs. But their use might also be extended to general and task lighting, under cabinet lighting and recessed down lighting. High intensity LEDs can also be explored for general illumination in the Virginia Tech building interiors.

1-2 Light Emitting Diodes (LEDs)

According to the US Department of Energy Website (2009):

> Light Emitting Diodes or LEDs differ from traditional light sources in the manner in which they produce light. In an incandescent lamp, electric current heats a tungsten filament until it glows or emits light. In a fluorescent lamp, an electric arc excites mercury atoms, which emit ultraviolet (UV) radiation. After striking the phosphor coating on the inside of glass tubes, the UV radiation is converted and emitted as visible light.
>
> A LED, in contrast, is a semiconductor diode. It consists of a chip of semi-conducting material treated to create a structure called a p-n (positive-negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side, or cathode, but not in the reverse direction. Charge-carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).
>
> The specific wavelength or color emitted by the LED depends on the materials used to make the diode. Red LEDs are based on aluminum gallium arsenide (AlGaAs). Blue LEDs are made from indium gallium nitride (InGaN) and green from aluminum gallium phosphide (AlGaP). "White" light is created by combining the light from red, green, and blue (RGB) LEDs or by coating a blue LED with yellow phosphor. (How LEDs work, para. 1).

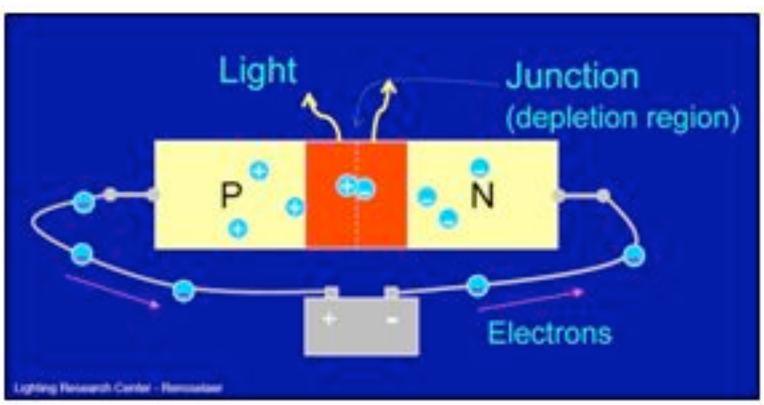


Figure 1-2: Schematic Diagram of P-N Junction (U.S. Department of Energy, 2009)

1-2-1 Background

Exploring alternative lighting solutions such as LEDs supports Virginia Tech's commitment to the improvement of living, learning and working environments. These findings may be extrapolated to other situations such as offices or classrooms.

One option is to use high intensity LEDs for general illumination in building interiors. At present the use of LEDs is limited to task lighting, under cabinet lighting, recessed down lighting and safety signage.

Virginia Tech is using red lettered LED lighted exit signs with diffused lenses. This is currently the only use of LEDs on the Virginia Tech campus.

1-2-2 Problem Statement

As per Virginia Tech design standards, installed lighting systems shall not exceed 1 Watt per square foot total.

This research was intended to explore the use of LEDs for general illumination while complying with the Virginia Tech design standards.

At present the fixture used in the interiors of Virginia Tech buildings is a 2' x 4' lay-in static troffer with a 0.125 inch thick prismatic lens that incorporates T8 lamps and an electronic ballast. This fixture is typically purchased from Lithonia and the lamps are from Philips.

This was the base system for cost/savings comparisons.

1-2-3 Test Hypothesis

The savings/cost benefit will be greater for the LED system when compared to the standard fluorescent system for general lighting applications on the Virginia Tech campus.

1-2-4 Goals and Objectives

The following objectives were applied to determine the opportunities to apply LEDs for general interior lighting in the buildings on the campus of Virginia Tech.

Objectives

- To determine the energy consumption of a typical building on the Virginia Tech campus without daylight harvesting and with standard Philips T8 lamps.

- To determine the energy consumption of a typical building on Virginia Tech campus with daylight harvesting and with standard Philips T8 lamps.

- To determine the energy consumption of a typical building on the Virginia Tech campus without daylight harvesting and with LED lamps.

- To determine the energy consumption of a typical building on the Virginia Tech campus with daylight harvesting and with LED lamps.

- To compare and analyze the results in the above-mentioned four options and determine the most desirable option.

- To qualitatively compare the perception of light from the standard Philips T8 lamps and the LED lamps.

- To compare the illuminance levels or the amount of light from the standard Philips T8 lamps and from the LED lamps on a given task surface.

1-2-5 Important assumptions and limitations

- The LED fluorescent lamp by iBright (ATG Electronics) was the only product considered for this study because of its affordability, availability and the ease with which it replaces the standard T8 Philips lamp.

- For determining the perception and quality of light from the T8 lamps and from the LED lamps the opinion of only one person was taken. It was assumed this person was representative of a larger group.

- For the computer modeling, except for the wattage and heat-of-light of the T8 lamps and the LEDs lamps, all the other parameters such as construction materials, construction type, HVAC system were kept constant for this study.

- The newly constructed Institute for Critical Technology and Applied Science (ICTAS) was selected for this study because it represented a typical new building on the Virginia Tech campus.

1-2-6 Simulation tool – eQuest

In this study the ICTAS building was considered as the base model. The building was simulated with four different models using the energy simulation tool eQUEST. The simulation "engine" within eQUEST is derived from the DOE-2 program. This energy simulation software caters to the whole building energy analysis and is accepted for simulation of US government buildings. The simulation results were analyzed to determine the feasibility and benefits of using LED lighting for general interior lighting.

Chapter 2 – Literature Review and Background

2-1 Hokie Light

Hokie light is an exterior light that is often found on roadways, parks, pathways and in the parking lots of the Virginia Tech campus. It has been used on the campus for 80 years. Since it has been in use for more than eight decades its appearance has become a part of the Virginia Tech architectural statement.

2-1-1 Components of the Hokie Light

With respect to light distribution two important components of the Hokie Light are-

1) The Globe, and

2) The lamp inside the globe.

For a detailed description of the components of the Hokie light refer to Section 1-1-1.

2-1-2 Hokie Light Photometrics-

The Model 424 Type V globe when coupled with the perforated LiteLid, Model 424 top and a 150W diffuse HPS lamp, produces 3337 candela at a 70° angle from the vertical axis (ITL48623). The Type V distribution is optimized with diffuse high-pressure sodium (HPS) and coated metal halide (MH) lamps.

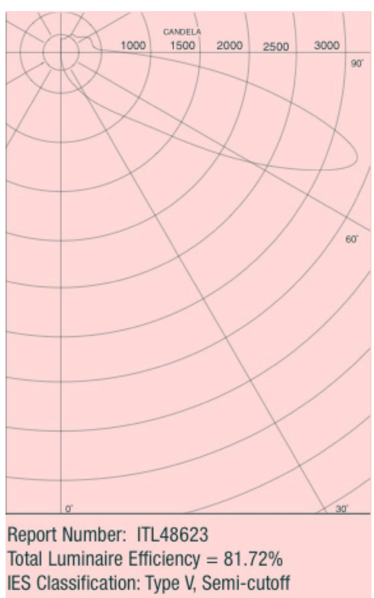


Figure 2-1-2a Photometric Distribution of 150W HPS Lamp (Lexalite International Corporation, 2009)

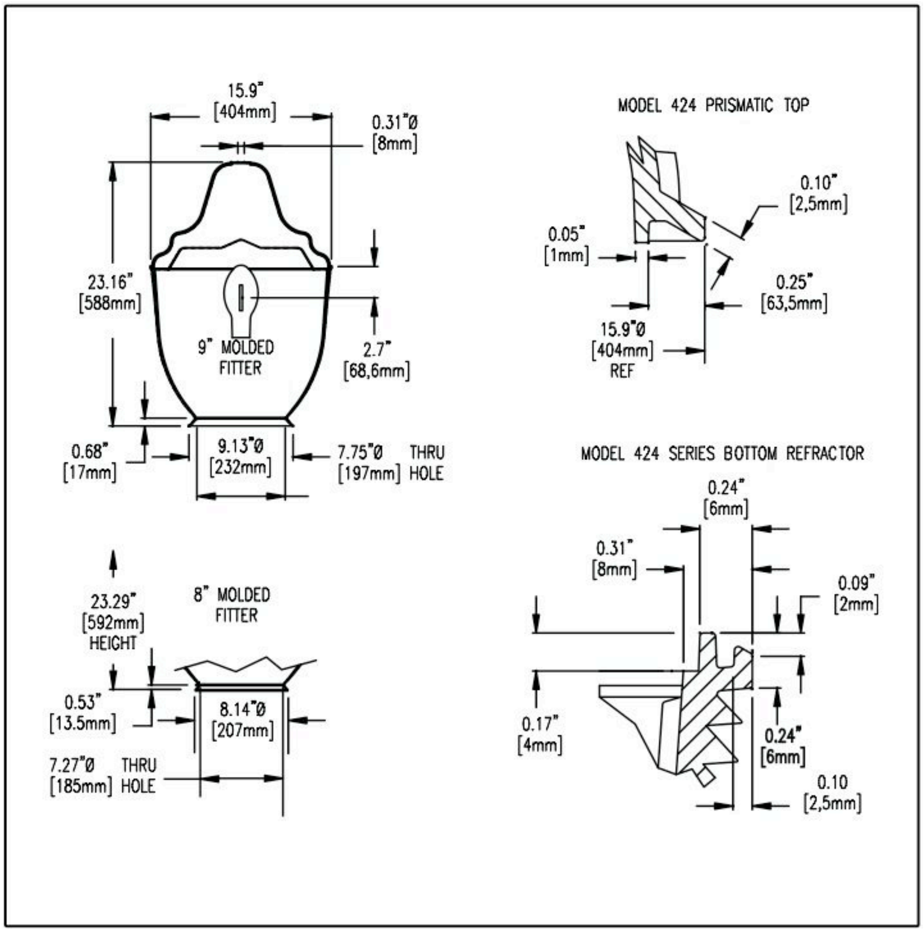


Figure 2-1-2b Luminaire details of the Hokie light (Lexalite International Corporation, 2009)

2-1-3 Conclusion

From the study of the materials, geometry and specifications of the globe from Lexalite International Corporation with Lundy 424 model the following recommendations are summarized:

- For the optimum performance the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit. This sets an important limit for the options to be tested for redistributing the uplight.

- The perforated LiteLid® should be placed in between the top and bottom components inside the Hokie Light to redirect the uplight and to increase the downlight. The intention of using the perforated LiteLid® is that the temperature inside the globe can be controlled and the heat generated inside it can escape. However on close inspection it was found that there is no outlet for the heat to escape. So one of the options for redistributing the uplight was to cover the perforations of LiteLid® and observe the resulting internal temperatures.

2-1-4 Luminaire Classification for Controlling Glare

The Illuminating Engineering Society of North America (IESNA, or IES) provides classifications for luminaries according to their glare control and high-angle brightness. These classifications include full cutoff, cutoff, semi-cutoff and noncutoff.

Table 2-1-4 Cutoff Classifications (Lithonia Lighting, 2009)

Classification	Definition	Benefits	Limitations
Full Cutoff	Zero intensity at or above horizontal (90º above nadir) and limited to a value not exceeding 10% of lamp lumens at or above 80º.	Limits spill light on to adjacent property, reduces glare. No light is emitted directly from the luminaire into the sky.	May reduce pole spacing to maintain uniformity and increase pole and luminaire quantities.
Cutoff	Intensity at or above 90º (horizontal) no more than 2.5% of lamp lumens, and no more than 10% of lamp lumens at or above 80º.	Small increase in high-angle light allows increased pole spacing.	May allow some uplight from luminaire. Typically a small overall impact on sky glow.
Semi-Cutoff	Intensity at or above 90º (horizontal) no more than 5% of lamp lumens and no more than 20% at or above 80º.	High-angle light accents taller vertical surfaces such as buildings. Most light is still directed downward.	Little control of light at property line. Potential for increased glare when using high wattage luminaires. Typically directs more light into the sky than cutoff.
Non-cutoff	No limitations on light distribution at any angle.	Uniform luminous surfaces such as internally illuminated signs or globes. Wattage should be limited. Suitable for sports lighting, façade, landscape or other applications where luminaires are tilted due to limitations in pole or fixture locations.	Location and aiming are critical. Most likely of all categories to produce offensive brightness and sky glow.

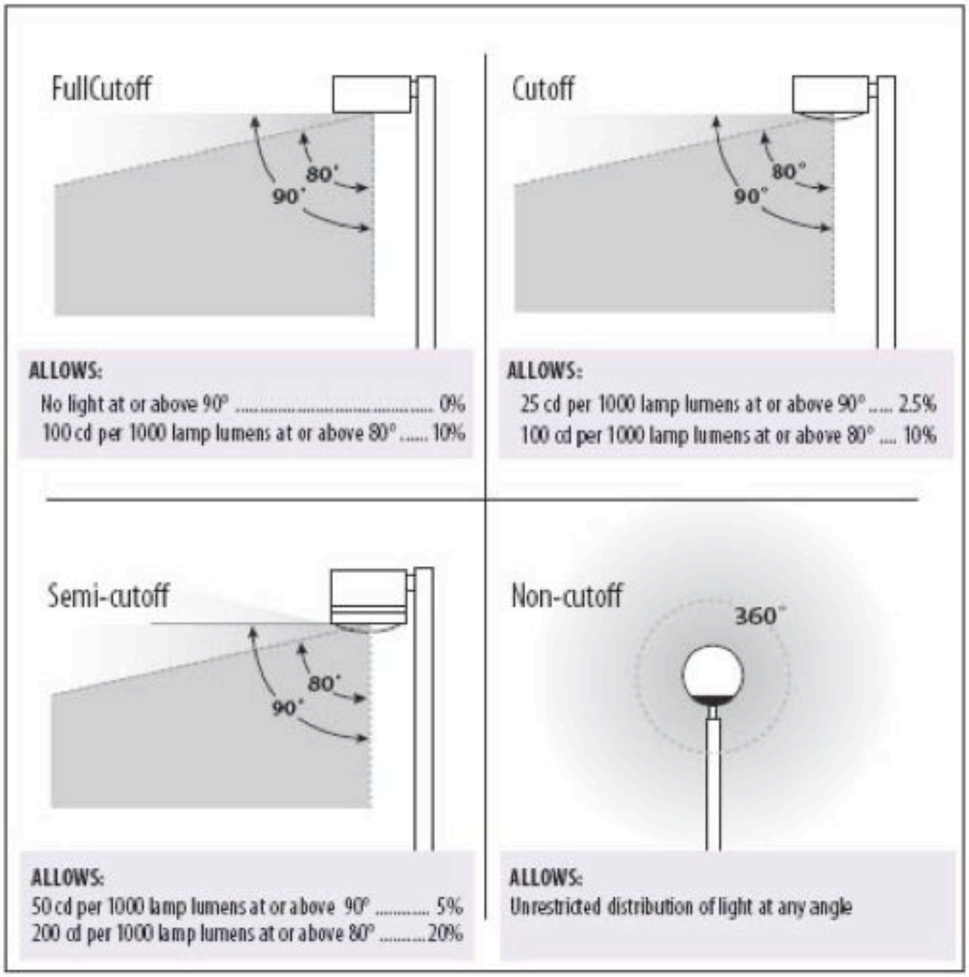


Figure 2-1-4 Cutoff fixtures illustrations (Lithonia Lighting, 2009)

As mentioned earlier the Hokie Light distributes 14% of the light upward. As per the above mentioned classifications it falls between the Semi-cutoff and Non-cutoff fixtures.

It was expected that the retrofit suggestions made for the Hokie Light would result in a re-classification of the light to the category of Semi-cutoff fixtures, i.e. with the uplight less than 5%.

2-1-5 Description of existing lamps currently used inside the Hokie light

The lamps were originally incandescent, then mercury vapor. Currently high pressure sodium lamps are in use.

Table 2-1-5 100W HPS Lamp Specifications (Philips Lighting, 2009)

Specifications of HPS lamps
Brand: Philips
Part Numbers: Philips C100S54/ALTO
Light Output: 9,400 Lumens
Wattage: 100
Hours: 24,000+
Color Temp (Kelvins): 2000K
Bulb Shape: ED23
Base: Mogul
Length (in): 7 3/4
Finish: Clear
CRI: 21

Figure 2-1-5: 100W HPS Lamp (Photo by author, 2008)

Comments-

- The lamp has high light output, i.e. 9,400 lumens.
- The lamp life rating is very good at more than 24,000 hrs.
- The lamp has a poor CRI of 21.

2-1-6 Possible options for the retrofitting of the Hokie light

After understanding the Hokie Light system, and reviewing the literature, the following light re-distribution options were identified

(a) Replace all the Hokie Lights with fixtures that have zero or low percent uplight or with the fixtures that are full cutoff fixtures.

Some of the options are shown in Figure 2-1-6a below.

Figure 2-1-6a Full cutoff fixture options (Selux Corporation USA, 2009)

All of the above fixtures are from SELUX Corporation USA and are:

- International Dark-Sky Association (IDA) approved.
- Full Cutoff fixtures.
- Suitable for parking lot, roadways and pedestrian walkways.
- Capable of accepting a 100W High Pressure Sodium Lamp.

(b) Replace the globe with an alternative that is consistent in appearance with the existing globe and has zero or low percent uplight such as shown in Figures 2-1-6b and c.

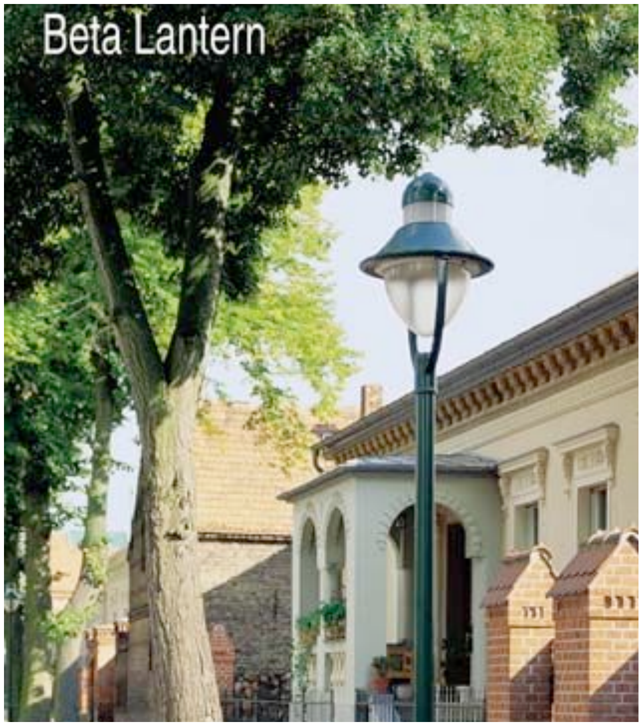


Figure 2-1-6b Beta Lantern (Selux Corporation USA, 2009)

Figure 2-1-6c Whatley Acron Fixture (Whatley Incorporated, 2009)

The fixtures in Figures 2-1-6b and 2-1-6c are the Beta Lantern fixture from Selux Corporation and the Whatley Acron Fixture. They could be possible options to the Hokie light for the following reasons:

- They are full cutoff fixtures
- They have an antique appearance and they can be easily merged with the Virginia Tech surroundings.

(c) Replace the current bulb with a bulb that throws light downward.

The light bulb by Bulbrite (Figure 2-1-6d) was one option for replacing the existing 100W HPS lamp inside the Hokie light.

Figure 2-1-6d Dark Sky Compact Fluorescent Light Bulb (Bulbrite, 2009)

- The above light bulb by Bulbrite is International Dark-Sky Association (IDA) approved.
- The bulb prevents uplighting and limits light trespass.
- The bulb consumes less electrical energy as compared to 100W HPS lamps.
- The bulb has better CRI in comparison to HPS lamps.

This option was the easiest for the retrofit of Hokie light because it only required replacing the current 100W HPS bulb with the Bulbrite Dark Sky Compact Fluorescent Light bulb.

(d) Reflective paint on the tip of the 100W HPS lamp.

A fourth option was to paint the tip of the currently used 100W HPS lamp with some reflective paint so that it reduced the uplight.

The paint needed for this option to work should:

- have reflective properties,
- be easy to work with,
- be inexpensive,
- have been previously used in similar applications and
- have the ability to withstand high temperatures.

The paint selected for the experimental purpose and that satisfies all the above mentioned criteria was the Quartz-Coat(TM) 845-Silver by Aremco Products.

The product catalogue of the Quartz-Coat(TM) 845- Silver Paint says:

> Quartz-Coat(TM) 845-Silver, a new high temperature, opaque, silvertop coating developed by Aremco Products, Inc., is now used to reduce glare in halogen lamps used in the automotive, dental, aircraft, stadium, and fire safety industries.
>
> Features-
>
> Quartz-Coat 845-Silver is a new, low expansion, ceramic-metallic formulation that bonds exceptionally well to glass and quartz halogen lamps. This formulation is a single part, water-based, inorganic system that is silver in appearance and enables the coating to absorb and evenly diffuse light at high temperatures.
>
> Quartz-Coat 845-Silver is stable in applications to 2000 °F (1093 °C).
>
> Quartz-Coat 845-Silver is a direct replacement for more conventional aluminum filled, silicone based, solvent-rich coatings. Because 845-Silver is water-based and odorless, it is an ideal replacement for silicone coatings that are flammable and toxic.
> Quartz-Coat 845-Silver is formulated to a viscosity range of 400-700 cps and solids content by volume of 42.0%. It is applied easily using conventional pneumatic spray equipment, and the typical dry film thickness is less than 1.0 mils. Curing can be accomplished rapidly in high-speed production systems by ramping the coating to 900-1000 °F for 5 minutes.
>
> After curing, the finish is tough and moisture resistant, and no outgassing will occur, even at high temperatures. Quartz-Coat(TM) 845-Silver is available in pint, quart and

gallon containers (Aremco Products Inc., 2009a, para.1).

(e) Replace the perforated LiteLid® inside the globe with non-perforated LiteLid®.

As discussed in Section 2-1-3, currently the perforated LiteLid® is placed in between the top and bottom components inside the Hokie Light to redirect the uplight and to increase the downlight. The idea of using the perforated LiteLid® is that the temperature inside the globe can be controlled and the heat generated inside can escape. But when looking at the globe closely it was found that there is no outlet for the heat to escape. So one of the options for increasing the downward efficiency of the Hokie Light was to cover the perforations of the LiteLid®.

For experimental purposes, the LiteLid® and its perforations were covered with aluminum foil because aluminum foil was easy to work with, has reflective properties and was readily available.

(f) Paint the top of the globe with reflective paint.

The concept behind using this option was to control the uplight and to enhance the downlight. The paint required for this should:

- be light in color so that it gives a pleasant look to the Hokie Light and complements the Virginia Tech surroundings;
- be easy to work with;
- have reflective properties;
- be inexpensive; and
- have the ability to withstand high temperatures.

The paint selected for the experiments and that satisfies all the above-mentioned criterion was Corr-Paint CP2010 Aluminum by Aremco Products.

The product catalogue of the Corr-Paint CP2010 Aluminum says:

> These epoxy and urethane based coatings are used for producing corrosion and wear resistant barriers to 500 ºF. Typical applications include tanks, pipelines, boilers, precipitators, scrubbers, bag houses, cyclones, hoppers and other process equipments used in the power, pulp and paper and chemical processing industries (Aremco Products Inc., 2009b, para.2).

(g) Cover the upper part of the globe on the outside.

It was expected that by covering the top of the bottom section of the Hokie light, the amount of light distributed above the horizontal plane would be reduced.

Figure 2-1-6e Image of the proposed option (g) (Photo by author, 2008)

For the purposes of the experiments aluminum foil was used because

- it was easy to work with;
- it had desirable reflective properties; and
- it was readily available.

The strip of aluminum foil could be painted with the Virginia Tech Brown color, i.e. with the same color as the post, or could remain as it is so that it would be camouflaged with the transparent nature of the globe of the Hokie Light.

(h) **Add a canopy to the globe.**

Figure 2-1-6f Image of the proposed option (h) (Photo by author, 2008)

The idea for this option was to bounce the light coming from the top of the globe back to the ground. The inspiration for this option came from the post tops used for the Saturn Magnum and Ritorno Round Symmetrical by Selux posts.

Figure 2-1-6g Ritorno Round Symmetrical (Selux Corporation USA, 2009)

Figure 2-1-6h Saturn Magnum (Selux Corporation USA, 2009)

These post tops give a pleasing glare-free, unobtrusive and uniform illumination with exceptional lumen output distribution.

2-1-7 Options Not Feasible

(a) and (b)

Since Virginia Tech has recently upgraded the globe of the Hokie light from the old polycarbonates to the acrylic Spectrus Lundy 424 for the entire campus and hence has a significant investment in the new globes, replacing the new globe again was not considered an option.

(c)

Though the lamps available for this option are IDA approved and redirect the uplight to the ground, unfortunately they have very poor light output and the expectancy life rating is low as compared to the existing 100W HPS lamp. So to replace the 100W HPS bulb with the suggested bulbs is to compromise the outdoor light levels at night and hence compromise the safety and security of the campus.

Also the rated life of these lamps is much less than the HPS lamps. Hence the maintenance and replacement cost will also increase.

(d)

The diameter of the canopy that covers the top of the Hokie light should be at least 2 feet. That makes the task of fitting the canopy on the top of the Hokie light difficult. The design of the globe is seamless and hence it requires care in detailing and workmanship for the canopy to sit on the globe. This is not going to be an easy retrofit for the thousands of Hokie lights on the Virginia Tech campus.

Also the canopy should withstand high-speed winds and snow loads. That makes the task of choosing the material for the canopy and designing it extremely difficult and time consuming.

Given the time frame for the research, this option was not considered.

2-1-8 Options Chosen for this Research

For the reasons given above the following options were chosen for experimental evaluation.

(d), (e), (f) and (g).

2-2 Light Emitting Diodes (LEDs)

2-2-1 Advantages of using LEDs

The advantages of using LEDs over other light fixtures are:

- LEDs are highly energy efficient as they draw less electrical power in comparison to its incandescent counterparts.
- Some LEDs are estimated to have a long service life of about 100,000 hours. This makes LEDs ideal for fixtures that are hard-to-reach or to maintain such as exit sign lighting.
- Application and environmental factors can affect the service life of LEDs. This includes heat and overdriven by the power supply.
- LEDs can emit light in a range of colors. White light can also be produced through color mixing of red, blue and green LEDs. Dramatic color-changing effects can be produced from a single fixture by using the combination of various-colored LEDs.
- LEDs produce little heat and no UV radiation. This makes LEDs ideal for illuminating objects that are sensitive to UV light such as works of art.
- The feature that LEDs do not contain any filament that can be damaged due to vibrations and shock makes them highly rugged and durable to use.
- LEDs are very small in size. This offers design flexibility in using LEDs as they can be combined in any shape to produce desired lumen output as the design goals and economics permit.
- LEDs lights up instantly, achieving full brightness in microseconds.
- LEDs can be dimmed easily. LEDs do not change their color whereas incandescent lamps turn yellow on dimming.
- LEDs operate on low-voltage power supply and that makes LEDs safe to use.
- LEDs do not contain mercury, while compact fluorescent lamps do (Lighting Design Lab, 2009).

2-2-2 Disadvantages of using LEDs

The disadvantages of using LEDs over other light fixtures are:

- Currently the availability of product choices for white LEDs that can be used for general illumination purpose in architectural applications is limited.
- Conventional lighting technologies currently are comparatively less expensive in terms of lumen package per unit, lumens per watt and initial capital cost basis.
- Color quality offered currently by white LEDs is poor in terms of color rendering and high color temperature.
- Ambient temperature of the operating environment plays an important role in LED performance. LED package may overheat if used in high ambient temperature conditions. This may eventually lead to device failure. Therefore it is required to have adequate heat sinking for maintaining long life especially in automotive, medical, and military applications (Lighting Design Lab, 2009).

2-2-3 Description of components of existing fluorescent fixture in the interiors of Virginia Tech buildings

One of the purposes of this research was to explore the feasibility of using high intensity LEDs for general illumination purposes for interiors of Virginia Tech buildings. The aim was to look for the LED lamps that could possibly replace the existing fixtures in the interiors of campus buildings.

When evaluating the cost/benefit of LED systems it was very important to know the performance characteristics and the properties of the existing fluorescent fixture.

The typical light fixture consists of three major parts:

(1) Fixture

Manufacturer:	Lithonia General Fluorescent
Lumcat:	2SP G 2 32 A12125 120 GEB
Luminaire:	Specification premium troffer, 2' x 4', two (2) lamp T8, acrylic prismatic lens 0.125 inches thick in steel door, electronic ballast, paint reflection = 0.932
Lampcat:	FO32/835
Number Lamps:	2

Lumens Per Lamp:	2850
Photometric Type:	Type C
Luminous Width:	1.78 ft
Luminous Length:	3.76 ft
Luminous Height:	0 ft
Ballast:	REL2P32-SC BF = 0.862
Input Watts:	57
Efficiency (Total):	85.5 %
Efficiency (Up):	0.0 %
Efficiency (Down):	85.5 %

(2) Lamp

PRODUCT DATA

Product Manufacturer	Philips
Product Number	272484
Full product name	F32T8 TL741 ALTO
Name Type	F32T8
Color Code	TL741 [CCT of 4100K]
Nominal Length [inch]	48
Feature	ALTO [ALTO®]
Base	Medium Bi-Pin[Medium Bi-Pin Fluorescent]
Base Information	Green Base
Bulb	T8
Life with 3h/day use [years][an]	7

Rated Avg. Life [3 hr Start][hr]	30000
Rated Avg. Life [12-Hr Start][hr]	36000
Energy Saving Product	Energy Saving
Watts [W]	32
Mercury (Hg) Content [mg]	3.5
Color Rendering Index [Ra8]	78
Color Temperature [K]	4100
Initial Lumens [Lm]	2800
Design Mean Lumens [Lm]	2660

(3) Ballast

The ballast that generally comes in the above-mentioned fixtures is comparable to an Advance Centium.

For retrofitting fixtures on campus with electronic ballasts, Virginia Tech is using a slightly more efficient ballast, the Advance Optanium 2.0.

Currently Virginia Tech is using the instant start version rather than the programmed start.

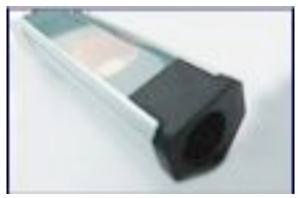
Analysis-

- The fixture has an excellent downward efficiency of 85.5%.
- The upward efficiency is 0% for the fixture.
- The lamp has good average rated life hours of 36,000 hours.
- The mercury content of the lamp is low.
- The lamp has good lumen output of 2800 lumens.
- The lamp has a reasonably good color-rendering index of 78 (refer to Section 3-2-3 for color rendering index).

2-2-4 Options for the replacement of existing fluorescent lighting with LED lamps in the interiors of the Virginia Tech buildings

For general illumination purposes in the interiors of Virginia Tech buildings the following LED lamps have been studied.

(a) Linear LED Module



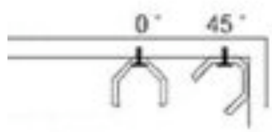


Figure 2-2-4a Linear LED Module Lamp (Linear LED Module, 2009)

The Linear LED Module is a "Plug N' Play" LED lighting fixture. It is designed to be installed at a 45 degree angle to project the LED light forward and down onto the work plane, or facing onto a wall or up onto the ceiling for cove lighting. The Linear LED Module can also be installed vertically facing down or up for display cases.

The flexibility of installation and applications is due to the design of the plastic mounting clip and the triangular shape of the Linear LED Module frame.

Physical and Electrical properties:

- Dimensions: 12.01 inches (306mm) x 0.65 inch (16.6mm) x 0.66 inch (16.8mm)
- Materials: Aluminum extrusion with black plastic end caps.
  Acrylic Lens
- Package Contents: Module plus 2 Mounting Clips and 2 # 6 screws

- Light Source: Six (6) 1 watt Nichia High Power SMD LED
- Power Consumption: 7 watts - 291mA
- Illuminance: 180 lumen @ 5500K for Daylight White
- Illuminance: 140 lumen @ 3300K for Warm White
- Optical Performance: 350 Lux @50cm - 76 CRI - Daylight White
- Optical Performance: 295 Lux @50cm - 73 CRI - Warm White
- Light Output: 42 watts Daylight - 34 watts Warm White
- Current Regulation: Constant Current Driver on board
- Operating Voltage: 24 Volt
- Operating Temperature: -20°C to 40°C - Indoors
- Warranty: 2 year with proper installation and power supply

Analysis:

- The fixture is easy to install.
- The fixture comes with built-in drivers although efficiencies are not clearly mentioned in the fixture description.
- The operating voltage for the fixture is low and hence it cannot be used in applications which require operational voltage of 240V or 277V.
- The lumen output of the fixture is extremely low as compared to the Philips Alto T8 lamps.
- The CRI of the Linear LED Module is a bit less than that of Philips Alto T8 lamps (refer to Section 3-2-3 for color rendering index).

(b) Triple Color™ RGB EXT by LEDWorks

Figure 2-2-4b Triple Color™ RGB EXT Lamp Image (LEDWorks, 2009)

Description

The Triple Color™ RGB EXT light strips are an exterior location linear lighting solution for commercial and residential applications. The light strips are installed in any length from 4 inches up to 10 feet, using light strip accessories and the LEDWorks® series of power supplies and controllers.

The Triple Color™ RGB EXT light strips are available in 4", 8" and 16" LED lengths. They feature side mounted power connect terminals to eliminate gaps when joining multiple units together for an even and fully saturated light wash. The light strips snap together for quick and easy installation in new or retrofit applications of up to10 feet per power run. Multiple units mounted in polycarbonate tubing are flexible and can conform to a 2-foot bend over a 10-foot light strip run to conform to a 28-foot radius.

Table 2-2-4a Product Specification of Triple Color™ RGB EXT (LEDWorks, 2009)

	16.00"	8.00"	4.00"
Input Voltage	24VDC	24VDC	24VDC
Input Current	210mA	105mA	105mA
Power	5.0W	2.5W	2.5W
LEDs Per Strip	48	24	12
LED Lumen Output	120	60	30
Driver Voltage	0 - 5 VDC	0 - 5 VDC	0 - 5 VDC
Strip Width	0.650"	0.650"	0.650"

Analysis:

- The operating voltage for the fixture is low and hence it cannot be used in applications which require operational voltage of 240V or 277V.
- The lumen output of the fixture is extremely low as compared to the Philips Alto T8 lamps.
- The power consumption of the fixture is much less than that of Philips Alto T8 lamps.

(c) Linear Display LED Light by THELEDLIGHT.com

Figure 2-2-4c Linear Display LED Light Lamp Image (TheLEDLIGHT.com, 2009)

The Linear Display LED Light with its 49.25 inch length, is intended to be applied where the distance per zone/walled-in area/display case section is near the Linear Display LED Light's length or lighting ability. There are 7.5" long connecting cables with barrel connectors attached at both ends of the Linear Display Light to connect up to 3 lengths. The cable also allows continuous power to 3 lengths when there are physical barriers to pass through.

The center image above shows a stainless steel metal clip that allows mounting of the Linear Display LED Light onto various surface types when the built-in end mounts (third image) cannot be used. The metal clip also allows for angling of the strip to provide the best area coverage.

Physical and Electrical properties:

- Dimensions: 49.25 inches (1250mm) x 1.19 inch (30.1mm) x 0.90 inch (22.85mm)
- Materials: Aluminum extrusion with black plastic end caps. Acrylic Lens
- Light Source: 24 (24) 1 watt Nichia High Power SMD LED
- LED View Angle: 60 or 120 degree
- Power Consumption: 28 watts - 1.67 amps

- Illuminance: 1320 lumen @ 5500K for Daylight White

- Illuminance: 1080 lumen @ 3300K for Warm White

- Optical Performance: 76 CRI - Daylight White

- Optical Performance: 73 CRI - Warm White

- Light Output: 165 watts Daylight White - 135 watts Warm White

- Current Regulation: Constant Current Driver on board

- Operating Voltage: 24 Volt

- Operating Temperature: -20°C to 40°C - Indoors

- Warranty: 2 year with proper installation and power supply

Applications:

- Refrigeration Lighting
- Freezer Case Lighting
- Jewelry Case Lighting
- Cabinet Interior Lighting
- Stage Lighting
- Product Display Lighting
- Bar Back Lighting
- Valance Lighting
- Closet Lighting

Analysis:

- This fixture has a desirable range of LED view angles from 60º to 120º, which indicates that it has a potential to be used for general illumination purposes.

- The power consumption of the fixture is marginally less than that of Philips Alto T8 lamps.

- The lumen output of the fixture is almost half that of the Philips Alto T8 lamps.

- The CRI of the Linear Display LED Light is less than that of Philips Alto T8 lamps (refer to Section 3-2-3 for color rendering index).

- The fixture requires a driver for current regulation. With the inefficiency of the driver the lumen output of the lamp is bound to decrease further.

- The operating voltage for the fixture is low and hence it cannot be used in applications which require operational voltage of 120V or 240V.

(d) eW™ Profile Powercore by Philips Solid-State Lighting Solutions

Figure 2-2-4d eW™ Profile Powercore Lamp Image (Philips Solid-State Lighting Solutions, 2009)

The eW™ Profile fixture illuminates work surfaces brightly and evenly, without glare or excessive heat. It lights kitchen counter tops (under kitchen cabinets), work stations (office desk tops), work benches (laboratories in commercial, research, or academic settings) and similar environments. The eW™ Profile Powercore also provides excellent light in display cases, show cases, and under shelves in retail stores, exhibits, and other venues. The eW™ Profile Powercore delivers high quality illumination, low heat, and long life in fixtures that are low profile, easy to install, and easy to operate.

Physical and Electrical properties:

- Low power consumption
- UL Listed for both permanent and portable installations in North America
- End-to-end connections
- Available in two color temperatures: 2700 K or 4000 K
- Up to 50 feet (15.25 m) of fixtures may be used in a series

- Three sizes: 11" (28 cm), 21" (53 cm), and 41" (104 cm)

- 50,000 hour life

- Powercore® technology supports direct line voltage input for simple installations and long runs

- DIMand™ technology provides smooth dimming capability with standard commercially available ELV-type dimmers

- Available with Line Voltage for 100, 120, or 220-240 VAC

Note- This product is still in its development stage. So data such as CRI, Total Output (Lumens), Efficacy (Lm/W) are not available.

Analysis:

- The fixture claims to have low power consumption, but the actual data of the power consumption is not known.

- The life rating hours is 50,000 hours, which is comparable with the Philips Alto T8 lamps.

- The fixture is easy to install.

- The fixture can work with the line voltage of 100, 120, or 220-240 VAC, which makes it applicable for interior lighting applications.

- The fixture is still under development, so it cannot be compared with the Philips Alto T8 lamps data for CRI, Lumen Output and Efficacy.

(e) iBright LED Fluorescent Light

Figure 2-2-4e System Diagram (iBright LED Fluorescent Light, 2009)

Figure 2-2-4f iBright™ in Office (iBright LED Fluorescent Light, 2009)

Figure 2-2-4g iBright™ in Supermarket (iBright LED Fluorescent Light, 2009)

Table 2-2-4b iBright Product Specifications (iBright LED Fluorescent Light, 2009)

Housing	Glass tube housing				
Operation Voltage	120VAC				
Socket Type	T8				
Color Temperature	3500K				
Color Range	White				
Beam Angle	15 degree and 160 degree				
IP Rating	IP54				
Part Number	Color	Voltage	LED Qty	Watts	Length
HFL-T8-276W-H1	White	120VAC	276	15W	1200mm

Analysis:

- The fixture has predominantly a white color range that makes it applicable for interior lighting applications.
- The power consumption of the fixture is less than half of the power consumption of Philips Alto T8 lamps.
- The rated life is 50,000 hours, which is comparable with the Philips Alto T8 lamps.
- The fixture claims to have low heat generation.
- The fixture requires no maintenance.
- The fixture does not contain mercury.
- The fixture has a desirable range of LED view angles from 15º to 160º that suggests it has the potential to be used for general illumination.
- The fixture can work with line voltages of 120, or 220-240 VAC, which makes it applicable for interior lighting applications.
- The data for the CRI of the iBright LED lamps is not mentioned in the product catalogue.
- The lumen output of the fixture is 1290 lumens, which is less than half of the lumen output of Philips Alto T8 lamps (2850).

After careful analysis it was decided to use option (e) i.e. iBright LED Fluorescent Light for this research. The reasons for choosing option (e) over other options were:

- The iBright LED Fluorescent Light was one of only a few products available in the market which claimed to be successfully used in interior lighting applications.
- The operating voltage of 120VAC for iBright LED Fluorescent Light was more suitable for interior lighting applications than the other 24VAC options.
- The rated life of the iBright LED Fluorescent Light was better than any of the options discussed above.
- The power consumption of iBright LED Fluorescent Light was less than half of the power consumption of Philips Alto T8 lamps.
- The iBright LED Fluorescent Light was the most readily available of all of the options.
- The iBright LED Fluorescent Light could easily replace the Philips Alto T8 lamps. Retrofitting was easiest with this option.
- The iBright LED Fluorescent Light did not require any electrical drivers for its operation.
- The range of LED view angles from 15º to 160º was best for iBright LED Fluorescent Light as compared to any of the options and thus it could be used for general illumination purposes.

Chapter 3– Methodology

For the studies of the Hokie light and application of LED lamps two separate test procedures were used.

3-1 Hokie Light

The aim of this first study was to experimentally evaluate the efficacy of the options chosen for reducing uplight distribution from the Hokie light.

For this, several methods could be employed-

1. Computer Simulation

   Using computer simulation, a 3D model of the Hokie light and its retrofit options could be generated by using software such as 3D Viz. Using rendering tools such as this the effect on the surroundings of the Hokie light retrofit options could be studied. But given that Hokie light is not a standard lighting option and the software has a long learning curve this method was not adopted.

2. In-Situ Study

   In-situ monitoring requires on-site light installation, light level measurements and analysis of the Hokie light and its retrofit options. Given the height of the Hokie light (10 feet) and the set up that would be required to measure the light levels above and below the light this method would have been extremely difficult. Also there would be interference by extrinsic factors such as weather and climate. Therefore this method was not adopted.

3. Laboratory Experimentation

   A third study option was laboratory experimentation.

   a) One such method called the One Inclined Mirror Method is shown in Figure 3-1a.

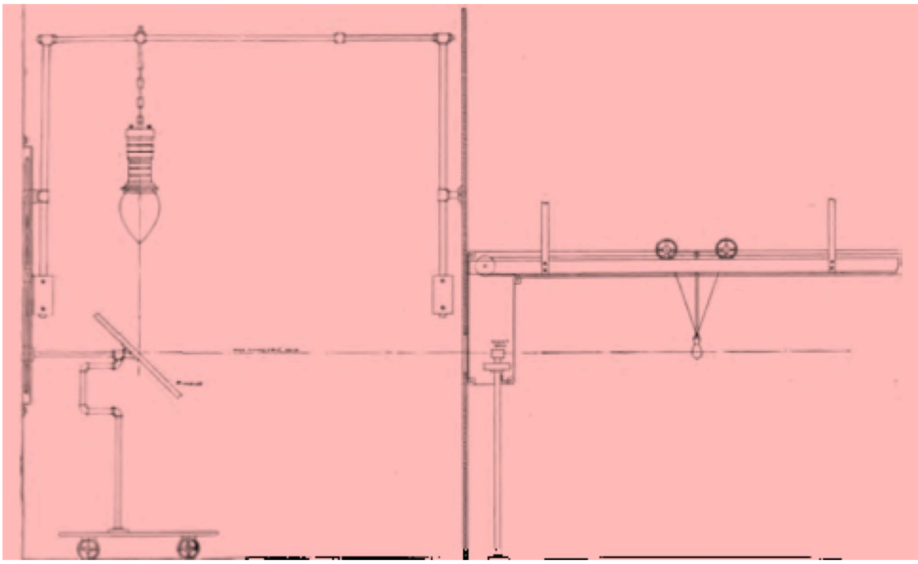


Figure 3-1a Experimental Setup for One Inclined Mirror Method (Gaster & Dow, 1915, p. 239)

Figure 3-1a shows the arrangement for determining the light distribution from arc lamps in the laboratory of the General Electric Co. of America (Stickney & Rose, 1911). As shown the lamp is suspended in a separate chamber, and its rays are reflected from an inclined mirror and pass through an aperture onto the sight-box of the photometer. Photometric balance is adjusted by moving the comparison incandescent lamp.

b) Two Inclined Mirrors Method

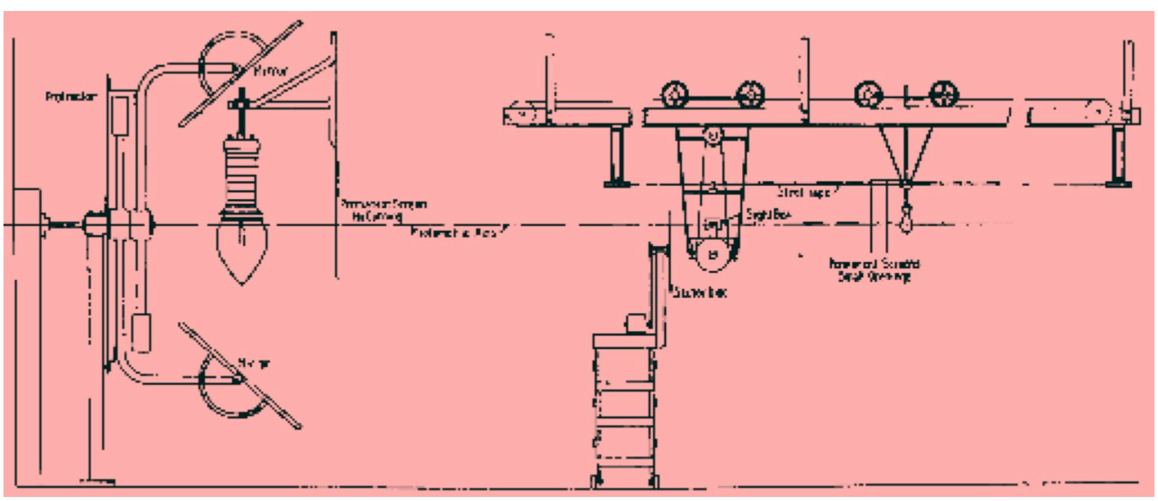


Figure 3-1b Experimental Setup for Two Inclined Mirror Method (Gaster & Dow, 1915, p. 241)

As shown in Figure 3-1b, a somewhat more elaborate method for determining the distribution of light from arc lamps involves the use of two inclined mirrors placed symmetrically on either side of the source (Stickney & Rose, 1911). The reflected rays pass through the adjustable reflector disc to the sight-box of the photometer. Photometric balance can be achieved by moving either the photometer or lamp, or by altering the aperture in the sector, so that there is a wide range of adjustment.

Given the complicated nature of the above two methods, with their time and cost constraints, a simpler yet effective method to measure the light levels around the Hokie Light was adopted.

For this simplified method the light distribution of the Hokie Light was measured at various angles and used to estimate the percentage of uplight for each of the design options. This method was free from interference from extrinsic factors such as weather and climate.

The material of the globe of the Hokie light is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80°Centigrade or 176° Fahrenheit for optimum performance. Therefore, to measure the temperature inside the Hokie light copper-constantan thermocouples couples were used.

3-1-1 Description of the Experimental Protocol

The test set up was located in the Environmental Systems Laboratory on Prices Fork Road, Blacksburg. The Environmental Systems Laboratory is located four miles from the main Virginia Tech campus. The laboratory was ideal for the experiment because access was limited and hence the chances of disruption and vandalism were minimal.

Figure 3-1-1a Picture of Environmental Systems Laboratory from outside showing obstructed windows (Photo by author, 2008)

Figure 3-1-1b Picture of “Blocked” window (Photo by author, 2008)

The room for this test set up was dark, devoid of any daylight, so it could be assumed that the Hokie light was the only light source.

The walls of the experimental room were painted black to minimize light reflection. The only window in the room was also blocked with 1/8th inch thick black foam board.

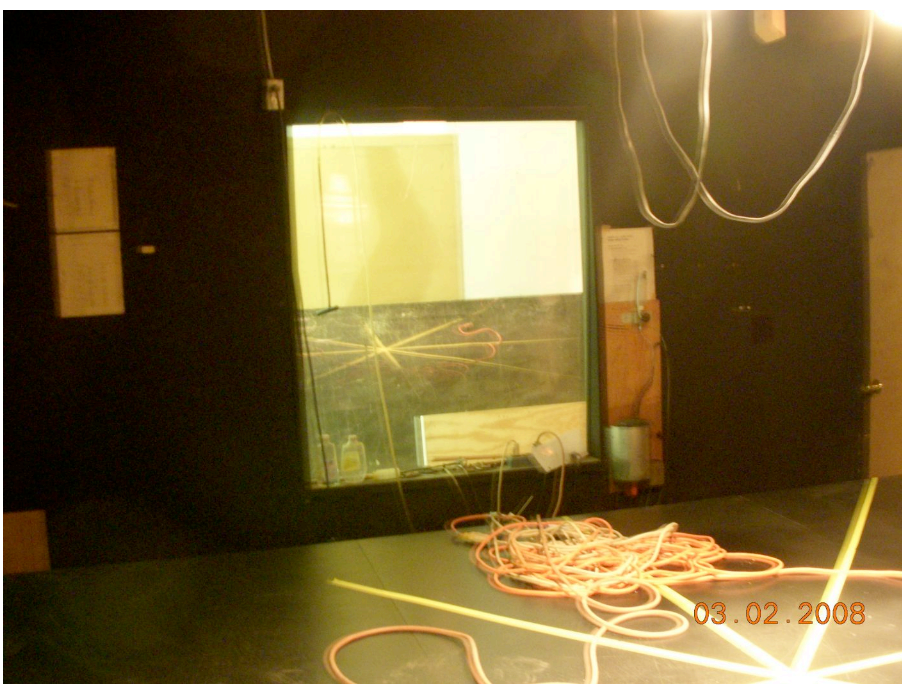


Figure 3-1-1c View of the wall on the left hand side of the experimental setup (Photo by author, 2008)

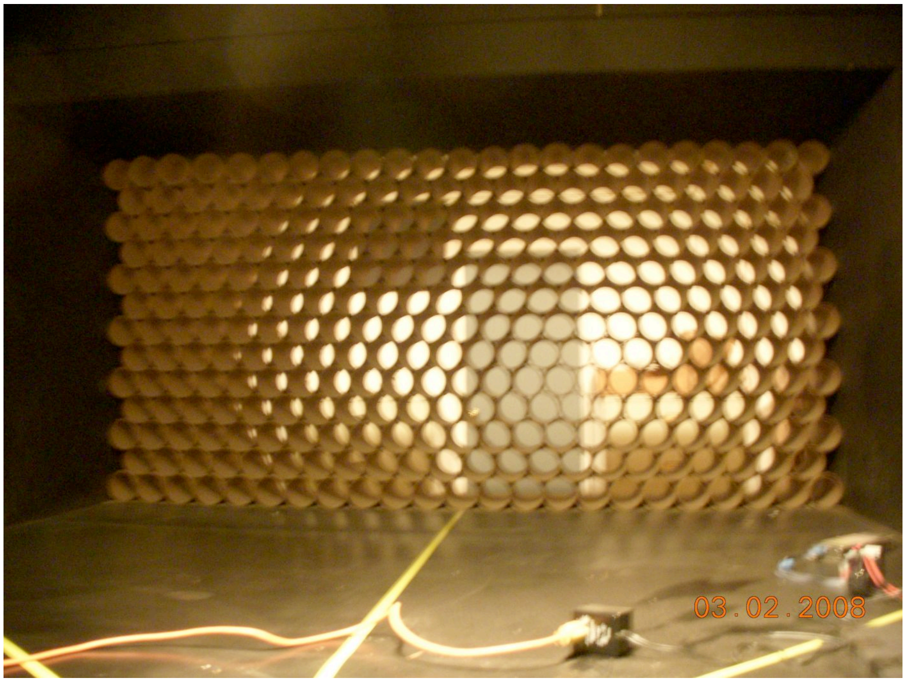


Figure 3-1-1d View of the wall on the front side of the experimental setup (Photo by author, 2008)

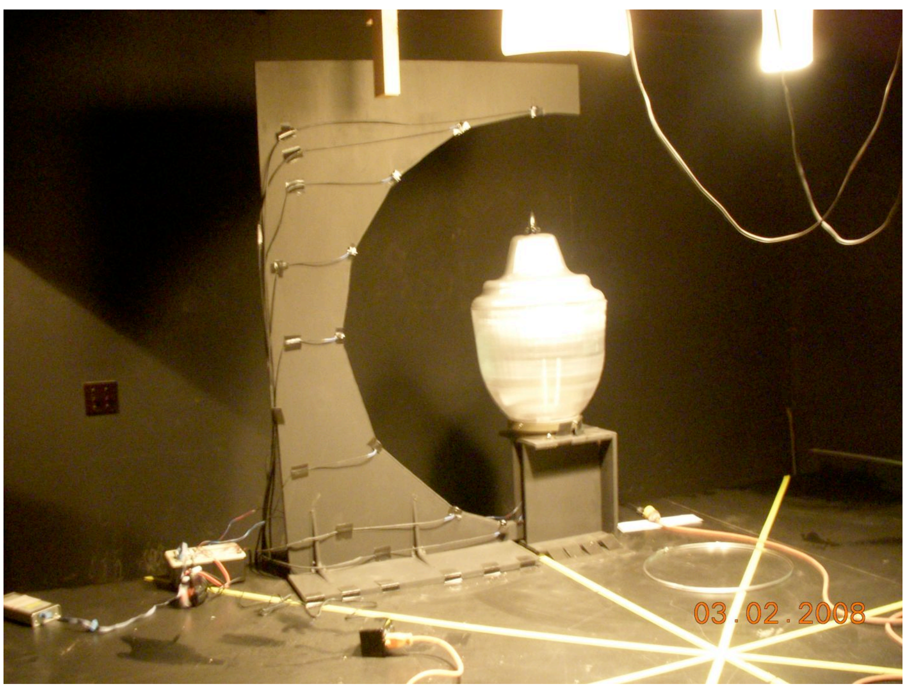


Figure 3-1-1e View of the wall on the right hand side of the experimental setup (Photo by author, 2008)

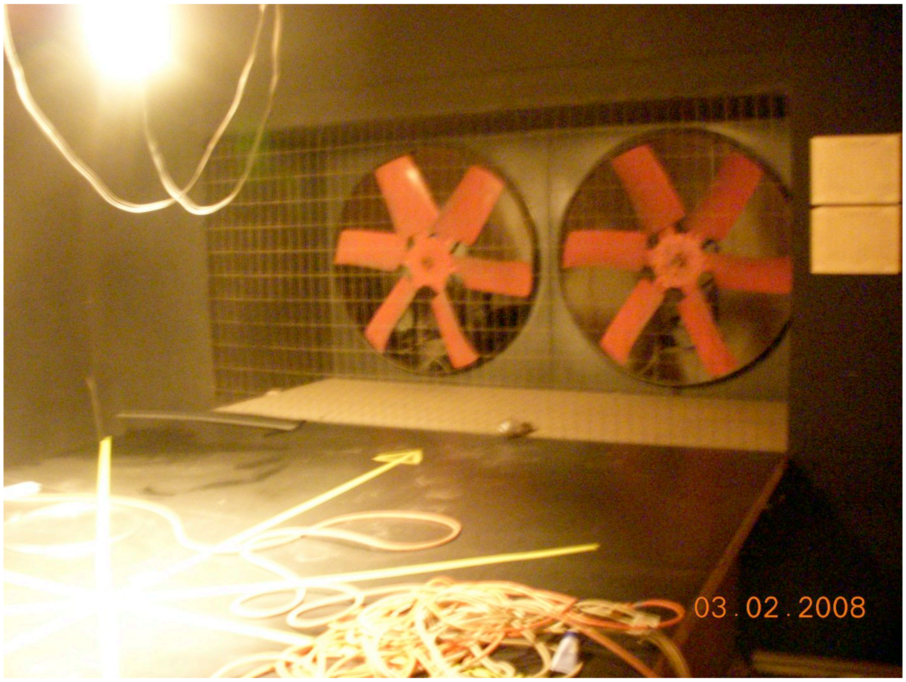


Figure 3-1-1f View of the wall on the backside of the experimental setup (Photo by author, 2008)

The equipment used for the experiments included:

1. LI- COR Photo Sensors
2. Campbell Scientific Datalogger

3-1-2 Photosensors

The photosensors used for the experiments were LI-COR Radiation Sensors model no. LI-190SZ

Figure 3-1-2a LI-COR Radiation Sensor Image (LI-COR Radiation Sensors Instruction Manual, 2009)

LI-COR quantum sensors measure photosynthetically active radiation (PAR) in the 400 to 700 nm waveband. It measures the quantity of light in discrete units of quantum flux called "photons".

Photon flux is commonly measured in units of micromoles per square meter per second (µmoles/m^2/s), where 1 mole of photons = 6.022 x 10^{23} photons. This is an objective measure therefore it needs to be converted to a light engineering unit such as Lux (lumen per square meter) for better understanding of the results. The calculator and table from Environmental Growth Chambers (www.egc.com) below were used to convert values from radiation of 400-700 nm from different lamp types, taken from the Plant Growth Chamber Handbook, 1997.

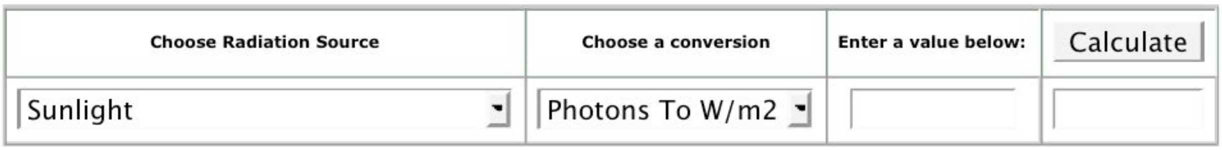


Figure 3-1-2b The Calculator for Conversion from Photons to Lux
(Environmental Growth Chambers, 2009)

Photon values are in µmoles/m^2/s. For other conversions, divide lux by 10.764 to obtain footcandles, or multiply footcandles times 0.0929 to obtain lux.

Table 3-1-2 Conversion Factors for Different Light Sources
(Environmental Growth Chambers, 2009)

Radiation Source	Photons To W/m^2	W/m^2 To Photons	Photons To Lux	Lux To Photons	Photons To F.C.	F.C. To Photons	W/m^2 To Lux	Lux To W/m^2
Sunlight	0.219	4.57	54	0.019	5.02	0.199	0.249	4.02
Cool white fluorescent	0.218	4.59	74	0.014	6.87	0.146	0.341	2.93
Plant Growth fluorscent (Gro-Lux)	0.208	4.80	33	0.030	3.07	0.326	0.158	6.34
High-pressure sodium	0.201	4.98	82	0.012	7.62	0.131	0.408	2.45
High-pressure metal halide	0.218	4.59	71	0.014	6.60	0.152	0.328	3.05
Low-pressure sodium	0.203	4.92	106	0.009	9.85	0.102	0.521	1.92
Incandescent 100W tungsten halogen	0.200	5.00	50	0.020	4.65	0.215	0.251	3.99

Therefore by using the above online calculator and table all the experimental readings were converted into Lux levels.

3-1-3 LI-190SZ Specifications

LI-COR SZ type sensors are characterized by having the sensor cable terminated with the two bare wire leads of the coaxial cable. This allows them to be used with the six current channels of the LI-1000 Datalogger located on the screw-down terminals of the 1000-05, 1000-06A, or 1000-10 terminal blocks. The shield of the coaxial cable is positive and the center conductor is negative.

Absolute Calibration: ± 5% traceable to the U.S. National Bureau of Standards (NBS).

Sensitivity: Typically 8µA per 1000 µmol/s/m^2.

Linearity: Maximum deviation of 1% up to 10,000 µmol/s/m^2.

Stability: <± 2% change over a 1 year period.

Response Time: 10µs.

Temperature Dependence: ±0.15% per ºC maximum.
Cosine Correction: Cosine correction up to 80º angle of incidence.

Azimuth: <± 1% error over 360º at a 45º elevation.

Tilt: No error induced from orientation.

Detector: High stability silicon photovoltaic detector (blue enhanced).

Sensor Housing: Weatherproof anodized aluminum case with acrylic diffuser and stainless steel hardware.

Size: 0.94" (2.38cm) Dia. X 1.0" (2.54cm) H.

Weight: 28g (1 oz.)

Cable Length: 10 ft (3.0m)

Accessories: 2003S Mounting and Leveling Fixture.

3-1-4 Experimental Setup

The distribution of light from the Hokie light is assumed to be symmetrical about the vertical y-axis. Therefore measurements from only one half of the Hokie light were taken into consideration for determining the light distribution.

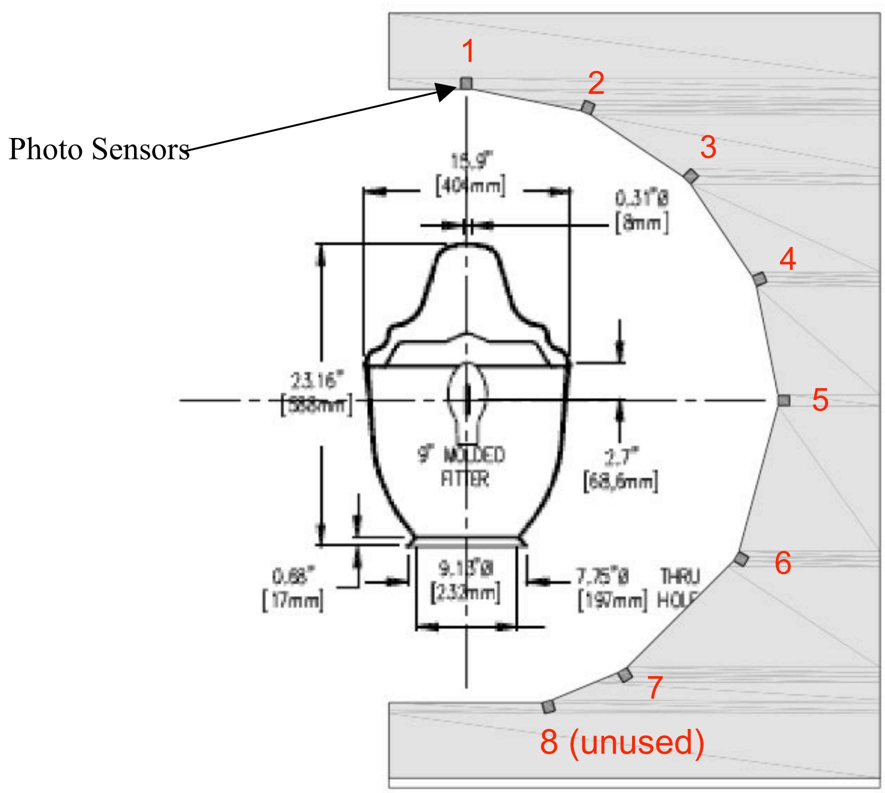


Figure 3-1-4 Schematic drawing for the experimental setup

For the sensor placement, a semicircle with a radius of 2 feet was located from the center of the lamp. This allowed any point from the globe surface to be a distance of at least 1 foot away. It was determined that a distance less than 1 foot would be too close for the photosensor and with a distance of more than 2 feet a good amount of light might not reach the photosensor.

Therefore a 2-foot radius semicircle was chosen.

Photosensors were positioned around the Hokie Light in the top and bottom quarter of the circle as shown in Figure 3-1-4.

Photosensor 1 was aligned vertically facing down while photosensor 5 was aligned horizontally from the centerline of the lamp. These two sensors were carefully located because photosensor 1 was to measure the amount of light distributed in the vertical direction and photosensor 5 would measure the light received at the horizontal plane.

More photosensors were placed in the top quarter of the circle than the bottom quarter because it was desirable to determine if there was any particular angle at which the uplight was maximum.

The top quarter of the circle was divided into 4 equal segments whereas the bottom quarter was divided into 3 parts. This was due to the limited number of sensors available. Photosensors were placed at an equal angular distances in the top and bottom quarter of the circle.

To arrange the photosensors around the semicircle adjacent to the Hokie Light, ½" thick plywood of size 3' x 5' was used. The location of each sensor was marked geometrically. The profile was cut as per the markings on the plywood. Notches were cut for the exact size as of the photosensors so that they could securely fit into the plywood. The frame was fixed vertically with the help of L-shaped metal angles on another piece of plywood. The entire assembly in turn was fixed on the 2.5' high flat platform in the test room.

A 1' high wooden platform was made for the Hokie light such that the center of the lamp inside it was in line with photosensor 1 and photosensor 5.

Table 3-1-4 Photosensor technical name

Sensor No.1	Serial Number
1	Q35521
2	Q35540
3	Q35332
4	Q35343
5	Q35331
6	Q35527
7	Q35541
8	Q35122

3-1-5 Data Logging

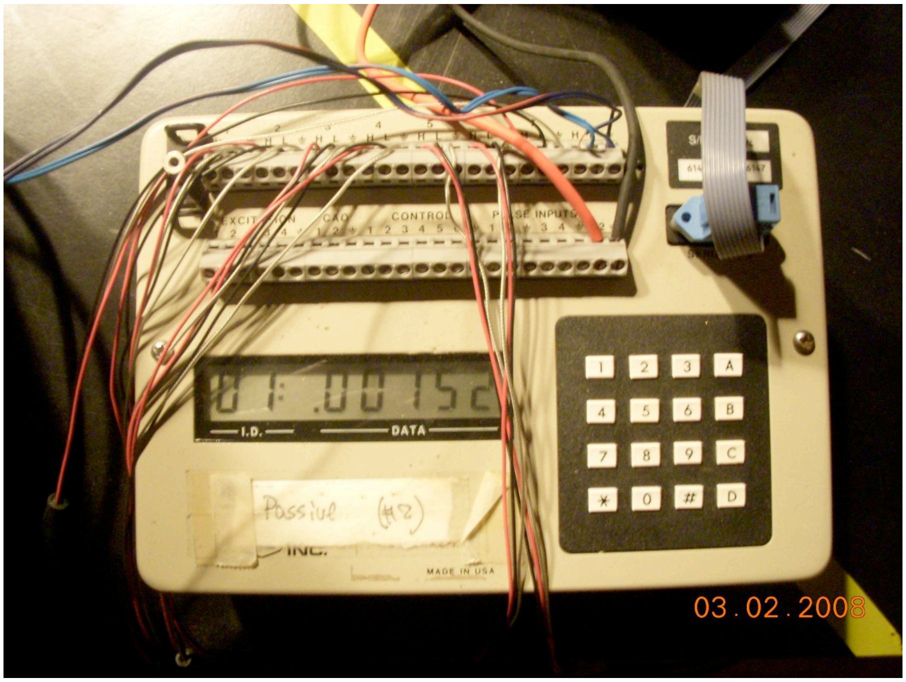


Figure 3-1-5 Campbell Scientific 21X Data Logger (Photo by author, 2008)

The datalogger used for this research was a Campbell Scientific 21X with nine analog input channels. Ideally it was desired to have ten channels, eight for photosensors and two for thermocouples, but this was beyond the capacity of the 21X.

The temperature readings at the top and the bottom of the Hokie Light were measured with copper-constantan thermocouples.

Because at least two temperature measurements were needed, a compromise was made by not including a photosensor at location 8. Since the main aim of the experiment was to measure the uplight for the retrofit options, and since location 8 would be the location of the lamppost in the installed system, it was thought that the exclusion of photosensor 8 for the calculations would not affect the overall results to a great extent.

3-1-6 Uplight Calculation Formula

Uplight is the percentage of the total light received by the sensors above the horizontal plane divided by the total light received by all the sensors.

Mathematically this may be calculated by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \times 100$$

3-1-7 Comments

- The surroundings for the test setup were dark, so that it could be assumed that all the light registered by the sensors was coming directly from the test setup without reflection.

- The experimental measurements were only taken at night to nullify any effects from outdoor light.

- The Hokie light pedestal and the photosensor setup were temporarily fixed to the platform so that they could be easily removed once all the experiments were completed.

- Before taking measurements the set up was run for 2 hours to allow the light output and the temperature inside the Hokie light to stabilize.

3-2 Light Emitting Diodes (LEDs)

The potential of using iBright LED Fluorescent lamps for general illumination purposes in buildings on the Virginia Tech campus was tested for three performance aspects.

1. Qualitative

2. Quantitative

3. Energy usage (includes impact on HVAC)

First for the qualitative assessment it was determined to monitor a room on the Virginia Tech campus which could satisfy the following criteria:

- Accessibility for the measurement of light levels for at least a two-week period should be possible.

- The room should be in use during office hours so that the performance and the light output of T8 and iBright lamps could be monitored and commented upon.

- The room should not have access to daylight so that it could be safely assumed that all the light measured within the room was only from the lamps.

- iBright LED Fluorescent lamps purchased for this research analysis run on 120V. Therefore the room should have the operational voltage of 120V so that it can be upgraded with the iBright lamps.

The room that satisfied all of the above-mentioned criteria was senior electrical engineer Ms. Kim Briele's office, who was also a committee member for this research.

3-2-1 Room Description

The test room had the following descriptive characteristics:

Location- Physical Plant Department, Sterrett Facilities Complex, Virginia Tech, Blacksburg.

Room Size- 12'X10'
Ceiling Height- 9'

Observations

- Walls were of CMU blocks with white color paint.
- The ceiling was composed of white acoustic lay-in ceiling tile in a 2' by 4' grid.
- The furniture was white laminated wood.

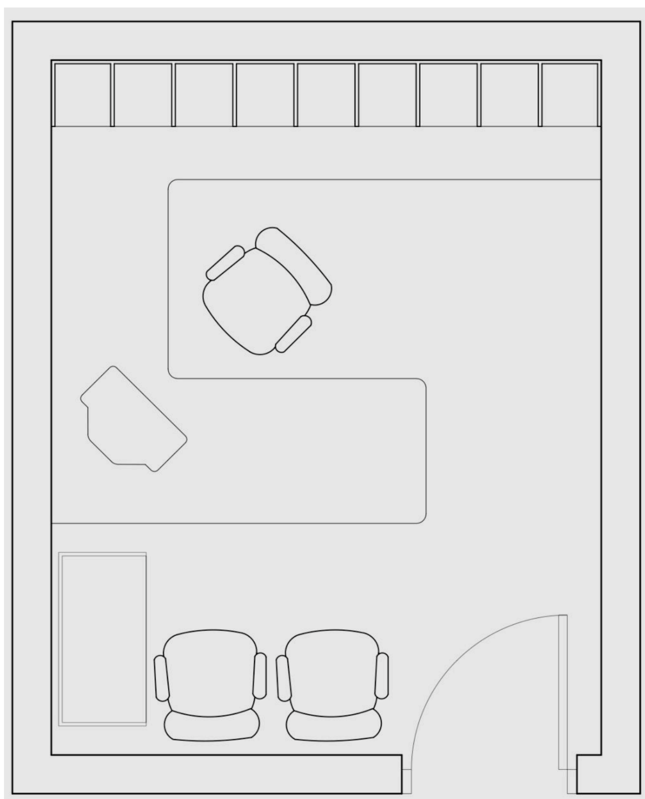


Figure 3-2-1a Plan of the test room

Figure 3-2-1b Inside view of the test room (Photo by author, 2008)

Comments

- The room had no access to daylight.
- The room appeared to be bright for its size.
- The old T8 lamps were replaced with new T8 lamps for comparison of their performance with new LED fluorescent lamps.

3-2-2 Quantitative Assessment

The aim of the first part of the test protocol was to determine the change in light levels from the T8 and iBright lamps.

The light levels were measured at a standard work desk height of 30” under the T8 and iBright lamps.

Three types of Light Meters were used-

1) Center 337 Mini Light Meter: This meter was newly purchased.
2) GE Mini Light Meter: This meter was purchased approximately 5 years prior to the time of testing.
3) Simpson Light Meter (Model 408): This meter was purchased approximately 15 years prior to the time of testing.

Figure 3-2-2a Center 337 Mini Light Meter - New Meter (Photo by author, 2008)

Figure 3-2-2b GE Mini Light Meter - Semi New Meter (Photo by author, 2008)

Figure 3-2-2c Simpson Light Meter (Model 408) - Old Meter (Photo by author, 2008)

3-2-3 Qualitative Method

The aim of this part of the test protocol was to qualitatively assess the perception and quality of the light. For this the color rendering characteristics were compared with the LEDs lamps and the T8 lamps. Other issues such as perceived quality of lighting and color were also compared.

A 8.5" x 11" chart comprising a wide spectrum of colors was prepared. The size of the color chart was chosen such that the entire chart could be photographed using a digital camera without a zoom feature.

Figure 3-2-3a Color Chart (Photo by author, 2008)

The camera used for this purpose was a Nikon CoolPix S50c.

To understand the color rendering ability of LEDs lamps and T8 lamps it was important to understand the terms “Color Temperature” and “ Color Rendering Index”.

1) Color Temperature

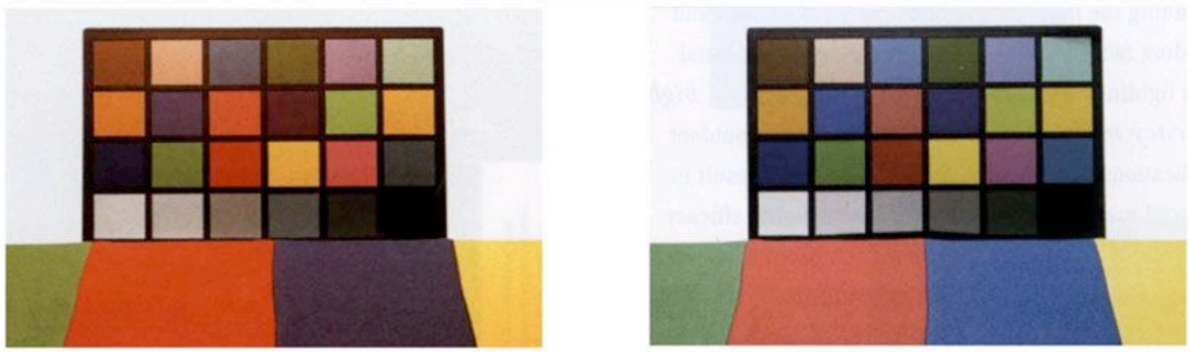
The “whiteness”, “yellowness” or “ blueness” of a light source, its warmth or coolness is defined by the term Color Temperature. Color temperature describes the color appearance of the light source and the light emitted from it. The appearance of the colors of objects when lighted by the given source is not defined by this term.

2) Color Rendering Index

A mathematical system called Color Rendering Index (CRI) was devised to compare how colors will appear under different light sources. How well subtle variations in color shades are revealed and how a light source makes the color of an object appear to human eyes is explained by the CRI.

By definition the light source in question is given a CRI of 100 if there is no change in appearance of colors when lighted by it as compared to the same colors lighted by a reference source of the same Color Temperature. The reference source is the Black Body Radiator for color temperature from 2000K to 5000K. For color temperature above 5000K, the reference source is an agreed upon form of daylight.

CRI of an incandescent lamp by the definition above is close to 100.



CRI 85 CRI 70

Figure 3-2-3b Comparison of color chart under two different light sources with same color temperature. Image courtesy GE Lighting (GElighting, 2009).

3-2-4 Energy Usage

Another parameter on which LED and T8 lamps were compared was the energy consumption and utility charges of a building on the campus of Virginia Tech. For this, annual energy usage was estimated for a selected building using the e-Quest software.

Typical as-built conditions were used to simulate and compare the annual energy consumption and costs with standard T-8 lamps and LEDs as general lighting throughout the building.

The building chosen for the analysis was the recently constructed Institute for Critical Technology and Applied Sciences (ICTAS).

Figure 3-2-4 Typical Floor Plan of the ICTAS Building

ICTAS was chosen because of the following factors:

1) It was recently constructed.

2) It was assumed that the building materials and the building construction and lighting practices were typical as per the Virginia Tech architectural standards.

3-2-4-1 eQuest modeling approach

The eQuest introductory tutorial (2003) described the following:

> The simulation "engine" within eQuest is derived from the DOE-2 program. The eQuest calculation engine extends and expands DOE-2's capabilities in several ways, including: interactive operation, dynamic/intelligent defaults, and other building system improvements. Also DOE-2 is often too difficult and time consuming to use for most projects, due to the time involved in describing the building. The eQuest simulation engine takes the designer through the creation of a detailed building model, allowing for parametric simulations of the design alternatives and providing intuitive graphics that compare the performance of the design and its alternatives (p. 3).

3-2-4-2 eQuest energy calculation method

The eQuest introductory tutorial (2003) described the following:

> eQuest calculates hour-by-hour building energy consumption over an entire year (8760 hours) using hourly weather data for the location under consideration. Input to the program consists of a detailed description of the building being analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat settings. eQuest also contains a dynamic daylighting model to assess the effect of natural lighting on thermal and lighting demands. eQuest provides accurate simulation of building features such as shading, fenestration, interior building mass, envelope building mass, and the dynamic response of differing heating and air conditioning system types and controls (p. 4).

3-2-4-3 eQuest building site information and weather data

The eQuest introductory tutorial (2003) described the following:

> Important building site inputs include latitude, longitude and elevation, plus information about adjacent structures or landscape forms capable of casting significant shadows on the proposed (or existing) building. The eQuest engine comes with long-term average weather data (~30-year average) for the sixteen standard climate zones in California. For areas outside of California, over 650 weather files are available. Some international locations are also available (p. 5).

3-2-4-4 Building shell, structure, materials and shades

The eQuest introductory tutorial (2003) described the following:

> eQuest takes into account the walls, roof, and floor of the proposed building in relation to their thermal properties, and their material properties with regard to heat transfer. It also

> takes into account the geometry and orientation of the building. This will include glass properties of windows and the dimensions of any window shades (e.g., overhangs and fins) (p. 5).

3-2-4-5 Heating and cooling load calculation

The eQuest introductory tutorial (2003) described the following:

> Heat gain from internal sources (e.g., people, lights, and equipment) can constitute a significant portion of the energy consumption in large buildings such as schools, both from their direct power requirements and the indirect effect they have on cooling and heating requirements. Internal loads frequently make large buildings relatively insensitive to weather. The performance of almost all energy-efficient design alternatives is impacted either directly or indirectly by the amount of internal load within a building. eQuest contains reasonable defaults by building type (p. 6).

For this study, the ASHRAE *Handbook of Fundamentals* edition 2005 was referenced.

3-2-4-6 Modeling information required

The following figure describes information needed to model the physical and operational conditions in the building.

Modeling Information Request
Project Name / Date

assignment

date1	date2	date3	INFORMATION	
			ARCHITECTURAL	
❑			floor plans	space layout/areas, surface orientations
❑			elevations	surface areas (windows, doors)
	❑		building/wall/roof sections	materials composition
❑			site plans	adjacent structures and landscape
	❑		roof plans	skylights and overhangs
❑			gross area & net (conditioned area)	
			ENVELOPE MATERIALS	
	❑		glazing shading coefficient, u-value, frame type, interior shading	
	❑		u-values: wall, roof, ceiling, skylight, slab & spandral	
			MECHANICAL	
	❑		HVAC plans	approximate HVAC zoning layout
❑			equipment types	
	❑		approx equipment sizes, design conditions, & efficiencies	
	❑		anticipated control sequences	
			ELECTRICAL / INTERNAL LOADS	
	❑		lighting plans	
	❑		lighting power density (by HVAC zone)	
	❑		design illuminance (by HVAC zone)	
	❑		peak occupancy (by HVAC zone)	
	❑		peak equipment (by HVAC zone)	
			OPERATIONS	
			per HVAC zone	
	❑		occupancy, lights & equipment schedules	
	❑		thermostat settings and schedules	
			per air handler	
	❑		anticipated coil leaving air temperatures	
	❑		minimum outside air	
	❑		fan schedules	
	❑		anticipated fan static & efficiency	
			central plant (if applicable)	
	❑		chilled & hot water temperatures	
	❑		equipment control sequences	
			ECONOMIC	
		❑	base case first costs (for equipment & systems affected by ECM's)	
		❑	ECM first costs	
❑			applicable & optional utility rates	
			POTENTIAL ECM's	
❑			envelope	
❑			lighting	
❑			mechanical	

Figure 3-2-4-6 eQuest Modeling Information Request (eQuest Introductory Tutorial, 2009)

3-2-4-7 Limitations of eQuest

One of the limitations of eQuest is that it is a generic tool and often unable to deal with the specific parameters of a given project. The suppliers of the program also acknowledge limitations of the tool with regards to the selected footprint shape that applies to all floors in the project. This is because the building geometry is limited to a fairly small set of typical orthogonal floor plans. Building geometries that are not represented by this floor plan set may not be modeled accurately.

The floor plan of the ICTAS building does not exactly correspond to any generic shape in the eQuest model. Therefore the original plan of the building was slightly modified into a rectangular plan to fit into the building types available in the eQuest library.

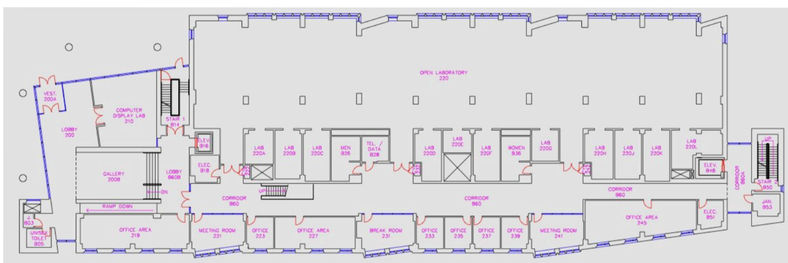


Figure 3-2-4-7a Original floor plan of the ICTAS building

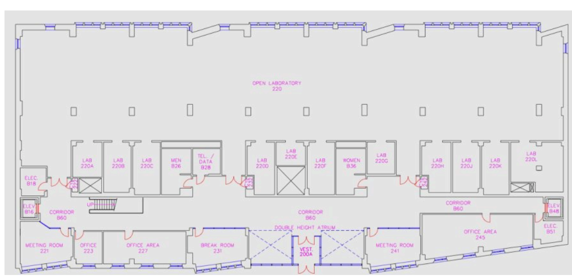


Figure 3-2-4-7b Modified floor plan of the ICTAS building

3-2-4-8 eQuest Model Description

Based upon the activities carried out in the ICTAS, the building was divided into four different thermal zones.

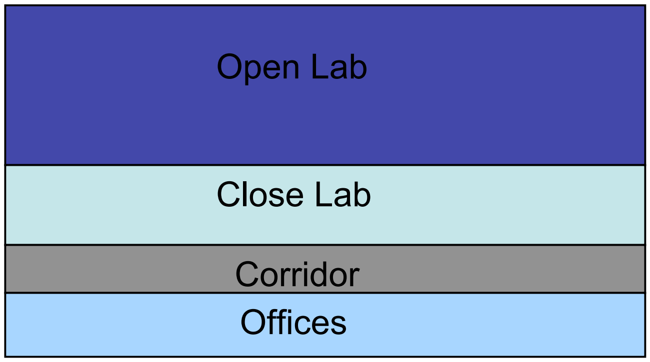


Figure 3-2-4-8 Schematic Thermal Zoning Layout

Using this zoning scheme four cases were analyzed:

a) The ICTAS building *without* daylight controls and standard T-8 lamps.

b) The ICTAS building *with* daylight controls and standard T-8 lamps.

c) The ICTAS building *without* daylight controls and LED fluorescent lamps.

d) The ICTAS building *with* daylight controls and LED fluorescent lamps.

3-2-4-9 eQuest Simulation Model Inputs

The following values were entered into eQuest to model the ICTAS building. The eQuest default values have been assigned to parameters not shown here. These parameters are derived from codes and standards and adjusted for building type and location.

3-2-4-9-1 Building Description

• Building Type – University Building

• Building Area – 76,416 sq ft

• No of Floors – Above Grade: 4 No. Below Grade: 0

• Cooling Equipment - Chilled Water Coils

• Heating Equipment – Hot water Coils

• Analysis year – 2008

• Daylighting Controls – no (case a and case c); yes (case b and case d)

• Foot Print shape – Rectangular Atrium

• Zoning Pattern – By activity area (Conditioned)

• Floor to Floor height - 16ft

• Floor to Ceiling height – 14.8ft

3-2-4-9-2 Building Envelope Construction

• Roof Surface

Construction: 8 in Concrete

Ext Finish / Color: Built up roof (Black, flat)

Exterior Insulation: 3 in polyisocyanurate (R-21)

• Above Grade Walls

Construction: 8 in CMU

Ext Finish / Color – Brick (Red, masonry)

Exterior Insulation – 2 in polyisocyanurate (R-14)

Additional Insulation –Grout 24 in o.c. and empty cells

Interior Insulation – R15 Furred insulation

• Ground Floor

Exposure: Exposed to ambient conditions

Construction: 6 in Concrete

Ext / Cavity Insulation: No Perimeter Insulation

Interior finish – Carpet with Fiber Pad

• Interior Construction

Ceilings: Lay in acoustic tile

Vertical walls: Wall type – Frame

Batt insulation – R-13 batt

• Exterior Door

Door type: Air Lock Entry (Single low-e glass)

No.- 2

Height – 7ft

Width – 6ft

Construction

Aluminum frame with break

Frame width – 2 in

• Exterior Windows

Window area specification method – Percent of gross wall area (floor to floor)

Type of glass used:

Double Low-e (e = 0.2) Clear 1⁄4 in, 1⁄2 in air (2004)

Frame Type – Aluminum with break, fixed, multiple spacer

Frame width - 2.25 in

Table 3-2-4-9-2a Window Dimensions

	Width	Height	Sill
Window -1	4’	5.5’	4.5’
Window -2	2.83’	10.83’	2.75’

Table 3-2-4-9-2b Percentage distribution of window areas on the building facade

% Window (Floor to Floor, including frame)				
	West	East	North	South
Window -1	15.4	5.8	1.9	1.9
Window -2	8.3	16.7	0	0

Estimated building gross (floor to floor) % window is 16.8% and net (floor to ceiling) is 18.1%.

Figure 3-2-4-9-2a View of the ICTAS building (Photo by author, 2008)

- Roof Skylights

Skylight roof top zones – Core only

Amount of skylights

% Coverage – 45% (Atrium Simulation)

Typical Skylight Dimensions

Width 1 = 39.5ft   Width 2 = 11.5ft

Skylight Glazing Type

Category – Flat/pyramid, aluminum frame with break

Type – Double polycarbonate clear (crystal)

Skylight Light Well

Depth – 1.17ft   Inside reflectance – 70.0%

- Exterior Lighting Load = 0.1 w/ft^2

<u>Active Areas Allocation</u>

Table 3-2-4-9-2c eQuest Simulation Model Inputs

Area Type	**Percent Area %**	**Design max Occ. (sq ft/person)**	**Design Ventilation (cfm/person)**
Laboratory, Medical	69%	34	40
Corridor	10%	1000	20
Office (General)	21%	144	25

Heat gain from internal sources (e.g., people, lights, and equipment) can constitute a significant portion of the energy consumption in large buildings such as ICTAS, both from their direct power requirements and the indirect effect they have on cooling and heating requirements. Internal loads frequently make large buildings relatively insensitive to weather. The performance of almost all energy-efficient design alternatives is impacted either directly or indirectly by the amount of internal load within a building. eQuest contains reasonable defaults by building type.

Based upon the activities carried out in the ICTAS, the building was divided into four different thermal zones (refer to Figure 3-2-4-8). Using this zoning scheme four cases were analyzed:

a) The ICTAS building *without* daylight controls and standard T-8 lamps.

b) The ICTAS building *with* daylight controls and standard T-8 lamps.

c) The ICTAS building *without* daylight controls and LED fluorescent lamps.

d) The ICTAS building *with* daylight controls and LED fluorescent lamps.

Interior Lighting Loads and Profiles

Table 3-2-4-9-2d eQuest Simulation Model Inputs – Case (a) and Case (b)

Area Type	**Percent Area %**	**Lighting (W/sqft)**	**Task Light (W/sqft)**
Laboratory, Medical	69%	1.7	0
Corridor	10%	1.06	0
Office (General)	21%	1.1	0

Table 3-2-4-9-2e eQuest Simulation Model Inputs – Case (c) and Case (d)

Area Type	**Percent Area %**	**Lighting (W/sqft)**	**Task Light (W/sqft)**
Laboratory, Medical	69%	1.5	0
Corridor	10%	0.95	0
Office (General)	21%	0.98	0

Note –The lumen output of the Philips T8 lamps was 2850 lumens (for case a and b) and it was more than the double the output of the iBright LED lamps (1290 lumens). Therefore to maintain the same light level as the T8 lamps in case (a) and (b), two LED lamps were considered for one T8 lamp.

Office equipment loads and profile

Office equipment load is the consumption of electricity in watts per square foot by office equipment such as computers, printers, scanners and projectors. This also includes personal items brought into the building like coffee makers, microwaves, personal refrigerators, heaters, popcorn poppers, toaster ovens and task lighting. The following is a summary of the input for the eQuest model. For this study eQuest-assigned default values were used for office equipment and miscellaneous loads.

Table 3-2-4-9-2f eQuest Simulation Model Inputs

Area Type	**Percent Area %**	**Office Equipment (W/sqft)**
Laboratory, Medical	69%	1.72
Corridor	10%	0
Office (General)	21%	1.25

<u>Miscellaneous Loads and profiles</u>

Table 3-2-4-9-2g eQuest Simulation Model Inputs

Area Type	**% Area**	**Electric**	
		Load (w/sqft)	**Sensible Heat (fraction)**
Laboratory, Medical	69%	1.00	1.00
Corridor	10%	0.00	1.00
Office (General)	21%	0.75	1.00

<u>HVAC System</u>

The HVAC system used in the ICTAS building was a Variable-air-volume (VAV) system. VAV systems save energy by slowing the fan in response to dynamic heating and cooling demands. When the rooms need full cooling, the fan is at full speed; while at partial cooling loads or during heating operation the fans speed and air volume are reduced.

Cooling Source – Chilled water coils

Heating Source – Hot water coils

Hot water Source – Hot water loop

System type – Standard VAV with Hot Water reheat

Return air path – Ducted

Temperatures and Airflow

Seasonal Thermostat Setpoints

Based upon the occupancy and usage patterns in the ICTAS building, thermostat setpoints were established to maximize performance from the HVAC system. The eQuest program uses indoor design temperatures to size air flow requirements.

Table 3-2-4-9-2h eQuest Simulation Model Inputs

	Occupied (deg F)		**Unoccupied (deg F)**	
	Cool	**Heat**	**Cool**	**Heat**
Breaks (winter, spring)	76.0	70.0	82.0	64.0
School in session	76.0	70.0	82.0	64.0
Low Use (Summer)	74.0	70.0	82.0	64.0

Table 3-2-4-9-2i eQuest Simulation Model Inputs

Design Temperatures	**Indoor**	**Supply**
Cooling Design Temp	75.0 ºF	55.0 ºF
Heating design	72.0 ºF	95.0 ºF

Air Flows : Minimum Design Flow - 0.50 Cfm / sq ft

Table 3-2-4-9-2j eQuest Simulation Model Inputs

VAV Minimum flow	**Core**	**Perimeter**
	40% of design flow	30% of design flow

To estimate the annual utility charges of the ICTAS building with T8 and LED lamps following electricity and natural gas charges were input to the eQuest model.

Table 3-2-4-9-2k eQuest Simulation Model Inputs

Electricity Charges			Natural Gas Charges
Demand charge	Rate change	Customer charge	
8.00 $/Kw	0.075 $/Kwh	$0.06 per month	0.8 $/Therm

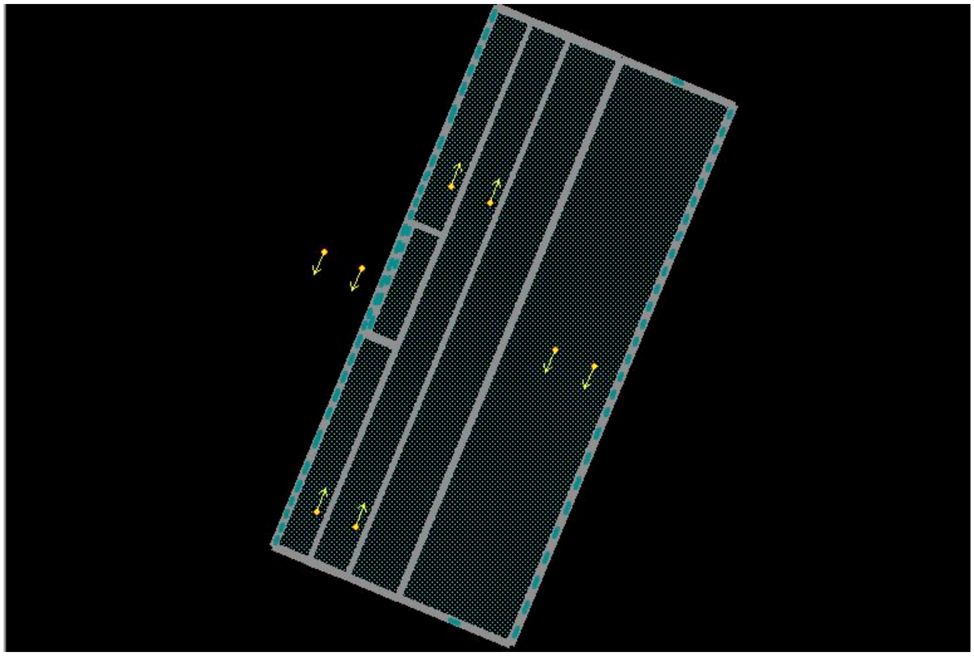


Figure 3-2-4-9-2b eQuest Generated Screen Shot – 2D Modified Plan of ICTAS Building

The figure above is the screen capture image of the ICTAS building generated by eQuest. The plan was generated based upon the inputs given at the start of the Section 3-2-4-9. The figure shows four different thermal zones the building was divided into (refer to Figure 3-2-4-8).

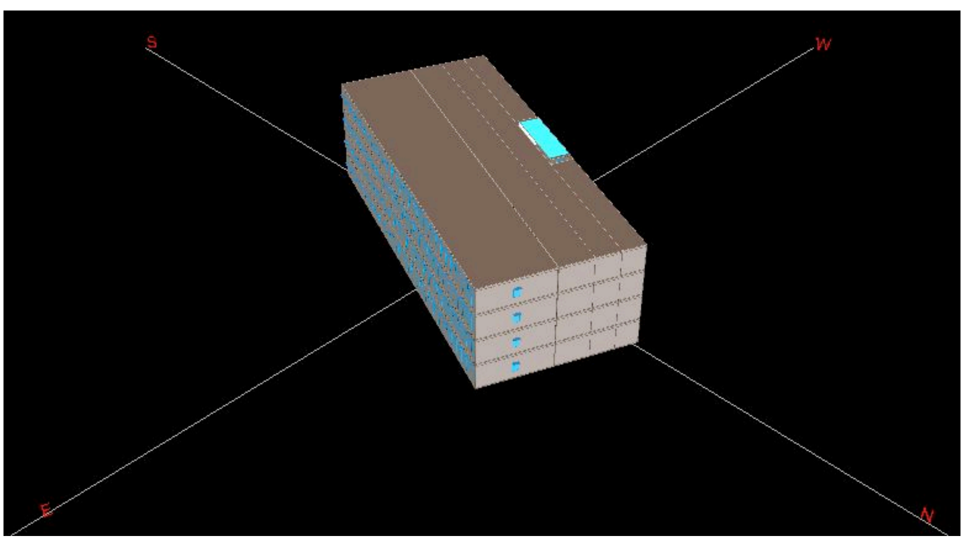


Figure 3-2-4-9-2c eQuest Generated Screen Shot – 3D View of Modified ICTAS Building

The figure above is the screen capture image of the modified ICTAS building generated by eQuest. The figure shows the orientation of the ICTAS building relative to the north direction. It also shows the distribution of windows and doors on all four facades of the building (refer to Table 3-2-4-9-2a and 3-2-4-9-2b).

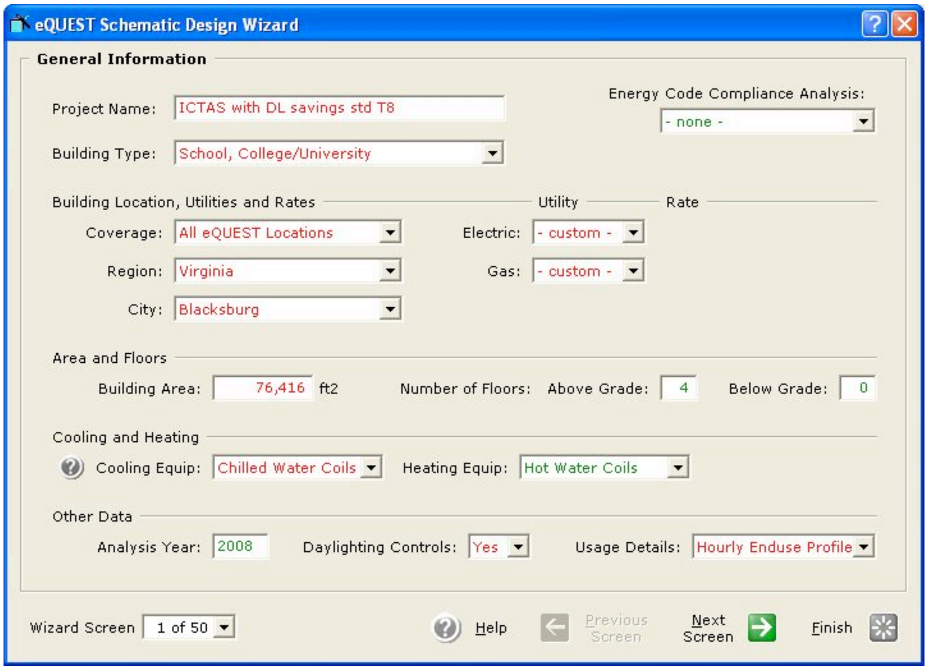


Figure 3-2-4-9-2d eQuest screen shots – Data input screen, Building Information

The figure above is the screen capture image of the data input screen where the building information for the ICTAS building was input into the eQuest model. In this screen information including building type, building location, building area and the number of floors were entered. This screen allows for selecting the coil type for cooling and heating of the building. Based on this information eQuest defaulted the available HVAC system types. This screen also enables/disables daylighting-related screens.

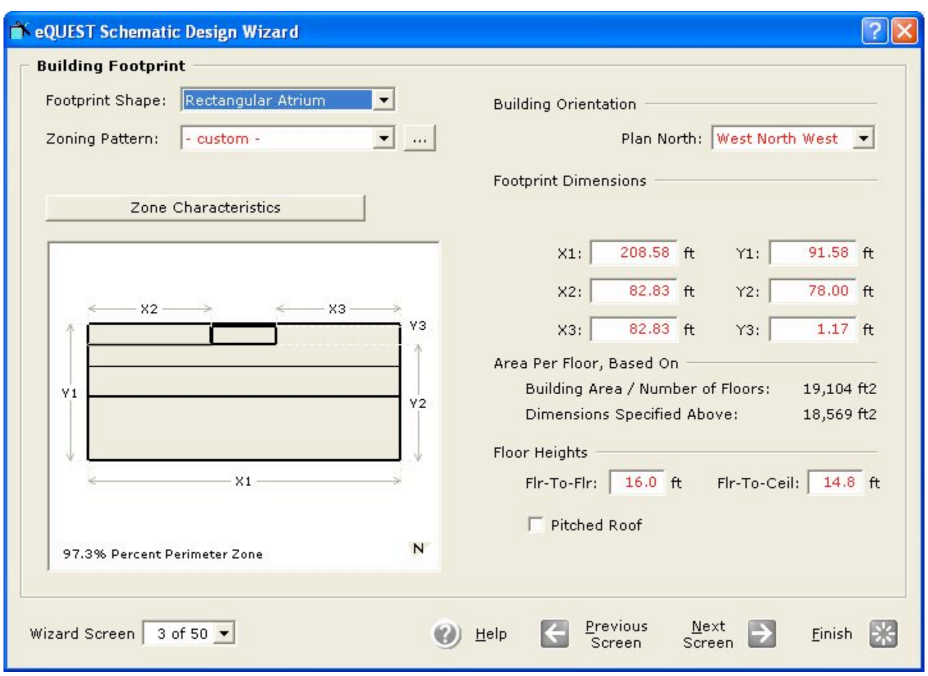


Figure 3-2-4-9-2e eQUEST screen shots – Data input screen, Building footprint

Figure 3-2-4-9-2e is the screen capture image of the data input screen where the zone characteristics and its dimensions for the ICTAS building were defined. The building footprint shape was chosen from the building types available in the eQuest library. The orientation of the building and the footprint dimensions were also defined in this screen. Floor to floor heights and floor to ceiling height were input into this screen.

3-2-4-10 Location of the Photosensors

As a result of the orientation and layout of the building only the open labs, offices and atrium receive substantial amounts of daylight. Therefore simulated control points were located in these spaces to make use of available daylight.

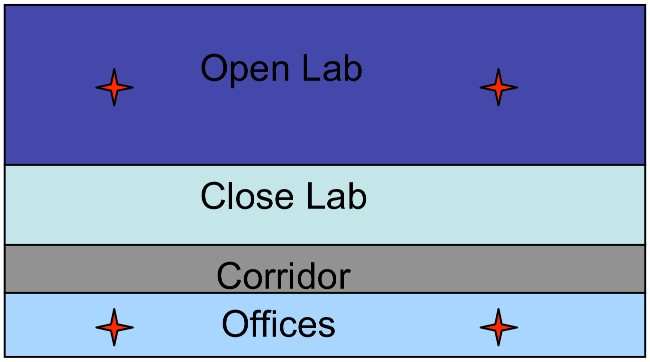


Figure 3-2-4-10a Schematic location of the photosensors

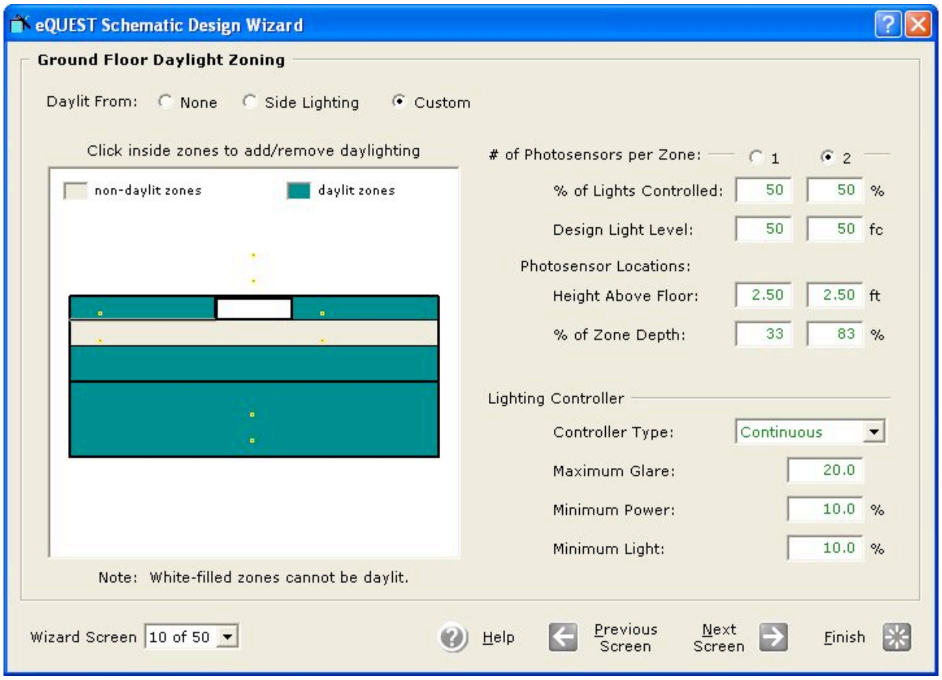


Figure 3-2-4-10b eQuest screen shots – Ground floor daylight zoning

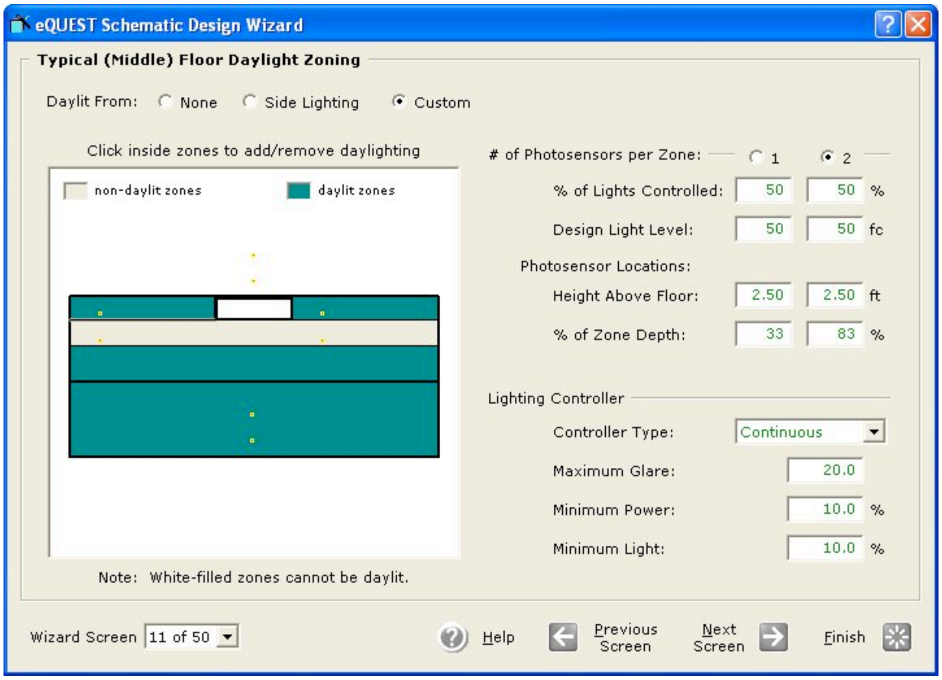


Figure 3-2-4-10c eQuest screen shots – First and second floor daylight zoning

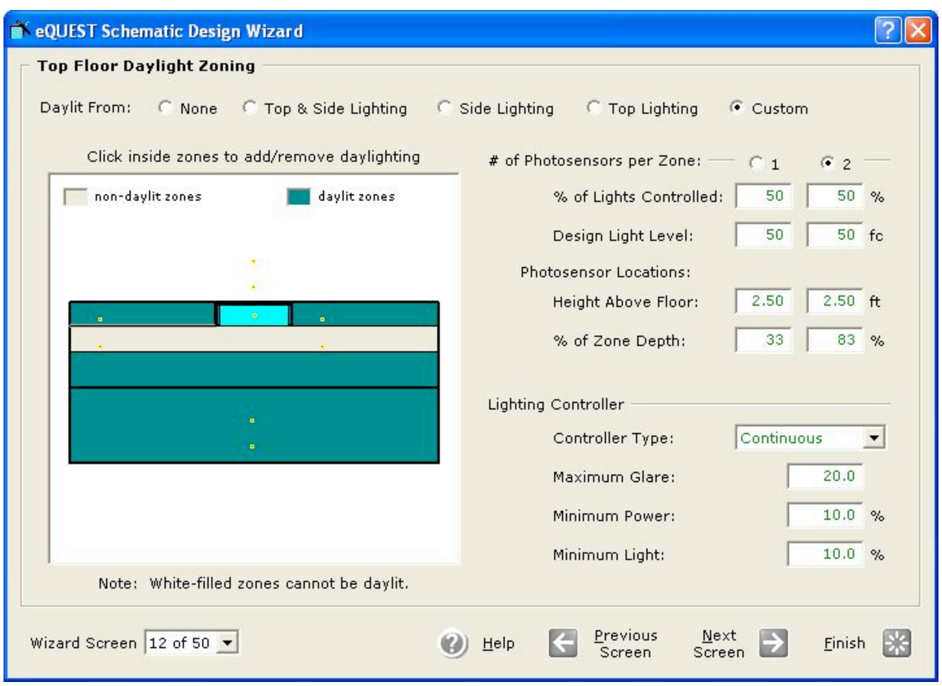


Figure 3-2-4-10d eQuest screen shots – Top/Fourth floor daylight zoning

3-2-4-11 Comparison of input power of various light sources

Table 3-2-4-11 compares the distribution rate of the input power for various light sources including incandescent lamps, fluorescent lamps, HID lamps and white LEDs.

The electrical power conversion to visible radiation is only about 12 – 20 % in the case of currently available white LEDs. Since white LEDs do not emit UV and/or IR radiation it can be assumed that the remaining part of the electric input power (80 – 88 %) is converted to heat loss (conduction & convection loss).

Table 3-2-4-11 Luminous efficacy and energy converting efficiency of various light sources (Kohmoto, 2006, p. 5)

light sources	UV radiation [%]	visible radiation [%]	IR radiation [%]	conduction & convection loss [%]
solar radiation	2～5	40～50	50～55	—
incandescent lamp	0～0.2	8～14	80～85	5～6
fluorescent lamp	0.5～1	25	30	44
HID lamp (HP mercury)	2～4	13～16	60	16～22
HID lamp (metal halide)	2～7	20～40	50～67	7～20
HID lamp (HP sodium)	0.3	27～30	47～63	10～23
white LED (dichromatic)	0	12～20	0～0.2	80～88

The percentage conversion of electrical energy to visible radiation is typically more for fluorescent lamps as compared to LED lamps. As a result, for the LED lamps there is more of the electrical input converted to heat, which is conducted and convected to the surroundings. The result is a greater impact on cooling loads for the space.

There was no direct method in the eQuest simulation software to account for the above-mentioned increase in heat output. An indirect method in terms of "Process Load" was adopted. Process Load just like Interior Lighting, Task Lighting, Office Equipment and Miscellaneous Equipment contributes to the space loads.

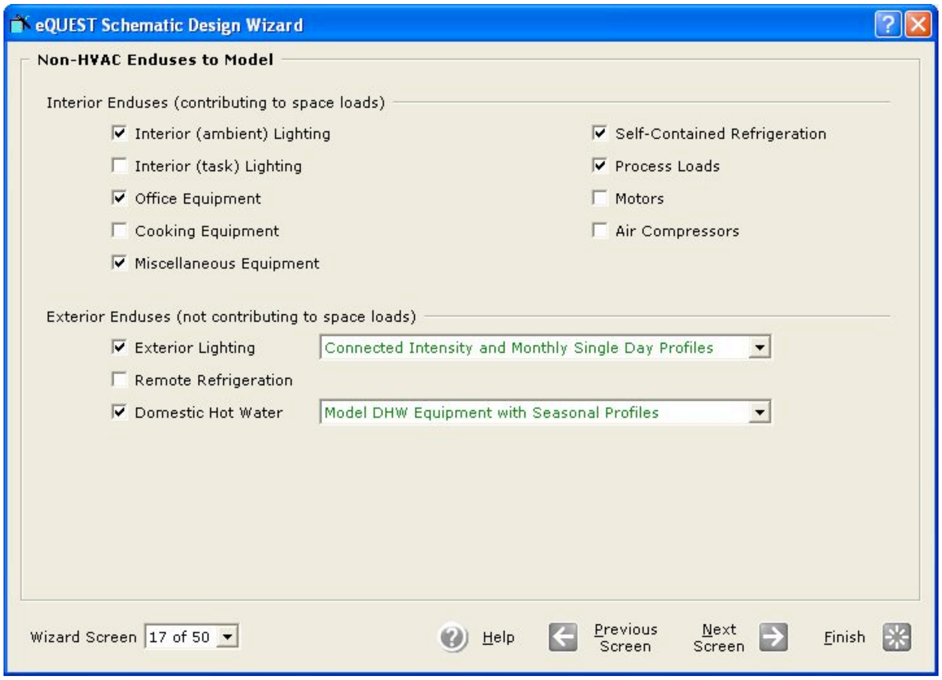


Figure 3-2-4-11a eQuest screen shots – Interior Enduses

The following formula was used for the calculation of process load for case (c) and case (d) to account for the additional heat gain from the LEDs.

Light Intensity x Heat Rejected x 3.41

where, Light Intensity = $\frac{\text{Total wattage of all the lamps used in the space}}{\text{Total area of the space}}$

Heat Rejected = Difference in heat generation from LED lamps "minus" fluorescent lamps.

3.41 is the multiplication factor required to convert watts into Btu/h.

For open and closed lab

Light Intensity = 1.5 watts/sq.ft.

Heat Rejected = 85% for LED lamps and 60% for fluorescent lamps

Therefore, total heat rejected = 85%-60% = 25% = 0.25

Hence Process Load = 1.5 x 0.25 x 3.41 = **1.28 Btuh/SF**

For Corridor

Light Intensity = 0.95 watts/sq.ft.

Heat Rejected = 85% for LED lamps and 60% for fluorescent lamps

Therefore, total heat rejected = 85%-60% = 25% = 0.25

Hence Process Load = 0.95 x 0.25 x 3.41 = **0.81 Btuh/SF**

For Offices

Light Intensity = 0.98 watts/sq.ft.

Heat Rejected = 85% for LED lamps and 60% for fluorescent lamps

Therefore, total heat rejected = 85%-60% = 25% = 0.25

Hence Process Load = 0.98 x 0.25 x 3.41 = **0.83 Btuh/SF**

Based upon the above calculations, process load values were input to the eQuest model (as shown in Figure 3-2-4-11b below). The sensible heat fraction for all the spaces was taken as 1.

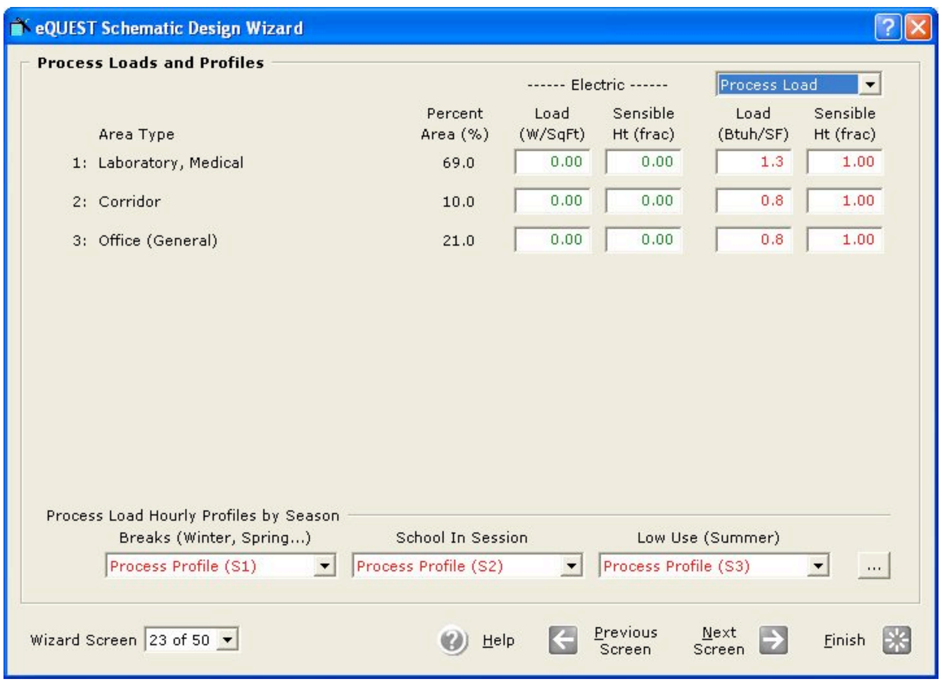


Figure 3-2-4-11b eQuest screen shots – Process Load

This completes the input description for the ICTAS building into eQuest.

Chapter 4 - Data Analysis and Results

The following summarizes the data analysis and results of the studies of 1) the Hokie light and 2) application of LED lamps.

4-1 Hokie Light

To evaluate the efficacy of the design options chosen for reducing uplight distribution from the Hokie light, experiments were conducted in the Environmental Systems Laboratory on Prices Fork Road, Blacksburg (refer to Section 3-1-1).

The aim of the experiments was to determine the photometric distribution of several Hokie light alteration strategies.

In addition to the light distribution the globe temperature measurements were recorded.

The following options were chosen for experimental evaluation:

4-1-1 Base case for the Hokie light

Before analyzing the performance of the options chosen for retrofitting the Hokie light, it was very important to determine the base performance. The available light distribution data for the Hokie light was from the manufacturer's product catalogue. Unfortunately there was no experimental data available describing the light distribution characteristics. Therefore the base case light distribution was derived experimentally.

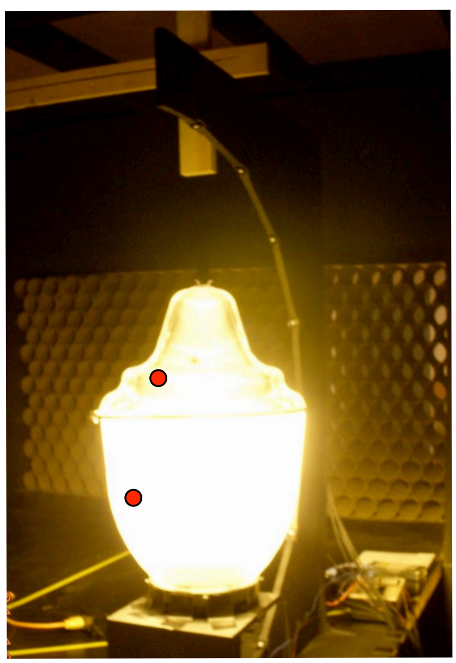


Figure 4-1-1a Experimental setup for the base case (Photo by author, 2008)

"●" Graphically represents the location of thermocouples inside the globe.

Globe temperatures were measured by using two copper-constantan thermocouples placed in the locations shown in Figure 4-1-1a.

Comments

- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 readings were taken for each of the photosensors and thermocouples. Table 4-1-1 below shows the average of the measurements.

- The room temperature for the test setup was 60º F.

- Recorded values from the sensors were in terms of photon flux received (µmoles/m^2/s). They were then converted into the more comprehensible units of Lux.

- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

- For each test the lamp was run for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-1 Photometric light distribution for the base case

Base Case									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19

Uplight is the percentage of the total light received by the sensors above the horizontal plane (sensor 5) divided by the total light received by all the sensors (refer to Section 3-1-6).

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \text{ X } 100$$

$$= \frac{1.61+1.40+2.11+3.42}{1.61+1.40+2.11+3.42+4.52+24.64+7.85} \text{ X } 100$$

$= 8.54/45.55 \times 100$

$= 18.75\%$

Observations-

- From the experimental results the uplight was more than what was claimed in the product catalogue. As per the product catalogue the uplight was 14%.
- Sensors 5, 6 and 7 received the most light (see Figure 4-1-1b).
- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.

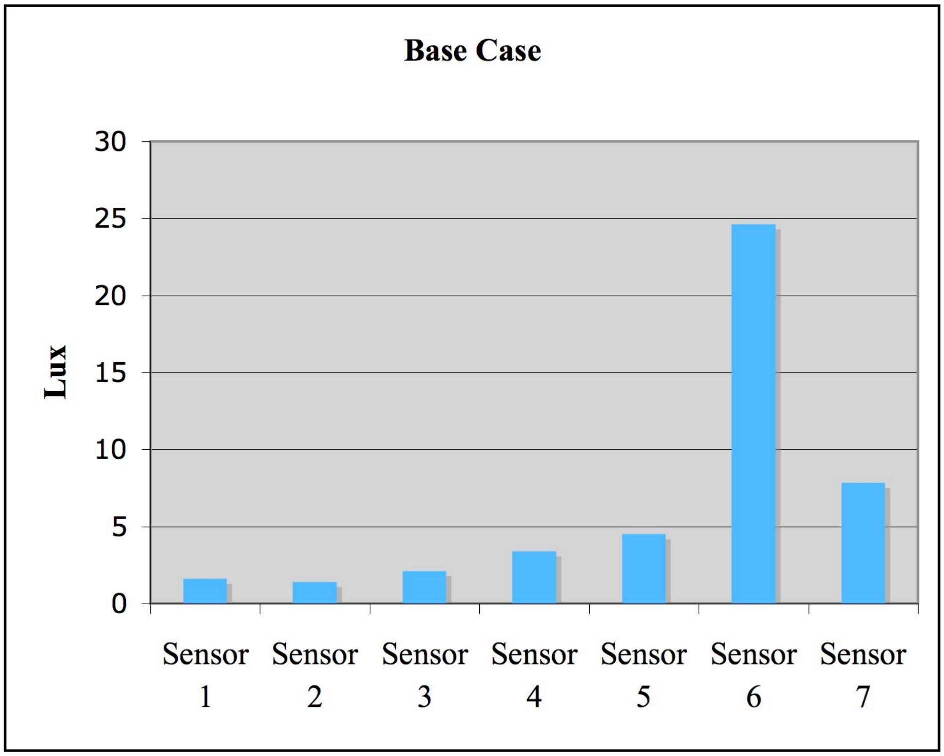


Figure 4-1-1b Light received by the sensors for the base case

The retrofit options for the Hokie light should (refer to Section 2-1-6):

- have reflective properties from inside to redirect the uplight downward,
- be easy to work with,
- be inexpensive,

- have the ability to withstand high temperatures,
- be readily available,
- not affect the current appearance of the Hokie Light. If it does then it should easily merge into the Virginia Tech surroundings.

The options that satisfied all of the above-mentioned criteria were:

Option 1 - Cover the upper part of the globe on the outside (refer to Section 2-1-6).

Option 2 - Replace the perforated LiteLid® inside the globe with non-perforated LiteLid® to decrease the uplight (refer to Section 2-1-6).

Option 3 – Application of Reflective Paint on the tip of the 100W HPS lamp (refer to Section 2-1-6).

Option 4 – Application of reflective paint on the inside of the top of the globe (refer to Section 2-1-6).

4-1-2 Option 1 - Cover the upper part of the globe on the outside.

It was expected that by covering the top of the bottom section of the Hokie light with a strip of aluminum foil, the amount of light distributed above the horizontal plane would be reduced.

Figure 4-1-2a Image of proposed option 1 (Photo by author, 2008)

The strip of aluminum foil could be painted with the Virginia Tech Brown color, i.e. with the same color as the post, or could remain as it is so that it would blend with the transparent nature of the globe of the Hokie light.

For this option a 3" wide strip of aluminum foil was used and wrapped around the top of the bottom section of the Hokie light.

Figure 4-1-2b Experimental setup for option 1 (Photo by author, 2008)

Comments

- The aluminum foil was very easy to work with. The task of wrapping the top of the bottom section of the Hokie light with aluminum foil was easily accomplished.

- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 readings were taken for each of the photosensors and thermocouples. Table 4-1-2 below shows the average of the measurements.

- The room temperature for the test setup was 60º F.

- Recordings from the sensors were in terms of photon flux received (µmoles/m2/s). They were then converted into the more comprehensible units of Lux.

- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

- For each test the lamp was on for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-2 Photometric light distribution for option 1

Option 1									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base Case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
Light Level Option 1	2.48	2.05	1.99	2.10	2.34	26.92	8.98	111.30	90.52
% Change in Light Levels	54.70	46.43	-5.68	-38.63	-48.16	9.23	14.45	9.71	8.80

Uplight is the percentage of the total light received by the sensors above the horizontal plane (sensor 5) divided by the total light received by all the sensors (Refer to Section 3-1-6).

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \text{ X } 100$$

$$= \frac{2.48+2.05+1.99+2.10}{2.48+2.05+1.99+2.10+2.34+26.92+8.98} \text{ X } 100$$

$$= 8.62/46.86 \text{ x } 100$$

$$= 18.39\%$$

Observations-

The test setup for option 1 was run under the same conditions as with the base case. The results from this option were then compared with the results from the base case.

- The uplight was only marginally reduced.
- Sensors 1, 5, 6 and 7 received the most light (See Figure 4-1-2c).

- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.

- The light received by Sensors 1 and 2 increased when compared to the base case (see Figure 4-1-2c).

- The light received by Sensors 4 and 5 decreased when compared to the base case (see Figure 4-1-2c).

- Sensors 6 and 7 received only marginally more light when compared to the base case (see Figure 4-1-2c).

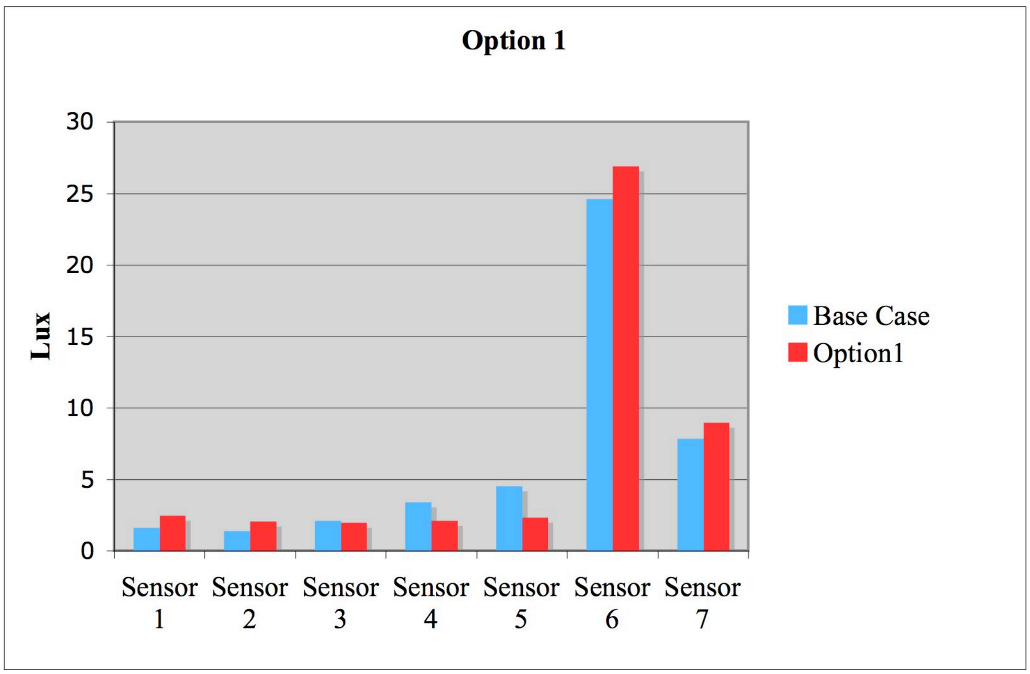


Figure 4-1-2c Photometric light distribution comparisons between base case & option 1

4-1-3 Option 2 - Replace the perforated LiteLid® inside the globe with a non-perforated LiteLid® to decrease the uplight.

At present in the Hokie light, the perforated LiteLid® is used to redirect the uplight and to control the heat generated inside (refer to Section 2-1-6).

For this option, the LiteLid® and its perforations were covered with aluminum foil as shown in Figures 4-1-3a and 4-1-3b.

Figure 4-1-3a Hokie light with non - perforated LiteLid® (Photo by author, 2008)

Figure 4-1-3b Perforated LiteLid® wrapped with aluminum foil (Photo by author, 2008)

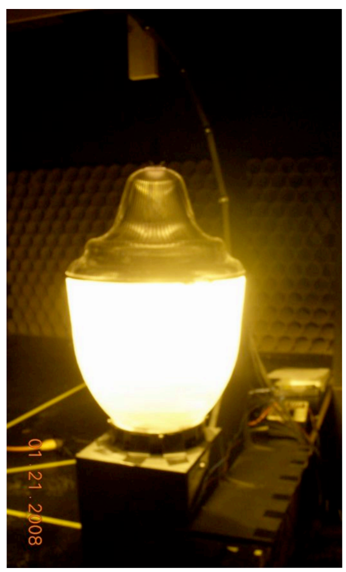


Figure 4-1-3c Experimental setup for option 2 (Photo by author, 2008)

Comments

- The task of wrapping the perforated LiteLid® with aluminum foil was easily accomplished.

- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 measurements were taken for each of the photosensors and thermocouples. Table 4-1-3 below shows the average of the measurements.

- The room temperature for the test setup was 60º F.
- Recordings from the sensors were in terms of photon flux received (µmoles/m2/s). They were then converted into the more comprehensible units of Lux.
- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.
- For each test the lamp was on for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-3 Photometric light distribution for option 2

Option 2									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base Case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
Light Level Option 2	0.63	0.28	1.11	2.50	4.55	25.29	8.10	110.86	86.53
% Change in Light Levels	-61.06	-80.14	-47.28	-26.83	0.55	2.63	3.16	9.27	4.01

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \times 100$$

$$= \frac{.63+.28+1.11+2.50}{.63+.28+1.11+2.50+4.55+25.29+8.10} \times 100$$

$$= 4.52/42.46 \times 100$$

$$= 10.64\%$$

Observations-

The test setup for option 2 was run under the same conditions as with the base case. The results from this option were then compared with the results from the base case.

- The uplight distribution was reduced.
- Sensors 5, 6 and 7 received the most light (see Figure 4-1-3d).
- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.
- The light received by Sensors 1, 2, 3 and 4 was decreased when compared to the base case (see Figure 4-1-3d).
- Sensors 6 and 7 received only marginally more light when compared to the base case (see Figure 4-1-3d).

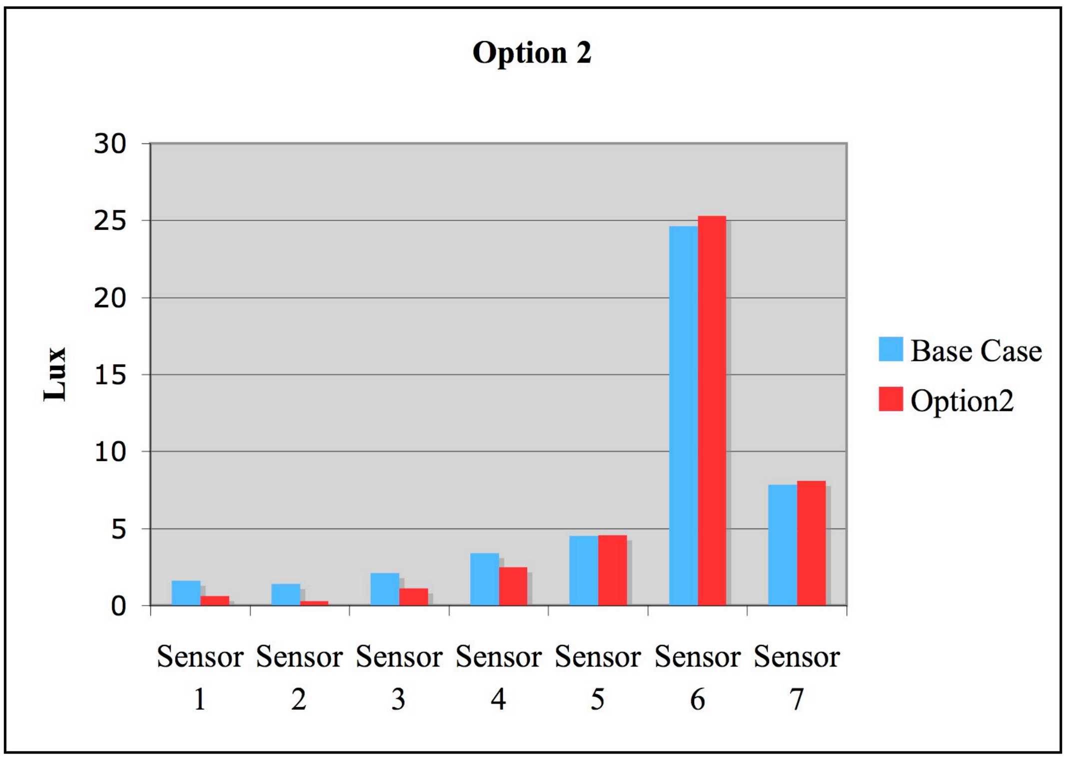


Figure 4-1-3d Photometric light distribution comparisons between base case & option 2

4-1-4 Option 3 - Application of Reflective Paint on the tip of the 100W HPS lamp.

It was expected that painting the tip of the bulb with reflective paint would reduce the light distribution in the upward direction by reflecting it downward.

The paint selected for this option was the Quartz-Coat(TM) 845-Silver by Aremco Products.

Figure 4-1-4a Reflective Paint on the tip of the 100W HPS lamp (Photo by author, 2008)

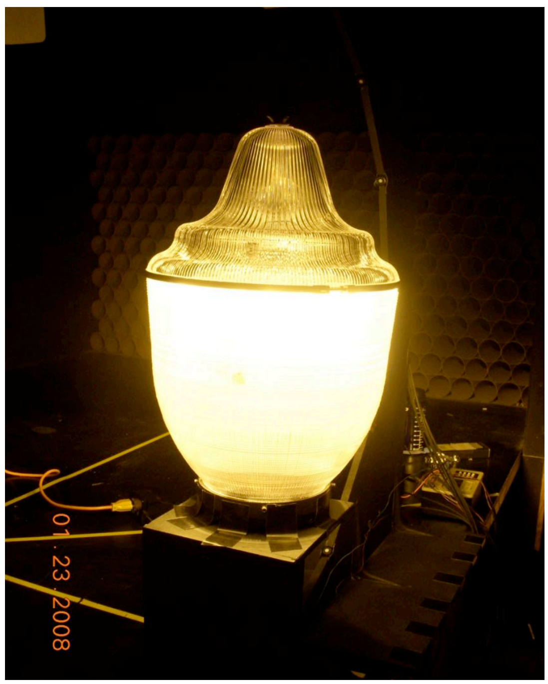


Figure 4-1-4b Experimental setup for option 3 (Photo by author, 2008)

Comments

- As per the product catalogue specifications for the Quartz-Coat (TM) 845-Silver Paint, the paint should be cured at a temperature of 900º F- 1000º F. But due to a lack of availability of a high temperature furnace, a normal kitchen oven was used with a maximum temperature setting of 450º F.

- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 readings were taken for each of the photosensors and thermocouples. Table 4-1-4 below shows the average of the measurements.

- The room temperature for the test setup was 60º F.

- Recordings from the sensors were in terms of photon flux received (µmoles/m2/s). They were then converted into the more comprehensible units of Lux.

- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

- For each test the lamp was on for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-4 Photometric light distribution for option 3

Option 3									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base Case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
Light Level Option 3	1.36	1.25	1.27	3.36	4.76	24.38	6.80	100.46	97.61
% Change in Light Levels	-15.14	-10.64	-39.90	-1.87	5.22	-1.06	-13.38	-0.98	17.3

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \times 100$$

$$= \frac{1.36+1.25+1.27+3.36}{1.36+1.25+1.27+3.36+4.76+24.38+6.8} \times 100$$

$$= 7.24/43.18 \times 100$$

= 16.76%

Observations-

The test setup for option 3 was run under the same conditions as with the base case. The results from this option were then compared with the results from the base case.

- The uplight distribution was reduced only marginally.
- Sensors 5, 6 and 7 received the most light (see Figure 4-1-4c).
- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.
- The light received by Sensors 1, 2, 3 and 4 was decreased by a relatively small amount when compared to the base case (See Figure 4-1-4c).
- Sensors 6 and 7 received less light when compared to the base case (see Figure 4-1-4c).

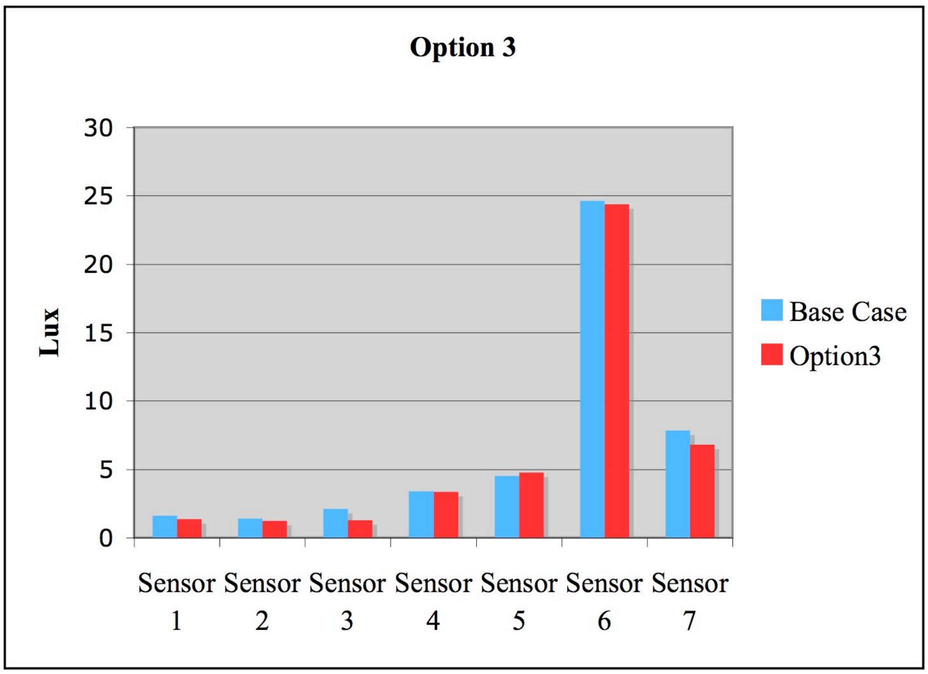


Figure 4-1-4c Photometric light distribution comparisons between base case & option 3

4-1-5 Option 4 – Application of reflective paint on the inside of the top of the globe.

The concept behind using this option was to decrease the uplight by reflecting it downward.

The paint selected for this option was the Corr-Paint CP2010 Aluminum by Aremco Products.

Figure 4-1-5a Experimental setup for option 4 (Photo by author, 2008)

Comments

- As per the product catalogue specifications for the Corr-Paint CP2010 Aluminum, the paint should be cured at a temperature of 200º F. For this a normal kitchen oven was used.

- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 readings were taken for each of the photosensors and thermocouples. Table 4-1-5 below shows the average of the measurements.

- The room temperature for the test setup was 60º F.

- Recordings from the sensors were in terms of photon flux received (µmoles/m2/s). They were then converted into the more comprehensible units of Lux.

- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

- For each test the lamp was on for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-5 Photometric light distribution for option 4

Option 4									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base Case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
Light Level Option 4	0.13	0.14	0.95	2.53	4.47	23.05	7.16	91.95	87.25
% Change in Light Levels	-92.21	-90.07	-55.04	-26.01	-1.26	-6.49	-8.79	-9.36	4.88

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \text{ X } 100$$

$$= \frac{0.13+0.14+0.95+2.53}{0.13+0.14+0.95+2.53+4.47+23.05+7.16} \text{ X } 100$$

$$= 3.75/38.43 \text{ x } 100$$

$$= 9.75\%$$

Observations-

The test setup for option 4 was run under the same conditions as with the base case. The results from this option were then compared with the results from the base case.

- The uplight distribution was reduced.
- Sensors 5, 6 and 7 received the most light (see Figure 4-1-5b).
- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.
- There was a 90% reduction in light received by Sensors 1 and 2 when compared to the base case (see Figure 4-1-5b).

- The light received by Sensors 3 and 4 was decreased (see Figure 4-1-5b).
- Sensors 6 and 7 received less light when compared to the base case (see Figure 4-1-5b).

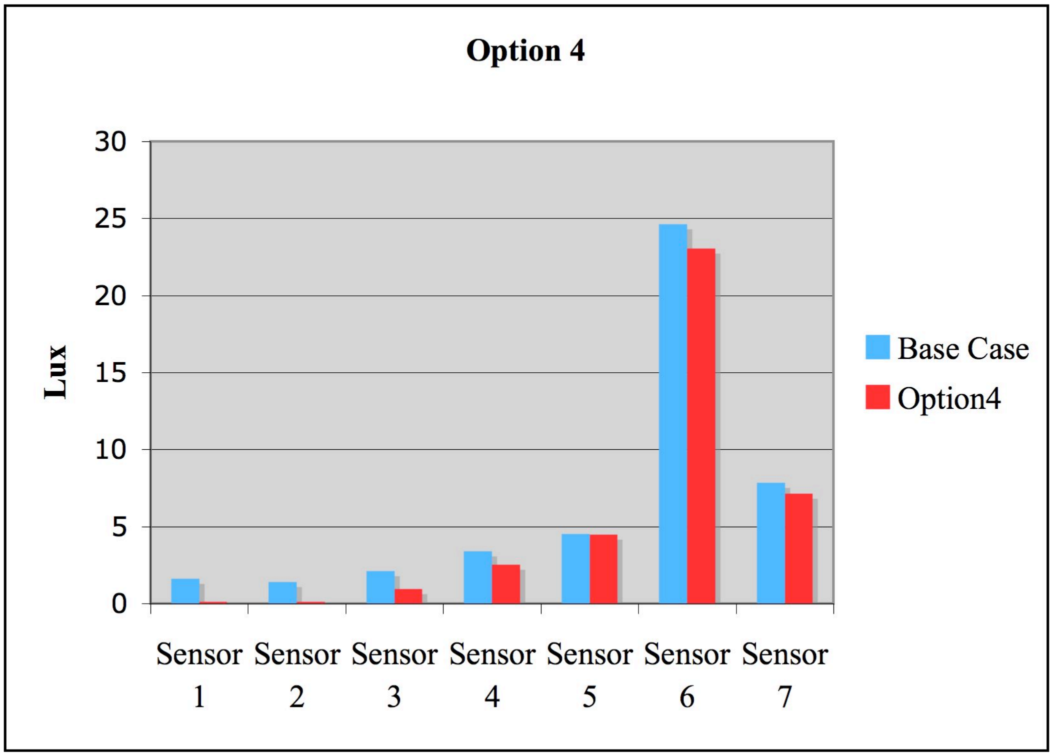


Figure 4-1-5b Photometric light distribution comparisons between base case & option 4

4-1-6 Option 5 – Application of reflective paint on the inside surface of the top of the globe with non-perforated aluminum LiteLid®.

The results from options 2 and 4 were favorable therefore option 5 was explored as a combination of these two options.

Figure 4-1-6a Experimental setup for option 5 (Photo by author, 2008)

Comments

- As per the product catalogue specifications for the Corr-Paint CP2010 Aluminum, the paint should be cured at a temperature of 200º F. For this a normal kitchen oven was used.
- With the above setup, measurements were taken every 5 minutes for the 7 photosensors and 2 copper-constantan thermocouples, for a period of 90 minutes. Hence, a total of 18 readings were taken for each of the photosensors and thermocouples. Table 4-1-6 below shows the average of the measurements.
- The room temperature for the test setup was 60º F.
- Recordings from the sensors were in terms of photon flux received (μmoles/m2/s). They were then converted into the more comprehensible units of Lux.

- The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

- For each test the lamp was on for 2 hours before taking readings. This was done to allow the light output and temperature inside the globe to stabilize.

Table 4-1-6 Photometric light distribution for option 5

Option 5									
(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Light Level Base Case	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
Light Level Option 5	0.13	0.14	1.13	2.64	4.68	24.28	7.58	115.97	95.28
% Change in Light Levels	-92.21	-90.07	-46.33	-22.76	3.49	-1.49	-3.44	14.31	14.5

The uplight distribution was determined mathematically by:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \text{ X } 100$$

$$= \frac{0.13+0.14+1.13+2.64}{0.13+0.14+1.13+2.64+4.68+24.28+7.58} \text{ X } 100$$

$$= 4.04/40.58 \text{ x } 100$$

$$= 9.95\%$$

Observations-

The test setup for option 5 was run under the same conditions as with the base case. The results from this option were then compared with the results from the base case.

- The uplight distribution was reduced.

- Sensors 5, 6 and 7 received the most light (see Figure 4-1-6b).
- The temperature inside the lamp was well within the manufacturer's suggested safe limit of 176° Fahrenheit.
- There was a 90% reduction in light received by Sensors 1 and 2 when compared to the base case (see Figure 4-1-6b).
- The light received by Sensors 3 and 4 was decreased (see Figure 4-1-6b).
- Sensors 6 and 7 received less light when compared to the base case (see Figure 4-1-6b).

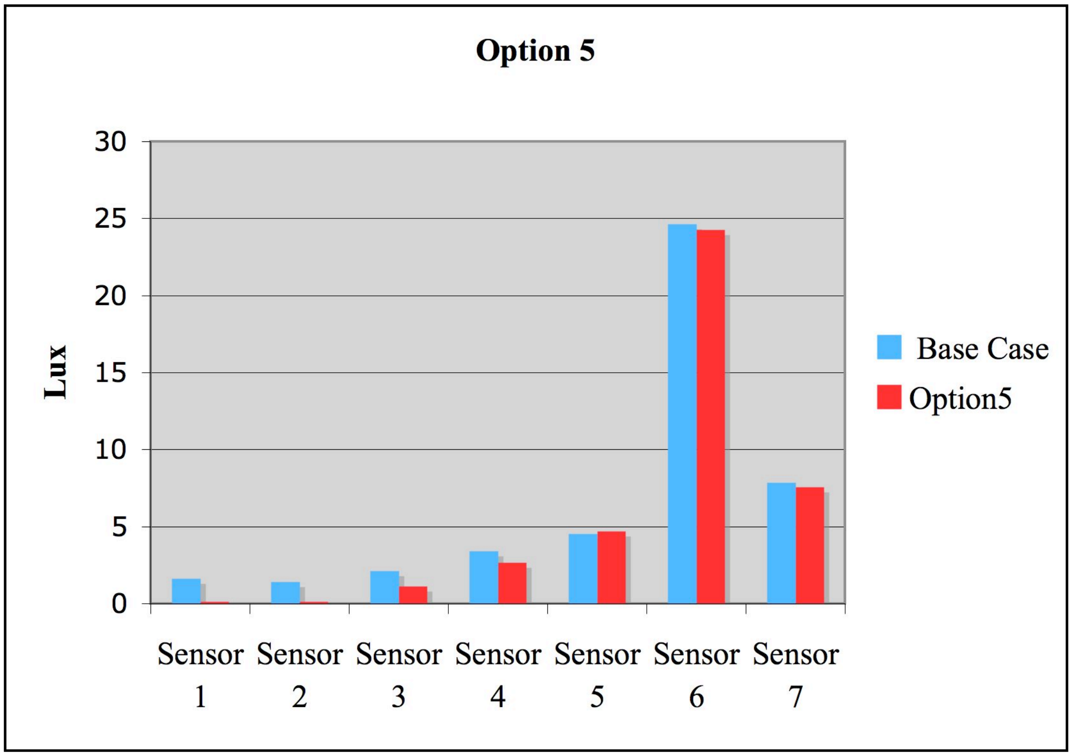


Figure 4-1-6b Photometric light distribution comparisons between base case & option 5

4-1-7 The performance of the Hokie light under two different temperature conditions

All of the experiments were carried out at a room temperature of approximately 60º F. This was assumed to be a typical summer nighttime temperature for Blacksburg.

It was desired to determine if changing the ambient temperature to 85º F would result in a significant change in light output or globe temperature.

For this, the room temperature for the test setup was adjusted to 85º F with the help of a room heater and the experiments were repeated for the base case, option 1 and option 2.

Table 4-1-7 Photometric light distribution for base case, option 1 and option 2 under two different temperature conditions.

(Lux)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Temp ºF (Bottom)	Temp ºF (Top)
Base Case (85º F)	1.52	1.41	2.20	3.71	4.96	25.06	8.33	104.21	90.97
Base Case (60º F)	1.61	1.40	2.11	3.42	4.52	24.64	7.85	101.45	83.19
% Difference	5.66	-0.85	-3.91	-7.66	-8.9	-1.68	-5.78	-2.65	-8.55
Option 1 (85º F)	2.52	2.08	1.95	2.18	2.35	26.73	9.21	135.03	112.4
Option 1 (60º F)	2.48	2.05	1.99	2.10	2.34	26.92	8.98	111.30	90.52
% Difference	-1.27	-1.44	2.21	-3.45	-0.34	0.72	-2.48	-17.57	-19.5
Option 2 (85º F)	0.71	0.43	1.27	2.78	4.76	25.61	8.34	133.44	111.6
Option 2 (60º F)	0.63	0.38	1.11	2.50	4.55	25.29	8.10	110.86	86.53
% Difference	-11.35	-11.62	-12.21	-9.83	-4.53	-1.23	-2.95	-16.92	-22.5

Observations

- The results indicated that for all options there was only marginal change in the light output and temperature of the Hokie light with the change in the ambient temperature.

  For the base case, the maximum percentage change was 8.9% for sensor 5 (refer to Figure 4-1-7a). For option 1 it was 3.45% for sensor 4 (refer to Figure 4-1-7b) and for option 2 it was 12.21% for sensor 3 (refer to Figure 4-1-7b). The change in the light output for the base case, option 1 and option 2 under different ambient temperature settings was little and was less than 0.5 lux for all the sensors.

- With the room temperature at 85º F, the inside temperature of the Hokie light was still within the manufacturer's suggested safe operating limits. The maximum temperature recorded for the base case was 104.21º F. For option 1 the maximum temperature recorded was 135.03º F and for option 2 133.44º F. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80°Centigrade or 176° Fahrenheit for optimum performance.

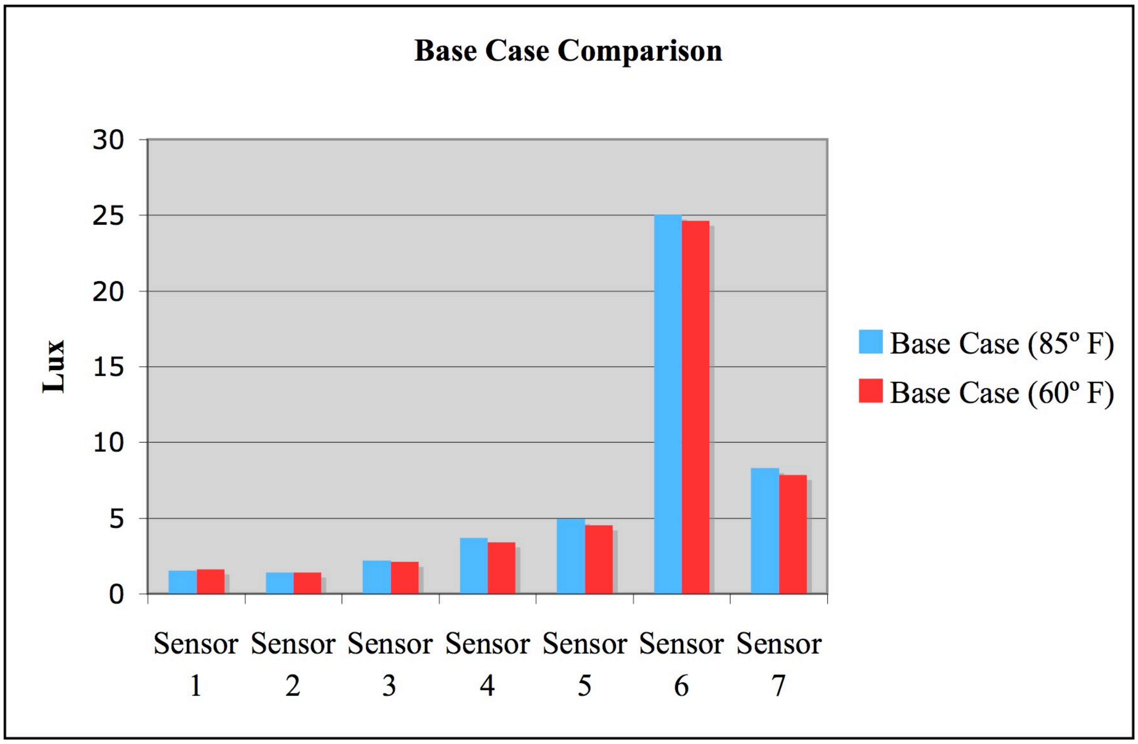


Figure 4-1-7a Photometric light distribution comparison for base case under two different temperature conditions.

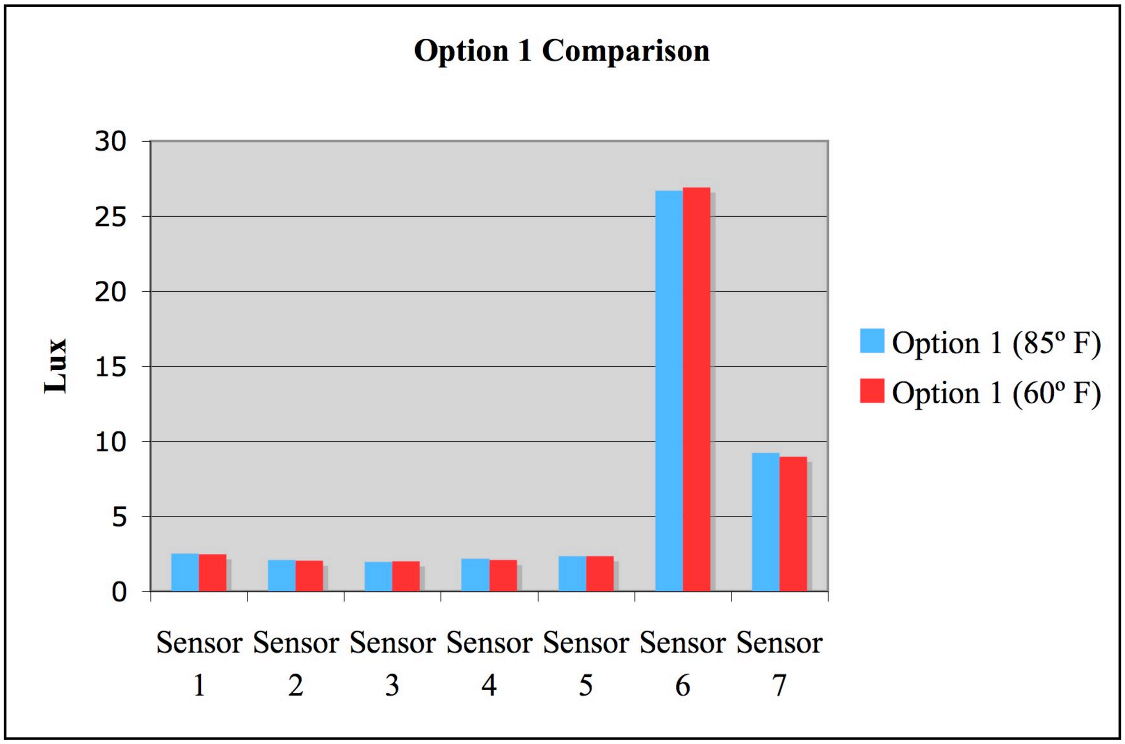


Figure 4-1-7b Photometric light distribution comparison for option 1 under two different conditions.

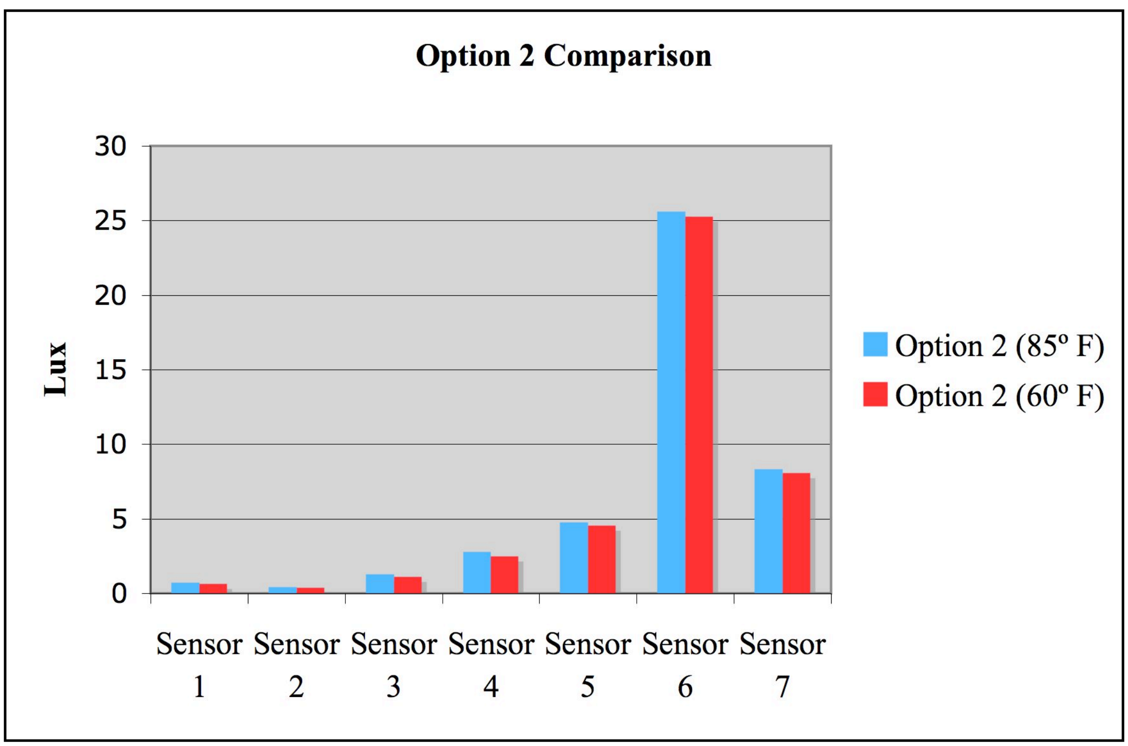


Figure 4-1-7c Photometric light distribution comparison for option 2 under two different temperature conditions.

4-1-8 Final comments concerning Hokie light experimentation

The datalogger used for this research was a Campbell Scientific 21X. It had nine input channels. Ideally it was desirable to have ten channels, eight for photosensors and two for thermocouples.

Since the datalogger had only nine input channels available, a compromise was made by not including photosensor 8 in the analysis.

The equation used to estimate the uplight percentage using data from the seven sensors is given in Equations 1 and 2.

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \times 100 \qquad \text{Equation 1}$$

The equation with 8 sensors will be,

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7+\mathbf{S8}} \times 100 \qquad \text{Equation 2}$$

where:

S1 to S4 are the sensor readings above the horizontal plane.

S1 to S7 are the sensor readings for all measured photometer locations.

Mathematically, the numerator is constant for equations 1 and 2, since in the actual installation sensor 8 corresponds to the location of the lamp post.

For the uplight calculation for this research, equation 1 was used.

4-2 Experimental Results for LED Analysis

Light Emitting Diodes (LEDs)

To evaluate the performance of iBright LED Fluorescent lamps for general illumination purposes in buildings on the Virginia Tech campus and to compare with standard T8 lamps, both were installed in a representative office (refer to Section 3-2-1).

The iBright lamps were tested for three performance mandates.

1 Quantitative (Illumination on the task surface)

2 Qualitative (Perception of light quality)

3 Energy usage (includes impact on HVAC)

4-2-1 Quantitative Analysis

For this investigation the change in light levels from T8 lamps and iBright lamps were measured and recorded.

The light levels were measured at a standard work desk height of 30 inches under T8 lamps and iBright lamps by using light meters.

Three Light Meters were used-

1) Center 337 Mini Light Meter (refer to Figure 3-2-2a)
2) GE Mini Light Meter (refer to Figure 3-2-2b).
3) Simpson Light Meter (Model 408) (refer to Figure 3-2-2c).

The first set of readings was taken using standard Philips T8 fluorescent lamps. Table 4-2-1a gives the light level measurements (fc) at standard work desk height at different times using T8 lamps. Measurements were taken with three light meters. Readings for each of the light meters were taken at 1200, 1215, 1230, 1245, 1300 hours. These five readings were taken every day during the same time of the day for all seven days of operation.

Table 4-2-1a Illumination level measurements using standard Philips T8 fluorescent lamps

Time	Date	Center 337 Mini Light Meter	GE Mini Light Meter	Simpson Light Meter (Model 408)
11:30 a.m.	12.19.2007	103.7fc	96fc	102fc
11:45 a.m.	12.19.2007	103.5fc	93fc	104fc
12:00 p.m.	12.19.2007	104.2fc	95fc	106fc
12:15 p.m.	12.19.2007	104fc	93fc	106fc
12:30 p.m.	12.19.2007	103.7fc	96fc	107fc
11:30 a.m.	12.20.2007	103.8fc	97fc	103fc
11:45 a.m.	12.20.2007	104.9fc	98fc	106fc
12:00 p.m.	12.20.2007	104.9fc	98fc	110fc
12:15 p.m.	12.20.2007	104.7fc	99fc	109fc
12:30 p.m.	12.20.2007	103.9fc	99fc	110fc
11:30 a.m.	01.02.2008	102.6fc	98fc	100fc
11:45 a.m.	01.02.2008	102.5fc	98fc	100fc
12:00 p.m.	01.02.2008	107.4fc	97fc	99fc
12:15 p.m.	01.02.2008	107fc	97fc	99fc
12:30 p.m.	01.02.2008	106.9fc	98fc	99fc
11:30 a.m.	01.03.2008	103.2fc	98fc	105fc
11:45 a.m.	01.03.2008	103.5fc	98fc	107fc
12:00 p.m.	01.03.2008	105.2fc	97fc	105fc
12:15 p.m.	01.03.2008	104.7fc	98fc	107fc
12:30 p.m.	01.03.2008	104.8fc	98fc	106fc
11:30 a.m.	01.04.2008	104.3fc	99fc	106fc
11:45 a.m.	01.04.2008	104.1fc	98fc	108fc
12:00 p.m.	01.04.2008	104.3fc	98fc	107fc
12:15 p.m.	01.04.2008	104.2fc	98fc	106fc
12:30 p.m.	01.04.2008	104fc	99fc	107fc
11:30 a.m.	01.07.2008	103.2fc	98fc	108fc
11:45 a.m.	01.07.2008	103.4fc	98fc	107fc
12:00 p.m.	01.07.2008	104.6fc	97fc	108fc
12:15 p.m.	01.07.2008	104.9fc	98fc	108fc
12:30 p.m.	01.07.2008	105.2fc	98fc	108fc
11:30 a.m.	01.08.2008	104.3fc	97fc	108fc
11:45 a.m.	01.08.2008	104.5fc	97fc	106fc
12:00 p.m.	01.08.2008	104.8fc	98fc	106fc

Time	Date	Center 337 Mini Light Meter	GE Mini Light Meter	Simpson Light Meter (Model 408)
12:15 p.m.	01.08.2008	104.7fc	98fc	107fc
12:30 p.m.	01.08.2008	104.7fc	98fc	107fc
Average Illumination Level		**104.4fc**	**97.4fc**	**105.6fc**

Comments

- Initially three light meters were used to measure the illumination levels in the selected space. However due to variation of the readings from the GE Mini Light Meter and Simpson Light Meter (Model 408) and their lack of recent calibration their readings were discarded.

- The recommended illumination for a typical office is 50 fc (Reference IES Standard 90.1-2001).

- With the fluorescent lamps installed the average illumination level for the entire set of readings was 104.4 fc.

- The office is over-designed in terms of illumination levels.

A second set of readings was taken using iBright LED fluorescent lamps.

Table 4-2-1b below gives the light level measurements (fc) at standard work desk height for different times using iBright lamps.

Measurements were taken with three light meters. Readings for each of the light meters were taken at 1200, 1215, 1230, 1245, 1300 hours. These five readings were taken every day during the same time of the day for all seven days of operation.

Table 4-2-1b Illumination level measurements using standard iBright LED lamps

Time	Date	Center 337 Mini Light Meter	GE Mini Light Meter	Simpson Light Meter (Model 408)
11:30 a.m.	01.11.2008	53fc	82fc	60fc
11:45 a.m.	01.11.2008	52.5fc	81fc	61fc
12:00 p.m.	01.11.2008	53.2fc	81fc	61fc
12:15 p.m.	01.11.2008	53fc	82fc	62fc
12:30 p.m.	01.11.2008	53.2fc	81fc	61fc
11:30 a.m.	01.14.2008	53.3fc	82fc	65fc
11:45 a.m.	01.14.2008	53.5fc	81fc	65fc
12:00 p.m.	01.14.2008	53.6fc	81fc	64fc
12:15 p.m.	01.14.2008	53.2fc	82fc	64fc
12:30 p.m.	01.14.2008	52.8fc	82fc	64fc
11:30 a.m.	01.15.2008	53.7fc	81fc	66fc
11:45 a.m.	01.15.2008	53.8fc	82fc	66fc
12:00 p.m.	01.15.2008	53.8fc	82fc	65fc
12:15 p.m.	01.15.2008	54fc	81fc	65fc
12:30 p.m.	01.15.2008	53.7fc	81fc	65fc
11:30 a.m.	01.16.2008	54.3fc	82fc	65fc
11:45 a.m.	01.16.2008	53.9fc	82fc	66fc
12:00 p.m.	01.16.2008	54.1fc	81fc	65fc
12:15 p.m.	01.16.2008	53.8fc	81fc	66fc
12:30 p.m.	01.16.2008	53.9fc	82fc	66fc
11:30 a.m.	01.18.2008	54.3fc	81fc	65fc
11:45 a.m.	01.18.2008	54.6fc	82fc	65fc
12:00 p.m.	01.18.2008	54.7fc	81fc	65fc
12:15 p.m.	01.18.2008	54.5fc	82fc	65fc
12:30 p.m.	01.18.2008	53.5fc	81fc	65fc
11:30 a.m.	01.22.2008	54.7fc	82fc	66fc
11:45 a.m.	01.22.2008	54.8fc	81fc	66fc
12:00 p.m.	01.22.2008	54.1fc	82fc	66fc
12:15 p.m.	01.22.2008	54.3fc	81fc	66fc
12:30 p.m.	01.22.2008	53.7fc	82fc	66fc
11:30 a.m.	01.23.2008	54.8fc	81fc	66fc
11:45 a.m.	01.23.2008	54.6fc	81fc	66fc

Time	Date	Center 337 Mini Light Meter	GE Mini Light Meter	Simpson Light Meter (Model 408)
12:00 p.m.	01.23.2008	55fc	81fc	66fc
12:15 p.m.	01.23.2008	54.9fc	81fc	66fc
12:30 p.m.	01.23.2008	54.8fc	81fc	66fc
Average Illumination Level		**53.9fc**	**81.4fc**	**64.9fc**

Comments

- Initially three light meters were used to measure the illumination levels in the selected space. However due to variation of the readings from the GE Mini Light Meter and Simpson Light Meter (Model 408) and their lack of recent calibration their readings were discarded.
- The recommended illumination for a typical office is 50 fc (Reference IES Standard 90.1-2001).
- The average illumination level with the iBright LED fluorescent lamps installed for the entire set of readings was 53.9 fc.
- With depreciation of the lumen output the office would be under-designed in terms of illumination levels.

4-2-2 Pictorial Comparison of Room with LED and T8 Lamps

Figure 4-2-2a Office with
Philips T8 fluorescent lamps
(Photo by author, 2008)

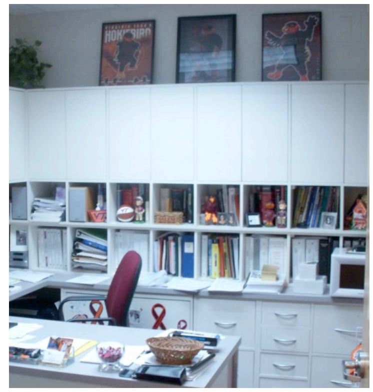


Figure 4-2-2b Office with
iBright LED fluorescent lamps
(Photo by author, 2008)

4-2-3 Qualitative Analysis

For the qualitative analysis the perception of colors or quality of light was compared for LED and T8 lamps.

A 8.5" x 11" color chart comprising a wide spectrum of colors was prepared and placed directly below the lights on the work desk. The digital pictures of the chart were taken on each of seven days with a camera focal distance of 1.5 feet. Pictures were taken using a Nikon CoolPix S50c digital camera.

The rated life for Philips T8 fluorescent lamps and iBright LED fluorescent lamps is more than 50,000 hours. Therefore it was assumed that the lumen depreciation for T8 lamps and for iBright lamps should be insignificant for the experimental analysis.

Figure 4-2-3a and Figure 4-2-3b show the pictures of the color chart taken under T8 lamps and iBright lamps respectively. All 7 pictures under T8 and iBright lamps were similar to one another. Therefore any one of the pictures of the color chart could be used for comparison purposes.

For this study, the picture of the color chart taken under T8 lamps on 01.08.2008 was compared with the picture of the color chart taken under iBright lamps on 01.23.2008.

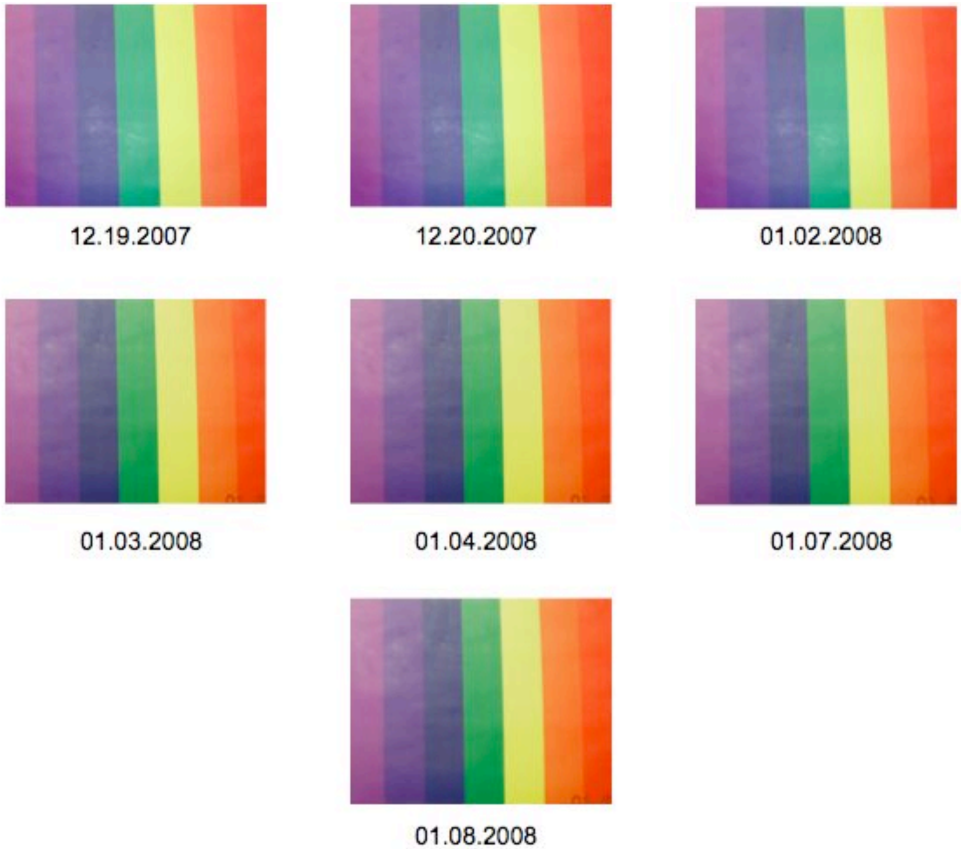


Figure 4-2-3a Color charts under Philips Alto T8 lamps (Photo by author, 2008)

Figure 4-2-3b Color charts under iBright LED fluorescent lamps (Photo by author, 2008)

4-2-4 Pictorial Comparison of Color Chart Under T8 and LED Lamps

Figure 4-2-4a Color chart under Philips Alto T8 lamps (Photo by author, 2008)

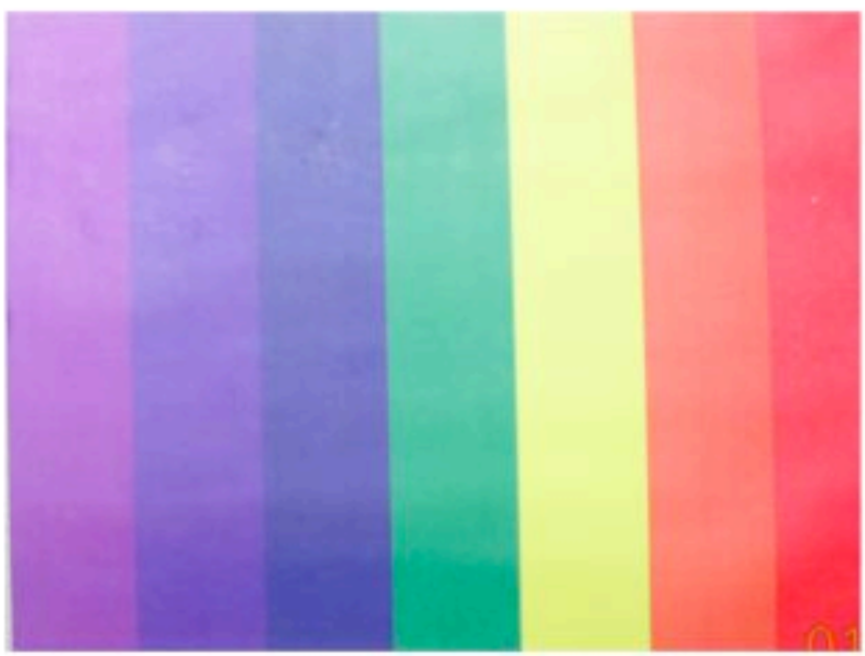


Figure 4-2-4b Color chart under iBright LED fluorescent lamps (Photo by author, 2008)

4-2-5 eQuest Simulation Results for Cases (a), (b), (c) and (d)

The ICTAS building was divided into four different thermal zones (refer to Figure 3-2-4-8) based upon the activities carried out. Four cases were analyzed using this zoning scheme:

a) The ICTAS building *without* daylight controls and standard T-8 lamps.

b) The ICTAS building *with* daylight controls and standard T-8 lamps.

c) The ICTAS building *without* daylight controls and LED fluorescent lamps.

d) The ICTAS building *with* daylight controls and LED fluorescent lamps.

For cases (a), (b), (c) and (d) annual utility bills were calculated using hourly simulation with the eQuest software. The following summarized the results.

Table 4-2-5 eQuest simulation results for cases (a), (b), (c) and (d)

	Case (a) without DL/T8	Case (b) with DL/T8	Case (c) without DL/LED	Case (d) with DL/LED
Custom Electric Rate $/year	214,367	194,960	212,071 Case (a)- Case (c) 2296	194,817 Case (b)- Case (d) 143
Custom Gas Rate $/year	75,771	71,670	76,422 Case (a)- Case (c) -651	72,706 Case (b)- Case (d) -1036
Total $/year	290,138	266,630	288,493 Case (a)- Case (c) 1645	267,523 Case (b)- Case (d) -893

Based upon the results obtained from the Sections 4-2-1, 4-2-2, 4-2-3, 4-2-4 and 4-2-5 general observations were made and classified below under quantitative observations, qualitative observations and energy usage comparison.

4-2-6 Observations

Quantitative Observations

- Though the illumination level was reduced to half the original value with LED lamps as compared to T8 lamps, the reduced illumination levels were still near the recommended illumination level for an office.

- The manufacturer suggests that the LED lamps should not be operated for more than 12 hours at a time. This may limit the application of the lamps.

Qualitative Observations

- The light from the LED lamps was perceived to be a bit more blue in appearance when compared to the T8 lamps.

- The colors looked brighter and more saturated under the T8 lights.

Energy Usage Comparison

- It was hypothesized that the annual utility bills for the ICTAS building should have been less with LED lamps because of their lower power consumption. However because the lumen output of the LED lamps is only about half of output of the Philips Alto T8 lamps, two iBright LED lamps were needed to maintain an equivalent illumination level. Therefore the total wattage consumption for the iBright LED lamps was 30W, which was only 2W less than the Philips Alto T8 lamps. As a result, there was little difference between the utility bills for case (a) and case (c), and for cases (b) and (d). However the utility bill was lowest for case (b), which was not surprising because LED lamps generate more heat as compared to the fluorescent lamps.

  As from Table 4-2-5, the predicted annual utility bill for the ICTAS building was least for case (b) from all the cases simulated in eQuest simulation software.

Chapter 5 - Analysis and Recommendations

The goal of this research study was to assist Virginia Tech in its pursuit of energy efficient and environmentally sensitive buildings. The Virginia Tech administration supported the research of alternative interior and exterior lighting solutions for improved lighting system performance. This research is a direct response to this goal to improve the light distribution of the "Hokie" light and determine the cost/benefit of general LED lighting on campus. This section presents the findings for the study of 1) the Hokie light and 2) application of LED lamps, and makes suitable recommendations in the following sections.

5-1 Hokie Light

To reduce the uplight distribution from the Hokie light several options were evaluated, discussed and commented upon (refer to Section 2-1-6). Based on careful analysis the following options were chosen:

Option 1 - Cover the upper part of the globe on the outside (refer to Section 2-1-6).

Option 2 - Replace the perforated LiteLid® inside the globe with a non-perforated LiteLid® to decrease the uplight (refer to Section 2-1-6).

Option 3 – Apply reflective paint to the tip of the 100W HPS lamp (refer to Section 2-1-6).

Option 4 – Apply reflective paint to the inside of the top of the globe (refer to Section 2-1-6).

Option 5 – Apply reflective paint to the inside surface of the top of the globe with non-perforated aluminum LiteLid® (refer to Section 4-1-6, Figure 4-1-6).

To evaluate the efficacy of these design options experiments were conducted in the Environmental Systems Laboratory on Prices Fork Road, Blacksburg (refer to Section 3-1-1).

The results for all the above options are discussed and listed in Section 4-1.

5-1-1 Comparison of light distribution for all options

Figure 5-1-1 below presents a 3D representation of the results for the photometric light distribution for options 1, 2, 3, 4 and 5. The height of the graph represents the amount of light received by the sensors from 1 to 7 in Lux.

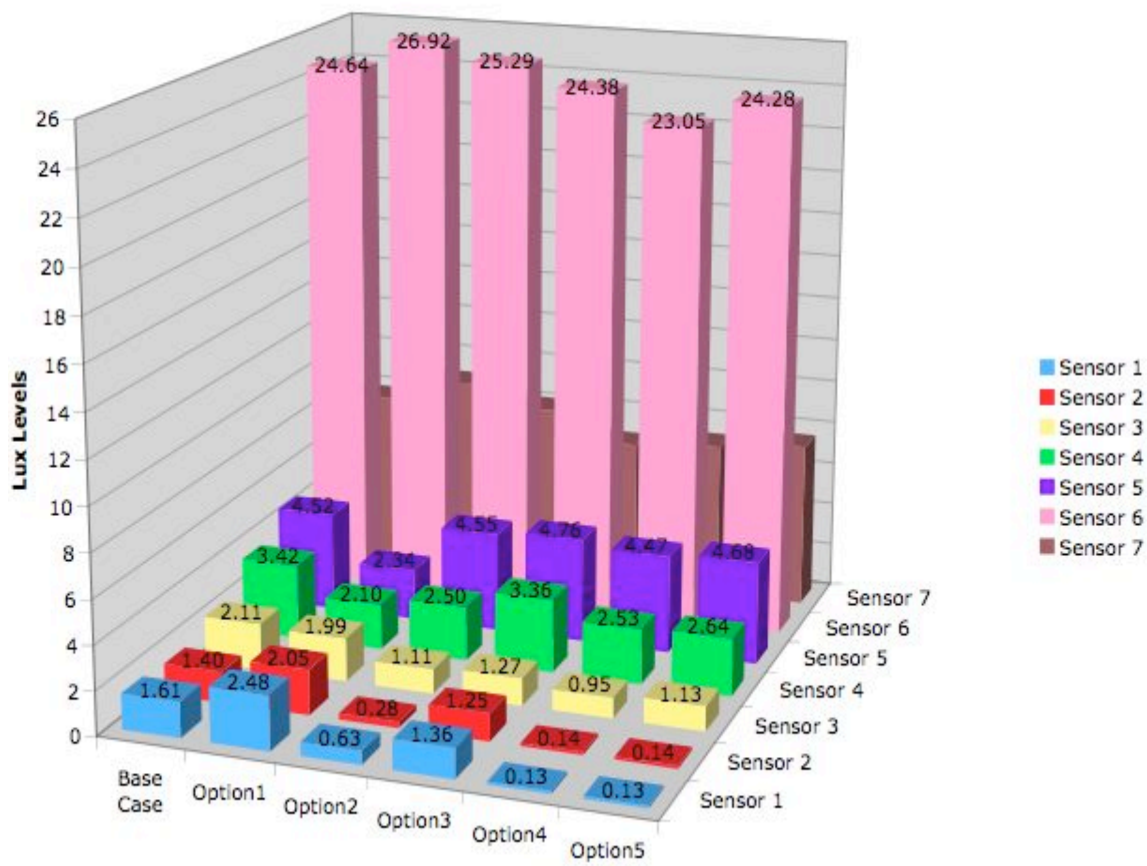


Figure 5-1-1 Comparison of light distribution for all options

Analysis

The aim of the experiments was to identify an option that reduced the uplight and redirected light downwards.

Mathematically the uplight was calculated by the equation:

$$\text{Percentage Uplight} = \frac{S1+S2+S3+S4}{S1+S2+S3+S4+S5+S6+S7} \times 100$$

Refer to Section 3-1-6 for more details. As per the above equation the lesser light readings for sensors 1, 2, 3 and 4 would indicate lesser uplight. Similarly increase in the readings for sensors 5, 6 and 7 would suggest the increase in downward efficiency.

Option 1- The uplight was only marginally reduced from the base case. Sensor 1 received 54.7% and Sensor 2 received 46.43% more light than the base case. This might be because of internal reflections caused by the blocking of light by the 3” aluminum strip around the globe. There wasn’t much reduction in the light received by Sensor 3. It decreased by only 5.68% as compared to the base case. But for Sensor 4, there was a reduction in the amount of light received by 38.63%. For Sensor 5 this option was counterproductive as it decreased the light by more than 48%. Downlight was increased by 9.23% and 14.45% for Sensor 6 and Sensor 7 respectively (refer to Section 4-1-2, Table 4-1-2, Figure 4-1-2c).

Option 2- The uplight distribution was reduced when compared to the base case.
The light received by Sensor 1, Sensor 2, Sensor 3, and Sensor 4 was decreased by 61.06%, 80.14%, 47.28% and 26.83% respectively when compared to the base case. Downlight was also increased by 0.55%, 2.63%, 3.16% for Sensor 5, Sensor 6 and Sensor 7 respectively (refer to Section 4-1-3, Table 4-1-3, Figure 4-1-3d).

Option 3- The distribution of uplight was reduced only marginally when compared to the base case. The light received by Sensor 1, Sensor 2, Sensor 3, and Sensor 4 was decreased by 15.14%, 10.64%, 39.90% and 1.87% respectively when compared to the base case. Downlight was increased only for Sensor 5 by 5.22%. For Sensor 6 and Sensor 7 downlight was decreased by 1.06% and 13.38% respectively (refer to Section 4-1-4, Table 4-1-4, Figure 4-1-4c).

Option 4- The uplight distribution was reduced when compared to the base case.
There was a 90% reduction in light received by Sensor 1 and Sensor 2 when compared to the base case. The light received by Sensor 3 and Sensor 4 was decreased by 55.04% and 26.01%. Downlight was also decreased by 1.26%, 6.49%, and 8.79% for Sensor 5, Sensor 6 and Sensor 7 respectively (refer to Section 4-1-5, Table 4-1-5, Figure 4-1-5b).

Option 5- The distribution of uplight was reduced when compared to the base case.
There was a 90% reduction in light received by the Sensor 1 and Sensor 2 when compared to the base case. The light received by Sensor 3 and Sensor 4 was decreased by 1.13% and 2.64%. Downlight was increased only for Sensor 5 by 3.49%. For Sensor 6 and Sensor 7 downlight was decreased by 1.49% and 3.44% respectively (refer to Section 4-1-6, Table 4-1-6, Figure 4-1-6b).

Only option 2, 4 and 5 showed considerable reduction in the uplight levels as compared to the base case. For options 2, 3 and 5 the downlight level was increased which makes them good options for retrofitting.

5-1-2 Temperature measurements comparison for all option

In addition to the light distribution the globe temperature characteristics were also experimentally determined for options 1, 2, 3, 4 and 5 (refer to Section 4-1). They were measured by using two copper-constantan thermocouples placed at the top and the bottom of the Hokie light (refer to Figure 4-1-1a).

Figure 5-1-2 shows the 3D representation of the results for the temperature measurements for options 1, 2, 3, 4 and 5. The height of the graph represents the temperature measured inside the Hokie light in degrees Fahrenheit.

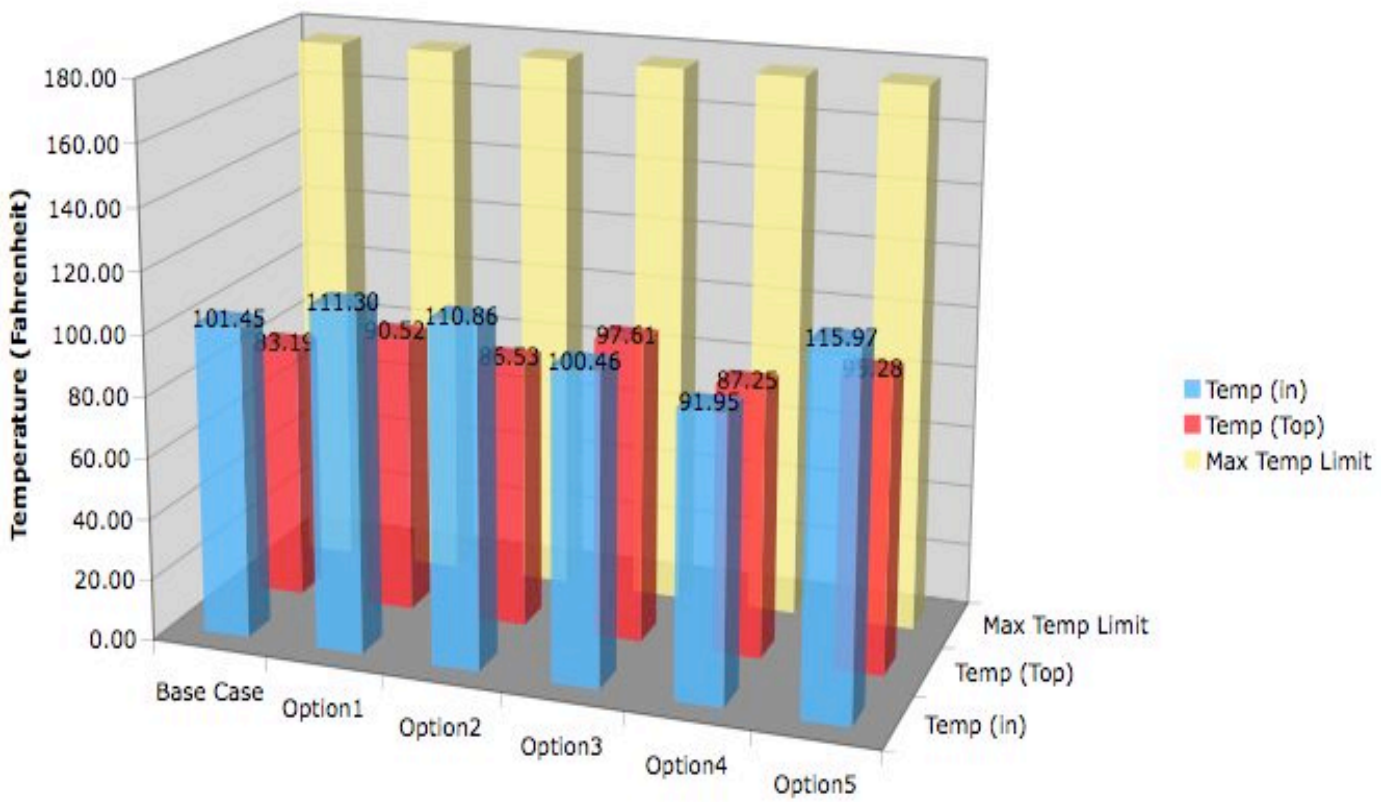


Figure 5-1-2 Temperature measurements comparison of all the options

The material of the globe is clear molded acrylic. As per the product catalogue, the surface temperature of the acrylic refractor should not exceed 80° Centigrade or 176° Fahrenheit for optimum performance.

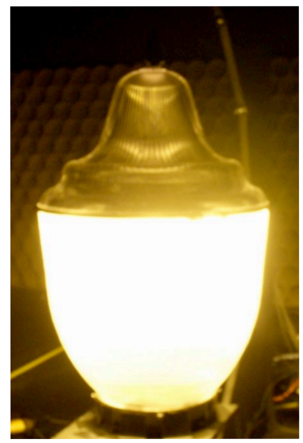
As shown in Figure 5-1-2 the temperatures inside the Hokie light were well below the 176º F upper limit for all of the options tested. Particularly for option 2, it was determined that by using the non-perforated LiteLid® instead of the perforated LiteLid® the temperature was not significantly greater.

Even with the room temperature at 85º F, the inside temperature of the Hokie light was still well within the manufacturer's suggested safe operating limits. The maximum temperature recorded for the base case was 104.21º F. For option 1 the maximum temperature recorded was 135.03º F and for option 2 it was 133.44º F (refer to Table 4-1-7).

5-1-3 Pictorial comparisons of the retrofit options


Base case


Option 1


Option 2


Option 3


Option 4

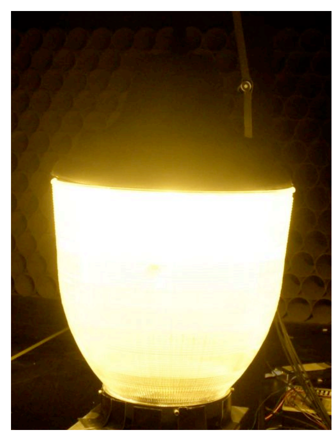

Option 5

Figure 5-1-3 Pictorial comparisons of the retrofit options (Photo by author, 2008)

5-1-4 Performance Matrix

Criteria were established for deciding among the options for retrofitting the Hokie light; these included:

Inside Temperature

The temperature inside the Hokie light globe should not exceed 80°Centigrade or 176° Fahrenheit for optimum performance.

Workability

The selected option for retrofit should not only considerably reduce the uplight but should also be easily replicated to the thousands of Hokie lights on the Virginia Tech campus.

Daytime Appearance

Due to its presence on campus the daytime appearance of the Hokie light is absolutely critical. Ideally the option for retrofit should not be overtly noticeable.

Nighttime Appearance

The selected retrofit option should not only increase downward output of light but should also allow sufficient uplight for the full shape of the globe to be visible at night.

Maintenance

The selected retrofit option should be low maintenance.

Uplight

The selected retrofit option should significantly decrease the uplight from the Hokie light and should increase the downward directed light output.

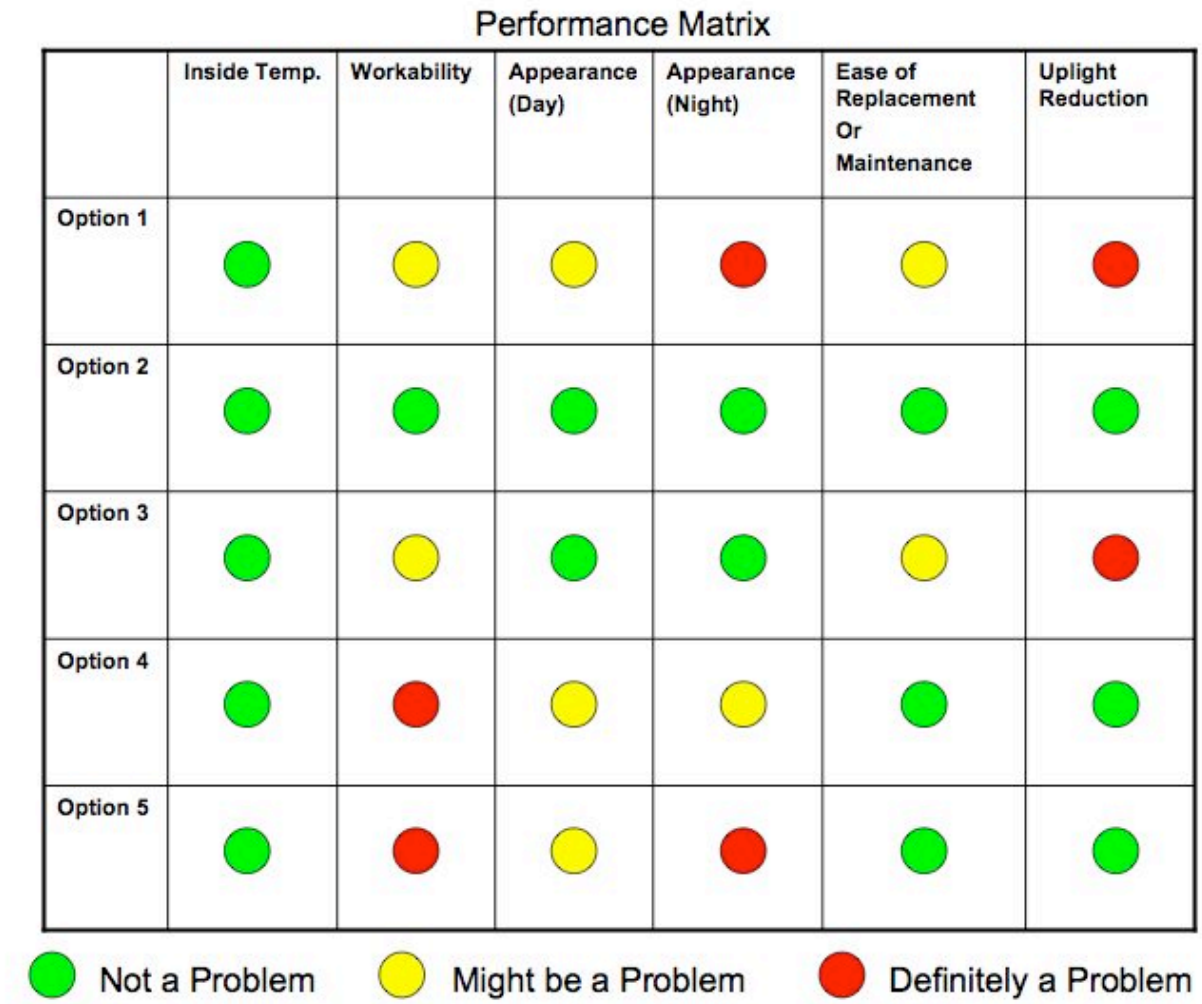


Figure 5-1-4 Performance matrix for the Hokie light retrofit options

Option 1

In this option it was expected that by covering the top of the bottom section of the Hokie light, the amount of light distributed above the horizontal plane would be reduced. Therefore a 3” wide strip of aluminum foil was used and wrapped around the top of the bottom section of the Hokie light (refer to Section 2-1-6, Figure 4-1-2a and Figure 4-1-2b).

The experiment was conducted in the Environmental Systems Laboratory on Prices Fork Road, Blacksburg (refer to Section 3-1-1). The room for this test set up was dark and devoid of any natural light. The walls of the experimental room were painted black to minimize light reflection. The only window in the room was also blocked with 1/8th inch thick black foam board. Therefore it was assumed that the Hokie light was the only light source.

Inside Temperature

The maximum temperature recorded for this option was 112.25º F and this was below the maximum safe temperature limit of 176º F. So it may be inferred that the temperature inside the globe was *not an issue* for this option.

Workability

For the purpose of conducting the experiments, aluminum foil was used because it was easy to work with and was readily available.

The primary aim of this investigation was to determine if this option would reduce the uplight as a result of the addition of the 3-inch strip. If this option were used for retrofitting of the Hokie light then issues like the final material for the strip, color of the strip or the method of attaching the strip would become important.

For this research the above-mentioned issues were not addressed in great detail. Therefore the workability of the material used for this option *might or might not be an issue*.

Daytime Appearance

The appearance of the Hokie light with the 3-inch strip looks good with aluminum foil. The foil can be painted a brown color to complement the color of the post for the Hokie light. But since the actual material of the strip was not tested, the daytime appearance of the Hokie light with 3-inch aluminum strip *might or might not be an issue*.

Nighttime Appearance

The 3-inch aluminum strip around the Hokie light was responsible for internal reflection inside the globe. Therefore there was more light in the vertical direction as compared to the original base case. This was evident from the readings of sensor 1 and sensor 2. Sensor 1 received 54.7% and Sensor 2 received 46.43% more light than the base case (refer to Table 4-1-2, Figure 4-1-2c). There was more than sufficient uplight for the full shape of the globe to be visible at night. This selected retrofit option would contribute more towards light pollution as compared to the base case performance. Therefore nighttime appearance with this option was *definitely an issue.*

Maintenance

Aluminum foil was used for the purpose of conducting the experiments. The actual material for this retrofit option was not determined.

Therefore the maintenance of the material *might or might not be an issue* for this option.

Uplight Distribution

The selected retrofit option decreased the uplight from the Hokie light by only 0.36 % and didn't increase the downward directed light output. Therefore the uplight was *not significantly decreased*.

Option 2

Currently the perforated LiteLid® is placed in between the top and bottom components inside the Hokie light to redirect the uplight and to increase the downlight. The idea of using the perforated LiteLid® is that the temperature inside the globe can be controlled and the heat generated inside can escape. But when looking at the globe closely it was found that there is no outlet for the heat to escape. Therefore for experimental purposes, the LiteLid® and its perforations were covered with aluminum foil because aluminum foil was easy to work with, had reflective properties and was readily available (refer to Section 2-1-6, Figure 4-1-3a and Figure 4-1-3b).

Inside Temperature

The maximum temperature recorded for this option was 111.24º F and this was below the maximum safe temperature limit of 176º F. So it may be inferred that the temperature inside the globe was *not an issue* for this option.

Workability

For the purpose of conducting the experiments, the perforated LiteLid® was wrapped with aluminum foil because it was easy to work with and was readily available.

For actual retrofit the non-perforated LiteLid® is commercially available. The replacement could be done easily by taking out the top of the Hokie light and by replacing the perforated LiteLid® with the non-perforated LiteLid®.

Therefore the workability with this option was *not an issue*.

Daytime Appearance

The outward appearance of the Hokie light was unaffected in this retrofit option because the perforated LiteLid® was internally replaced with the non-perforated LiteLid®.

Therefore the daytime appearance of the Hokie light was *not an issue*.

Nighttime Appearance

This retrofit option allowed sufficient uplight for the full shape of the globe to be visible at night.

The nighttime appearance of the Hokie light was enhanced from the original base case. Therefore it was *not an issue*.

Maintenance

After replacing the perforated LiteLid® with a non-perforated LiteLid®, this retrofit option did not require further maintenance.

Therefore maintenance was *not an issue*.

Uplight Distribution

The selected retrofit option decreased the uplight from the Hokie light by 8.11% and also increased the downward directed light output.

Therefore the uplight was *improved*.

Option 3

It was expected that by painting the tip of the bulb with reflective paint the light distribution in the upward direction would be reduced by reflecting it downward (refer to Section 2-1-6, Figure 4-1-4a and Figure 4-1-4b).

The paint selected for this option was the Quartz-Coat(TM) 845-Silver by Aremco Products.

Quartz-Coat(TM) 845-Silver was selected because it had reflective properties, it was easy to work with, it was inexpensive, and it had the ability to withstand high temperatures.

Inside Temperature

The maximum temperature recorded for this option was 101º F and this was well below the maximum safe temperature limit of 176º F. So it may be inferred that the temperature inside the globe was *not an issue* for this option.

Workability

As per the product catalogue specifications for the Quartz-Coat (TM) 845-Silver Paint, the paint should be cured at a temperature of 900º F- 1000º F. But due to lack of availability of a high temperature furnace, a normal kitchen oven was used with a maximum temperature setting of 450º F.

Workability with this retrofit option depends upon an availability of a high temperature furnace.

Therefore workability *might or might not be an issue* with this option.

Daytime Appearance

This option required replacing the existing 100W HPS bulb with the 100W HPS bulb whose tip was painted with Quartz-Coat(TM) 845-Silver paint. The outward appearance of the Hokie Light was unaffected with this option.

Therefore the daytime appearance of the Hokie light was *not an issue*.

Nighttime Appearance

This retrofit option allowed sufficient uplight for the full shape of the globe to be visible at night.

The nighttime appearance of the Hokie light was enhanced from the original base case. Therefore this performance issue was *not a concern*.

Maintenance

Replacing a lamp in the Hokie light is easily accomplished. But to replace a lamp, whose tip is painted, requires planning as the lamps in stock should be cured and painted in advance.

It is unknown if the paint degrades with age. Therefore maintenance *might or might not be an issue* with this option.

Uplight Distribution

The selected retrofit option decreased the uplight from the Hokie light by only 1.99 % and didn't increase the downward directed light output.

Therefore the uplight was *not significantly decreased*.

Option 4

It was expected that applying reflective paint on the inside of the top of the globe would reduce the light distribution in the upward direction by reflecting light downward (refer to Section 2-1-6, Figure 4-1-5a).

The paint selected for this option was the Corr-Paint CP2010 Aluminum by Aremco Products. Corr-Paint CP2010 Aluminum was selected because it had reflective properties, it was easy to work with, it was inexpensive, it had the ability to withstand high temperatures and it was light in color so that it gave a pleasant look to the Hokie light and complemented the Virginia Tech surroundings.

Inside Temperature

The maximum temperature recorded for this option was 92.72º F and this was well below the maximum safe temperature limit of 176º F. So it may be inferred that the temperature inside the globe was *not an issue* for this option.

Workability

As per the product catalogue specifications for the Corr-Paint CP2010 Aluminum, the paint should be cured at a temperature of 200º F. For this a normal kitchen oven was used.

The globe of the Hokie light is made of acrylic and the melting point of acrylic is 266º F. Though the top of the globe was cured below the melting point of the acrylic there was noticeable deformation in the material. The deformation was such that the top of the globe did not fit properly when reinstalled.

Therefore workability was *definitely an issue* with this option.

Daytime Appearance

The Corr-Paint CP2010 Aluminum is dark grey in appearance. During the daytime it could be noticeable because of its different color from the Hokie light.

It could also be looked upon as if it is complementing the grey color of the Hokie stone in the Virginia Tech buildings.

Therefore the daytime appearance of the Hokie light with CP2010 Aluminum paint on its top *might or might not be a problem*.

Nighttime Appearance

The Hokie light with CP2010 Aluminum painted inside the top of the globe looked pleasant at night. But the shape of the globe was not clearly visible.

Therefore the nighttime appearance of the Hokie light with this retrofit option *might or might not be an issue*.

Maintenance

The paint sets permanently to the globe of the Hokie light after it is cured at the recommended temperature of 200º F.

Therefore the maintenance of the globe with the CP2010 Aluminum paint was *not thought to be an issue*.

Uplight Distribution

The selected retrofit option decreased the uplight from the Hokie light by 9 % but didn't increase the downward directed light output.

Therefore the uplight was *noticeably reduced for* this option.

Option 5

This retrofit option involved application of the reflective paint on the inside surface of the top of the globe with the non-perforated aluminum LiteLid®.

Since the results from options 2 and 4 were favorable, option 5 was explored as a combination of these two options (refer to Section 4-1-6, Figure 4-1-6a).

Inside Temperature

The maximum temperature recorded for this option was 116.52º F and this was below the maximum safe temperature limit of 176º F. So it may be inferred that the temperature inside the globe was *not an issue* for this option.

Workability

This option was a combination of option 2 (refer to Section 2-1-6) and option 4 (refer to Section 2-1-6).

As per the product catalogue specifications for the Corr-Paint CP2010 Aluminum in option 4, the paint should be cured at a temperature of 200º F. For this a normal kitchen oven was used.

The globe of the Hokie light is made up of acrylic and the melting point of acrylic is 266º F. Though the top of the globe was cured below the melting point of the acrylic there was noticeable deformation in the material. The deformation was such that the top of the globe did not fit properly when reinstalled.

Therefore workability is *definitely an issue* with this option.

Daytime Appearance

In option 2, the internal replacement of the perforated LiteLid® with the non-perforated LiteLid® resulted in no noticeable change in the outward appearance of the Hokie light.

In option 4, the Corr-Paint CP2010 Aluminum is dark grey in appearance. During the daytime this treatment of the globe could be noticeable because of its different color from the Hokie light. It might also be looked upon as complementing the grey color of the Hokie stone on the Virginia Tech campus.

Therefore the daytime appearance of the Hokie light with this retrofit option *might or might not be an issue*.

Nighttime Appearance

The use of the non-perforated LiteLid® and the CP2010 Aluminum paint inside the globe reduces uplight distribution resulting in a darker upper globe when compared to the base case. In fact from a distance the top of the globe was not visible and the Hokie light looked truncated.

Therefore the nighttime appearance of the Hokie light with the combination of option 2 and option 4 was *definitely an issue.*

Maintenance

For option 2, after replacing the perforated LiteLid® with a non-perforated LiteLid®, no further maintenance was required.

Therefore maintenance was *not thought to be an issue*.

For option 4, the paint sets permanently to the globe of the Hokie light after it being cured at the recommended temperature of 200º F. Therefore the maintenance of the globe with the CP2010 Aluminum paint was *not thought to be an issue*.

Uplight Distribution

The selected retrofit option decreased the uplight from the Hokie light by 8.8 % when compared to the base case but did not increase the downward directed light output.

5-1-5 Recommendations

The objective of this research study was to decrease the uplight from Hokie light to meet the LEED-EB criteria. Currently the Hokie light throws a high percentage of light upward. As per the product literature the uplight is 14% of the total light output by the lamp. One of the objectives of this research was to reduce the percentage of uplight from 14% to below 5%. If this were achieved, it was believed that the solution would also be eligible for points in the U.S. Green Building Council's LEED-EB (Version-2) building rating system. Therefore a series of experiments were undertaken to evaluate the photometric light distribution of several Hokie light alteration strategies in an effort to identify the most cost effective solution (refer to Section 4-1).

After analyzing the performance of a variety of options, use of a non-perforated aluminum LiteLid® (option 2) was selected as the most promising though it did not meet the LEED-EB criteria. The benefits from option 2 include:

- The temperature inside the Hokie light is under the safe limit. This suggests that the globe of the Hokie light will not get yellowed over its lifetime and therefore it will maintain the constant downlight performance.

- It is easy to replace the perforated LiteLid® with non-perforated LiteLid®. The replacement can be done easily by taking out the top of the Hokie light and by replacing the perforated LiteLid® with the non-perforated LiteLid®.

- It does not affect the daytime appearance of the Hokie light because the perforated LiteLid® is internally replaced with the non-perforated LiteLid®.

- It has a pleasant nighttime appearance. This retrofit option allowed sufficient uplight for the full shape of the globe to be visible at night.

- It requires little or no maintenance beyond the current solution. After replacing the perforated LiteLid® with a non-perforated LiteLid®, this retrofit option does not require further maintenance.

- The uplight distribution with non-perforated LiteLid® is 10.64%. To get one credit point in the U.S. Green Building Council's LEED-EB (Version-2) building rating system the uplight should not be more than 5%. Though this option does not bring the uplight distribution below 5%, it reduced the uplight by 8.11% when compared to the current solution.

5-1-6 Future Scope

It could be hypothesized that combinations of certain options might help in reducing the uplight. For this research only the combination of option 2 and option 4 was studied. Other combinations of options could also be tried out to determine if performance could be further improved.

5-2 LED Lamps

To explore the possibility of using LED lamps for general illumination in buildings on the Virginia Tech campus several LED lamps were considered (refer to Section 2-2). After careful analysis it was decided to evaluate the performance of the iBright LED lamp. The iBright lamps were tested for three performance aspects.

1. Quantitative- For this the light levels were measured and compared for T8 lamps and iBright lamps (refer to Section 4-2-1).

2. Qualitative- For this perceptual differences in color rendition and light quality were compared for the T8 and LED lamps (refer to Section 4-2-3).

3. Electrical energy usage- Utility charges for a representative building on the campus of Virginia Tech were estimated by using the eQuest software with standard Philips Alto T8 fluorescent lamps and iBright LED lamps (refer to Section 3-2 and Section 4-2-5). The building chosen for the analysis was the recently constructed Institute for Critical Technology and Applied Sciences (ICTAS). Four cases were analyzed for the ICTAS building:

a) The ICTAS building *without* daylight controls and standard T-8 lamps.

b) The ICTAS building *with* daylight controls and standard T-8 lamps.

c) The ICTAS building *without* daylight controls and LED fluorescent lamps.

d) The ICTAS building *with* daylight controls and LED fluorescent lamps.

5-2-1 Analysis

The following analyses were done based upon the results obtained and presented in Sections 4-2-1, 4-2-2,4-2-3, 4-2-4 and 4-2-5:

1. The lumen output of the Philips T8 lamps is 2850 lumens, which is more than double the output of the iBright LED lamps (1290 lumens). Therefore to maintain the same light level as with the T8 lamps two LED lamps are required for each T8 lamp. Retrofitting with iBright lamps on the Virginia Tech campus would mean doubling the number of lamps in comparison to the Philips T8 lamps (refer to Table 5-2-1a and Table 5-2-1b).

Figure 5-2-1a presents a reflected ceiling plan of the test office with Philips AltoT8 Lamps. The acoustic grid tile area is 104.0 sq.ft. and the Philips AltoT8 lamps fixture area is 9.0 sq.ft. for the total ceiling area of 113.0 sq.ft. (refer to Table 5-2-1a).

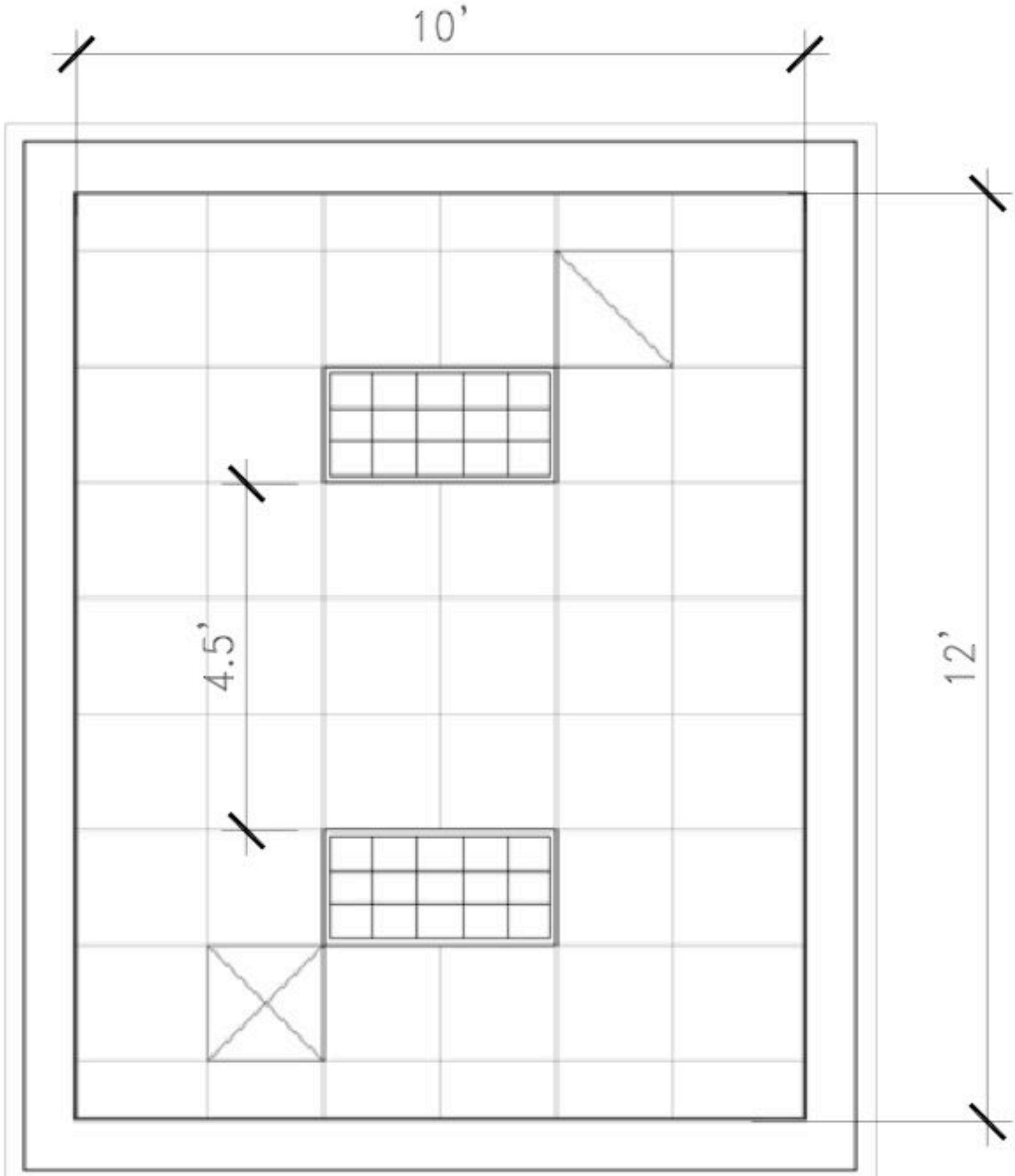


Figure 5-2-1a Reflected ceiling plan of the test office with Philips AltoT8 lamps

Table 5-2-1a Ceiling characteristics of the test office with Philips AltoT8 lamps

Ceiling Area	113.0 Sq. Ft.
Acoustic Grid Tile Area	104.0 Sq. Ft.
Philips AltoT8 Lamps Fixture Area	9.0 Sq. Ft.
No. Of Philips AltoT8 Lamps	4
Average Illumination Level At The Work Desk	104.4 FC

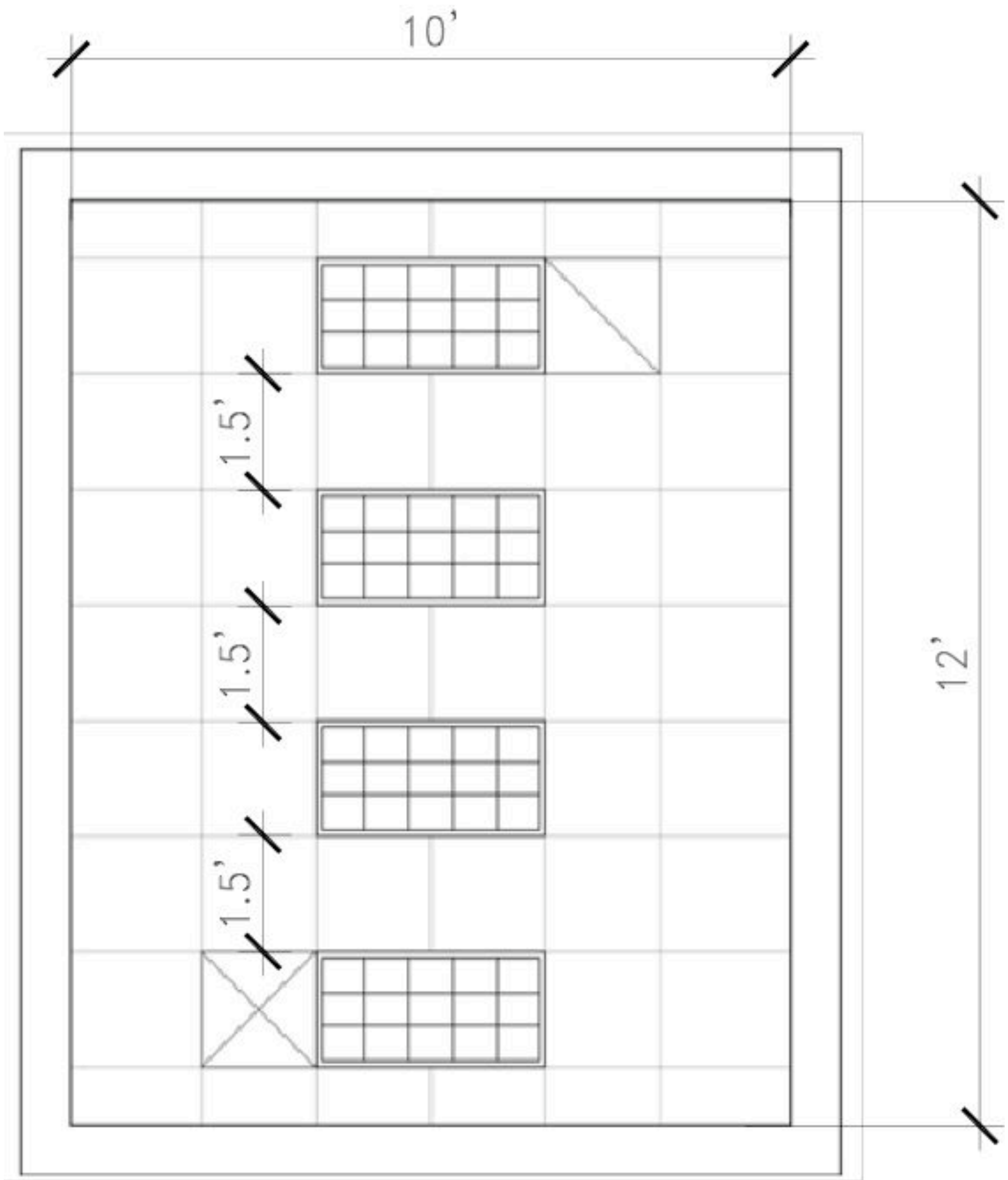


Figure 5-2-1b Proposed reflected ceiling plan of the test office with iBright LED lamps

Table 5-2-1b Ceiling characteristics of the test office with iBright LED lamps

Ceiling Area	113.0 Sq. Ft.
Acoustic Grid Tile Area	95.0 Sq. Ft.
iBright LED Fluorescent Fixture Area	18.0 Sq. Ft.
No. Of iBright LED Fluorescent Lamps	8
Average Illumination Level At The Work Desk	107.9 FC

Figure 5-2-1b shows the proposed reflected ceiling plan of the test office with iBright LED lamps. The acoustic grid tile area is 95.0 sq.ft. and the iBright LED lamps fixture area is 18.0 sq.ft. for the total ceiling area of 113.0 sq.ft. (refer to Table 5-2-1b).

Note- The average illumination level measured at a standard work desk height in the test office was 53.93 fc (refer to Table 4-2-1b) with 4 iBright LED lamps. Based upon Table 4-2-1b illumination level was extrapolated to 107.9 fc for 8 iBright LED lamps.

2. The Color rendition index (CRI) seemed very low for the LED lamps as compared to the T8 lamps. There was no technical data available for the CRI of iBright LED lamps. The colors looked brighter and more saturated under the T8 lights (refer to Figure 4-2-4a and Figure 4-2-4b).

3. The standard of measurement of rated life for fluorescent lamps and LED lamps are defined using different parameters. The rated life of the iBright LED lamps is 50,000 hours and according to the product manufacturer's catalogue it is described as the time when the lumen output of a lamp decreases by 50%. Whereas for the fluorescent lamp, rated life is described as the time when 50% of a test group of lamps fail. Therefore the rated life of the iBright LED lamps could not be compared directly to the rated life of the Philips Alto T8 lamps.

4. As per the Virginia Tech energy conservation standards the installed lighting power density should not exceed 1 Watt per square foot total. The lighting power density calculated for the ICTAS building in this study was more than 1 watt per sq. ft. with Philips Alto T8 lamps (refer to Table 3-2-4-9-2d). With iBright LED lamps the lighting power density was also more than 1 watt per sq. ft. (refer to Table 3-2-4-9-2e). Therefore the Virginia Tech energy conservation standards were not met with either the Philips Alto T8 lamps or the iBright LED lamps.

5. With a one to one replacement the annual utility bills for the ICTAS building were predicted to be less with LED lamps because of their lower power consumption. However the lumen output of the LED lamps was only about half that of the Philips Alto T8 lamps, Therefore two iBright LED lamps were needed to maintain an equivalent illumination level. Therefore a second simulation was performed with two LED lamps for each replaced T8 lamp. The total power consumption for the iBright LED lamps was 30W, which was only 2W less than the Philips Alto T8 lamps.

Figure 5-2-1c represents the graphical comparison of annual electric utility bills for cases (a), (b), (c) and (d) (Refer to Section 3-2) as estimated by eQuest for the ICTAS building.

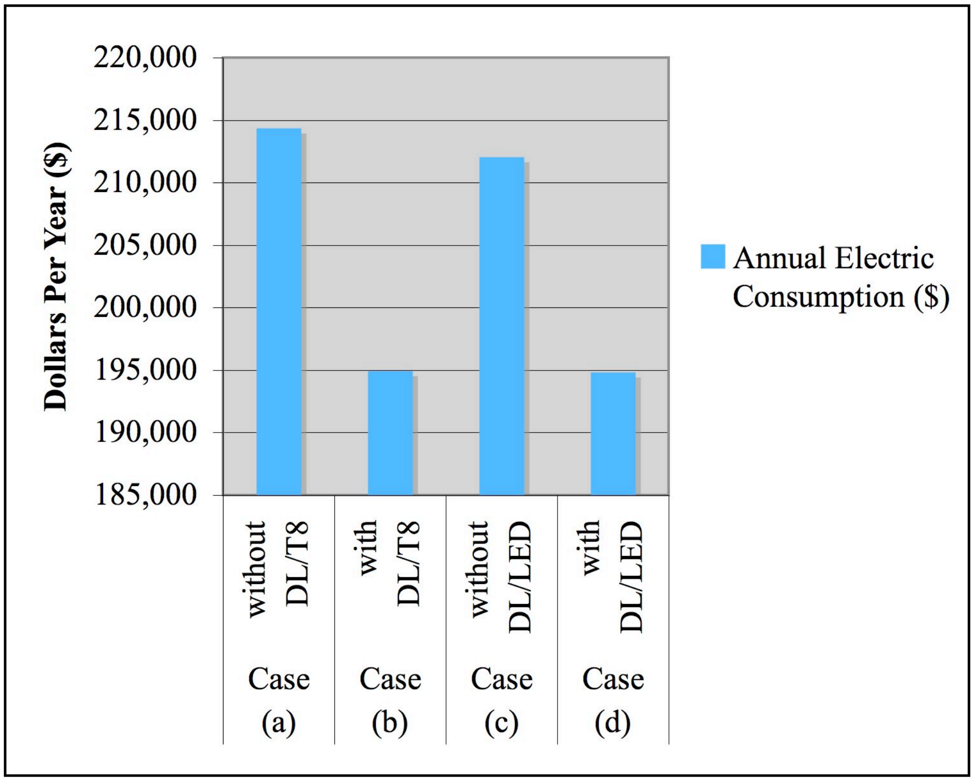


Figure 5-2-1c Comparison of Annual Electric Utility Bill

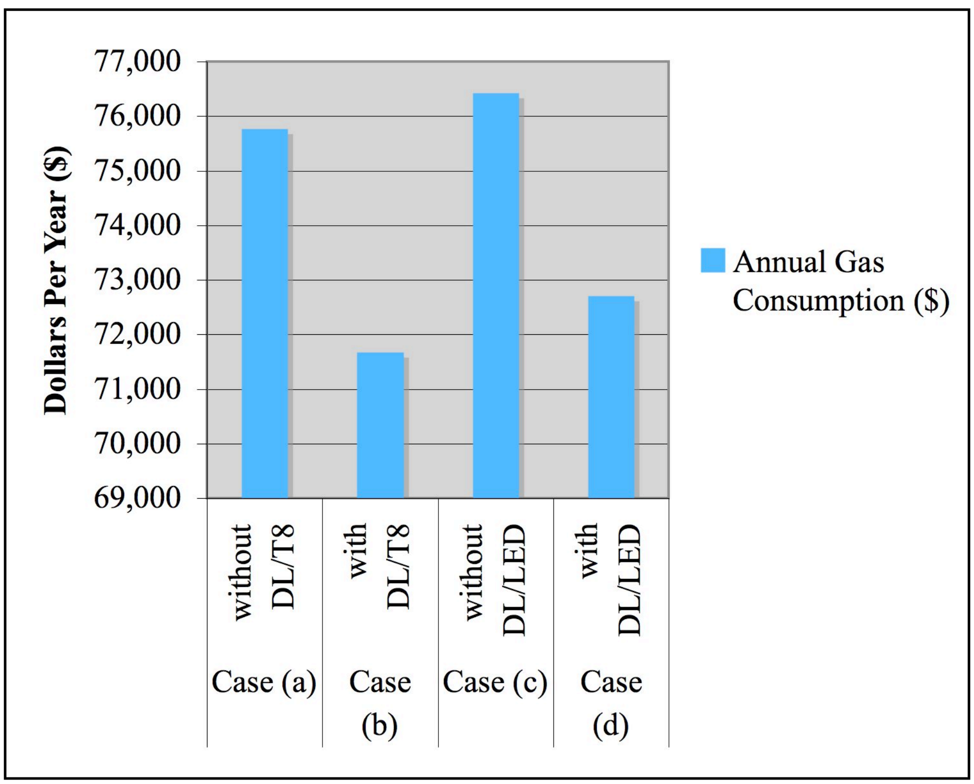


Figure 5-2-1d Comparison of Annual Gas Rates

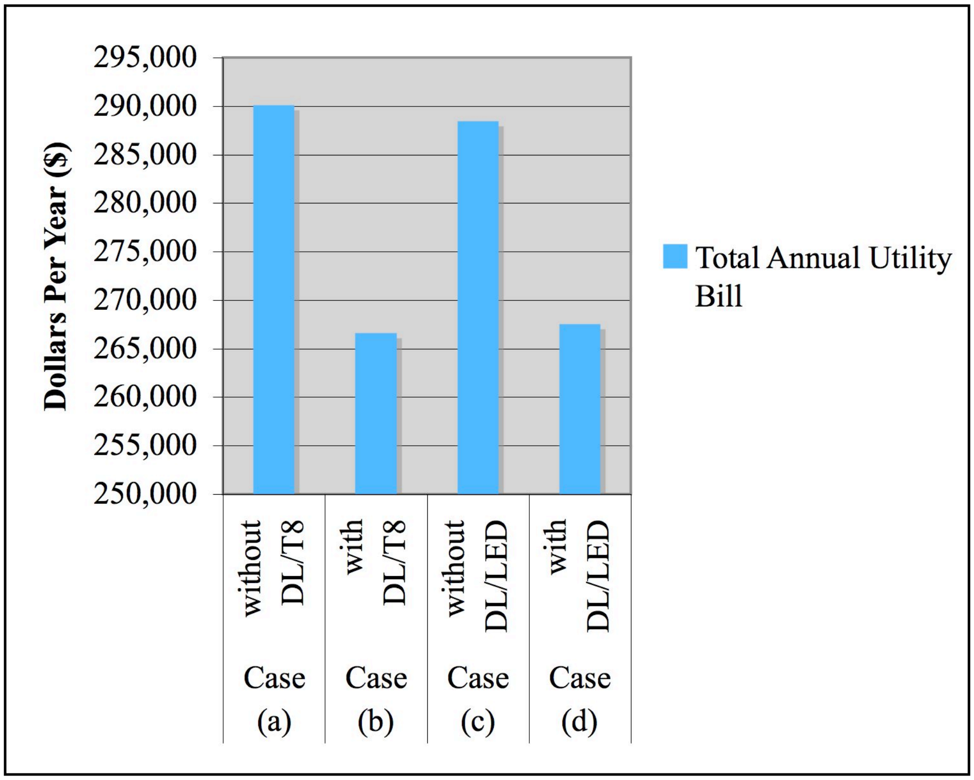


Figure 5-2-1e Comparison of Total Annual Utility Bill

As evident from Figures 5-2-1c, 5-2-1d and 5-2-1e, there was little difference between the utility bills for case (a) and case (c), and for cases (b) and (d). However the annual utility bill was lowest for case (b), which was not surprising because LED lamps generate more heat as compared to the fluorescent lamps (refer to Table 3-2-4-11).

6. The iBright LED lamps did not offer good working conditions in terms of the color rendition which was slightly blue in appearance though the product catalogue claimed the light by iBright LED lamps to be white in appearance (refer to Figure 4-2-2b)

7. It is recommended that iBright LED lamps should not used more than 12 hours at a time for optimum performance and to prevent burn out due to heat dissipation. Therefore they are not appropriate for spaces with more than 12 hours operation.

8. iBright LED lamps can operate only with 120V service. Hence they cannot be used at places where the voltage is higher.

5-2-2 Recommendations

1. From the analysis of the LED lamps it is NOT recommended that they be installed on the Virginia Tech campus.

2. Products like eW™ Profile Powercore by Philips Solid-State Lighting Solutions (refer to Section 2-2) which are still in development might be products to evaluate in the future.

Chapter 6 - Summary

To support the Virginia Tech commitment in reducing energy usage and in making its campus sustainable, this research work undertook a series of experiments. Alternative interior and exterior lighting solutions were investigated towards the goal of improved lighting system performance of the Virginia Tech campus (refer to Section 4-1 and 4-2).

Strategies to improve the light distribution of the Hokie light were studied. A series of experiments were undertaken to evaluate the photometric light distribution of several Hokie light alteration strategies in an effort to identify the most cost effective solution. Based on careful analysis the following options were chosen, experimented and analyzed:

Option 1 - Cover the upper part of the globe on the outside (refer to Section 2-1-6).
In this option the temperature inside the Hokie light was under the safe limits but this option decreased the uplight from the Hokie light by only 0.36 % and didn't increase the downward directed light output (refer to Section 5-1-4).

Option 2 - Replace the perforated LiteLid® inside the globe with a non-perforated LiteLid® to decrease the uplight (refer to Section 2-1-6). In this option the temperature inside the Hokie light was under the safe limits and it did not required maintenance beyond the current solution. The Hokie light had the pleasant nighttime appearance and the uplight was reduced by 8.11% when compared to the current solution (refer to Section 5-1-4).

Option 3 - Apply reflective paint to the tip of the 100W HPS lamp (refer to Section 2-1-6). In this option the temperature inside the Hokie light was under the safe limits and had the pleasant nighttime appearance. This option decreased the uplight from the Hokie light by only 1.99 % and didn't increase the downward directed light output (refer to Section 5-1-4).

Option 4 - Apply reflective paint to the inside of the top of the globe (refer to Section 2-1-6). In this option the temperature inside the Hokie light was under the safe limits and it did not required maintenance beyond the current solution. Though this option decreased the uplight from the Hokie light by 9 % but it did not increased the downward directed light output. The permanent deformation caused in the globe during experiments makes it unsuitable as the retrofit option for the Hokie light (refer to Section 5-1-4).

Option 5 – Apply reflective paint to the inside surface of the top of the globe with non-perforated aluminum LiteLid® (refer to Section 4-1-6, Figure 4-1-6). In this option the temperature inside the Hokie light was under the safe limits and it did not required maintenance beyond the current solution. Though this option decreased the uplight from the Hokie light by 8.8 % but it did not increased the downward directed light output. The permanent deformation caused in the globe during experiments makes it unsuitable as the retrofit option for the Hokie light (refer to Section 5-1-4).

Option 2 with the non-perforated aluminum LiteLid® was selected as the most promising and cost effective solution after analyzing the performance of all the options (refer to Section 5-1-5).

One of the objectives of this research was to reduce the percentage of uplight from 14% to below 5%. To eligible for points in the U.S. Green Building Council's LEED-EB (Version-2) building rating system, the uplight from the Hokie light should be below 5%. The uplight for option 2 with the non-perforated aluminum LiteLid® was 10.64% and it did not met the 5% threshold as required by LEED-EB.

This thesis also presented the findings for the study of application of LED lamps. LED lamps performance was experimentally compared with the existing fluorescent lamps on the Virginia Tech campus on the parameters such as the quality of light, color of the light and quantity of the light. eQuest simulation software was used to estimate and compare the utility bill of a building on the Virginia Tech campus.

Low lumen output of the LED lamps, burnout due to heat dissipation, and poor color rendition index (CRI) of LED lamps make LED lamps still unviable for interior applications (refer to Section 5-2-1).

Appendix

The room used to determine the feasibility of using LED lamps for the general illumination in the buildings of Virginia Tech was Ms. Briele's office (refer to Section 3-2-1). She worked for seven days under Philips Alto T8 lamps and then seven days under iBright LED lamps therefore a questionnaire was prepared to get her subjective feedback on the performance of both the lamps.

Questionnaire -

1) Were you satisfied with the color of the light emitted by LEDs?

   No, the cooler blue color was not preferable to the whiter light of the T8.

2) Did you feel comfortable working under LEDs?

   Working under this type of lighting was not uncomfortable.

3) Were you satisfied with the light levels provided by the LED lamps?

   Light level was a concern. While the wattage was reduced, so was the light level. Personally, I prefer a higher light level on my desk than the LEDs are providing.

4) Do you think the color rendition of these lights was acceptable to you?

   No. Maroon looks brown, oranges weren't vibrant and whites were gray.

5) Was there any difficulty in replacing the T8 fixtures with LED lights?

   No, easy retrofit.

6) What do you feel were the perceivable advantages of the LED lights in comparison with T8 fixtures?

   No advantages with this particular product.

7) What do you feel were the perceivable disadvantages of the LED lights in comparison with T8 fixtures?

   The design of this lamp with all LEDs on one side of the lamp may not be suitable for all types of fluorescent lighting fixtures. Other significant disadvantages was that the lamps were not UL listed, were not to be burned for longer than 8-12 hours, significantly higher material cost of the lamps, lower lumen output and the color rendering was not pleasing for many applications and the color temperature was not pleasing to all persons.

8) Any special comments?

The 50,000 hour rating of the LED lamp, per the manufacturer's literature, is defined as the time when "less than 50% lumen maintenance of original light output" vs. the typical rating of the fluorescent lamp which is defined as the point when 50% of a test group of lamps fail.

I would assume that this lamp in this test fixture would need to be replaced prior to deterioration down to 50% lumen output in an over the desk, office environment due to lack of lumen output.

This raises the question of how quickly does the lumen maintenance depreciate? If for the majority of its rated life, it is operating at 60% lumen maintenance then would it be an acceptable alternative? This test was only for 7 days of operation.

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