The Pennsylvania State University

The Graduate School

College of Agricultural Sciences

THE IMPLEMENTATION OF LED TECHNOLOGY IN ENVIRONMENTAL GROWTH CHAMBERS:

PLANT REPONSES, ENERGY EFFICIENCIES AND PRACTICALITY OF GROWTH CHAMBER RETROFITTING

A Thesis in

Horticulture

by

Daniel C. Frechen

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Masters of Agriculture

May 2011

The thesis of Daniel C. Frechen was reviewed and approved* by the following:

Robert Berghage
Associate Professor of Horticulture
Thesis Co-Advisor

William Kenyon
Associate Professor of Theatre, Lighting Design
Thesis Co-Advisor

Dennis Decoteau
Professor of Horticulture and Plant Ecosystem Health

Kathleen Brown
Professor of Postharvest Physiology
Graduate Program Coordinator

*Signatures are on file in the Graduate School

Abstract

Environmental growth chambers are valuable tools in plant research and specialty crop production. These chambers provide an internal environment completely independent of external influences of irradiance, temperature, and humidity. Operators can program a multitude of settings to obtain the desired internal environment. Researchers can investigate a diverse range of plant reactions in growth chambers, including those of light-mediated photochemicals, or pigments. Specialty crop producers can create a stable environment for high value plant material. But regardless of the operator or plant material, one of the largest challenges experienced when using growth chambers is the electrical demands imposed by the lighting technology.

Lighting in growth chambers is often a combination of fluorescent and incandescent lamps. This arrangement emits considerable quantities of heat while also consuming significant quantities of electricity. To remove the heat and maintain the stable internal environment, compressors, humidifiers, and other components also command large quantities of electricity. A quickly developing lighting technology, light-emitting diodes (LEDs), holds the potential to greatly reduce electrical consumption in growth chambers. The objective of this research was to investigate the impacts LED lighting has on energy and mechanical demands of a chamber, and to evaluate whether plant material responds as it does under conventional lighting sources.

Two growth chambers were utilized over two runs of experiments. During each run, a chamber was retrofitted with two bi-spectral LED units, and the other chamber retained the factory installed lighting of fluorescent and incandescent lamps. Plant samples included *Phaseolus vulgaris* 'Fresh Pick' (bush beans), *Raphanus sativus* 'D'Avignon' (long French radish), and *Lolium perrenne* 'Double Eagle'™ (perennial ryegrass). Growth inputs, internal chamber environments, and electrical loads were recorded over 21 days. Overall, plant material responded favorably to both lighting treatments, with a slight advantage in dry weight going to beans germinated in the CONTROL chamber. While under LEDs, plant material experienced more stable PAR, air temperature and humidity, and soil temperature and moisture levels. Lighting in the LED chamber consumed 85% less electricity than lighting in the CONTROL chamber, a 40% decrease in overall electrical consumption of the chamber. The low heat in the LED chamber resulted in lower mechanical stresses on growth chamber components responsible for maintaining the programmed optimal internal environment.

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

ACKNOWLEDGEMENTS

It would be unjust and rather conceited to not properly acknowledge all those persons and institutions which have allowed me the numerous privileges I've enjoyed over the course of the research. Influential professors and mentors are the cornerstone of anyone's education, and those most indispensable during my years at Penn State University are plentiful. I will brief each party in no particular scale of substance or partiality to the other.

I thank: Jay Holcomb for showing interest in my LED lighting idea and helping me begin LED plant growth trials as an undergraduate. My committee members, Rich Marini, Dennis Decoteau, Robert Berghage, and William Kenyon for all the educational direction and course flexibility. The entirety of the Horticulture department and the numerous professors, support and office staff who were always excited to help out. Nick Gonsman at Electronic Theatre Controls for the extended loans of LED fixtures and his LED lighting industry insight. Blair Malcom for his passion and expertise in LED retrofitting and campus sustainability issues. Those in the College of Arts and Architecture and School of Theatre, and the College of Agriculture for financial assistance.

Special appreciation is directed towards William Kenyon. We both started at Penn State the fall of 2004, he as a lighting professor, and me as his student. Over seven years he has far exceeded the duties of professor, and today I owe the vast majority of my education in and, more so, out of the classroom to him. William has become a vital mentor over the years as my focuses and educational track transformed, resulting in the work which is presented in this thesis. I am truly fortunate to have had the opportunity to learn, work, and be able to call William a close friend.

Much of the monetary support for this project stems from a seed grant provided through The Penn State Institute of Energy and the Environment. Penn State Office of Physical Plant (OPP) is the principle contributor to the grant. W. Blair Malcom, P.E., LEED AP, electrical engineer at OPP assists as a co-principle investigator with the grant. Some of the grant funded the high costs of LED lighting equipment and graduate stipend support. The goals of the university grant are closely aligned to the goals of this thesis.

DEDICATION

I dedicate this work to Mom in admiration of her recently achieving her PhD and for all her past efforts and frustrations in molding this middle child.

Her work continues on the latter…

Chapter 1: INTRODUCTION

1.1 Research Genesis

At a large university such as this, many opportunities for interdisciplinary education and research are perpetually accessible for educators and students. With such a diverse breadth of subject matter present, in combination with the University's integrated academic, research and operational culture, a student such as I can pursue curiosities of almost any imaginable track. The following research will illustrate such a case. While the research possesses a somewhat unique pedigree, I resist characterizing it as unique in execution. Born from a spark in this undergraduate's head during a greenhouse management course, the fruition of this thesis owed to that day's "Ah-ha" moment.

As an undergraduate majoring in Theatre Production with an emphasis in Lighting Design, I was in constant contact with the newest lighting technologies and their subsequent programming methods. Although this knowledge was primarily based within the entertainment and stage industry, I was aware of the impact the newest lighting technology revolution could have on another industry in which I had background. Raised working in many facets of agriculture and pursuing a minor in horticulture during my undergraduate period, I was fluent in the challenges faced by this industry too.

The theatre and touring entertainment industry has many of the same lighting challenges as the horticulture industry. Whereas a lighting designer grapples with color outputs, intensities, projection size, and programmability for the purpose of stage presentation, a grower also is challenged by these lighting conditions in attempts to provide the highest quality illumination for a particular crop. Possibly because of the higher emphasis placed on lighting within the entertainment industry, and thus more research and development funding sources available, the cutting edge of lighting technology and control is being advanced in an especially un-horticultural field. While the source may be foreign and industries distant, the sharing and hybridization of lighting technology and knowledge may aid the horticulture industry in transitioning towards the next method of lighting.

1.2 Horticultural and Academia Drivers

My experience in crop production and coursework at Penn State University has offered me the chance to witness the limitations of using conventional lighting techniques. Frequently, in addition to sunlight, greenhouse growers use supplemental lighting sources such as High-Intensity Discharge (HID) lamps of High-Pressure Sodium (HPS) or Metal Halide (MH). These HD sources provide a high intensity point source with minimal overhead footprint, but they also have expensive lamps and ballasts and produce excess heat. Incandescent lamps are also commonly used as a rudimentary night interruption lighting source or rough spectral balance for fluorescent lighting because of their installation ease, flexibility and low cost. They, like the HID sources, waste large of portions of energy by transferring electrical power into heat instead of light.

In growth chambers the primary lighting source is commonly fluorescent lamps. This discharge source also requires a ballast to operate and it like the lamp produces excess and unwanted heat. Many times, incandescent lamps are also intermixed among the fluorescent lamps as a means to inexpensively supplement wavelengths not provided by fluorescent lamps. In some cases, high-intensity growth chambers solely use HPS and MH lamps. These chambers are usually larger, walk-in types, and the lighting source often requires two separate cooling systems to handle the total heat generated. One cooling system is used for the room and another for the lighting, which is often encased to further protect the plants from the intense heat.

Throughout the commercial industry, government, and academia growth chambers are utilized for tissue culture, incubation/ germination, plant growth, and insectary purposes. These chambers range in size from the smaller reach-in to the larger walk-in styles. A growth chamber's purpose is to provide a stable internal environment by controlling temperature, humidity, and lighting. Unfortunately, no matter the scale these valuable tools are voracious energy consumers which can wreak havoc on budgets and profits.

For anyone using growth chambers, whether it is a researcher or grower, these scorching lamps of every type are the cause of many research and crop failures. The incredible heat emitted by the lamps places constant stress on HVAC units, humidifiers, and other components attempting to maintain the programmed environment. All too often these components wear out and waste valuable material, time and money.

In the United States, much like the world at large, issues concerning energy costs and their management are quickly becoming critical in production and research budgets across numerous industries. Presently, increasing premiums on energy usage means curtailing consumption is vital for a profitable business and thriving research institution. It is rare and certainly valuable to recognize when one tool widely used throughout industry and research can slash lighting energy costs by over 70% and provide many secondary benefits.

Chapter 2: LITERATURE REVIEW

2.1 Plant Photochemical/ Light Relationships

Light is critical to a plant's survival because two major and independent mechanisms rely on the duration, intensity, and quality of light. The first mechanism is where the green pigment chlorophyll transforms light energy into carbohydrates for plant food through the process of photosynthesis. The second mechanism called photomorphogenesis utilizes accessory pigments to induce various physiological adjustments and is more dependent on spectral composition rather than intensity.

Photosynthesis requires relatively high amounts of energy to perform the task of producing food for the plant. Chlorophyll accepts a wide range of wavelengths in order to meet these energy demands. In contrast, the accessory pigments that produce photomorphogenic responses often require 100x less energy to cause physiological changes (Decoteau, 2005). These accessory pigments respond to very low fluxes in wavelengths that depend on the family of pigments. Photomorphogenesis relies on the four primary families of photoreceptors which include phytochromes (red (R)/ far-red sensitive (FR)), and cryptochromes, phototropins, and the ZTL/ADO family (blue-light sensitive) (Wada, 2005).

Phytochrome was identified nearly 40 years before any blue-light photoreceptor, and it is consequently better understood today. It was in 1952 in a USDA lab in Beltsville where phytochrome and its R/FR photo-reversible form were first characterized (Borthwick *et al.,* 1952). By the early nineties, phytochrome A through E, or phyA-phyE, were discovered (Clack, 1994). In 1993 Dr. A.R. Cashmore's group indentified the first blue-light pigment called cryptochrome in Arabidopsis (Ahmad and Cashmore, 1993). Soon after, another blue-light sensitive family called phototropins was indentified (Huala *et al.,* 1997). Most recently, in 2003, the ZTL/ADO family, was identified using Arabidopsis, but is still somewhat unproven and disputed (Imaizumi *et al.* 2003). The action spectra are less defined for the blue-light sensitive families (Cashmore, 2005). Currently, the Arabidopsis genome has been shown as having five phytochromes, three cryptochromes, and two phototropins (Cashmore 1997, Briggs and Huala 1999, Nagy and Schafer 2002, Quail 2002, Lin and Shalitin 2003).

Each of these pigment families reacts to specific wavelength profiles and generates specific photomorphogenic responses. Phytochromes generally affect internode elongation (phyE), seedling germination (phyB), seedling de-etiolation (phyA and phyB), leaf size, photoperiodism, and chlorophyll production (Smith, 2000). Cryptochromes influence stem elongation, leaf expansion, photoperiodic flowering, and the circadian clock (Cashmore 2005, Hart 1988). Phototropins regulate phototropism, stomatal opening, chloroplast relocation, solar tracking, and leaf expansion to name a few (Briggs and Christie, 2002). The newest proteins in the ZTL/ADO family show similar responses to that of cryptochromes and blue light as they also play a role in regulating photoperiodism and the circadian clock (Briggs, 2005). Interestingly, in 2002 the laboratory of Reppert and Weaver (2002) concluded that cryptochromes 1 and 2, or cry1 and cry2, are a mammalian requirement in regulating the circadian clock and behavioral expressions. This illustrates just one example where a research chamber outfitted with programmable wavelength outputs could prove valuable for both plant and animal research.

Recent studies targeting Arabidopsis flowering have shown a complex interaction between phytochromes and cryptochromes. Through varying mutants with members of each family (phy1, phy2, cry1, cry2, etc.), researchers observed flower initiation earlier with PHYB, PHYC, PHYD, and PHYE gene mutants than in that of the wild type (Reed *et al*. 1993, Devlin *et al.* 1998, Franklin *et al*. 2003). Oddly though, mutants with the PHYA genes had the reverse effect.

Green light has been shown as a growth inhibitor in tissue cell culture (Klein, 1964). It was observed in growth chambers housing green-rich fluorescent lamps, that crown gall callus growth was repressed in relation to the quantity of green light supplied. It makes evolutionary sense for a plant not to grow in a green-light rich environment. As Fig. 2.1.1 illustrates below, the wavelengths transmitted through a thick vegetative canopy is primarily green and far-red. A plant interprets a bulk of these wavelengths as a signal that there is much competition in the environment and that it should avoid or alter its growth.

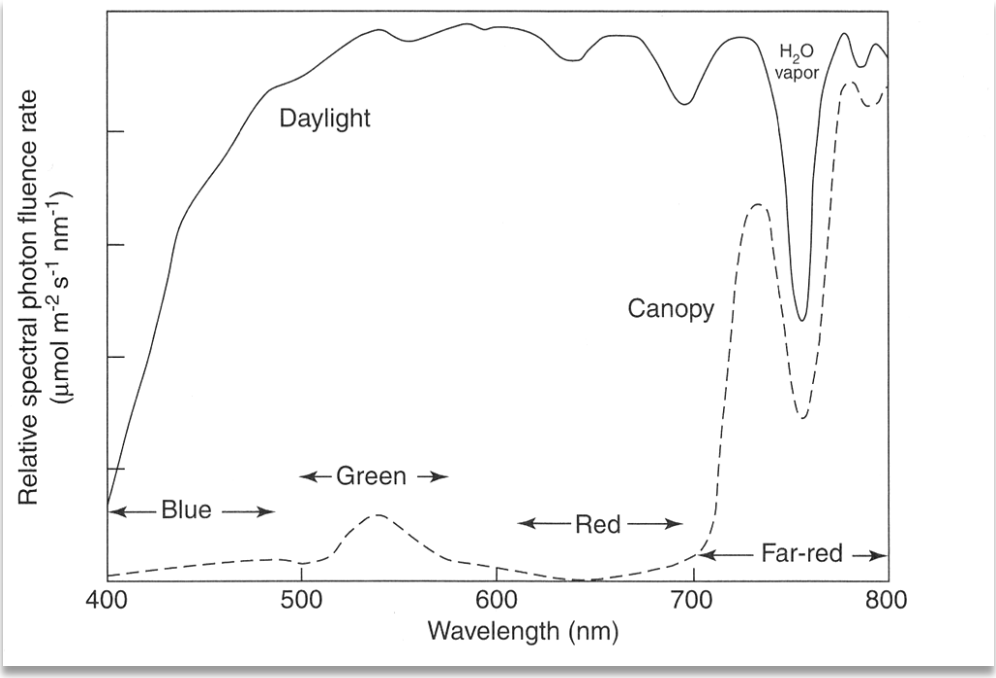


Fig. 2.1.1 Smith, H. 1994. A generalized spectral distribution of sunlight above (solid) and below (dash) a vegetation canopy.

Phytochrome can exist in two photoreversible forms. Plants synthesize phytochrome in the ground form Pr, r indicates the pigments sensitivity to red, or R (peak near 650-670nm) wavelengths. When the Pr form of phytochrome is exposed to R light, Pr transforms into the more physiologically active Pfr form, fr indicating far-red state and sensitivity to FR wavelengths (peak near 700-740) (Nelson, 2003). The Pfr state is far more active than Pr in signal transduction and gene expression throughout a plant (Nagy and Schafer, 2002). Exposure of Pfr to FR light will transform the phytochrome back to the ground state of Pr. Fig. 2.1.2 illustrates a typical transformation cycle of a phytochrome and light mediated responses. The transformation between forms can occur over just a few minutes (Kasperbauer, 2000). Also, a plant's phytochrome state immediately before a dark period or night will be maintained until next light or dawn.

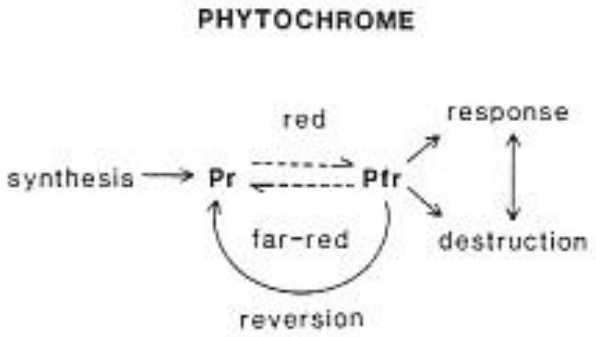


Fig. 2.1.2 Vince-Prue, 1991. Typical phytochrome photochemical cycles.
If Pr is exposed to R light, the reversion arrow will continue clockwise
as it transforms back into the active Pfr form.

It is highly unlikely at any one time that a plant will experience isolated R or FR light. Since Pr and Pfr spectral profiles overlap in most portions as seen in Fig. 2.1.3, it is implausible for a plant to exclusively contain either Pr or Pfr forms of phytochrome. Instead, plants contain both forms and physiological responses rely on the ratio of the two (Vince-Prue, 1991). The R/FR light ratio reported by the phytochrome pigment is valuable as plants use this ratio as means of determining competition and appropriate physiological adaptations (Kasperbauer, 2000).

Seed germination, vegetative growth and reproductive phases are all affected by the balance of R and FR (Smith *et al*., 1991). Some seeds exposed to FR light will not germinate as photochemical processes react to low R/FR ratio. Irradiance with high quantities of FR wavelengths is a signal to seeds that a potentially competitive terrestrial environment currently exists above. Seeds exhibiting this sensitivity to shade and FR treatment are commonly small, rich in fat seeds from non-domesticated species (Decoteau, 2005). Seeds from domesticated species often do not respond to R/FR ratios, or even light amounts at all in some cases, as most seeds are products of breeding programs designed to ease germination difficulties in commercial production (Hartmann *et al.,* 2002).

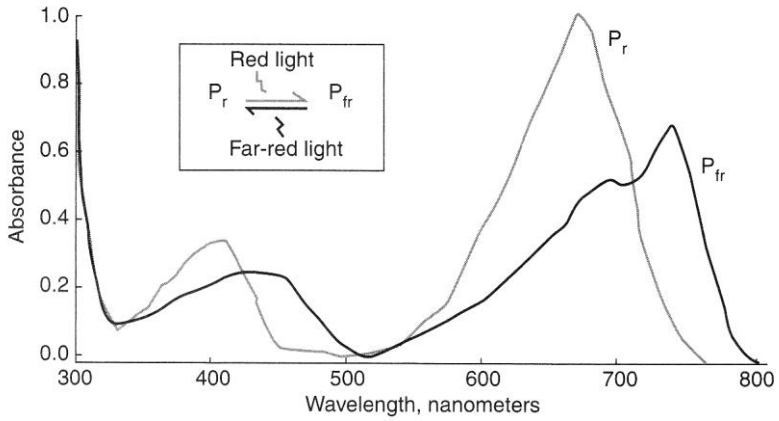


Fig. 2.1.3 Decoteau 2005. Optimal absorption spectrums of phytochrome in red (R) and far-red (FR) photo-reversible forms.

Although many photomorphogenic responses can be attributed to various accessory pigments, it must also be recognized that other physiological responses are not due to spectral composition, but rather simply low light conditions. Some of these plant responses mimic one another and this was evident in early experimental trials in our research. Certain LED fixtures were unable to produce sufficient PAR but provided plenty of spectral capability.

Photosynthesis harvests radiant energy and transforms it into chemical energy, in the form of carbohydrates (Hart, 1988). A variety of chlorophyll and carotenoid pigments allows plants to absorb radiant energy from a wide breadth of wavelengths in a reaction that depends more on quantity of energy (W/m^2), rather than quality of energy (400nm, 500nm, etc.). The photosynthesis compensation point is roughly 10 W/m^2 and the saturation point varies around 200-300 W/m^2. A cloudy day emits roughly 100 W/m^2 and summer sunlight at noon emits roughly 1000 W/m^2 (Bjorn, 1976).

Under low light conditions a plant begins using more carbohydrates from its reserve than it creates during photosynthesis. If this cycle persists the plant will exhaust its food supply and starve. To survive the plant adapts by transforming various structural features and photochemical processes, as presented in Table 2.1.1. Through evolution the plant is programmed in low light conditions to quickly redirect resources into reaching for more light and transitioning from a vegetative state into a reproductive state. This new objective provides the plant optimal chance for offspring and continued survival of the species.

Physiological Process	Response to Shade
Extension growth	Accelerated
Internode elongation	Rapidly accelerated
Stem	Thinner and less weight
Petiole elongation	Rapidly accelerated
Leaf development	Changed
Area per leaf	Increased
Leaf thickness	Reduced
Chloroplast development	Retarded
Chloroplast synthesis	Retarded
Chlorophyll a/b ratio	Changed
Apical dominance	Strengthened
Branching	Inhibited
Flowering	Accelerated
Rate of flowering	Increased
Seed set	Reduced
Fruit development	Truncated

Table 2.1.1 Decoteau, 2005. Physiological responses to shade.

Flowering is one of the responses induced by low light exposure, but flowering can also be induced by R/ FR light treatments (Hartmann *et al*., 2002). Fig. 2.1.4 shows the importance of the Pr and Pfr ratio in a species requiring photoperiod treatment to induce flowering. A long-night species requires a low presence of Pfr in order to allow flowering (Vince-Prue *et al.,* 1984). Pfr levels quickly build during the daytime and through the night slowly diminish. Seasonal lighting conditions affect photoperiod sensitive species in outside environments. In controlled environments photoperiodic specie's flowering can be manipulated by day/ night ratios (Hartmann *et al*., 2002). It is conceivable too that spectral treatments exposing a species to higher levels of R light rather than FR light could produce a higher Pr/Pfr ratio and promote flowering.

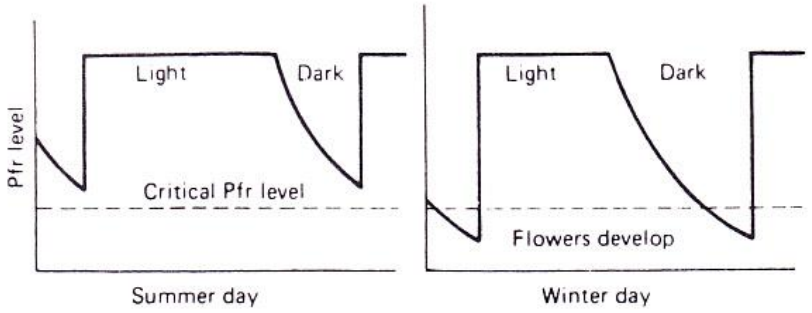


Fig. 2.1.4 Nelson 2003. Diminishing Pfr levels affect on flower initiation in short-day species.

From the perspective of researchers working in horticulture and other plant science fields, it is conceivable that a lighting technology like LEDs, which allows for instant and programmable wavelength and intensity adjustments, can be an enormous advantage over the current growth chamber lighting systems. It is important to understand that plants utilize light for more than just photosynthesis, but rather also for environmental cues and adaptive responses (Sager *et al*., 1988). Plants have amazing mechanisms to adapt and thrive in all sorts of environmental conditions, and scientists are continuing to indentify more and more light-mediated mechanisms.

If growth chambers are converted to programmable LED light fixtures I believe researchers will quickly gravitate to them and begin opening new windows of research previously hindered by traditional lighting technologies. Other lab procedures and equipment are increasingly becoming precise; accordingly, so should light technology.

2.2 Lighting Measurement Metrics

In order to properly justify later data a brief review of the various measurement methods is necessary. On the surface light measurements may seem simple and less contestable than some other growth inputs, but in reality, lighting metrics can become quite complicated. Much of the confusion stems from nearly incompatible measurement metrics. If not fully understood by growers or researchers, then purchased lamps and lighting systems may not be providing adequate wavelengths and intensities. Also, companies can deceive consumers by providing misleading lighting specifications in order to move product.

Knowing what lighting metric to use or trust begins with knowing the purpose of the lighting being measured. Measurement scales differ and wavelength outputs become especially important. In the case of this research, the purpose of the lighting is to grow plants. However, most lighting sources or lamps are characterized in photometrics based on human vision. Any measurement terminology expressing units in foot-candles, lux, or lumens is part of the photometry method of lighting metrics specifically biased for the human eye (Li-Cor Ltd., 1982). As illustrated in Fig. 2.2.1, the human eye is very sensitive to green and yellow wavelengths and least sensitive to colors on the margins, that including blue and red. This curve is defined by Commission Internationale de l'Eclairage (C.I.E) and is referred to as the photopic response curve.

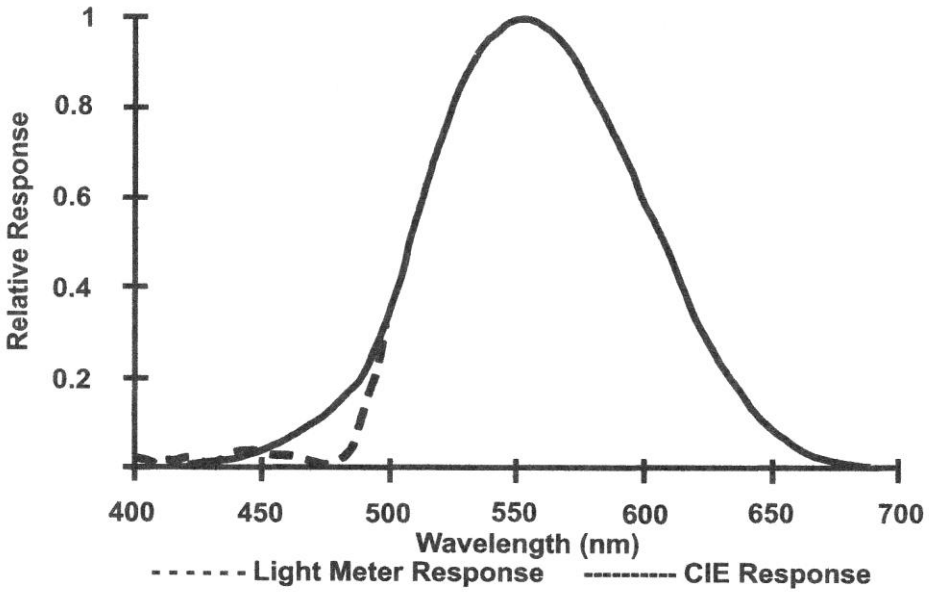


Fig. 2.2.1 The Luminosity Function of the Human Eye.
Courtesy of Extech Corporation, Extech.com

Light measurement instruments based on photometry calculate readings by weighing a green and yellow wavelength much more heavily than a blue or red wavelength (Hartmann *et al*., 2002). So while a lamp may include of high foot-candle reading and make potential consumers interested in purchasing, the truth is the lamp may simply posses little more than intense green wavelengths. To a plant this area of wavelengths is least important of all wavelengths in the visible wavelength region which roughly spans from 400-700 nm (Hart, 1988).

To understand what wavelengths are vital to healthy plant growth it first is important to understand the correct lighting measurement method for plants. The most useful measurement method of light for plant purposes is called photosynthetically active radiation (PAR) (Dole and Wilkens, 2005). PAR is classified as the measurement of irradiance used by plants for photosynthetic purposes. This method actually umbrellas two more specific measurement metrics, but both only meter between 400-700 nm . The first type measures photosynthetic photon flux density of the PAR (Decoteau, 2005). This measurement provides units in microEinstein/m^2/s, photon/m^2/s, or mircromole/m^2/s. During this research the unit microEinstein/m^2/s was utilized. The other type of PAR measures photosynthetic irradiance and is provided in terms of Wm^{-2}.

Measurements in PAR , microEinstein/m^2/s, are unbiased to any specific wavelengths. Equal weight to all wavelengths between 400nm and 700nm comprise the final measurement (Li-Cor Ltd., 1982). While not perfect (no method is), it certainly is more appropriate and useful when plants are involved.

As the human eyes are sensitive to particular wavelengths, the same is true for plant pigments. Depending on a plant's pigment composition and genetic programming, a mix of applied wavelengths can cause a myriad of physiological responses (Davies, 2004). Specific families of photoreceptors activate within regions of wavelengths as shown in Fig. 2.2.2 below. Nearly opposite human vision, a plant's sensitivity is primarily in the margins of blue and red wavelengths. This is why it seems misguided to calibrate lighting techniques for plant growth using photometry.

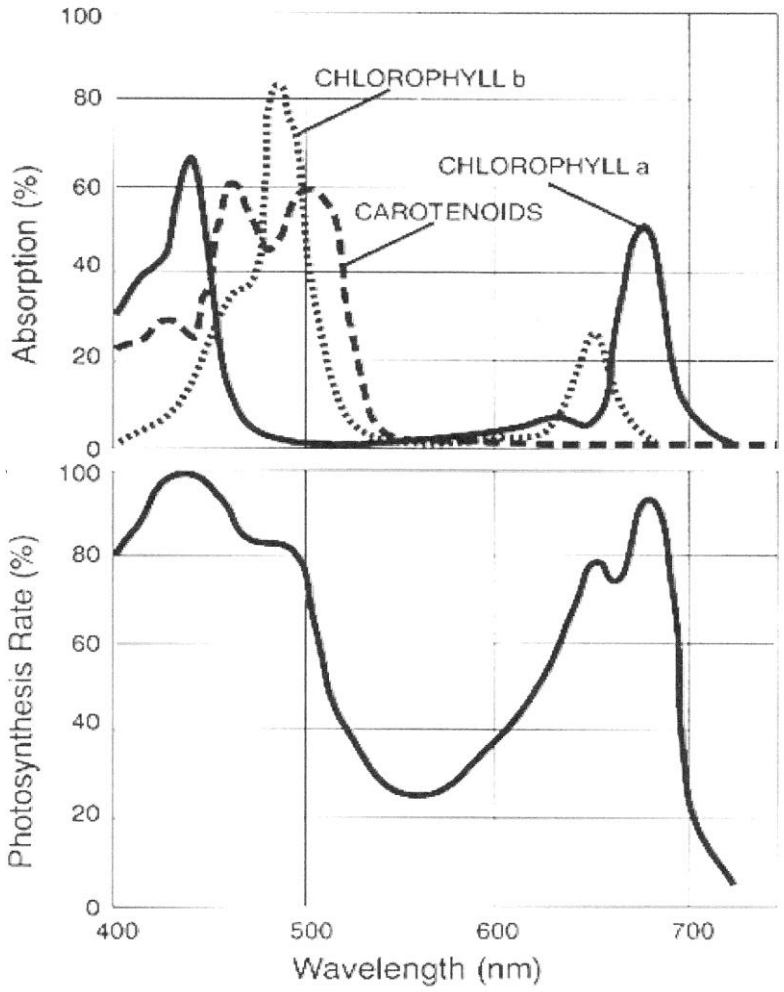


Fig. 2.2.2 Optimal Wavelengths for Photoreceptor Activation.
Courtesy of Wikipedia.com

Researchers and growers should prefer any lighting measurements to be performed using PAR. Using the PAR method also has its shortfalls as shown in Fig. 2.2.3. In this figure, both the red and the blue dominant wavelengths provide a PAR reading of approximately 30 microEinsteins/m^2/s, but that isn't the whole story of what is important when comparing lighting sources. For effective plant growth it is critical to understand a lighting source's PAR measurement and wavelength distribution. This ensures proper light intensities in the most effective regions of plant pigments.

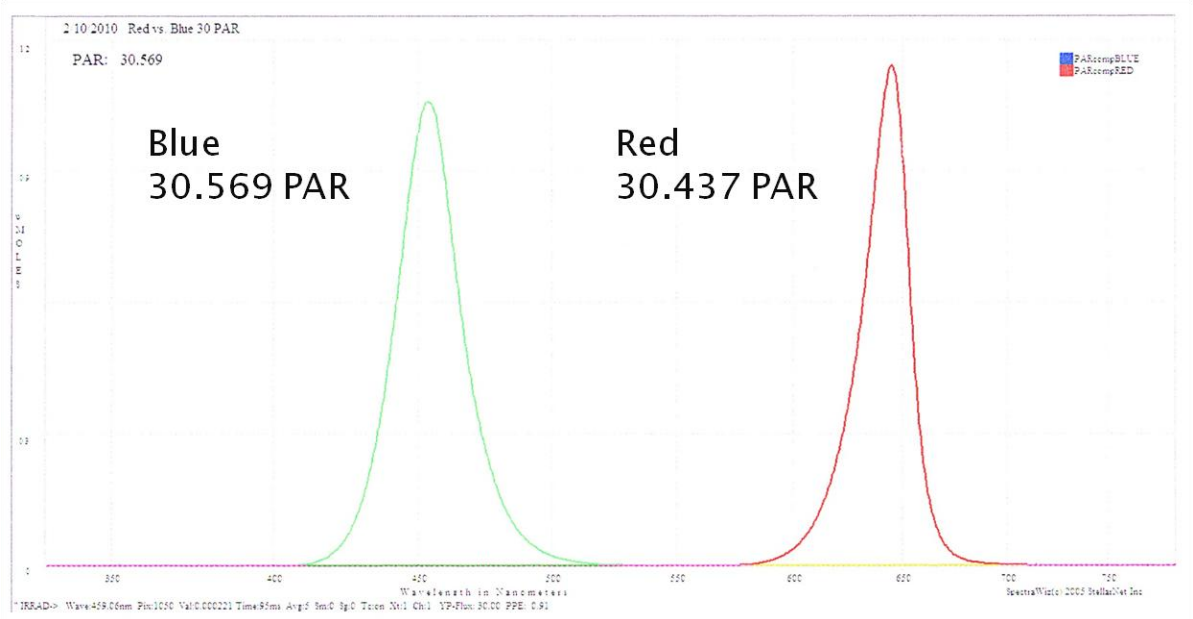


Fig. 2.2.3 Comparison of PAR Outputs by LEDs.

Fig. 2.2.4 and Fig. 2.2.5, illustrate the challenges faced during this research when specifying lighting technologies. As most lighting data is presented in units based in photometry, it becomes difficult to properly translate those units into PAR. While a light source may possess a high foot-candle value, it may also possess a low PAR value. The inverse may also be true for other lighting sources. In preparation for this research the exact situation illustrating this lighting metrics disparity was encountered. The chambers using a fluorescent and incandescent mix produced a higher foot-candle value but a lower PAR value compared to the chamber using the LED lighting source.

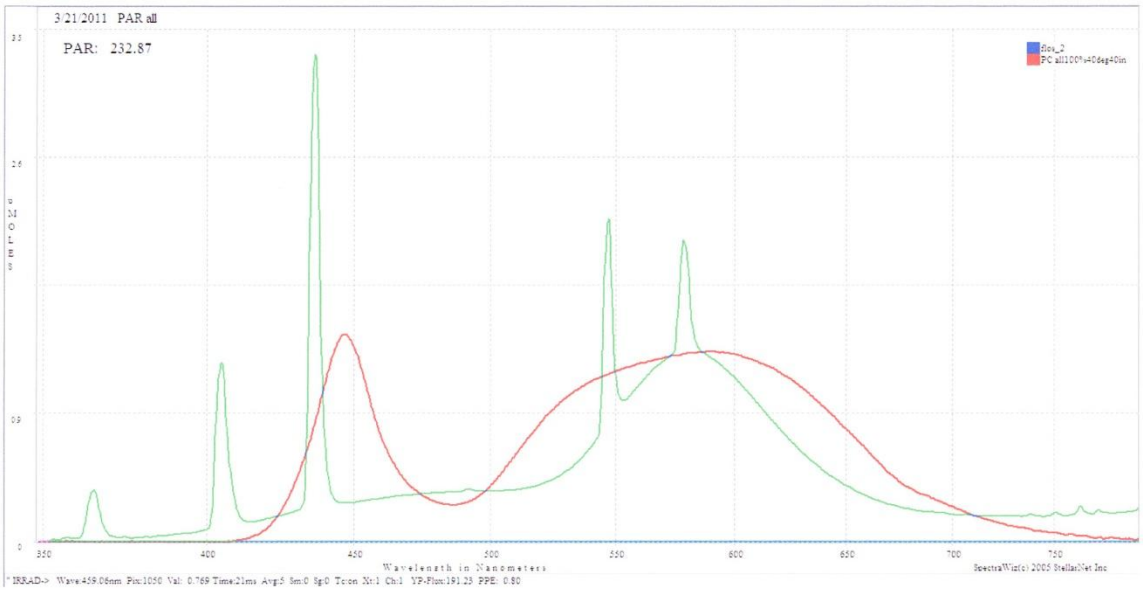


Fig. 2.2.4 Spectral profiles of CONTROL (green line) and LED (red line) measured in PAR.

The CONTROL chamber outfitted using 10x 160w fluorescent tubes and 10x 100w incandescent lamps (green) measured 189 PAR. The LED chamber outfitted with only LEDs (red) measured 232 PAR. When measuring the CONTROL chamber PAR, readings varied (sometimes as much as about 80 PAR) due to the flickering characteristics of fluorescent technology. The value of 189 PAR was about the average during these fluctuations.

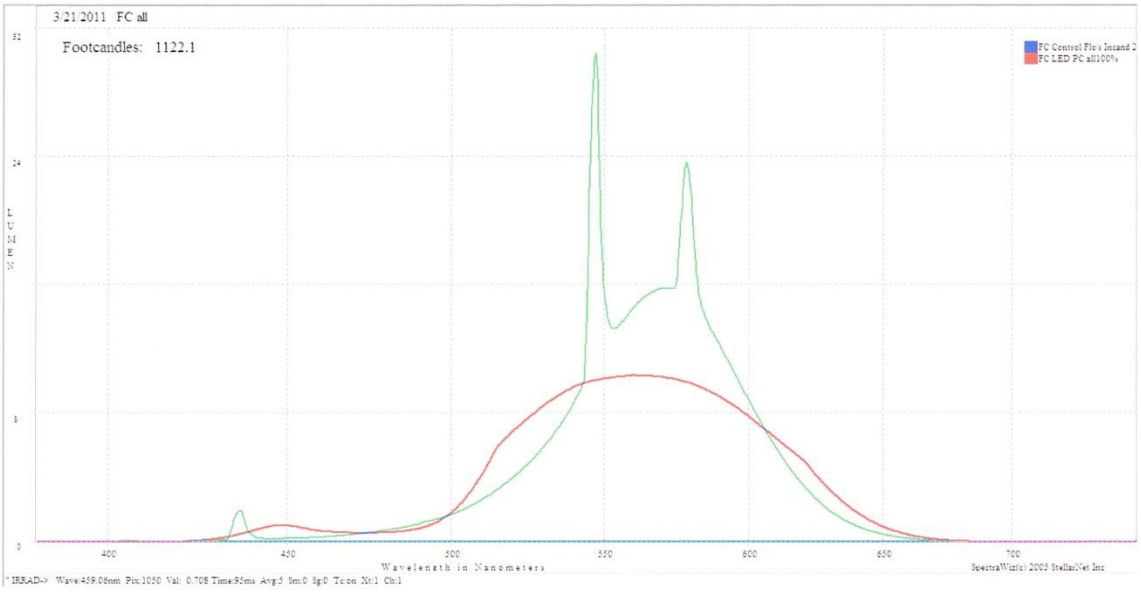


Fig. 2.2.5 Spectral profiles of CONTROL (green line) and LED (red line) measured in foot-candles (fc).

The same CONTROL (green) and LED (red) chamber lighting are shown in Fig. 2.2.5, but now using the photometry method which is biased on the sensitivity of the human eye. Now the CONTROL chamber measures 1316 fc and the LED chamber measures 1122 fc. While lighting in the CONTROL chamber may sound more advantageous for plant production in terms of foot-candle units, the spectral profiles illustrate the flaws in accepting only photometry measurements when specifying supplemental lighting sources to be used for plant growth. Wavelengths, especially those vital to photosynthesis and photomorphogenesis, are neglected when using the photometry method of measuring light outputs. But as previously stated, even when using the PAR method it is important to consider the spectral profile in conjunction with the PAR value for the most accurate understanding of a potential lighting source.

2.3 Conventional Lighting Sources

The industry standard for illumination inside environmental growth chambers consists of fluorescent, incandescent, and high-intensity discharge (HID) sources such as metal-halide (MH) and high-pressure sodium (HPS) (Hartmann *et al*., 2002). Although there are many systems, it is common practice in growth chamber installations to utilize fluorescent lighting as the primary lighting technology. Each conventional lighting source possesses advantages and drawbacks and these are weighed for the particular growth chamber application and size.

Smaller growth chambers will almost always be outfitted with fluorescent lighting (Nelson, 2003). These chambers range in size from the smallest reach-in type (about 5 cu ft.) to the larger multi-door types (about 90 cu ft.). The chambers used throughout this study were about 70 cu ft. Tube fluorescents offer desirable uniform and bright coverage over a production area. Lamp tubes are relatively cheap and easy to swap for different wattages or spent tube replacement. Also, the ballasts needed to condition the current can be positioned outside of the growth chamber thus reducing potentially bulky internal infrastructure and avoiding the accumulation of more heat within the chamber.

Fluorescent lighting also has its drawbacks when used for growth chambers. As with any lighting source, spectral outputs become an issue. The spectral output of fluorescent tubes varies only slightly between manufacturers but all fluorescent tubes share common overall wavelength characteristics (Nelson, 2003). Fluorescent lamps emit wavelengths throughout the visible spectrum with intermittent peaks at various wavelengths. Peak wavelengths of 410nm, 440nm, 550nm, and 580nm were emitted from fluorescent lamps in this study

Incandescent lamps are the often used in growth environments for balancing other supplemental lighting such as fluorescents. Generally, fluorescent lighting is deficient in the warmer wavelengths and incandescent is deficient in the cooler wavelengths. The incorporation of the two lights creates a rough overall spectral composition favorable to plants. Incandescent lamps are sometimes also used as a night-interruption source to affect photoperiodic responses of species. Any use of incandescent lamps is vastly wasteful of electricity as this lighting source is only about 7% efficient.

2.4 Light –Emitting Diode (LED) Overview

LEDs are a solid-state lighting platform, and thus they do not use any filament suspended in gas nor require hazardous gases like mercury in fluorescence to provide irradiance. Instead, a small diode is encased in plastic which in turn wastes very little energy in the form of heat and makes for a robust and compact lighting source. A basic diagram of LED structure is presented in Fig. 2.4.1. The inherent nature of the diode structure provides extreme longevity since it does not “burn” the filament agent like traditional sources (the driver of much energy transfer inefficiency). Also, the composition of diodes is safer with spectral outputs determined by semiconductor doping materials such as aluminum, gallium, and silicon to name the few most common.

By using different mixes of elements in the semiconductor to form the diode, various LED colors are possible, and are further outlined in APPENDIX B. What this all means is a new light source with low electrical requirements, low heat outputs, dozens of wavelength options, dimmable properties, no hazardous material concerns, and a long life.

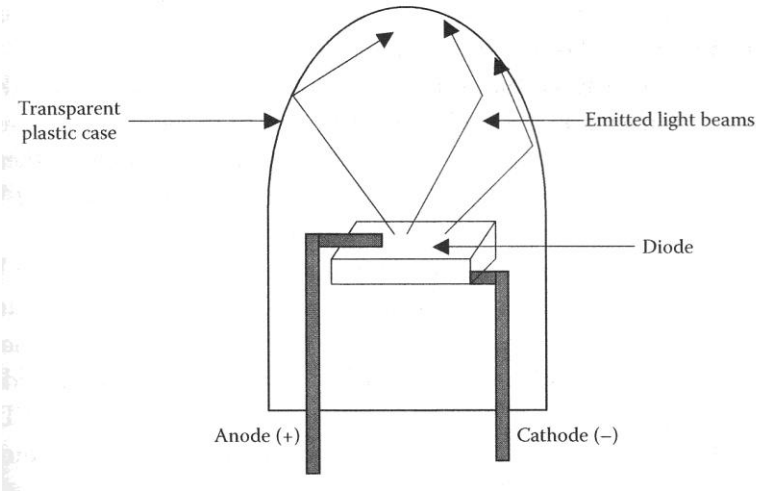


Fig.2.4.1 Held 2009. Simple LED Construction.

To a researcher who relies on growth chambers as vital tool, LED lighting fixtures offer a new level of precision and unique opportunities in research. Depending on the diode doping materials, LEDs produce specific wavelengths. The fixtures used in this study incorporate LEDs representing two major color groups, cool and warm, thus providing a "white" spectrum if entirely on. To fully capitalize on this setup, a digital programming protocol called DMX-512 (see APPENDIX C), which is used worldwide for entertainment and architectural lighting, is employed for control of the overall spectral outputs. By selectively dimming wavelength groups, the overall wavelength mixture and intensity can be precisely manipulated for a desired output. Before, researchers could only change spectral outputs by changing lamps or using nondurable filters, and intensity was usually only offered in lamp on/off procedures.

LED lighting also has disadvantages. Since LED spectral outputs are highly specific or near monochromatic, to produce light with a balance of wavelengths across the visible spectrum requires a LED fixture to incorporate numerous wavelength-specific LEDs. While this multi-color fixture presents advantageous capabilities of generating millions of spectral compositions at the discretion of the researcher or designer, the fixture now unfortunately requires a sufficient "blending" distance. LEDs typically project light in narrow beam angles so to blend the various spectra and produce a

somewhat uniform output can require some distance. A blending constraint is regrettable since LEDs emit little heat which allows close proximity of LED fixtures to plant material (less wasted irradiance, energy, and more material per space). A fixture composed of smaller-sized LEDs of limited, or single, spectral outputs requires less distance to sufficiently blend individual spectrums and produce uniform spectral and intensity coverage. Most commercial LED fixtures also offer various lens options to blend and manipulate beam spreads.

2.5 Environmental Growth Chambers

For decades traditional chamber lighting has consisted of fluorescent sources with other lesser common irradiance sources like high-pressure sodium (HPS), metal halide (MH), and incandescent also being incorporated. All these high energy demanding lighting sources generate massive quantities of excess heat requiring other high energy demanding cooling and humidifying systems to react to maintain the desired growth parameters. Since these chambers usually operate for weeks or months nonstop, the electrical inputs and associated costs are severe.

Chapter 3: MATERIALS AND METHODS

3.1 Materials and Methods

The focus of these experiments was to investigate the affects LED lighting had on plant material, compare this against conventional growth chamber lighting methods, and monitor the energy impacts of each lighting setup. To accomplish this two growth chambers were commissioned over two experimental runs. They are later referred to as experimental Run 1 and 2. A preliminary trial was performed to attune all equipment. Growth chambers, Model GC-15, were manufactured by Environmental Growth Chambers in Chagrin Falls, Ohio and installed in Tyson Building, University Park, PA in 1988 were used in this study.

During each run the LED chamber was retrofitted with two iW Reach Powercore LED units mounted with 23˚ diffusion lens, both manufactured by Philips. Each LED unit contained LEDs of color temperatures of 2700˚K and 6500˚K. For this study the LED units were programmed at 100% ON so the resulting color temperature was about 4600˚K. The CONTROL chamber remained stock with ten Philips 160w F72T12/CW/VHO fluorescent tubes and Sylvania ten 100w incandescent bulbs. Lighting treatments of each chamber were switched between experimental runs to account for chamber-specific electrical variances. Switching of the lighting treatments was the only variable affected between experimental runs.

HOBO monitoring equipment manufactured by Onset Computer Corp., Bourne, MA, was installed in each chamber and in the growth chamber room. All sensors recorded values, averaged over ten second intervals, every ten minutes The change in lighting and heat emissions, combined with the slight variance inherent in growth chamber mechanics, necessitated calibration of programmed chamber temperatures between experimental runs. Chamber temperatures were set and calibrated for 72 ˚F during the day. The temperature sensors as part of the HOBO logging equipment were installed in each chamber and used to calibrate internal temperatures. The objective was providing an internal environment of 72 ˚F day and night, but because of the excess heat emitted by fluorescent and incandescent lighting during the day in the CONTROL chamber, night temperatures decreased.

The day temperature of the CONTROL chamber could be considered “artificially” programmed to a lower temperature to compensate for the high heat loads from fluorescent and incandescent lighting. A separate night temperature for the CONTROL chamber could have been programmed to account for the absent daytime heat, but it

wasn't. Part of the study was investigating the impact heat loads of fluorescent and incandescent lamps have on chamber components in maintaining internal conditions. We felt calibrating and programming for the 16 hour portion of the day was the best option for this study.

The LED chamber required only temperature calibration due to slight chamber component variances, due to temperature sensor corrosion, compressor wear, etc. LED lighting, as seen in data, generated a low heat load which caused little mechanical stress on the chamber thereby forgoing the need for special day and temperature programming as was the case in the CONTROL chamber. To help ensure standardized performance throughout the experimental runs, both chambers were operated for two days under these settings before runs were commenced plant material was introduced.

Each chamber was outfitted with two humidifiers below the internal growth platform. Each chamber's humidifiers would cycle ON and OFF in unison when the chamber controller called for change in humidity depending on chamber sensor readings. As with lighting, special calibration, this time using the HOBO relative humidity sensors, and programming was required in both chambers, but especially in the CONTROL chamber. An internal setting of 70% was the day and night objective for each chamber, and the setting customization was for the 16 hour lights ON portion of the day. The "artificial" setting for daytime humidity was to compensate for the high heat emitted from fluorescent and incandescent lighting in the CONTROL chamber. The absence of CONTROL lighting heat loads caused night humidity to rise as the humidifiers could fully reach the programmed setting, still set for lights ON heat loads. The LED chamber only required slight calibration to adjust the humidity to 70%. Low heat loads from the LED lighting caused little stress on humidifiers to maintain internal humidity. To help ensure standardized performance throughout the experimental runs, both chambers were operated for two days under these settings before runs were commenced and plant material was introduced.

Each chamber contained HOBO series data sensors for air and soil temperature, relative humidity, PAR, and soil moisture. The room was outfitted with a temperature and relative humidity sensor. Also, since the chambers' chilled water supplies were linked, a temperature sensor was attached to the surface of the water line's Sch. 40 steel pipe. To monitor overall electrical consumption a HOBO 50-amp transformer was installed into the breaker boxes of each chamber. These sensors relayed measurements to the HOBO U30 Data logger. APPENDIX J provides a full listing of all materials, equipment and software used throughout this investigation.

The growth chambers were powered by 3-phase power which allowed for separate monitoring of each of the legs A, B, and C. Initially, after reviewing and manually confirming chamber electrical schematics (see APPENDIX E), each chamber component's amperage draw was measured using a CMT-80 40 Amp handheld multimeter made by Greenlee Textron, Inc., Southaven, MS. Selective breaker tripping and disconnecting of components allowed precise amperage measurements. This understanding of Amp loads and which leg of electrical phase each component was on allowed proper restructuring of legs A, B and C. Ideally legs in a 3-phase feed should be under about the same loads.

With each component's Amp draw in hand, the chamber's legs were rewired to carry specific components. The objective was to isolate the lighting loads yet still not off balance overall leg loads too much. Each chamber's compressor load was always split between legs A and C. See Table 3.1.1 for further designation of which components were on specific electrical legs. Leg B was used as the leg carrying all electrical loads associated with lighting. Although the chamber brain, unused canopy outlets, humidifiers, and ghost load were also on leg B, these collectively only added about 2.6 Amps and remained unchanged between experimental runs.

A Sentinel Data Logger (AEMC Instruments Inc., Foxborough, MA) was installed around each phase leg to record electrical consumption in Amps. The mean of electrical phase leg A, B, and C of each chamber under both experimental runs was then calculated to eliminate chamber bias in later data.

CONTROL Growth Chamber Electrical Loads by Phase

Phase A	**Phase B**	**Phase C**
See Note Below-		
	Fluorescent #2 (5 tubes)	
	Fluorescent #3 (5 tubes)	
	Incandescent (10 bulbs)	
	Fans	
Compressor #1 (split)		
		Compressor #2 (split)
	Ghost Load *	
	Humidifiers	
	Canopy Outlets	
	Chamber Brain	

LED Growth Chamber Electrical Loads by Phase

Phase A	Phase B	Phase C
	LED Fixtures	
	Fans	
Compressor #1 (split)		
		Compressor #2 (split)
	Ghost Load *	
	Humidifiers	
	Canopy Outlets	
	Chamber Brain	

Note: Fluorescent #1 (6 tubes) was left on Leg A, but disabled through chamber programming in order to balance spectral outputs with the LED chamber.

*We were unable to determine the source of this load; it was present even with all the internal breakers off. If might be an imbalance in the phases, but it is minimal.

Table 3.1.1 Chamber components per electrical leg per chamber lighting treatment.

The LED fixtures were also programmed using DMX-512 protocol (see APPENDIX C and APPENDIX D). DMX-512 is a common digital programming language primarily utilized for lighting in live entertainment and architectural settings. It allows light fixtures to be connected in series and controlled from a computer. For this study, the lighting schedule was programmed and maintained by products of Electronic Theatre Controls (ETC) Middleton, WI. The lighting program was created with free ETC Expression Off-line software, transferred into the ETC Lighting Playback Controller (LPC) by floppy disk, and then was loaded to begin active control of the LED fixtures.

Each chamber received three plant species samples. Each chamber housed eight containers of bush beans (*Phaseolus vulgaris*), two eight cell trays of radishes (*Raphanus sativus*), and two pots of ryegrass (*Lolium perenne*' Double Eagle'™) all freshly seeded into Sunshine #5 Mix (Sun Grow Horticulture Canada Ltd., Seba Beach, AB) Duration of each experimental round was three weeks. Bean seeds were not inoculated with rhizobia by Johhny's Selected Seeds of Winslow, Ma, or by investigators of this study.

Watering was performed once every two days and the amounts recorded. Watering amounts were determined by visual observation and lifting of containers. It was hypothesized that plants in the CONTROL chamber would need more water and our individualized, although subjective, watering method would be further strengthened by the soil moisture sensors. No fertilizer was used throughout the study.

After each experiment, plants were visually evaluated and rated for quality. Quality criteria included general structure, leaf color, and plant development. The rating scale used ranged from 1 to 4, with 1 = Poor Quality, 2 = Acceptable Quality, 3 = Good Quality (only minor deficiencies noted in quality criteria), and 4 = Excellent Quality (no deficiencies noted).

Photographs of each plant type and group were taken before harvest. Plant material processing included the cutting off of all plant material above the soil line for beans and rye grass. For radishes the entire plant was harvested. All plant material was dried in a lab oven over three days at about 70 ˚C and then masses were taken. Root systems were visually inspected for any structural, color variances.

Data collection included weekly offloading of the HOBO U30 Data logger using HOBOware Pro software. Sentinel loggers were offloaded weekly using Sentinel SL2 software and DataView was used to process some of this data. Microsoft Excel v.2007 was also used to process some of the data. Plant quality and dry weight data were analyzed using 2 way ANOVA with replication (Excel 2004 for Mac, version 11.6.2, Microsoft Corp.).

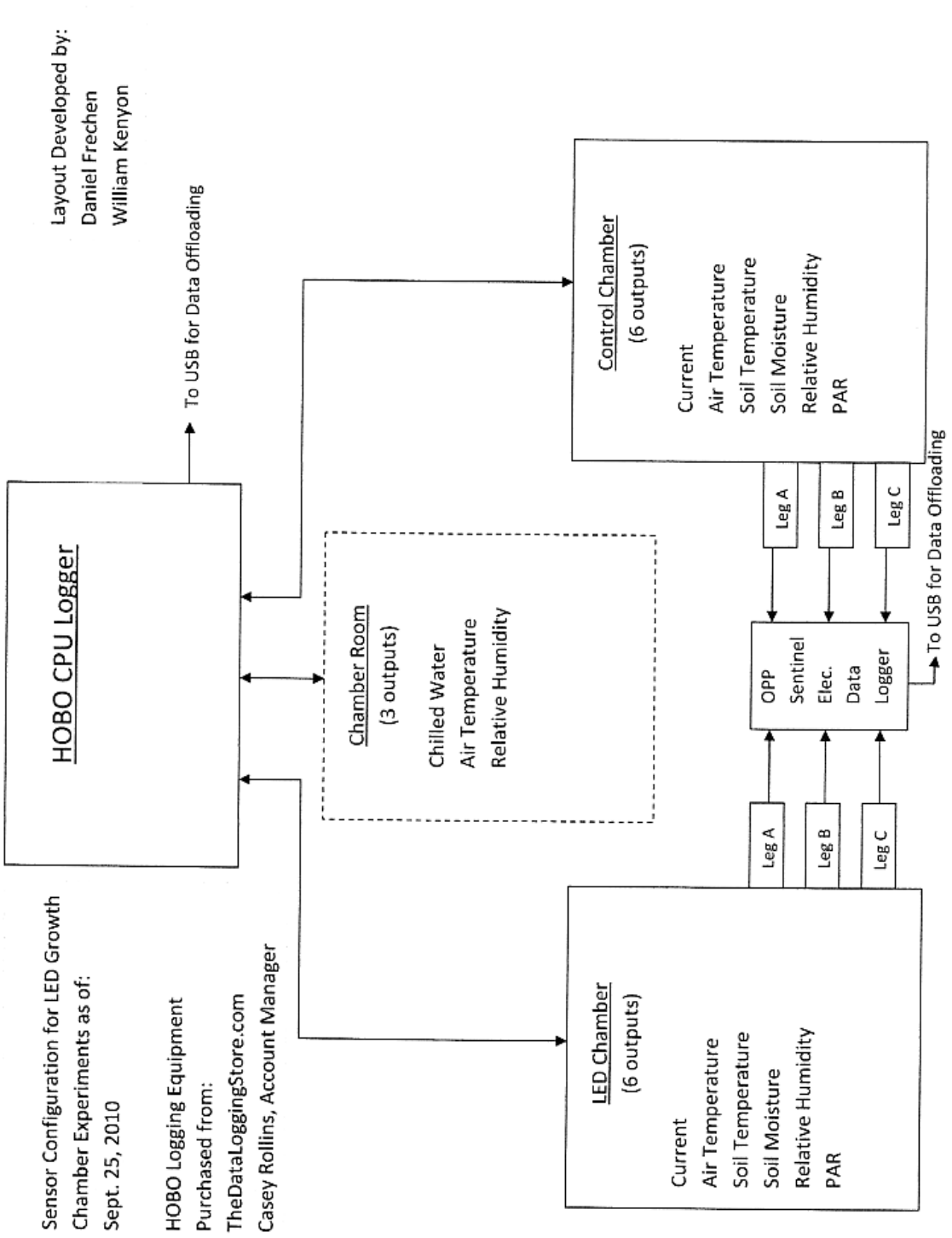


Fig. 3.1.1 Experiment Configuration.

3.2 Equalizing Lighting Outputs

To equalize PAR outputs between the LED chamber and the CONTROL chamber PAR measurements were performed using a spectroradiometer manufactured by StellerNet Inc., Tampa, FL and the PAR sensor installed in each chamber. Using two PAR meters helped verify measurements and further ensure accurate light equalization between chambers. The LED fixtures were programmed to 100% power output and the CONTROL chamber lighting was calibrated to match. Through moving the lighting carriage within the chamber, PAR values were matched as best possible to PAR values of the LED chamber. One PAR sensor was part of the installed monitoring equipment in each chamber.

Some difficulty was experienced when acquiring PAR values from the control chamber, mainly due to the nature of fluorescent tube technology. Electric starters positioned at each end of a fluorescent tube emit intermittent electric pulses which charge and illuminate gases within the tube. These pulses cause PAR values to flux roughly 40 PAR in 15 seconds at times. (It is this flux which can cause some working under fluorescent lighting for long hours to experience sore eyes and headaches). The average of these fluxes was used to equalize PAR output with the LED fixtures.

3.3 Growth Chamber Failures

This research required plant material and numerous technologies working in harmony to attain viable data. Growth chambers are unpredictable as they can randomly change program settings, experience mechanical failures, and are affected by outside electrical supplies and, in this setup, chilled water supply fluxes. These alterations or disruptions in mechanical processes cause deregulation of the internal environment. Plants are sensitive to these changes which can result in skewed results. While some of alterations only cause minor or temporary changes in growth habits, other, more extreme alterations can wipe out an entire experiment in less than an hour. Challenges like these were experienced, but not unexpected. To reduce these variables an HVAC technician was brought in to aid in calibrating the chambers so internal conditions were more dependable and provide more reliable data.

The growth chambers used in this study are somewhat unusual in their design and installation. This model of growth chambers is water-cooled. Further, the cooled water supply of each chamber are “in-line” with another. The Tyson building housing the growth chambers uses chilled water lines to run many systems in the building, and

one of these systems is the growth chambers. All the chambers in the room are connected in series and dependant on chilled water flow and temperature. During normal operation, flow and temperature remains near constant, but sometimes other building systems maintenance disrupts chilled water supply to the chambers. Commonly when chilled water is disrupted the chamber cannot transfer out enough heat which results in the chamber quickly overheating causing an automatic safety shutdown. Although disruptive, these incidents provided unintended useful data and interesting topics in the Discussion chapter of this thesis.

Growth chambers are more commonly designed and installed as 'stand-alone" units meaning their cooling and heating requirements are handled solely by onboard components. In these installations electrical demands are greater than those involved during this research. Because this research's chambers rely on chilled water supply the chambers compressors remain ON at all times. The compressors include a "gate" to regulate heating and cooling processes simultaneously. This research only can effectively measure increased electrical demands commanded by the lighting elements. The chilled water return (the exiting direction from chambers) was outfitted with a temperature sensor to monitor fluxes. The chambers shared chilled water so even though the temperature readings were a culmination of both chambers, though chilled water disruptions it was possible to distinguish between chamber heat transfers.

Chapter 4: RESULTS

4.1 Plant Dry Weights and Photographs

Plant Type:	Germination Chamber	Finishing Chamber	Run 1	Run 2	Average Mass per Plant
Radish	LED	LED	2.8	2.2	0.313
	CONTROL	LED	2.7	2	0.294
	CONTROL	CONTROL	2.9	1.8	0.294
	LED	CONTROL	2.5	1.8	0.269
Bean	LED*	LED	3.3	3	1.050
	CONTROL*	LED	3.7	4	1.283
	CONTROL	CONTROL	3.7	3.4	0.888
	LED	CONTROL	3.2	3.4	0.825
Grass	LED	LED	5	3.1	4.050
	CONTROL	LED	4.7	0**	4.700
	CONTROL	CONTROL	4.4	2.8	3.600
	LED	CONTROL	4.9	4.2	4.550

* Only 3 of the 4 seeds germinated.

** Disease occurred early and sample was discarded.

Table 4.1.1 Dry Weights (g) of Run 1 and Run 2 in the same growth chamber. The gray shaded cells indicate significantly different weights at the .05 level.

Analysis shows no significant effects for radish or rye grass, as expected. Surprisingly though, bean dry weights were higher for the plants that were germinated in the CONTROL chamber than those germinated in the LED chamber. There were no differences in weights associated with the finishing chamber lighting regime. As shown in Fig. 4.2.4, soil temperatures remained higher in the CONTROL chamber which may explain why bean seeds started in the CONTROL would germinate better or earlier. Other data provides no explanations other than soil temperatures.

Overall Plant Health Ratings

Fig. 4.1.1 C/L Beans Under LED Lighting.

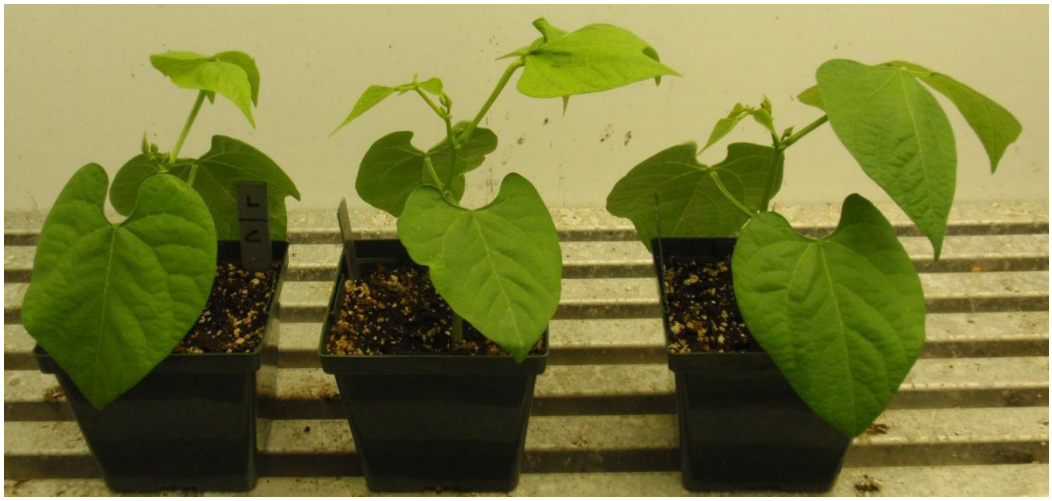


Fig. 4.1.2 L/C Beans Under CONTROL Lighting.

Fig. 4.1.3 Radish Whole Plant, L/L (left), C/C (right). Both exhibit healthy growth in the final crop at 21 days.

Plant Type:	Germination Chamber	Finishing Chamber	Run 1	Run 2	Average Rating
Radish	LED	LED	4	3.5	3.75
	CONTROL	LED	3.5	3.5	3.50
	CONTROL	CONTROL	4	3	3.50
	LED	CONTROL	3	3.5	3.25
Bean	LED	LED	4	4	4.00
	CONTROL	LED	4	3.5	3.75
	CONTROL	CONTROL	3	3	3.00
	LED	CONTROL	3	4	3.50

Table 4.1.2 Plant Quality Ratings of Bean and Radish.

No significant differences were observed between radish or bean crops in rated plant quality. Overall plant qualities were indiscernible between lighting regimes. Ratings for rye grass samples were not performed due to the low sample rate.

4.2 Watering and Soil Environment

Water consumption was an important aspect of this study. Watering was performed every two days. Water amounts applied were determined by visual inspection and lifting of plant containers. Watering data during Run 1 closely resembled Run 2, and raw data sheets for both experiments are located in APPENDIX H and APPENDIX I.

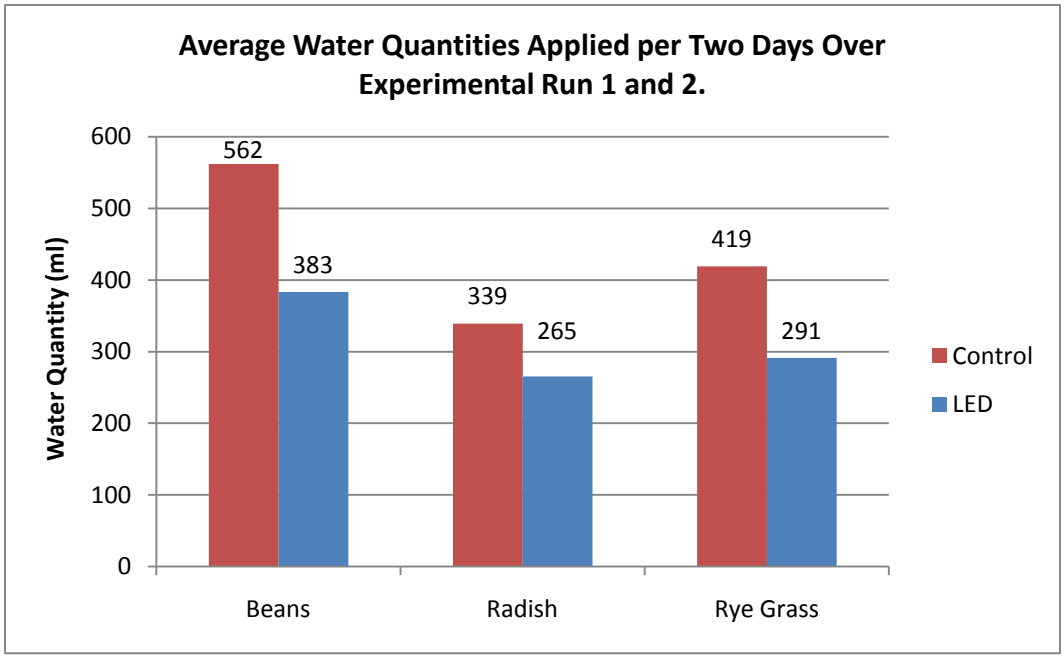


Fig 4.2.1 Average Water Quantities (ml) Applied per Two Days Over Experimental Run 1 and 2.

	Beans		Radish		Rye Grass	
	Control	LED	Control	LED	Control	LED
Avg. of Run 1 and Run 2	562	383	339	265	419	291
Standard Deviation	203	119	130	71	164	97

Table 4.2.1 Average Quantities (ml) and Standard Deviations of Water Applied per Two Days Over Experimental Run 1 and 2.

Average waterings over each two day period were less for plants under the LED lighting treatment. Under LEDs, beans were watered with 32% less, radishes with 22% less, and grass with 31% less water than what was applied in the CONTROL chamber.

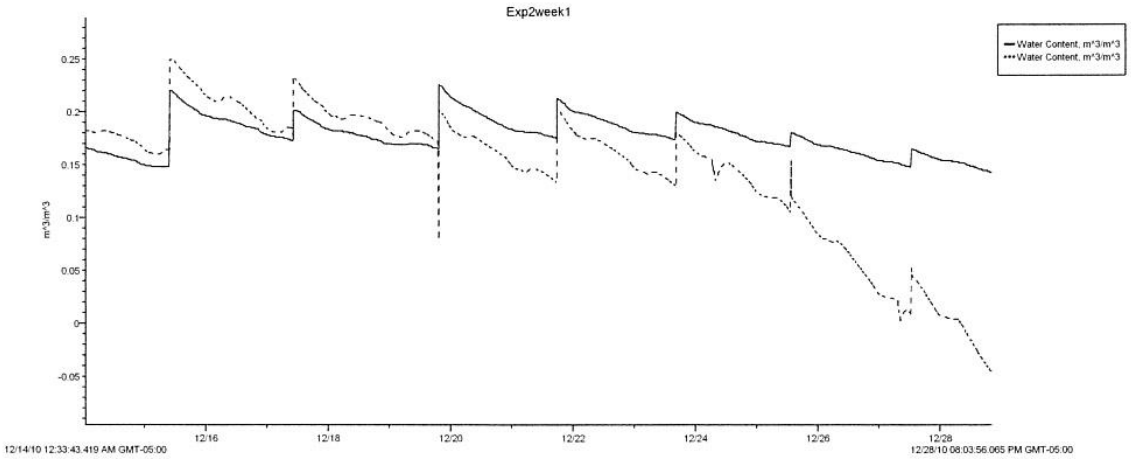


Fig. 4.2.2 Run 1 Soil Moisture Content (m^3/m^3). Sample over 15 days. LED chamber (solid line) and CONTROL chamber (dashed line).

The soil moisture content rapidly decreased as the plants size increased. The HOBO soil moisture sensor was inserted into the center of the roughly 6”w x 4” h circular container of rye grass. The soil rapidly decreased in moisture in the last few days of the experimental run. This sharp decline could be attributed to a possible accelerated stage of growth where the plant was consuming higher rates of water, or a possible decrease in the functioning of a humidifier. The CONTROL chamber increasingly struggled to maintain internal humidity and temperatures nearer the end of the experimental run, most likely causing more evaporation and plant transpiration. This Fig. in conjunction with Fig. 4.2.1, illustrates that even with roughly 30% less water applied, the plants under LED treatment maintained higher soil moisture levels. Moisture levels may have fluctuated differently in the bean and radish containers due to varying cell and container proportions.

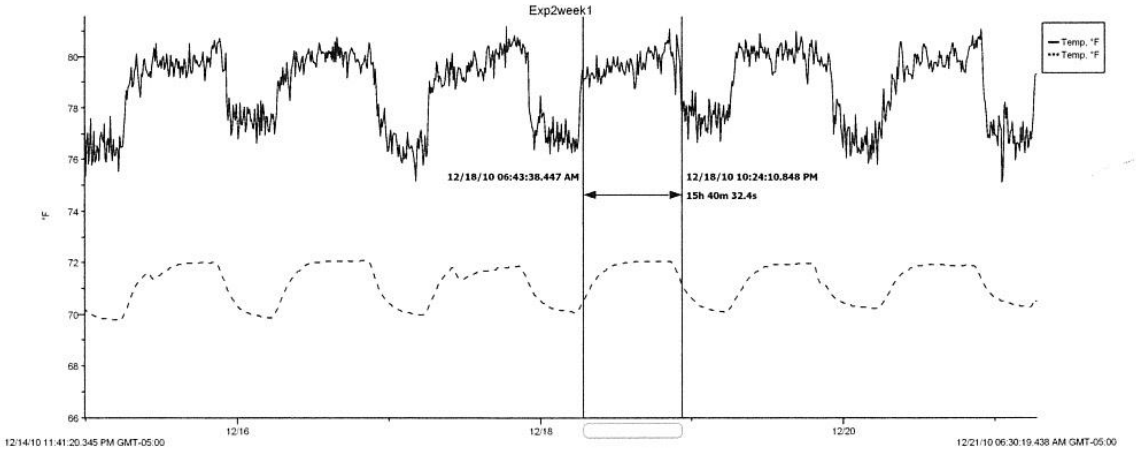


Fig. 4.2.3 Run 1, Soil Temperatures (˚F). Shown over 6 days.
LED chamber (dashed line) and CONTROL (solid line).

Lights ON

	CONTROL	LED
Max	81	72
Min	79	71
Avg.	80	72
St. Dev.	0.502	0.388

Lights OFF

	CONTROL	LED
Max	78	71
Min	76	70
Avg.	77	70
St. Dev.	0.507	0.206

Table 4.2.2 Run 1, Soil Temperatures (˚F).

The CONTROL chamber continually struggled to maintain internal temperatures as a result of the heat loads of the conventional lighting. Soil temperature fluctuations closely mimic those of air temperature shown in Fig. 4.3.3. Soil temperatures continually remained higher in the CONTROL chamber. Soil temperatures also varied less in the LED chamber during both periods of the daily growth cycle.

4.3 Chamber Environment and Chilled Water Response

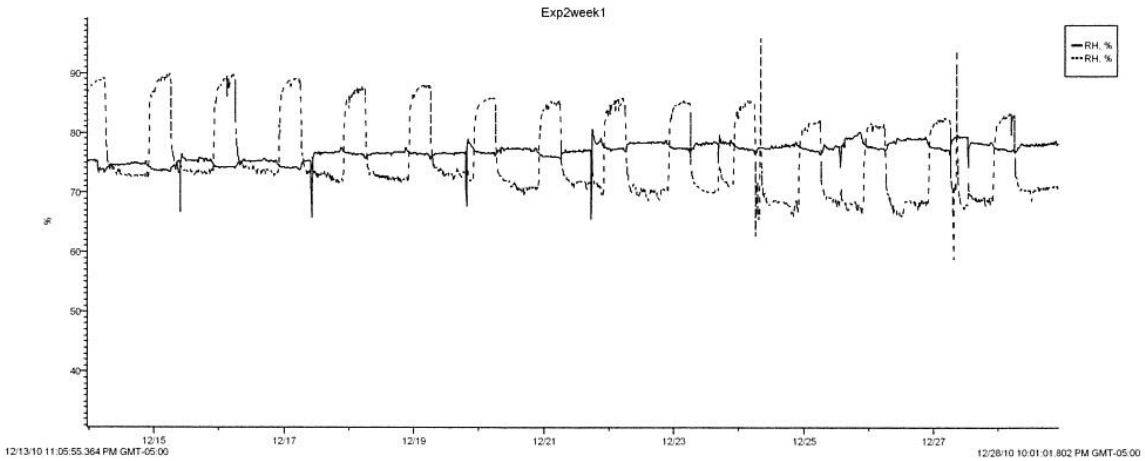


Fig. 4.3.1 Run 1, Relative Humidity. Shown over 15 days.
LED chamber (solid line) and CONTROL chamber (dashed line).

	CONTROL	LED
Max	98	81
Min	32	66
Avg.	74	77
St. Dev.	8.88	1.51

Table 4.3.1 Run 1, Relative Humidity. Sample over 15 days.

In the LED chamber, humidity remained steady because of lower lighting-induced heat loads. Humidifiers operated less and provided a more optimal environment for plant material. As mentioned in chapter section 3.1, humidity levels in the CONTROL chamber would rise during the dark period as heat loads from fluorescent and incandescent lighting was eliminated. The CONTROL humidity levels appear to also slowly decrease over the “normal” portion. This could be due to the system being gradually overwhelmed by the demand.

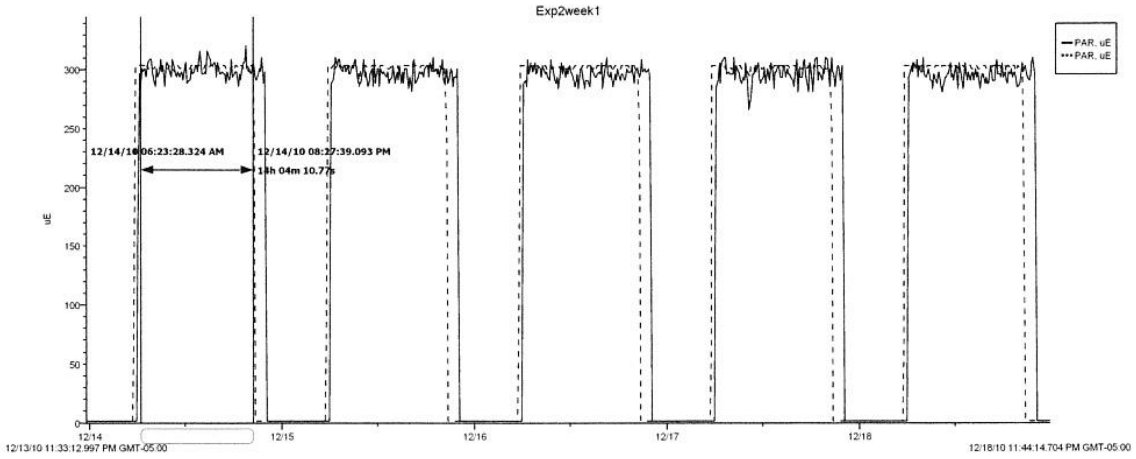


Fig. 4.3.2 Run 2, PAR Levels. Shown over 5 days.

	CONTROL	LED
Max	321	304
Min	286	299
Avg.	300	302
St. Dev.	7	1.5

Table 4.3.2 Run 2, PAR Levels. Sample over 16 hours.

PAR values in the LED chamber remained much steadier than in the CONTROL chamber. The fluctuation observed in the CONROL is due to the nature of fluorescent lamp technology as described in chapter section 2.3. Light treatments ON and OFF times were not precisely initiated in unison, thereby causing the slight “echo-like” PAR plateaus. Each chamber though was programmed to supply 16 hours of light.

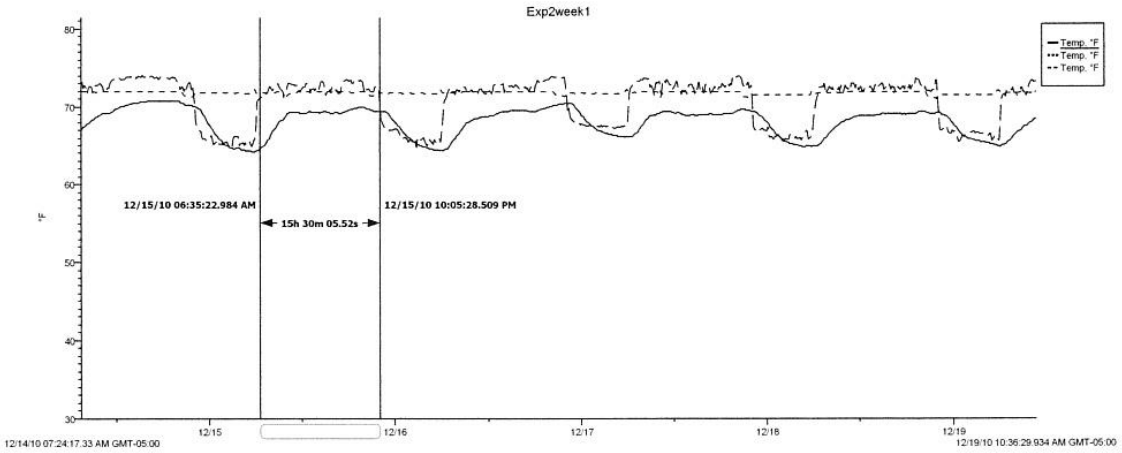


Fig.4.3.3 Run 1, Normal Relationship of Chamber Temperature (˚F) and Chilled Water. LED temp. (short dash line), CONTROL temp. (long dash line), and chilled water temp. (solid line). Shown over 6 days.

Lights ON

	CONTROL	LED	Chilled Water
Max	74	72	70
Min	70	71	64
Avg.	72	72	66
St. Dev.	0.623	0.199	1.258

Lights OFF

	CONTROL	LED	Chilled Water
Max	67	72	70
Min	65	72	64
Avg.	66	72	66
St. Dev.	0.588	0.066	1.794

Table 4.3.3 Run 1, Normal Relationship of Chamber Temperature (˚F) and Chilled Water Temperature (˚F).

Air temperature remained more stable in the LED chamber. Chilled water temperatures lagged slightly behind CONTROL chamber temperatures as the CONTROL chamber heated up under lighting periods. The LED chamber remained very steady through any lighting period not requiring special corrective temperature calibration as described in Chapter 3. Absent the heat load produced by fluorescent and incandescent lighting, the CONTROL chamber's air temperature decreased about 6 ˚F during the dark night period.

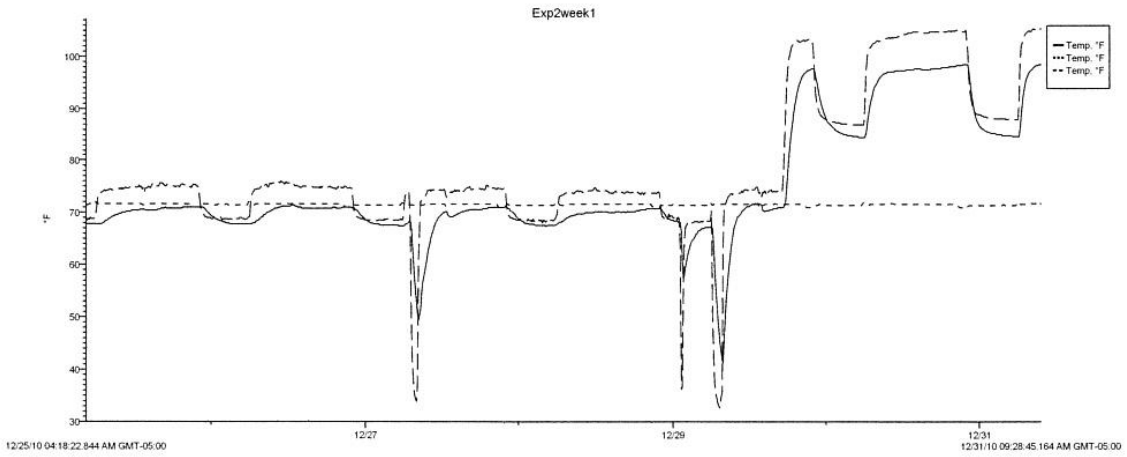


Fig. 4.3.4 Run 1, Abnormal Relationship of Chamber Temperature (˚F) and Chilled Water. LED temp. (short dash line), CONTROL temp. (long dash line), and chilled water temp. (solid line). Shown over 6 days.

Fig.4.3.3 illustrates the reliance of the CONTROL chamber on chilled water supply for heat offloading. As a mechanical disruption caused the CONTROL chamber to wildly fluctuate over time, thereby causing the slightly lagging chilled water to also fluctuate as the CONTROL chamber offloads heat into it, it can be seen that the LED chamber remains completely unaffected. Because of the extremely low heat emitted by LEDs, the LED chamber relies little on cooling systems such as chilled water in this situation.

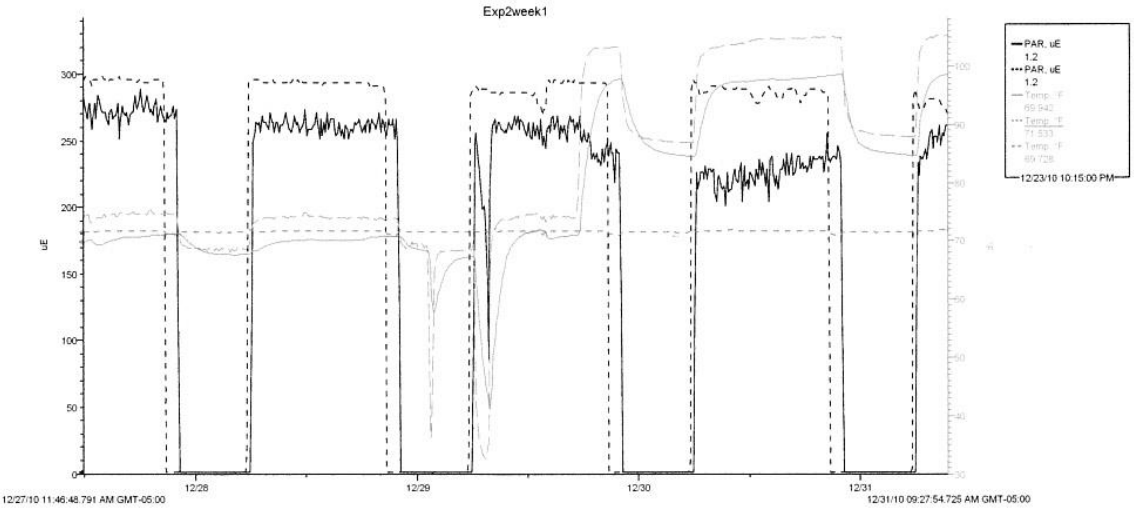


Fig. 4.3.5 Affect of high compressor loads on CONTROL lighting. LED temp. (short gray dash line), CONTROL temp. (long gray dash line), and chilled water temp. (gray solid line). Dark lines indicate PAR readings, LED chamber (dashed line) CONTROL chamber (solid line).

The overlay of PAR values over Fig. 4.3.3 shows an unusual condition in CONTROL chamber lighting when extreme air temperature fluctuations occur. The Fig. appears to show a decrease in PAR when these extreme temperatures occur. A possible explanation could be that during these extreme events high electrical demands from chamber components like the compressor, which are attempting to control the fluctuations, are so high that lighting amperage is drained. The chamber is under high mechanical stress to maintain internal conditions, but power feed into the chamber may be near maximum.

4.4 Electrical Demands

Lighting elements were isolated onto Leg B with other components like humidifiers, fans, and chamber brain (see Chapt. 3). The compressor was separated to Leg A and C. Figure 5.1 and 5.2 display electrical loads over roughly a week's duration of the **same** chamber over both experimental runs.

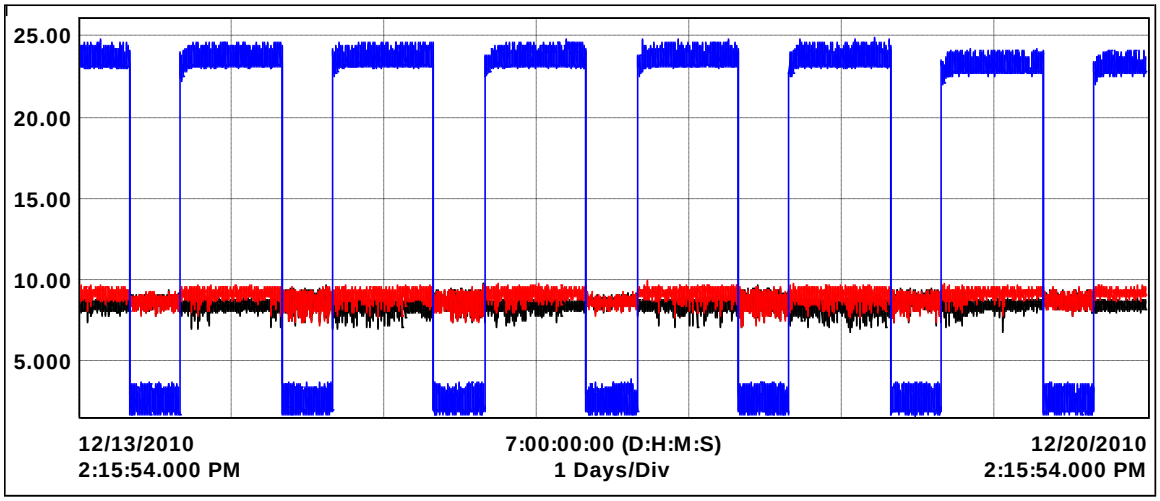


Fig. 4.4.1 Run 1 Week 1, CONTROL Chamber Amps. Leg A (black), Leg B (blue) and Leg C (red).

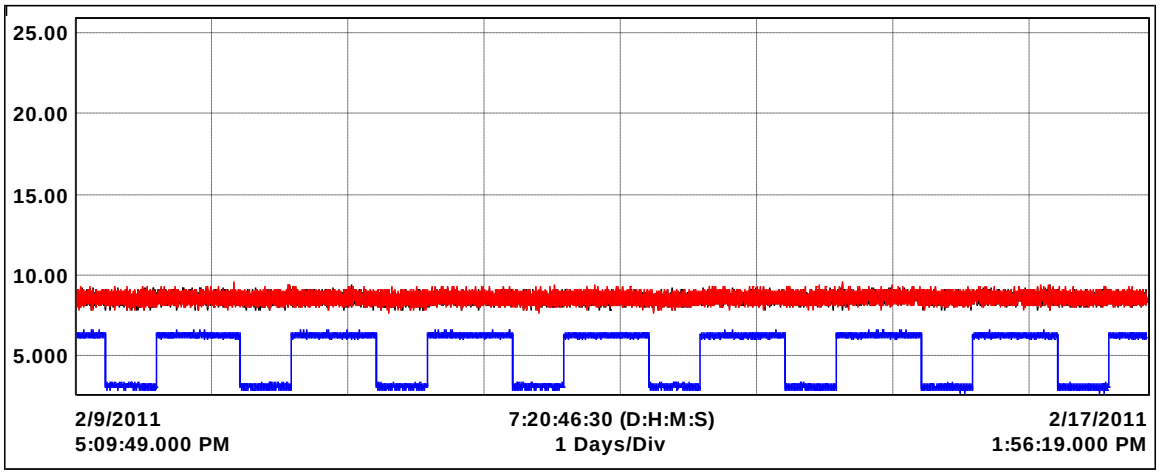


Fig. 4.4.2 Run 2 Week 3, LED Chamber Amps. Leg A (black), Leg B (blue) and Leg C (red).

These two figures illustrate the marked decrease in electrical loads when using the same chamber when it is outfitted with different lighting technologies. Graph lines and figures in Table 4.4.1 also show the variance in electrical draws in the CONTROL chamber in contrast to the much smoother draws in the LED chamber.

		Chamber 1 CONTROL (run 1)	Chamber 1 LED (run 2)
Leg A	Max	9.8	9.4
	Min	6.8	7.8
	Avg.	8.5	8.6
	St. Dev.	0.309	0.238
Leg B (lights ON)	Max	24.8	6.6
	Min	21.9	6
	Avg.	23.7	6.3
	St. Dev.	0.473	0.102
Leg B (lights OFF)	Max	3.9	3.3
	Min	1.7	2.9
	Avg.	2.6	3.1
	St. Dev.	0.585	0.108
Leg C	Max	10	9.6
	Min	7.1	7.7
	Avg.	9	8.6
	St. Dev.	0.349	0.253

Table 4.4.1 Amperage Amounts of Fig. 5.2 and Fig. 5.3. This table shows how the same chamber will respond when outfitted with different lighting treatments. When outfitted with the LED fixtures, all chamber phase legs maintained a more stable operating state.

Lighting Treatment	Leg	Run 1	Run 2	Average of Both Chambers
CONTROL	A	8.5	11.6	10.05
	B (lights ON)	23.69	20.56	22.125
	B (lights OFF)	2.61	2.36	2.485
	C	9	11.1	10.05
LED	A	11.4	8.6	10
	B (lights ON)	5.05	6.28	5.665
	B (lights OFF)	2.31	3.08	2.695
	C	11.1	8.6	9.85

All electrical consumption in terms of Amps.

The chamber brain and accessories consume roughly 2.5 amps at all times.

Table 4.4.2 Chamber Electrical Consumption. This table compares amperage demands of both growth chambers to obtain overall chamber average and eliminate chamber bias. One chamber highlighted in blue, another highlighted in orange.

Chamber in orange had a tendency to draw more amperage on leg A and leg C than did chamber in blue. By subtracting the amperage loads present when lighting elements are OFF, it is evident that lighting in the LED chamber consumes 85% less electricity than the lighting in the CONTROL chamber, a substantial decrease in operational costs.

Chapter 5: DISCUSSION

5.1 Plant Responses

There were no obvious differences in plant growth and growth and development were normal in both chambers and lighting regimes. Germination vigor and plant development appeared similar in most cases with a slight (statistically insignificant) advantage to those bean plants germinated under LEDs. This result supports the hypothesis that LED lighting sources are compatible with plant growth and comparable to standard existing lighting systems regarding normal growth responses.

There was one growth response observed where LED lighting appeared to affect plants differently than was observed with standard chamber lighting. The roots of bean revealed exceptionally healthy nodule development of legume-colonizing, nitrogen-fixing bacteria species *Rhizobium* in the LED grown beans (Fig. 5.1.1 and Fig. 5.1.2). In a symbiotic relationship, the bacteria feed off plant carbohydrates through puncture of the root walls, and in turn fix nitrogen from the air for the plant to then use as nutrients (Decoteau, 2005). A possible explanation is that the soil and air conditions in the LED chamber were much more stable thus allowing for healthier colonization. It is conceivable that the extra nitrogen in combination with the stable environment is part of why the beans in the LED chamber appeared slightly healthier.

Fig. 5.1.1 *Rhizobium* Colonization in Beans. The two leftmost samples are from the LED chamber, and the two rightmost samples are from the CONTROL chamber. Photo taken at conclusion of Run 1.

Fig. 5.1.2 *Rhizobium* colonization in Beans allowed to grow to full maturity (7weeks) in the LED chamber.

5.2 Growth Inputs

A large decrease in water demands was experienced by plants in the LED chamber. Roughly 30% less was added to each plant species. Since the LED chambers required little heat management, little humidity was lost (Fig. 4.3.1). With more humidity and less heat plants were under less stress and transpired less. A benefit of less watering would be the potential need for reduced fertilizer inputs because less fertilizer would be lost due to leaching. Also, even with less water, the soil of the plants under LEDs maintained a higher and more stable moisture level. A possible outcome could be plants would allocate more energy resources for green tissue such as leaf and stem growth instead of having to commit those resources for more root growth in reaction to soil moisture stress and the need to produce more roots in search of water. Fig 5.1.1 shows a common visual observation made; roots were slightly more extensive in the CONTROL chamber and appeared somewhat browned or tinged, while roots in the LED chamber appeared whiter.

5.3 Growth Chamber Responses and Energy Reductions

The results of this study show the significant energy savings potential in a chamber outfitted with LED lighting over a chamber with fluorescents and incandescent. The LED chamber used roughly 85% less electricity for lighting purposes in each chamber. Overall LED chamber electrical consumption decreased by 40% compared to the CONTROL chamber. In an environment that relies solely on supplemental lighting inputs, this savings in electricity could potentially become considerable.

Other components of growth chambers also receive benefits through LED lighting. In this study the chambers were in series using chilled water supply for most of the temperature regulation while the compressors remained ON at all times. This means that most of the energy costs for cooling were incurred off site. Even so, the compressors in the CONTROL chamber did experience greater electrical demands and stress in Legs A and C as evidenced by the much greater variance in electrical demand in legs A and C shown in Fig. 4.4.1. This variance suggests greater cycling of the cooling and heating components and the compressor. The hardest working component of a chamber is the compressor which regulates air temperature. It is very likely that there will be much higher electrical demands and stresses in a “stand-alone” chamber not reliant on chilled water supply.

Unlike conventional lighting sources, LEDs by design convert almost all electricity energy into light, instead of heat. During these experiments and preliminary work not reported here, the chamber with the LEDs never failed. A compressor responsible for cooling a chamber with installed LEDs has very little work load because LEDs emit nearly no heat. Even when the building's chilled water supply was disrupted once and all other chambers operating quickly overheated and shut down, ruining experiments, the LED chamber remained unaffected (Fig. 4.3.4). Because of the extremely low heat output of the LED units the chamber's cooling was not dependant on the chilled water supply and the chamber was able to function without it. Exterior ambient air was clearly sufficient to keep the chamber from overheating. By nearly eliminating heat loads, the LED chamber was a "stand-alone" unit. The chamber and the material inside were less reliant on the external source of chilled water and at less risk of being impacted by these external inputs, lowering the probability of data loss.

Other chamber components with reduced work load in the LED chamber are the humidifiers and fans. The heating of chamber air by conventional lighting causes more water loss because there is more heat removal from the air. This reduces the humidity and causes the plant to transpire more. This transpiration requires the plant to then consume more water (Fig. 4.2.2). All of this makes for an unstable, overstressed growth chamber, and in the end, produces higher risks of crop failure and high operational budgets.

5.4 Potential Growth Chamber LED Retrofitting

To research and crop production budgets these advantages spell new savings across the board. This research indicates the chambers retrofitted with LED units eliminated roughly 40% of overall electrical consumption. Normally the excessive quantities of heat generated by traditional growth chamber lighting applies considerable stress and cycling to HVAC systems and humidifiers. With LED systems in place, it is conceivable these environmental conditioning devices will enjoy an increased life with less maintenance and electrical consumption. The extended life of the LEDs themselves reduces maintenance and lamp replacement costs. And, not being constructed of hazardous materials as are traditional light sources, LEDs require no special or costly strategies for safe use and disposal.

The increased reliability due to the low heat loads and low mechanical demands provides possibly the biggest advantage for researchers. Some research can span months and even a slight chamber malfunction can ruin it in minutes. Research requires high investments of time and money and a reliable chamber is an extremely valuable tool.

5.5 Implications for Greenhouse Crop Production

There is an expanding LED market catering to greenhouse production. During this researcher's investigation of many of these LED units and their possible use in growth chambers, it was concluded many would be ineffective. As the popularity of LED technology quickly develops, researchers and growers must beware of exaggerated claims and misleading spectral data. Table 5.5.1 is an example of the low-grade LED equipment in the greenhouse lighting marketplace. The Grow Panel Pro 300w LED fixture ($1,136) is billed as the best on the market (as they all are). Consider this units advertised spectral characteristics:

1. Although bonus points are given for incorporating PAR units, these PAR levels are too low for adequate photosynthesis in most plants. At 3'10" directly above the meter the fixture emits only 45 PAR. Each Philips' LED fixture used in this study was hung 3'4" above the plant deck and produced an average PAR level of 302 microEinstein/m^2/s (Fig. 4.3.2).
2. Even if we were to base a purchase on the lux measurement, the lux level at 3' 8" is 151 lux, again hardly adequate for most plants.
3. Note the typo in the second row, second to last distance. It should be 150, not 250.

Vertical Distance (cm)	290				203				117			
Horizontal Distance (cm)	0	100	150	200	0	100	150	200	0	100	250	200
Photon Flux Density (m mol • m^{-2} • s^{-1})	9.70	8.17	7.10	5.63	17.47	12.41	8.93	6.33	45.06	15.12	8.57	5.05
Illumminance (Lx)	98.2	82.3	71.3	77.0	175.1	125.2	89.6	63.7	450.6	151.2	85.9	50.6
Irradiance (W • m^{-2})	21.7	1.9	1.6	1.2	38	27	18	13	100	32	18	10

(Measuring Instrument: Licor-6400; FGH-1 • Condition for Measure: Full Dark)

Table 5.5.1 Grow Panel Pro LED Fixture Spectral Characteristics. From www.growlightsupply.com, 2011.

Advertisement for greenhouse LED lighting solutions like above illustrate the necessity for proper understanding of lighting metrics as it relates to plant growth. For the research in this experiment, investigators had to find LED units with intense enough and spectrally acceptable outputs. Architectural LED units designed to illuminate 800 feet up a building façade met these requirements.

Intensive breeding programs continually create new cultivars with characteristics beneficial to greenhouse production. Cultivars may increasingly become less sensitive to R:FR for germination, growth, and reproductive stages depending on SD, LD, and DN genetic programming. However many crops remain photoperiodic and have large responses to light quality. LEDs may offer a way for growers to manipulate phytochrome responses in a semi-controlled environment.

For example, a grower producing a crop of chrysanthemums, a facultative SD plant, needs to decrease the amount of Pfr present in the plant to promote flowering at a desired time (see Fig. 2.1.4). Because of LEDs narrow wavelength outputs, an application of FR light by LEDs may possibly be used as a treatment to revert more Pfr back to the inactive Pr form. Creating enough FR light during daylight hours and produce a Pr:Pfr ratio high enough for flower initiation may not be practical or feasible. Although, applying FR light during dusk and early night should conceivably transform enough phytochrome back to the Pr form. Pfr slowly diminishes as the night progresses, and so a LED treatment of FR light should accelerate this natural process and hasten a flowering response.

Another application of LED technology in greenhouses is in retrofitting existing greenhouse lighting without added infrastructure costs. Many greenhouses were not engineered to support the electrical requirements for photosynthetic lighting. As market trends change crop selection and production systems, greenhouses may need more supplemental lighting to properly adjust. Unfortunately, because of increasing copper prices, new wiring is expensive and labor costs are high. LEDs consume so little electrical energy that capital might be better spent on highly energy efficient lighting with reduced need to waste money on infrastructure.

5.6 Cost Benefit Analysis for The Penn State University

Universities are under quickly increasing pressures to curtail energy consumption in the wake of rising energy rates and slashed operating budgets. Combine this with pressure from the 2007 Federal Energy Bill mandating the elimination of incandescent and certain fluorescent lamps over the next few years, and the need to find solutions becomes abruptly clear. Penn State fully understands it is in this dismal situation and how it must enact swift changes by January 1, 2012 or be in violation of federal law.

Information provided by the Penn State news office and OPP provide background into this predicament for the university. In 2008 the Pennsylvania Utility Commission allowed Penn State's University Park campus electricity supplier, West Penn Power, to lift rate caps starting in 2009. These caps kept rates below market rate, but with them removed, Penn State estimates a massive increase in their electric bill. In 2008, Penn State spent about $13 million on electricity, and, with caps removed, Laura Miller at OPP estimates a $9 million per year increase in electricity costs, and this is only the University Park campus.

Demand for electricity has steadily increased at the University Park campus. Figures compiled starting in 1975 through 2005 show this increase. During 1975-2005 demand grew by 3.1%, during 1990-2005 by 3.9%, during 1995-2005 by 3.1%, and 2000-2005 by 3.5%. Fig. 5.6.1 shows this overall increase of electrical demand of about 3.4%. As other energy sources demands fluctuate, electricity demands maintain a firm trajectory.

Penn State University Park Annual Energy Trend Charts

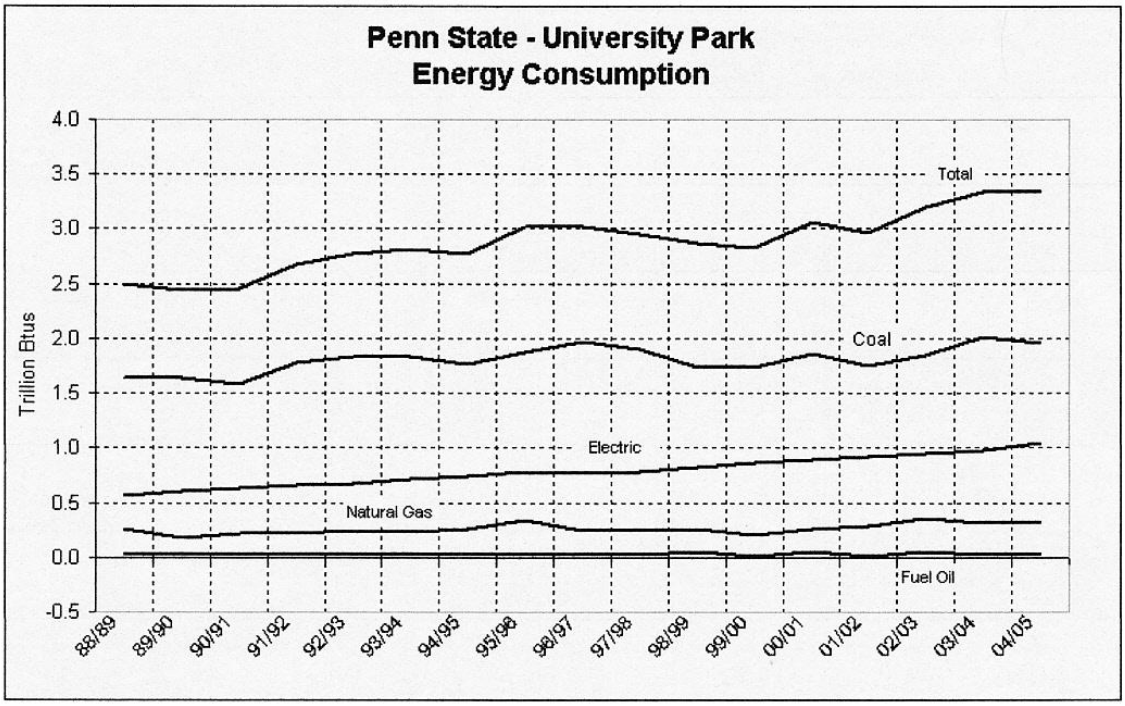


Fig. 5.6.1 PSU University Park Energy Trends.

The Horticulture Department operates the Tyson Building and their September 2010 Energy Report from OPP provides precise figures. That month Tyson used 17,057 TonHr of chilled water at a cost of $3,752, and 47,200 kWh of electricity at a cost of $4,262 (see APPENDIX K for a full breakdown from OPP). By replacing growth chamber lighting from fluorescent and incandescent to LED, the Horticulture Department stands to possibly decrease electrical costs by about $96/ month/ chamber (if under the same operating settings as in this study, and adhering to current electrical rates). Although small and difficult to calculate, the chilled water supply expenses should also decrease.

		CONTROL and LED
Dark Period	over 8 hours	$2.21
	per hour	$0.28

		CONTROL	LED	Savings of:
Light Period	over 16 hours	$8.23	$5.01	
	per hour	$0.51	$0.31	$0.20

Total Costs:	Daily	$10.43	$7.22	$3.21
	Monthly	$312.89	$216.50	$96.39
	Yearly	$3,754.68	$2,598	$1,156.68

Table 5.6.1 Electrical Costs between CONTROL and LED chamber.

Calculations based on:

-Growth chamber LED outfitted with (2) Philips iW Reach Powercore
-Growth chamber CONTROL left stock, using (10x) F72T12 160w fluorescent tubes and (10x) incandescent bulbs
-Leg A and C were both 10 Amps in both chambers
-Lights ON period of 16 hours, OFF of 8 hours
-Market rate electricity of $.10/ kWh
-Voltage in Tyson is 122 volts
-30 day month

Table 5.6.1 illustrates a significant savings in electrical costs for the LED chamber. The table neglects long-term labor and maintenance costs. Each Philips iW Reach Powercore was purchased at discount for $2000 each ($4000 total), each retails at roughly $4000 each ($8000). Simply taking the savings from reduced lighting consumptions of the LEDs, a payback period of the two LED fixtures is about 6.9 years (at retail value of $8000). Lamp replacements, hazardous lamp disposal, ballast replacement, and labor costs will add costs to the CONTROL chamber and shorten the payback period of the LED fixtures.

Switching to a new lighting technology can be initially capital-intensive. New technologies often take time to lower in price in response to increases in market demand and manufacturing scale in combination with technological advancements. While smaller, low-output LEDs have recently experienced dramatic decreases in price, the high-brightness (HB) or high-output (HO) LEDs are still relatively new and prices reflect this. Particular colors of LEDs present manufacturing challenges and prices reflect this as well.

Retrofitting with LEDs may initially be expensive, but the vast savings in operational costs and long life provide a surprisingly short return on investment (ROI). Retrofitting lighting technologies, even without LEDs, will soon be a requirement by law so why not introduce the next evolution in lighting sooner rather than later. The Federal Energy Bill of 2007 mandates that starting in 2012 no 100w incandescent bulbs will be manufactured or allowed to be imported. In 2013 this mandate applies to 75w bulbs, and in 2014, 60w and 40w bulbs are cut. Also, soon to be phased out is the T12 fluorescent tube which is common in commercial settings and equipment such as the growth chambers. According to the National Lighting Board (NLB), a ban effective July 1, 2010, will begin to phase out T12 tubes because of their less efficient magnetic ballasts, although excess inventory and T12 bulbs will continue to be sold

Chapter 6: CONCLUSION

The objective of this study was to begin to evaluate the developing potential of LEDs in a horticultural setting. New technologies are sometimes unfortunately overhyped with misleading information and false promises ahead of their time. Potential users might quickly buy-in, but just as quickly become disillusioned upon discovery of the truth. Valuable research and crop production opportunities might be unnecessarily overlooked as a result. LED lighting is certainly a new and swiftly developing technology and requires thorough examination before possible implementation into to horticultural environment.

In this study LEDs were shown to provide a more stable and potentially more optimal environment within a plant growth chamber, a result of vastly decreased heat loads and electrical demands. As budgets increasingly tighten, energy costs rise, and federal mandates prohibit inefficient lighting technologies, users of plant growth chambers must consider LEDs as the true next evolution of lighting technology.

For all the enticing advantages of LED lighting has to offer, it also has technological obstructions hampering its production costs and immediate adoption industry-wide. LEDs of this brightness and spectral composition are an expensive, but like with all new technology, prices should quickly drop. Some growth chamber users may not be comfortable retrofitting with LEDs yet, and justifiably so as the initial costs are significant. I feel over the next year or two, high-brightness LEDs' prices will lower to a point where the already shown advantages far outweigh the technology investment costs.

BIBLIOGRAPHY

Ahmad, Margaret and Anthony Cashmore. "HY4 Gene of A. Thaliana Encodes a Protein With Characteristics of a Blue-Light Photoreceptor." Nature (1993): 366: 162-166.

Bjorn, L. O. Light and Life. Sevennoaks: Hodder and Stoughton, 1976.

Borthwick, H. A., Hendricks, S. B., Parker, M. W., Toole, E. H., Toole, V. K. "A Reversable Photoreaction Controlling Seed Germination." Proc Natl Acad Sci USA (1952): 38: 662-666.

Briggs, W. R. and E. Huala. "Blue-Light Photoreceptors in Higher Plants." Annual Review of Cell Development Biology (1999): 15: 33-63.

Briggs, W. R. and J. M. Christie. "Phototropings 1 and 2: Versatile Plant Blue-Light Receptors." Trends in Plant Science (2002): 7: 204-210.

Briggs, Winslow R. "Phototropin Overview." Light Sensing in Plants. Hicom, Japan: Springer Media, 2005. 139-146.

Cadena, Richard. Automated Lighting. Burlington: Elsevier, 2006.

Cashmore, Anthony. "A Crytochrome Family of Photoreceptors." Plant Cell Environment (1997): 20: 764-767.

Cashmore, Anthony. "Crytochrome Overview." Light Sensing in Plants. Hicom, Japan: Springer Media, 2005. 121-130.

Clack, T., Mathews, S., Sharrock, R. A. "The Phytochrome Apoprotein Family in Arabidopsis is Encoded by Five Genes: The Sequences and Expression of PHYD and PHYE." Plant Molecular Biology (1994): 25: 413-427.

Davies, Kevin. Plant Pigments and Their Manipulation. Boca Raton: Blackwell Publishing Ltd., 2004.

Decoteau, Dennis. Principles of Plant Science. Upper Saddle River, NJ: Pearson Education Ltd., 2005.

Devlin, P. F., S. R. Patel and G. C. Whitelam. "Phytochrome E Influence Internode Elongation and Flowering Time in Arabidopsis." Plant Cell (1998): 10: 1479-1488.

Dole, John M. and Harold F. Wilkens. Floriculture: Principles and Species, 2nd ed. Upper Saddle River, NJ: Pearson Education, Inc., 2005.

Hart, J. W. Light and Plant Growth. London: Unwin Hyman Ltd., 1988.

Hartmann, Hudson T., Dale E., Davies, Fred T. Jr. Kester and Robert L. Geneve. Plant Propagation: Principles and Practices 7th ed. Upper Saddle River, NJ: Pearson Education, Inc., 2002.

Held, Gilbert. Introduction to Light Emitting Diode Technology and Applications. Boca Raton, FL: Auerbach Publications, 2009.

Huala, E., et al. "Arabidopsis NPH1: A Protein Kinase With a Putative Redox-Sensing Domain." Science (1997): 278: 2120-2123.

Imaizumi, T., et al. "FKF1 is Essential For Photoperiodic-Specific Lighting Signalling in Arabidopsis." Nature (2003): 426: 302-306.

Kasperbauer, Micheal J. "Phytochrome in Crop Production." Wilkinson, Robert E. Plant-Environment Interactions, 2nd ed. New York: Marcel Dekker Inc., 2000. 407-436.

Klein, H. H. "Repression of Tissue Culture Growth by Visible and Near-Visble Radiation." Plant Physiology (1964): 39: 539-546.

LI-COR Ltd. Radiation Measurements and Instrumentation. Lincoln, NE, 1982.

Lin, C. and D. Shalitin. "Crytochrome Structure and Signal Transduction." Annual Review of Plant Biology (2003): 54: 469-496.

Nagy, F. and E. Schafer. "Phytochromes Control Photomorphogenesis by Differentially Regulated, Interacting Signaling Pathways in Higher Plants." Annual Review of Plant Physiology and Plant Molucular Biology (2002): 3: 329-355.

Nagy, Ferenc and Eberhard Schafer. "Phytochromes Control Photomorphogenesis by Defferentially Regulated, Interacting Signalling Pathways in Higher Plants." Annual Reviews Plant Biology (2002): 329-355.

Nelson, Paul V. Greenhouse Operation and Management, 6th ed. Upper Saddle River, NJ: Prentice Hall, 2003.

Quail, P. H. "Phytochrome Photosensory Signalling Networks." National Review of Molecular Cell Biology (2002): 3: 85-93.

Quail, Peter H. "Phytochrome Overview." Light Sensing in Plants. Hicom Japan: Springer Media, 2005. 21-35.

Reppert, S. M. and D. R. Weaver. "Coordination of Circadian Timing in Mammals." Nature (2002): 418: 935-941.

Sager, J. C., et al. "Photosynthetic Efficiency and Phytochrome Photoequilibria Determination Using Spectral Data." 1988.

Smith, H. Photomorphogenesis in Plants, 2nd ed. Netherlands: 1994, 1994.

—. "Phytochromes and Light Signal Perception by Plants - and Emerging Synthesis." Nature (2000): 407: 585-591.

Smith, H., G. C. Whitelam and A. C. McCormac. "Do the Members of the Phytochrome Family Have Different Roles? Physiological Evidence From Wild-Type, Mutant and Transgenic Plants." Thomas, Brian and Christopher B. Johnson. Phytochrome Properties and Biological Action. Berlin: Springer-Verlag, 1991. 217-236.

Vince-Prue, Daphne. "Light and Flowering Process." Cockshull, K. E,, Bryan Thomas and Daphne Vince-Prue. Light and The Flowering Process. London: Academic Press, Inc., 1984. 3-15.

Vince-Prue, Daphne. "Phytochrome Action Under Natural Conditions." Thomas, Brian and Christopher B. Johnson. Phytochrome Properties and Biological Action. Berlin: Springer-Verlag, 1991. 313-319.

Wada, Masamitsu. "Preface." Light Sensing in Plants. Hicom, Japan: Springer Media, 2005. V.

APPENDIX A:

Useful Internet Websites:

Philips Lighting Division
http://www.usa.lighting.philips.com
http://www.philipslumileds.com/products

Electronic Theatre Controls, ETC
http://www.etcconnect.com

Penn State University Office of Physical Plant, OPP, Energy Department
http://energy.opp.psu.edu/

APPENDIX B: LED Doping Material and Wavelength Output Chart

(List does not include all known combinations, only major examples)

Color	Wavelength (nm)	Semiconductor material
Infrared	$\lambda > 760$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
Blue	$450 < \lambda < 500$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	$400 < \lambda < 450$	Indium gallium nitride (InGaN)
Purple	multiple types	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	Diamond (235 nm) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)
White	Broad spectrum	Blue/UV diode with yellow phosphor

Chart Adapted as Shown Courtesy of Wikipedia.com, 2011.

APPENDIX C: DMX-512 Protocol and Basic Programming

Simply put, DMX-512 is the worldwide standard in entertainment and architectural lighting language. It allows various lighting and other technology to communicate without proprietary or regional issues (Cadena, 2006). The United States Institute for Theatre Technology (usitt.org) may state it best,

> *"DMX512 is a standard that describes a method of digital data transmission between controllers and lighting equipment and accessories. It covers electrical characteristics (based on the EIA/TIA–485 standard), data format, data protocol, and connector type. This standard is intended to provide for interoperability at both communication and mechanical levels with controllers made by different manufacturers."*

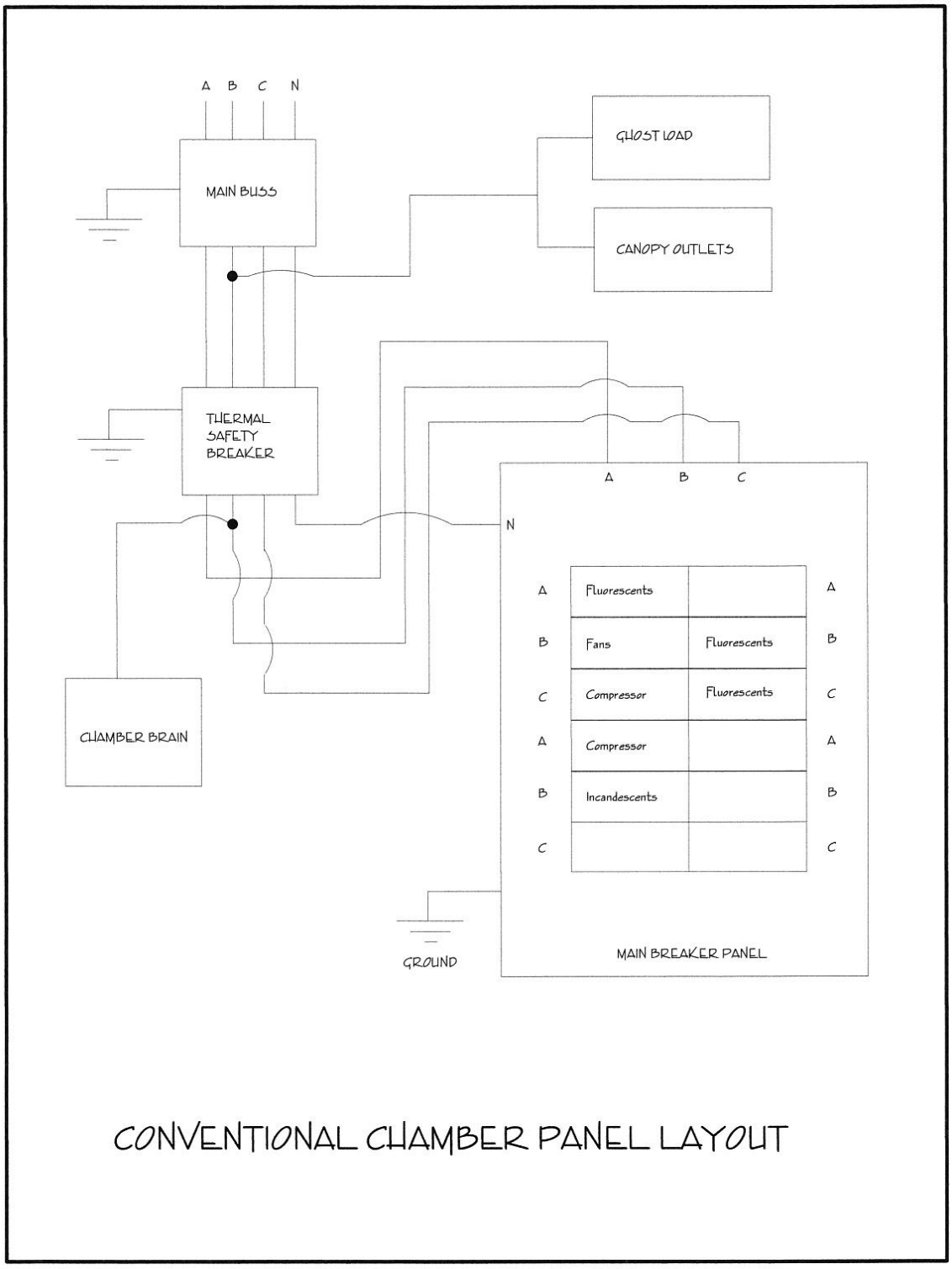
APPENDIX D: Cue List Program for LED Fixtures

Expression 3 Version 3.11 — Electronic Theatre Controls, Inc.
Page 1 — 30 March 2011

Cue List

Cue/Type	Up/Down	Wait	Link	Follow	Rate	Label
1	30	0		90:00		Light WarmUp
2	5			90:00		
3	5			90:00		
4	5			90:00		
5	5			90:00		
6	5			90:00		
7	5			90:00		
8	5			90:00		
9	5			90:00		
10	5			60:00		
11	5	30		90:00		Dark Period
12	5			90:00		
13	5			90:00		
14	5			90:00		
15	5			90:00		
16	5			90:00		
17	5		1	30:00		

APPENDIX E: Wiring and Load Diagram of CONTROL EGC



CONVENTIONAL CHAMBER PANEL LAYOUT

Schematic by William Kenyon.

APPENDIX F: Philips iW Reach Powercore Specification Sheets

Date: _____ Type: _____

Firm Name: _____

Project: _____

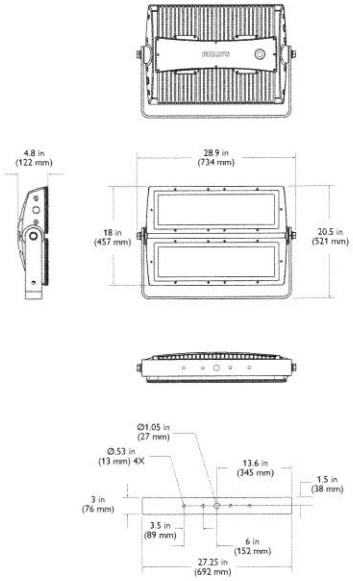
iW Reach Powercore

40° Spread Lens

Intelligent white LED floodlight for signature façades and structures

iW® Reach Powercore, the intelligent white light version of our flagship, high-performance exterior architectural floodlight, is the first LED fixture powerful enough to brilliantly illuminate large architectural façades with washes of white light in color temperatures ranging from a warm 2700 K to a cool 6500 K. iW Reach Powercore combines all the benefits of LED-based lighting in an elegant fixture specifically designed for large-scale installations, such as commercial skyscrapers, casinos, large retail exteriors, bridges, piers, public monuments, and themed attractions. With significantly more lumen output than any other competitive fixture and unprecedented light projection of over 800 ft (243.8 m), this powerful fixture represents the next generation in exterior illumination.

- Integrates Powercore® technology — Powercore technology rapidly, efficiently, and accurately controls power output to iW Reach Powercore fixtures directly from line voltage. The Philips iW Data Enabler merges line voltage with control data and delivers them to the fixture over a single standard wire, dramatically simplifying installation and lowering total system cost.
- Unparalleled light output — With an output of over 10,000 lumens and light projection of over 800 ft (243.8 m), iW Reach Powercore is the first fixture to offer legitimate LED-based, color-controllable white light illumination of large-scale structures and objects.
- Wide range of color temperature and brightness — Channels of warm white and cool white LEDs produce color temperatures ranging from 2700 K to 6500 K. Fixture brightness can be adjusted while varying or maintaining constant color temperature.
- Versatile optics — Exchangeable spread lenses of 8°, 13°, 23°, 40°, 63°, and an asymmetric 5° x 17° support a variety of photometric distributions for a multitude of applications, including spotlighting, wall grazing, and asymmetric wall washing. Bezel and gasket ship with spread lenses for easy user installation.
- Simple fixture positioning — Rugged, slim-profile mounting bracket allows simple positioning and fixture rotation through a full 360°. Side locking bolts reliably secure fixture with standard wrench.
- Universal power input range — iW Reach Powercore accepts a universal power input range of 100 to 240 VAC, allowing simple, location-independent installation.



For detailed product information, please refer to the iW Reach Powercore Product Guide at www.colorkinetics.com/ls/intelliwhite/iwreach/

PHILIPS

Specification Sheets Courtesy of Philips International, at colorkinetics.com.

Specifications

Due to continuous improvements and innovations, specifications may change without notice.

Item	Specification	Details
Output	Beam Angle	8° / 13° / 23° / 40° / 63° spread lenses, 5° x 17° asymmetric spread lens
	Lumens†	4,692 (40° spread lens, half unit)
	Color Temperature	2700 K – 6500 K
	Efficacy (lm/W)	37.5 (40° spread lens, half unit)
	CRI	68.5
	Mixing Distance	50 ft (15.2 m) to uniform light
	Lumen Maintenance‡	70,000 hours L_{70} @ 25° C 37,000 hours L_{70} @ 50° C 90,000 hours L_{50} @ 25° C 68,000 hours L_{50} @ 50° C
Electrical	Input Voltage	100 – 240 VAC, auto-switching, 50 / 60 Hz
	Power Consumption	250 W maximum at full output, steady state (full unit)
	Power Factor	.981 (40° spread lens, half unit)
Physical	Dimensions *(Height x Width x Depth)*	20.5 x 28.9 x 4.8 in (521 x 734 x 122 mm)
	Weight	75 lb (34 kg)
	Effective Projected Area (EPA)	0.42 m^2
	Housing	Die-cast aluminium, powder-coated finish
	Lens	Tempered glass
	Fixture Connections	6 ft (1.8 m) unified power / data cable
	Operating Temperature	-40° – 122° F (-40° – 50° C) Operating -4° – 122° F (-20° – 50° C) Startup
	Humidity	0 – 95%, non-condensing
	Fixture Run Lengths Per iW Data Enabler*	5 @ 110 VAC 6 @ 120 VAC 11 @ 220 VAC 12 @ 240 VAC *Configuration:* *20 A circuit, standard 6 ft (1.8 m) Leader Cables, 5 ft (1.5 m) jumper cables*
Certification and Safety	Certification	UL / cUL, FCC Class A, CE
	LED Class	Class 2 LED product
	Environment	Dry / Damp / Wet Location, IP66

† Lumen measurement complies with IES LM-79-08

‡ See iW Reach Powercore Product Guide for specific applications

* These figures, provided as a guideline, are accurate for this configuration only. Changing the configuration can affect the fixture run lengths.

Fixtures and Accessories

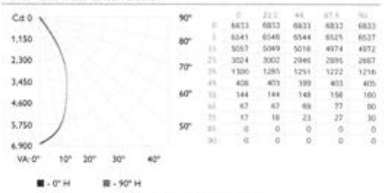
Item	Type	Item Number	Philips 12NC
iW Reach Powercore *Includes 6 ft (1.8 m) leader cable*	UL / cUL and CE / PSE	523-000045-00	910503700625
Replacement Leader Cable 6 ft (1.8 m)	UL / cUL	108-000043-02	910503700453
	CE / PSE	108-000043-03	910503700454
iW Reach Powercore Spread Lens with bezel	13°	120-000068-00	910503700506
	23°	120-000068-01	910503700507
	40°	120-000068-02	910503700508
	63°	120-000068-03	910503700509
	5° x 17°	120-000068-04	910503700510
	8°	120-000068-05	910503700511
iW Data Enabler	UL / cUL	506-000001-00	910503700190
iW Data Enabler / Data Enabler Aux *For CE / PSE installations only*		506-000001-01	910503700791
iW Scene Controller		503-000001-00	910503700189

Use Item Number when ordering in North America.

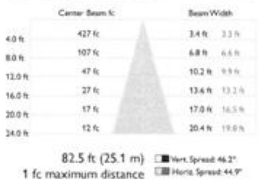
Photometrics

40° Spread Lens

Polar Candela Distribution



Illuminance at Distance



82.5 ft (25.1 m)
1 fc maximum distance

■ Vert. Spread: 46.2°
■ Horiz. Spread: 44.9°

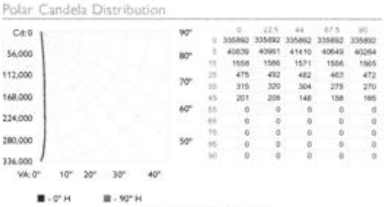
Half

Power Consumption	125 W
Lumens	4,692
Efficacy	37.5 lm/W

For lux multiply fc by 10.7

Without spread lens, half unit

Polar Candela Distribution



Illuminance at Distance

579 ft (176.5 m)
1 fc maximum distance

■ Vert. Spread: 5.4°
■ Horiz. Spread: 5.4°

Power Consumption	125 W
Lumens	5,406
Efficacy	43.2 lm/W

iW Reach Powercore fixtures are part of a complete line-voltage system which includes fixtures and:

- One or more iW Data Enablers.
- One Leader Cable to connect each fixture to a junction box or iW Data Enabler.
- 4-conductor copper wire to connect fixtures in series or in parallel.
- iW Scene Controller (up to four per single run of iW Data Enablers).

For detailed product information, please refer to the iW Reach Powercore Product Guide at www.colorkinetics.com/ls/intelliwhite/iwreach/

Philips Color Kinetics
3 Burlington Woods Drive
Burlington, Massachusetts 01803 USA
Tel 888.385.5742
Tel 617.423.9999
Fax 617.423.9998
www.colorkinetics.com

DAS-000030-05 R01 08-09

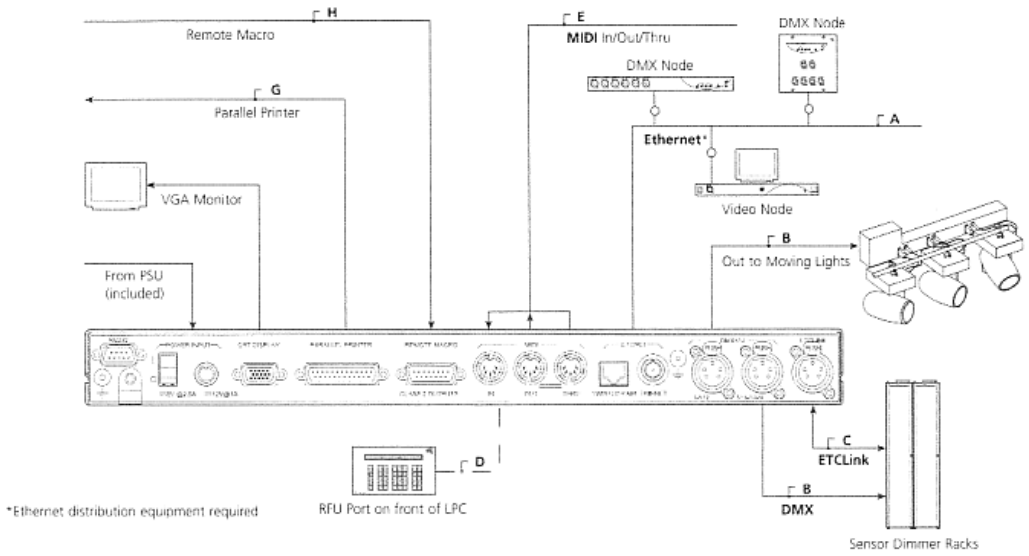
Specification Sheets Courtesy of Philips International, at colorkinetics.com.

APPENDIX G: ETC Express™ Lighting Playback Control Unit

ETC — Express™ Lighting Playback Control

LPC Series

TYPICAL SYSTEM RISER DIAGRAM



Express LPC Connection Wires

Device	Wire Type	
Sensor Racks	**DMX** (XLR5) (1) Belden 9729 **ETCLink** (XLR6) (1) Belden 9729 (2) #16 AWG Stranded	B C
Video Node	**Category 5** Ethernet (UTP) 1-Belden 1583 RJ45	A
DMX Node rack mount	**Category 5** Ethernet (UTP) 1-Belden 1583 RJ45	A
DMX Node wall mount	**Category 5** Ethernet (UTP) 1-Belden 1583 RJ45	A

Device	Wire Type	
MIDI	Standard **MIDI** Cables 5 Pin Din Connector	E
DMX (Out)	**DMX** (XLR5) Belden 9729	B
Printer - Parallel	Standard Parallel Printer Cable	G
Remote Macro	DB 15 Consult Manual or ETC Technical Services for details	H
Remote Focus Unit	**RFU** (XLR6) (1) Belden 9728 (2) #16 AWG Stranded	D

Express LPC Dimensions*

Model	Height		Width		Depth	
	inches	cm	inches	cm	inches	cm
Express LPC	1.8	4.5	17.0	43.2	12.5	32.0

Express LPC Weights*

Model	Weight		Shipping Weight	
	lbs	kgs	lbs	kgs
Express LPC	11.0	5.0	18.3	8.3

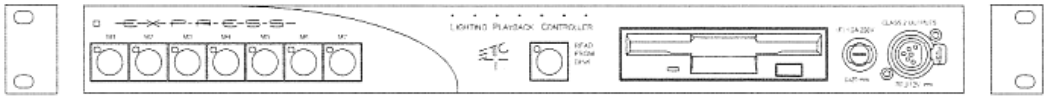
*Weights and Dimensions typical

Corporate Headquarters ▪ 3031 Pleasant View Rd, PO Box 620979, Middleton WI 53562 0979 USA ▪ Tel +1 608 831 4116 ▪ Fax +1 608 836 1736
London, UK ▪ Unit 26-28, Victoria Industrial Estate, Victoria Road, London W3 6UU, UK ▪ Tel +44 (0)20 8896 1000 ▪ Fax +44 (0)20 8896 2000
Rome, IT ▪ Via Ennio Quirino Visconti, 11, 00193 Rome, Italy ▪ Tel +39 (06) 32 111 683 ▪ Fax +39 (06) 32 656 990
Holzkirchen, DE ▪ Ohmstrasse 3, 83607 Holzkirchen, Germany ▪ Tel +49 (80 24) 47 00-0 ▪ Fax +49 (80 24) 47 00-3 00
Hong Kong ▪ Room 605-606, Tower III Enterprise Square, 9 Sheung Yuet Road, Kowloon Bay, Kowloon, Hong Kong ▪ Tel +852 2799 1220 ▪ Fax +852 2799 9325
Web ▪ www.etcconnect.com ▪

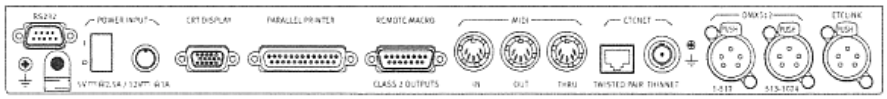
ETC

Express™ Lighting Playback Control

LPC Series



FRONT VIEW



REAR VIEW

GENERAL INFORMATION

Complete automated show control in compact unit. Playback of shows prerecorded on ETC Express console.

APPLICATIONS
- Show Control
- Store Windows
- Themed Retail
- Themed Restaurants

FEATURES
- 1024 DMX outputs
- 600 Cues
- 500 Groups
- 2000 Macros
- Ethernet for DMX, Video and other signal distribution
- MIDI, MIDI Show Control and MIDI Time Code interface
- Astronomical Time Clock
- 4 Remote Macro Inputs
- Remote Trigger
- Supports ETCLink Dimmer feedback
- 1U 19" rack, table or wall mount

ACCESSORIES
- Video Node
- DMX Node
- Remote Focus Unit (RFU)
- Expression Offline
- Expression Offline for Windows

For full product specifications, please consult Express data sheet

ORDERING INFORMATION

Express LPC

Model#	Description
LPC/96	96 - channel Express LPC
LPC/192	192 - channel Express LPC
LPC/250	250 - channel Express LPC

Express LPC Accessories

Model#	Description
DNODE-RF	DMX Node - rack mount front entry
DNODE-RB	DMX Node - rack mount rear entry
DNODE-W	DMX Node - wallbox mount
VNODE-R	Video Node
RFU	Remote Focus Unit
M218	VGA Color Monitor
M219	LCD Flat Screen Display
4000A4003	Monitor Dust Cover
M604	Parallel Printer
EOL	Expression Offline

Electrical

- Voltage input 100-240 VAC, 50-60 Hz
- Maximum current 0.8 amps

Built-in interfaces

- 1,024 DMX512 outputs – 2 universe
- Parallel printer
- RS-232C serial port
- Remote Focus Unit
- Supports CE dimming systems
- Remote Macro control
- Remote Trigger option
- MIDI time code control
- ETCLink

System capacity

- 600 cues per show
- 96, 192 or 250 control channels
- Proportional patching of up to 1,024 DMX512 dimmers
- Eight-part multipart cues
- Thirty-three dimmer profiles, all but one of which are editable
- 500 groups
- 99 focus points
- 2,000 macros
- 24 overlapping submasters
- Ten pages of submaster memory

Playback controls

- Seven front panel push-buttons

Timed control

- Internal or external clock
- 12-hour or 24-hour timing
- References sunrise and sunset with astronomical clock
- Up to 500 user-created, Real Time Programs

Display functions

- VGA video output
- Stage
- Blind
- Fader
- Effects
- Spreadsheets: Cues, Submasters, Groups and Focus Points
- Patch
- Park
- Setup
- Flexichannel (displays only recorded channels)
- Channel attributes

Submaster functions

- Ten pages of 24 recorded submasters each
- Fully overlapping channel assignments
- Proportional channel levels
- Programmable fade and wait times
- Live and programmed rate control
- Submasters either overlapping pile-on or inhibitive
- All submasters programmable with effects
- Update function
- Control keypad features
- Spreadsheet editing
- Submaster list

Channel functions

- 8-bit and 16-bit data types
- Both highest level (Highest Takes Precedence) and last action (Latest Takes Precedence) channel types
- Group function to allow channels to be manipulated as proportionally balanced groups
- [And], [Except], [Only], and [Thru] functions to select
- [Full] function
- [Level] sets a channel to a user-selectable default value
- Independent channels
- Flip channel

Moving light functions

- Fixture personalities load from diskette
- Patch fixtures by assigning personalities, starting channels, starting DMX512 address, remote dimmer, swap focus, pan or tilt flip
- Five attribute categories
- Fixture box level adjustment
- Fixture focus with Solo

Cue functions

- Up to 600 cues in the range 0.1 to 999.9
- Discrete upfade and downfade times (00:00-99:59) for each cue
- Linked cue sequences
- Effect cues
- Split wait times
- Follow time
- Link to cue or macro
- Eight-part multipart cues
- Selective cue recording
- Update cue command
- Attribute range editing
- Subroutines, with cue or style steps
- Spreadsheet editing
- Cue list

Group functions

- Up to 500 groups
- Any cue or submaster may be accessed as a group
- Spreadsheet editing
- Group list

Focus point functions

- up to 99 preset focus points
- Update cues and submasters when focus point changes
- Record level of focus point without link
- Available in effects
- Printout available
- Spreadsheet editing
- Focus point list

Diskette functions

- 3.5-inch high-density diskette drive for show storage
- One show per disk
- Software updates installed through diskette drive
- Retrieve show and configuration contents separately or together

Macro functions

- Seven front panel push-button macro controls
- Up to 2,000 macro selections for programming
- Macros may activate any control sequence
- Live Learn mode
- Macro editing
- Macros programmable for **Macro wait**
- Can include in real time programs
- Can include in time code events
- Four macros operated by remote switches
- Powerup macro
- Remote Trigger function

Effects functions

- Effects may be recorded as cues or submasters
- Up to 100 steps each
- Live effects recording
- Spreadsheet editing
- 8-bit and 16-bit data types
- Variability of rate during playback
- Step times
- In/Dwell/Out Step fade times
- High/Low Levels
- In/Dwell/Out Effect fade times
- Range editing of effect attributes and step values

Profile functions

- Profiles may be assigned to dimmers
- Ten preset profiles, nine of which are editable
- Twenty-three additional profiles that may be programmed

Options

- Parallel printer
- Remote Focus Unit
- Remote Macro controls
- Remote interface devices

APPENDIX H: Run 1 Watering Data

Watering Record			Watering Performed by:		
LED Experiment #2				Daniel Frechen	
Start: 12-13-2010				William Kenyon	
End: 1-3-2011					
Date:		Beans	Radish	Rye Grass	Watering by:
13-Dec	LED	initial planting			
	Control				
15-Dec	LED	430	250	350	D+W
	Control	740	270	570	
17-Dec	LED	310	180*	290	D+W
	Control	740	230*	390	
19-Dec	LED	510	260	690*	D
	Control	740	250	740*	
21-Dec	LED	380*	290	360	D
	Control	670*	550	680	
23-Dec	LED	450	340	350	D
	Control	740	440	460	
25-Dec	LED	290	200	175	W
	Control	340	260	200	
27-Dec	LED	330	275	260	W
	Control	445	375	380	
29-Dec	LED	500	360	410	W
	Control	670	490	520	
31-Dec	LED				
	Control	chamber malfunction			
2-Jan	LED				
	Control				
3-Jan	Harvest				
Totals water applied in 8 periods		Beans	Radish	Rye Grass	
	LED	2820	1975	2195	
	Control	4415	2635	3200	
Avg. portion of water applied per 2 days		Beans	Radish	Rye Grass	
	LED	352.5	246.875	274.375	
	Control	551.875	329.375	400	
Note:	Replaced 5 incandescent lamps before Exp. #2 began.				
	Replaced 1 incandescent lamp on 2/25.				
	Replaced 1 incandescent lamp on 2/29.				
	Replaced 4 before Exp #3 began.				

APPENDIX I: Run 2 Watering Data

Watering Record			Watering Performed by:		
LED Experiment #3				Daniel Frechen	
Start: 1-27-2011				William Kenyon	
End: 2-18-2011					
Date:		Beans	Radish	Rye Grass	Watering by:
27-Jan	LED	initial planting			
	Control				
29-Jan	LED	120	90	90	D
	Control	120	90	90	
31-Jan	LED	330	290*	460	D
	Control	410	220*	390	
2-Feb	LED	290	220	280	D
	Control	540	250	540	
4-Feb	LED	500*	230	270*	D
	Control	590*	200	410*	
6-Feb	LED	390	250	180	D
	Control	410	350	330	
9-Feb	LED	450	340	220	D
	Control	670	520	490	
11-Feb	LED	260	220	265	W
	Control	315	235	180	
13-Feb	LED	530	280	320	D
	Control	740	360	440	
15-Feb	LED	540	360	340	D
	Control	740	410	590	
17-Feb	LED	Harvest	Harvest	Harvest	
	Control	Harvest	Harvest	Harvest	
Totals water applied in 8 periods		Beans	Radish	Rye Grass	
	LED	2910	1990	2155	
	Control	3945	2415	3050	
Avg. portion of water applied per 2 days		Beans	Radish	Rye Grass	
	LED	363.75	248.75	269.375	
	Control	493.125	301.875	381.25	
Note:	Replaced 6 incandscent lamps by experiment #3 conclusion.				

APPENDIX J: Materials Used List

Data Measurement and Recording:

1 – Onset HOBO U30 NRC – USB Logger
1 – Onset Adapter Kit for U30, increases sensor input from 5 to 10 (15 total)
2 – Sentinel Logger with triple phase adapters
5 – Onset Temperature Sensor w/ 6m cable
3 – Onset Temperature/ RH Sensor w/ 8m cable
2 – Onset Photosynthetic Light (PAR) Sensor w/ 3m cable
2 – Onset Soil Moisture Sensor, 10 cm w/ 5m cable
2 – Onset Magnelab 0-50amp Split-Core AC current transformer
1 – Onset Flex Smart TRMS Module (2 channels) w/ modular plug
1 – StellerNet Inc. spectroradiometer
1 – Extech Photometry meter

*All temperature and relative humidity (RH) sensors were NIST calibrated before installation and use. Records remain on file with author.

Data Processing:

Onset HOBOware Pro Software
DataView v2.04, Chauvin Arnoux Inc.
Sentinel SL2 version 1.02, Chauvin Arnoux Inc.
Spectrowiz Software
Microsoft Excel

Lighting Equipment:

2 – Philips iW Reach Powercore LED unit outfitted w/ 23 degree spread lens
1 – Philips Data Enabler
100-150’ DMX-512 data cable
16 – 160w T-12 Fluorescent lamps
12 – 100w Incandescent lamps

Lighting Control Equipment:

1 – ETC Expression lighting playback controller (LPC)(APPENDIX G)
1 – ETC remote (RFU)
1 – ETC Expression Offline Editor
1 – USB external floppy disk drive

Environmental Growth Chamber Type:

2 – Environmental Growth Chamber (EGC)

- each dual door, reach-in style, 70 sq. ft.
- onboard programming console
- water supply shared amongst all chambers in room and building

Plant and Potting Material:

1 – packet(175 count) EZ Pick bush beans (*Phaseolus vulgaris*)

1 – packet(265 count) D'Avignon Long French radish (*Raphanus sativus*)

1 – 60lb bag Double Eagle perennial ryegrass (*Lolium perenne*)

Potting soil is Sunshine #5 Mix

APPENDIX K: Tyson Building Energy Report

PENNSTATE

Office of Physical Plant

Building Energy Report

Utility Month: Sep-10

Tyson Bldg

Click Here for Building Photo
Building Number: 0110000
College of Agricultural Sciences
Construction Year: 1949
Gross sq.ft.: 45,780.00
Assignable sq.ft.: 28,569.00

Smart Energy Tip:
Buy Energy Star rated equipment, which can be found at www.energystar.gov

Penn State Energy Projects:
Continuous Commissioning Program
Energy Saving Program
Energy Conservation Measures

Energy Units and Costs
Sep-10 month only

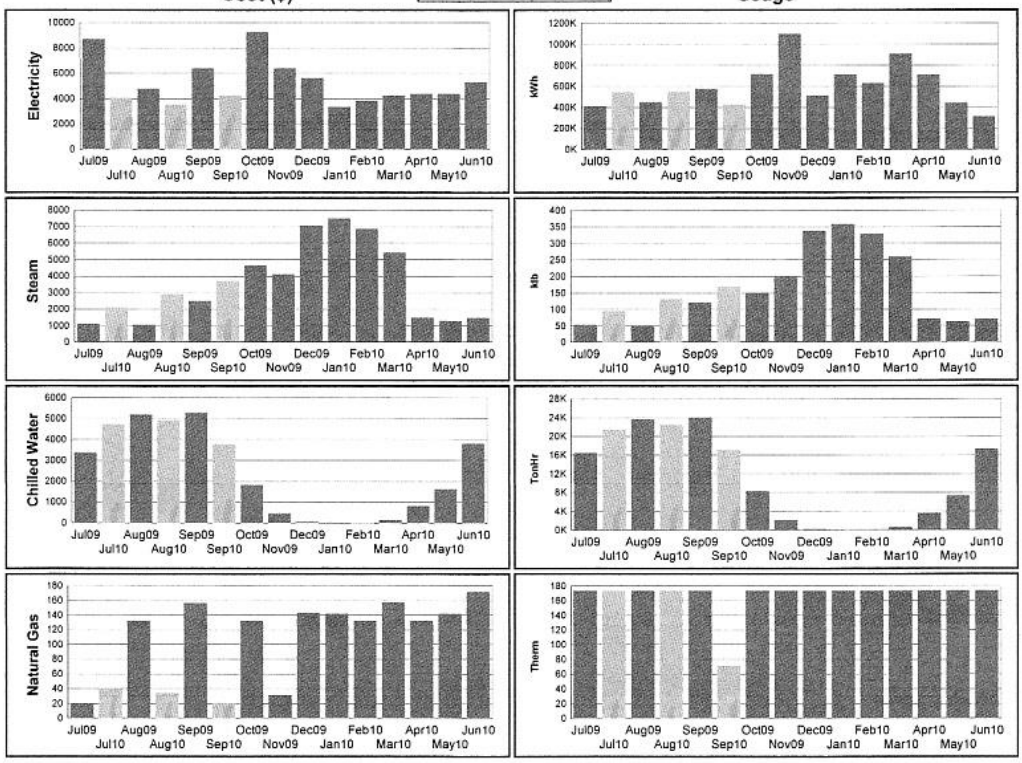
Utility	Units	Cost
Chilled Water	17,056.46 TonHr	$3,752.42
Electricity	47,200.00 kWh	$4,261.61
Natural Gas	10.20 Therm	$9.87
Steam	167.67 klb	$3,717.18
	Total:	$11,741.08

Sep-09

Chilled Water	24,003.88	TonHr	$5,280.85
Electricity	63,600.00	kWh	$6,391.40
Natural Gas	0.00	Therm	$0.00
Steam	119.46	klb	$2,502.62
		Total:	$14,174.87

Previous Fiscal Year
Fiscal Year to Date

Cost ($) | **Usage**



Request Additional Data

Report Energy Waste