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Project 5.2 Evaluation of Electronic Ballasts and Related Controls for HID Lighting Systems

FINAL REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for Project 5.2 under Contract Number 500-01-041, conducted by Lawrence Berkeley National Laboratory. The report is entitled Evaluation of Electronic Ballasts and Related Controls for HID Lighting Systems. This project contributes to the PIER Lighting Research Program.

The key deliverables for each project, in the form of guidelines and technical reports, are attachments to this report and are listed and described at the start of the attachment section. Due to market dynamics and the normal passage of time between the completion of research and the publication of research results, products anticipated for market delivery in this report may not necessarily reflect the actual array of products as delivered, or planned for delivery, by manufacturers. Therefore, the reader is advised to contact the lighting product manufacturers directly to ascertain the current status of products.

For more information on the PIER Program, please visit the Commission's web site at http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at (916) 654-5200.

Abstract

This report describes the results of a research effort to characterize the performance of electronic ballasts operating metal halide lamps. For systems below 200 watts, the performance of two lamp types, quartz and ceramic metal halide (CMH), were compared. The study found that CMH lamps were the lamps of preference for several reasons, including improved efficacy, reduced lumen depreciation, better color rendering, greater color stability, and more flexibility in lamp construction. The study also found that the electronic ballasts were the preferred technology for this application, resulting in higher lamp/ballast system efficacy, maintained flux and color quality, and improved efficiency over halogen and incandescent sources.

With regard to lamp/ballast systems greater than 200 watts, the study found that the controllable electronic ballast lighting systems have performance characteristics that limit the use of the technology in this application. These deficiencies include reduced efficacy with reductions in power, reduced light output at 75% of full power, and degraded color quality below 75% of full power. Comparison of the system performance characteristics to other competing technologies suggests that the studied technology may not be the most cost effective and effective method for achieving controllable lighting in daylit spaces having high ceilings.

Executive Summary

Introduction

The past 10 years has seen a significant advancement in technologies associated with high intensity discharge (HID) lamps. This includes the incorporation of ceramic lamp envelopes and the ability to construct lamps with very exact dimensions. This has permitted the development of low wattage metal halide sources that have comparable light output to less efficient point-source technologies such as incandescent and halogen lamps, creating the opportunity for these systems to be used in retail and commercial applications. Magnetic ballasts have traditionally ballasted metal halide sources. Electronic ballasts have been available, but their market penetration has been limited due to size, cost, and efficiency. Recent developments in electronic circuitry suggest that these barriers have been overcome. Additionally, this new ballast technology can now provide variable light control. The ability to control the light expands the opportunity of the new electronic ballast to reduce lighting loads in spaces that have supplemental daylight.

The current electronic ballast technologies are new to the market and are not being readily adapted by luminaire manufacturers due to the uncertainty in proven performance. To date, there has been no independent study of the performance of these new systems, aside from manufacturer's claims. Project 5.2 has performed an evaluation of available commercial product to better define the operation characteristics and energy saving opportunity of the technology. With this information, it is expected that the adoption of this new energy efficient technology can be accelerated.

Project Objectives

The goals of this project are to:

- Test, analyze and determine the potential of electronic ballasts for HID lighting systems in cooperation with manufacturers as an emerging energy efficient technology to reduce lighting loads in commercial, industrial, and municipal applications.
- Identify control strategies to further improve the energy efficiency of these systems with a municipal partner.
- Provide appropriate recommendations for incorporating these technologies into current state codes and regulations.

The objective of this project is to evaluate the potential of electronic ballasts and related controls for HID lighting systems to improve the efficiency of current technology. These technologies promise to improve the operating efficiency of HID lighting systems by as much as 40 percent through improved performance in both the ballast and lamp operation, and through control of the light output. Special attention will be paid to applications that replace less efficient light sources and that provide control of the light output. Electrical and photometric characteristics of the lamp, ballast, and lighting

systems will be tested, and the results will be compared to the current technology of magnetic ballasted systems. The evaluation will determine the performance improvements for each component of the system. ANSI standards will be followed in performing these tests. The energy savings potential for applications in California will be analyzed and estimated.

Conclusions

The conclusions of Project 5.2 are divided according to the wattage of the lamp ballast system. For lamp/ballast systems of less than 200 watts, the study focuses on the performance of electronic ballasts operating two different lamp types, quartz and ceramic metal halide (CMH). The application of this technology could result in the replacement of less efficient incandescent and halogen sources with these more efficient systems. The study found that CMH lamps were the lamps of preference for several reasons, including improved efficacy, reduced lumen depreciation, better color rendering, greater color stability, and more flexibility in lamp construction.

The study also found that the electronic ballasts were the preferred technology for this application for the following reasons:

1. The electronic lamp/ballast system efficacy was 10% higher than the comparable magnetic systems for wattages equal to or greater than 70 watts.
2. For lamp wattages below 70 watts, the electronic lamp/ballast system efficacy was greater than 10% higher than the comparable magnetic systems and increased with decreasing lamp wattage.
3. The electronic ballast maintains a constant power over a variance of 10 % of line voltage, resulting in a maintained flux and color quality.
4. The electronic lamp/ballast systems are 3 to 4 times more efficient than halogen sources and 4 to 5 times more efficient that standard incandescent sources.

With regard to lamp/ballast systems greater than 200 watts, the study found that the controllable electronic ballast lighting systems have performance characteristics that limit the use of the technology in the intended applications of the study for the following reasons:

1. While the efficiency of the ballast is maintained over the controllable range, the efficacy of the lamp and system decrease with any reduction in power.
2. The light output of the source falls to 50% at 75% of full power.
3. The color quality of the light significantly degrades below 75% full power.

Comparison of the system performance characteristics to other competing technologies suggests that the studied technology may not be the most cost effective and efficient method for achieving controllable lighting in daylit spaces having high ceilings.

The products evaluated in Project 5.2 are all commercially available. The activity of this project was focused on determining the performance characteristics that the market values in the adoption of a new technology. Hence, the commercialization potential

depends upon defining the applications where this technology will make a significant contribution to the end-user to warrant changing from existing practice.

Recommendations

For electronic ballasts operating metal halide lamps in the low-wattage range (35/39-175W), researchers recommend these additional activities:

- Improve utility rebate programs by providing more thorough and accessible information about the benefits of the technology.
- Monitor and verify the performance of several different types of installations that can be used as demonstration of performance for the utility programs and to support new energy codes.
- Develop new codes written to support the move to this technology.
- Determine life performance of the lamp and ballasts to provide further useful information to the market.
- Collaborate with Indy Lighting to improve optics of the product to allow variable focus that can project the light uniformly over various focus settings. This feature would help overcome the limitations of not being dimmable, making the overall product more versatile for retail and display applications.

With regard to dimming electronic ballasts operating metal halide lamps in a higher wattage range (200-500W), previous work on fluorescent lighting systems indicates that high-output fluorescent lamp systems offer significant advantages over the proposed controllable metal halide lighting systems in applications using supplemental daylighting, such as large box stores, warehouses, and industrial facilities. Therefore, researchers recommend that emphasis be shifted from any further support of metal halide dimming systems to supporting efforts to define the energy saving attributes of the new fluorescent T5, H0T5, and Super T8 systems utilizing controls. researchers also recommend that case studies be prepared to quantify these differences between the three systems and the standard T8 system for the lighting community and for the establishment of data that would support the development of new energy codes.

Benefits to California

The application of the technologies studied in Project 5.2 can have benefit to California in two key areas. The first is the application of ceramic metal halide (CMH) lamps powered by electronic ballasts in the commercial sector to replace less efficient incandescent lamps.

California represents roughly 10% of the total lighting energy used nationally in the retail sector, or 2.4 TWh per annum. The system efficiency of the technology proposed is 4 to 5 times greater than the incandescent equivalent. Hence, very large energy savings could be realized if this technology achieved significant penetration of the market.

In a second application, it was demonstrated in this project that on average high intensity discharge (HID) lamp/ballast systems using electronic ballast are 10% more efficient than

the corresponding system using a magnetic ballast. Outdoor lighting for both building parking lots and street lighting utilize magnetic ballasted HID lighting systems. Nationally, 53 TWh are consumed by these lighting systems each year. Changing the ballasts to electronic ballasts would reduce this use by 5.3 TWh nationally and approximately 0.5 TWh in California.

In conclusion, the technologies studied in Project 5.2 have the potential to significantly impact the energy use for electric lighting in the state of California and nationally. The resulting savings for the state could be over 2 TWh annually if the technologies were successfully deployed.

Introduction

Background and Overview

The past 10 years has seen a significant advancement in technologies associated with high intensity discharge (HID) lamps. This includes the incorporation of ceramic lamp envelopes and the ability to construct lamps with very exact dimensions. This has permitted the development of low wattage metal halide sources that have comparable light output to less efficient point-source technologies such as incandescent and halogen lamps, creating the opportunity for these systems to be used in retail and commercial applications. Magnetic ballasts have traditionally ballasted metal halide sources. Electronic ballasts have been available, but their market penetration has been limited due to size, cost, and efficiency. Recent developments in electronic circuitry suggest that these barriers have been overcome. Additionally, this new ballast technology can now provide variable light control. The ability to control the light expands the opportunity of the new electronic ballast to reduce lighting loads in spaces that have supplemental daylight.

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Project Tasks

The project's work scope involves the following technical tasks:

5.2 Task 1.	Performance Characterization of Lamp/Ballast System below 200 Watts Performance Characterization of Lamp/Ballast Systems above 200 Watts
5.2 Task 2.	Lifetest and Lumen Maintenance Testing
5.2 Task 3.	Control Strategies Evaluation
5.2 Task 4.	Technology Transfer Activities
5.2 Task 5.	Production Readiness Plan
5.2 Task 6.	Monthly Progress Reports
5.2 Task 7.	Annual Report
5.2 Task 8.	Final Report

This project was modified to distinguish between low and high wattage lamp/ballast systems. Also, given the number of systems that were tested and the time constraints of the LRP, the researchers were unable to perform any lamp life and lumen maintenance testing. Evaluation of control strategies were nominal since no controllable ballast were received for the low wattage range and only one manufacturer submitted properly operating ballast for the high wattage range.

Project Outcomes

Experimental Setup

The measurements to characterize the performance of lamp-ballast systems were performed in the laboratory of the Lighting Research Group located at the Lawrence Berkeley National Laboratory. Both electrical and spectral performance measurements were made on the systems, and these measurements were separated into three different categories: lamp performance, lamp-ballast performance, and starting and run-up performance. Figures 1 and 3 show the schematic of the equipment used in these measurements. Following is a brief description of the test equipment.

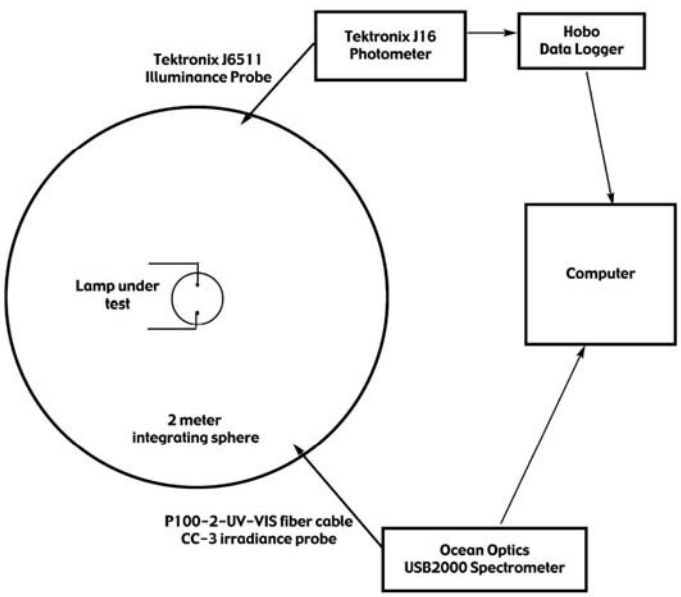


Figure 1: Experimental setup for spectral performance measurements.

A 2-meter integrating sphere was used to measure the total luminous flux and spectral distribution of the lamps. The sphere is coated with LMT paint that is 80% reflective. The lamp under test is positioned in the center of the integrating sphere. The total flux of the lamp is measured with a J6511 probe, located on the side of the sphere, and Tektronix J16 photometer. The probe and photometer are calibrated using a NIST calibrated lamp. For measurements of lamp run-up time, the photometer is interfaced with an Onset Computer Corporation H08-004-02 HOBO data logger that stores the data, the luminous

intensity as a function of time, throughout the measurement. The data is downloaded from the logger through a serial port to PC operating Windows-2000. This data is later graphed (Figure 2) to determine the time required for the lamp to reach its maximum luminous intensity after startup.

Spectral measurements are made using an Ocean Optics USB2000-VIS-NIR spectrometer that views the source through a CC-3 irradiance probe located on the side of the sphere and is coupled to the spectrometer through a P100-2-UV-VIS fiber cable. The spectrometer is calibrated in the spectral range 380 to 780nm against a working standard supplied by the manufacturer. The color rendering index (CRI) and the correlated color temperature (CCT) are calculated according to the CIE method from the relative spectral power distribution recorded for the source.

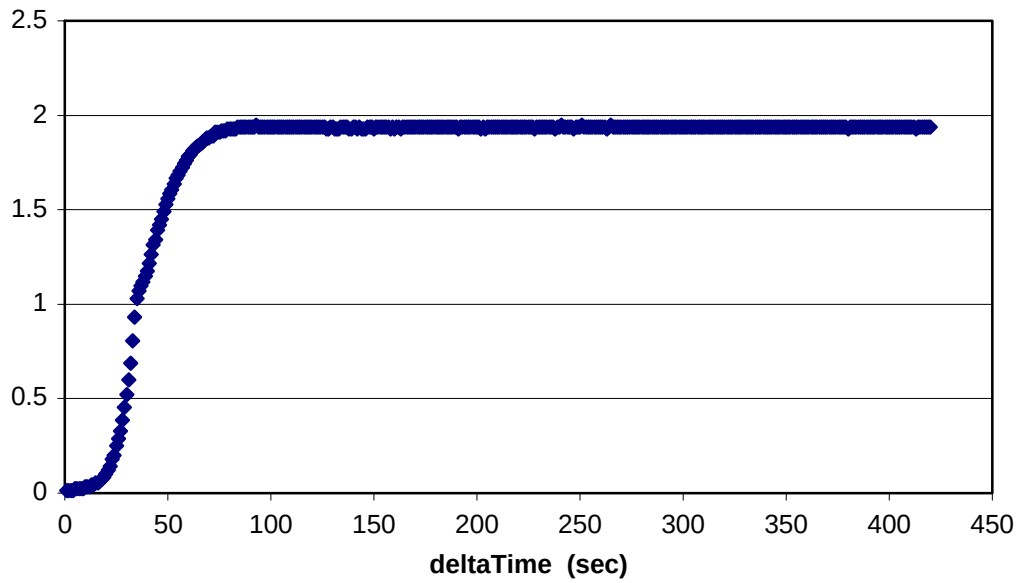


Figure 2: Lamp run-up time.

Power for the lamp/ballast systems was supplied by a 120VAC source and an Elgar 6000B line conditioner regulated variations in the supply voltage. The supply voltage to the ballast was adjusted to 120V by a variac. A step-up transformer was inserted into the system after the variac for ballasts requiring higher input voltage, as shown in Figure 3.

Electrical performance measurements on the lamp and lamp-ballast system were made using a three channel Voltech PM3000A Power Analyzer, which was electrically connected across the ballast-under-test as shown in Figure 3. Using two channels of the power analyzer, electrical measurements on the ballast input and on the ballast output were made simultaneously. The values measured for both lamp and system were: voltage, current, power, power factor, current crest factor, peak current, total harmonic distortion, and operating frequency. Additional values measured for the ballast included: power loss and ballast efficiency. The Voltech is programmable, allowing the operator to measure

the values given above with a single command. The data is collected by the Voltech and automatically downloaded to a computer for future analysis.
Electrical and photometric measurements of the lamps were referenced to measurements of the sources powered by the reference ballast. The reference ballast used was a variable linear reactor and resistor. The inductance and resistance were set according to the ANSI specification per the lamp being measured.

Other operating and starting performance characteristics were measured using a Tektronix 7623A oscilloscope with a 7A13 differential amp plug-in, two Tektronix P6015A 1000:1 HV probes, and a P6302 current probe. For some measurements, pictures of the screen were taken and saved for later analysis.

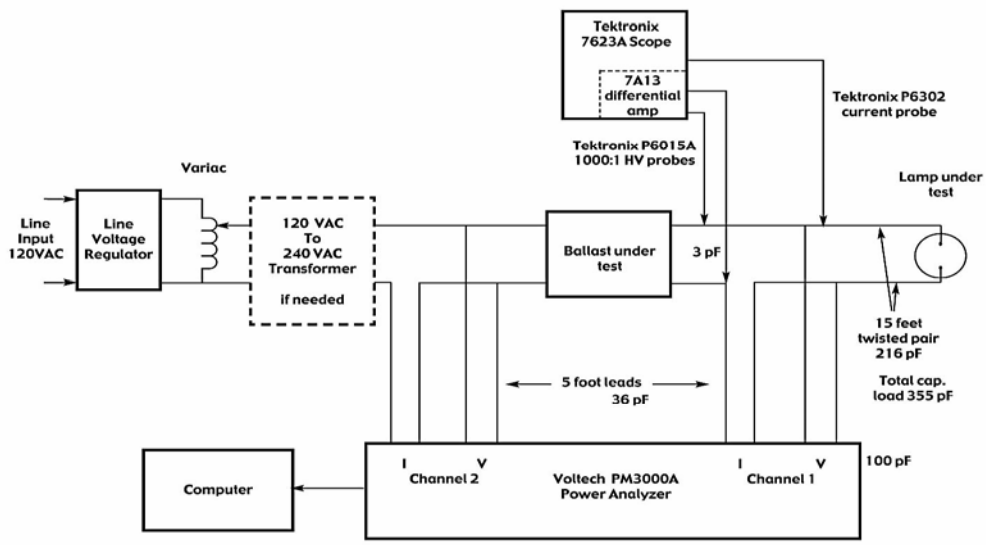


Figure 3: Experimental Setup for Electrical Performance Measurements

Measurement Procedure

Performance of the lamp-ballast system was performed using the experimental equipment described in the preceding section. All lamps were aged 100 hours(hrs) prior to use in this test procedure. Measurements made on the operating characteristics of the lamp-ballast system were subdivided for reporting purposes into *Lamp Performance Measurements* and *Lamp-Ballast Performance Measurements*.

Separate sets of experiments were performed to measure the *Starting and Run-Up Performance* characteristics of the lamp-ballast systems.

Lamp and Lamp-Ballast Performance Measurements

The normal operating procedure was to supply power to the system and allow the lamp to warm up until it reached stabilization. The light output of the lamp was monitored during the warm-up period to insure that the system had reached a stable operating condition prior to any measurements. Lamps from all four of the US lamp manufacturers were represented in the product tested. Lamps using a quartz arc tube were readily available from three of the manufacturers and lamps using a ceramic arc tube were available from three manufacturers, but only two manufactures were tested.

For a given lamp wattage, multiple quartz and at least one ceramic lamp were measured using the reference ballast according to the appropriate ANSI standard specification. One or two quartz lamps and one ceramic lamp were then selected for further testing with the magnetic and electronic ballasts.

Lamp and Lamp-Ballast Performance measurements include electrical, spectral, and total luminous flux measurements. The spectral and flux measurements were made using the equipment described above, once the lamp reached a stable operating condition. The optical measurements were taken coincident with the electrical measurements of the lamp-ballast system.

Several pieces of information were recorded manually. The output of the photometer and the ballast case temperature were recorded at the time that the electrical measurements were made. Also, taken at the time of these measurements was a trace of the lamp current waveform using the oscilloscope. A photograph of the trace was later analyzed to determine the percent modulation. Figure 4 is representative of such a trace and the method of calculating the % Modulation, where Emax is the largest peak-to-peak current throughout the line frequency (60Hz) modulation cycle, and Emin the smallest difference in current during the same cycle. The percent (%) modulation is defined as:

% Modulation = (Emax - Emin) / (Emax + Emin) * 100.

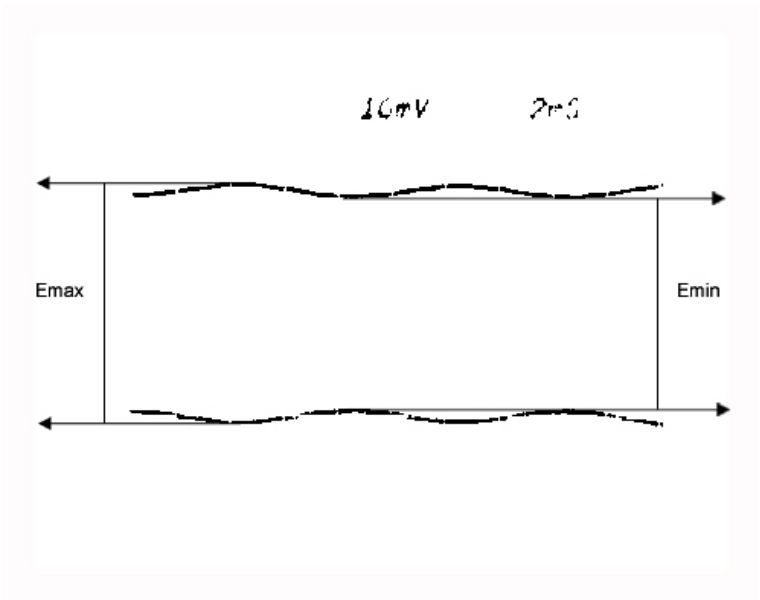


Figure 4: Percent (%) modulation.

Starting and Run-Up Performance Measurements

The starting and run-up performance measurements were performed for all electronic ballasts and selected magnetic ballasts.

Starting measurements

Automatic Shutoff
Verification of the manufacturers claim for a ballast automatic shutoff function was performed at a later time. The test was performed by operating the ballast with no lamp connected and monitoring the ballast ignition pulses using the oscilloscope. The ignition sequence and time to end of ignition pulses was recorded. If the ballast continued to produce ignition pulses for longer than 30 minutes after turn-on, it was recorded as having "no automatic shutoff."

Short Circuit Current
The lamp terminals are shorted and the current is measured with the Voltech when the circuit is supplied power. A measurement is taken immediately, before the ballast shuts down.

Inrush Current
The maximum observed inrush current and the average inrush current were measured using the Voltech over a number of starts. If both values were consistent in the first ten measurements, the test was stopped. If there was a significant variance in the values from start to start, then measurements were continued for another 10 starts to determine a maximum values. The number of observations made was recorded.

Open Circuit Voltage (OCV) Waveform, and the Peak and the RMS Values
The ballast output was measured with the oscilloscope and the display was photographed for analysis. The OCV waveform was measured with no lamp connected. The OCV waveform for virtually all ballasts was a square wave; hence, the OCV Peak Values and OCV RMS Values were essentially the same.

Ignition Characteristics of the Ballasts
Pulse ignition was the method of starting for all but one of the electronic ballasts tested, the other ballast used resonance ignition.

Ignition Waveform. Ignition pulses were measured with the oscilloscope using Tektronix P6015A 1000:1 high voltage probes and a 7A13 differential preamp, as a differential measurement, ie. the voltage between the ballast output leads. Measurements of the ignition pulse were made on the ballast leads with no lamp connected and represent analysis of the short pulse observed on the leading edge of the OCV waveform. Figure 5, for example, shows a pulse ignition waveform. The type of waveform is reported, defining the method of ignition either *pulse* or *resonant*.

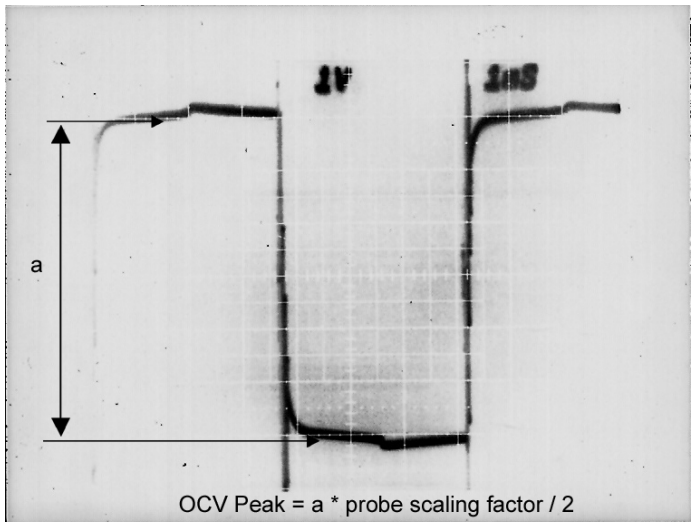
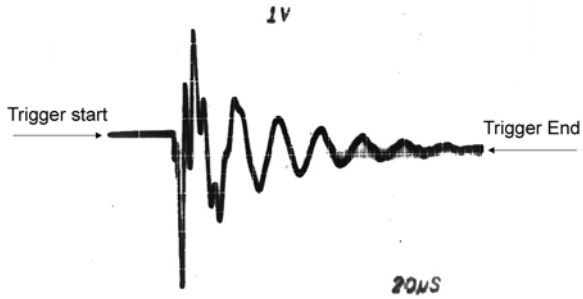


Figure 5: Open Circuit Voltage (OCV) waveform.

Pulse Ignition Waveform. Time amplification of the pulse is given in Figure 6, which illustrates a ringing pattern common to this starting mechanism. Further time amplification for the pulse is given in Figure 7. The resultant photographs were analyzed to determine the peak voltage or pulse height, pulse width at 2700V, pulse rise and fall times, repetition rate and ignition type (pulse or resonant). The polarity of the ignition pulse versus the OCV can be determined from the photographs. A full explanation of the analysis of the reported pulse height, rise time, and fall time will be described in the subsequent discussion of Starting/Run-up Performance**.**



Pulse has same polarity as OCV

Figure 6

Figure 7 was used to calculate the ignition pulse characteristics. It is the same as Figures 5 and 6 but was magnified in order to better demonstrate the pulse characteristics.

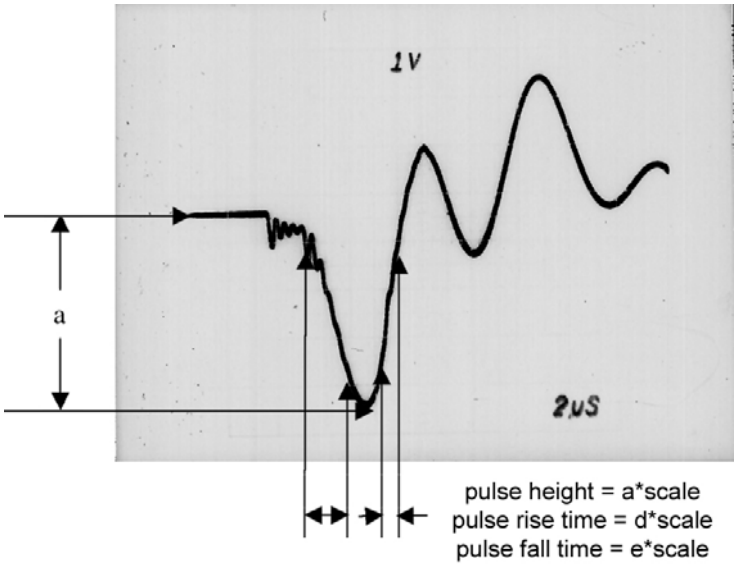


Figure 7

Pulse Height. Pulse height is a measure of the maximum voltage applied by the ballast during the ignition pulse and is measured as the distance between the pulse trigger start line and the pulse peak on the oscilloscope trace.

Pulse Width at 2700 Volts. Pulse width is a measure of the time (microseconds) that the pulse voltage is greater than 2700 volts.

Pulse Rise Time. Pulse rise time is the time (microseconds) required for the pulse to transition from 10% maximum value to 90% of maximum value.

Pulse Fall Time. Pulse fall time is the time (microseconds) required for the pulse to transition from 90% of maximum value to 10% of maximum value.

Pulse Polarity versus OCV. Figure 6 is a picture taken, from the scope screen, right after the ballast was started and therefore, it demonstrates the waveform, near the initial plateau of the square wave OCV. It was used to determine the pulse polarity versus OCV. As shown in this picture, the trigger ending line is below the starting line and since the trigger pulse has a negative peak, then in this case, the pulse polarity was determined to be the same polarity as the OCV waveform. For all of the ballasts tested, the trigger pulse polarity was the same as the OCV polarity, which is the OCV was aiding the trigger. See Figure 6.

Resonance Ignition Waveform. As Figure 5 showed the pulse ignition waveform, Figure 8 shows the high frequency pulse characteristic of the resonance ignition waveform. The resonance pulse, generated every 850 msecs as shown in Figure 8, is composed of a series of high frequency bursts, which are repeated at a frequency of 1 kHz for a period of 50 msec, as shown in Figure 9. Two bursts are shown in Figure 10 and each burst is composed of a 150 kHz waveform, as shown in Figure 11. The maximum voltage of the pulse was measured from Figure 8 and recorded. The measurements shown in Figures 8 through 11 were made without a lamp connected as described in the ignition waveform discussion. A lamp was connected and Figure 12 demonstrates two resonance pulses, where the second pulse starts the lamp. It can be seen in Figure 13 that once the lamp ignites, the voltage across the lamp decreases to the normal operating value within 200 msec.

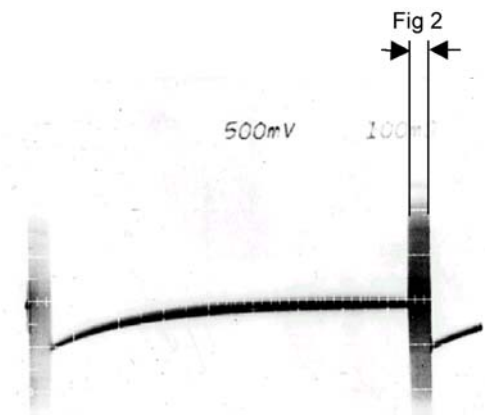


Figure 8

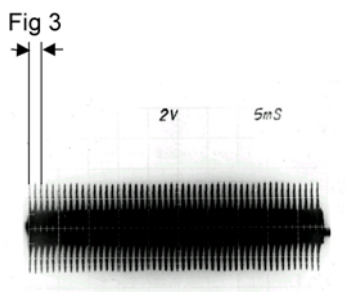


Figure 9

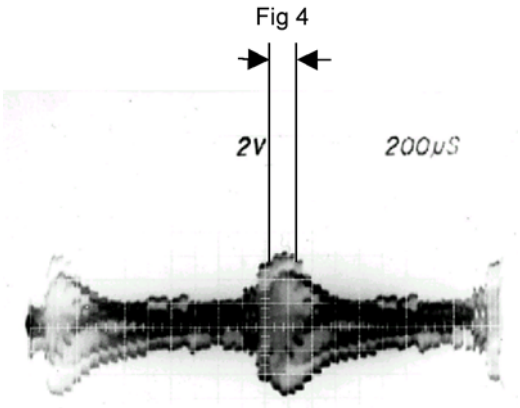


Figure 10

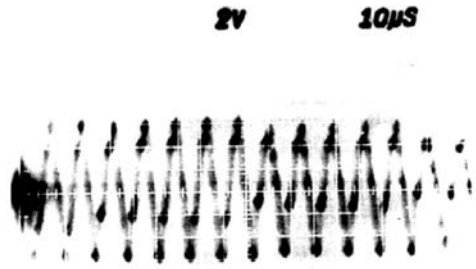


Figure 11

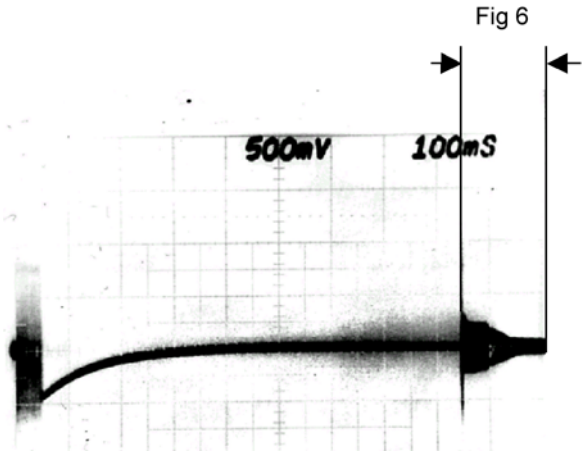


Figure 12

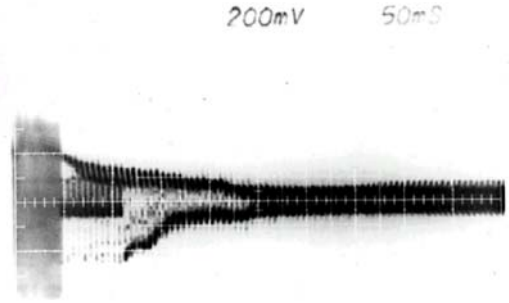


Figure 13

Run-Up Measurements

Run-Up Time

As described in the equipment section, the data logger was used to measure the lamp run up time, being started when the lamp was turned on and stopped after the lamp had reached a maintained maximum intensity. The data logger made measurements of the luminous intensity of the lamp at 5-second increments. The data was stored in Excel formatted files, which were down loaded to a computer and later graphed for analysis. Figure 2 is characteristic of the run up curves observed for these lamps. The run up time is reported for three relative intensities: 80%, 95%, and 100% of full light output. It was felt that the three values more clearly define the performance of the system since it takes a very short period of time for the lamp to reach 90% of full light output, which is a very useful amount of light, but a much longer time to achieve 100% of full light output.

Run-Up Current

Ballast run-up current was measured and photographed with the current probe connected to the oscilloscope as shown in Figure 3. The measurement is taken just after the lamp starts. A sweep speed of 5 seconds per centimeter (cm) was used to record the starting

behavior of the ballast. Since the current waveform is a square wave, the recorded value is half of the peak-to-peak displayed.

Hot Restrike Time

To determine the Hot Restrike Time, the lamp was operated until stabilized, and then turned off. Power was applied at 30 seconds intervals for a 15 second period until the lamp reignited. The time to restrike was recorded manually with a stopwatch. The above timing sequencing was selected to avoid the ballast's automatic shutoff mechanism from being activated.

Lamp Performance

This section discusses the performance characteristics of the two types of lamps, Ceramic and Quartz Metal Halide Lamps, used in this study. The discussion will focus on the performance characteristics of these lamps as provided in the manufacturers specifications. Comment will be made on these same performance characteristics relative to the measured values obtained in the study. However, these comments are only indicators since it was not within the scope of the project to test a statistically significant number of lamps of each lamp construction for every wattage and color temperature to determine these values. Each lamp type will be discussed separately and then a comparison will be made of their performance characteristics.

Ceramic Metal Halide Lamps

The ceramic metal halide lamps have three types of construction. The E17 lamp types have a bulbous glass outer envelope 2 1/8 inch diameter with the arc tube centered in the bulb. The T6 to T7 lamp types have a straight tubular glass outer envelope that conforms closely to the diameter of the small ceramic arc tube. The PAR lamp types have the arc tube located at the focal point of a silvered glass reflector that focuses the light out a glass lens. The three lamp geometries are shown below in Figure 14.

T-type **PAR – type** **E-17 type**

Figure 14: The three lamp geometries of ceramic metal halide lamps.

The ceramic metal halide lamps are available in two color temperatures, 3000 and 4000 degree Kelvin (3000K and 4000K), and the lamp performance is slightly different according to the color temperature and lamp construction. The product life of the different lamp embodiments increases with lamp wattage, going from 10,000 hours for the lowest watt lamps to 15,000 hours for the higher wattage lamps, with the exception of the 150W (4000K) lamps.

Table 1: Rated Life of Ceramic Metal Halide Lamps (000 hrs)

Wattage	**39**	**50**	**70**	**70**	**100**	**100**	**150**
Bulb Type	**T**	**E17**	**T**	**E17**	**E17**	**T**	**E17**
Rated Life (3000K) khr	12	10	15	10	12.5	15	
Rated Life (4000K) khr		10	12	15	15	6	9

The notable difference between the 3000K and the 4000K ceramic lamps is that the 3000K lamps have a color rendering index, CRI, in the 80's, whereas nearly all the 4000K lamps all have a CRI greater than 90. Ceramic Lamps having both 3000K and 4000K were measured for the different wattages and in all cases the CRI was equal to or better than the value specified by the manufacturer, as given in Table 2.

Table 2: Color Rendering Index of Ceramic Metal Halide Lamps

Wattage	**39**	**50**	**70**	**70**	**100**	**150**	**150**
Bulb Type	**T**	**E17**	**T**	**E17**	**E17**	**T**	**E17**
CRI (3000K)	81	85	85	82	82	85	
CRI (4000K)		82	92	92	93	96	92

The efficacy (lumens per watt) of the lamps in general increases with wattage. The initial efficacy is based on the initial lumen output of the lamp and the mean efficacy is based on the lumen output at 40% of lamp rated average life. The efficacy of the lamps measured varied from the manufacturers specifications with the 50W, 70W, and 150W lamps being roughly 5% lower than the specified value and the 100W lamp being 10% higher than the specification. Due to the limited number of lamps used in this testing program, it would appear that the manufacturers' specifications reasonably represent the performance of the lamps.

Table 3: Efficacy of Ceramic Metal Halide Lamps (Lumens per Watt)

Wattage	**39**	**50**	**70**	**70**	**100**	**150**	**150**
Bulb Type	**T**	**E17**	**T**	**E17**	**E17**	**T**	**E17**
LPW (3000K) initial	87.2	92.9	88.3	80.0	86.6	93.0	
LPW (4000K) initial		71.2	94.3	85.7	90.0	94.7	82.7
LPW (3000K) mean	66.7	74.3	70.7	60.0	70.9	75.0	
LPW (4000K) mean		52.8	75.4	68.6	72.0	75.7	66.1

Quartz Metal Halide Lamps

The construction of metal halide lamps is very similar to the E17 construction of the ceramic metal halide lamps with the quartz arc tube center in a bulbous glass outer envelope. The small tubular and the reflector PAR type constructions are not available for quartz lamps. Like ceramic metal halide lamps, the discussion on performance can be separated according to the two color temperatures, 3000K and 4000K, of the emitted light. The rated average lamp life of quartz is comparable to the ceramic lamps and varies between 10,000 and 15,000 hours. (The data presented in the tables to follow for quartz lamps are a compilation of the product specifications of three of the major US manufacturers of quartz metal halide lamps in clear glass envelopes.)

Table 4: Rated Life of Quartz Metal Halide Lamps (000 hrs)

Wattage	**50**	**70**	**100**	**150**	**175**
Rated Life (3000K) khr	12.5	12.5	15	12.5	15
Rated Life (4000K) khr	10	12	15	15	15

The color rendering index, CRI, of these lamps is lower than the ceramic lamps and varies between 65 and 75. In the test program, lamps having a color temperature of 4000K were the only lamps measured. The measured CRI for these lamps was comparable to the manufacturers specification given in the Table 5.

Table 5: Color Rendering Index of Quartz Metal Halide Lamps

Wattage	**50**	**70**	**100**	**150**	**175**
CRI (3000K)	70	75	70	75	65
CRI (4000K)	65	75	75	75	75

Like the ceramic lamps, the efficacy of the quartz lamps increases with increasing wattage. In general, the 4000K ceramic lamps had higher efficacy than their 3000K counterparts, this trend is reversed in quartz lamps with the 3000K quartz lamps being more efficacious. The exception is the very high performance of the 175-watt (4000K) lamp.

Table 6: Efficacy of Quartz Metal Halide Lamps (Lumens per Watt)

Wattage	**50**	**70**	**100**	**150**	**175**
LPW (3000K) initial	69.0	74.3	90.0	86.0	97.1
LPW (4000K) initial	64.0	67.1	81.0	78.0	100.0
LPW (3000K) mean	40.0	48.6	62.0	66.7	71.4
LPW (4000K) mean	42.0	42.9	58.0	54.0	74.3

Measure values of the efficacy for the quartz showed greater variance from the manufacturers specifications than that experienced for the ceramic lamps. Lamps from multiple manufacturers were tested and the variance between manufacturers was noticeable. For the 4000K lamps measured, researchers found noticeably better performance for the 100W lamps and poorer performance for the 175W lamps.

Comparison of Performance Characteristics between Quartz and Ceramic Metal Halide Lamps

Two features that are similar for both lamp types are the universal operating position of the lamps and the similar average rated life of the lamps. One manufacturer of quartz lamps specifies different average life ratings for horizontal and vertical burning positions for some lamp types, but in general both technologies can be operated in any orientation of the arc tube. Comparing the preceding tables, it can be demonstrated that the rated average life for the quartz and the ceramic lamps is comparable for similar wattages and outer envelope construction, with exception of the short life of the 150W 4000K ceramic lamp. Therefore, comparisons of lamp efficacy and lamp maintenance at initial life and at 40% of rated average life are valid.

The ceramic lamps are more efficacious than the comparable quartz lamp from the initial start of the lamp, as is given in the following comparison table. This difference is most significant at the lower wattages. The ceramic lamp does have limitations in life and availability in the 150W and 175W lamp size. In contrast, quartz lamps are available in this wattage range with high initial efficacy, but lower color rendering properties.

Table 7: Initial Efficacy of Lamps (Lumens per Watt)

Wattage	50	70	100	150	175
3000K Lamps					
Ceramic	92.9	80.0	88.6		
Quartz	69.0	74.3	90.0	86.0	97.1
4000K Lamps					
Ceramic	71.2	85.7	90.0	82.7	
Quartz	64.0	67.1	81.0	78.0	100.0

Ceramic lamps also have a lower rate of lumen depreciation relative to quartz lamps, which is demonstrated by comparison of the lumen depreciation of the lamps at 40% of average rated life given in Table 8.

Table 8: Fraction of Initial Lumens Maintained at 40% of Average Rated Life

Wattage	50	70	100	150	175
3000K Lamps					
Ceramic	0.80	0.75	0.80		
Quartz	0.58	0.65	0.69	0.78	0.74
4000K Lamps					
Ceramic	0.74	0.80	0.80	0.80	
Quartz	0.66	0.64	0.72	0.69	0.74

Given the greater efficacy and better maintenance over life, the ceramic lamp appears to be a better value for the end user. In addition, the ceramic lamps have much higher color rendering index than the comparable quartz lamp, with all lamps having a CRI above 80 and most of the 4000K lamps having a CRI in the 90s. The ceramic lamps show much

greater color stability over life of the lamp relative to quartz lamps, making the ceramic lamps a preferred source for color sensitive applications, such as retail sales.

Finally, the ceramic arc tube can be incorporated in different lamp constructions such as the tubular and reflector lamp types. This allows manufacturers to optimize the luminaire optical design for the much smaller ceramic arc source or to directly incorporate the reflector lamp. The focus of the industry is to capitalize upon the attributes of the ceramic lamps in the lower wattage range to produce a more efficacious long life alternative to incandescent and halogen sources.

For those applications where color rendering or variability between sources is not of critical importance, a value indicator, that can be used for deciding on which lamp type to select, is the product of the life of the lamp times the rated mean efficacy of the lamp. A comparison of the quartz and the ceramic lamps shows the ceramic lamps has a slight edge over quartz lamps in the 3000 degree Kelvin range and a significant edge in the 4000 degree Kelvin range up to 150 watts.

Researchers also found greater variability in the quartz lamps performance characteristics, relative to the corresponding ceramic lamp, between lamps of a common wattage and manufacturer and for a single lamp over multiple measurements. This is reflected in the manufacturers specification for color temperature where quartz lamp can have a variation of 600K over life, while the corresponding ceramic lamp specification is only 200K.

One of the most significant determinations of the measurements on lamp performance done was the evaluation of lamp performance as a function of ballast type. The measurements performed on both the ceramic and the quartz lamps demonstrated that no statistical difference existed in the performance of the lamps on either a magnetic or electronic ballast as can be seen from Table 9 where the efficacies were normalized to the lamp efficacy measured on a reference ballast. Hence, any improvement in the efficacy of the electronic lamp/ballast system to be discussed in the next section of this report can be solely attributed to the improvement in the performance of the ballast.

Table 9: Normalized Efficacy (LPW/ Reference Ballast LPW) for
Magnetic and Electronic Ballasts Operating Quartz and Ceramic Lamps

Wattage	Magnetic Ballast Quartz Lamp	Electronic Ballast Quartz Lamp	Magnetic Ballast Ceramic Lamp	Electronic Ballast Ceramic Lamp
35			1.01	1.02
39			1.00	1.00
50			1.06	0.99
70	0.96	1.00	1.02	1.03
100	1.01	1.06	1.01	1.02
150	1.02	1.00	1.00	1.02
175	1.06	1.02		

Lamp/Ballast System Performance

Performance Characterization of Lamp/Ballast System Below 200 Watts

This section will discuss the performance characteristics of lamp/ballasts systems operating the ceramic metal halide (CMH) and quartz lamps discussed in the preceding section. The discussion will focus on performance improvements relative to the standard magnetic ballast system. The results of the lamp performance measurements summarized in Table 9 of the *Lamps Performance* section show that there was no improvement in performance of either the CMH or the quartz lamps when operated on the electronic ballasts tested versus the magnetic ballast. It can be concluded that any improvement in the performance of the lamp/electronic ballast system over the lamp/magnetic ballast system can be attributed to a difference in performance between the two ballast types. None of the ballasts tested in this wattage range were controllable.

The measured performance characteristics that best define the difference in performance between the electronic and magnetic lamp/ballast systems are the ballast efficiency and the power loss in the ballast. The difference in performance between the electronic ballasts and the magnetic ballast is best described graphically. The following graphs in this section of the report are plotted as a function of ballast manufacturers, each represented by a different color, for the respective lamp wattages. The results will be presented as a function of the two different lamp constructions, since the lamps span different wattage ranges and their differences in operating characteristics at a given wattage can have an effect on ballast performance.

The discussion will initially focus on the efficiency of the electronic ballasts relative to the standard magnetic ballast. The ballast efficiency is a measure of the conversion efficiency of power into the ballast to power into the lamp. A value of 90% indicates that 10% of the total power supplied to the lamp/ballast system was lost in the ballast.

The measured ballast efficiency for the various electronic ballasts operating the CMH lamps was nearly constant both as a function of manufacturer and as a function of lamp wattage, as shown in Figure 15. All the electronic ballasts had ballast efficiencies in the high 80 percentile over the lamp wattages tested. This is in comparison to the magnetic ballast which had ballast efficiencies of nearly 80 percent for wattages above 70 watts but become increasing less efficient at the lower wattages, dropping to 70 percent efficient for the 35 watt lamps.

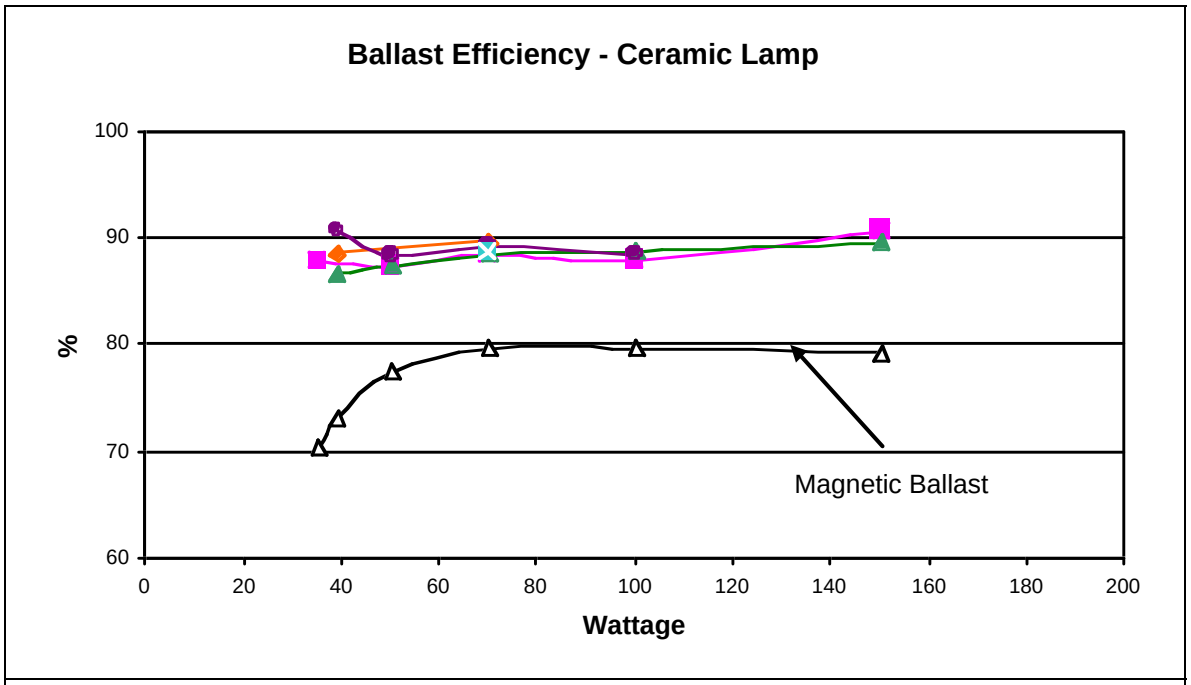


Figure 15. Ballast Efficiency as a Function of Wattage for Ceramic Lamps

A similar pattern was observed for the operation of the quartz lamps on the respective electronic and magnetic ballasts, as shown in Figure 16. However the efficiency of both the electronic ballasts and the magnetic ballasts were lower for the quartz lamps relative to the CMH lamps for wattages below 120 watts. At the highest wattage, 175 watts, both the electronic and magnet ballast achieved their highest efficiency observed in this study, attaining a ballast efficiency of greater than 90% for the electronic ballast.

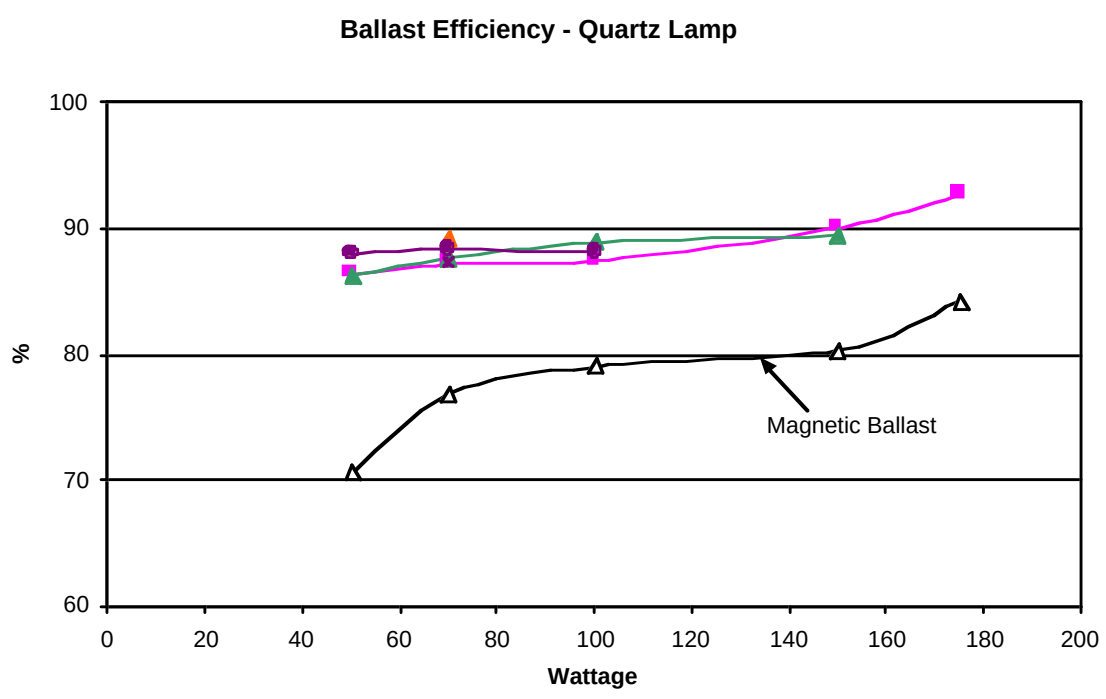


Figure 16. Ballast Efficiency as a Function of Wattage for Quartz Lamps

The ballast efficiency directly corresponds to the power lost in the ballast for a given lamp wattage. A comparison of the power loss in both the electronic and magnetic ballasts as a function of lamp power is graphically represented in Figures 17 and 18 for the CHM and quartz lamps, respectively.

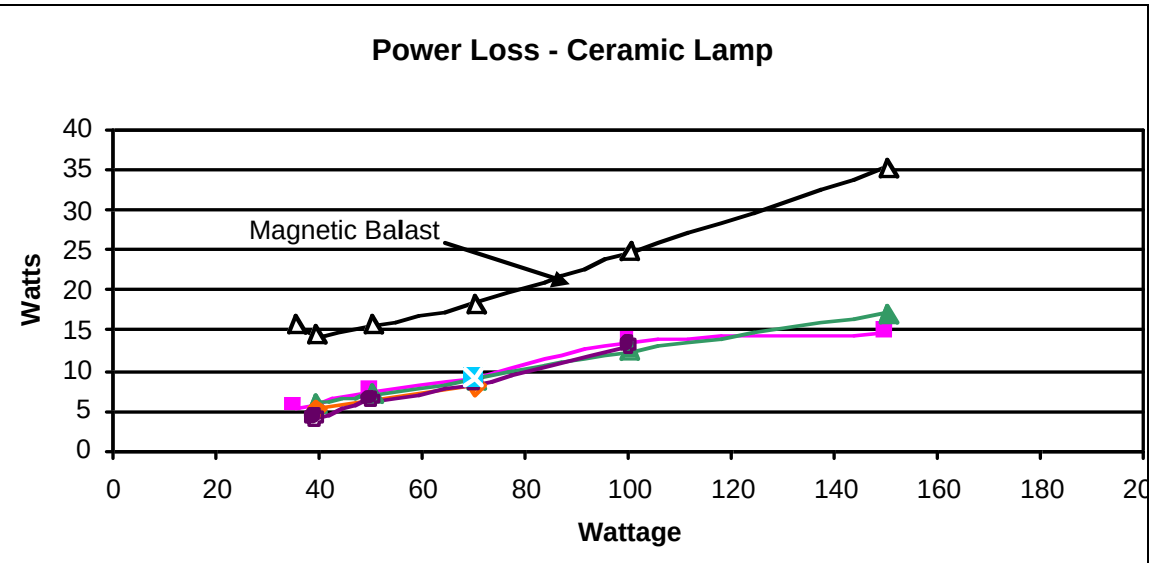


Figure 17. Power Loss as a Function of Wattage for Ceramic Lamps

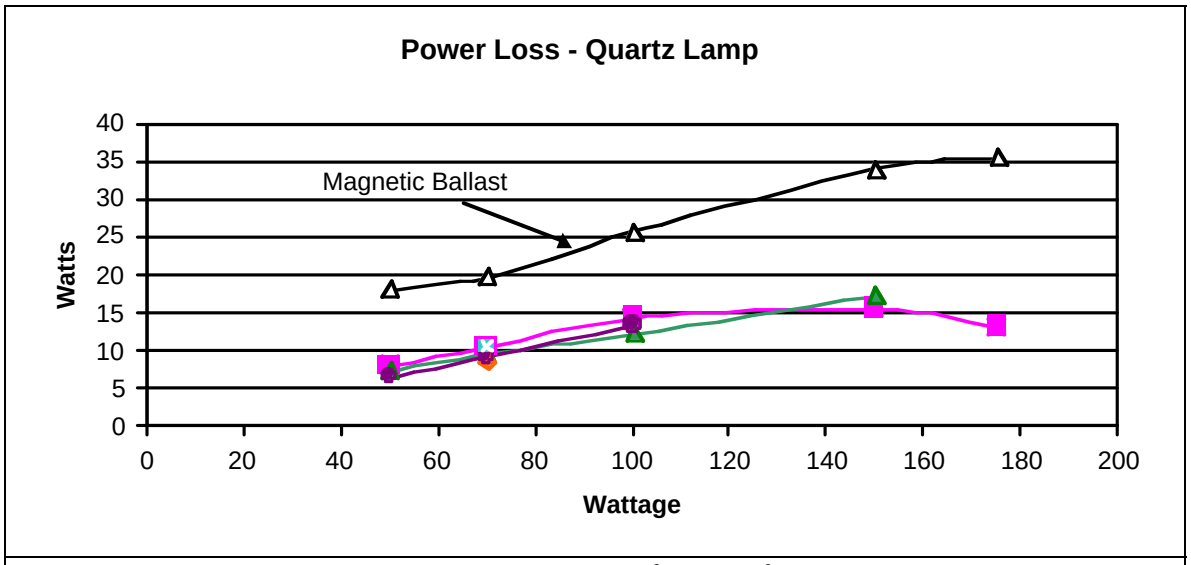


Figure 18. Power Loss as a Function of Wattage for Quartz Lamps

The comparison of the power loss in the magnetic ballast versus the electronic ballast at a given lamp wattage defines the inherent difference in efficiency of the two technologies, and amplifies the point that as the power increases this becomes an increasingly larger number.

Table 10 quantifies the results of the difference in the ballast efficiency for the electronic and magnetic ballasts as a function of ceramic lamp wattage. The power loss in both the magnetic and electronic ballast increases with increasing lamp wattage, as may be expected. But the difference in the values remains constant, approximately 9.3 watts, for the lower lamp wattages between 39 and 70 watts, as shown in the Power Savings row of the table. This value is significant when considering the application of this technology for the replacement of halogen sources. The lowest wattage lamps will have the greatest opportunity to replace halogen sources. The use of electronic ballasts will make an additional significant improvement in system performance at all levels and especially at the lower lamp wattages. The last row, % Lamp Watts, provides an indicator of energy savings that can be realized by the conversion from magnetic to electronic ballast as a function of lamp wattage. In general, it can be stated that a savings of 13% of the lamp wattage will be realized for lamp wattages of 70 watts and above, and an increasingly larger percentage would be realized as wattages decrease below 70 watts.

Table 10. Ballast Power Loss (W) as a Function of Lamp Wattage

Lamp Wattage	**39**	**50**	**70**	**100**	**150**
Magnetic Power Loss (W)	14.6	15.9	18.6	24.9	35.5
Electronic Power Loss (W)	5.2	7.0	8.9	13.2	16.0
Power Savings (W)	9.4	8.9	9.7	11.7	19.5
% Lamp Watts	24	18	14	12	13

Starting/Run-up Performance

Table 11 lists the run up time in seconds for the lamp to reach 80% of the full light output. The data is separated by lamp type into ceramic and quartz data sets according to the ascending lamp wattage, and each lamp wattage is subdivided by ballast manufacturer. The organization of data discussed in this section will follow this same format throughout the tables.

The 80% run-up time was selected for analysis because it would represent a time to reach a minimum luminous flux to meet the end users' expectations. However, the spectral characteristics of the lamp will change until it achieves a state of stable operation characteristic of full light output.

A general characteristic observed for the run-up times is that for both ceramic and quartz lamp types the run up time on the various electronic ballast manufacturers is equal to or less than the comparable run up time on the magnetic ballast and that the time to reach 80% light output for the both magnetic and electronic ballast are comparable in magnitude. It was also observed that the run-up time for the ceramic lamp can be achieved in less than 1 ½ minutes with the exception of the 150 watt lamps. The quartz lamps appeared to have slightly faster run-up times and in general will reach 80% of light output within 1 minute.

Table 11: 80% Run-up Time

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	82	59				
39	Ceramic-X	63		52	53	61	
50	Ceramic-W	67	68	66		36	
70	Ceramic-W	128	80	86	72	87	76
100	Ceramic-W	54	50	55		53	
150	Ceramic-W	155	129	145			
50	Quartz-X	60	67	58		67	
70	Quartz-Y	108	45	70	35	58	65
70	Quartz-X	35	29				
100	Quartz-Y	54	47	48		58	
100	Quartz-X	51	34				
150	Quartz-X	87	39	41			
175	Quartz-W	66	143				
175	Quartz-X	138	74				

The trends observed in the 80% run-up times are also observed in the data for both 95 and 100% run-up times. Consequently, there is no significant difference in the run-up times between the magnetic ballast and the electronic ballasts. The quartz lamps do appear to have a slightly faster run-up versus the ceramic lamps, but this difference is not sufficient to result in a differentiation of the product in the market.

Table 12 uses the same format as Table 11 to compare the ratio of the run-up current to the operating current as a function of ballast and lamp type. The ratio increases as one goes from lower powers to higher powers and is less for electronic ballasts relative to the standard magnetic ballast.

Table 13 is the average observed in rush current and is consistent with any manufacturer. Manufacturer D demonstrates a high average in rush current that exceeds that of the standard incandescent ballasts (determining if this is important to the utilities and to the circuit breakers may be important to the end user). It is clear that manufacturers can control this as done by the other manufacturers. This high averaging rush current is reflected in Table 14. In general, more than 10 measurements were always made for those ballasts having a high in rush current.

Table 15 demonstrates the performance of the electronic ballasts for hot restrike. There seems to be a large variability between lamp wattages within the ceramic lamps and the quartz lamps with the ceramic lamps generally taking longer to restrike for a given wattage. It is notable that in the 50 watt both ceramic and quartz lamps restrike times are generally under one minute increasing the acceptability of this lamp for an incandescent replacement.

Looking at the pulse ignition starting characteristics of the lamps, Table 16 gives the pulse height on ignition. The observed pulse height is fairly consistent as a function of manufacturer, irrespective of wattage and lamp type (variance as mnft).

The pulse width of the ignition pulse at 2700 volts is given in Table 17 and shows to have greater variability between wattages and manufacturers than the pulse height. The pulse repetition rate, the pulse rise time, and the pulse fall time are given in Tables 18, 19, and 20, respectively. The results again appear to be a function of the manufacturer and irrespective of lamp type. Hence, the greater body of data gathered on the starting characteristics of the pulse ignition system are principally manufacturer dependent. The starting process can have a significant impact on lamp life relative to degradation of the cathode. It remains unanswered if the observed differences between the manufacturers have a consequential effect on lamp life, since the study did not perform lifetest measurements for these systems.

Table 12: Run-up current/operating current

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	1.00	0.75				
39	Ceramic-X	0.95		0.75	1.05	1.75	
50	Ceramic-W	1.20	0.75	0.60		1.00	
70	Ceramic-W	1.60	1.50	1.20	1.10	1.40	1.10
100	Ceramic-W	1.60	1.20	1.60		1.50	
150	Ceramic-W	3.50	2.10	2.50			
50	Quartz-X	1.20	0.75	0.90		1.45	
70	Quartz-Y	1.60	1.20	1.25	1.80	1.50	1.10

Wattage	Lamp Type	Magnetic	A	B	C	D	E
70	Quartz-X	1.40	1.30				
100	Quartz-Y	2.30	1.40	1.50		1.75	
100	Quartz-X	2.00	1.20				
150	Quartz-X	3.20	1.80	2.00			
175	Quartz-W	3.20	2.10				
175	Quartz-X	3.30	2.20				

Table 13: Average observed inrush current

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	11.39	5.00				
39	Ceramic-X	11.39		5.80	5.50	14.00	
50	Ceramic-W	13.40	6.39	5.50		39.49	
70	Ceramic-W	15.80	7.60	8.50	6.35	19.50	2.54
100	Ceramic-W	20.80	4.13	8.40		8.00	
150	Ceramic-W	22.06	5.90	3.77			
50	Quartz-X	13.40	6.39	5.50		39.50	
70	Quartz-Y	15.80	7.60	8.50	6.35	19.50	2.54
70	Quartz-X	15.80	7.60				
100	Quartz-Y	20.80	7.82	8.40		8.00	
100	Quartz-X	20.80	7.82				
150	Quartz-X	22.06	5.90	3.77			
175	Quartz-W	13.07	18.93				
175	Quartz-X	13.07	18.93				

Table 14: Maximum observed inrush current

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	13.88	11.73				
39	Ceramic-X	13.88		6.25	8.90	67.50	
50	Ceramic-W	17.24	12.72	7.60		72.52	
70	Ceramic-W	21.14	11.66	10.82	14.80	69.40	7.67
100	Ceramic-W	25.40	30.10	12.30		15.70	
150	Ceramic-W	25.95	32.68	10.80			
50	Quartz-X	17.24	12.72	7.60		72.50	
70	Quartz-Y	21.14	11.66	10.82	14.80	69.40	7.67
70	Quartz-X	21.14	11.66				
100	Quartz-Y	25.40	12.09	12.30		15.70	
100	Quartz-X	25.40	12.09				
150	Quartz-X	25.95	32,68	10.80			
175	Quartz-W	19.18	32.48				
175	Quartz-X	19.18	32.48				

Table 15: Hot restrike time

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	415	440				
39	Ceramic-X	465		200	345	270	
50	Ceramic-W	550	495	45		30	
70	Ceramic-W	435	470	330	415	280	540
100	Ceramic-W	120	100	405		360	
150	Ceramic-W	605	583	510			
50	Quartz-X	45	55	35		30	
70	Quartz-Y	275	240	240	280	210	300
70	Quartz-X	270	182				
100	Quartz-Y	280	255	255		270	
100	Quartz-X	120	230				
150	Quartz-X	210	150	210			
175	Quartz-W	150	130				
175	Quartz-X	180	140				

Table 16: Pulse height

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	3200	2900				
39	Ceramic-X	3200		3300	3600	4000	
50	Ceramic-W	1800	2900	3200		4000	
70	Ceramic-W	700	3000	N/A	3700	4400	3100
100	Ceramic-W	2800	2900	3500		4400	
150	Ceramic-W	2200	3600	3500			
50	Quartz-X	1800	2900	3200		4000	
70	Quartz-Y	700	3000	N/A	3700	4400	3100
70	Quartz-X	700	3000				
100	Quartz-Y	2800	2900	3500		4400	
100	Quartz-X	2800	2900				
150	Quartz-X	2200	3600	3500			
175	Quartz-W	1800	3600				
175	Quartz-X	1800	3600				

Table 17: Pulse width at 2700

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	20.00	0.40				
39	Ceramic-X	20.00		0.80	0.60	0.25	
50	Ceramic-W	N/A	0.40	1.20		0.00	
70	Ceramic-W	N/A	0.50	N/A	0.60	0.40	0.90
100	Ceramic-W	5.00	0.50	1.40		0.30	
150	Ceramic-W	N/A	0.90	2.60			
50	Quartz-X	N/A	0.40	1.20		0.40	

Wattage	Lamp Type	Magnetic	A	B	C	D	E
70	Quartz-Y	N/A	0.50	N/A	0.60	0.40	0.90
70	Quartz-X	N/A	0.50			0.30	
100	Quartz-Y	5.00	0.50	1.40		0.30	
100	Quartz-X	5.00	0.50				
150	Quartz-X	N/A	0.90	2.60			
175	Quartz-W	N/A	0.90				
175	Quartz-X	N/A	0.90				

Table 18: Pulse rep rate

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	119.94	312.50				
39	Ceramic-X	119.96		277.78	416.70	249.56	
50	Ceramic-W	120.04	312.50	277.78		245.78	
70	Ceramic-W	120.02	277.78	N/A	400.00	243.44	166.67
100	Ceramic-W	119.96	277.78	294.10		239.26	
150	Ceramic-W	119.96	256.40	294.10			
50	Quartz-X	120.04	312.50	277.78		245.18	
70	Quartz-Y	120.00	277.78	N/A	400.00	243.58	166.67
70	Quartz-X	120.04	277.78				
100	Quartz-Y	120.00	277.78	294.10		240.86	
100	Quartz-X	119.90	277.78				
150	Quartz-X	119.96	256.40	294.10			
175	Quartz-W	120.06	256.40				
175	Quartz-X	120.04	256.40				

Table 19: Pulse rise time

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	20.0	0.8				
39	Ceramic-X	20.0		1.2	0.6	0.35	
50	Ceramic-W	30.0	0.8	1.4		0.2	
70	Ceramic-W	40.0	0.8	N/A	0.7	0.4	1.2
100	Ceramic-W	10.0	1.0	1.6		0.3	
150	Ceramic-W	20.0	0.8	3.3			
50	Quartz-X	30.0	0.8	1.4		0.15	
70	Quartz-Y	40.0	0.8	N/A	0.7	0.4	1.2
70	Quartz-X	40.0	0.8				
100	Quartz-Y	10.0	1.0	1.6		0.3	
100	Quartz-X	10.0	1.0				
150	Quartz-X	20.0	0.8	3.3			
175	Quartz-W	20.0	1.0				
175	Quartz-X	20.0	1.0				

Table 20: Pulse fall time

Wattage	Lamp Type	Magnetic	A	B	C	D	E
35	Ceramic-W	20.00	0.60				
39	Ceramic-X	20.00		0.80	0.90	1.00	
50	Ceramic-W	30.00	0.60	1.20		1.20	
70	Ceramic-W	30.00	0.70	N/A	0.80	1.10	1.20
100	Ceramic-W	10.00	0.80	1.30		1.00	
150	Ceramic-W	50.00	0.40	1.80			
50	Quartz-X	30.00	0.60	1.20		1.20	
70	Quartz-Y	30.00	0.70	N/A	0.80	1.10	1.20
70	Quartz-X	30.00	0.70				
100	Quartz-Y	10.00	0.80	1.30		1.00	
100	Quartz-X	10.00	0.80				
150	Quartz-X	50.00	0.40	1.80			
175	Quartz-W	50.00	0.40				
175	Quartz-X	40.00	0.40				

Performance Characterization of Lamp/Ballast System Above 200 Watts

The ballasts in this section of the report were selected for controllability with the expectation that they could be used in commercial, industrial, and retail spaces that have supplemental daylighting. The controllable ballast offers an opportunity to reduce the lighting load through a measured response to the ambient daylight.

Multiple manufacturers were contacted to participate in the performance evaluation of their controllable ballasts that operated metal halide lamps with wattages above 200 watts. Three manufacturers submitted product for testing. Of these, one manufacturer's product never successfully started the lamps, another manufacturer's product failed during testing and, although repeated requests were made, no replacement ballast was supplied. The final manufacturer supplied three different ballasts that operated 250, 350, and 450 watt lamps, respectively. The lamp/ballast system performance was measured for the three lamp/ballast wattages.

The operating frequencies of the ballast measured in this section were significantly different from those measured in the preceding section for static ballasts under 200 watts. The static ballasts had a high frequency component contained within a waveform whose polarity oscillated at a frequency below 300 Hertz (Hz); hence, the lamp performed as though it were being operated by a low frequency power supply. The operating frequency of the controllable ballasts is greater than 100 kHz and increases, as the power to the lamp decreases. The operating frequency at full power for the 250, 350, and 450 W systems were 180k, 104k, and 120k Hertz, and the frequency increased to 300k, 190k, and 195k Hertz, respectively, at the lowest power settings. This appears to be a good approach to design controllable ballasts that are efficient.

The ballast efficiency was high for all three systems and was maintained over the entire dimming range of the system. The ballast efficiency for the ballast that controlled the 250W lamp was 90% over the entire dimming range. The ballast efficiency for the 350W lamp/ballast system increased from 84% at the lowest range to 95% at full power. The ballast efficiency for the 450W lamp/ballast system improved from 87% at the lowest power setting to 92% at full power.

The only anomaly observed for the three ballasts was a increase in the total harmonic distortion (THD) on the supply side of the ballast for the 350-W system as the power was decreased to the lamp. The THD was very low at all power settings in both the 450W and 250W systems, and was as low for the full power setting of the 350W lamp system, but increased for the lower power settings of this system. Given that the other wattage systems tested at low levels throughout the power range, it is expected that the 350W system could achieve these same performance levels.

The performance characteristics, except where noted, were comparable between the different wattages. Therefore, the data for 350 W metal halide lamp/ballast systems will be discussed as representative of all three lamp/ballast systems. Unlike the previous section that evaluated static ballasts, where the improvement in efficiency was realized through improved performance of the electronic ballast relative to the magnetic ballast, this section focuses on improved system performance realized in the application of the controllability of the lighting system versus a static system. Hence, it is critical to understand the system performance characteristics as the power to the lamp is reduced.

The following graph, Figure 19, demonstrates the linearity between the lamp power and the system power over the dimming range of the system, indicative of high ballast efficiency at all power settings.

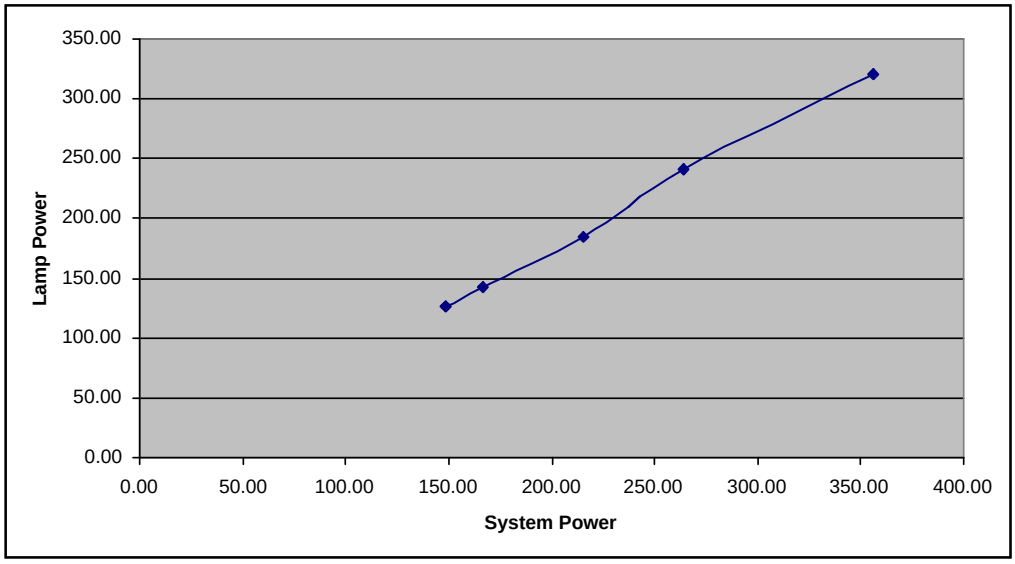


Figure 19. Lamp Power as a Function of System Power

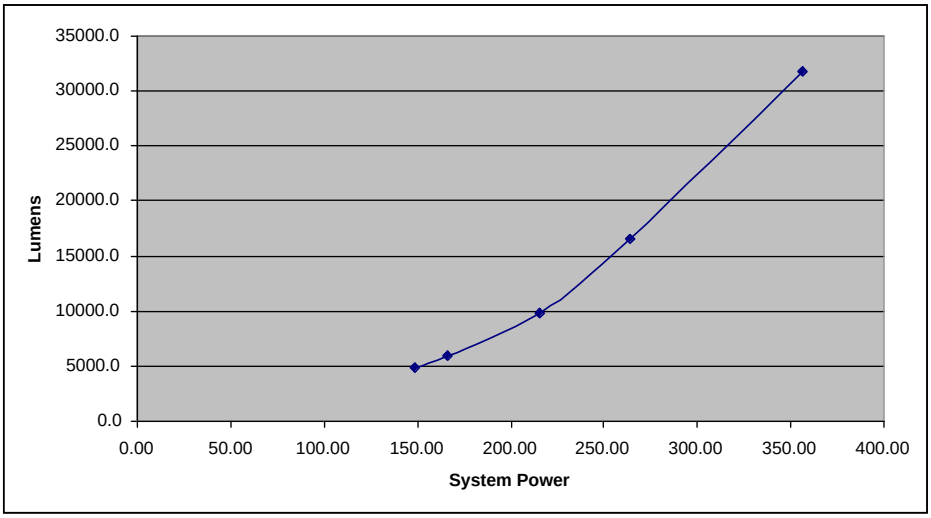


Figure 20. Lumen Output as a Function of System Power

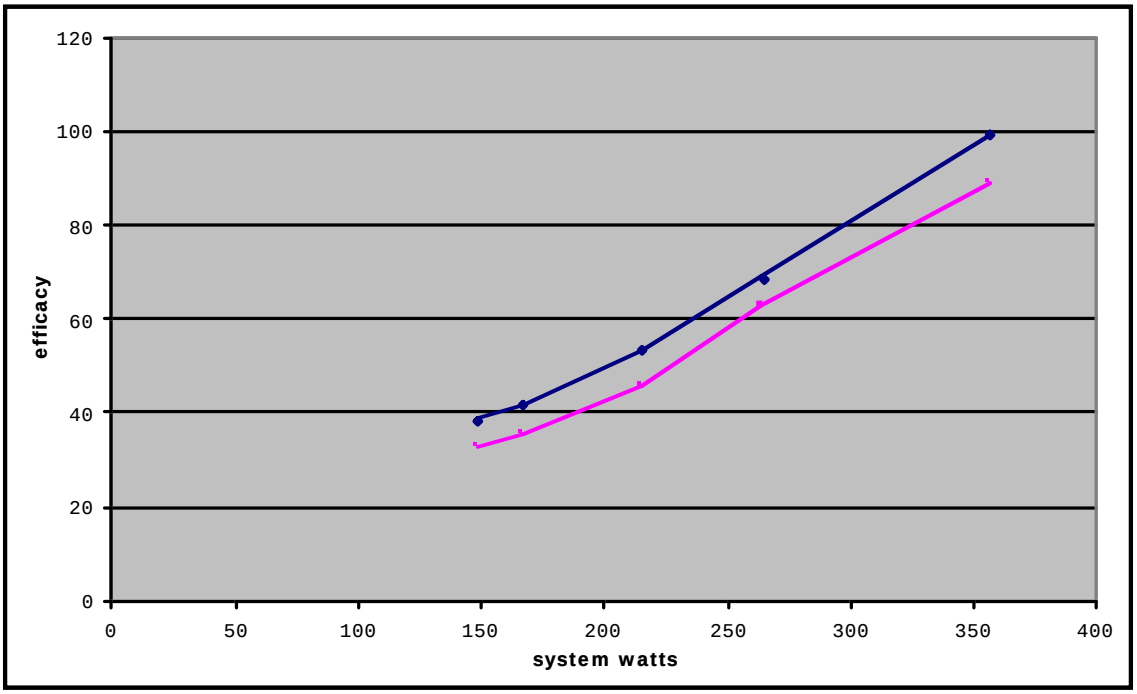


Figure 21. Efficacy as a Function of System Watts

In Figure 20, the same proportional and linear relationship does not exist between the light output (lumens) and system power as between the lamp power and system power, shown in Figure 19. There is a much steeper decrease in light output over this same power range. Since the light output decreases more rapidly than the lamp power, there will be a corresponding decrease in efficacy (lumens per watt) as the power to the lamp is decreased. The efficacies for the lamp and lamp/ballast system as a function of system power are shown in Figure 21. The lamp efficacy is the top most line and is 100 lpw when the lamp is operated at full power. The lower line is the system efficacy and is lower than the lamp efficacy by a percentage proportional to the ballast efficiency. The

system efficacy parallels the lamp efficacy because the ballast efficiency varies little over the controllable power range.

Associated with the reduction in power is a change in the chemistry of the arc in the discharge tube and this is reflected in a change in the color temperature and color rendering index (CRI) of the system. As the wattage is reduced, the temperature of the arc tube decreases resulting in a change in the concentration of metal salts in the discharge. It can be seen in Figure 22 that, as the power in the arc is reduced below 250 watts, the color temperature rises with a corresponding degradation of the CRI. The change in these two values may not be acceptable in most commercial and retail applications. This behavior was observed for all three-lamp wattages when the power was reduced below 75% of the rated power of the lamp. Hence, it would appear that the useful dimming range of the system is 25% in power which corresponds to nearly 50% in light output. Greater reductions in wattage, although achievable, are not appropriate for many applications.

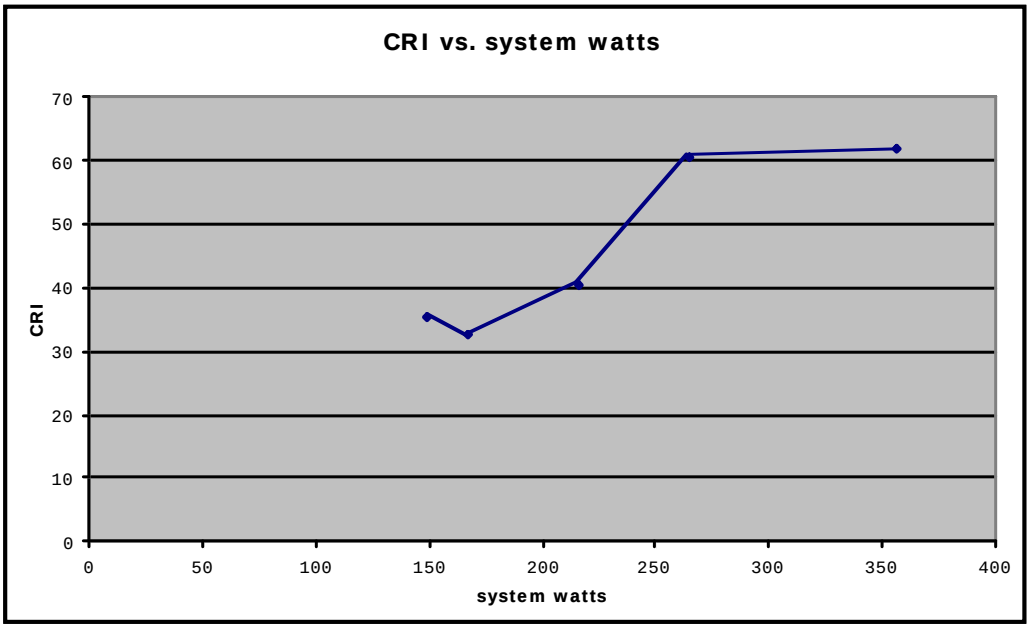


Figure 22. Color Rendering Index as a Function of System Watts

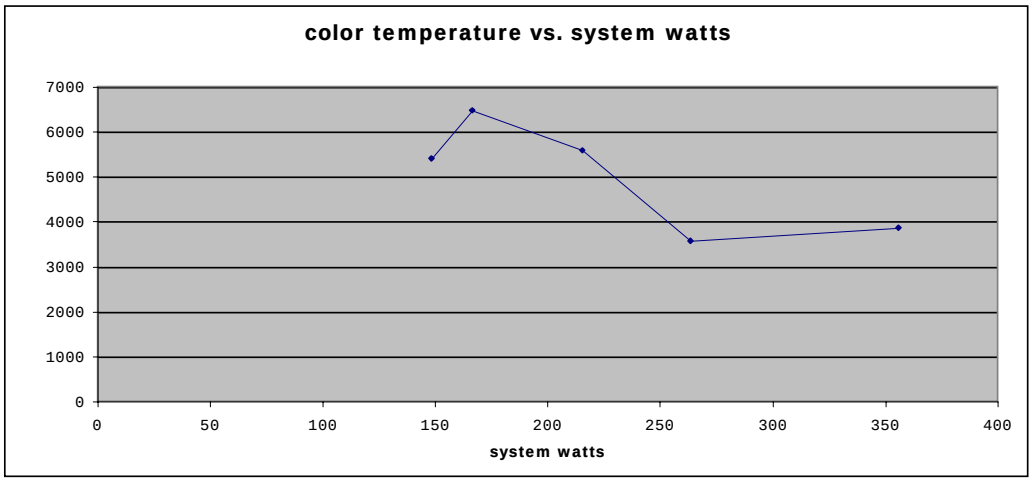


Figure 23. Color Temperature as a Function of System Watts

In conclusion, the advantages of controllable metal halide ballasts are best realized for power reductions of no greater than 25%, corresponding to a light output reduction of 50%. If control of the system is maintained within this limit, there will not be a serious degradation of color performance characteristics required for most applications.

Conclusions and Recommendations

Recommendations

Project 5.2 focused on two applications of electronic ballasts for use with high intensity discharge (HID) lamps, specifically metal halide lamps.

Application 1: The purpose of this study was to evaluate the performance of electronic ballasts operating metal halide lamps in the low-wattage range (35/39-175W).

The intent of the study was to develop confidence in the market for the performance of this new technology. The ballasts are static and not dimmable. The recommendations that follow from this study for this application are broken into the following "next steps".

Next Step 1: The energy saving potential of the ceramic metal halide (CMH) lamp used with an electronic ballast has been realized by the utilities, and is incorporated in the PG&E Express efficiency lighting rebate program (http://www.pge.com/docs/pdfs/biz/rebates/express_efficiency/application/lighting_v8.pdf) in which a $25 rebate is given for each new luminaire.

In discussions with Gary Fernstrom at PG&E, there is disappointment at the utility in the very low response to this rebate program. PG&E would like to provide a more effective program in 2005. Gary feels that the program could be restructured in a better way.

- There is a need for raising the level of awareness in the market about the rebate opportunities.
- Support materials need to better define the benefits of the product for end user applications.
- There needs to be more definition of the improved efficacy of the lamp/ballast system relative to the existing product, and more definition of the efficacy of the luminaire performance relative to the existing product.
- There needs to be monitoring and verification of installations which can be used as demonstration of performance and which can be used to support new energy codes.
- There needs to be new codes written to support the move to this technology.

Next Step 2: Project 5.2 defined the operating characteristics of the electronic ballasts and the advantages of the new technology. The results demonstrated that the CMH lamp/ballast systems of the lowest wattages (39 and 50 watts) are ideal candidates for energy efficient replacement of incandescent sources, and that the recent introduction of the 20 to 25 watt lamps further extends that opportunity. The remaining questions are the life performance of both the lamp and ballasts. Lifetests were not possible in the current project but should be done to provide this final piece of information to the market, specifically for the low wattage CMH systems.

Next Step 3: Indy Lighting, a company within the Juno Corporation (http://www.junolighting.com/), was an early adopter of the CMH technology and developed one of the first display track lights using this technology. They are interested in increasing the utility of the product as suggested by Fernstrom, and doing so by working with LBNL to change the output optics of the product, in which one changes the diameter of the focused beam while maintaining uniformity across the beam. In current halogen applications, frequently many lamps are focused on one object, either to illuminate a large object, or to increase the contrast ratio between the object and the background. Most fixtures do not have a variable focus that can project the light uniformly over various focus settings. Recent developments in optical design make this opportunity feasible with moderate cost to the luminaire.

Consequently, a single fixture can focus from a 8^0 spot to a 25^0 flood to a 45^0 wide flood with a near uniform distribution across the projected beam. This has the effect of significantly increasing the versatility of the product, providing an opportunity for general lighting of large objects or focusing to achieve high contrast ratios. These are features that help to overcome the limitations of not being dimmable and making the overall product more versatile for retail and display applications, thereby accelerating the introduction and application of the technology.

Application 2: The purpose of this second study was to evaluate the performance of dimming electronic ballasts operating metal halide lamps in a higher wattage range (200-500W).

The intent of the study was to determine the energy savings potential of the systems and controls when used in conjunction with spaces having daylight, and evaluate the change in critical performance attributes of the lamp/ballast system as the power was varied.

The application of products having these controllable attributes is for highbay lighting where control of the light source provided energy savings for areas that have supplemental daylighting, such as large box stores, warehouses, and industrial facilities. At the time the proposal was written, this was an important emerging technology in reducing energy consumption in these spaces, given the excitement generated by Lisa Heschong's findings about daylighting increasing sales in retail spaces. However, in the interim of writing the proposal and measuring the systems, high-output T5 fluorescent lamp systems have been introduced for the same applications. A typical 5 lamp T5 luminaire can replace a single 400-watt HID source. The light output can be controlled in a sequential fashion by turning the lamps on or off, or by providing dimming ballast capabilities. Among the advantages of the fluorescent lamp system are their instant on and off capability, which allows them to be turned on and off with occupancy sensors, their ability to maintain color as they are dimmed, and their high color rendering characteristic. Consequently, these lamps have received wide acceptance in retrofit applications, replacing both metal halide and high pressure sodium luminaires in highbay applications.

In conclusion, it is apparent that continued support of the dimmable electronic ballasts is not warranted given the attributes of the new T5 systems.

Next step 4**:** Emphasis should be to define the energy savings and control attributes of the HID dimming systems and the new fluorescent T5, HO T5, Super T8 and biax systems. There is confusion in the appropriate application of the different technologies and the energy saving potential of the respective systems. Case study measurements are needed to quantify these differences for the lighting community and for the establishment of data that would support the development of new energy codes.

Commercialization Potential

The products evaluated in Project 5.2 are all commercially available. The activity of this project was focused on determining the performance characteristics that the market values in the adoption of a new technology. Hence, the commercialization potential depends upon defining the applications where this technology will make a significant contribution to the end-user to warrant changing from existing practice.

The electronic ballasts studied in Application 1 are used for indoor lighting applications currently dominated by incandescent and halogen sources. Coincident with the emergence of the electronic ballasts for metal halide sources was the introduction of ceramic metal halide (CMH) lamps, superseding quartz envelope technology. Ceramic metal halide lamps encase the plasma discharge in an aluminum oxide, Al_2O_3, housing that can be made with great precision, allowing for higher pressures and much better control of the discharge parameters. The result is a lamp with better color properties and maintenance over the life of the lamp. The combination of CMH lamps and electronic ballasts provided a lamp/ballast system that meets the color performance of tungsten-halogen, while having much longer life and higher efficacy. Unlike halogen or incandescent sources, the lamp requires a starting time of 60-90 seconds, and the system cannot be dimmed. The majority of retail and commercial spaces do not require the instant-on attribute, or the ability to dim. The target market for this system is the replacement of tungsten-halogen and incandescent sources where dimming and/or instant on is not required.

The barriers to the adoption of this technology are often stated as: 1) inability to dim; 2) low lumen packages; and 3) long starting and restrike time. The following discussion will provide further explanation of these limitations.

Dimming: There are no dimming ballasts available for these lamps, and it is expected that dimming would generally change the color performance of the lamps. Dimming may be important if it is required to go to low light levels, i.e., in restaurant applications. However, for applications in which the dynamic range is not used in the dimming system, lower light level can be achieved by using sources of a lower wattage. This may seem obvious, but given the much greater efficacy of the CMH systems, the lowest wattage lamp at the start of this study, a 35 or 39-watt lamp, which is comparable to a 125-watt halogen lamp, may provide more light than is demanded in certain applications.

Low lumen packages: Since the start of this study, an additional light source has recently been introduced into the market, it is a 20-watt CMH system, which furthers expands the series and helps to address the lower lumen requirements for certain applications.

Starting/Restrike Time: The starting or restrike time of 60-90 seconds may be a barrier if the light sources are the only sources within a space. However, these systems are most often used in conjunction with fluorescent lighting. Under these conditions, the fluorescent lights provide the instant-on ambient light necessary while the CMH systems are achieving full light output. In general, the starting time of these systems is much shorter that larger wattage HID light sources and should not be a barrier once the market is educated.

The great attribute of these systems is their energy savings potential. As can be seen from the Table 21, a 39 watt CMH lamp can replace a 150 watt incandescent source, reducing the energy load of the facility for both lighting and air conditioning. An additional advantage of the sources is the longer life of the product.

Table 21. Performance Characteristics of HID Electronic Ballasts

OPERATING PERFORMANCE	**39W**	**50W**
Lamp Power (Watts)	39.93	51.05
System Power (Watts)	46.03	58.39
Lumens	2474.2	4278.0
Lumens per lamp watt	62.0	83.8
Color Rendering Index	88.8	84.8
Color Temperature (Kelvin)	2784	2695
Incandescent Equivalent W	**150W**	**250W**

Despite these attributes, commercialization is limited by the system costs that incorporate relatively expensive ballast and lamp. Utility rebate programs are helping to reduce this barrier.

Benefits to California

The application of the technologies studied in Project 5.2 can have benefit to California in two key areas. The first is the application of ceramic metal halide (CMH) lamps powered by electronic ballasts in the commercial sector to replace less efficient incandescent lamps.

This benefit can be quantified by determining the annual energy used nationally for incandescent lighting, including both standard and tungsten halogen sources, in the commercial sector. The total commercial lighting energy budget is 391 TWh of which 32% is used by incandescent sources, which equates to 125 TWh. California uses approximately 10% of the annual lighting energy; therefore, the use in California is about 12.5 TWh annually. A significant percentage of this energy could be saved with the use of more efficient technologies. The CMH lamp provides the critical performance

characteristics necessary to meet the requirements of many applications currently using incandescent sources.

One application that CMH systems are beginning to penetrate is use in retail spaces. The following table shows how the national lighting energy use is partitioned within the retail building sector and the use of incandescent sources within those spaces.

Table 22. Total Lighting Electricity Use in Commercial Buildings by the Retail Sector

		INCANDESCENT	TWh
Strip shopping	29.6 TWh	31%	9.2
Retail (excluding mall)	33.2 TWh	32%	10.3
Enclosed shopping center/mall	13.5 TWh	31%	4.2
			23.7 Total

Again, California would represent roughly 10% of this value or 2.4 TWh per annum. The system efficiency of the technology proposed is 4 to 5 times greater than the incandescent equivalent. Hence, substantial energy savings could be realized if this technology made significant penetration into this market.

In a second application, it was demonstrated in this project that on average high intensity discharge (HID) lamp/ballast systems using electronic ballast are 10% more efficient than the corresponding system using a magnetic ballast. Outdoor lighting for both building parking lots and street lighting utilize magnetic ballasted HID lighting systems. Table 23 shows that 53 TWh are consumed nationally by these lighting systems each year. Changing the ballasts to electronic ballasts would reduce this use by 5.3 TWh nationally and approximately 0.5 TWh in California.

Table 23. Application of Electronic Ballasts to Outdoor Lighting

Street Lighting	31.96 TWh
Parking Lots	22 TWh
	53 TWh total
Changing Ballast	5.3 TWh

In conclusion, the technologies studied in Project 5.2 have the potential to significantly impact the energy use for electric lighting in the state of California and the US. The resulting savings for the state could be over 2 TWh annually if the technologies were successfully deployed.

Conclusions

The conclusions of Project 5.2 are divided according to the wattage of the lamp ballast system. For lamp/ballast systems of less than 200 watts, the study focuses on the performance of electronic ballasts operating two different lamp types, quartz and ceramic metal halide (CMH). The application is for the replacement of all types of incandescent sources with these very much more efficient systems.

To replace the incandescent sources, the light source must meet certain critical performance criteria. The study found that CMH lamps were the lamps of preference for the following reasons:

1. The rated average life for the quartz and the ceramic lamps is comparable for similar wattages and outer envelope construction.
2. The ceramic lamps are more efficacious than the comparable quartz lamp from the initial start of the lamp.
3. Ceramic lamps have a lower rate of lumen depreciation relative to quartz lamps.
4. The ceramic lamps have much higher color rendering index (CRI) than the comparable quartz lamp, with all lamps having a CRI above 80 and most of the 4000K lamps having a CRI in the 90s.
5. The ceramic lamps show much greater color stability over life of the lamp relative to quartz lamps.
6. The ceramic arc tube can be incorporated in different lamp constructions such as the tubular and reflector lamp types. This allows manufacturers to optimize the luminaire optical design for the much smaller ceramic arc source or to directly incorporate the reflector lamp.

The focus of the industry is to capitalize upon the attributes of the ceramic lamps in the lower wattage range to produce a more efficacious long life alternative to incandescent and halogen sources. Given the attributes of the CMH lamps as listed above, the ceramic lamp appears to be a better value for the end user.

The measurements performed on both the ceramic and the quartz lamps demonstrated that there was no statistical difference in the performance of the lamps on either magnetic or electronic ballast. Hence, the improvements in the efficacy of the electronic lamp/ballast system relative to the magnetic lamp/ballast system are solely attributed to the improvement in the performance of the electronic ballast.

The study found that the electronic ballasts were the preferred technology for this application for the following reasons:

1. The electronic lamp/ballast system efficacy was 10% higher than the comparable magnetic systems for wattages equal to or greater than 70 watts.
2. For lamp wattages below 70 watts, the electronic lamp/ballast system efficacy was greater than 10% higher than the comparable magnetic systems and increased with decreasing lamp wattage.
3. The electronic ballast maintains a constant power over a variance of 10 % of line voltage, resulting in a maintained flux and color quality.
4. The electronic lamp/ballast systems are 3 to 4 times more efficient than halogen sources and 4 to 5 times efficient that standard incandescent sources.

The second set of conclusions of Project 5.2 refer to the evaluation of lamp/ballast systems of greater than 200 watts, focusing on the performance of characteristics of

controllable electronic ballasts operating metal halide lamps. The application of products having these controllable attributes is for highbay lighting where control of the light source provides an energy savings potential for areas that have supplemental daylighting, such as large box stores, warehouses, and industrial facilities.

The study found that the controllable electronic ballast lighting systems have performance characteristics that may limit the use of the technology in this application for the following reasons:

1. While the efficiency of the ballast is maintained over the controllable range, the efficacy of the lamp and system decrease with any reduction in power.
2. The light output of the source falls to 50% at 75% of full power.
3. The color quality of the light significantly degrades below 75% full power.

Comparison of the system performance characteristics to other competing technologies suggests that the studied technology may not be the most cost effective and effective method for achieving controllable lighting in daylit spaces having high ceilings.