INCANDESCENT LIGHT POWER EFFICIENCY: AN IMPACT STUDY ON THE POWER CONSUMPTION OF THE VAAL UNIVERSITY OF TECHNOLOGY'S LIGHT SOURCES.

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DECLARATION

I, Adewumi Olujana Adeniyi, hereby declare that this dissertation is my own original work, that all sources have been recorded and acknowledged, and that this document has not previously, in its entirety or in part, been submitted at any other university to obtain an academic qualification.

Signed ………………………..

Date: 12 December 2013

DEDICATION

This study is dedicated to my late father, His Royal Majesty Oba S.T. Adeniyi J.P., whose quest for education motivated me, but an inevitable death prevented him from witnessing my graduation. Adieu!

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ABSTRACT

In view of the energy consumption problems, an impact study, extensive laboratory tests and an investigation towards comparable energy saving light sources was carried out on the light sources identified in the survey conducted at the Vaal University of Technology (VUT), Vanderbijlpark campus.

Three types of identified incandescent light sources were purchased and extensively tested in order to obtain viable statistical data on the life span, luminance delivered per unit, power consumption and economic effect, as well as identifying relevant energy efficient light sources for replacement purposes. A suitable computerised maintenance program has been developed to be introduced to the VUT that currently does not have a lighting system maintenance program.

The case study was located within the empirical-analytical paradigm, using quantitative data. The identified aims and goals place the empirical part of the study in the category of implementation evaluation research that provides an overview of a maintenance plan.

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BASIC UNIT AND SYMBOLS

The basic units and symbols used in the study are given in the table below.

Table 1 Basic units and symbols

SYMBOL	DESCRIPTION	UNITS
P	Power	Watts
U	Terminal r.m.s. Voltage	V
I	Current	A
ϕ	Luminous Flux	lm
E	Illuminance level	lux
K	Luminous efficacy	lm/w
L	Length of space	m
W	Width of space	m
H	Height of fixture from the plane of measurement	m
A	Area	m^2
F	Average luminous flux	lm
N	Number of lamps required	
UF	Utilization factor	Per unit or %
MF	Maintenance factor	Per unit or %
E_n	Orbital energy	Joules
C	Light velocity	m/s
M	Radiance emittance	Joules

DESCRIPTION OF TERMS

Circuit watts:	Total power consumption of lamps plus ballasts in the lighting feeder/circuit under consideration.
Colour Rendering Index (CRI):	A measure of the effect of light on the perceived colour of objects. A low CRI indicates that some colours may appear unnatural when illuminated by the lamp.
Installed Load Efficacy:	The average maintained illuminance provided on a horizontal working plane per circuit watt with general lighting of an interior expressed in **lux/W/m².**
Installed Load efficacy ratio:	The ratio of Target load efficacy and Installed load efficacy.
Lumen:	Unit of luminous flux; the flux emitted within a unit solid angle by a point source with a uniform luminous intensity of one candela. One lux is one lumen per square meter.
Luminaire:	A complete lighting unit, consisting of a lamp or lamps together with the parts designed to distribute the light, position and protect the lamps, and connect the lamps to the power supply.
Lux:	The metric unit of measure for illuminance of a surface. Average maintained illuminance is the average of lux levels measured at various points in a defined area. One lux is equal to one lumen per square meter.
Mounting height:	The height of the fixture or lamp above the working plane.
Rated luminous efficacy:	The ratio of rated lumen output of the lamp and the rated power consumption expressed in lumens per watt.
Room Index:	The ratio, which relates the plan dimensions of

	the whole room to the height between the working plane and the plane of the fittings.
Target Load Efficacy:	The value of Installed load efficacy considered being achievable under best efficiency, expressed in lux/W/m².
Utilisation factor (UF):	The proportion of the luminous flux emitted by the lamps, which reaches the working plane. It is a measure of the effectiveness of the lighting scheme.
Maintenance factor:	The allowance for reduced light output because of deterioration and dirt.

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AMI	Advance Metering Infrastructure
CFL	Compact Fluorescent Light
CO_2	Carbon dioxide
CRI	Colour rendering index
DC	Direct Current
DSM	Demand Side Management
ESKOM	South African Electricity Supply Commission
HEI	High Efficiency Incandescent
GWP	Global-warming potential
GHG	Greenhouse gas
IES	Illumination Engineering Society
IDM	Integrated Demand Management
LED	Light Emitting Diode
CH_4	Methane
NERSA	National Energy Regulatory of South Africa
PCB	Polychlorinated biphenyls
S A	South Africa
SANS	South African National Standards
SCADA	Supervisory Control and Data Acquisition
SCENIHR	European Commission Scientific Committee
SMPS	Switch Mode Power Supply
THD	Total Harmonic Distortion
TOU	Time of Use
UV	Ultra Violet
VUT	Vaal University of Technology

CHAPTER 1 - ORIENTATION TO THE STUDY

1.1 INTRODUCTION

The amount of the daily energy, or in other words, power consumed by the Vaal University of Technology's (VUTs) main campus is high; an average of R789 069.82 monthly (VUT 2012). The recent tariff hike of 25,8 percent, by the National Energy Regulatory of South African (NERSA) amounts to an electricity increase of 52 cents per kilowatt hour (c/kwh) used (Lana 2010:1). There is, therefore, a need for the university to consider switching over to light sources that are more efficient, as this may reduce the energy consumption on the campus.

A lighting energy saving initiative generally involves replacing incandescent light with an energy efficient light source and replacing magnetic ballasts of existing fluorescent luminaire with electronic ballasts. Incandescent light source is the main source of illumination at the VUT, and there are wide-ranging assumptions that incandescent light sources are less efficient (Derbyshire 2009:1).

The focus of this research is on incandescent light (classic light, halogen and discharge lamp) sources, identified in the survey conducted on the VUT main campus during the early stage of the study. These light sources are used internally in offices, lecture rooms and laboratories, as well as externally on the grounds, in hallways, and in driveways.

Each light source emits light as luminance. Luminance is a photometric measurement of the luminous intensity per unit area of light travelling in a given direction (Theraja & Theraja 2006:2021). The luminance delivered by each of the tested light sources would be determined.

In this study, the elements of luminous efficiency and life span are integral aspects of incandescent light sources. Luminous efficiency, a figure of merit, is defined as the ratio of luminous efficacy to the theoretical maximum luminous efficacy (Tipler & Llewellyn 2003:1; Klipstein 2006:2). Life span (a measure of the maximum period) of light sources was observed and the power consumption and the economic effect of light sources were highlighted.

This study was in accordance with the South African National Standards (SANS) (2006) on illumination. SANS is a statutory body that was established as the national institution for the promotion and maintenance of standardisation and quality. The International Electro-technical Commission (IEC) consolidated SANS version on tungsten filament IEC 60064, edition number 6.3 code: 29.140.20 and on incandescent lamps, IEC 60432-1, 2, and 3, were complied (SANS 2006).

The progress of conserving energy has generally run parallel to the transformation of incandescent light source to a more efficient source.

1.2 HISTORICAL BACKGROUND

The invention of the classic light has a history spanning from the early 1800s. Until that time, available light sources consisted of candles, oil lanterns and gas lamps (Bellis 2008:1).

In 1809, an English chemist, Humphrey Davy, started the journey to the invention of a practical classic light source (Burgin 2009:1). De La Rue, in 1820, made the first known attempt to produce a classic light with platinum. Although it was an efficient design, but due to the purchase cost of filament, it was impracticable for commercial use (Pierce & Smith 2006:1).

Throughout the 1800s, many scientists and inventors (De La Rue 1820, Grove 1840, Daper 1846, Shepard 1850, Gobel 1854, De Chagny 1856, Way 1860, Lodyguine 1872, Swan and Edison 1879, Gobel 1893, Auer 1898) strove to create a cost effective, practical, long life span, classic light. The primary hurdle was creating a long-lived, high temperature filament, the key to a practical incandescent light (Klipstein 2006:2).

In 1879, Edison and Swan developed the first classic light that practically lasted for 13.5 hours, and based on a carbon fibre filament derived from cotton (Friedel & Israel 1986:15-17; Klipstein 2006:1-3). Edison developed a bamboo filament in 1880 that lasted up to 1200 hours (Pierce & Smith 2006:2).

Classic light is simply a resistor, which if electrically powered, converts to heat in the filament (Hughes 2004:15; Burgin 2009:95-108). After it is heated, the filament gives off light in a process called incandescence (Wallace 2001:2; Klipstein 2006:2).

The efficiency of a classic light design is centered on attaining a high filament temperature without degradation and loss of heat (Klipstein 2006:2).

Edison (1879) earlier selected a carbon filament (melting point of 3695^0K/6192^0F), with a disadvantage of evaporation and rapid sublimation (Friedel & Israel 1986:8). Karl Auer (1898) on the other hand used Osmium filament (melting point of $2996^oC/5425^oF$), which drew attention because it operates at a higher temperature, with a longer life span and less evaporation (Parker 2008:1).

Classic lighting was improved by using tantalum filament, and later tungsten filament, which evaporates (disintegrates) slower than carbon filaments. However, the early tungsten filaments still sublimed too quickly at higher temperature. As they sublimed, they also coated the bulbs with a thin black tungsten film, thereby reducing their light output. Inert gas such as nitrogen and argon were added to reduce the tungsten evaporation and sublimation, and increase filament life (Parker 2008:3; Bellis 2008:2).

The introduction of ductile tungsten in 1906 by General Electric and William Coolidge, set off the development of the modern tungsten filament classic light (Smith 2006:2).

To this day, continuous research has been conducted on incandescent light source principles, in order to provide an improved output for the amount of energy consumed (Selvon 2008:1-2). The discharge lamp has been subjected to criticism ever since its introduction in 1930s. In 1989, the German Power Station published measurement results on the compact fluorescent lamp (CFL), stating that this type of light source was less economical than claimed by the lighting industries (Stanjek 2007:1).

Various forms of discomfort have repeatedly been reported by physicians (medical doctor) and ergonomists (scientist who used the applied science of equipment design to maximise productivity by reducing operator fatigue and discomfort) on employees who constantly had to work under compact fluorescent light sources. Some of the discomforts identified were eye strain, inflammations, headaches and loss of performance (Stanjek 2007:9).

Compact fluorescent lights, like all other fluorescent lamps, contain small amounts of mercury vapour inside the glass tubing. Most compact fluorescent lights contain 3 – 5 mg per bulb, with some brands containing as little as 1 mg per bulb. Even these small amounts of mercury are a concern to environmentalists. The major concern pertaining to landfills and waste incinerators, where the mercury from the lamps may be released and then contribute to air and water pollution (Daley 2008:1-2). In order to make compact fluorescent light sources last longer, they must be in use for long periods. As a result, constant switching on and off should be discouraged (Masamitsu 2007:2).

A potentially valuable light emitting diode (LED) may be more efficient than the classic light, the discharge lamp, and the halogen lamp. It may also produce a better luminance in relation to the power consumed. Therefore, a light source that overcomes the challenges of incandescent light sources is also examined.

1.3 PROBLEM STATEMENT

In view of the high energy consumption at VUT, this study aims is to effectively test some of the light sources used on the VUT main campus, in order to determine the life span, luminance delivered per unit, power consumption, economic effect, as well as identifying an energy efficient light source for replacement purposes, in order to save energy and lessen the utility cost, where after a suitable computerised maintenance program will be introduced to the VUT that currently do not have a lighting system maintenance program.

1.4 PURPOSE OF THE STUDY

The purpose of this study is to give the university an insight into how much energy could be saved, if the incandescent light sources used on the VUT campus is replaced with a more efficient light source. An energy efficient light source presents the quintessential green-green situation; saving money and helping the environment. The introduction of a computerised lighting system maintenance package will provide for an improved efficiency and enhanced, effective service delivery.

Throughout this study, the researcher draws on the epistemic knowledge obtained from the literature and on the practical knowledge acquired over the years from working in the engineering industry.

This research also has personal value to the researcher, as it will provide a sense of achievement and actualisation associated with the awareness of having contributed meaningfully to knowledge that may improve society.

1.5 OBJECTIVE OF THE STUDY

The main objective of the study is to conduct research on incandescent light sources used on the campus.

The following aims have been formulated for the study:

- To carry out a survey at the VUT to determine the different types of incandescent light sources currently in use
- To describe the various light sources in detail
- To determine if the identified light sources are utilised cost effectively
- To establish how utility costs could be lessened
- To maintain the same value of service with improved efficacy.

The following research goals have been formulated for the study:

- Analyse the incandescent light sources used on the campus
- Establish the luminance delivered by each identified incandescent light source
- Establish the monetary value of the energy consumed by VUT regarding the light sources that are being research
- Compare the use of classic light, halogen and discharge lamp with an energy-saving light source (LED)
- Design, develop and implement a computerised maintenance schedule and a software program for use on the campus in order to monitor the lighting system.

1.6 RESEARCH METHODOLOGY

This section describes the research procedures and methodology that was engaged in for the empirical portion of the study. The study was located within the empirical-analytic paradigm; an in-depth ascription on incandescent light sources used on the campus was dealt with during the study.

Yin (2002), suggests that the case study approach should be defined as a research strategy, an empirical enquiry that investigates a phenomenon within its real-life context.

According to him, case study research means single and multiple case studies, which can include quantitative evidence, and which relies on multiple sources of evidence and benefits from the prior development of theoretical propositions. Single-subject research provides the statistical framework for making inferences from quantitative case study data (Flyvbjerg 2006:219-245; Sutherland 2009:10).

The descriptive case study for this research was positioned mainly in the positivism paradigm; a depiction that implies examining the same light sources at different time intervals within the same bounded context (Welman, Kruger & Mitchell 2005:96).

Case studies should not be confused with qualitative research and they can be based on quantitative evidence. However, case study methodology engages in an in-depth ascription on the incandescent light sources. Case studies provide a systematic way of looking at events, collecting data, analysing information and reporting the results (Lamnek 2005).

Quantitative data for the study were obtained from the laboratory test experiment conducted, and compared with literature review undertaken in conjunction with SANS (2006) rules.

An artificial light usage profile (usage profile) form an integral part of energy saving calculations in energy efficient light study. A method of obtaining a usage profile has required information supplied by the users. This results in inaccuracy and a lack of scientific validity. Therefore, the validity of using a light on/off data logger as light logging equipment will be investigated.

As a result, the researcher may gain a sharpened understanding of why the instance happened as it did, and identify what might be important to look at more extensively in future research.

Given the background to the incandescent light power efficiency, and the aim of the study, which is to reduce the energy consumption in Kwh used by the spatial light sources, a call for total eradication of the incandescent light source, as a result of energy consumption, may be an indication of the need to switch over to a more efficient energy saver that can be effectively maintained.

Design, develop and implement a versatile methodology for accurately maintaining light sources through an integrated software program would be embarked upon. Microchip (PIC C), an efficient, cost effective, easy to use lighting system maintenance program that could be tailored to all scenarios, will be used.

A detailed description of the methodology for the empirical part of the study is provided in Chapter 3.

1.7 DELIMITATION

This study is particularly directed at the incandescent light sources (classic light, halogen and discharge lamp) used on the campus. The study is limited to both the C and E blocks of VUT campus; the blocks comprise of offices, lecture rooms and laboratories. These blocks were considered viable because they are typical of the other blocks contained on the campus. The main thrust of the case study is the introduction of a lighting system maintenance program.

1.8 RESEARCH OUTCOME

The outcome of the study on incandescent light power efficiency is seen as documentation provided in the form of a dissertation that give an insight into the energy conservation, carbon footprint reduction, design, develop and implementation of the lighting system maintenance program, possible conference publications and articles published in accredited journals.

1.9 CLARIFICATION OF KEY CONCEPTS

Individuals involved in the engineering sectors know the terminology used within the study, there are terms that may cause confusion regarding the different fields of engineering. These terms are discussed here to mitigate any potential misconception.

During the study, the term ‘energy’ was used to describe one kilowatt of power delivered, for a period of one hour, while the term ‘power’ refers to the rate at which energy is transmitted. The term ‘energy’ has not been altered within the concept referred to in the study, but should be interpreted in context.

The term ‘luminance’ was used to describe a photometric measure of luminous intensity per unit area of light travelling in a given direction, while the term ‘illumination’ was used to describe a measure of the intensity of the incident light.

The term ‘conceptual framework’ was described in this study as an underlying set of ideas, principles, agreements or rules that provide the basis or outline for study on incandescent light power efficiency. In context, it provides the general background to and context for the particular action on incandescent light sources used at VUT.

The term ‘luminous efficacy of radiation’ measures the fraction of electromagnetic power which is useful for lighting while ‘luminous efficacy of source’ is a measure of how well a light source produces visible light.

1.10 CHAPTER CLASSIFICATION

This chapter described the orientation to the study, why it was undertaken, how it was undertaken and when it was undertaken. It also provided a brief overview of the study. In addition, the research questions formulated for the study were outlined. These research questions clarify why the study had to be in line with the energy consumed on the VUT campus.

Chapter 2 places emphasis on the theoretical background of the light sources that strives to explain the conceptual perspectives on light emission phenomenon, energy efficiency drives in South Africa, carbon footprint, environmental effect and Government policies.

Chapter 3 focused on the research approach and methodologies used in the empirical portion of the study. The research design, data collection procedures and analysis that incorporate the experimental set-up are described. The validity and reliability of the study are also dealt with in this chapter. The integration of the quantitative data findings through a process of triangulation is described.

Chapter 4 presents analyses of the laboratory test experiment that incorporated the efficiency, validation of measurement accuracy and economical effect.

Chapter 5 draws together all the results of the previous chapters, providing a synthesis of the interpreted findings with the theory that was discussed in the literature study. Introduction of a maintenance software program and schedule for an efficient utilisation of the lighting system. The chapter closes with the conclusions and recommendations for the VUT lighting system.

1.11 SUMMARY

This chapter places emphasis on the scientists and inventors that have been working since the early 1800s, towards rectifying the challenges associated with incandescent light sources. Some of these efforts involved the use of a carbon filament from cotton, bamboo filament that lasted 1200 hours. However, the primary hurdle was the creating of a long-lived, high temperature filament. The efficiency of incandescent light is centered on attaining high filament temperature without degradation. This has inspired various scientists to develop an efficient, cost effective filament that evaporated and sublimed slowly.

The aim of the study on incandescent light sources’ efficiency was pivoted towards the conservation of energy by swapping the traditional incandescent light source with an energy efficient light source.

Switching from traditional incandescent light source to an energy efficient light source is a change that everyone can make in order to reduce the electricity usage and prevent greenhouse gas emission that leads to global climate change. An introduction of a computerised lighting system maintenance program for an improved light efficiency and enhanced effective service delivery is being presented.

The next chapter, Chapter 2, deals with the theoretical background of incandescent light sources. In addition, it discusses the concept of light as energy, the drives of energy efficiency and management in South Africa, as well as the carbon footprint. The environmental effect and discomfort of constantly working under compact fluorescent light and various government policies were emphasised.

CHAPTER 2 - LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a contextual overview of the light energy, efficiency of light sources, classic light, halogen lamp, discharge lamp and the light emitting diode. A detailed theoretical background of the identified light sources, observed during the survey conducted on the campus, is included in this chapter.

The energy efficiency drive, carbon footprint, environmental effects, and the application of government policies are also discussed.

2.2 LIGHT ENERGY

Emission is the formation of light from any surface, and this is generated naturally by transferring energy through space. An atom that is in an excited state can produce light. An atom is a fundamental piece of matter (anything that can be touched physically) that emits light at specific energy. The electron of an atom revolves in elliptical orbits (a definite discrete orbit) around a nucleus of proton and neutron (Coeffey 2010:2; Blair 2011:1).

There is an excitation of energy when an electron moves from a position close to the nucleus of an atom to a position farther away from the nucleus (from a lower to a higher energy level). The electron in an excited atom quickly moves back to its original level (de-excited). When the electron has a transition from one orbit to another, energy is being released. The energy released is given off in the form of electromagnetic radiation.

The atom emits light due to the process of excitation and de-excitation (see Figure 1) (Prentiss 2005:705; Theraja & Theraja 2006:2019; Coeffey 2010:2).

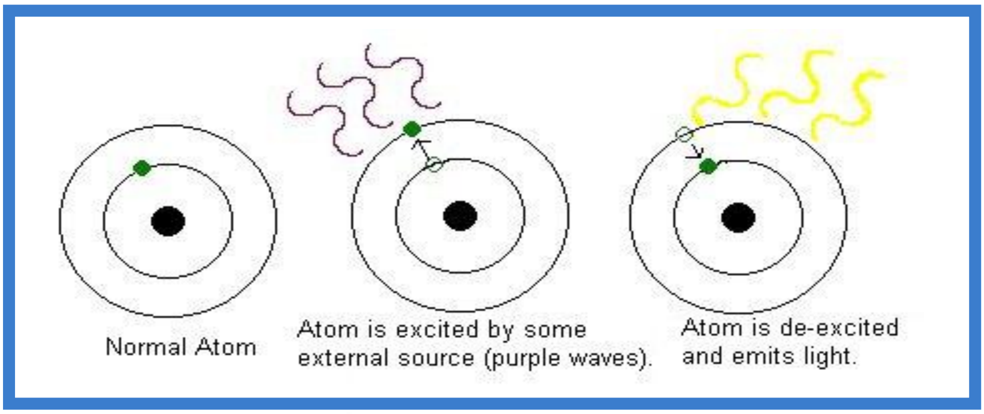

FIGURE 1: Excitation and de-excitation of atom
(Theraja & Theraja 2006:2019)

The orbital energy (E_n) of a revolving electron is given by kinetic energy and potential energy (Dorf 1993:159):

$$E_n = -\frac{mz^2e^4}{8\varepsilon_0^2 n^2 h^2} \quad [J] \qquad (1)$$

Where; m is the mass, e is charge of the electron, z is the atomic number, n is an integer and h is the Planck's constant.

According to Klipstein (2006), emission of light energy from an atom occurs in a pulse of radiation called photons. The light emission can be spontaneous or stimulated. In spontaneous emission, an atom at a sufficiently high energy level emits photons of a characteristic energy. This is the process by which discharge lamps works.

During stimulated emission, an atom in an excited state is perturbed by a photon of light and gives rise to a further photon of light. This phenomenon is the process that gives rise to laser emission (many photons of the same wavelength and phase); the higher the frequency, the greater the energy. The energy level is proportional to the light frequency (Dorf 1993:159; Klipsten 2006:2; Keefe 2007:1).

The wavelength determines the colour; ultra violet (UV) in the visible range or infrared outside the visible range. The element of an atom has a different pattern of electron energy level and emits light with a characteristic pattern of frequencies. This is termed the element's emission spectrum. The frequency of light emitted is a function of energy transition. Therefore, the more frequency is given off by the element of an atom in transition, the brighter is the colour (Klipstein 2006:2; Jannsen & Mecklenburg 2007:65-134; Burgin 2009:2).

Electromagnetic spectrum is the distribution of electromagnetic radiation according to the wavelength. Electromagnetic spectrum covers a wide range of wavelength and this wavelength extend from radio wave (1 m - 100,000 kilometer (km)), microwave radiation (1 millimeter (mm) - 1 m), infrared radiation (750 nanometer (nm) - 1 mm), Visible radiation (390 nm - 750 nm), Ultra violet (10 nm - 400 nm), X-ray (0.01 nm -10 nm), and Gamma radiation (less than 0.02 nm). The visible light spectrum (see Figure 2) is a section of the electromagnetic radiation spectrum that is visible to the human eye. It ranges in wavelength from approximately 380 nm - 760 nm. Visible light constitutes a very small portion of the electromagnetic spectrum. UV is an electromagnetic radiation with a wavelength of between 10 nm - 400 nm. The wavelength of UV is shorter than the wavelength of the visible light spectrum but longer than that of X-rays (Fedorovich, Zak & Ostrovskii 1994:204-206; Mohr, Taylor, & Newell 2008:633-646; Burgin 2009:2; Glenn 2010:1).

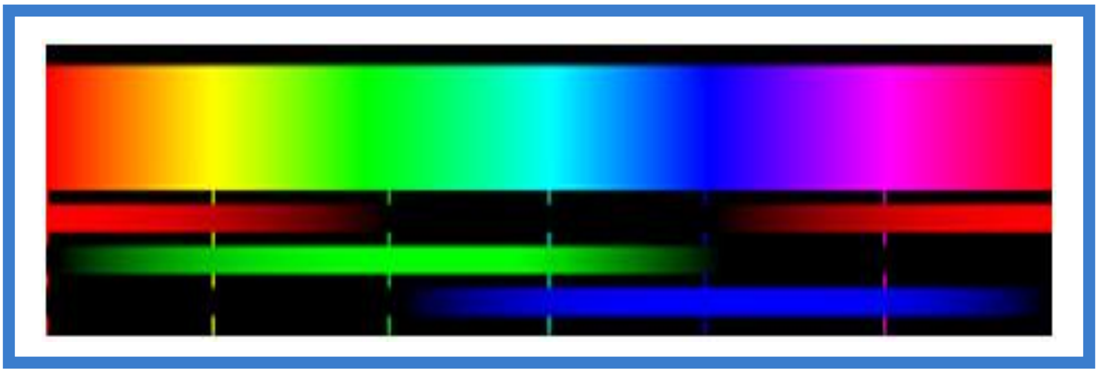

FIGURE 2: Visible light spectrum (Mohr *et al*. 2008)

2.3 EFFICIENCY OF LIGHT SOURCES

Efficiency of light sources (lm/w) is a figure of merit that describes the extent at which the source provides visible light. The amount of total light output from a luminary in a given period of time is expressed in lumens (lm), which in turn is a measure of flux (Φ). Luminous intensity (I) of a point source in any particular direction is given by the luminous flux radiated out per unit solid angle in that direction (Keebler 2009:1-2).

Illuminance (E) is the total luminous flux incidence on a surface area, a measure of the intensity of the incident light (lm/m^2= lux). Tipler & Llewellyn (2003:1) gives the relationship between illuminance and intensity as:

$$E = \frac{\mathrm{I}\cos\theta}{r} \quad \text{[lux]} \qquad (2)$$

Where r is distance between the light source and the surface area.

Luminance (L) is a photometric measure of luminous intensity per unit area of light travelling in a given direction and is given by Theraja & Theraja (2006:2021) as:

$$L = E\frac{\rho}{\pi} \quad \text{[cd/m}^2\text{]} \qquad (3)$$

Where ρ is the reflectance of the surface.

Luminous efficacy is of two types: Luminous efficacy of radiation (LER), which is the ratio of visible light flux emitted (luminous flux) to the total power radiated over all wavelength (Tipler & Llewellyn 2003:1; Klipstein 2006:2).

$$\text{Luminous efficacy of radiation } (\eta_r) = \frac{\phi_v}{\phi_e} \qquad (4)$$

These describe how well a given quantity of electromagnetic radiation from a source, produces visible light.

Luminous efficacy of source (LES) is the ratio of the visible light flux (luminous flux) emitted, to the total power input. It is the measure of efficiency by which, the source provides visible light from electricity (Tipler & Llewellyn 2003:1; Klipstein 2006:2).

$$\text{Luminous efficacy of source } (\eta_s) = \frac{\phi_v}{p_{in}} \quad [\text{lm/w}] \qquad (5)$$

The relationship between lumen and an electric unit of power (watt) is given as (Theraja & Theraja 2006:2020):

1 [lm] = 0.0016 [w] (approximate)

This accounts for the input energy that is lost as heat.

Luminous efficiency is the luminous coefficient expressed as a value between zero and one, with one corresponding to an efficacy of 683 lm/w.

The luminous efficiency of various light sources is as shown in the table below.

TABLE 2: Luminous efficacy and efficiency of various light sources (Elliott 2010)

CATEGORIES	TYPE	OVERALL LUMINOUS EFFICACY (LM/W)	OVERALL LUMINOUS EFFICIENCY
Combustion	candle	0.3	0.04%
	gas mantle	1-2	0.15-0.3%
Incandescent	100-200 W tungsten incandescent (230 V)	13.8-15.2	2.0-2.2%
	100-200-500 W tungsten glass halogen (230 V)	16.7-17.6-9.8	2.4-2.6-2.9%
	5-40-100 W tungsten incandescent (120 V)	5-12.6-17.5	0.7-1.8-2.6%
	2.6 W tungsten glass halogen (5.2 V)	19.2	2.8%

	tungsten quartz halogen (12-24 V)	24	3.5%
	photographic and projection lamps	35	5.1%
Light-emitting diode	white LED (raw, without power supply)	4.5-150	0.66-22.0%
	4.1 W LED screw base lamp (120 V)	58.5-82.9	8.6-12.1%
	6.9 W LED screw base lamp (120 V)	55.1-81.9	8.1-12.0%
	7 W LED PAR20(120 V)	28.6	4.2%
	8.7 W LED screw base lamp (120 V)	69.0-93.1	10.1-13.6%
Arc lamp	xenon arc lamp	30-50	4.4-7.3%
	mercury-xenon arc lamp	50-55	7.3-8.0%
Fluorescent	T12 tube with magnetic ballast	60	9%
	9-32 W compact fluorescent	46-75	8-11.45%
	T8 tube with electronic ballast	80-100	12-15%
	PL-S 11W U-tube with traditional ballast	82	12%
	T5 tube	70-104.2	10-15.63%
	Spiral tube with electronic ballast	114-124.3	15-18%
Gas discharge (raw without supply)	1400 W sulfur lamp	100	15%
	metal halide lamp	65-115	9.5-17%
	high pressure sodium lamp	85-150	12-22%
	low pressure sodium lamp	100-200	15-29%
Cathodo-luminescence	electron stimulated luminescence	30	5%

	Truncated 5800 K blackbody	251	37%
Ideal sources	Green light at 555 nm (maximum possible LER)	683.002	90%

2.4 CLASSIC LIGHT

Classic light is an electrical light source that works by incandescence. Incandescence is the emission of light from a hot object due to its temperature. Classic light differs from normally emitted light in that its emission spectrum is composed of an infinite number of frequencies. The reason being that atoms undergoing incandescence are always packed close together; the atoms bounce off, and interfere with, each other. The peak frequency is the highest frequency emitted by a classic light substance. The peak frequency increases as the temperature increases. The emission spectrum from a classic light source is continuous, however, if the classic light is send through a gas and then through a spectroscope, the spectrum will not be continuous, and this is an absorption spectrum (Darrigol 2005:1; Burgin 2009:2).

The filament of classic light is the little wire inside of a light bulb that glows either reddish or orange when an electric current flows through it. This process is understood as the theoretical body, known as black body. A black body is defined as a surface, which absorbs all radiation incidents upon it. Kirchoff’s law of radiation is given as (Laughton 2003:2; Hughes 2004:20):

$$\frac{w}{a} = \text{constant} = wB \tag{6}$$

As the filament gains energy from the electrical power, the filament tries to equalise its energy with its surroundings by radiating its excess energy. The filament does this by emitting light, first in the infrared, and as the filament gets hotter, it has more energy and the radiation moves more into the visible spectrum (Laughton 2003:2).

The filament of a classic light source is made of tungsten, otherwise known as tungsten filament. The resistance of the tungsten filament, when cold (lamp off), is about $\frac{1}{15}th$ of the filament resistance when hot (lamp on). The filament is heated up by an electric current to a temperature ranging from 2000^0K to 3300^0K (3100^0F - 5400^0F). This is well below tungsten's melting point of 3695^0K (6192^0F) (Friedel & Israel 1986:8).

As a result of its strength, ductility and workability, tungsten can readily be formed into filament coils. The filament is wound tightly, like a spring, apportioning additional length to emit light (see Figure 3).

FIGURE 3: Filament of a classic light (Lander 2007:1)

The oxygen in the air will cause oxidation (a reaction between oxygen molecules and substances such as metal) if in contact with the hot filament of the classic light. Enclosing the filament in a glass tube (amorphous solid) prevents this. The tube is filled with an inert gas (argon) to reduce evaporation of the filament by preventing egression of the evaporative gases from the aperture of the tube (Selvon 2008:1; Broydo 2009:1).

The ductile tungsten filament has many favorable properties such as a high melting point of 3695^{o}K/6192^{o}F, a low evaporation rate at high temperature of micro torr at 2757^{o}C/4995^{o}F, and a tensile strength greater than steel.

The temperature of a filament depends on size, shape and type. Classic lights are being produced in a wide range of sizes (A15, A19, A21, R14, R16, G10, G20, G40) and shapes (standard pear-shaped, globe-type bulb, parabolic aluminised reflector (PAR)) of different voltages ranging from 1.5V to about 300V (Osram 2008:1; Zaimov 2011:1) .

As depicted in Figure 3, the filament of a classic light is a pure resistive load with a unity power factor. This indicates that the actual power consumed (watt), and the apparent power usage (volt-ampere), are equal. The current stabilises at about 100 milliseconds (ms) and the light reaches 90 percent of its full brightness after about 130 ms. Classic lights are marked by the electrical power consumed, which is measured in watts (Boshel 2007:2).

Despite its popularity, the operating efficiency of a classic light makes it a poor choice for illumination. A 100 watt bulb rated at 1750 lumens has an efficacy of 13.8 lm/w (Klipstein 2006:4; Boshel 2007:2).

According to Chunlei (2006), by applying a femtosecond laser-blacking technique directly to the tungsten filament of a classic light, the lamp dramatically brightens, and its emission efficiency approaches 100 percent. This made a 60 watt bulb as bright as a 100 watt bulb, without increasing its power requirement.

Tests measuring the life cycle of a classic light show that the average life expectancy is approximately 750 hours. Therefore, in an application that requires illumination of 11.23 hours/day, a 100 watt classic light will operate for a period of 0.2 year (Wallace 2001:2; Mooney 2006:4; Berardelli 2009:1).

A classic light relies on heat to produce light, and is considered vastly inefficient. The tungsten of the filament evaporates, more efficient filaments evaporate faster and because of this, the life span of a classic light is a trade-off between efficiency and longevity (Jaeger 2002:24; Parker 2008:1).

The lifespan of classic light is approximately proportional to voltage. The life span may range from as low as two to six hours for floodlights, where life has been sacrificed in order to obtain a higher efficiency and a higher colour temperature. By reducing the efficacy and light output, the lifespan of a classic light can increase. The trade-off is typically set to provide a lifetime of several hundred to 2000 hours for classic light (Klipstein 2006:2).

A classic light requires no external regulatory equipment, it works with both alternating current (AC) and direct current (DC), although better with AC. AC power operates on a smaller gauge wiring, requires no constant charging, and the AC can produce the required power without incorporating an inverter to a battery bank. AC has a low manufacturing cost, and this study uses AC supply, as this is the supply source available on the campus. A small percentage (10%) of the energy consumed by a classic light is emitted as a visible light; while the highest percentage (90%) is given off as wasted energy in form of heat (I^2R). The heat produced by a classic light can be made use of in applications like dry processes, incubator, easy-bake ovens and heat lights for reptiles (Mooney 2006:4; Burgin 2009:2).

2.5 HALOGEN LAMP

A halogen lamp is an incandescent light source in which the filament is of tungsten material, sealed into a compact transparent envelope, filled with an inert gas such as argon, nitrogen or krypton, and a small amount of halogen such as iodine or bromine (see Figure 4). The filament gives off light after it is heated in a process called incandescence. The types of halogen lamps available are parabolic aluminised reflector (PAR), single-ended halogen, AR48, AR70 and AR111 (Wallace 2001:2; Klipstein 2006:2).

The halogen cycle (a chemical reaction produced by the combination of the halogen gas and the tungsten) is as follows, the tungsten filament is vaporised and intends to stream to the cooler lamp bulb. The tungsten atoms deposit on the bulb and this causes blackening. Blackening means reducing light output, as the deposited tungsten material absorbs the light.

1. Outline of Glass bulb
2. Inert gas (argon, neon, nitrogen)
3. Tungsten filament
4. Head Quarts arc tube
5. Contact wire
6. Insulation
7. Electrical contact

FIGURE 4: Xenon halogen lamp (105 watt) (Burgin 2009:3)

The halogen lamp contains a small quantity of active halogen gas such as bromine. While the inert gas suppresses the evaporation of the tungsten filament, the halogen gas acts to reduce the amount of tungsten deposited on the interior wall of the lamp. The halogen gas reacts with the tungsten that evaporates, migrates outward and then deposits onto the lamp wall. When the lamp wall temperature is sufficient, the halogen reacts with the tungsten to form tungsten bromide, which is freed from the wall of the lamp and migrates back to the filament. The tungsten bromide compound reacts with the filament of the lamp and deposits the tungsten on the filament, which is freed to repeat the cycle again (Wallace 2001:11; Kane 2006:76; Selvon 2008:1-2).

The process of the halogen cycle increases the life span of the lamp, keeps the bulb clean and generates a constant light output. Problems with uneven filament evaporation and uneven deposition of the tungsten onto the filament during halogen cycle occur, and this limits the ability of the halogen cycle to prolong the life span of the lamp (Wallace 2001:11; Burgin 2009:2).

The filament of a halogen lamp operates at a higher temperature (3683^{0}K/ 6170^{0}F/ 3410^{0}C) than a standard gas-filled lamp of similar power without loss of operating life. Molybdenum can be used as a support to the filament. If the filament is mounted on molybdenum wire, the wire will act as both heat sinkage and support, while lowering the temperature at the support junction (Lide 1994:18; Broydo 2009:2).

The halogen lamp, like any other classic light, is rated for a certain light output (lumens) at a rated wattage (w) when operated at the rated voltage. Efficacy of the lamp is calculated as lumen/watt, and the life of the lamp changes with the applied voltage. For small changes in voltage (<10%) life is inversely proportional to the applied voltage, the exponent being 13. Thus, a 5.5 percent higher voltage will reduce the lamp life by a factor of two. Efficacy increases with voltage, the exponent being 1.9 (Hughes 2004:4; Klipstein 2006:2; Broydo 2009:2).

Therefore, rated lamp lives are a function of colour, temperature and efficacy. Rated values for a 1000 watt lamp are given below.

TABLE 3: Rated values of a 1000 watt lamp (Burgin 2009)

Colour Temperature kelvin (k)	Lumen/watt	Rated Lamp Life (hour)
3400º K	33	50
3200º K	26	200
3000º K	21	2000
2500º K	9	> 5000

The halogen lamp is often 10 to 20 percent more efficient than the classic light of similar voltage, wattage and life expectancy. The efficiency and lifetime depends on whether a premium fill gas (usually krypton, xenon or argon) is used (Burgin 2009:2).

The halogen lamp fails the same way as the classic light, usually from melting or breakage of a thin spot in an ageing filament. The thin spots can develop in the filaments of halogen lamps, since the filaments can evaporate unevenly and the halogen cycle does not re-deposit evaporated tungsten in a perfectly even manner. However, filament notching or necking can also cause failure in halogen lamp. When the lamp is on, the neck end of the filament heats up more rapidly than the rest of the filament; the neck can overheat and melt or break during the current surge that occurs when the lamp is turned on (Osram 2004:2; Pierce & Smith 2006:1).

The consumer should be cautious about the hazards of a halogen light source for reasons ranging from excess heat to UV emission. A halogen lamp gets hotter than a regular classic light because, the heat is concentrated on a smaller surface, and the surface is close to the filament. This poses fire and burning hazards. Small amounts of the element hydrocarbon can be mixed with the quartz (a hard crystalline) that the halogen lamp is made of, so that the doped quartz blocks the harmful UV radiation (Mohr *et al.* 2008:635).

The first commercialised lamp (sold to the public) used elemental iodine and was called quartz iodine lamps. Bromine was found to have more advantages than iodine, but it cannot be used in elemental form because of the presence of unsaturated bonds (a link between atoms, and the attachment of valences of an atom, in a constitutional formula). Halogen lamps are rated in watts at a specified voltage. They are not affected by variations in frequency of supply voltage, provided the periodicity (a function of frequency) is not so low that flickering (a flashing effect displeasing to the eye) is caused (Osram 2004:2; Pierce & Smith 2006:1).

Amongst the advantages of halogen lamps are, low cost, and easy incorporation into electrical systems, while the disadvantages include low efficacy, short life span, and a large amount of heat produced.

2.6 DISCHARGE LAMP

2.6.1 Fluorescent lamp

A fluorescent lamp is a gas discharge lamp that uses electricity to excite a mixture of noble gasses (argon, neon, krypton and helium) and mercury vapour, resulting in plasma that produces short wave UV light. This then causes phosphorus fluorescence, and produces light.

Fluorescent lamps require a magnetic or electronic ballast (a device that controls the starting and operating voltage) to regulate the flow of power through the lamp. The main principle of fluorescent tube operation is based around inelastic scattering (deviation from a straight trajectory) of electrons (Kaufman 1981:8-10; Osram 2004:3; Hammer 2008:2; Thayer 2009:1).

The discharge procedure is as follows, when the ballast supplies a high voltage to initiate the current discharge, an electric field is generated in the tube. This field accelerates free electrons in the ionised gas. The UV light has more energy than the visible light, from the proportionality of energy to frequency. Excitation causes electrons of the gas mixture to move to higher energy orbits, raising the atoms to a higher excited state. The electrons jump several energy levels instead of just one, because of the great energy of the UV light. The electrons move down only one energy level at a time when the atom de-excites, releasing energy in the form of photons (see Figure 1). The process of producing visible light, when excited by UV light, is called fluorescence (Hammer 1987:2; Klipstein 2006:2; Thayer 2009:1).

Characteristically, the wavelength of the light is related to the energy levels of the excited states of the gas involved. Since the light is produced by fluorescence and phosphorescence, the spectral content of light does not follow Planck's radiation laws, but is rather characterised by coating (Hammer 2008:3; Thayer 2009:2; Keebler 2009:1-2).

The inner surface of the fluorescent tube is coated with a coating made of varying blends of metallic and rare-earth phosphor salt (see Figure 5) (Masamitsu, 2007:2). The fluorescence conversion occurs in the phosphor (material that absorb energy for a period of time, then gives off light for a longer period) crystal on the inner surface of the fluorescent tube. Typically, the fluorescent tube cathode is made of coiled tungsten, which is coated with a mixture of barium, strontium and calcium oxides. When the light is turned on, the electric power heats up the cathode enough to ionise noble gas atoms in the tube surrounding the filament. This forms plasma by a process of impact ionisation (a process by which one energetic charge carrier can lose energy through creation of another charge carrier) (Masamitsu 2007:2; Thayer 2009:3; Broydo 2009:2)

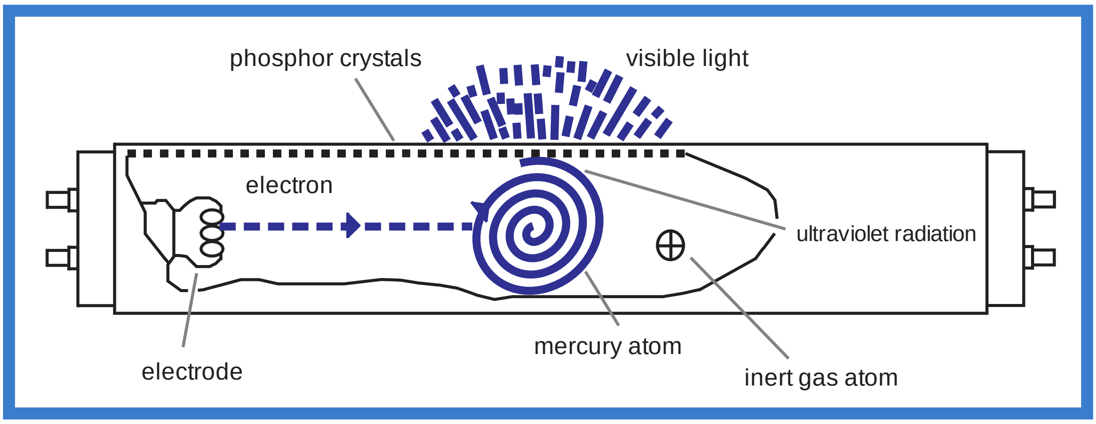

FIGURE 5: Fluorescent lamps (Hammer 2008:1)

The mercury, which exists at a stable, vapour pressure equilibrium point of about one part per thousand inside the tube, is then likewise ionised before the arc strike. The instant starter fluorescent tube uses a high enough voltage to breakdown the gas and mercury column and thereby starts the arc condition. The mercury atoms produce UV light, the light strikes the phosphors in the tube and this phosphor then emits visible light in many different frequencies. These frequencies combine to produce white light (Durba 2005:1; Klipstein 2006:1).

Discharge lamps are very efficient at producing light (compare to classic light and halogen lamp). A 40-watt discharge lamp (fluorescent) rated at 2650 lumens, with a 14 watt ballast, will have an efficacy of 49.0 lm/w.

System efficacy can be improved by using a two- or three-lamp ballast. A two- lamp ballast (requiring 92 watts) increases efficacy to 68.2 lm/w, while a three-lamp ballast (consuming 140 watts) produces a system efficacy of 67.5 lm/w (Atkinson 2004:4).

The efficacy of a discharge lamp is achievable by the tube, ballasts (magnetic and electronic) and starter from which it is made.

2.6.2 Tube

The tube of a fluorescent lamp contains mercury vapour, which is harmful to health. The glass tube seals the inner parts from the atmosphere. This glass tube contains two electrodes, as well as a coating of activated powdered phosphor and mercury. Tubes are designated by their shape, identified by a code such as FT8, where F is for fluorescent, T indicates that the shape of the bulb is tubular, and the number is the diameter in eighths of an inch (Atkinson 2004:4).

FIGURE 6: T8 fluorescent tube (Klipstein 2006:1)

FTB with the B indicating bending of the tube, however, in most respects, it is identical to the FT12, but during manufacturing, the glass tube of roughly four feet in length is formed into a U shape. In the 1970s, a U-tube, a tube with a U shape, was introduced. A miniature double U-tube was later introduced, but created a problem of length versus light (Durba 2005:1; Klipstein 2006:1).

FIGURE 7: U shape fluorescent tube (Klipstein 2006:2)

The length dictates how much surface area is available for the phosphor coating that creates the light, and if the length is reduced, less light is produced. This can be compensated for by using more current arcing through the gas in the lamp, but shortens the life span of the lamp. The length problem was solved by taking the miniature U-tube and bending it, not once, but multiple times (Atkinson 2004:4; Osram 2004:2).

2.6.3 Ballasts

Ballasts (sometimes called the control gear) are devices required to operate the gas discharge lamps.

Ballasts serve two functions;

- To provide the initial starting voltage to a gas lamp. The initial starting voltage provided by the ballasts creates an electrical arc that excites the gasses in the lamp, thus producing light (Turner 2007:2; Dellaporta 2011:1).

- To limit the current to the proper value. Ballasts stabilise the current through an electrical load. These are most often used when an electrical circuit or device presents a negative resistance to the supply (Derry & Williams 1993:4; Goldwassher 2003:1; Turner 2007:2).

FIGURE 8: Ballast (Turner 2007:2)

The ballast unit comprises of a transformer, capacitor and a thermal cut-off switch or safety fuse (ANSI STD 2002:1).

A tarlike substance, designed to muffle the noise that is inherent in the operation of the ballasts, surrounds these components. When a ballast fails, excessive heat can be generated, and this heat will melt or burn the tar material, creating a characteristic foul odor. A puncture or any other damage to the ballasts in a lighting system exposes an oily, tar-like substance. If this oily, tar-like substance contains polychlorinated biphenyls (PCBs), the ballasts and any materials in contact with the PCBs are considered to be PCBs contaminated (ANSI STD 2002:1).

According to Green (2006:14), the primary concern regarding the disposal of used ballasts is the health risk associated with PCBs. Human exposure to these possible carcinogens can cause skin, liver and reproductive disorders.

Conventional lamp ballasts do not operate on dc. If a dc supply with a high enough voltage to strike the arc is available, a resistor can be used to ballast the lamp, but this leads to low efficiency due of power losses occurring in the resistor (Atkinson 2004:3).

2.6.3.1 Resistor ballasts

A resistor ballast compensates for normal or incidental changes in the physical state of a system. A fixed or variable resistor may be used. The resistor ballast has a large resistance that resists most current in the circuit, even with the negative resistance presented by the neon lamp (IEEE STD 2007:83).

Commonly, a fixed resistor is used for simple, low-powered loads, such as a neon lamp.

A variable resistor is a component that has the property of increasing the resistance as current through it increases, and proportionally decreases the resistance as the current decreases. If the current increases, the ballast resistor gets hotter, its resistance goes up and its voltage drop rises. If the current decreases, the ballasts resistor gets colder, its resistance drops and the voltage drop decreases. The ballasts resistor reduces variations in the current despite variations in the applied voltage. This device is sometimes termed barrelters (IEEE STD 2007:84).

2.6.3.2 Magnetic ballasts

Magnetic ballasts are also called inductive or electromagnetic ballasts. Magnetic ballasts use an aluminum coil wrapped around an iron core to generate and regulate voltage (Durba 2005:3; Turner 2007:3).

An inductor is very common in line-frequency ballasts in order to provide the proper starting and operating electric current to power-up a fluorescent lamp. The inductor has two benefits;

- Its reluctance limits the power available to the lamp, with only minimal power losses in the inductor

- The voltage spike produced when current through the inductor is interrupted rapidly is used in some circuits to first strike the arc in the lamp (Atkinson 2004:2).

Current in an inductor is shifted out of phase with the voltage producing a poor power factor.

Magnetic ballasts are considered the least efficient type of fluorescent ballasts. Magnetic ballasts operate T12 lamps, some T8 lamps, 2-pin compact fluorescent lamp (CFL), and are susceptible to humming and flickering (Donovan 2007:3).

2.6.3.3 Electronic ballasts

The electronic ballast is a device that uses solid-state electronic circuitry to regulate starting voltage and maintain the proper operating current.

According to Durba (2005:2), electronic ballasts usually change the frequency of the power supply from the standard mains, 50 Hz frequency, to 20,000Hz or higher, substantially eliminating the stroboscopic effect of flicker (a product of the line frequency) associated with frequency lighting.

An electronic ballast can operate from one to four lamps at a time. Commonly, it is used for T8, T5 and T12 fluorescent lamps in both standard and high output. Electronic ballasts are often based on the switch mode power supply (SMPS) topology; first rectifying the input power and then chopping it at a high frequency. Electronic ballasts are up to 25 percent more efficient than magnetic ballasts. As a result of the higher efficiency of the ballasts and the improvement of lamp efficacy, its pulse appears faster, like a steady stream of light compared to the slower pulsed waves, and this offers a higher system efficacy (ANSI STD 2002:13; Masamitsu 2007:3).

Variation in the supply voltage can result in an increase or decrease of the lamp output. Voltage transient could cause a decrease in the life span of electronic ballasts, since electronic ballasts can be at risk to moderate and high-level spikes; it is desirable to establish whether the available electronic ballasts could withstand such spikes (Gary & Fox 2007:3). Electronic ballast operates at a high frequency, and as a result produces radio interference frequency. Radio interference frequencies are a subset of electromagnetic interference that affects the operation of sensitive electrical equipment's (Durba 2005:3).

2.6.3.4 Ballast factor

According to Donovan (2007:2), the ballast factor is defined as the ratio of the light output (lumen) of test ballast, to the light output of laboratory reference ballasts that operates the lamp at its specified nominal power rating. Electronic ballasts, which produce more light in a fluorescent lamp than the reference test ballasts that operates the lamp with the line frequency current, has a ballast factor greater than one. In lighting design, the ballast factor must be considered. A low ballast factor saves energy but produces less light.

2.6.4 Starter

A starter (automatic starting switch) is a device that creates a high enough voltage to break down the gas and mercury column (ionised), thereby starting arc conditions.

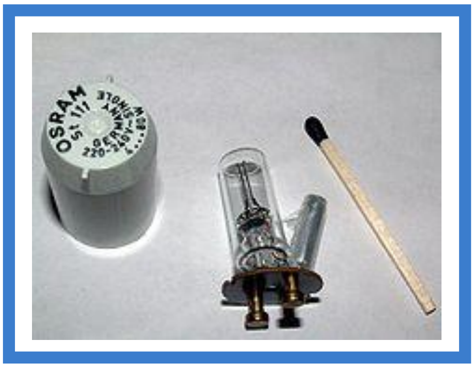

FIGURE 9: Automatic fluorescent lamp starter (Atkinson 2004:2)

The mercury atoms in the fluorescent must be ionised before the arc can strike within the tube. A small lamp does not take a high voltage to strike the arc, but larger tubes require a substantial voltage (in the region of a thousand volts) (Atkinson 2004:2).

A pre-heat technique uses a combination filament/cathode at each end of the lamp in conjunction with a mechanical or automatic switch. This initially connects the filament in series with the ballasts and thereby pre heats the filament prior to striking the arc (Osram 2004:2; Aktinson 2004:2; Turner 2007:3).

The automatic fluorescent lamp starter, (see Figure 9) consists of a small gas-discharge tube that contains neon or argon and is fitted with a bi-metallic electrode. The special bi-metallic electrode is the key to the automatic starting mechanism (Bellis 2008:3).

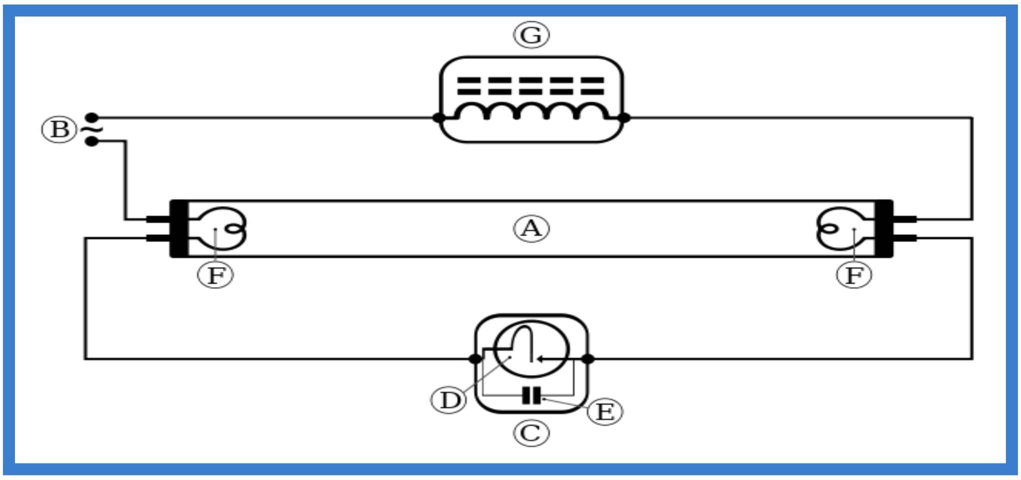

FIGURE 10: A Pre-heat fluorescent lamp circuit (Atkinson 2004:3)

During pre-heating, the filament emits electrons into the gas column by thermionic emission creating a glow discharge around the filament. When the starting switch opens, the inductive ballasts and a small value capacitor across the starting switch create a high voltage that strikes the arc. The tube strike is reliable but the glow starter often cycles a few times before letting the tube stay lit, which causes objectionable flashing during starting. Once the tube is struck, the impinging main discharge then keeps the filament/cathode hot, permitting continued emission. Should the cathode fail to strike and then extinguish, the starting sequence is repeated. With an automated starter such as a glow starter, a failing tube will cycle endlessly, the emission will be insufficient to keep the cathode hot and the lamp current will be too low to keep the glow starter open (Ohno 2004:2; Green 2009:2;).

The life expectancy of discharge lamp is much longer than the classic light and the halogen lamp. A 36-watt discharge lamp (fluorescent) has a life rating of 20 000 hours. Assuming its operating period to be 11.23 hours/day, the 36 watt discharge lamp (fluorescent) will last for a period of 4.9 years (Klipstein 2006:4).

The end-of-life failure mode for discharge lamps varies; this depends on the control gear type and the usage.

There are four main failure modes;

- Emission mix runs out. The emission mix on the tube filament/ cathode is necessary to enable electrons to pass into the gas via thermionic emission at the tube operating voltage. The mix is slowly sputtered off by the bombardment of electrons and mercury ions during operation, but a larger amount is sputtered off each time the tube is started with the cold cathode (method of starting the lamp) (Laughton 2003:14). The sputtered emission mix forms the dark marks seen at the end of tubes. When the entire emission mix is gone, the cathode cannot pass sufficient electrons into the gas fill to maintain the discharge at the designed tube operating voltage (Klipstein 2006:1).
- Failure of integral ballast electronic circuitry. This is only relevant to CFL with integral ballasts. Ballast electronic failure is a somewhat random process, which follows the standard failure

profile for any electronic devices. There is an initial small peak of early failures, followed by a drop and steady increase over lamp life. Life span of electronic ballasts is heavily dependent on operating temperatures. The quoted average life is usually at 25^0C ambient (Donovan 2007:2). In some fittings, the ambient temperature could be well above this, in which case, failure of ballast electronics may become the predominant failure of the lamp. Running a CFL back-up will result in a hot electronic components, and this could shortened the life.

- Failure of the phosphor. This reduces the efficiency of the discharge lamp. By around 25 000 operating hours, it will typically be half the brightness of a new lamp. Lamps that do not suffer failures of the emission mix or integral ballasts electronic failure will eventually develop a failure of the phosphor. They will still work but have become dim and inefficient (Yen & Yamamoto 2006:84). This process is slow, and often only becomes obvious when a new lamp is operating next to the old lamp.
- Tube runs out of mercury. Mercury is lost from the gas fill throughout the lamp life as it is slowly absorbed into the glass tubing. This has not been a problem because tubes have had an excess of mercury. However, environmental concerns are now resulting in low mercury content tubes, which are sufficient to last the expected life of the lamp. The failure symptom of a tube that runs out of mercury is similar to other failure modes, except that the loss of mercury initially causes an extended run-up time (time to reach full light output), and finally causes the lamp to glow a dim pink when the mercury runs out and the argon base gas takes over as the primary discharge (ANSI STD 2002:2; Turner 2007:2; Donovan 2007:3; Keebler 2009:2).

Discharge lamps are negative resistance devices. As current flows through, the electrical resistance of the discharge lamp decreases, allowing more current to flow, hence the lamp requires the ballast to control the flow of current (Atkinson 2004:4; Green 2009:2).

The power delivered to the lamp drops to zero twice per cycle (sinusoidal wave), the discharge lamps, which operate directly from the main supply AC frequency, will flicker (fluctuate in intensity) at twice the main supply frequency. This means that the light flickers at 120 times per second for 60 Hz and 100 times per second for 50 Hz frequency.

Humming is a generic name for a series of phenomena involving a persistent and invasive low frequency. Both the annoying hum and flicker are eliminated in lamps with high frequency electronic ballasts (Boshel 2007:4; Bellis 2008:2).

2.6.5 Compact fluorescent lamp

CFLs are a fairly recent innovation with a primary target to overcome the challenges of the classic light and heavy weight of fluorescent lamps, which made it possible to be used in small lamp sockets (see Figure 11). This type of fluorescent lamp produces light largely by converting UV energy from a low-pressure mercury arc to visible light. Phosphor, a chemical that absorbs radian energy (energy of electromagnetic wave) of a given wavelength, and re-radiates it at a longer wavelength, produces the visible light in CFL (Kane 2001:185; Klipstein 2006:1; Turner 2007:2).

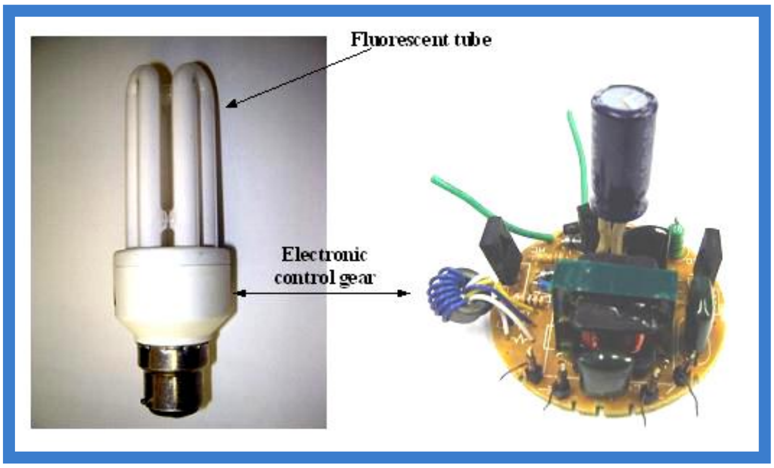

FIGURE 11: Compact fluorescent lamp (Pavouk 2003:11)

CFL is made up of two main parts, the gas fill tube, and the magnetic or electronic ballast integrated in the bulb. The tube contains about 5mg of mercury vapour, which is harmful to health. The glass tube seals the inner parts from the atmosphere and contains two electrodes with a coating of activated powdered phosphor and a small amount of mercury. The electrodes provide a source of free electrons to initiate the arc, and the arc converts to the external circuit through the ends of the lamp (Turner 2007; Masamitsu 2007:2).

The short-wave UV energy converts to visible light by phosphor particle film formed on the inner surface of a translucent glass tube, having electrodes arranged at both ends. When the mercury vaporises during arcing, the UV radiation that causes fluorescence is produced. Inert gases such as argon, krypton or neon, introduced in small quantities, provide the ions that facilitate the starting procedure of the lamp (Kane 2001:185; Masamitsu 2007:2).

The instant-start cathodes may be either cold or hot. Hot cathode is the type of cathode where the electrode emits electrons due to thermionic emission. The tungsten filament is heated up to over 900^{0}F, this causes the filament to ignite and consequently excite the mercury vapour in the glass tube. Cold cathode is a misnomer; the cathode does not include tungsten, but instead heats itself up to around 200^{0}F. Cold cathode consists of a coiled wire coated with an emissive material that yields electrons freely, a smaller diameter tube, a longer life, and lower power consumption. With cold cathode, electrons are excited only by the amount of potential difference (voltage) provided; while with hot cathode, greater lamp current is permitted and this lowers the overall lighting costs (Goldwassher & Klipstein 2006:3; Yuen, Sproul & Dain 2010:66-76).

The inability of CFLs to start during cold weather has been overcome with the cold cathode (Goldwassher & Klipstein 2006:3; Lorelei 2009:3).

Eye sensitivity changes with the wavelength; commonly, the output of a lamp is measured in lumen. CFL produce a lesser light output at the later stage. The light output depreciation is exponential; with the greatest losses being soon after the lamp is first used. A CFL can be expected to produce 70 – 80 percent of the original light output by the end of its life (Ohno 2004:3).

The efficiency of a CFL is better than the classic light. An 11-watt CFL rated 780 lumen, with 5-watt integral ballast, has an efficacy of 48.8 lm/w.

The life expectancy is approximately 8000 hours. Therefore, in applications that require 11.23 hours/day, an 11-watt CFL bulb will last for a period of 1.95 years (Thumann 1991:123; Donovan 2007:3).

The circuit of a CFL operates on high frequency ballasts having a poor power factor of 0.5, and like all discharge lamps, create harmonics distortion (changing of AC voltage waveform sinusoidal to complex waveform) on the system because the control system limits the plasma (an electric arc) current which produces light. If the power distribution system is overloaded with the discharge lamp (inductive load) more than 40 percent, there will be a negative effect on the distribution system. The power factor will be lower and total harmonic distortion will be high. The harmonic currents are injected into the distribution system due to the non-linear characteristics of the ballast. The power quality issues associated with CFL have largely been ignored, as the number of lamps on the distribution system is small, and the associated impact is difficult to quantify (Nashandi & Atkinson 2007:1; Prodanovic, De Bradandere, Van de Keybus, Driesen & Driesen 2007: 432-438).

The innovation on the size and light output makes CFL expensive. In the mid-1990s, a solution to the manufacturing cost was attained, and this was to build a tube that has gradual twists – a design that looks a lot like a soft-serve ice-cream cone (Derry & Williams 1993:4; Ohno 2004:2).

Today, it is difficult to find a CFL that does not use the twist tube design. The new tube is constructed of wafer-thin flexible sheets that arrange plasma in an array of micro cavities in a sheet of aluminum foil, sealed with a very thin glass sheets, creating a bulb (Parnell 2011:1).

Advantages of CFLs include the purchase price, which is three to five times greater than halogen lamps, but the price difference is complemented by the life span, low energy usage, and relevant efficiency of the CFLs.

There are some deficiencies with the CFL, amongst which is poor colour rending index (CRI), relatively poor power factor, high initial current, and that it may suffer instantaneous failure with moisture entering in the gas chamber.

2.7 LIGHT EMITTING DIODE

The light emitting diode (LED) is the panacea of the lighting world, a promising replacement for the classic light, the halogen and the discharge lamps, which reduces energy consumption and keeps harmful chemicals out of landfills (Zarr 2009:1; Turner 2007:2).

The LED is a forward biased (+Ve battery terminal connected to P-region and –Ve terminal to N-region of the semiconductor) P-N junction (a doped P-type impurity and the other half N-type impurity), which emits visible light when energised.

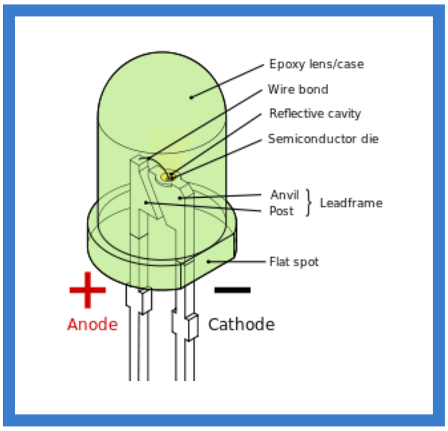

FIGURE 12: Light emitting diode (Schubert 2005:10)

The charge carrier recombination takes place when electrons from the N-side cross the junction and recombine with the holes on the P-side (see Figure 13).

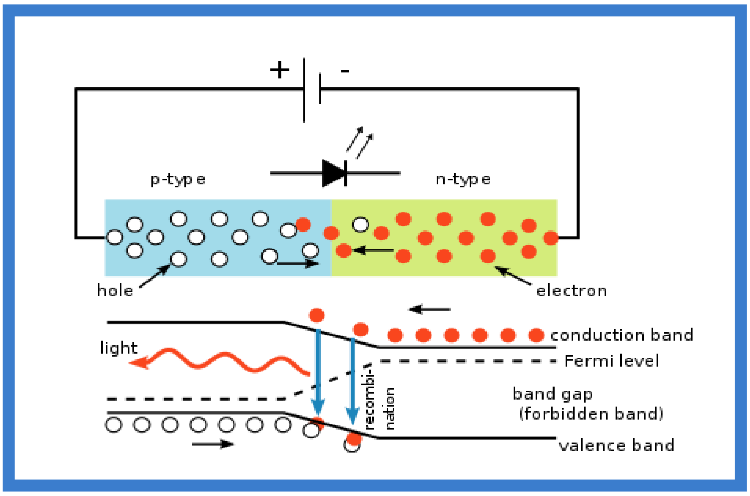

FIGURE 13: Inner working of light emitting diode (Schubert 2005:10)

Electrons are the higher conduction band on the N-side, while holes are in the lower valence on the P-side. During combination, some of the energy differences are given up in the form of heat and light (photon) in either infrared or visible, depending on the material from which the junction was constructed (Schubert 2005:10; Theraja & Theraja 2006:2045).

For Si and Ge junctions, more of the energy is given up in form of heat, and the amount of light is insignificant, unlike semiconductors, the likes of gallium arsenide (G_aA_s), gallium-phosphide (G_aP) and gallium-arsenide-phosphide (G_aA_sP). The greater percentage of the energy released during recombination is given out in the form of light. If the semiconductor material is translucent, light is emitted and the junction becomes a light source (Theraja & Theraja 2006:2045).

The LED emits light in response to a sufficient forward current (see Figure 14).

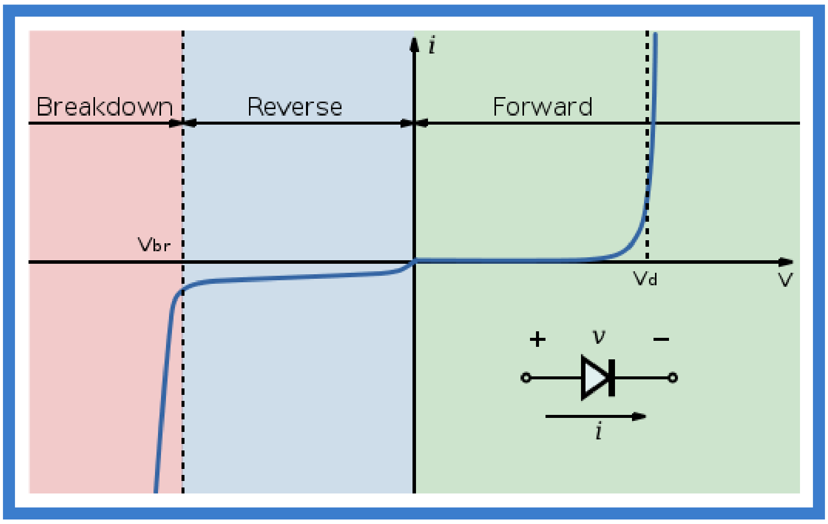

FIGURE 14: Forward and reverse biased of light emitting diode (Schubert 2005:10)

The amount of power output translated into light is directly proportional to the forward current. The greater the forward current, the more the light output. The colour of light emitted depends on the type of material used (Theraja & Theraja 2006:2045). LED that emits blue is also available, but the most common are:

G_aA_s - Infrared radiation (invisible)

G_aP - Red or green light

G_aA_sP - Red or yellow (amber) light

LED emits no light when reverse-biased (holes are attracted by the –Ve battery terminal and electrons, by the +Ve terminal of the battery), both hole and electron move away from the junction and away from each other. Since there is no electron-hole combination, no current will flow and the junction will offer a high resistance. LED could be damaged if operated in a reverse direction.

It is, therefore, convenient to consider the emission process consisting of excitation, recombination and extraction, when considering the efficiency of LED. Photons created by electron recombination on the p-type side are emitted from the surface layer. The LED current, I is made up of electron (I_n), hole (I_p) and space-charge region (I_r) recombination components respectively.

The electron injection efficiency (which provides the excitation) is given as (Dorf 1993:159):

$$\gamma_n = \frac{I_n}{I_n + I_p + I_r} \qquad (7)$$

However, the electron mobility, (μ_n) is greater than that of a hole (μ_p), since

$$\frac{I_n}{I_p} = \frac{N_d \mu_n}{N_a \mu_p} \qquad (8)$$

Where, N_d is the n-type donor doping density, and N_a is the p-type acceptor doping density.

A greater electron efficiency γ_n is attainable for a given doping ratio than a hole injection efficiency (γ_p).

LEDs are usually p-n$^+$ diodes, constructed with the p-layer at the surface. Some of the recombination, undergone by the excess electron distribution (Δ_n) in the p-type region, will lead to radiation of the photon, but others will not because of the existence of doping and various impurity levels in the band gas.

Most of the generated photons on either side of the junction will pass through sufficient bulk semiconductors to be re-absorbed. The photon energy would be suited for re-absorption if the energy exceeds the semiconductor direct band gap. It is obvious then, why G_aA_s is opaque and G_aP transparent to photons from G_a (A_s:P) junction (Dorf 1993:160; Theraja & Theraja 2006:2045).

A greater efficiency is expected from the transparent substrate with reflecting contact. LED is thus efficient, an efficient light source that uses a fraction of power to produce luminance. A 13-watt LED bulb rated 960 lumen, with a 3-watt driver, has an efficacy of 60 lm/w (Dorf 1993:160).

An LED has a life expectancy of 50 000 hours; if used for ten hours a day, it would last for a period of 13.9 years.

Amongst the advantages of LED is the colour, size, on and off time, shock resistance, life span and focus, while the disadvantages are a higher initial price, temperature dependence, voltage sensitivity and droop.

2.8 ENERGY EFFICIENCY DRIVE

South Africa (SA), in its drive for energy efficiency, has embarked on a new electricity build programme to meet the demands of electricity, increase access to affordable energy services, improve energy governance, and stimulate economic development that encourages competition within the energy market (Green 2010:1).

FIGURE 15: Factors that guide and drive the energy sector in SA (Green 2010:2)

Energy efficiency improvement could be achieved largely via enabling instruments and intervention, economic regulation and legislation, efficiency labels and performance standards, promotion of efficient practice, as well as energy management (Green 2010:1).

2.8.1 Energy management

Energy management is the process of monitoring, controlling and conserving energy.

2.8.1.1 Demand side management

Demand side management (DSM), also known as energy demand management, is the modification of consumer demand for energy through various methods such as financial incentive and education. The DSM goal is to save energy. The saving of energy needs to be quantified to an acceptable accuracy by measurement and verification (Loughran & Kulick 2004:1; Pacific Corp. 2010:4).

2.8.1.2 Energy management services (Audit)

Energy audit involves survey, inspection and analysis of energy consumption in a system. The end goal is to identify the areas of high usage and waste, and determine services or systems that will reduce energy demand or control usages, without decreasing production.

2.8.2 Eskom incentives

Eskom has launched an attractive incentive scheme that rewards property developers or energy service companies that is able to deliver a verifiable savings at a fixed amount per kw/h over a period of three years (South Africa Association of Alternative Energy 2010:1).

Eskom introduced the integrated demand management (IDM) standard programme to optimise energy consumption. There is an introduction of a residential time-of-use (TOU) tariff, called Homeflex. Homeflex has a peak and off-peak rate. This implies that the rate of electricity is lower during the off-peak than peak period, and this rate differs between seasons.

The benefits of Homeflex (Eskom Homeflex 2012) are as follows;

- A saving on the bill if the electricity usage in the home is optimised
- Remote monthly time-of-use billing (limit bill estimations)
- Wireless one-way communication to the customer
- Free conversion to time-of-use tariff (no conversion charge payable)
- Electricity information provided in the customers home, and enhanced messaging from Eskom with the in-home display
- Customers ability to manage own usage and automated appliance control (no manual switch on/off).

An automated metering system called advanced metering infrastructure (AMI) has been introduced. An Excel modelling tool, produced by Eskom, will enable the consumer to model and determine how much could be saved by reducing consumption or shifting energy usage period (Eskom Homeflex 2012:17).

2.9 CARBON FOOTPRINT

A carbon footprint is the total set of greenhouse gas (GHG) emissions caused by an organisation, event, product or person (Karl & Trenberth 2003:17; Hanova & Dowlatabadi 2007:4).

GHG can be emitted through transport, production, consumption of food, manufacturing of goods, materials, building and services. The direct sources of carbon footprint are the emissions that come from burning fuel directly in cars or stoves. Most of the carbon footprint emissions for households come from indirect sources; fuel burned to produce goods far away from the final consumer (Hanova & Dowlatabadi 2007:5). Wright, Kemp and Williams (2011) describe carbon footprint as a measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined system, activity or population, considering all relevant sources within the spatial and temporary boundaries.

The main influence on carbon footprint emission is energy. CO_2 emissions into the atmosphere are often associated with the burning of fossil fuel like natural gas, crude oil and coal. The exchange of energy between the source (sun), the earth surface, earth atmosphere and the outer space is illustrated (see Figure 16). The ability of the atmosphere to capture and recycle energy emitted by the earth surface is the defining characteristic of greenhouse effect. Incandescent light sources do not contain mercury, but are responsible for more mercury emission due to much higher energy consumption and the polluting gasses emitted by the power plant that feed the energy hogs (Chambers 2009:1; Blizzard 2012:2).

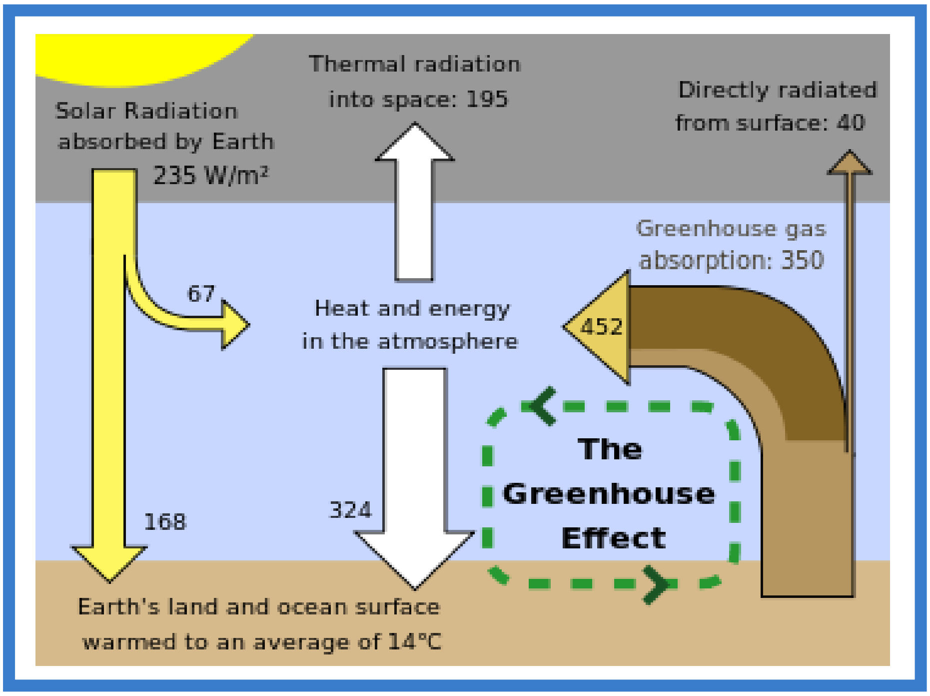

FIGURE 16: Greenhouse effect of energy flow between space, atmosphere and earth surface (Jacobson 2005:11)

Table 4 shows the emission factors of various fuels.

TABLE 4: Emission factors of various fuels (Wright *et al* 2011:68)

FUEL/ RESOURCE	THERMAL G(CO_2-EQ)/MJ	ENERGY INTENSITY W·H	ELECTRIC G(CO_2-EQ)/KW·H
Coal	91.50–91.72 94.33 88	2.62–2.85 3.46 3.01	863–941 1,175 955
Oil	73	3.40	893
Natural gas	68.20 68.4	-	577 751 599
Geothermal Power	3	-	0–1 91–122
Uranium Nuclear power	-	0.18 0.20	60 65
Hydroelectricity	-	0.046	15

Conc. Solar Power	-	-	40±15
Photovoltaic	-	0.33	106
Wind power	-	0.066	21

From Table 4, it is noted that hydroelectric, wind and nuclear power sources produce the least CO_2 per kilowatt-hour of the electricity sources. A nation, organisation or individual's carbon footprint can be measured by using the global-warming potential (GWP). GWP is the measure of how much heat a GHG traps in the atmosphere. The GWP compares the amount of heat trapped by a certain mass of gas to the amount trapped by a similar mass of CO_2 (Elrold 1999:1703). It is imperative to reduce the amount of GHG emitted to the atmosphere.

The most common way to reduce the carbon footprint is to reduce, reuse and recycle. According to McLendon (2011), switching to an energy efficient light source is the best way to reduce the energy consumption and shrink the GHG emission that lead to global climatic change.

The carbon handprint movement emphasises and encourages an individual form of carbon offset; using more public transport or planting trees in deforestation regions (Jones & Kammen 2011:4089).

Intervention of government by adopting climate change policies could slow and reverse the emissions trend and stabilise the level of GHG in the atmosphere (Summers & Carrington 2008:1).

2.10 ENVIRONMENTAL EFFECTS

The environmental effect of light sources is an important issue to be considered. Measures need to be taken to prevent harmful effects on humans. There are some environmental effects caused by light pollution, although artificial light has benefited society by extending the length of the productive day, and offering more time not just for working, but also for recreational activities that require light (Scheling 2006:281-282). When artificial outdoor light becomes inefficient, annoying and unnecessary, it is known as light pollution. In an environment where there is artificial light at night, there is more opportunity for exposure of the retina to photons, which may disrupt circadian rhythm (Ham 1993:101-103; Chepesiuk 2009:1; Kitchel 2009:1-4).

Adams (2003:1) observe that the older-style fluorescent tube lighting, which is still in use in many buildings, has continued to be a serious problem for many individuals with visual perception disabilities. The effects of lighting on the human functioning and development, as well as psychological effects, are indeed profound.

CFLs contain problematic quantities of toxic element mercury. The amount of mercury in CFLs depends upon the type of the lamp as well as the year of manufacture. The mercury in CFLs made prior to 1992 was > 40mg in Ft 12 (1.5 inch diameter tube) and > 30mg in Ft 8 lamp (1 inch diameter tube). In 1997, the mercury was reduced to < 21mg in Ft 12 and < 10mg in Ft 8 lamp, respectively (Apisitpuvakul, Piumsomboon, Watts & Koetsinchai 2009:1047). Mercury is a known neurotoxin and elevates blood mercury levels, which may lead to retardation and deformation in children. It can also cause chest pain, dyspnoea, coughing and haemoptysis (Adams 2007:1; Elliott 2010:1).

Physicians and ergonomists have repeatedly reported various forms of discomfort on employees who constantly work under compact fluorescent light sources. Some of the discomforts identified were eyestrain, inflammations, headaches and loss of performance (Clarke & Glynn 2006:2; Stanjek 2007:9; Harter, Conder & Towle 2010:141-145). CFLs can be irritating to sensitive individuals and people with autism, aspergers, skin disorders and migraine sufferers. According to the United Kingdom National Autistic Society, CFLs could hurt the eyes of a person with autism (Lorelei 2009:8).

The idea of allowing mercury to be placed in an easily breakable consumer product is fraught with public safety risk (Adams 2007:2; Alexander 2007:1; Chepesiuk 2009:1). According to the European Commission Scientific Committee on Emerging and Newly Identified Health Risk (SCENIHR), UV and blue light radiation emitted by compact fluorescent light source poses an added health risk (Green 2009:1). It was also found that in photo laboratories, life sciences and hi-tech environments involved in the development of microchips, UV rays contribute to unwanted chemical reactions and bacterial growth (Randall 2009:2).

No widely available light source is without drawbacks; a recent study by a California-Irvine University shows that LED contains high levels of several dangerous toxins; lead and arsenic. However, the amount in a bulb is not a big risk but could be a tipping point when combined with other exposed toxins. As with CFL mercury, LEDs may pose a collective threat as discarded bulbs accumulate in the environment (McLendon 2011:3).

Due to higher energy consumption, the polluting gasses emitted by the power plant that generates energy and health risk problems on the environment by light sources, there are various government policies to phase out incandescent light sources.

2.11 GOVERNMENT POLICIES

In the face of the enactment of legislation around the world, the future of the trusted incandescent light sources has been looking dim (Brandon 2009:1). As a result of higher energy usage in comparison to a more energy efficiency alternatives (LED), there have been government policies from various countries around the globe to phase out incandescent light sources (Chameides 2008:1; Hurst 2008:1; Brandon 2009:1). Brazil and Venezuela started the phasing out in 2005 (Mollard 2009:1). In 2006, ESKOM distributed more than seven million CFL energy-saver bulbs to replace incandescent light sources (Baggini 2009:1).

In 2009, Australia, Ireland and Switzerland started phasing out incandescent light sources, and Argentina, Italy, Russia and UK in 2011. Between 2012 and 2014, Canada and the USA will phase out incandescent light sources (Whitney 2007:1; Carney 2008:1; Brandston 2009:1). According to Mollard (2009:1), a Mission Revolution Energetica was launched in November 2007 to substitute 52 million incandescent lamps with lower energy consumption light source by 2012. By 2014, incandescent light source, as created by Thomas Edison in 1879, will be all but banned for most uses (Rosenthal 2009:1). The incandescent light sources intrinsic to modern life is highly inefficient; the goal is to reduce energy usage and carbon footprint by households (Mollard 2009:1).

2.12 SUMMARY

This chapter offered contextual and conceptual overviews of light as energy. The emission of light due to the process of excitation and de-excitation. It also emphasised on incandescence as the emission of light from a hot object. An in-depth ascription on the theoretical background of incandescent light sources and energy efficient light source that uses a fraction of power to produce luminance was described.

An account of the light source efficiencies; the luminous efficacy of radiation and luminous efficacy of source were emphasised. The energy efficiency drive in South Africa that incorporated the ESKOM incentives, carbon footprint, a measure of the total amount of carbon dioxide and methane emissions of a defined system was discussed. The environmental effect and various government policies to eradicate the traditional incandescent light sources were emphasised.

Chapter 3 outlines the methodology used for the empirical part of the study and provides a comprehensive discussion on how these methods were employed.

CHAPTER 3 - RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter describes the approach, research design and methodology used for the empirical section of this study. The intention is to provide a rationalisation for the selection of the used research approaches, methods and techniques applied.

The experimental set up, accuracy, validity, reliability and triangulation are also discussed.

3.2 RESEARCH APPROACH

Quantitative research, within the context of a repetitive measurement, was used to determine whether there is a statistical difference between the classic light, the halogen lamp, the discharge lamp used on the campus and the energy saver light sources. A quantitative approach (positivist approach) emphasises observable facts and excludes subjective speculation. This approach is based on a phenomenological approach known as a logical positivism. Measurement is often regarded as a means by which observations are expressed numerically in order to investigate causal relations (Welman *et al*. 2005:6).

Measurement play a vital role in quantitative research, the objective is to develop and employ theories pertaining to phenomena. The quantitative data collected on the tested light sources were based on the measurement theories. A theory is a contemplative and rational type of abstract that provides an explanatory framework for some observation. This can be normative or prescriptive that provides goals, norms and standard. A consistent theory is semantic (does not contain contradiction). The measurements on the various tested light sources were taken repetitively and the data collected were consistent for each of the sources. The phenomenologist are not concerned with the description of phenomena, because these exist independently of the participant's experience of them, but with their experience of these phenomena (Welman *et al*. 2005:6; Franklin 2009:65).

An empirical analytical paradigm quantitative research approach was used in order to establish the luminance delivered, energy consumed and the life span of each identified light source. The information is in the form of numbers that can be quantified and summarised, the mathematical process is the norm for analysing the numerical data (Johnson & Onwuegbuzie, 2004:14).

The research approach is formal and systematical. Quantitative research is a process in which the numerical data are utilised (Sutherland 2009:90).

The research approach is intended to be as objective as possible in order to reduce biased interpretations of results. As a result, the study primarily was aimed at that which can be observed and measured objectively. The aim of this approach is to obtain knowledge in the form of testable explanations that can predict the result of future experiments. This implies that an individual, other than the researcher, would agree with what was observed, such as the score that the observation registered on the measuring instrument (Welman *et al*. 2005:6; Lindberg 2007:362). These allow the researcher to gain an understanding of reality, and use the understanding to intervene in its mechanism (Karl 2003:42).

3.3 RESEARCH DESIGN

A research design is a work plan that details what has to be done to complete the study, and this will flow from the study's research design. The function of a research design is to ensure that the evidence obtained enables questions to be answered, no matter how ambiguous they are (Yin 2002:9).

According to Yin (2002), research design deals with a logical problem and not a logistical problem.

Given the background and the aim of the study, there is a need to switch over to a more efficient energy saver and completely eradicate incandescent light. The study addresses the research problem, which was articulated by the question: What comprises the energy consumption of the light sources used on the VUT campus?

The following sub questions emanated from the research problem:

- What is the luminance delivered, per unit, of the identified light sources?
- How long does the light source stay on before the expiration of life time (maximum period of time)?
- What is the monetary value of the energy consumed?
- Are the light sources used effectively?
- What maintenance program is in place for the lighting system on the campus?

These questions will provide a basis for the formulation of a conceptual framework that designates the phases of the study. A conceptual framework is the representation of the main components of a system, showing their interrelationships or linkages. This serves to develop a common understanding of which issues should be included in an assessment. The framework also assists in the identification of data or knowledge gaps in the context of the energy consumption of the light sources used on the VUT main campus, these gaps may form a focus for extending the assessment in the future.

The conceptual framework of the study was established, and this is illustrated in Figure 17.

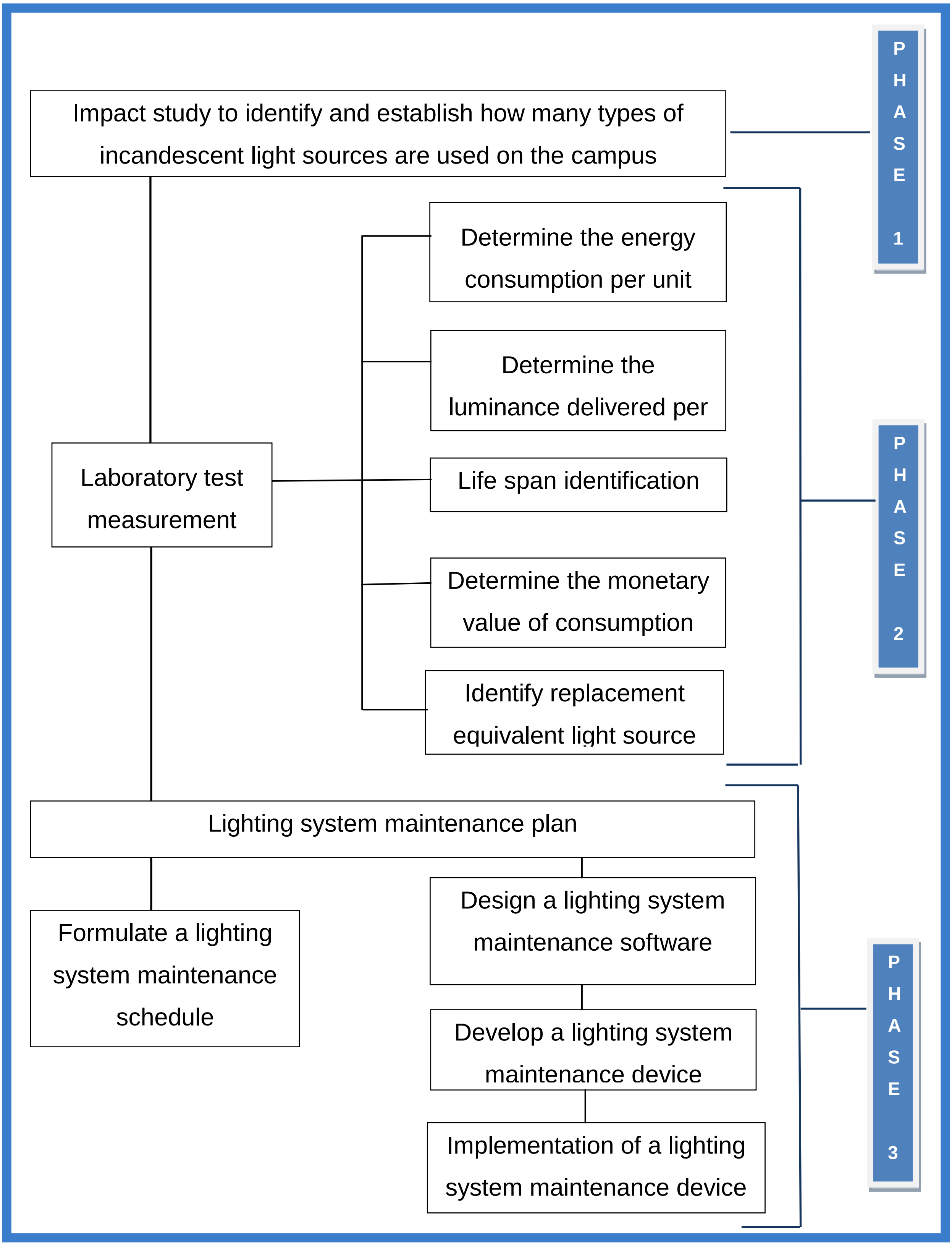

FIGURE 17: Conceptual framework of the study

During phase 1 of the study, which was an impact study, a technique of observation was conducted on the VUT Vanderbijlpark campus. This phase provides a unique opportunity to discover the specific incandescent light sources in use. The impact study was limited to both the C and E blocks of VUTs main campus; the blocks comprise of offices, lecture rooms and laboratories. These blocks were considered viable because they are typical of the other blocks contained on the campus.

In the phase 2 of the study, an extensive laboratory test measurement on the identified light sources was pursued, utilising the quantitative method for data collection. A quantitative research approach is the collection of numerical data that are analysed using mathematically-based methods. This is based on a precise measuring instrument (Keeves 1997:386-394). A quantitative approach may involve the use of proxies as stand-ins for other quantities that cannot be measured. In quantitative research, the aim is to determine the relationship between an independent and a dependent variable (Gravetter & Forzano 2003:87).

Quantitative purists articulate assumptions that are consistent with what is commonly called a positivist philosophy (Johnson & Onwuegbuzie 2004:14). Specifically, quantitative purists believe that observations should be treated as entities in much the same way the physical scientists treat physical phenomena. In addition, they argue that the observer is separate from the entities and subject to observation. Quantitative purists maintain that the scientist's inquiry should be objective. Time and context-free generalisations are desirable and possible, the real causes of scientific outcomes can be determined reliably and validly (Nagel 1986:5; Sutherland 2009:90).

Assigning of numerals to objects or events according to rules is termed measurement. One may perceive measurement from this definition as necessarily objective, quantitative, and statistically relevant (Gravetter & Forzano 2003:87). Measurement can be about numbers or objective hard data. Often, measurement is regarded as being the only means by which observations are expressed numerically. The role of measurement in a quantitative research is divergent, when measurement departs from theory it is likely to yield mere numbers (Hewitt 2006:180). The measurement process is central to quantitative research because the fundamental connection of the empirical observation and mathematic expression are provided (Johnson & Onwuegbuzie, 2004:14). The measuring instrument applied here was the luminance meter and data logger.

The goal was to verify if the light sources used on the campus are efficiently utilised and introduce to the VUT a lighting system maintenance program for an effective service delivery.

During the phase 3 of the study a lighting system maintenance schedule and an integrated software program were designed, developed and implemented.

3.4 DATA COLLECTION AND ANALYSIS

3.4.1 Experimental setup

The laboratory test experiment was carried out on each of the identified light sources use on the campus and the energy-saver LED light source to determine:

- How much energy is consumed while the lights were on
- How much luminance is delivered at the on-instance and over a range of times (period)
- How long does the light source stay on before the lifetime expires.

The laboratory-test experiment was carried out bearing in mind the safety precautions of the laboratory that needed to be adhered to, in conjunction with the SANS (2006) on illumination. The experiment was set up at the VUT illumination laboratory.

There were three different stages (conditions) at which the test was carried out:

- Under an ideal condition (dark room).
- In a condition where one side of the room is white (one side open) while other sides are dark.
- In a normal working condition (all sides open).

The light sources were suspended at the centre of the laboratory. Some measuring points and angles on the working planes, away from the suspended light sources, were chosen with different supply voltages.

For these objectives, the measurement diagram below has been used (see Figure 18).

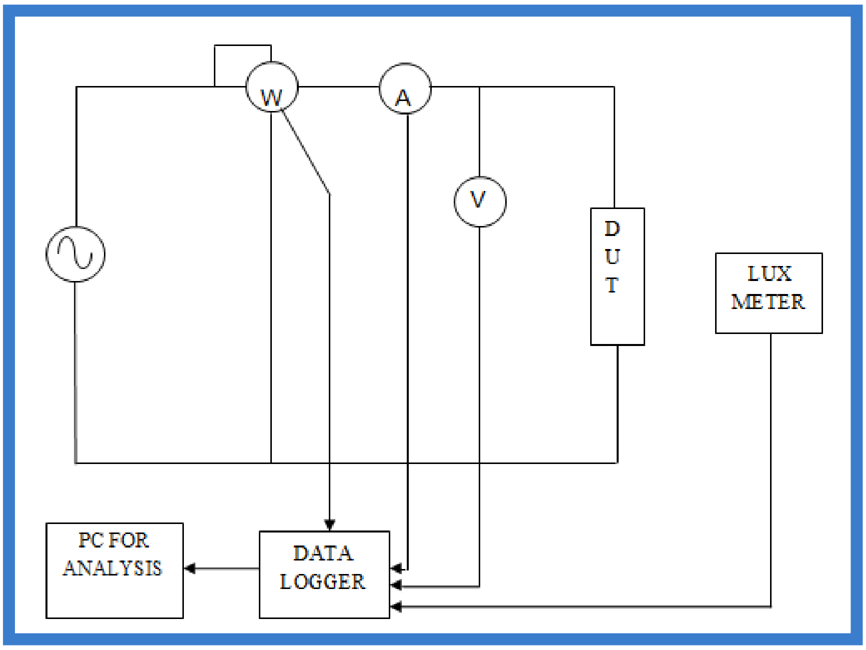

FIGURE 18: Measurement circuit diagram

The luminance delivered by each of the tested light sources was measured with a lux meter, at the various marked points and angle points in the laboratory, one after the other.

The lux meter (T630) (see Figure 19) was preferred because it is precise, highly accurate in measuring, and has an easy read out. The lux meter permits a wide range of light measurements, the LCD display provides low power consumption, clearly read out ambient light, adjusting zero automatically and excellent operation.

FIGURE 19: Lux meter (T630)

A data logger (see Figure 20) an electronic device that measures/records data over time, was connected in series with each of the light sources to enable accurate readings. The data logger (PRO) is an easy-to-use, accurate, affordable PC-based recording. Due to its compact size, rugged design and battery power, it can be placed just about anywhere.

FIGURE 20: Data logger (PRO)

The following measurements were carried out on each light source:

- RMS voltage
- RMS current
- Active power
- Power factor
- Luminance
- Life span

The light sources under test were energised with a 230V supply. The luminances delivered with the supply voltage variation, were also observed. The information was obtained in the form of numbers that can be quantified and summarised; the mathematical process is the norm for analysing the numerical data.

The readings were taken three times a week, for twenty months, in order to observe the effect of the supply voltage variation on the drawn current, power consumption, and luminance delivered by various light sources.
Thereafter, the overall quantitative data of incandescent light and energy-saver light sources were obtained and analysed. A photometric software tool was used to validate the accuracy of the measurement. The efficiency and the cost-effectiveness of the light sources were also analysed.

The basic concept is to give insight into how much energy could be saved, determine from each of the tested light sources which could be more efficient, and deliver much more luminance at low energy consumption, and a longer life span.

The measurement and verification procedure is essential to the study, as this will quantify the energy savings level of accuracy. Verification is an independent procedure intended to check that the measurement meets specifications. The verification procedures involve performing tests to a portion, or the entirety of the system, then performing a review or analysis of the results. Verification procedures involve regularly repeating tests devised specifically to ensure that the lighting system continues to meet the initial specifications and that it fulfills its intended purpose.

The selection of research paradigms and methodologies was based upon a triangulation approach, which provided the best of the quantitative (validation) results obtained. This placed the empirical part of the study in the category of implementation evaluation research.

The researcher participated throughout the research project, and endeavoured to ensure that the goals of the study were reached.

3.4.2 Accuracy, validity and reliability

Accuracy of a measurement system is the degree of (veracity) closeness of measurements of a quantity to that quantity's actual value. A measurement system can be accurate but not precise, or precise but not accurate. Precision of a measurement system, also known as reproducibility, is the degree to which repeated measurements, under unchanged condition, show the same results. If an experiment contains a systematic error, increasing the sample size generally increases precision but does not improve accuracy (Acken 1997:281-306; Taylor 1999:4).

There are two elements to accuracy:

- The correct class at the correct location. This is often termed classification accuracy; in other words have the data at point X been classified correctly.
- The second element is far less accurate but contains more useful information, allowing a certain level of error.

Therefore, a measurement system is designated valid if it is both accurate and precise. Care was taken in ensuring that all the measurements were taken accurately and precisely.

Validity and reliability are tools of an essential positivist epistemology. The criteria root for validity was found in a positivist tradition and to an extent; positivism has been defined by a systematic theory of validity (Welman *et al*. 2005:6). Within the positivist terminology, validity resided amongst, and was the result and culmination of other empirical conceptions; universal laws, evidence, objectivity, truth, actuality, deduction, reason, fact and mathematical data, just to name a few (Schwandt 2000:189-213).

The most common classification schemes attempting to categorise the validity underlying measurement is content, face, criterion and construct validity.

Wainer and Braun (1998) describe the validity in quantitative research as construct validity. The construct is the initial concept, question or hypothesis that determines which data is to be gathered and how it is to be gathered.

A photometric software tool and lighting level calculator were employed to validate the test measurement accuracy and the efficiency of the tested light sources.

A valid measuring device provides an adequate sample of all content or elements of the phenomenon being measured. It was important to measure the concept in question accurately, as accuracy cannot be obtained if another concept is measured instead. The reliability of the measuring instrument data logger and the lux meter, used in this research, was established. Care was taken to ensure that the lux meter instrument actually measures the concept in question, and that the concept was measured accurately. To determine content validity, two questions were asked: Does the measuring instrument really measure the concept, other than the energy consumption of the incandescent light sources? Does the instrument provide an adequate sample of items that represent the reasons for measurement, other than the relevant values?

Gravetter and Forzano (2003), suggest that face validity is the simplest and least scientific definition of validity. It concerns the superficial appearance or face value of a measurement procedure.

The relevant question relating to this research is: Does the measurement technique look as if it measures the concept, other than the luminance delivered, to correlate with the energy consumption?

The reliability is the extent to which a measurement procedure produces the same results on repeated trials. It is the accuracy, consistency, stability, and repeatability of the measurement.

Reliability is the idea of consistency or repeatability of results or observation. Kirk and Miller (1986), identify three types of reliability referred to in quantitative research:

- The degree to which a measurements given repeatedly remain the same
- The stability of measurements over time
- The similarity of measurements within a given time period.

This measures the instrument's ability to yield consistent numerical results each time it is applied; results that do not fluctuate unless there are variations in the variable being measured (Creswell 1998:3; Gravetter & Forzano 2003:91).

In other words, if the same variable was to be measured under the same conditions, a reliable measurement procedure produces almost identical measurements. High reliability does not guarantee valid results, but there can be no valid results without reliability (Bostwick & Kyte 1981:120-121).

3.4.3 Triangulation

Triangulation is the validity procedure where researchers search for convergence among multiple and different sources of information to form themes or categories in a study (Creswell & Miller 2000:126). Padgett (2006) describes triangulation in implementation research as the convergence of multiple perspectives, which can provide greater confidence that what is being targeted is being accurately captured. Triangulation is used in quantitative research to test the reliability and validity (Golafshani 2003:597-607).

However, there are no guidelines on the practical application of the principle of triangulation. Denzin (1984) identified four different types of triangulation methods. The study comprised quantitative data collection and analysis. Priority was given to quantitative data, while implementation was primarily used to strengthen the argument and to support the obtained quantitative data. Data collection was connected, and integration occurred at the data interpretation stage as well as in the discussion. The typical data source triangulation method denotes the use of data to remain constant (the same) in different contexts. This is one of four types of triangulation methods, as described by Denzin (1984) and applied throughout this study.

The selection of research paradigms and methodology were based upon a triangulation approach, which provided the best of the quantitative results obtained. The three points of triangulation in this study are the quantitative measurement result (phase 2), the lighting system maintenance package (phase 3) and the literature gathered on the study.

The triangulation of the data aimed to provide scientific support for claims on incandescent light power efficiency.

3.5 SUMMARY

The chapter outlines the methodology used for the empirical part of the study. A research approach that investigates phenomena, acquires new knowledge and integrates the previous knowledge is described. During the design and methodological stages, it was established, by means of a theoretical framework that the first phase of the study identified the specific incandescent light sources used on the campus. The quantitative data of the tested light sources was established in the second phase of the study. Data collection was connected, and integration occurred at the data interpretation stage as well as in the discussion. The third phase focused on the design, development and implementation of a maintenance device aimed to improve the lighting system on the campus.

The analysis of the data generated through the application of the research methods, which follows in the next chapter, Chapter 4, sheds light on the efficiency, validation of the test results, and the cost effectiveness.

CHAPTER 4 - ANALYSIS AND INTERPRETATION OF TEST RESULT

4.1 INTRODUCTION

The greatest benefit of a laboratory experiment dwells in the fact that it is artificial. This simply means that the experiment allows observation in a situation that has been designed and created by investigations, rather than that which occurs in nature.

Based on the objectives of this study, the aims are to test the light sources used on the campus, deduct facts on the light sources observed, verify if the light sources are efficiently utilised, or make alternative recommendations for a more efficient energy saver light source for replacement purposes.

Replacement in the context of this work means to set an energy efficient light source in the same light point where an incandescent light source exists.

4.2 EXPERIMENTAL RESULT ANALYSIS

There were differences in the readings taken under different room conditions. The luminance readings in a dark room condition are higher than in a one-side-open condition, while in an all-sides-open condition, the luminance readings were lower than one-side-open conditions. This indicates that all light was absorbed by the black colour, no reflection of light was detected.

The results of the laboratory test experiments conducted on the various light sources are illustrated below.

A data logger (see Figure 20) was used to measure the drawn current and the power consumed while lux meter (see Figure 19) was used to measure the luminance delivered by the tested light sources.

Table 5 explicates the data generated in order to establish which of the tested light sources delivered a better luminance as compared to the power consumed. The category descriptors in Table 5 are as follows: L1 (8ft fluorescent lamp), L2 (6ft fluorescent lamp), L3 (4ft fluorescent lamp), L4 (2ft fluorescent lamp), L5 (spot light), L6 (4ft LED), L7 (LED bulb) and L8 (CFL).

TABLE 5: Power consumption and drawn current

CATEGORY		L1	L2	L3	L4	L5	L6	L7	L8
COUNT	P	97.5	71.4	46.3	27.6	62.1	4.8	1.9	5.8
ROW %		31.11	22.78	14.77	8.81	18.54	1.53	0.61	1.85
COUNT	S	0.57	0.33	0.21	0.13	0.25	0.08	0.06	0.09
ROW %		33.14	19.19	12.21	7.56	14.53	4.65	3.49	5.23
P = Power (Watt)					**S = Drawn Current (Ampere)**				

As depicted in Table 5, the L1 drew a relatively high current, while the L8 drew a lower current, and these currents are more than the drawn currents by the L6 and L7 respectively.

The result indicated that L1 consumed the most power, L2, L3, L4 and L5 are relatively high while the L6, L7 and L8 consumed the least power (see Table 5). The amount of power consumed correlates with the current drawn.

The actual power consumed by the tested light sources is not the same as claimed by the manufacturers. According to the manufacturer specification (L1 (75 W), L2 (58 W), L3 (36 W), L4 (18 W), L5 (60 W), L6 (6 W), L7 (16 W), and L8 (11 W)) written on the boxes of the tested light sources, the actual power consumed by the tested light sources (L1, L2, L3, L4 and L5) are more than the manufacturers' specifications while in the energy efficient light sources tested (L6, L7 and L8), the actual power consumed is lesser than the manufacturers' specifications (see Table 5). Figure 21 illustrate the power consumption of the tested light sources expressed in percent.

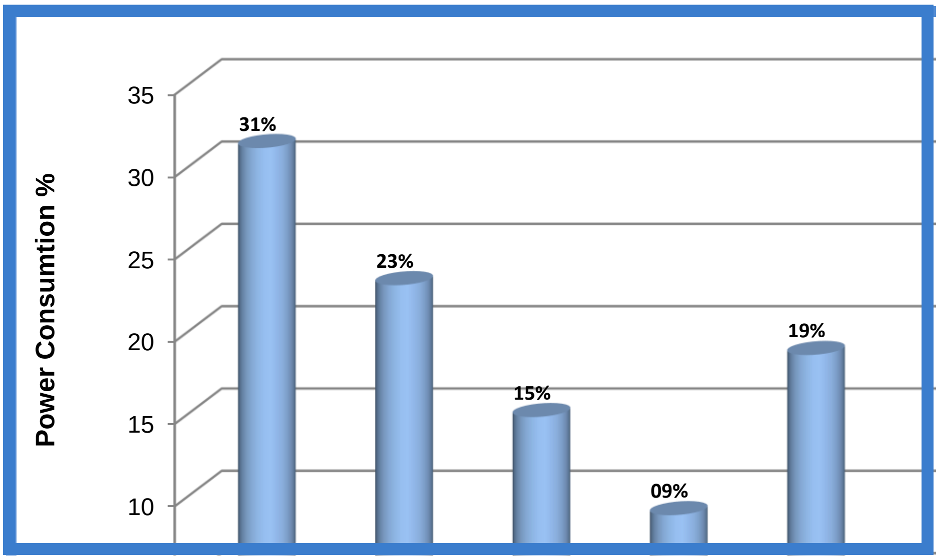

FIGURE 21: Power consumption of light sources

On L1, L2, L3, L4 and L5, it was noted that more power is consumed than L6, L7 and L8 and the consumed power correlates with the drawn current (see Table 5). It is very imperative to compare the power consumed with the luminance delivered by the light sources, as this will explicates on the level of the light sources efficiency (see Figure 37).

The luminance delivered by the tested light sources is illustrated in Table 6 below.

TABLE 6: Luminance of light sources

CATEGORY		L1	L2	L3	L4	L5	L6	L7	L8
COUNT	P	97.5	71.4	46.3	27.6	62.1	4.8	1.9	5.8
ROW %		31.11	22.78	14.77	8.81	18.54	1.53	0.61	1.85
COUNT	K	5448	3288	2645	1145	2048	958	558	776
ROW %		32.30	19.49	1568	6.78	12.16	5.68	3.31	4.60

P = Power (Watt) **K = Luminance (Lumen)**

Figure 22 illustrates the luminance delivered by the light sources.

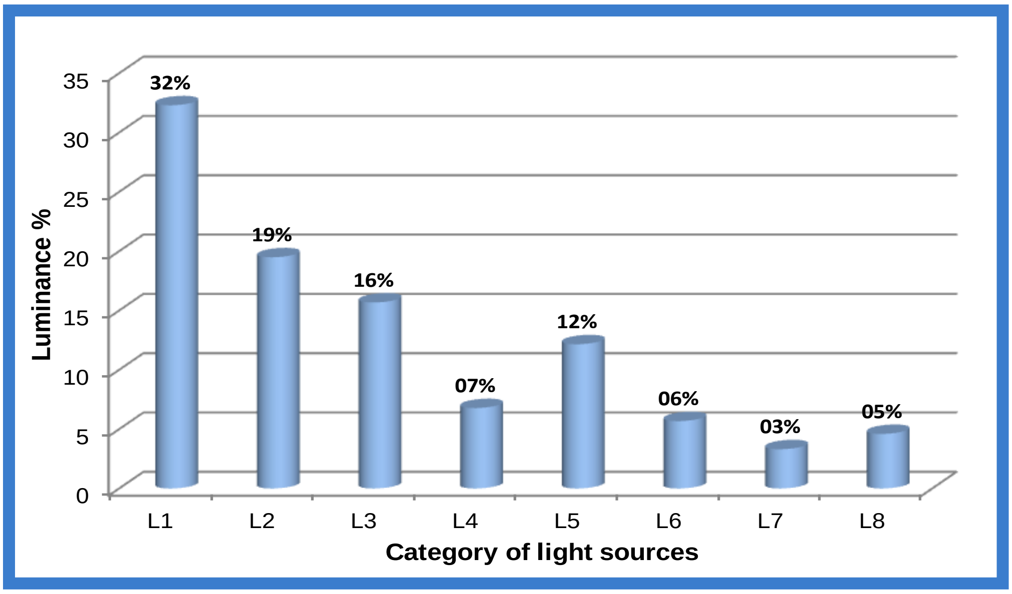

FIGURE 22: luminance of light sources

The luminance of the tested light sources is shown in Figure 22. The luminance is express in percent over the total luminance delivered by the tested light sources in order to quantify the luminance according to the measurement. L1 (8ft fluorescent) delivered 32.30 percent, L2 (6ft fluorescent) 19.49 percent, L3 (4ft fluorescent) 15.68 percent, and L4 (2ft fluorescent) 6.78 percent. The L5 (spot light) delivered 12.16 percent, L8 (CFL) 4.6 percent while the L6 (4ft LED) and L7 (LED bulb) delivered 5.68 and 3.31 percent respectively. The luminance efficiency of the tested light sources is illustrated in Figure 37.

The luminance delivered by the tested light sources differs from the manufacturers' specification (L1 (5230 lm), L2 (3120 lm), L3 (2410 lm), L4 (1070 lm), L5 (1890 lm), L6 (840 lm), L7 (480 lm), and L8 (670 lm)) written on the boxes of the tested light sources. Correlating the power consumption of the light sources and the luminance delivered, although the L1 delivered the most luminance, the power consumed is relatively high. More power is being consumed by L2 and L4, as well as the L5, as compared to the luminance delivered. The L8 and L3 are relatively better, than but not as good as the L6. The L7 consumes less power and delivers a better luminance.

The luminance delivered at various tested distance points is illustrated in Figure 23.

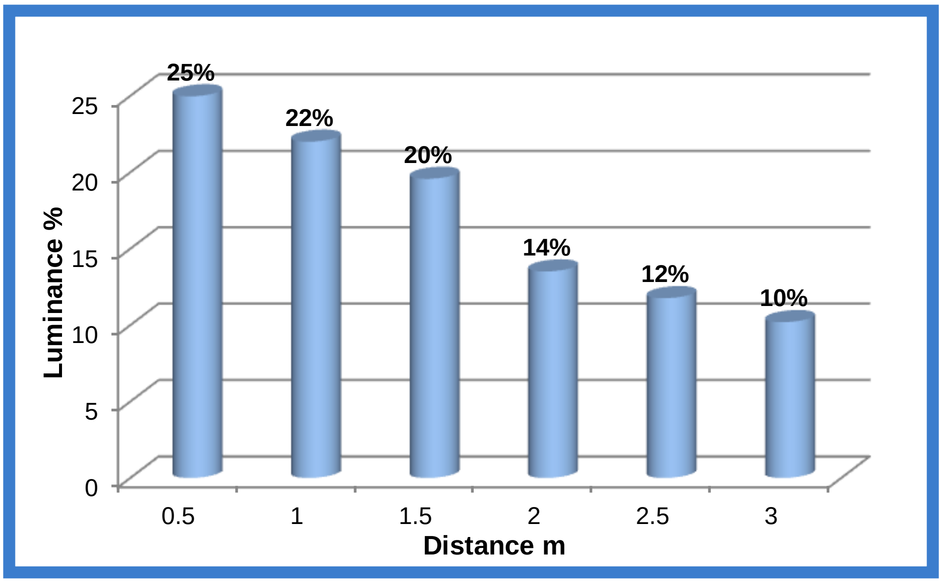

FIGURE 23: Luminance at various distances

The result (see Figure 23) indicates that the luminance at 0.5m is more, and as the distance increases, the luminance decreases. The relationship between the luminance and distance which is inversely proportional is the same as the manufacturers' specification.

Based on the experimental results, the following were deducted:

4.2.1 Fluorescent lamp

A variety of the fluorescent light sources (L1 (8ft), L2 (6ft), L3 (4ft) and L4 (2ft)) were tested in order to observe the consistency, the effect of the supply voltage variation on the luminance delivered, and the power consumption.

It was observed that all the tested discharged lamps show the same trend, the relationship between the luminance and the distance is inversely proportional. As the distance from the light sources increases, the luminance decreases. Figure 24 is the result of the tested fluorescent lamps luminance. Observation shows that there was a correlation between the current drawn and the luminance delivered. It was noted that variation in the supply voltage resulted in a variation in the luminance delivered.

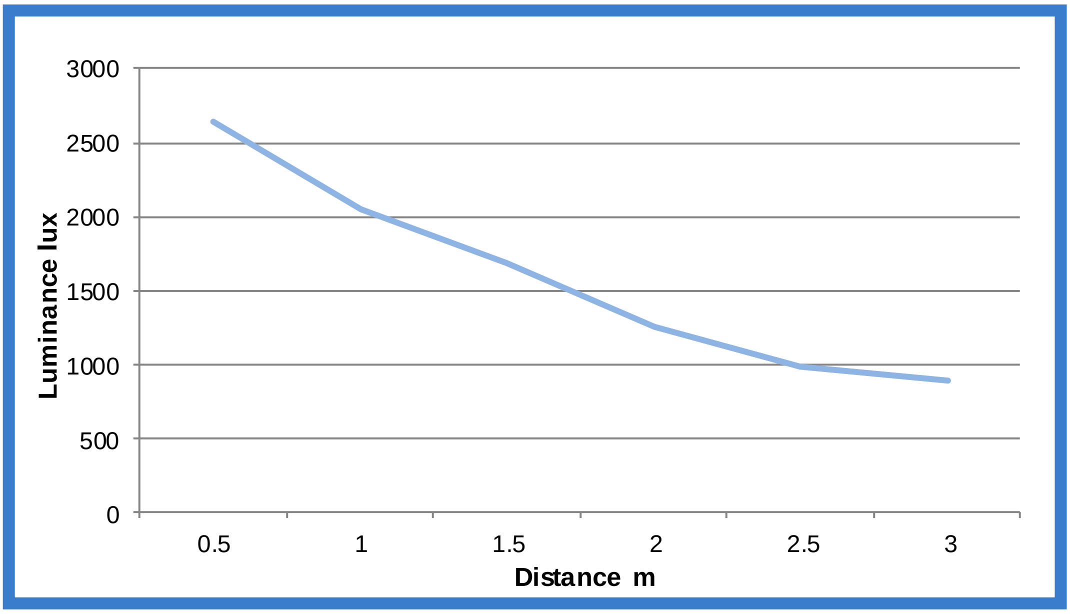

FIGURE 24: Luminance of a fluorescent lamp

Figure 24 shows that at a distance of 0.5 m away from the light source, the luminance is more and as the distance increases, the luminance decreases. The power consumption of the fluorescent light source is directly proportional to the magnitude of the supply voltage. In L2, the reactive power decreases and the harmonics distortion is relatively moderate, while in L3, the reactive power increases as the supply voltage increases. This explained the differences in the current drawn by L2 and L3 as shown in Table 5.

The supply voltage and current waveforms of a fluorescent lamp (see Figure 25) indicate that current waveform of a fluorescent lamp is not a purely sinusoidal and it is characterised by a rapid amplitude change and creates distortion in the voltage waveform.

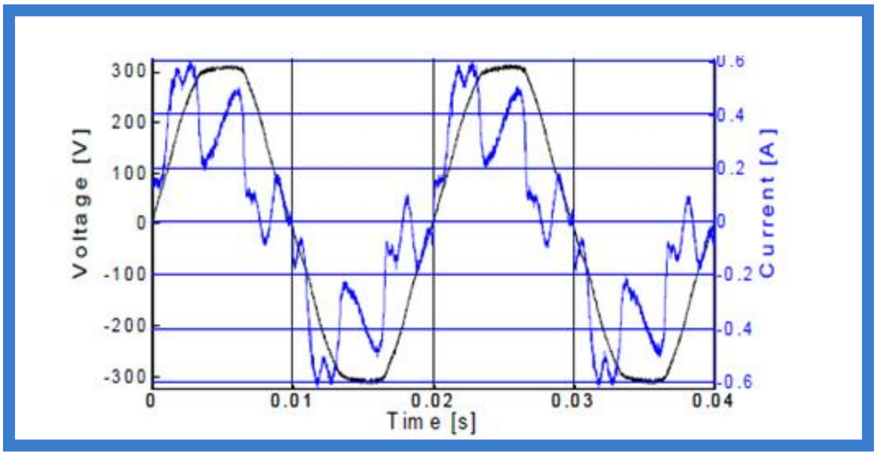

FIGURE 25: Supply voltage and current waveforms of a fluorescent lamp

Harmonics are electric voltages and currents that appear on the electric power system as a result of non-linear electric loads. Harmonics are caused by distortion, therefore harmonic waveform is a distortion of the normal sine wave. The fluorescent lamp induces a distorted current waveform; however, the ballast of a fluorescent lamp is a source of the higher order harmonic component of current.

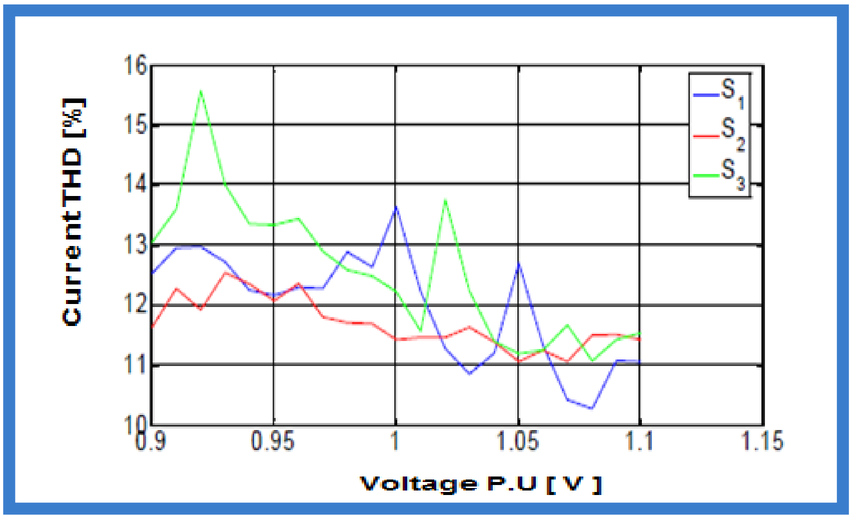

FIGURE 26: Total harmonic distortion of the voltage and current waveforms of a fluorescent lamp

The magnitude of the third harmonic relative to the fundamental is illustrated in Figure 26. The S_1, S_2, and S_3 depicted the first, third and the fifth harmonics respectively.

S_1 shows the first harmonic of current waveform when distorted while S_2 and S_3 indicated the third and the fifth level of current waveform distortion respectively.

It was noted that by increasing the supply voltage harmonics, a slight additional current distortion is observed. The current waveform is distorted and exhibits the properties of a full wave rectifier with an active load.

4.2.2 Compact fluorescent lamp

CFLs of different manufacturers and ratings were tested in order to observe the consistency, effect of the supply voltage variation on the delivered luminance, and the power consumption.

Observation shows that there was a correlation between the current drawn and the luminance delivered. It was noted that variation in the supply voltage resulted in a variation in the luminance delivered. The measurement from different makes of CFLs shows the same trend in the luminance delivered as depicted in Figure 27.

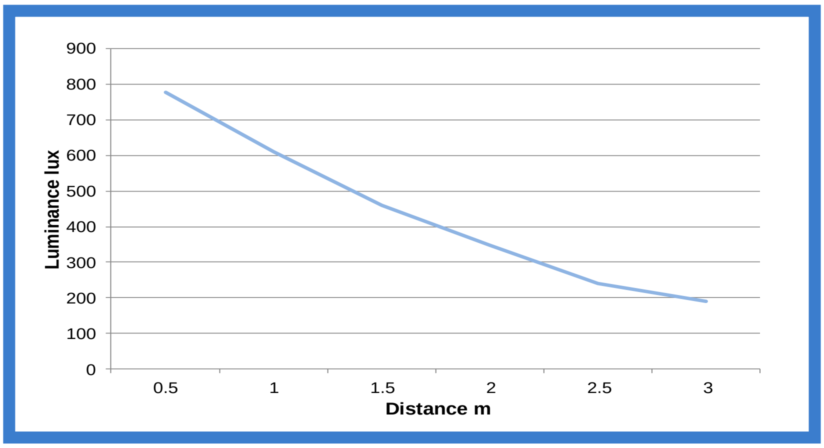

FIGURE 27: Luminance of an 11W CFL

The power consumed is directly proportional to the magnitude of the supply voltage; the current drawn increases as the supply voltage increases. The characteristic of reactive and apparent power measurement is linear, while the power factor decreases for a slight increase in the supply voltage. The current waveform is distorted, but symmetrical for both the +Ve and –Ve halves of the voltage waveform as shown in Figure 28.

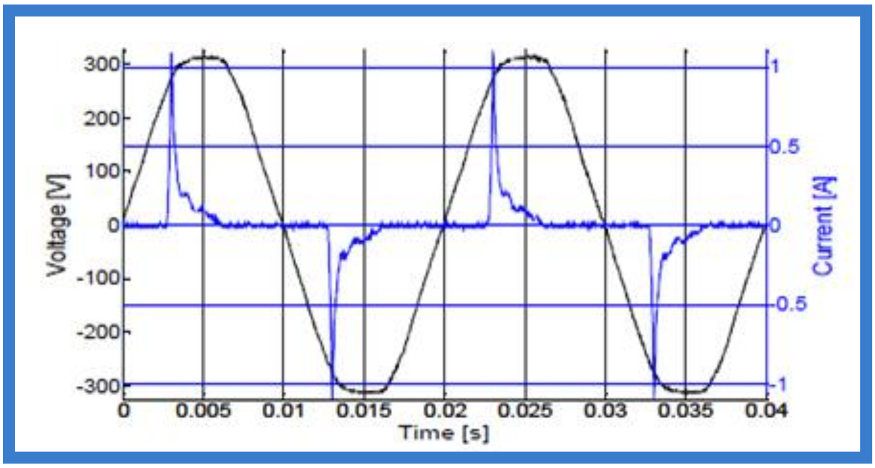

FIGURE 28: Supply voltage and current waveforms of an 11W CFL

As depicted in Figure 28, the current of a CFL is not a purely sinusoidal waveform. It is characterised by a rapid changes of the amplitude that creates distortion of the voltage waveform. There was an apparent phase displacement between the voltage and current.

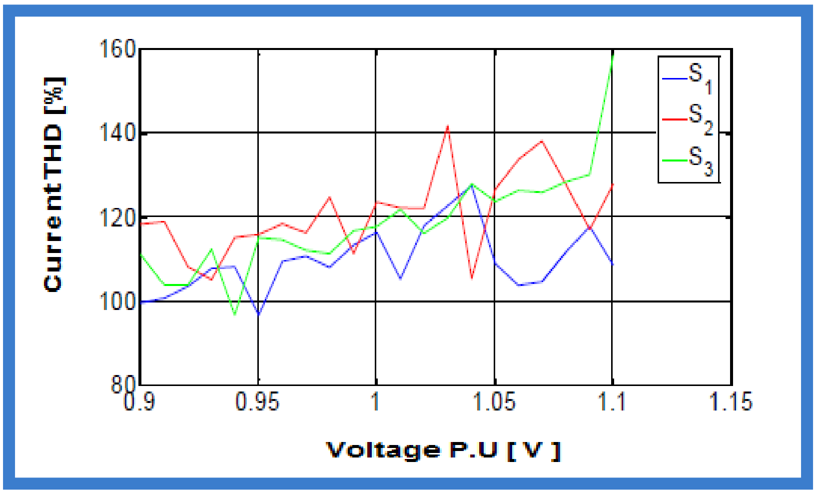

FIGURE 29: Total harmonic distortion of the voltage and current waveforms of an 11W CFL

Figure 29 illustrates the magnitude of the third harmonic relative to the fundamental for an 11W CFL. The S_1, S_2, and S_3 depicted the first, third and the fifth harmonics respectively.

S_1 shows the first harmonic of current waveform when distorted while S_2 and S_3 indicated the third and the fifth level of current waveform distortion respectively.

A non-linear load produces a highly distorted current; therefore, the total harmonic distortion of current increases with an increase in the supply voltage and this could result in harmonic distortion without a dimension index. The harmonic injected are as a result of the ballast which provides a high voltage to create an arc, hence a current waveform that is of higher harmonic is drawn. The harmonic current causes distortion in the voltage waveform.

The current distortion power, the voltage distortion power, and the harmonic apparent power are related to both the voltage and current distortion.

4.2.3 Spot light

Three samples of the spot light were tested in order to observe the consistency, the effect of supply voltage variation on the luminance delivered, and the power consumption.

Observation shows that there was a correlation between the drawn current and the luminance delivered. Variation in the supply voltage has a little effect on the luminance delivered. The higher the voltage supply, the more current drawn and the better the delivered luminance.

It was observed that there was more concentration of luminance at the centre than at the various sides, and as the distance from the light source increases, the luminance decreases.

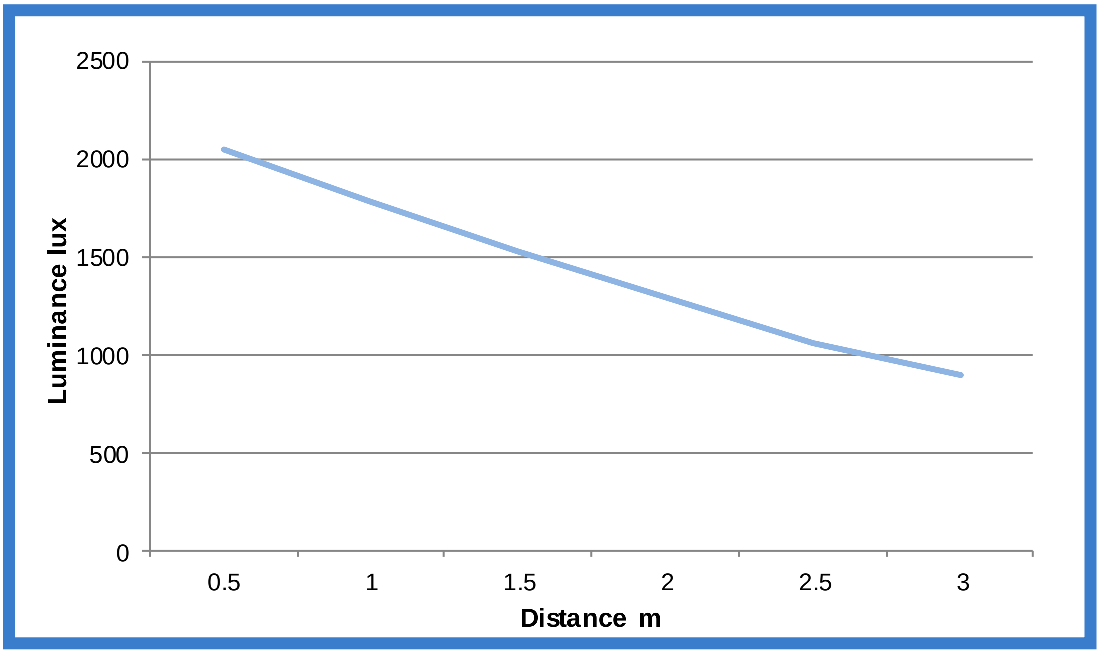

FIGURE 30: Luminance of a 60W spot light

The magnitude of the supply voltage and the active power consumption is not the same for the square law relationship normally assumed for a spot light. This could be attributed to the filament having some properties of a thermistor. The power factor and the reactive power are constant, while the apparent power and current show a linear trend.

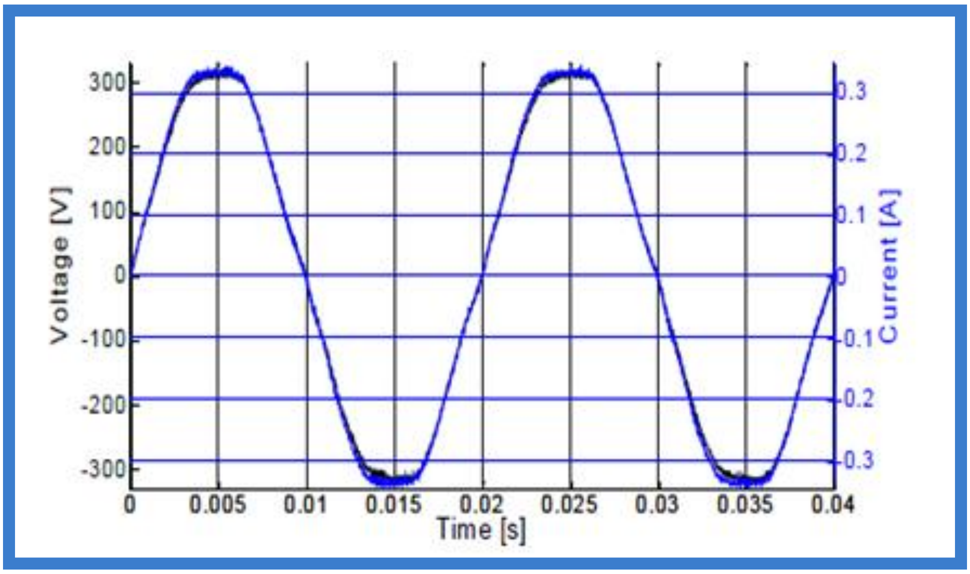

FIGURE 31: Supply voltage and current waveforms of a 60W spot light

The current waveform is distorted slightly but highly sinusoidal. A low harmonic is present in the current waveform, as shown in Figure 31.

It was observed that the sinusoidal current waveforms are in phase with the voltage waveforms.

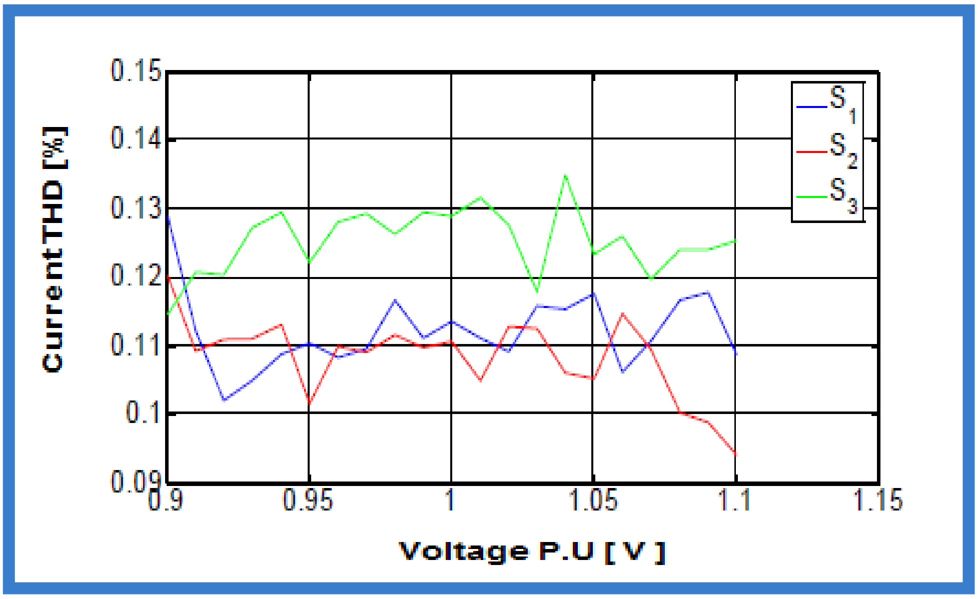

FIGURE 32: Total harmonic distortion of the voltage and current waveforms of a 60W spot light

Figure 32 illustrates the magnitude of the third harmonic relative to the fundamental for a 60W spot light. The S_1, S_2, and S_3 depicted the first, third and the fifth harmonics respectively.

S_1 shows the first harmonic of current waveform when distorted while S_2 and S_3 indicated the third and the fifth level of current waveform distortion respectively.

Figure 32 exhibits a low degree of harmonic distortion and the harmonic distortion of the current waveform as a function of the RMS supply voltage for the tested spot light.

4.2.4 LED

A variety of LED were tested in order to observe the effect of the supply voltage on the luminance delivered and the power consumption.

It was observed that there was a correlation between the power consumption and the current drawn. A variation in the supply voltage does not result in variation in the delivered luminance. This is applicable to all the conditions under which the test was carried out, and there is more concentration at the centre than the sides.

It was observed that variation in the current drawn is proportional to the power consumed, irrespective of the supply voltage variation (207V - 240V).

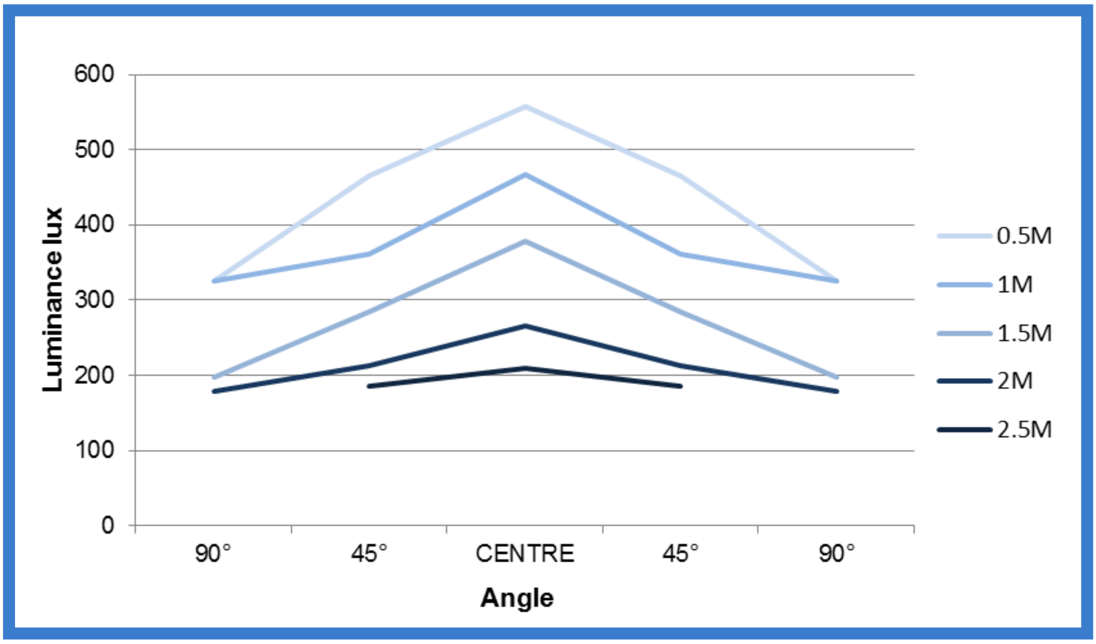

FIGURE 33: Concentration of luminance at the centre (LED)

The lumen output is not the best measurement of LEDs capabilities. The delivered light is the best and most relevant measure of evaluating LED. This articulated on how much a useful light can be delivered. As shown in Figure 34, the luminous intensity was evenly distributed and there is more concentration at the centre.

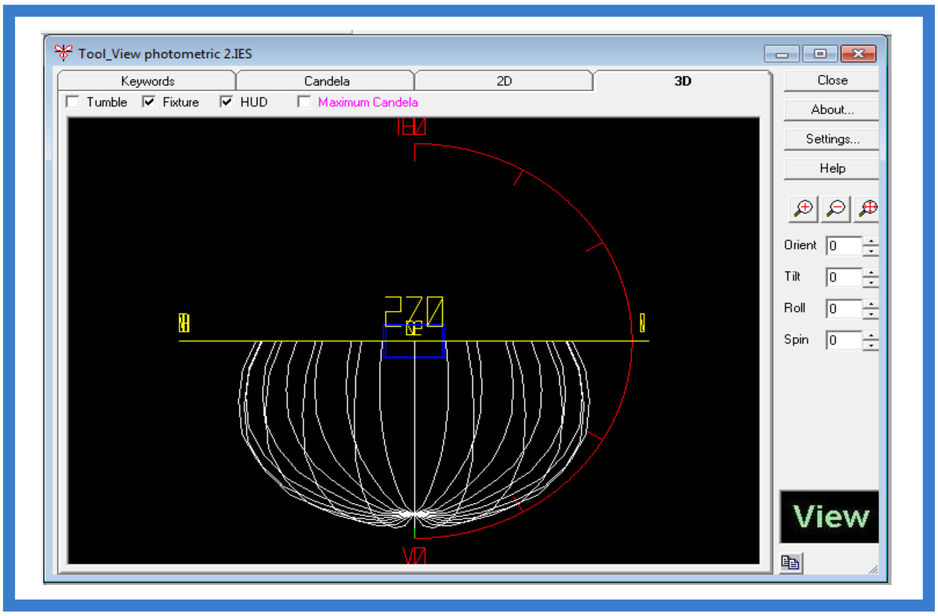

FIGURE 34: Photometric lighting view of a 6W LED (AGI 32)

There is no light dispersion; the LEDs are inherently directional and therefore minimise losses. The needs for reflectors and diffusers that can trap light in a specific direction are also reduced. Usually, the deviation of waveform from perfect sinusoidal is expressed in terms of harmonic distortion of the current and voltage waveforms. LED bulbs produce a highly distorted current due to the non-linear characteristics, as illustrated in Figure 35.

The current waveforms are affected by high distortion, while the voltage waveform is virtually sinusoidal.

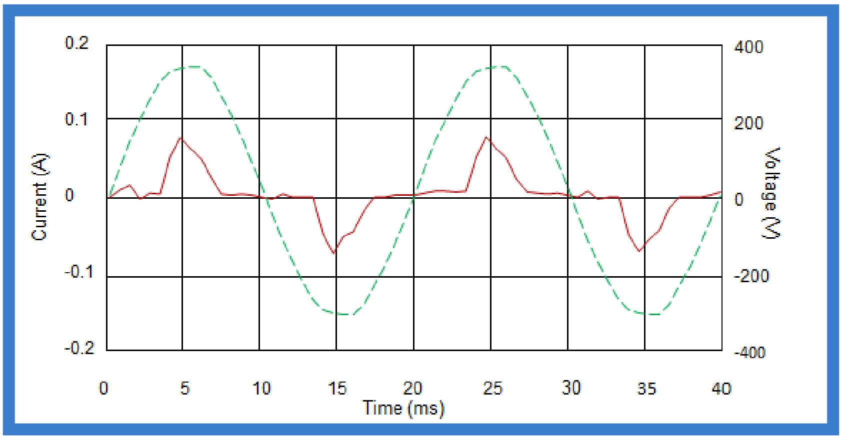

FIGURE 35: Supply voltage and current waveforms of a 6W LED

The voltage and current first harmonic does not have a large phase shift. The current waveforms are characterised by a high derivative and significant part of the period that is characterised by a spectrum-subjugated harmonics. The current waveforms change in amplitude with a constant direction and shape.

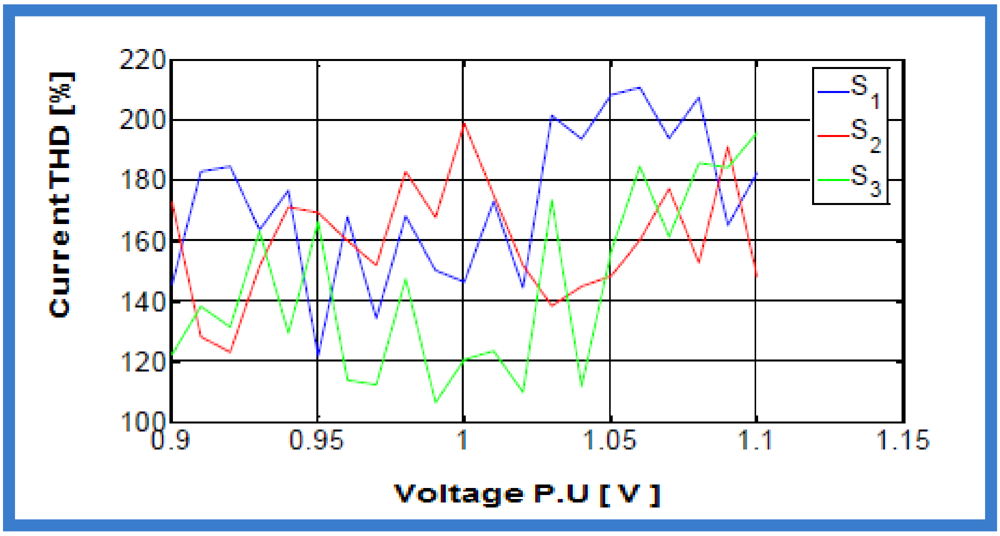

FIGURE 36: Total harmonic distortion of the voltage and current waveforms of a 6W LED

The magnitude of the third harmonic relative to the fundamental for a 6W LED is illustrated in Figure 36. The S_1, S_2, and S_3 depicted the first, third and the fifth harmonics respectively. S_1 shows the first harmonic of current waveform when distorted while S_2 and S_3 indicated the third and the fifth level of current waveform distortion respectively.

Figure 36 shows that LED generate a higher harmonic distortion.

4.3 EFFICIENCY OVERVIEW

The luminance meter (see Figure 19) measures the lux delivered by each light source. The measure of efficiency by which the light sources provide visible light from electricity is given in lumen per watt. Therefore; 1 lumen = 1 lux at the centre (angle 0^0), a distance of 1m from the light source.

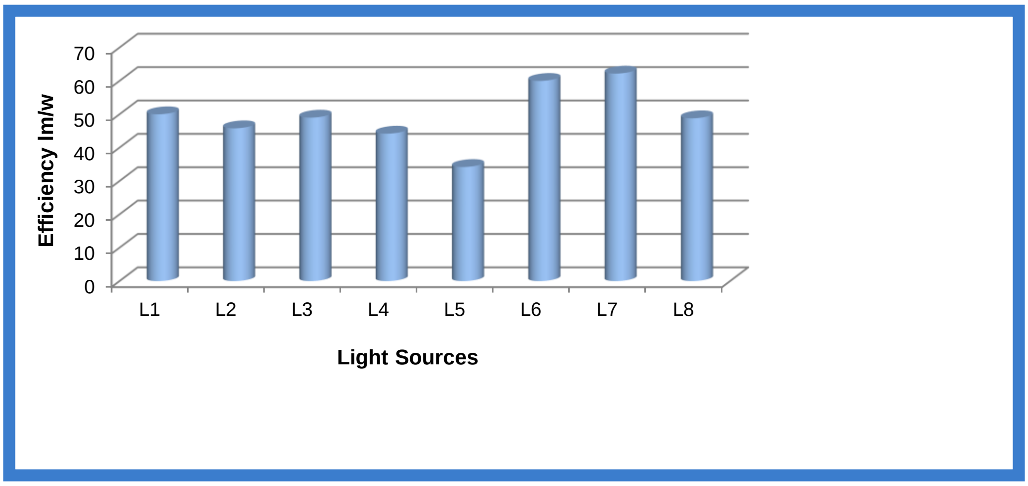

FIGURE 37: Light sources efficiency

Figure 37 shows the relationship between the power consumption and the luminance delivered by the tested light sources, which resulted in the L6 (60 percent) and L7 (62.2 percent) as the most efficient of the tested light sources. The L1 (50 percent), L2 (45.8 percent), L3 (49 percent), L4 (44.2 percent) and L8 (48.8 percent) are slightly better while L5 (34.2 percent) is the least efficient source. The efficiency of the tested light sources is as specified by the manufacturers' specification written on the boxes of the tested light sources. Though the power consumed and the luminance delivered is not as specified, but the ratio is the same.

4.3.1 Light sources efficiency software tools

The light sources efficiency software tools (AGI 32) were used to validate the accuracy of the light sources efficiency.

4.3.1.1 Validation of the light sources accuracy

The measurement accuracy and efficiency of the light sources were validated using a photometric software tools. The data of all the light sources tested were input into the photometric toolbox to verify the accuracy of the laboratory test result and the efficiency in conjunction with the IES (2003) standards. The IES (2003) standards recommended an illumination of between 300 - 500 lux for an office, lecture room and laboratory. An office

(6.5 m by 2.7 m) and a lecture room (10.6 m by 8.2 m) were considered. It was observed that L6 and L7 is the most efficient of the tested light sources.

4.3.1.2 Lighting calculator

Lighting level calculator software (see Figure 38) was also used to verify the accuracy of the measurement. The measured luminance values were input into the lighting calculator; the lighting level was determined and compared with the IES (2003) standards on illumination.

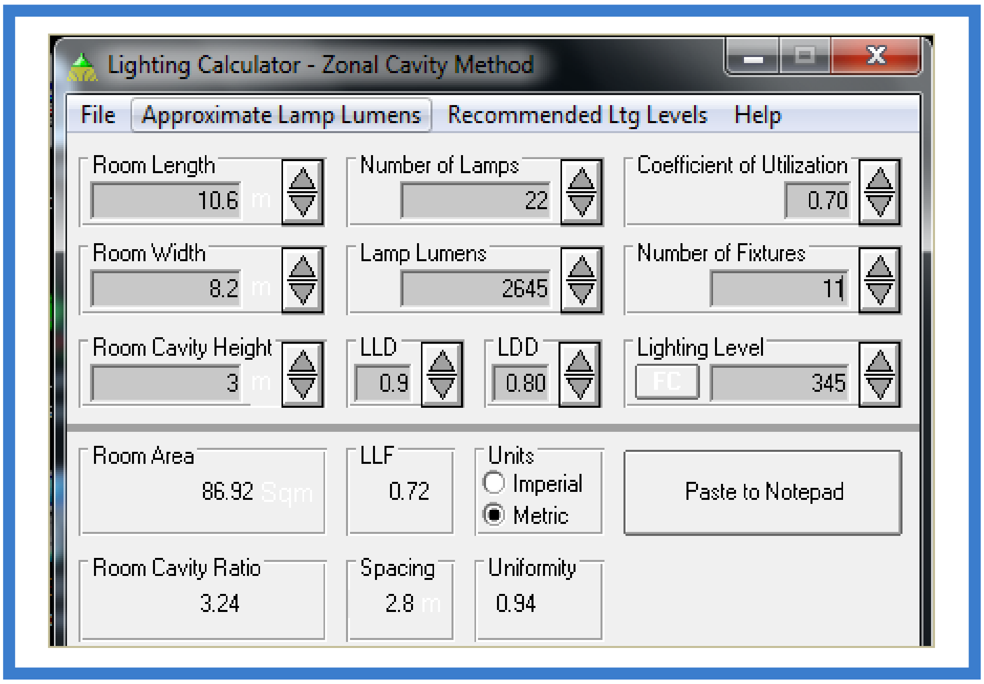

FIGURE 38: Lighting level calculator (MC Group)

4.4 ECONOMIC ANALYSIS

Analysing the economic effect of various light sources is highly essential in this study; this will institute how much could be saved if the traditional incandescent light sources are replaced with energy saver light sources.

The National Energy Regulatory of South Africa (NERSA) approved the lower increase of 25.8 percent for the 2011/12 financial year, which brings the electricity tariff to 52c kw/h (Lana, 2010:1).

4.4.1 Cost analysis of a 4ft LED and 4ft fluorescent lamp

The total cost has been analysed (see Table 7) considering the purchase cost and the operating cost of the lamps. The total cost has being calculated for L6 (4ft LED) having a lifespan of 40 000 hours over L3 (4ft fluorescent) with a lifespan of 9 000 hours because, L6 has a longer lifespan.

Table 7 shows the amount of saved cost and energy.

TABLE 7: Cost analysis of a 4ft LED and a 4ft fluorescent lamp

FEATURES	4FT FLUORESCENT (36W)	4FT LED (16W)
Lamp life	9000	40000
No of lamps used	5	1
Cost of lamp	R175	R220
Electricity usage	1440 kwh	640 kwh
Utility cost	R749	R333
Total cost	R924	R553
ENERGY SAVED	800 kwh	
SAVED COST (ANNUALLY)	R81.36	

Table 7 shows the total cost analysed for L6 (40 000 hours) over L3 (9 000 hours). The energy consumed (kwh) or in other word the electricity usage was calculated, considering the lifespan of L6 over L3, an energy amount to 800 Kwh and the sum of R81.36 would be saved annually.

The actual saved amount is not the same as the manufacturers', the manufacturers power consumption specification is lower than the actual power consumed, the utility cost depend on the power consumption.

4.4.2 Cost analysis of a LED bulb and a spot light

The total cost has been analysed (see Table 8) considering the purchase cost and the operating cost of the lamp. The total cost has being calculated for L7 (LED) having a lifespan of 50 000 hours over L5 (spot light) with a lifespan of 1 824 hours because, L7 has a longer lifespan.

Table 8 shows the amount of saved cost and energy.

TABLE 8: Cost analysis of a LED bulb and a spot light

FEATURES	SPOT LIGHT (60W)	LED BULB (6W)
Lamp life	1 824	50 000
No of lamps used	27	1
Cost of lamp	R432	R160
Electricity usage	3 000 kwh	300 kwh
Utility cost	R1 560	R156
Total cost	R1 992	R316
ENERGY SAVED	2 700 kwh	
SAVED COST (ANNUALLY)	R294	

Table 8 shows the total cost analysed for L7 (50 000 hours) over L5 (1 824 hours). The energy consumed (kwh) or in other word the electricity usage was calculated, considering the lifespan of L7 over L5, an energy amount to 2 700 Kwh and the sum of R294 would be saved annually.

The actual saved amount is not the same as the manufacturers', the manufacturers power consumption specification is lower than the actual power consumed, the utility cost depend on the power consumption.

4.4.3 Cost analysis of a LED bulb and a CFL bulb

The total cost has been analysed (see Table 9) considering the purchase cost and the operating cost of the lamp. The total cost has being calculated for L7 (LED bulb) having a lifespan of 50 000 hours over L8 (CFL) with a lifespan of 6 000 hours because, L7 has a longer lifespan.

Table 9 shows the amount of saved cost and energy.

TABLE 9: Cost analysis of a LED bulb and a CFL bulb

FEATURES	CFL BULB (11W)	LED BULB (6W)
Lamp life	6 000	50 000
No of lamps used	8	1
Cost of lamp	R360	R160
Electricity usage	550 kwh	300 kwh
Utility cost	R286	R156
Total cost	R646	R316
ENERGY SAVED	250 kwh	
SAVED COST (ANNUALLY)	R57	

Table 9 shows the total cost analysed for L7 (50 000 hours) over L8 (6 000 hours). The energy consumed (kwh) or in other word the electricity usage was calculated, considering the lifespan of L7 over L8, an energy amount to 250 Kwh and the sum of R57 would be saved annually. The actual saved amount is not the same as the manufacturers', the manufacturers power consumption specification is lower than the actual power consumed, the utility cost depend on the power consumption.

4.4.4 Cost analysis of a CFL bulb and a spot light source

The total cost has been analysed (see Table 10) considering the purchase cost and the operating cost of the lamp. The total cost has being calculated for L8 (CFL) having a lifespan of 6 000 hours over L5 (spot light) with a lifespan of 1 824 hours because, L8 has a longer lifespan. Table 10 shows the amount of saved cost and energy.

TABLE 10: Cost analysis of a CFL bulb and a spot light

FEATURES	SPOT LIGHT (60W)	CFL BULB (11W)
Lamp life	1 824	6 000
No of lamps used	4	1
Cost of lamp	R64	R45

Features	Spot Light (60w)	CFL Bulb (11w)
Electricity usage	444 kwh	66 kwh
Utility cost	R231	R34
Total cost	R295	R79
Energy saved	378 kwh	
Saved cost (Annually)	R126	

Table 10 shows the total cost analysed for L8 (6 000 hours) over L5 (1 824 hours). The energy consumed (kwh) or in other word the electricity usage was calculated, considering the lifespan of L8 over L5, an energy amount to 378 Kwh and the sum of R126 would be saved annually.

The actual saved amount is not the same as the manufacturers', the manufacturers power consumption specification is lower than the actual power consumed, the utility cost depend on the power consumption.

4.4.5 Payback period

The payback period could be classified in terms of months or years, depending on the usage time of light sources per day. The longer the daily usage of light sources, the shorter will be payback period. These also depend on both the cost price and the life span of light sources.

TABLE 11: Payback period

Light Sources	Purchase Cost (R)	Life Span (H)	Cost/ 1000h	Total Cost Saved	Payback Period (H)
4ft LED	220	40000	6	231	8062
LED bulb	160	50000	3.2	1260	6349
CFL	45	6000	7.5	124	2177

Table 11 shows the payback period of the energy efficient light sources (L6, L7, and L8) expressed over the lifespan. The L8 (13.1 percent) has the least payback period, while L6 and L7 has (48.6 percent) and (38.3 percent) respectively.

It was deducted from the cost analysis of the various tested light sources that L6 and L7 are more cost effective and energy efficient than any of the other light sources.

A 56 percent saving on energy would result from the replacement of L3 (4ft fluorescent lamp) with L6 (4ft LED) (see Table 7). There would be a 90 percent conservation of energy if L5 (spot light) is replaced with L7 (LED bulb) (see Table 8), for L7 (LED bulb) replaced with L8 (CFL) 45.5 percent energy would be saved (see Table 9), while 85 percent energy would be conserved for L8 (CFL) replacing L5 (spot light) (see Table 10).

The LED light source is more expensive than every other light source, but the efficiency and lifespan compensates for the purchase price.

It will cost the sum of R220 to purchase a new L6 light source, the saved cost (annually) is R81.36 (see table 7). Therefore, the breakeven point for L6 replacing L3 will be after 2.7 years.

The purchase price of a new L7 light source is R160 and the saved cost (annually) is R294 (see Table 8) therefore, the breakeven point for L7 replacing L5 will be after 7 months.

It will cost the sum of R160 to purchase a new L6 light source, the saved cost (annually) is R57 (see table 9). Therefore, the breakeven point for L6 replacing L8 will be after 2.8 years.

The purchase price of a new L8 light source is R45 and the saved cost (annually) is R126 (see Table 10) therefore, the breakeven point for L8 replacing L5 will be after 4 months.

The purchase price of an LED is becoming relatively cheap because it is being promoted and embraced by the general populace.

Figure 39 shows the life span of various tested light sources.

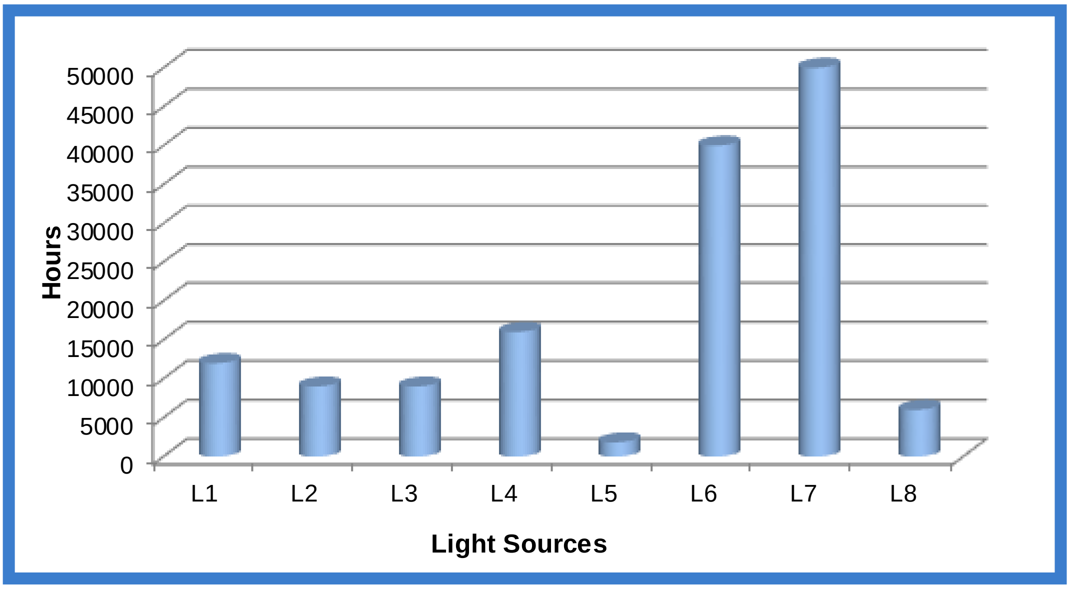

FIGURE 39: Lifespan of light sources

4.5 SUMMARY

This chapter emphasised the laboratory test experiments conducted on the various tested light sources. The consistency, effect of the supply voltage variation on the luminance delivered, and the power consumption were analysed for each light source.

Correlation between the power consumption and the luminance delivered were noted, and there is more concentration of luminance at the centre than the sides.

On the L3, the reactive power increases as the supply voltage increases, while in L2, the reactive power decreases and the harmonics distortion is relatively moderate. The power factor and reactive power are constant in a spot light source, while the apparent power and current show a linear trend.

The high trend of distorted current in the LED was due to the non-linear characteristics.

Efficiency of the various tested light sources was also analysed as this forms the main thrust of the study. Photometric software was used to validate the measurement accuracy, and this was in conjunction to the IES (2003) standards on illumination.

The economic effects of the tested light sources were analysed, as this constituted how much could be saved if the traditional incandescent light source is replaced with an energy efficient light source.

The next chapter, Chapter 5, focuses on the synthesis of the study, a proposed maintenance plan for the VUT lighting system, conclusion and recommendation of the study.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The study aimed to investigate and deduct facts on incandescent light sources used on the VUT campus. The objective was to test and verify if the light sources are utilised effectively, and recommend a better energy-efficient light source for replacement purpose.

The data regarding potential savings, while effectively utilising the power supply and having a better luminance, will be available to the general populace. This provides an opportunity to know the exact electrical power consumption, and the economic effect thereof, on the incandescent light sources identified as being used on the VUT campus.

A viable and suitable computerised maintenance plan will be introduced to the VUT campus.

5.2 SYNTHESIS OF THE STUDY

The main objective of the study was formulated to analyse the incandescent light sources used on the campus. Therefore, the main research question was formulated as: How much energy could be conserved, if the incandescent light source is replaced with an energy efficient light source?

From the background of the problem investigated in this study, it seemed that energy is being wasted as a result of the inefficient use of the incandescent light sources.

An overview of the light sources efficiency highlighted the notion that various government policies and incentives are processes of establishing a better method of conserving energy.

The study was contextualised within the identified light sources used on the campus. An extensive laboratory test was carried out on the identified light sources and the LED light source. The luminance delivered per unit, power consumed, efficiency, lifespan and economic effects were determined.

Data obtained from the laboratory test were analysed and validated using photometric software tools and lighting level calculator software, and compared with the SANS (2006) on illumination.

A constant light output for a better productivity, efficiency and high level of security is essential in this study. A lighting system maintenance schedule was formulated and a lighting level maintenance software programme was design, developed and implemented. This programme monitors the light sources' lighting level for efficient and effective utilisation.

5.3 LIGHTING SYSTEM MAINTENANCE PLAN

Regular maintenance is essential to ensure that facilities receive the desired quantity and quality, as well as energy efficiency, from the light sources. Scheduled maintenance could produce a range of benefits including a brighter and cleaner work place, a higher level of security and enhanced productivity.

It is essential in the study to introduce a sustainable computerised maintenance program to the VUT that currently does not have a lighting system maintenance plan.

5.3.1 Maintaining light level

Light level, or luminance, is the total luminous flux incident on a surface per unit area. Luminance of light sources decreases with age and use. The reduction of the light source output will affect the appearance of the space; the brightness will reduce. It is, therefore, essential to maintain the level of the light source output. A lighting system maintenance schedule has been formulated (see Table 12) for an efficient and constant light output.

TABLE 12: Lighting system maintenance schedule

DESCRIPTION	COMMENTS	MAINTENANCE FREQUENCY			
		DAILY	WEEKLY	BI ANNUALLY	SCHEDULE
Overall visual inspection	Complete overall visual inspection to ensure that all lighting systems are operating and safety systems are in place		X		
Lighting use / Sequencing	Turn off unnecessary lights	X			
On time	Repair, assess and reduce lighting where possible on time	X			
Use day lighting	Make use of day lighting where possible	X			
Replace burned out lamps	Burned out lamps can damage ballast if not replaced		X		
	For large facilities, consider group re-lamping				X
Replace lenses	Replace lens shielding that has become yellow or hazy			X	
Illumination levels	Measure light levels, compare to the specification. Identify area for			X	

	reduction or increase in luminance				
Clean lamps and fixtures	Lamps and fixtures should be wiped clean to ensure maximum efficiency			X	
Clean walls and ceilings	Clean surfaces allow maximum distribution of light within the space			X	
Visual inspection	Inspect fixtures and controls to identify excessive dirt, degraded lenses, ineffective or inoperable control			X	
Evaluate lamps and ballasts for potential upgrade	Rapid change in technology may result in a significant saving through re-lamp or retrofit				X

The lighting system level needs to be maintained, a lighting system maintenance schedule was formulated (see table 12). In the formulated schedule, overall visual inspection of light sources and replacement of burned out lamps were done weekly, unused lights were turned off and the use of day light was encouraged daily. Lamps fixtures, wall, ceilings were cleaned and lenses were replaced bi-annually. Lighting levels were measured bi-annually while evaluation of lamps and ballast for potential upgrade were done as schedule. By following the formulated maintenance schedule, there was improvement on the delivered luminance, the light sources were utilised effectively.

Table 13 shows the lighting system failure mode and effective analysis worksheet.

TABLE 13: Lighting system failure mode and effect analysis worksheet

LIGHTING SYSTEM FAILURE MODE AND EFFECT ANALYSIS WORKSHEET

Date: ______________________

Building: ___________________

Maintenance team: ___________

NO	ITEM DESCRIPTION	FAILURE MODE CAUSES	EFFECT/DAMAGES		SYMPTOMS OF FAILURE MODE	FAILURE MODE DETECTION METHOD	RECTIFICATION METHOD	ACTION TO PREVENT FUTURE CAUSES
			ITEM	WHOLE SYSTEM				

5.3.2 Lighting system maintenance software tools

A software program, to facilitate the effective monitoring of the lighting system on the VUT campus, was designed, developed and implemented for use. This will enhance the on-time and effective maintenance of the light sources for a better efficiency. The program was written using PIC-C compiler software application (see Annexure A) and simulated in a Proteus7 professional software environment.

Figure 40 shows the simulation circuit of the lighting system maintenance device. The simulation circuit shows the application of the lighting system maintenance device aimed to monitor the lighting level at 0.7 utilisation factor.

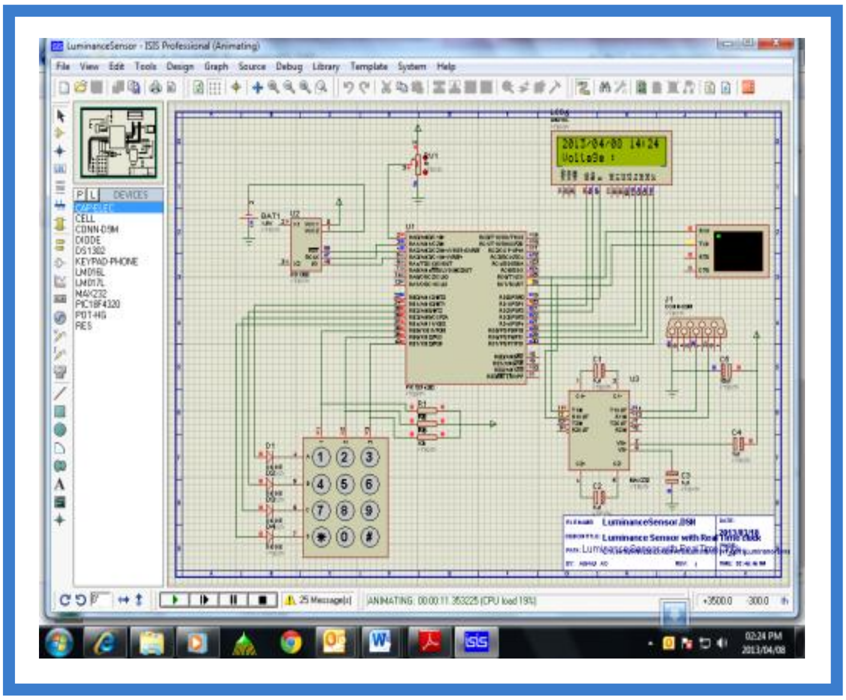

FIGURE 40: Simulation circuit of the lighting system maintenance device (Proteus 7 professional)

A transducer (sensor; light intensity-to-voltage) that changes one form of energy into another was used; both the light dependent resistor (LDR) and photo diode were tested. Photo diode is stable and sensitive, application in a reverse bias (cathode +ve and anode –ve) greatly improves the linearity of the device. LDR (see Annexure D) was chosen for this study because its sensitivity was deemed to be sufficient to detect the luminous intensity differences expected in the proposed application, the response time is adequate, and it is cheaper and more readily available than other light sensitive devices. LDR is packaged in hermetically sealed cans, plastic cases, or coated in moisture resistant epoxy. LDRs are ideal for position sensing, daylight sensing and switching applications.

An LDR measures the intensity of the light sources. The measured luminance was sent to the microchip (PIC 18F4320) of the lighting system maintenance device. The PIC 18F4320 (Annexure E) in the lighting device was programmed, the lighting system maintenance device key features include:

- Converting luminance value to a PIC value
- Define maintenance at the task level
- Easily establish unlimited number of calendar
- User-definable and manageable maintenance groups or routes
- Ability to update maintenance task and display the update
- Multi-featured maintenance tool and schedule setting

The simulated circuit (lighting system maintenance device) was developed and tested at different lecture rooms and offices working.

Figure 41 shows a developed lighting level maintenance device. Lighting system maintenance device is a device that monitors the lighting level and report in the form of a message whenever there is a drop in the level of the luminance delivered by the light sources. To verify the effectiveness of the device, it was tested in offices and lecture rooms of different sizes and under different conditions (with a window blind, day light reflection and at night) of randomly working.

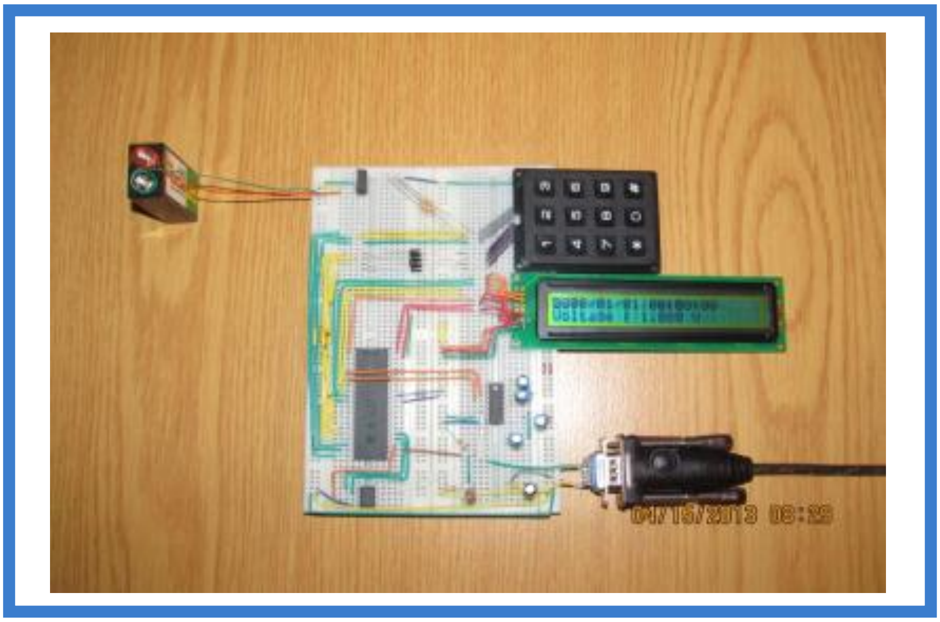

FIGURE 41: Lighting system maintenance device

It was noted in venues without a window blind that the daylight contributed greatly to the illumination, while at night, the light source luminance was the only source of illumination. Even with daylight, the lighting system maintenance device was able to function properly.

In an office (6.5 m by 2.7 m), a single sensor was effective and communicated directly to the lighting system maintenance device, while in a large lecture room (10.6 m by 8.2 m), a single sensor was not sufficient. Figure 42 below shows a LDR sensor mounted in a lecture room

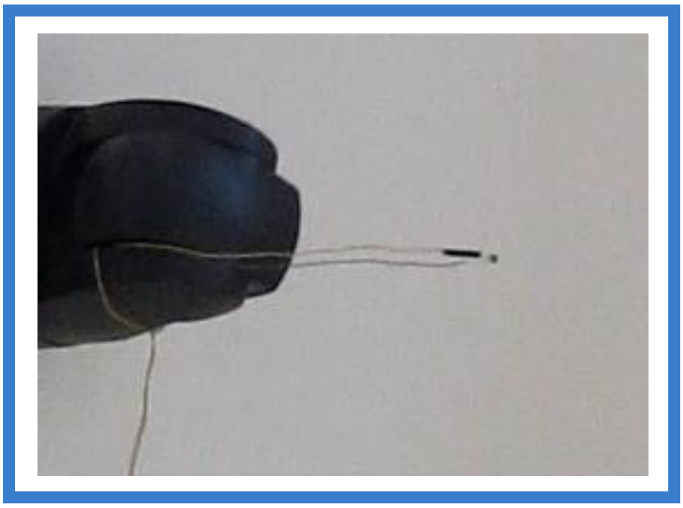

FIGURE 42: A LDR sensor

The lighting system maintenance device has a sub-system unit for a large lecture room. The large lecture room was divided into four different sections and a sensor was allocated to monitor the lighting level in each of the sections. The sensor monitors the lighting level and sends the luminance value to the microchip. The microchip PIC 18F2220 (Annexure E) was programmed (see Annexure B) to convert the luminance value to PIC value and send the PIC value in the form of a signal to the microchip (PIC 18F4320) of the lighting system maintenance device. The simulated circuit is shown (see Annexure C).

The output of the lighting level device is being displayed via an integrated circuit, MAX232CPE (Annexure F) in the form of message as shown (see Figure 43) under the tested conditions, at different lecture rooms and offices.

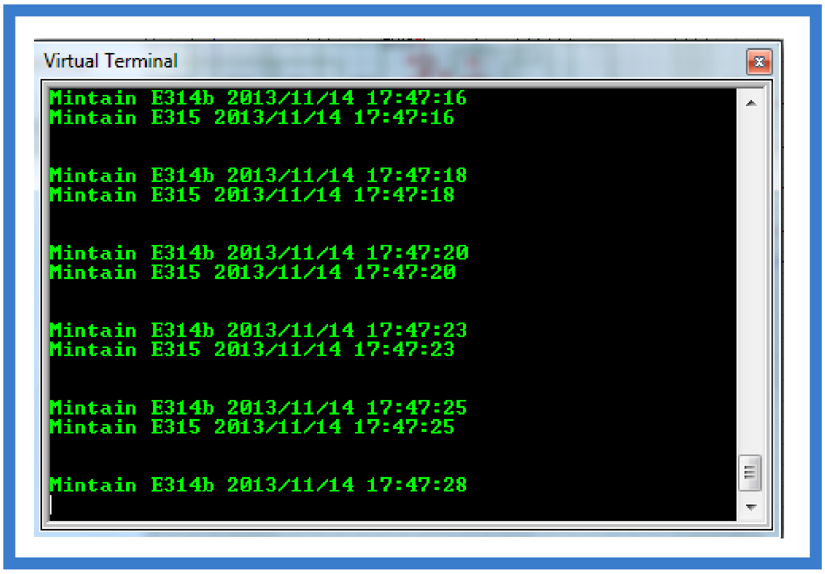

FIGURE 43: PIC value displayed in the form of message (Putty)

In a situation when there is no faulty light source, there would not be any message display via an integrated circuit and the visual terminal will be as shown in Figure 44.

FIGURE 44: Visual terminal at no faulty light source (Putty)

5.4 CONCLUSIONS

Based on the findings of the study, several conclusions are drawn, and consequently discussed.

Regarding the current drawn, variation in the supply voltage to L1 (8ft fluorescent) and L5 (spot light) resulted in the variation of the drawn current, while in L2 (6ft fluorescent), L3 (4ft fluorescent) and L4 (2ft fluorescent), variation in the voltage supply does not result in variation of the current drawn; the current is constant. In the energy saver light sources (L6 (4ft LED), L7 (LED bulb) and L8 (CFL), current drawn is constant, irrespective of slight variations in the supply voltage.

The power consumed by the light sources is proportional to both the supply voltage and the current drawn. The consumed power varies from one light source to another. A slight variation in the voltage supplied to L6, L7 and L8 has no noticeable effect on the power consumed, while in L5, variation in the supply voltage has a noticeable effect. A L6 and L7 consumed a lower power compared to L8, and L5 consumed less power compared to both L1 and L2 at a unity power factor.

The test conducted shows that variation in the voltage supply resulted in the variation of the luminance delivered by L1, L2, L3, L4 and L5. The higher the supply voltage, the more luminance delivered. Considering the L6, L7 and L8, variation in the supply voltage does not result in luminance variation the luminance remains constant. Therefore, it can be concluded that L6, L7 and L8 are at an advantage over other light sources.

The luminance produced by L8 is more diffused than for the L5. It can be seen that there is a difference between the claimed and the measured luminous flux. L6 and L7 does not need to have the same luminous output as the L5, but should be compared with L5 according to the luminance level, CRI and the uniformity of the light.

Regarding the efficiency of light sources (lm/w), the L6 and L7 source is the most efficient of all the tested light sources. The L8 also delivered a better luminance to the power consumed. Although L1, L2, L3 and L4 delivered a good luminance but, the power consumed is relatively high, while L5 is the least efficient light source. This provides an indication of why, according to Brandon (2009:1), various government policies are against the traditional incandescent light source.

Figure 39 illustrated the life span of the various light sources tested, it was concluded that the L6 and L7 light source has the longest life span. This is followed by L1 and L4 that have a reasonable life span. The L2 and L3 have a shorter life span, followed by the L8 and finally, the L5, which has the shortest life span.

5.5 RECOMMENDATIONS

The aims and objectives of the study pivot on recommending an energy saver light source for replacement purposes, if the light sources identified as being used on the VUT campus are not effectively utilised.

The following recommendations stem from the conclusions drawn from the study:

5.5.1 Recommendation 1

It was deducted that the L7 is a very efficient light source. Even though the purchase price is high, this could be complemented by the utility cost, the life span and the payback period; for the lifespan of a single L7, a L8 would be replaced eight times, while L8 would be replaced twenty seven times (see Chapter 4, Section 4.4.2 and 4.4.3). This placed the L7 over L8 and L5; therefore, the recommendation is made to replace the L8 and L5 used on the campus with L7.

5.5.2 Recommendation 2

It was noted from the conclusion that variation in the supply voltage to L3 resulted in luminance variation, while the L6 luminance remains constant. The L6 is more efficient than L1, L2, L3 and L4, but has a higher purchase price. The purchase price of L6 could be complemented by the life span and the payback period; a L3 would have been replaced 5 times before the end of the life of a L6 (see Chapter 4, Section 4.4.1). Therefore, the L6 is recommended to replace the fluorescent light sources used on the VUT campus. The findings of this study indicate that if the identified light sources presently used on the campus are replaced with the recommended L6 and L7, it would result in VUT saving money

5.5.3 Recommendation 3

Regarding maintenance, the VUT project and services department uses a spot re-lamp method in maintaining the light sources on the campus, but both group and spot re-lamp methods are recommended for effective maintenance of the light sources. The lighting system maintenance-monitoring device, maintenance schedule, the failure mode and work sheet, are hereby recommended for implementation on the VUT campus (see Chapter 3, Section 3.4.3 and Chapter 5, section 5.3.1 and 5.3.2). These save time, as there would not be any need to report faults, and the clock card system for light source maintenance will be out of practice, resulting in an improved efficiency and enhancing effective service delivery.

Below is a self-check that can be applied to determine the level of efficiency and maintenance of light sources.

Locate an area of 200 fixtures, preferably with the same lamps per fixture:

- Count the number of missing, burned out or flickering lamp
- Divide this number by the number of lamps per fixture
- Count the number of fixtures with broken or missing parts

- Count the number of dirty fixtures
- Add the value from step 2, 3, and 4
- Check the value you get after adding step 2, 3, and 4 against the table 14 below.

TABLE 14: Self-check for efficiency level and maintenance of light sources

OUTCOME	RECOMMENDATIONS
0 - 20	Keep up good work
21 - 40	Need to spend more time on maintenance
41 – and more	Spend much more time on maintenance or outsource

The main recommendation from the findings of this study is formulated on the conceptual framework. This framework aims at providing structured guidance for testing to be conducted on the light sources identified as being used on the campus in order to determine if they are effectively utilised.

The framework could also be described as a sustainable practice that comprises a methodology technique and innovative use of resources that has a proven record of success in effectively utilising light sources.

This framework will enable the university, and the world at large, to effectively utilise power, cut costs and be adequately sustainable. In addition, further research on application of energy efficiency light source in both old and new building, evaluation of glare and light performance at night (street light as case study for energy efficient light source), energy efficiency control of indoor environment and loss of the night network using energy efficient light source needs to be undertaken in the future.

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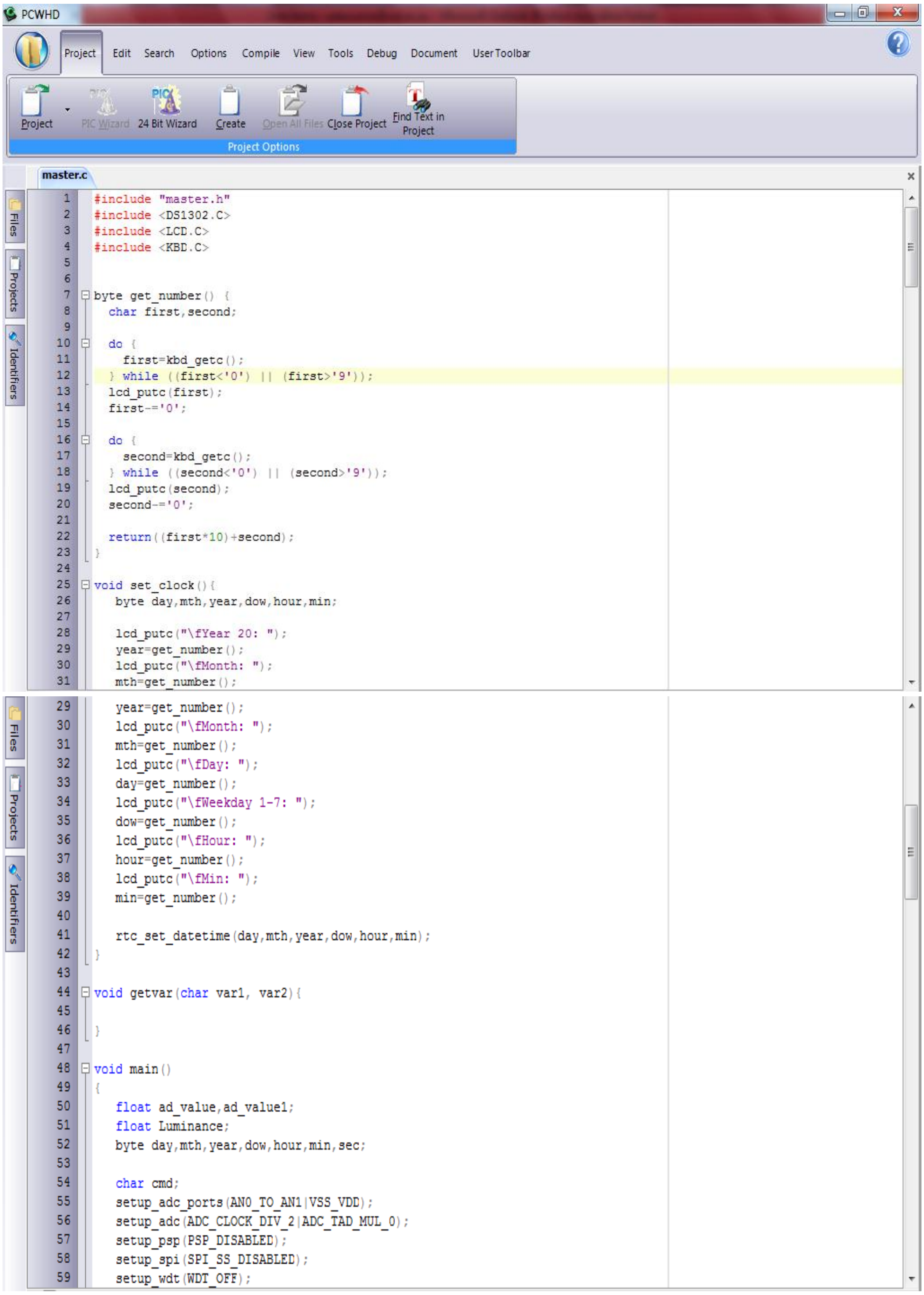
Annexure A - Lighting system maintenance PIC (18F4320) program

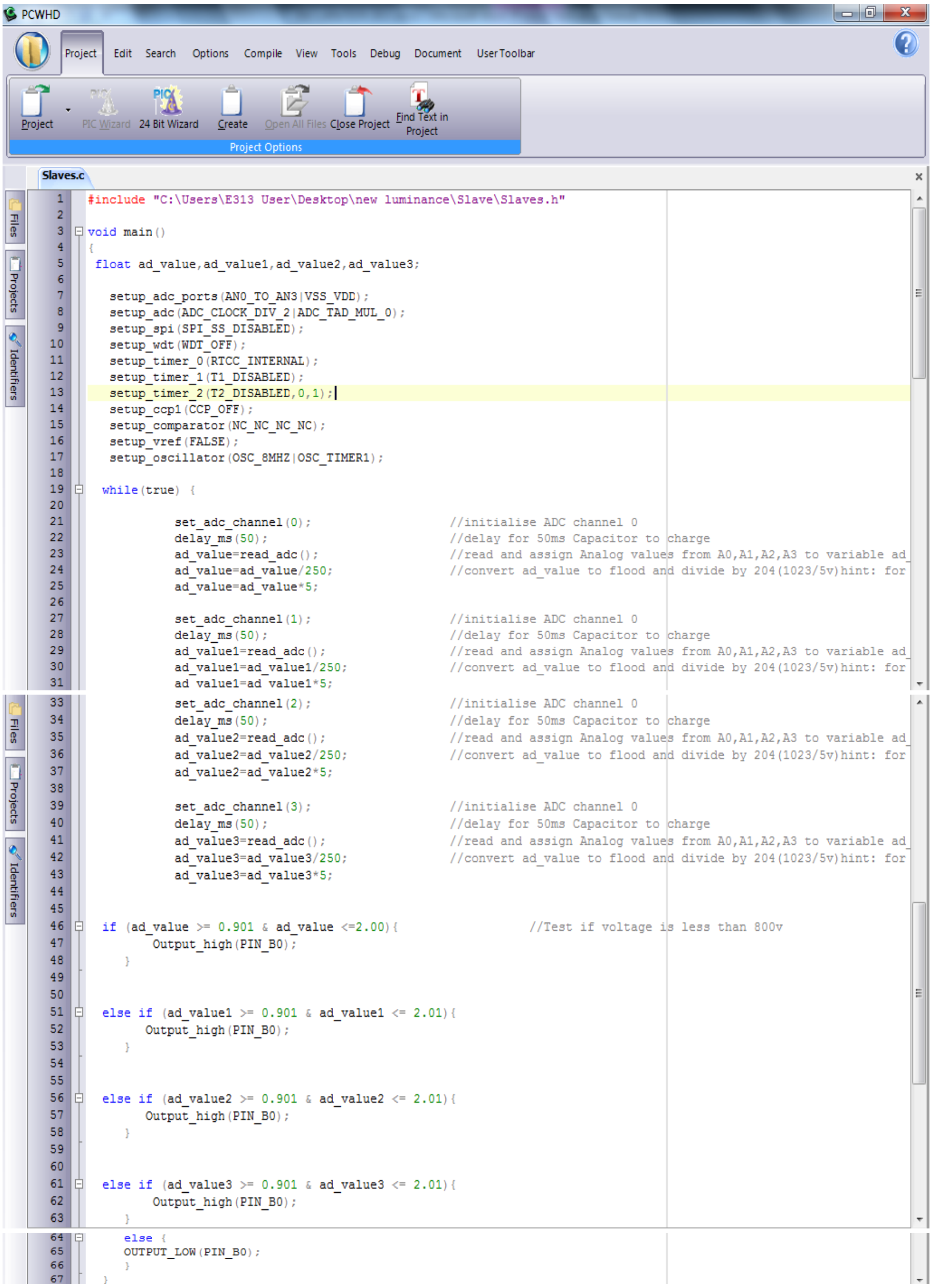



```c
#include "master.h"
#include <DS1302.C>
#include <LCD.C>
#include <KBD.C>


byte get_number() {
  char first,second;

  do {
    first=kbd_getc();
  } while ((first<'0') || (first>'9'));
  lcd_putc(first);
  first-='0';

  do {
    second=kbd_getc();
  } while ((second<'0') || (second>'9'));
  lcd_putc(second);
  second-='0';

  return((first*10)+second);
}

void set_clock(){
   byte day,mth,year,dow,hour,min;

   lcd_putc("\fYear 20: ");
   year=get_number();
   lcd_putc("\fMonth: ");
   mth=get_number();
   lcd_putc("\fDay: ");
   day=get_number();
   lcd_putc("\fWeekday 1-7: ");
   dow=get_number();
   lcd_putc("\fHour: ");
   hour=get_number();
   lcd_putc("\fMin: ");
   min=get_number();

   rtc_set_datetime(day,mth,year,dow,hour,min);
}

void getvar(char var1, var2){

}

void main()
{
   float ad_value,ad_value1;
   float Luminance;
   byte day,mth,year,dow,hour,min,sec;

   char cmd;
   setup_adc_ports(AN0_TO_AN1|VSS_VDD);
   setup_adc(ADC_CLOCK_DIV_2|ADC_TAD_MUL_0);
   setup_psp(PSP_DISABLED);
   setup_spi(SPI_SS_DISABLED);
   setup_wdt(WDT_OFF);
```

```
 setup_timer_1(T1_DISABLED);
 setup_timer_2(T2_DISABLED,0,1);
 setup_timer_3(T3_DISABLED|T3_DIV_BY_1);
 setup_ccp1(CCP_OFF);
 setup_comparator(NC_NC_NC_NC);
 setup_vref(FALSE);
 rtc_init();
 lcd_init();
 kbd_init();
 setup_oscillator(OSC_8MHZ|OSC_TIMER1);
 port_b_pullups(TRUE);

lcd_putc("\f1: Change, \n2: Display");
printf("\fReady\r") ;

 while(true){

 do {
    cmd=kbd_getc();
 } while ((cmd!='1')&&(cmd!='2'));

 if(cmd=='1')
   set_clock();



    while(true) {
         set_adc_channel(0);                     //initialise ADC channel 0
         delay_ms(50);                           //delay for 50ms Capacitor to charge
         ad_value=read_adc();                    //read and assign Analog values from A0,A1,A2,A3 to variable ad
         ad_value=ad_value/250;                   //convert ad_value to flood and divide by 204(1023/5v)hint: fo
         ad_value=ad_value*5;

         set_adc_channel(1);                     //initialise ADC channel 0
         delay_ms(50);                           //delay for 50ms Capacitor to charge
         ad_value1=read_adc();                    //read and assign Analog values from A0,A1,A2,A3 to variable a
         ad_value1=ad_value1/250;                   //convert ad_value to flood and divide by 204(1023/5v)hint:
         ad_value1=ad_value1*5;



    rtc_get_date( day, mth, year, dow);
    rtc_get_time( hour, min, sec );

if (ad_value >= 0.901 & ad_value <=2.00){                  //Test if voltage is less than 800v
       printf("Mintain E313 20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to th
       printf(lcd_putc,"\f ERROR ROOM E313");    //print to the Terminal
       delay_ms(1000); }
       else {                  //Test if voltage is less than 800v
           printf("             \r\n");   //print to the Terminal
            printf(lcd_putc,"\f20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to
            printf(lcd_putc,"System Healthy");    //print to the Terminal
            delay_ms(100);
   }

if (ad_value1 >= 0.901 & ad_value1 <= 2.01){
       printf("Mintain E314a 20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to t
       printf(lcd putc,"\f ERROR ROOM E314a");    //print to the Terminal
```

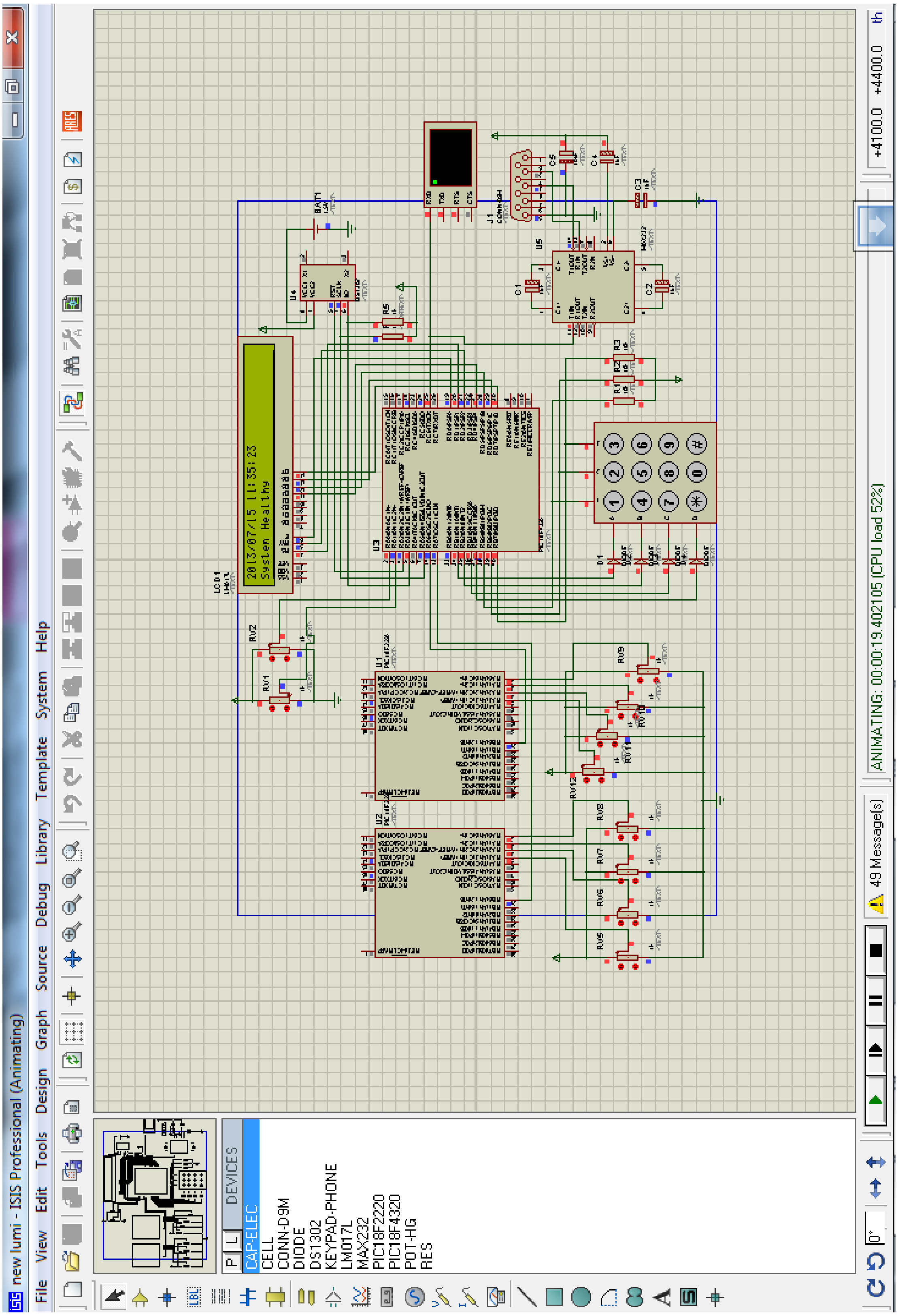
```
        else {                  //Test if voltage is less than 800v
            printf("            \r\n");   //print to the Terminal
             printf(lcd_putc,"\f20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to
             printf(lcd_putc,"System Healthy");    //print to the Terminal
             delay_ms(100);
    }
if (Input(PIN_A6)){
      printf("Mintain E314b 20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to th
        printf(lcd_putc,"\f ERROR ROOM E314b");    //print to the Terminal
        delay_ms(1000); }
        else {                  //Test if voltage is less than 800v
            printf("            \r\n");   //print to the Terminal
             printf(lcd_putc,"\f20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to
             printf(lcd_putc,"System Healthy");    //print to the Terminal
             delay_ms(100);
    }


if (Input(PIN_A7)){
      printf("Mintain E315 20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to the
        printf(lcd_putc,"\f ERROR ROOM E315");    //print to the Terminal
        delay_ms(1000); }
        else {                  //Test if voltage is less than 800v
            printf("            \r\n");   //print to the Terminal
             printf(lcd_putc,"\f20%02u/%02u/%02u\ %02u:%02u:%02u \r\n",year,mth,day,hour,min,sec);    //print to
             printf(lcd_putc,"System Healthy");    //print to the Terminal
             delay_ms(100);
    }


     }
        delay_ms(50);
        cmd=kbd_getc();
        if(cmd=='1')
        set_clock();
```

Annexure B - Lighting system maintenance PIC (18F4220) program




```c
#include "C:\Users\E313 User\Desktop\new luminance\Slave\Slaves.h"

void main()
{
 float ad_value,ad_value1,ad_value2,ad_value3;

   setup_adc_ports(AN0_TO_AN3|VSS_VDD);
   setup_adc(ADC_CLOCK_DIV_2|ADC_TAD_MUL_0);
   setup_spi(SPI_SS_DISABLED);
   setup_wdt(WDT_OFF);
   setup_timer_0(RTCC_INTERNAL);
   setup_timer_1(T1_DISABLED);
   setup_timer_2(T2_DISABLED,0,1);
   setup_ccp1(CCP_OFF);
   setup_comparator(NC_NC_NC_NC);
   setup_vref(FALSE);
   setup_oscillator(OSC_8MHZ|OSC_TIMER1);

  while(true) {

            set_adc_channel(0);                  //initialise ADC channel 0
            delay_ms(50);                        //delay for 50ms Capacitor to charge
            ad_value=read_adc();                 //read and assign Analog values from A0,A1,A2,A3 to variable ad_
            ad_value=ad_value/250;               //convert ad_value to flood and divide by 204(1023/5v)hint: for
            ad_value=ad_value*5;

            set_adc_channel(1);                  //initialise ADC channel 0
            delay_ms(50);                        //delay for 50ms Capacitor to charge
            ad_value1=read_adc();                //read and assign Analog values from A0,A1,A2,A3 to variable ad_
            ad_value1=ad_value1/250;             //convert ad_value to flood and divide by 204(1023/5v)hint: for
            ad_value1=ad_value1*5;
            set_adc_channel(2);                  //initialise ADC channel 0
            delay_ms(50);                        //delay for 50ms Capacitor to charge
            ad_value2=read_adc();                //read and assign Analog values from A0,A1,A2,A3 to variable ad_
            ad_value2=ad_value2/250;             //convert ad_value to flood and divide by 204(1023/5v)hint: for
            ad_value2=ad_value2*5;

            set_adc_channel(3);                  //initialise ADC channel 0
            delay_ms(50);                        //delay for 50ms Capacitor to charge
            ad_value3=read_adc();                //read and assign Analog values from A0,A1,A2,A3 to variable ad_
            ad_value3=ad_value3/250;             //convert ad_value to flood and divide by 204(1023/5v)hint: for
            ad_value3=ad_value3*5;


  if (ad_value >= 0.901 & ad_value <=2.00){                  //Test if voltage is less than 800v
         Output_high(PIN_B0);
     }


  else if (ad_value1 >= 0.901 & ad_value1 <= 2.01){
        Output_high(PIN_B0);
     }


  else if (ad_value2 >= 0.901 & ad_value2 <= 2.01){
        Output_high(PIN_B0);
     }


  else if (ad_value3 >= 0.901 & ad_value3 <= 2.01){
         Output_high(PIN_B0);
     }
     else {
     OUTPUT_LOW(PIN_B0);
     }
  }
```

Annexure C - Simulated circuit of the main lighting system maintenance device with a sub-system



Annexure D - Light dependent resistor data sheet

RS Data Sheet

Light dependent resistors

NORP12 RS stock number 651-507
NSL19-M51 RS stock number 596-141

Two cadmium sulphide (cdS) photoconductive cells with spectral responses similar to that of the human eye. The cell resistance falls with increasing light intensity. Applications include smoke detection, automatic lighting control, batch counting and burglar alarm systems.

Guide to source illuminations

Light source	Illumination (Lux)
Moonlight	0.1
60W bulb at 1m	50
1W MES bulb at 0.1m	100
Fluorescent lighting	500
Bright sunlight	30,000

Circuit symbol

Light memory characteristics

Light dependent resistors have a particular property in that they remember the lighting conditions in which they have been stored. This memory effect can be minimised by storing the LDRs in light prior to use. Light storage reduces equilibrium time to reach steady resistance values.

NORP12 (RS stock no. 651-507)

Absolute maximum ratings

Voltage, ac or dc peak	320V
Current	75mA
Power dissipation at 30°C	250mW
Operating temperature range	-60°C to +75°C

Electrical characteristics

T_A = 25°C. 2854°K tungsten light source

Parameter	Conditions	Min.	Typ.	Max.	Units
Cell resistance	1000 lux	-	400	-	Ω
	10 lux	-	9	-	kΩ
Dark resistance	-	1.0	-	-	MΩ
Dark capacitance	-	-	3.5	-	pF
Rise time 1	1000 lux	-	2.8	-	ms
	10 lux	-	18	-	ms
Fall time 2	1000 lux	-	48	-	ms
	10 lux	-	120	-	ms

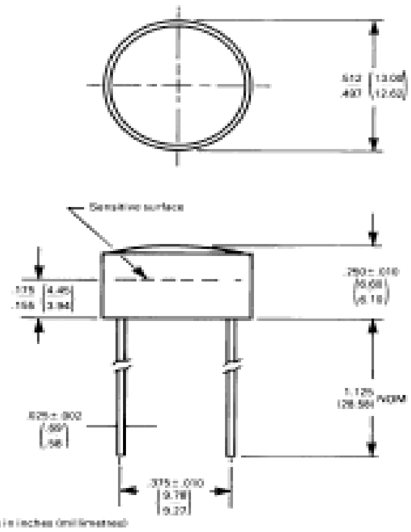
1. Dark to 110% R_L
2. To 10 × R_L

R_L = photocell resistance under given illumination.

Features

- Wide spectral response
- Low cost
- Wide ambient temperature range.

Dimensions



232-3816

Figure 1 Power dissipation derating

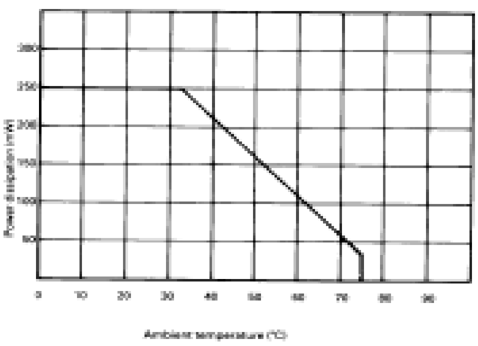
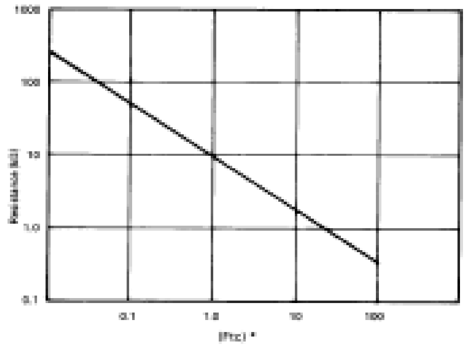
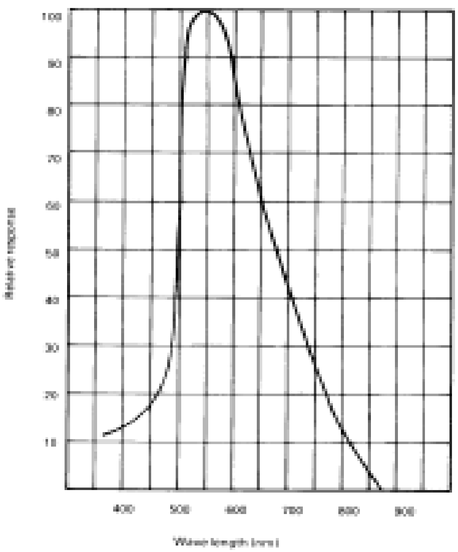


Figure 3 Resistance as a function of illumination



*1Ftc=10.764 lumens

Figure 2 Spectral response



Absolute maximum ratings

Voltage, ac or dc peak ______________ 100V
Current ______________ 5mA
Power dissipation at 25°C ______________ 50mW*
Operating temperature range ______________ -25°C +75°C

*Derate linearly from 50mW at 25°C to 0W at 75°C.

Electrical characteristics

Parameter	Conditions	Min.	Typ.	Max.	Units
Cell resistance	10 lux 100 lux	20 -	- 5	100 -	kΩ kΩ
Dark resistance	10 lux after 10 sec	20	-	-	MΩ
Spectral response	-	-	550	-	nm
Rise time	10ftc	-	45	-	ms
Fall time	10ftc	-	55	-	ms

Dimensions

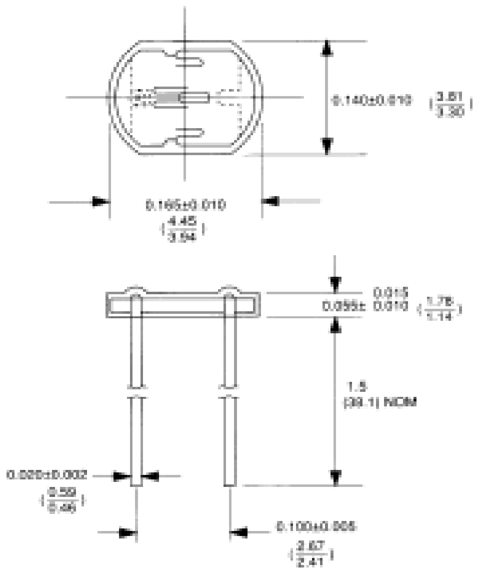


Figure 4 Resistance as a function illumination

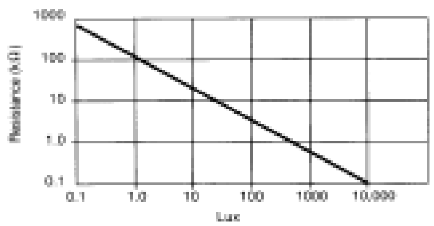
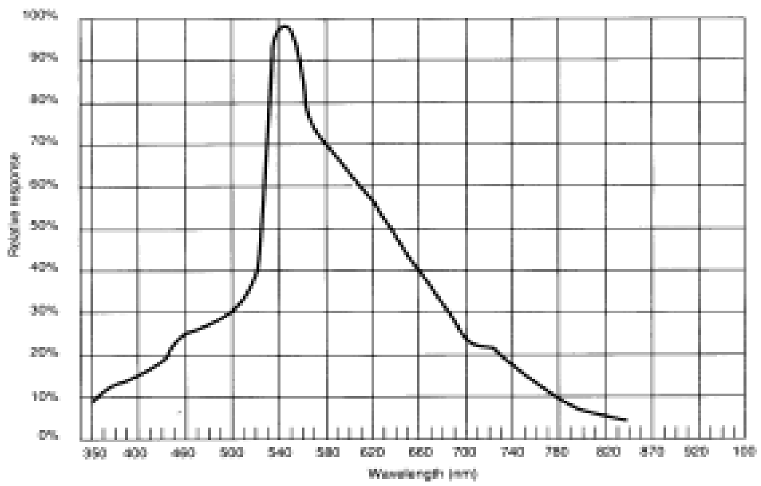


Figure 5 Spectral response



Annexure E - PIC 18F4220 / 4320 data sheet

MICROCHIP **PIC18F2220/2320/4220/4320**

28/40/44-Pin High-Performance, Enhanced Flash MCUs with 10-bit A/D and nanoWatt Technology

Low-Power Features:

- Power Managed modes:
  - Run: CPU on, peripherals on
  - Idle: CPU off, peripherals on
  - Sleep: CPU off, peripherals off
- Power Consumption modes:
  - PRI_RUN: 150 µA, 1 MHz, 2V
  - PRI_IDLE: 37 µA, 1 MHz, 2V
  - SEC_RUN: 14 µA, 32 kHz, 2V
  - SEC_IDLE: 5.8 µA, 32 kHz, 2V
  - RC_RUN: 110 µA, 1 MHz, 2V
  - RC_IDLE: 52 µA, 1 MHz, 2V
  - Sleep: 0.1 µA, 1 MHz, 2V
- Timer1 Oscillator: 1.1 µA, 32 kHz, 2V
- Watchdog Timer: 2.1 µA
- Two-Speed Oscillator Start-up

Oscillators:

- Four Crystal modes:
  - LP, XT, HS: up to 25 MHz
  - HSPLL: 4-10 MHz (16-40 MHz internal)
- Two External RC modes, up to 4 MHz
- Two External Clock modes, up to 40 MHz
- Internal oscillator block:
  - 8 user selectable frequencies: 31 kHz, 125 kHz, 250 kHz, 500 kHz, 1 MHz, 2 MHz, 4 MHz, 8 MHz
  - 125 kHz-8 MHz calibrated to 1%
  - Two modes select one or two I/O pins
  - OSCTUNE – Allows user to shift frequency
- Secondary oscillator using Timer1 @ 32 kHz
- Fail-Safe Clock Monitor
  - Allows for safe shutdown if peripheral clock stops

Peripheral Highlights:

- High current sink/source 25 mA/25 mA
- Three external interrupts
- Up to 2 Capture/Compare/PWM (CCP) modules:
  - Capture is 16-bit, max. resolution is 6.25 ns ($T_{CY}/16$)
  - Compare is 16-bit, max. resolution is 100 ns (T_{CY})
  - PWM output: PWM resolution is 1 to 10-bit
- Enhanced Capture/Compare/PWM (ECCP) module:
  - One, two or four PWM outputs
  - Selectable polarity
  - Programmable dead-time
  - Auto-Shutdown and Auto-Restart
- Compatible 10-bit, up to 13-channel Analog-to-Digital Converter module (A/D) with programmable acquisition time
- Dual analog comparators
- Addressable USART module:
  - RS-232 operation using internal oscillator block (no external crystal required)

Special Microcontroller Features:

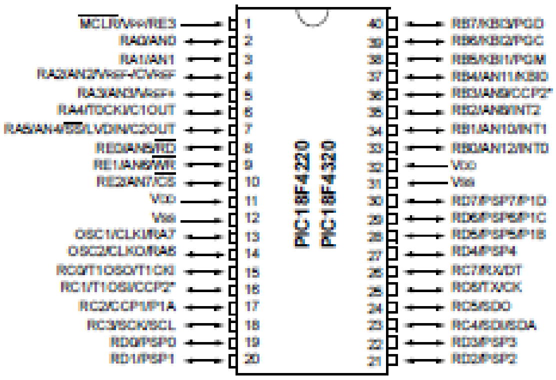
- 100,000 erase/write cycle Enhanced Flash program memory typical
- 1,000,000 erase/write cycle Data EEPROM memory typical
- Flash/Data EEPROM Retention: > 40 years
- Self-programmable under software control
- Priority levels for interrupts
- 8 x 8 Single-Cycle Hardware Multiplier
- Extended Watchdog Timer (WDT):
  - Programmable period from 41 ms to 131s
  - 2% stability over V_{DD} and Temperature
- Single-supply 5V In-Circuit Serial Programming™ (ICSP™) via two pins
- In-Circuit Debug (ICD) via two pins
- Wide operating voltage range: 2.0V to 5.5V

Device	Program Memory		Data Memory		I/O	10-bit A/D (ch)	CCP/ ECCP (PWM)	MSSP		USART	Comparators	Timers 8/16-bit
	Flash (bytes)	# Single Word Instructions	SRAM (bytes)	EEPROM (bytes)				SPI™	Master I²C™			
PIC18F2220	4096	2048	512	256	25	10	2/0	Y	Y	Y	2	2/3
PIC18F2320	8192	4096	512	256	25	10	2/0	Y	Y	Y	2	2/3
PIC18F4220	4096	2048	512	256	36	13	1/1	Y	Y	Y	2	2/3
PIC18F4320	8192	4096	512	256	36	13	1/1	Y	Y	Y	2	2/3

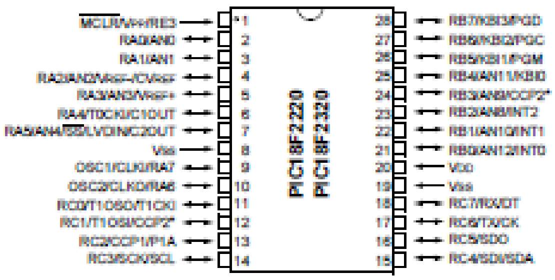
 DS39599C-page 1

Pin Diagrams

PDIP



SPDIP, SOIC

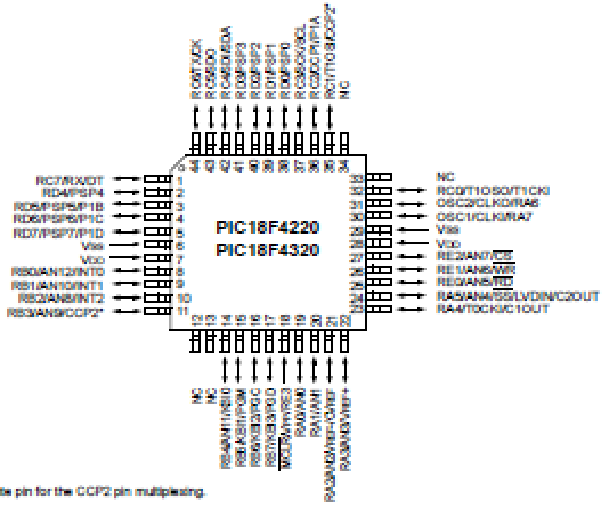


* RB3 is the alternate pin for the CCP2 pin multiplexing.

Note: Pin compatible with 40-pin PIC16C7X devices.

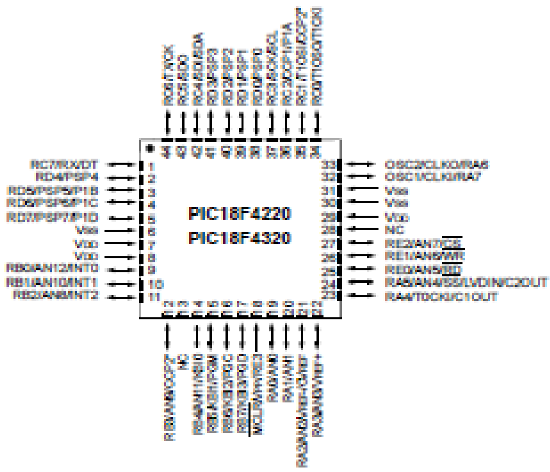
Pin Diagrams (Cont.'d)

TQFP



* RB3 is the alternate pin for the CCP2 pin multiplexing.

QFN



* RB3 is the alternate pin for the CCP2 pin multiplexing.

1.3 Details on Individual Family Members

Devices in the PIC18F2220/2320/4220/4320 family are available in 28-pin (PIC18F2X20) and 40/44-pin (PIC18F4X20) packages. Block diagrams for the two groups are shown in Figure 1-1 and Figure 1-2.

The devices are differentiated from each other in five ways:

1. Flash program memory (4 Kbytes for PIC18FX220 devices, 8 Kbytes for PIC18FX320)
2. A/D channels (10 for PIC18F2X20 devices, 13 for PIC18F4X20 devices)
3. I/O ports (3 bidirectional ports and 1 input only port on PIC18F2X20 devices, 5 bidirectional ports on PIC18F4X20 devices)
4. CCP and Enhanced CCP implementation (PIC18F2X20 devices have 2 standard CCP modules, PIC18F4X20 devices have one standard CCP module and one ECCP module)
5. Parallel Slave Port (present only on PIC18F4X20 devices)

All other features for devices in this family are identical. These are summarized in Table 1-1.

The pinouts for all devices are listed in Table 1-2 and Table 1-3.

TABLE 1-1: DEVICE FEATURES

Features	PIC18F2220	PIC18F2320	PIC18F4220	PIC18F4320
Operating Frequency	DC – 40 MHz	DC – 40 MHz	DC – 40 MHz	DC – 40 MHz
Program Memory (Bytes)	4096	8192	4096	8192
Program Memory (Instructions)	2048	4096	2048	4096
Data Memory (Bytes)	512	512	512	512
Data EEPROM Memory (Bytes)	256	256	256	256
Interrupt Sources	19	19	20	20
I/O Ports	Ports A, B, C (E)	Ports A, B, C (E)	Ports A, B, C, D, E	Ports A, B, C, D, E
Timers	4	4	4	4
Capture/Compare/PWM Modules	2	2	1	1
Enhanced Capture/ Compare/PWM Modules	0	0	1	1
Serial Communications	MSSP, Addressable USART	MSSP, Addressable USART	MSSP, Addressable USART	MSSP, Addressable USART
Parallel Communications (PSP)	No	No	Yes	Yes
10-bit Analog-to-Digital Module	10 Input Channels	10 Input Channels	13 Input Channels	13 Input Channels
Resets (and Delays)	POR, BOR, RESET Instruction, Stack Full, Stack Underflow (PWRT, OST), MCLR (optional), WDT	POR, BOR, RESET Instruction, Stack Full, Stack Underflow (PWRT, OST), MCLR (optional), WDT	POR, BOR, RESET Instruction, Stack Full, Stack Underflow (PWRT, OST), MCLR (optional), WDT	POR, BOR, RESET Instruction, Stack Full, Stack Underflow (PWRT, OST), MCLR (optional), WDT
Programmable Low-Voltage Detect	Yes	Yes	Yes	Yes
Programmable Brown-out Reset	Yes	Yes	Yes	Yes
Instruction Set	75 Instructions	75 Instructions	75 Instructions	75 Instructions
Packages	28-pin SPDIP 28-pin SOIC	28-pin SPDIP 28-pin SOIC	40-pin PDIP 44-pin TQFP 44-pin QFN	40-pin PDIP 44-pin TQFP 44-pin QFN

Annexure F - MAX232CPE data sheet

TEXAS INSTRUMENTS

MAX232E

www.ti.com

SLLS723B – APRIL 2006 – REVISED NOVEMBER 2009

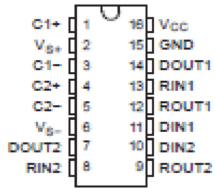
DUAL RS-232 DRIVER/RECEIVER WITH IEC61000-4-2 PROTECTION

Check for Samples: MAX232E

FEATURES

- Meets or Exceeds TIA/RS-232-F and ITU Recommendation V.28
- Operates From a Single 5-V Power Supply With 1.0-µF Charge-Pump Capacitors
- Operates up to 250 kbit/s
- Two Drivers and Two Receivers
- ±30-V Input Levels
- Low Supply Current . . . 8 mA Typical
- ESD Protection for RS-232 Bus Pins
  - ±15-kV Human-Body Model (HBM)
  - ±8-kV IEC61000-4-2, Contact Discharge
  - ±15-kV IEC61000-4-2, Air-Gap Discharge

D, DW, N, NS, OR PW PACKAGE
(TOP VIEW)



APPLICATIONS

- TIA/RS-232-F
- Battery-Powered Systems
- Terminals
- Modems
- Computers

DESCRIPTION/ORDERING INFORMATION

The MAX232E is a dual driver/receiver that includes a capacitive voltage generator to supply TIA/RS-232-F voltage levels from a single 5-V supply. Each receiver converts TIA/RS-232-F inputs to 5-V TTL/CMOS levels. This receiver has a typical threshold of 1.3 V, a typical hysteresis of 0.5 V, and can accept ±30-V inputs. Each driver converts TTL/CMOS input levels into TIA/RS-232-F levels. The driver, receiver, and voltage-generator functions are available as cells in the Texas Instruments LinASIC™ library.

Table 1. ORDERING INFORMATION[1]

T_A	PACKAGE[2]		ORDERABLE PART NUMBER	TOP-SIDE MARKING
0°C to 70°C	PDIP – N	Tube of 25	MAX232ECN	MAX232ECN
	SOIC – D	Tube of 40	MAX232ECD	MAX232EC
		Reel of 2500	MAX232ECDR	
	SOIC – DW	Tube of 40	MAX232ECDW	MAX232EC
		Reel of 2000	MAX232ECDWR	
	TSSOP – PW	Tube of 25	MAX232ECPW	MA232EC
		Reel of 2000	MAX232ECPWR	
–40°C to 85°C	PDIP – N	Tube of 25	MAX232EIN	MAX232EIN
	SOIC – D	Tube of 40	MAX232EID	MAX232EI
		Reel of 2500	MAX232EIDR	
	SOIC – DW	Tube of 40	MAX232EIDW	MAX232EI
		Reel of 2000	MAX232EIDWR	
	TSSOP – PW	Tube of 25	MAX232EIPW	MB232EI
		Reel of 2000	MAX232EIPWR	

(1) For the most current package and ordering information, see the Package Option Addendum at the end of this document, or see the TI website at www.ti.com.
(2) Package drawings, thermal data, and symbolization are available at www.ti.com/packaging.

Table 2. FUNCTION TABLES

Each Driver[1]

INPUT DIN	OUTPUT DOUT
L	H
H	L

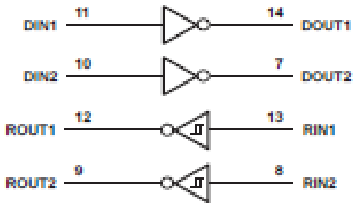
(1) H = high level, L = low level

Table 3. Each Receiver[1]

INPUT RIN	OUTPUT ROUT
L	H
H	L

(1) H = high level, L = low level

LOGIC DIAGRAM (POSITIVE LOGIC)



Absolute Maximum Ratings [1]

over operating free-air temperature range (unless otherwise noted)

			MIN	MAX	UNIT
V_{CC}	Input supply voltage range [2]		–0.3	6	V
V_{S+}	Positive output supply voltage range		V_{CC} – 0.3	15	V
V_{S-}	Negative output supply voltage range		–0.3	–15	V
V_I	Input voltage range	Driver	–0.3	V_{CC} + 0.3	V
		Receiver		±30	
V_O	Output voltage range	DOUT	V_{S-} – 0.3	V_{S+} + 0.3	V
		ROUT	–0.3	V_{CC} + 0.3	
	Short-circuit duration	DOUT		Unlimited	
θ_{JA}	Package thermal impedance [3] [4]	D package		73	°C/W
		DW package		57	
		N package		67	
		PW package		108	
T_J	Operating virtual junction temperature			150	°C
T_{stg}	Storage temperature range		–65	150	°C

(1) Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) All voltages are with respect to network GND.
(3) Maximum power dissipation is a function of T_J(max), θ_{JA}, and T_A. The maximum allowable power dissipation at any allowable ambient temperature is $P_D = (T_J(max) - T_A)/\theta_{JA}$. Operating at the absolute maximum T_J of 150°C can affect reliability.
(4) The package thermal impedance is calculated in accordance with JESD 51-7.

Recommended Operating Conditions

			MIN	NOM	MAX	UNIT
V_{CC}	Supply voltage		4.5	5	5.5	V
V_{IH}	High-level input voltage (DIN1, DIN2)		2			V
V_{IL}	Low-level input voltage (DIN1, DIN2)				0.8	V
	Receiver input voltage (RIN1, RIN2)				±30	V
T_A	Operating free-air temperature	MAX232EC	0		70	°C
		MAX232EI	–40		85	

Electrical Characteristics [1]

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted) (see Figure 4)

PARAMETER		TEST CONDITIONS		MIN	TYP [2]	MAX	UNIT
I_{CC}	Supply current	V_{CC} = 5.5 V,	All outputs open, T_A = 25°C		8	10	mA

(1) Test conditions are C1–C4 = 1 µF at V_{CC} = 5 V ± 0.5 V.
(2) All typical values are at V_{CC} = 5 V and T_A = 25°C.

DRIVER SECTION

Electrical Characteristics[1]

over recommended ranges of supply voltage and operating free-air temperature range

PARAMETER			TEST CONDITIONS		MIN	TYP[2]	MAX	UNIT
V_{OH}	High-level output voltage	DOUT	R_L = 3 kΩ to GND		5	7		V
V_{OL}	Low-level output voltage[3]	DOUT	R_L = 3 kΩ to GND			–7	–5	V
r_o	Output resistance	DOUT	$V_{S+} = V_{S-} = 0$,	V_O = ±2 V	300			Ω
I_{OS} [4]	Short-circuit output current	DOUT	V_{CC} = 5.5 V,	V_O = 0		±10		mA
I_{IS}	Short-circuit input current	DIN	V_I = 0				200	µA

(1) Test conditions are C1–C4 = 1 µF at V_{CC} = 5 V ± 0.5 V.
(2) All typical values are at V_{CC} = 5 V and T_A = 25°C.
(3) The algebraic convention, in which the least-positive (most negative) value is designated minimum, is used in this data sheet for logic voltage levels only.
(4) Not more than one output should be shorted at a time.

Switching Characteristics[1]

V_{CC} = 5 V, T_A = 25°C (see Note 4)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
SR	Driver slew rate	R_L = 3 kΩ to 7 kΩ, See Figure 2			30	V/µs
SR(t)	Driver transition region slew rate	See Figure 3		3		V/µs
	Data rate	One DOUT switching		250		kbit/s

(1) Test conditions are C1–C4 = 1 µF at V_{CC} = 5 V ± 0.5 V.

ESD protection

PARAMETER	TEST CONDITIONS	TYP	UNIT
DOUT, RIN	HBM	±15	kV
	IEC61000-4-2, Air-Gap Discharge	±15	kV
	IEC61000-4-2, Contact Discharge	±8	kV