# Facts and Myths Surrounding Streetlight Photocells

By : Ian Mclaren of ***COSINE DEVELOPMENTS***
Derek Curry of **ETHEKWINI ELECTRICITY DEPARTMENT**

# Contents

# Facts and myths surrounding streetlight photocells

*Streetlight photocell failures continue to plague the lighting industry resulting in energy wastage and high maintenance costs. The job of the photocell is simply to turn the streetlight on at dusk and off at dawn. This paper highlights the actual problems and failure modes encountered in real life situations from data captured by the Ethekwini Electricity Department. The paper also includes corrective actions with suggested solutions.*

## 1. OVERVIEW

Many countries are striving to reduce their energy consumption and South Africans are encouraged to do the same. With this emphasis on saving energy the simple street light photocell has been highlighted as the source of many of the problems associated with street lighting. "The national average annual maintenance budget for a streetlight is typically R200 whether actually maintained or not. For that money, too many are burning during the day; too many aren't burning at night. The most common failure is the photocell, it may be stuck on, stuck off, or it leaked water into the ballast or bulb."

In countries such as France, Germany, Belgium, UK and the northern part of the US, street lamps are burning an average of 4000 hours per year. Considering that the average wattage of a lamp is around 150 watts, considering that a 100,000 inhabitant city contains about 18,000 lamps, such a city spends around 11Giga watt-hour (11 billion watt hours). Considering that producing 1KWH implies the emission of 340 grams of $CO^2$ (average in Europe), the streetlights of such a city is responsible for the emission of 3700 tons of $CO^2$ in the atmosphere per year. The average carbon dioxide emission per person is S.A. is 6.5 tons.

Technologies and techniques now exist to:

a. save electricity without impacting the lighting level as perceived by the citizen.
b. automatically identify 99% of the lamp, ballast and associated component failures, to save on maintenance cost and increase the security in town.
c. leverage the same technologies and the same infrastructure to monitor other environmental data (through temperature, humidity, air pollution, air quality and noise sensors) to build up a real time environmental database and enhance our control for future generations.

Lighting consumes one fourth of all energy consumed worldwide, and case studies have shown that commonly 50 to 90 percent of building lighting is unnecessary for the purposes required. Energy is wasted when light does not fall on its intended target, as when lighting fixtures allow light to go up instead of (as is generally preferred) downward. Waste also occurs when more light is generated than needed. Many governments are looking for ways to reduce energy use after signing the Kyoto Protocol, and individuals, organizations and local authorities are increasingly improving lighting efficiency in order to reduce energy consumption.

Over-illumination stems from several factors:

- Not using timers, photocells, occupancy sensors or other controls to extinguish lighting when not needed.
- Improper design, especially of workplace spaces, by specifying higher levels of light than needed for a given task.
- Incorrect choice of fixtures or light bulbs, which do not direct light into areas as needed.
- Improper selection of hardware to utilize more energy than needed to accomplish the lighting task.
- Incomplete training of building managers and occupants to use lighting systems efficiently.
- Inadequate lighting maintenance resulting in increased stray light and energy costs.

Most of these issues can be readily corrected with available, inexpensive technology; however, there is considerable inertia in the field of lighting design and with landlord/tenant practices that create barriers to rapid correction of these matters. Most importantly public awareness would need to improve for industrialized countries to realize the large payoff in reducing over-illumination.

Lighting technology is advancing with better efficiency, lower maintenance, and more environmental friendliness. Our understanding of nighttime lighting is better than ever in the past 50 years, and so we will save energy, and will improve nighttime visibility at the same time.

Our task in this paper is to identify the factors which establish the requirements and the reasonable margin of error, to highlight the problems of streetlight switching found particularly in the Ethekwini area and to analyse the extent to which the errors can be rectified.

## 2. HISTORY OF STREET LIGHTING

Before incandescent lamps, gas lighting was employed. The earliest lamps required that a lamplighter tour the town at dusk, lighting each of the lamps, but later designs employed ignition devices that would automatically strike the flame when the gas supply was activated.

The first electric street lighting employed arc lamps, initially the 'Electric candle', 'Jablochoff candle' or 'Yablochkov candle' developed by the Russian Pavel Yablochkov in 1875. This was a carbon arc lamp employing alternating current, which ensured that the electrodes burnt down at the same rate. Yablochkov candles were first used to light the Grand Magasins de Louvre, Paris where 80 were deployed. Soon after, experimental arrays of arc lamps were used to light Holborn Viaduct and the Thames Embankment in London - the first electric street lighting in Britain. More than 4,000 were in use by 1881, though by then an improved differential arc lamp had been developed by Friederich von Hefner-Alteneck of Siemens & Halske. The United States was swift in adopting arc lighting, and by 1890 over 130,000 were in operation in the US, commonly installed in exceptionally tall moonlight towers.

Ultimately, however, arc lights suffered from two major disadvantages. Firstly they emitted an extremely intense and harsh light which, although useful at industrial sites like dockyards, was discomforting in the context of ordinary city streets. Second, they required a high level of maintenance, as the carbon electrodes burned away quite swiftly. With the development of cheap, reliable - and bright - incandescent light bulbs in the closing years of the 19th century, they swiftly passed out of use for street lighting, though they were retained in industrial use for rather longer.

Incandescent lamps, continued to be used for street lighting until the advent of high-intensity discharge lamps, were often operated as high-voltage series circuits.

Today, street lighting commonly uses high-intensity discharge lamps, often HPS high-pressure sodium lamps. Such lamps provide the greatest amount of Photopic illumination for the least consumption of electricity. However when Scotopic/Photopic light calculations are used, it can be seen how inappropriate HPS lamps are for night lighting. White light sources have been shown to double driver peripheral vision and increase driver brake reaction time at least 25%. When S/P light calculations are used HPS lamp performance needs to be reduced by a minimum value of 75%. This is now a standard design criterion for many countries.

However, street lighting has other problems. i.e.

- Light Pollution
- Energy Waste
- Lifespan

Before these topics are discussed it is best that street lighting and it associated components be analysed.

## 2.1 History of Streetlight Switching

A brief history of seasonal switches used in South Africa:-

### 2.1.1 Clocks

Photocells where not the first choice of light switching used as the accepted norm, this honour went to the clock. In the beginning the clocks were straightforward on and off analogue devices. The technology of clocks progressed to a point where the times could be changed. The more sophisticated ones incorporated what was then termed “solar correction” where a crude form of time alteration for the different seasons was possible.

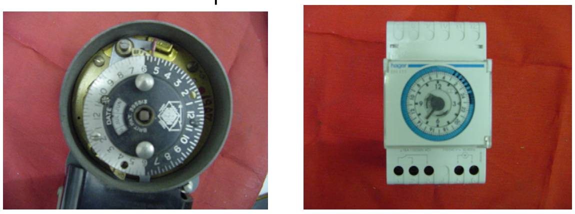


***Photo 2-1** – Various Clock showing night and day plus the months and day screw.*

These simple clocks were improved even further with the advent of digital electronics. Times could be programmed digitally and included the automatic change with the seasons by using longitude and latitude lines as reference points. These devices were known to be very accurate.
Although the more sophisticated digital clocks were accurate they still exhibited many problems to the user and were considered expensive. A more reliable and cheaper controller emerged on the market.

The photocell was born. Photocells have benefits over time switches since they turn the lights on when the light falls, ensuring that light is provided when there is poor visibility prior to dusk, yet providing optimum control on clear evenings, taking full opportunity of good daylight.

### 2.1.2 Photo Electric Control Units - PECU’s

From these early beginnings Town councils moved on to the use of photocell switching for street lighting. The photocell devices are commonly known as Photo Electric Control Units (PECU’s)

***Photo 2-2** - Typical PECU*

***Photo 2-3** - PECU housed on a streetlight*

# 3. CHARACTERISTICS OF PHOTO ELECTRIC CONTROL UNITS (PECU’s)

## 3.1 The Requirement

PECUs are light operated switches. They switch the supply ON to a load when the light level falls beneath a given value (usually at Dusk), and switch the supply OFF when it rises above another level (usually at Dawn). The function of a lighting controller is to switch power to a resistive or reactive load. The function of a photoelectric controller (PECU) is to automatically activate this switching action in accordance with selected levels of ambient illuminance. The requirements for a photoelectric controller for use with street lighting are defined by:

I. the ***illuminance profile*** with time which the lighting engineer wishes to obtain.
II. the ***electrical requirements*** in terms of load, supply, etc.
III. the ***lifetime requirement*** that is the requirement to maintain correct operation under the harsh environmental conditions that are likely to occur for a specified time.

A switch which fails to operate within some reasonable margin of error over its lifetime, has failed to meet its requirements.

### 3.1.1 The illuminance profile requirement at dusk and dawn

At dusk, the human eye adapts slowly to the decrease of daylight. It is required that a smooth transition be made between the declining natural light levels and the artificial levels that are to replace these. Indeed, the gradual increase in luminous flux of the artificial light sources during the run-up period can extend the adaptation time. Thus, it is required that a match be made between the declining light levels, typical examples of which are shown in Fig. 3-1, and the lamp run-up light curves, typical examples of which are shown in Fig. 3-2. At dawn, the PECU should only switch off the artificial light when daylight is at a level that again provides for easy adaptation of the eye from artificial to natural light.

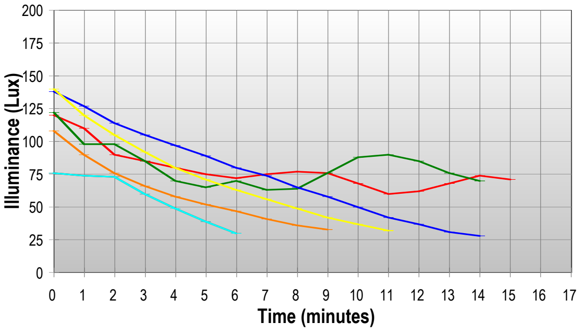


***Fig. 3-1*** *- Typical light curves at sunset showing the variability of lux levels with which the PECU has to cope with.*

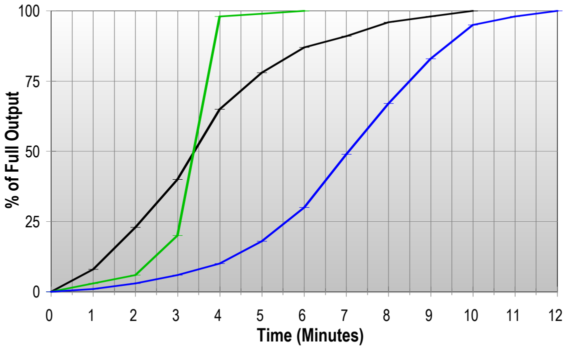


***Fig. 3-2*** *- Run-up curves of [Black line] High pressure lamps, [Blue Line] Low pressure sodium lamps and [Green Line] Mercury lamps as published by one manufacturer.*

**To determine a switch-ON level, three factors must be considered:**

I. the typical sunset light curve at a given latitude (the fastest onset of darkness occurs during sunset at the spring and autumn equinoxes and the slowest at the summer and winter solstice),
II. the longest run-up time for the discharge lighting to be switched, and
III. the level of artificial light to be provided.

It is generally proposed that a switch ON/OFF level of 55 lux would generally meet these requirements, although, in practice, both in the interest of safety and because of the excessive negative tolerance on the calibration levels of many existing PECU's, a switching level of 70 lux is now preferred.

These considerations lead to the primary photometric requirement of the switch; viz., that it should switch-on and switch-off at specified lux levels. The ratio between the two light levels (dusk &dawn) is known as the switching ratio.

#### 3.1.1.1 Switching ratio

i. **Positive Ratio**
   When the ON level is lower than the OFF level (e.g. if the load switched ON at 70Lux and switched OFF again at 105Lux, then the unit has a ratio of 1:1.5). As can be seen from Table 3-1, positive ratio units have significantly longer annual burning hours than negative ratio units.
ii. **Unity Ratio**
   When the ON and OFF levels are the same (1:1 ratio).
iii. **Negative Ratio**
   Most street lighting loads have a warm-up time during which the lamp achieves full brightness. This is typically a number of minutes, and the idea of negative ratio units is that the ON level needs to predict when the lamp will achieve sufficient output, whereas the OFF level is when the light is no longer needed. Typically a 1:0,5 ratio is ideal for this (e.g. turning on at 70Lux and OFF at 35Lux).

### 3.1.2 The electrical requirements

The PECU is expected to operate on 50/60 hertz AC mains supply maintaining correct performance over supply voltages, normally from 195 to 265 volts. The switch should be capable of handling loads of up to 15 amps reactive load including all associated transients. The PECU's generally fail in the ON mode to facilitate daytime maintenance. Power consumption within the switch unit should be sufficient to avoid stress to the components during extreme low temperatures, yet not so high as to represent a significant load in terms of cost or heating effects within the unit. A maximum consumption of one (1) watt is reasonable. The unit is expected to incorporate a delay between threshold activation and switching so as to avoid erroneous switching due to transient dark or bright events. A 30-second delay is usually suitable for this purpose.

#### 3.1.2.1 Load Switches

PECU's typically use one of three devices to switch the load:

- Thermal Relay
- Electromagnetic Relay
- Semiconductor

i. **Thermal Relay**

These relays are suited to use with CdS sensors. They have a number of drawbacks, principally power consumption and size. Products using other load switches are increasingly replacing them. They operate by the action of a heating element on a bi-metal strip, as the strip deflects it causes contacts to make, or break.

ii. **Electromagnetic Relays**

These relays are widely used in many applications. They are both small and capable of operation at low power. They are relatively poor at transferring high inrush loads (common to many street lighting applications); this can be mitigated by techniques such as predictive load transfer.

iii. **Semiconductor**

There are a number of semiconductor devices capable of switching street lighting loads. Triacs are the most common, however Thyristors and MOSFETs have also been used. These devices are reliable, simple to control, and have a good ability to transfer high inrush loads. It is relatively easy to implement zero-cross switching with semiconductor switches.

| | Consumption | Load Switching Capacity | Load Holding Capacity | Size |
|---|---|---|---|---|
| **Thermal Relay** | Poor | Moderate | Excellent | Large |
| **Electromagnetic Relay** | Moderate | Moderate | Excellent | Moderate |
| **Semiconductor** | Excellent | High | High | Small |

***Table 3-1*** *- Load Switching Devices*

#### 3.1.2.2 Energy Consumption

PECU's affect energy consumption in two ways:

i. **PECU Consumption**

The PECU consumes energy. The amount varies according to the technology used. Generally consumption is less than 5W (approx 44kWh/year consumption) and many are less than 0.25W (which equates to 2.2kWh/year)

ii. **Burning Hours**

Burning hours have the most dramatic effect on consumption. A further 100hrs/year on a typical 100W load results in an additional 10kWh/year consumption. Switching level, switching accuracy, and switching ratio most affect burning hours.

A major consideration is how accurately and consistently the load is controlled over a long period of time. PECU's have benefits over time switches since they turn the lights on when the light falls, ensuring that light is provided when there is poor visibility prior to dusk, yet providing optimum control on clear evenings, taking full opportunity of good daylight. The total number of hours that a PECU operates the light for each year is called the annual burning hours. Table 3-2 below shows a typical example of the burning hours for PECU's with various switching ratios and switching levels. The actual number of hours will vary according to the weather profile of the year, and exact location of the installation.

| Switching Level | Switching Ratio | Annual Burning Hours |
|---|---|---|
| 70 Lux | 1:3 | 4365 |
| | 1:2 | 4290 |
| 55 Lux | 1:0.5 | 4145 |
| | 1:0.4 | 4115 |

***Table 3-2*** *- Comparison of typical burning hours*

### 3.1.3 The lifetime requirement

PECU's are applied in a wide range of environments ranging from office parking lots to all forms of street lighting. It is important that the PECU be capable of functioning in the application environment. Such factors are humidity, salt spray, rain, extreme heat, extreme cold, shock, vibration, corrosive atmospheres, large stray magnetic fields, rapid thermal transition, and chemical exposure can influence a PECU's performance.

The user will expect that a PECU will remain reliable for its stated useful life; where reliability is the ability of the product to perform a required function (without failure) under these stated conditions for a stated period of time.

Failure for a PECU does not just include the complete lack of ability to perform the required function, i.e., to switch the load, but includes those partial failures which result in the unit deviating in its switching parameters beyond specified limits. Despite the effects of harsh environment and component aging, the PECU must continue to switch within the tolerances permitted on the calibrated values.

## 3.2 Meeting the Photometric Requirement

### 3.2.1 Sensors used in PECU's

The most critical part of any PECU is the light sensor. The spectral sensitivity and long-term stability play an important role in providing reliable daylight detection.

Daylight contains much more than just visible light, however our eyes are only sensitive to a specific band of wavelengths. See Fig 3-3 below.

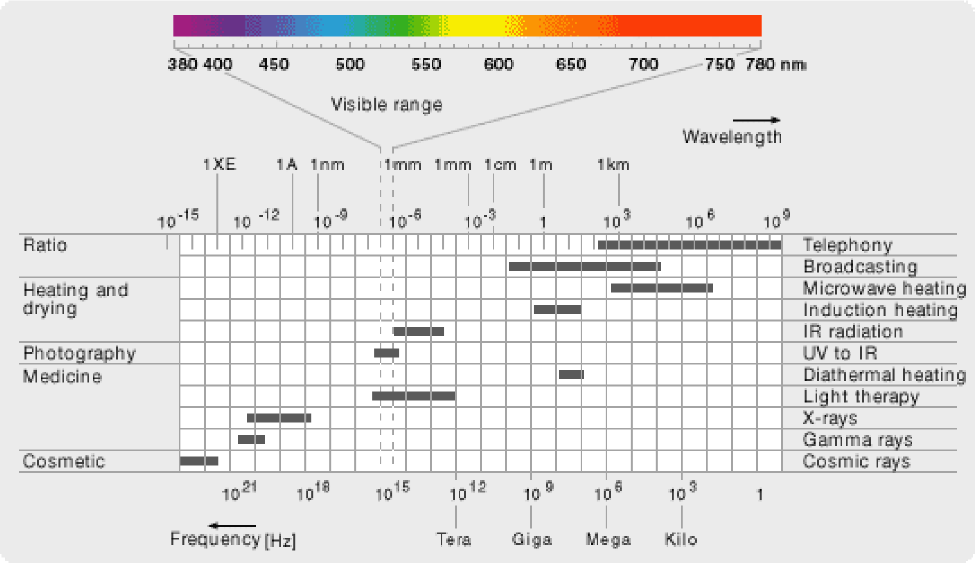


***Fig 3-3** - Complete spectrum of electromagnetic radiation and the spectrum of visible light 780 nm. This band is called **visible light**.*

Photometric values always take into consideration the spectral luminous efficiency curve (V(λ) curve) of the human eye. Consequently, photometric values are linked specifically to human sensitivity. Visible light measurement revolves around a Photopic standard developed in 1924 by the CIE. And are based upon Human retinal response to visible light centered about 560 nanometers and energy >3 cd/m$^2$.
Photometric values are derived from the lumen.
The luminous efficiency curve results from the following relationships: Radiation that is visible to the human eye lies between wavelengths of 380 nm for blue light and 780 nm for red light. Refer to Fig 3-4 below. The eye is most sensitive in the green area of the spectrum around 555 nm. At longer and shorter wavelengths the eye is less sensitive, which means that a higher radiated power is needed for these wavelengths to achieve an impression of identical brightness. The ratio between the radiated power at 555 nm (1 nm = 10-9 m) and the radiated powers for the various wavelengths in the visible spectrum is called the spectral luminous efficiency V (λ). A graph of these values is called the V (λ)-curve.

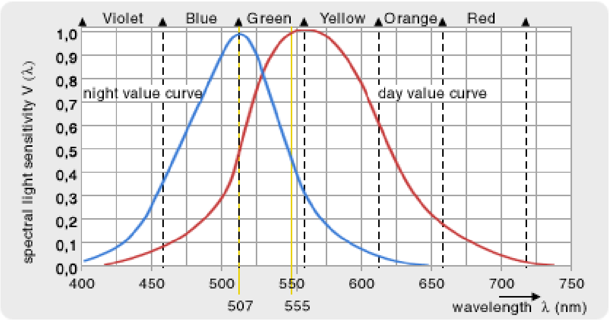


***Fig 3-4** - In order to see, humans make use of electromagnetic radiation in only a small wavelength band between 380nm and 780nm*

The intensity of visible light, corrected for the eyes' varying sensitivity to colour is measured in Lux. Wavelengths of daylight that the eye is not sensitive to do not contribute to a measurement of Lux.
The day-night cycle results from the earth's rotation. A consequence of this is a relatively quick decline of light at dusk. (Typically 7lux /minute). The proportion of visible light to other wavelengths varies not only on a diurnal cycle, but also seasonally and as a result of weather conditions. This means that only direct measurement of visible light level can accurately reflect the level of light that our eyes see as a result of daylight. This poses a problem when sensors used in PECU's have marked sensitivity to wavelengths of daylight outside of that visible to our eyes. Some examples of lux level :-

| Examples | Lux |
|---|---|
| Summer sunshine | 50,000 |
| Overcast sky | 5,000 |
| Well lit shop or office | 500 |
| Minimum light for easy reading | 300 |
| Stairs/passages in daylight | 60 |
| Night - well lit main road | 15 |
| Night - Normal main road lighting @ Sunset | 10 |
| Normal side road lighting | 5 |
| Minimum security risk lighting | 2 |
| Twilight | 1 |
| Clear full moon | 0.3 |
| Moonlight with cloudy sky | 0.1 |
| Average starlight | 0.001 |
| Poor starlight | 0.0001 |

These light sensors, although very accurate, may not be accurate at measuring Lux. A particular issue is Infra-Red (IR). Daylight contains significant infra-red however IR is strongly affected by atmospheric conditions and can be strongly attenuated in conditions where visible light is much less affected. Accordingly, IR levels can be much lower than those anticipated by the level of visible light. Many semiconductor sensors have marked sensitivity to IR as well as visible light; hence a PECU with significant IR sensitivity could switch on before reaching the target visible light level (in Lux). Sensors with IR sensitivity tend to underestimate equivalent visible light levels in daylight rather than over-estimating them, hence they always tend to operate in a 'safe' manner.

| | | Drift | Dusk/Dawn Switching Repeatability | Spectral Sensitivity vs Photopic Response | Other |
|---|---|---|---|---|---|
| **Cadmium Sulphide (CdS)** | | Moderate | Moderate | Good | Contains Cadmium |
| **Photodiode/ Phototransistor** | **Unfiltered** | Imperceptible * | Moderate | Moderate | |
| | **IR Filtered** | Imperceptible * | Poor | Very Poor | Insensitive to Visible Light |
| | **Glass Filtered** | Imperceptible * | Excellent | Excellent | |
| | **DyeMatch Filtered** | Imperceptible * | Excellent | Excellent | |

*** -** Impossible or difficult to perceive by the mind or senses, so subtle, slight, or gradual as to be barely perceptible

***Table 3-3*** *- Comparison of sensors commonly used in PECU's*

#### 3.2.1.1 Cadmium Sulphide (CdS)

CdS sensors operate as light dependant resistors. They have conductivity approximately proportional to the level of light. They were the predominant sensor in the early 1990s and are still frequently used. CdS sensors are becoming less popular due to environmental considerations and they are also subject to some long-term drift.

#### 3.2.1.2 Photodiode Sensors

Photodiodes are light sensitive semiconductor devices that are manufactured in essentially the same way as semiconductor diodes used in conventional electronic circuits. The primary differences are that photodiode chips are larger and they are packaged to allow light onto the sensitive area of the diode.

Photodiodes offer many conveniences and advantages that make them very practical for a wide range of applications:

- They can easily measure from picowatts to milliwatts of optical power
- They come in standard packages or the package can be tooled to fit your application exactly
- Depending on the semiconductor material used, they can detect wavelengths form 190 to > 2,000 nm
- They are small and light weight
- They have very reproducible sensitivity
- They are inexpensive, with million piece pricing for small area detectors less than R3.00
- They can be very responsive, with rise times as fast as 10 picoseconds

If noise presents a problem when measuring a few picowatts of light with a standard photodiode, consider the advantages of an avalanche photodiode which offers a current gain internal to the photodiode structure of up to about 100.

Photodiodes generally require a pre-amplifier to give signal gain for applications to detect picowatts of light power. But for high optical power (<10 microwatt) levels, a simple load resistor configuration can give adequate performance and TTL compatible voltage swings.

Silicon based photodiodes cover the wide range of wavelengths from 190 to 1100 nm (the lower limit is set by absorption of ultraviolet light in air). Germanium (Ge) photodiodes overlap the silicon response spectrum and are usable to about 1600 nm. Semiconductors that are compounds of gallium, arsenide, indium, antimonide and phosphorous can be specially fabricated to cover small sections of the 190 to 2000 nm spectral range. For instance, the fiber optics industry uses indium-gallium-arsenide (InGaAs) detectors for the 800 to 1800 nm range. More exotic and expensive photodiodes can sense energy much further out in the IR spectrum.

Photodiodes are widely used in our high-tech society, in applications ranging from sensors for door openings, assembly line controls, load levelers in luxury cars, to personal blood sugar meters for diabetics, sun-tan exposure meters, smoke detectors, x-ray baggage inspection systems and even cranial pressure sensors for head injury patients.

#### 3.2.1.3 Phototransistors

Phototransistors are transistors designed to capture light and are assembled in a transparent package. Phototransistors are examples of photodiode-amplifier combinations integrated within a single silicon chip. These combinations are put together in order to overcome the major fault of photodiodes: unity gain. Many applications demand a greater output signal from the photo detector than can be generated by a photodiode alone. While the signal from a photodiode can always be amplified through use of an external op-amp or other circuitry, this approach is often not as practical or as cost effective as the use of phototransistors. The phototransistor can be viewed as a photodiode whose output photocurrent is fed into the base of a conventional small signal transistor. While not required for operation of the device as a photo detector, a base connection is often provided allowing the designer the option of using base current to bias the transistor. The typical gain of a phototransistor can range from 100 to over 1500.

The built in gain allows the phototransistor to be coupled with a load resistor to accommodate TTL level voltages for a wide range of light levels. Because of their ease of use, low cost and TTL compatible signal levels, phototransistors have become popular for applications where there is more than a few hundred nanowatts of available optical power. These devices however, do have some drawbacks compared to photodiodes. The frequency bandwidth and linearity are relatively limited and spectral response is restricted to between 350 and 1100 nm. In addition, there are very large variations in sensitivity between individual devices and few standard package options. They are usable with almost any visible or near-infrared light source such as IREDs; neons; fluorescent, incandescent bulbs; lasers; flame sources; sunlight; etc

| Description | Wavelength range |
|---|---|
| Ultraviolet radiation - C (UV-C) | 100 - 280 nm |
| Ultraviolet radiation - B (UV-B) | 280 - 315 nm |
| Ultraviolet radiation - A (UV-A) | 315 - 380 nm |
| Visible light | 380 - 780 nm |
| Infra-red A (IR-A) | 780 nm - 1.4 µm |
| Infra-red B (IR-B) | 1.4 - 3 µm |
| Infra-red C (IR-C) | 3 µm - 1 mm |

***Table 3-4** - **Wavelength** Range of various bands of light*

### 3.2.2 Measuring the illuminance level

The illuminance is assumed to be measured in a standard and repeatable manner. The ideal luxmeter for this purpose is described by its responsivity (output per unit at 555nm, the peak of the CIE photopic V(l) curve) and its angular and spectral characteristics. Its angular response should be such that it senses luminance as a function of angle with respect to its optic axis with a cosine response variation. Its spectral response should be that of the V(l) curve. A Luxmeter need not be an ideal luxmeter in order to comply. A Luxmeter is expected to operate within its limits of error ( ± 10% or ± 15% for Type P1 or Type P2 photometer respectively) only when operated under a light source having a colour temperature of 2854 ± 20K and for normal illuminance. Additional variance of ± 5% or ± 10% is allowed for illuminance up to 65 degrees off the normal and a variation of ±5% in readings is allowed for sources of colour temperatures 3000K and 2500K.

Fig.3-5 shows the spectral curves of sources with colour temperatures of 2500, 2854 and 3000K compared with the V(l) curve.

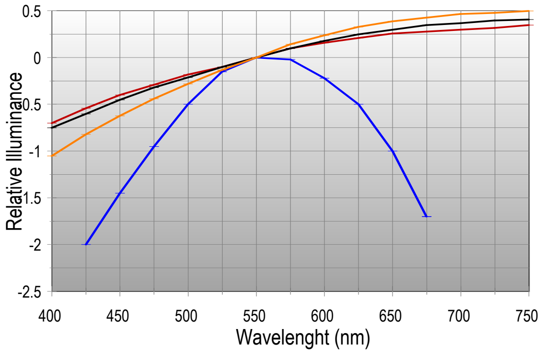


***Fig. 3-5** - Relative illuminance for colour temperatures 3000, 2854, 2500K(a, b, c). CIE Photopic V******

### 3.2.3 Characteristics of the reference light meter

The present state of the photometric art permits a fairly precise ( ±5% or better) match of sensor to the V(l) curve at many visible wavelengths. Nevertheless, when the spectral response of the sensor is precisely matched to the V(l) curve at a few wavelengths, other wavelengths can differ by several hundred per cent. In practice, therefore, a luxmeter will have (i) near cosine angular response, (ii) a spectral response which may approximate to the V(l) curve, and (iii) which may require a list of corrective factors to be applied when the meter is used for monitoring sources with colour temperatures other than 2854K.

### 3.2.4 Photometric characteristics of the PECU

The PECU can also be considered and described in the same way as a luxmeter, although it only has a binary output state. Its photometric performance can be described by the same three parameters; its:-

- responsivity,
- its angular and
- its spectral characteristics.

### 3.2.5 The sky as a source at dawn and dusk

The sky at dusk or dawn does not behave in any easily described manner. Its colour and its angular luminance distributions are highly variable. Some examples of these results are shown in Fig. 3-6. The spectral radiances are plotted on a logarithmic scale and thus the slopes across the visible region can be compared with the corresponding slopes for which luxmeters are calibrated. In addition, the angular distribution of the sky luminance is far from uniform. For the clear sky situation depicted in Fig. 5, it can be seen that the sky colour can vary from predominantly red near the horizon, to white or even blue at the zenith. One is aware of these and even more exotic colours and angular distribution changes which nature displays under the sorts of ever changing mixed cloud conditions that can occur.

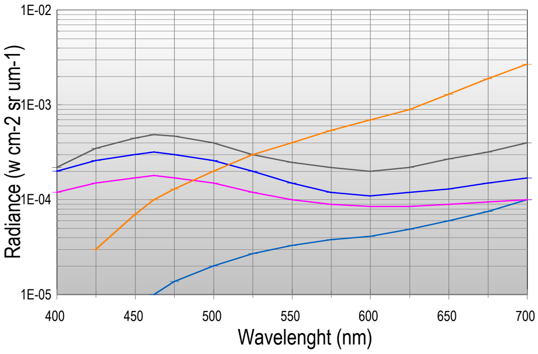


***Figure 3-6** - The spatial and spectral variability of sky radiance close to sunset. Sun elevation 0.5 degrees*

| Curve | Relative Azimuth | Zenith Angle |
|---|---|---|
| Light Blue | 180, | 85 |
| Purple | 0, | 0 |
| Blue | 180, | 45 |
| Black | 0, | 45 |
| Orange | 0, | 85 |

### 3.2.6 Comparison of PECU and luxmeter

A luxmeter and a PECU will agree with each other under all daylight conditions only if the spectral and angular response functions of both are identical. This would be the case if both used the same detector/filter and cosine corrector, and/or if both were equivalent to the "perfect" eye response and cosine corrected meter.

Examining the detector/filter properties of existing PECU's it is found that these can be classified into three basic types:

a) those which rely on the spectral response of a photoconductive cell,
b) those which rely on the spectral response of a photovoltaic detector,
c) those in which the response is improved (i.e., brought nearer to the V(l) curve) by the use of filters.

Type (a) detectors, usually CdS cells, are used in the traditional thermal PECU's. The newer electronic PECU's may use photovoltaic detectors, some with filters; these are employed as much for their improved stability as for their spectral response characteristics. Some typical spectral response curves are given in Fig. 3-7 and Fig 3-8 shows the spectrum of solar radiation.

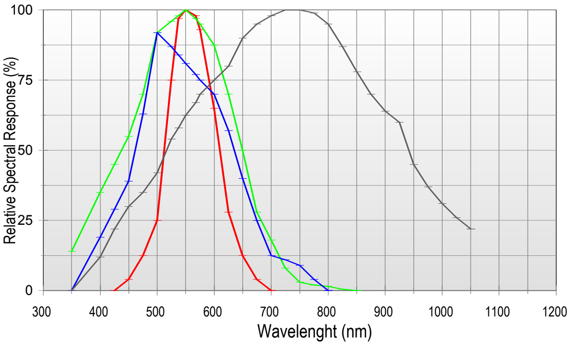


***Figure 3-7*** *- Some typical spectral response curves of detectors. [Blue] – CdS, [Green] - Silicon photodiode with filter, [Red] - V Photoptic curve, [Black] - silicon photodiode*

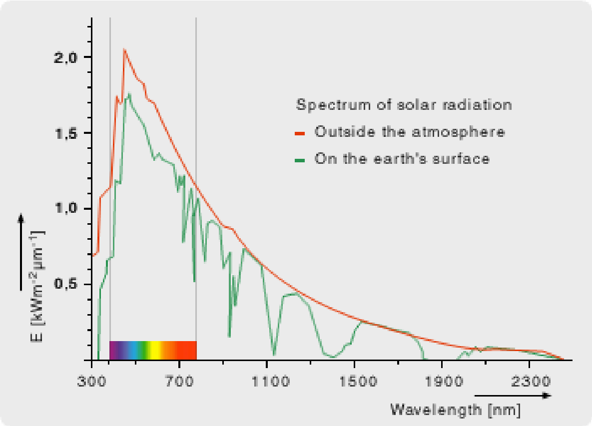


***Figure 3-8*** *-* ***Spectrum*** *of solar radiation***.**

The angular response characteristics of PECU's must also be taken into consideration. Obviously, the angular response of a detector facing the north sky, as specified in the American National Standard, will differ enormously from that of the zenith-facing units. It has been determined that the angular response of the type (b) detector (filtered, photovoltaic) differed greatly from the cosine response; it showed considerably less sensitivity to illuminance at large zenith angles. This restricted field of view prevented this type of detector from viewing the horizon region where red light is likely to predominate; this lack of ability to observe horizon light compensated for the fact that this detector had inferior matching to the V(l) curve in the red. In practice it was found that this type of PECU gave better agreement with a good quality luxmeter because its restricted field of view compensated for the deficiencies in its spectral response.

### 3.2.7 The Relation between switching level and burning hours

A European Country carried out tests on a number of fully electronic units set to various ON/OFF switching levels to ascertain the burning hours in a 12-month period from 10 October 1988 to 9 October 1989, and to establish experimentally the relationship between switching levels and burning hours From the measurements of daylight at dusk and dawn, the average time interval in changing from one lux value to another (generally in increments of 10 lux) was established. The results of the Corporation's analysis are shown in Table 3-5. These results are presented in the form of predictions of the additional or reduced burning hours to be expected when the threshold ON level is adjusted by reference to 70 lux and when the threshold OFF level is adjusted by reference to 100 lux. The burning hours for the reference ON/OFF of 70/100 lux is 4,124 hours.

| Switch ON lux. | Time Difference in Mins per day from Switch ON of 70 lx | Time difference in Hours per yr. from Switch ON of 70 lx. | Switch OFF lux. | Time Difference in Mins per day from Switch OFF of 100 lx | Time Difference in Hours per yr. from Switch OFF of 100 lx |
|---|---|---|---|---|---|
| 40 | -4.6 | -28 | 35 | -7.7 | -46.8 |
| 50 | -2.8 | -1.7 | 40 | -6.8 | -41.4 |
| 55 | -2.1 | -12.7 | 50 | -5.3 | -32.2 |
| 60 | -1.4 | -8.5 | 60 | -3.8 | -23.1 |
| 70 | zero ref | zero ref | 70 | -2.8 | -17.0 |
| 80 | +1 | +6.1 | 80 | -1.9 | -11.6 |
| 90 | +1.9 | +11.6 | 90 | -0.9 | 5.5 |
| 100 | +2.8 | +17 | 100 | zero ref | zero ref |
| 110 | +3.5 | 21.3 | 110 | +0.8 | +4.9 |
| 120 | +4.1 | +24.9 | 120 | +1.6 | +9.7 |
| 130 | +4.6 | +28.0 | 130 | +2.3 | +14.0 |
| 140 | +5.1 | +31.0 | 140 | +3.1 | +18.9 |
| 150 | +5.6 | +34.1 | 150 | +3.9 | +23.7 |

***Table 3-5*** *- Difference in burning hours expected for ON/OFF levels differing from 70/100 for which burning hours of 4124 were determined in Dublin.*

| ON / OFF Lux. | Hours |
|---|---|
| 55/35 | 4064 |
| 70/35 | 4077 |
| 55/70 | 4094 |
| 100/35 | 4094 |
| 70/70 | 4107 |
| 100/50 | 4109 |
| 55/110 | 4116 |
| 70/100 | 4124 |

***Table3-6*** *- Further examples of annual burning hours at various switch levels*

# 4. CHARACTERISTICS OF A STREET LIGHTING

## 4.1 Individual and Section Feed loads.

### 4.1.1 Individual

Most street lighting is controlled by an individual PECU. i.e. one photocell to one fitting. A typical load for a single streetlight is 400W. There are however, some inherent drawbacks using individual PECU's. These are:-

- Cost
- Maintenance

### 4.1.2 Section Feed

The second method of controlling streetlights is known as section feed. The most common used is the section feed with one PECU which is capable of driving four (4) street lights via a separate set of contacts. The advantage and disadvantages of using this method of control is :-

- Reduces Cost
- Reduced maintenance.

## 4.2 Street Lighting loads

Typical lighting loads have a number of principle characteristics:

### 4.2.1 Inrush Current

Most discharge lighting loads require Power Factor Correction. The most common method of providing this is by the use of PFC capacitors. When connected to the supply it is possible for many hundreds of amps to flow momentarily. The magnitude and duration of the inrush current depends upon the value of capacitance (measured in µF), and the impedance of the supply network. This current is capable of welding together contacts of relays and other switching devices. It is also possible for these currents to fuse semiconductors, and it is reliant on good product design to ensure that the effect of inrush has been taken into account. Power factor can dramatically change the characteristics of a load. Whilst a load may be 100W, and draw about 0.4A at unity power factor, it will draw over 1A with a power factor below .035 (common for discharge loads with failed PFCs). Also, various common lamp or ballast faults can give rise to a situation where just the PFC is connected. In this case although no power is consumed the current through the PFC will also be above 1A. Hence the PECU must be capable of operating the load over the range of likely load conditions, including common failure modes of lantern control gear.

### 4.2.2 Ratings

It is important to ensure that the maximum ratings are not exceeded; care must be taken to observe both the current rating and also the maximum capacitive load that can be connected.

## 4.3 **Formats for Photocells**

### 4.3.1 **NEMA**

The 'NEMA' socket is partially defined in BS5972 and has become the de facto connector for most photocells. The three connections are the incoming live, the switched live out, and a neutral connection (used only in powering the PECU).

### 4.3.2 **Conduit Mounting**

This allows for the direct mounting of a photocell onto a Ø20mm thread. Connection is made via wire leads. This arrangement is often used for 'special' photocells where more than three connections are required.

## 5. **"FAILURE MODES" – REAL WORLD CONDITIONS**

The failure modes can be separated into two categories:-

- Functional Failures
- Catastrophic Failures

### 5.1 **Functional Failures**

The functional failures although not complete failure and not as noticeable as catastrophic failures can be attributed to the following issues:-

- Component Drift – Instability of components resulting in switching levels changing.
- Total Annual burning hours - Inaccurate switching resulting in longer burning hours and increased energy wastage

These functional failures may not be high on the agendas of Electricity departments, however with the ever increasing requirement to reduce energy levels these failure modes will no doubt become important in the future.

### 5.2 **Catastrophic Failures**

The Ethekwini Municipality area has installed the following number of street light as of 2005.

| | |
|---|---|
| 80W HPMV | 103074 |
| 250W HPMV | 11464 |
| 400W HPMV | 3951 |
| 150W HPS | 2178 |
| 250W HPS | 4125 |
| 400W HPS | 7197 |
| TOTAL | **131989** |

An analysis of photocell failures at Ethekwini City Council has revealed that of the total 15,500 failures monitored per annum the main causes of failures are:-

| | |
|---|---|
| Relay Contact welding | - 90% |
| Component Failure | - 4% |
| Lightning Strikes | - 3% |
| Misuse of Photo Cells | - 2% |
| Miscellaneous | - 1% |

- *Loose Contacts*
- *Electronic failure*
- *Bimetal Characteristics Shift*

Switch arcing and heating of the relay make by far the most significant contribution to PECU failure rates. Therefore with the high number of relay contacts welding failures it is obvious that this dilemma should be addressed first. The following paragraphs try and highlight the associated problems of relays uses in PECU's.

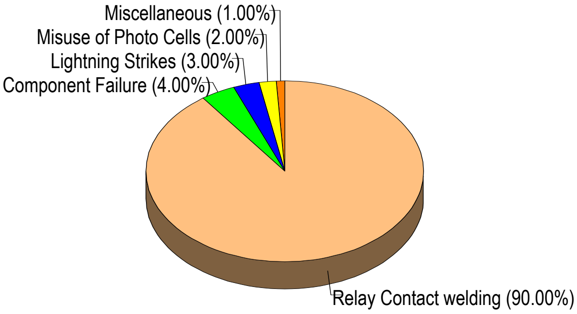


***Fig 5-1*** *– Graphical depiction of PECU failures in the Ethekwini Municipality Area*

### 5.2.1 **Switching Technology**

Many relay application problems occur because of the difference between the relay user's real-life relay load requirements and the relay manufacturer's rated contact load.

#### 5.2.1.1 **Contact Ratings**

The meaning of relay contact ratings is not uniformly defined and understood. Unless otherwise indicated, the current rating of a relay contact is a statement of the magnitude of resistive current that can be switched at rated voltage, frequency, and given cycle rate, for the number of operations specified.

#### 5.2.1.2 **Ratings for AC**

Relay contact alternating current (AC) ratings apply only for the frequency specified. If the rating specified is for 400 Hz, the 60 Hz switching is usually appreciably less.

#### 5.2.1.3 **Load Types**

One of the most common problems in applying relays is the assumption that a relay contact can switch its rated current no matter what type of load it sees. Nothing could be more disastrous. High in-rush currents, high induced back EMF's, and the like can erode, or even weld, contact to the point where life is cut drastically. To better understand the effect of various loads, a brief discussion of each load type is given.

#### 5.2.1.4 **Relay Contact Welding**

i. **Switching surge currents (In-rush Currents)**

The electromechanical units switch power to the load by the opening or closing of a pair of heavy-duty contacts. The line voltage will have a peak value of over 340 volts which is sufficient to cause arcing across the contacts as they open or close. This, in turn, causes pitting of the electrical surfaces, resulting in a short device lifespan. Indeed, transients in the mains supply and high-back EMFs created by many discharge lamps and their associated control gear can result in voltages in excess of 1,000 volts at the switch contacts. The real world electrical load is far from benign. Although the steady state current may indicate a healthy margin of safety when compared to the rating of the switching contacts, it is usually the inrush current that does the damage. A typical streetlight load is shown in figure 5-2. It is clear that the power factor correction capacitor can present a difficult load during switch on. If the switching instant occurs at a mains voltage maximum then the capacitor inrush current is a maximum and only limited by capacitor E.S.R. (equivalent series resistance) and line impedance back to the nearest sub-station. Laboratory measurements have revealed peak in-rush currents up to 250A using a 400 W HPS lamp with its associated 45μF power factor correcting capacitor. This huge inrush current can cause contacts to weld together permanently. The results of this type of photocell failure can be attributed to many of the errant streetlights burning during the day. In practice corrective action may simply be taken by tapping the photocell, which sometimes causes the weld to break, however, subsequent current surges may form new welds if the contact ratings are marginal. And, besides, going around tapping streetlight photocells hardly fits the profile of cost effective maintenance and so proper design is ultimately preferred.

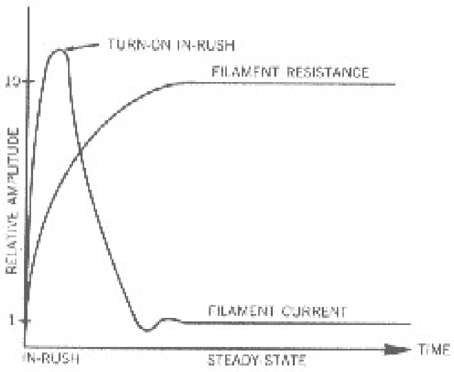


Figure 1

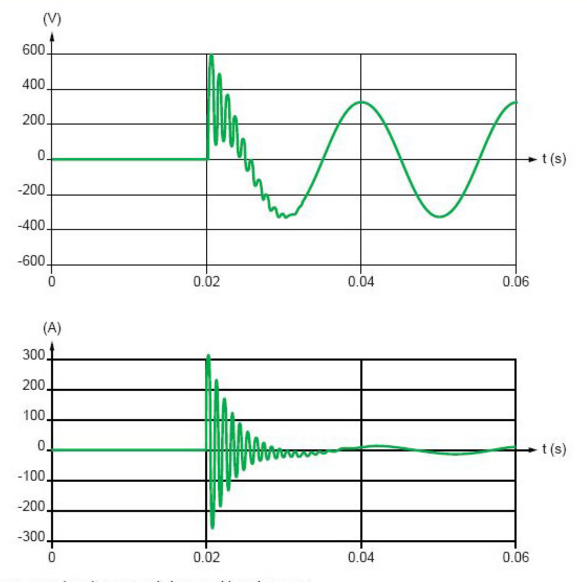


***Figure 5-2*** *- In-rush current due to PFC capacitor*

### 5.2.1.5 <u>Type of Load and Inrush Current</u>

The type of load and its inrush current characteristics, together with the switching frequency, are important factors which cause contact welding.
A relay with ample margin of safety should be selected.
Table – 5-1 shows the relationship between typical loads and their inrush currents.

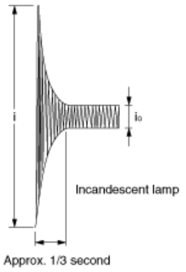
| Type of load | Inrush current |
|---|---|
| Resistive load | Steady state current |
| Solenoid load | 10 to 20 times the steady state current |
| Motor load | 5 to 10 times the steady state current |
| Incandescent lamp load | 10 to 15 times the steady state current |
| Mercury lamp load | Approx. 3 times the steady state current |
| Sodium vapor lamp load | 1 to 3 times the steady state current |
| Capacitive load | 20 to 40 times the steady state current |
| Transformer load | 5 to 15 times the steady state current |

***Table 5-1*** *- Type of load versus Inrush current*

### 5.2.1.6 <u>Load Inrush Current Wave and Time</u>

#### i. <u>Incandescent Lamp Load</u>

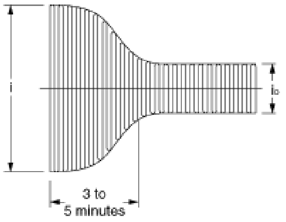
The cold resistance of a tungsten filament lamp is extremely low; this results in in-rush currents that may exceed 15 times the value of the steady-state current. Such high in-rush currents can cause contacts to erode rapidly, or even weld. Series, current-limiting resistors or a small, continuous current flow through the lamp can significantly reduce the inrush by keeping the lamp filament warm.



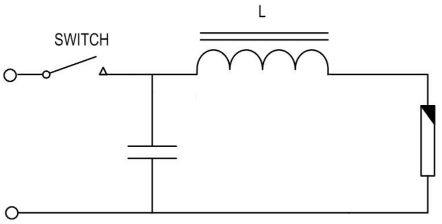
**Inrush current/rated current=$i/i_o$ = 10 to 15 times**

#### ii. <u>Mercury Lamp Load $i/i_o$neary equal 3 times</u>

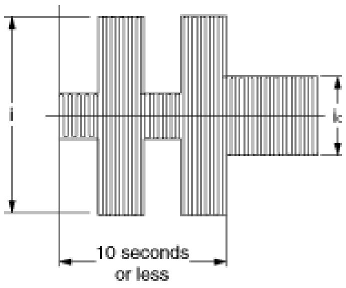
The charging current to a capacitive circuit can be extremely high. The capacitor initially acts as a short circuit and the current is limited only by the circuit resistance. Sometimes the user may not be aware that his load is capacitive. He should note that long transmission lines, filters for EMI elimination, power supplies, etc., are highly capacitive. A series, current-limiting resistor can mitigate this problem.



The discharge tube, transformer, choke coil, capacitor, etc., are combined in common discharge lamp circuits. Note that the inrush current may be 20 to 40 times, especially if the power supply impedance is low in the high power factor type.



iii. **Fluorescent Lamp Load $i/i_o$ neary equal 5 to 10 times**



#### 5.2.1.7 **Contact Arc Phenomenon or *Material Transfer Phenomenon***

Material transfer of contacts occur when one contact melts or boils and the contact material transfers to the other contact. As the number of switching operations increases, uneven contact surfaces develop such as those shown in photos 5-1 and 5-2. After a while, the uneven contacts lock as if they were welded together. This often occurs in circuits where sparks are produced at the moment the contacts "make" such as when the DC current is large for DC inductive or capacitive loads or when the inrush current is large (several amperes or several tens of amperes).

Contact protection circuits and contact materials resistant to material transfer such as AgSnO, AgW or AgCu are used as countermeasures. Generally, a concave formation appears on the cathode and a convex formation appears on the anode. For DC capacitive loads (several amperes to several tens of amperes), it is always necessary to conduct actual confirmation tests.

"Constriction" refers to the very first, tiny area of contact surface to make, and the very last point to break.

Melt Voltage is that amount of voltage that exists across the constriction which will cause a current sufficient to liquify the contact material at the constriction.

Arc Voltage is that amount of voltage that exists on contacts separated by a small gap that will cause an electric discharge across the gap.

And, lastly, Arc Current is that amount of current necessary to just sustain an arc caused by the arc -voltage electric discharge.

The end result of contact arcing is shortened contact life. Depending on the severity and duration of the arc, each time an arc ignites, contact erosion occurs. This erosion causes a loss of contact material which will result in one of two conditions.

Condition #1 is where so much material is lost from the contacts that they fail to electrically close the load circuit. Condition #2 is where one contact loses so much material to the other contact that a spike-and crater results.

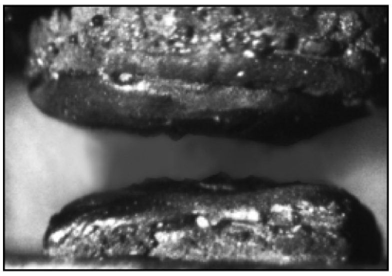
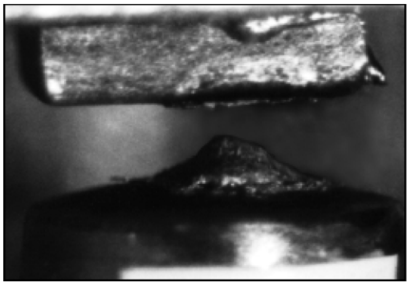


***Photo 5-1*** *- Condition #1*



**Condition #2**

***Photo 5-2*** *- Condition #2*

Another result of severe arcing which may occur now and then is contact welding. Usually, though, when this happens, it is evidence that the relay has been misapplied in a circuit where voltage and/or current are much greater than that particular relay can handle.

Regarding a spike-and-crater condition, when the condition gets severe enough, the high spot—that is, the spike—may mechanically hang up on the rim of the crater. Then when the relay is de-energized, the contacts fail to open, and the load is in an uncontrolled-on condition. Needless to say, this is an undesirable situation.

### 5.2.2 **Component Failures**

#### 5.2.2.1 **Structural**

Both the intensity and ageing effects of direct sunlight are often underestimated. These effects have been found to include the usual rapid ageing of certain plastics as well as less obvious contributions towards electronic component ageing and light sensor overexposure.

The problems here are that the domes are not correctly UV stabilized or are of a poor quality. They tend to break / crack causing the photocell to fail due to moisture ingress.

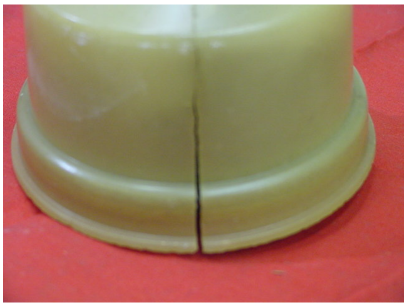
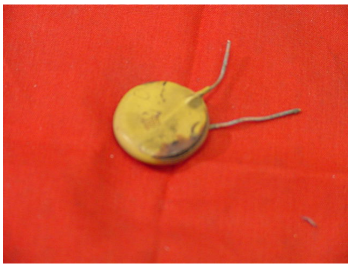


***Photo 5-3 & 5-4*** *- Photocell with cracked and discoloured dome*

The domes also tend to discolour and this affects the photometric properties, thus giving an incorrect switching levels. Also some are so well sealed that they do not allow for expansion and these break off at the base once again allowing the ingress of moisture leading to the photocells demise.

### 5.2.2.2 Electronic

The next problem here is component failure. This varies from mov's been blown to relays falling off the P.C. board, tracks of the Printed Circuit Boards (PCB) and finally burnt P.C.B's.



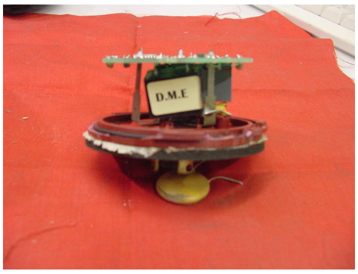


***Photo 5-5*** *- Blown MOV,* ***Photo 5-6****- Hanging relay.*

Sometimes the components heat up to such a degree that the actual dome becomes blistered, as shown below.

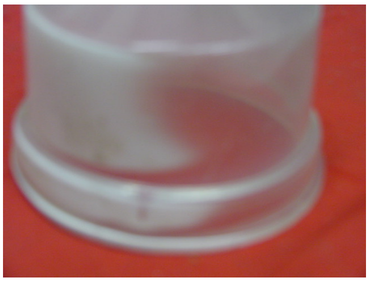


***Photo 5-7*** *- Heat has caused this to blister the dome.*

### 5.2.3 Design

Other smaller issues to consider are the design of the photocell. Poor design methods that are used are:-

a) off centered pins and / or the pins are the wrong size – neutral pins used for the live and load.
b) Poor selection of components or incorrect use of components.
c) Incorrect selection of materials for the dome and base of the photocell.
d) Bad choice in the method of attaching the pins or components onto the P.C. board.
e) Attachment of the dome to the base is either too tight or to lose.
f) Lastly the materials used for the dome and base expand at different rates also causing a problem.

### 5.2.3 Lightning Strikes

With the PECU situated so high up in the air it is with no surprise that lightning strikes will destroy a certain number of PECU's. The percentage of PECU's damaged is considered low.

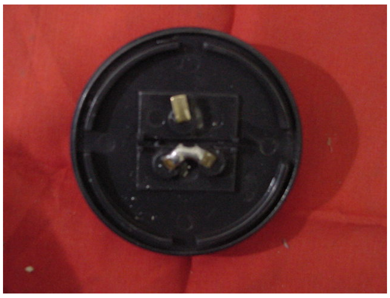
### 5.2.4 Misuse of Photocells

Lack of care and incorrect storage practices bends pins, cracks bases allowing the ingress of water. Photometric properties are altered by scratching of the dome which adds to transmission losses.

***Photo 5-8 -*** *Damage caused by incorrect handling.*

### 5.2.4.1 Dummy Photocells.

Dummy photocells also have problems. Even though a dummy photocell is simply a bridging of the incoming live and the outgoing live ( LI or LO ) this has also given some manufacturers design teams a problem. Some LI and the LO pins are merely soldered together. In these cases the solder becomes pliable with the current passing through it and with the pressure of the springs on the pins this eventually pops open and an open circuit is produced.



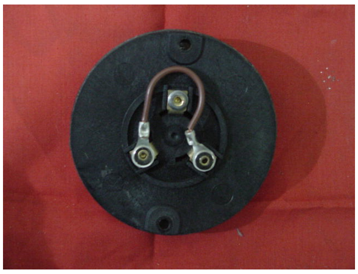


**Photo 5-9** - Soldered Connection, **Photo 5-10** - Riveted connection

One manufacturer uses pop rivets with a wire bridge. Although this is a much better idea some wires are not properly crimped. They become loose and arc and eventually causing an open circuit. Another manufacturer solves this problem by using a solid brass plate to do the bridging and is bolted on for a real solid connection.

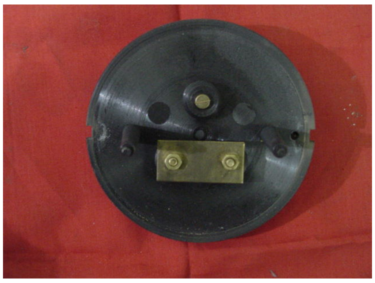


***Photo 13** - Solid plate connection*

### 5.2.5 Solar radiation

With the rapid ageing of certain plastics and electronic component the light sensor becomes overexposed. This results in poor sensitivity and to overcome this problem and in order to improve sensitivity, the photo-electric sensors are aimed to stare at the sun. However, the inherent construction of a typical photo-electric sensor, *viz*. a silicon phototransistor, includes a lens to focus incident light on the sensor semiconductor and so by positioning the photo-sensor to stare at the zenith the direct sun is magnified onto the sensor chip causing excessive temperatures and early ageing. This problem is usually manifested by streetlights being energised due to passing clouds and premature dusk switching as the sensor loses sensitivity.

Premature ageing of photocell electronic components, especially capacitors, due to solar radiation can also lead to early failure. Figure 5-3 shows the average monthly incident power due to solar radiation. With an average photocell footprint of 50 cm$^2$ we can expect peak solar radiation to produce photocell heating of 2.5 Watts. This power must be added to dissipation by internal electronic components to predict temperature rise inside the photocell.

## 6. CORRECTIVE ACTION

### 6.1 Catastrophic Failures

With failures found by the Ethekwini Electricity Department This section attempts to offer corrective actions and suggested solutions.

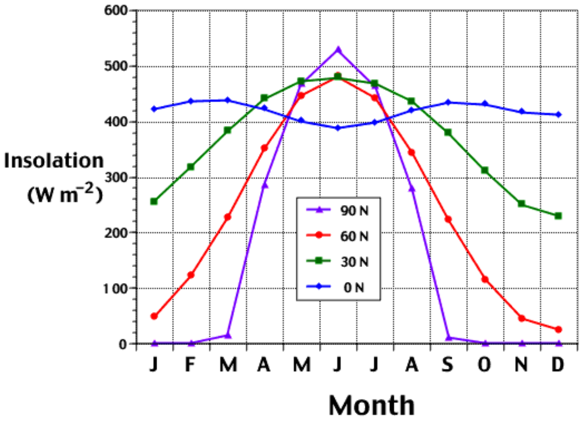


***Figure 5-3** - Insolation power (courtesyPhysicalgeography.net)*

### 6.1.1 Relay

With 90% of failures resulting from relay failures we have decided to concentrate on this mode of failure. A commonly used method of avoiding arcing is the use of semiconductor switching devices, such as triacs. These can handle high voltages without arcing; however, there will always be some dissipation in the device itself (typically, one watt per ampere in this application). If the controller is to be properly sealed from the weather, the dissipated heat will require to be dumped outside the unit in order to avoid excessive heating of the components in the enclosure. Otherwise, the high temperatures inside the unit will drastically reduce its lifespan and require that more attention be paid to the effect of these temperatures on the threshold switching level of the unit.

A method of switching, known as the relay assisted triac (RAT), has been developed to overcome the arcing and heat dissipation problems described above. In this method, a relay and triac are operated in parallel. When power is to be applied to the load, the triac is switched in first. A few milliseconds later the relay is "made". This protects the relay from high voltages in the "make" mode and avoids arcing. Once the relay is conducting, the triac is opened, so that triac dissipation only occurs for the few milliseconds. This triac does not now require heat sinking, so that the internal temperature now remains moderate. This RAT switching technique has been tested over 40,000 ON and OFF operations (equivalent to 100 years of daily switching) and shows no significant wear of components.

The switching mechanism must always fail in the "ON" condition. This is easily achieved in cases where the switching action is relay based; either the thermal delay devices or the RAT devices. Purely solid state units cannot be guaranteed to fail in the conduction mode.

#### 6.1.1.1 Contacts

The contacts are the most important elements of relay construction. Contact performance conspicuously influenced by contact material, and voltage and current values applied to the contacts (in particular, the voltage and current waveforms at the time of application and release), the type of

load, frequency of switching, ambient atmosphere, form of contact, contact switching speed, and of bounce.
Because of contact transfer, welding, abnormal wear, increase in contact resistance, and the various other damages which bring about unsuitable operation, the following items require full investigation.

### 6.1.1.2 Contact circuit voltage, current, and load

#### i. Voltage, AC and DC

When there is inductance included in the circuit, a rather high counter emf is generated as a contact circuit voltage, and since, to the extent of the value of that voltage, the energy applied to the contacts causes damage with consequent wear of the contacts, and transfer of the contacts, it is necessary to exercise care with regard to control capacity. In the case of DC, there is no zero current point such as there is with AC, and accordingly, once a cathode arc has been generated, because it is difficult to quench that arc, the extended time of the arc is a major cause. In addition, due to the direction of the current being fixed, the phenomenon of contact shift, as noted separately below, occurs in relation to the contact wear. Ordinarily, the approximate control capacity is mentioned in catalogs or similar data sheets, but this alone is not sufficient. With special contact circuits, for the individual case, the maker either estimates from the past experience or makes test on each occasion. Also, in catalogs and similar data sheets, the control capacity that is mentioned is limited to resistive load, but there is a broad meaning indicated for that class of relay, and ordinarily it is proper to think of current capacity as that for 230Vac circuits. Minimum applicable loads are given in the catalog; however, these are only provided as a guide to the lower limit that the relay is able to switch and are not guaranteed values.
The level of reliability of these values depends on switching frequency, ambient conditions, and change in the desired contact resistance, and the absolute value.
It is generally accepted to use relays with AgPd contacts when minute analog load control or contact resistance no higher than 100 MΩ is desired (for measurement and wireless applications, etc.).

#### ii. Current

The current at both the closing and opening time of the contact circuit exerts important influence. For example, when the load is either a motor or a lamp, to the extent of the inrush current at the time of closing the circuit, wear of the contacts, and the amount of contact transfer increase, and contact welding and contact transfer make contact separation impossible.

### 6.1.1.3 Characteristics of Common Contact Materials

In-rush transients at contact closure can be destructive to contacts due to the fact that there is always some melting at the actual point of contact. This causes a weld which tends to break asymmetrically in dc circuits, resulting in some metal transfer and resulting in roughened contact in ac circuits. In extreme cases, the weld is sufficiently strong to prevent the contacts from reopening.

Corrections for this condition can include:-

1. Choice of a suitable contact material which combines high thermal and electrical conductivity with little tendency to produce welds.
    a) Fine silver and fine-grained silver have the longest lives for many applications.
    b) Silver-cadmium oxide or silver-tin-oxide can be used in extreme cases of sticking.
    c) More exotic material combinations such as palladium-copper versus silver alloys are often used for cyclic lamp loads
    d) Tungsten contacts have been used in some lamp applications (although it is high resistance and tends to form tenacious oxide layers requiring high contact pressures).
2. The relay should be designed to have:-
    a.) Heavy contact force both closing and opening.
    b.) Minimum contact bounce
    c.) Weld-breaking contact motion such as rocking or shearing motions.
    d.) Some armature travel before the actual contact separation.
3. It may be possible to add small values of resistance to the circuit to limit the current transients.

Characteristics of contact materials are given table 6-1 below.

| | | |
|---|---|---|
| **Contact Material** | **Ag (silver)** | Electrical conductivity and thermal conductivity are the highest of all metals. Exhibits low contact resistance, is inexpensive and widely used. A disadvantage is it easily develops a sulfide film in a sulfide atmosphere. Care is required at low voltage and low current levels. |
| | **AgCd (silver-cadmium)** | Exhibits the conductivity and low contact resistance of silver as well as excellent resistance to welding. Like silver, it easily develops a sulfide film in a sulfide atmosphere. |
| | **AgSnO$_2$(silver-tin)** | Exhibits superior welding resistance characteristics equal or better than AgCdO. Like silver, it easily develops a sulfide film in a sulfide atmosphere? |
| | **AgW (silver-tungsten)** | Hardness and melting point are high, arc resistance is excellent, and it is highly resistant to material transfer. However, high contact pressure is required. Furthermore, contact resistance is relatively high and resistance to corrosion is poor. Also, there are constraints on processing and mounting to contact springs. |
| | **AgNi (silver-nickel)** | Equals the electrical conductivity of silver. Excellent arc resistance. |
| | **AgPd (silver-palladium)** | At standard temperature, good corrosion resistance and good sulfidation resistance. However, in dry circuits, organic gases adhere and it easily develops a polymer. Gold clad is used to prevent polymer buildup. Expensive. |

| | | |
|---|---|---|
| **Surface Finish** | **Rh plating (rhodium)** | Combines perfect corrosion resistance and hardness. As plated contacts, used for relatively light loads. In an organic gas atmosphere, care is required as polymers may develop. Therefore, it is used in hermetic seal relays (reed relays, etc.) . Expensive. |
| | **Au clad (gold clad)** | Au with its excellent corrosion resistance is pressure welded onto a base metal. Special characteristics are uniform thickness and the nonexistence of pinholes. Greatly effective especially for low level loads under relatively adverse atmospheres. Often difficult to implement clad contacts in existing relays due to design and installation. |
| | **Au plating (gold plating)** | Similar effect to Au cladding. Depending on the plating process used, supervision is important as there is the possibility of pinholes and cracks. Relatively easy to implement gold plating in existing relays. |
| | **Au flash plating (gold thin-film plating)** | Purpose is to protect the contact base metal during storage of the switch or device with built-in switch. However, a certain degree of contact stability can be obtained even when switching loads. |

***Table 6-1*** *- Characteristics of contact materials*

i. **Silver Tin Oxide $AgSnO_2$**

We have found that tin oxide makes the material more resistant to welding at high making current peaks. Has a very high burn out resistance when switching high loads. Low degree of material migration under DC loads. Minimum contact load 20V/50mA. Useful where very high inrush currents occur, such as lamp loads including fluorescent. Silver Tin Oxide is frequently chosen as the replacement relay contact material for Silver Cadmium Oxide as the latter is withdrawn.

#### 6.1.1.4 Contact Protection

Other methods can be incorporated to help to prevent contact welding. When switching inductive loads with a DC relay such as relay sequence circuits, DC motors, DC clutches, and DC solenoids, it is always important to absorb surges (e.g. with a diode) to protect the contacts.
When these inductive loads are switched off, a counter emf of several hundred to several thousand volts develops which can severely damage contacts and greatly shorten life. If the current in these loads is relatively small at around 1A or less, the counter emf will cause the ignition of a glow or arc discharge. The discharge decomposes organic matter contained in the air and causes black deposits (oxides, carbides) to develop on the contacts. This may result in contact failure.

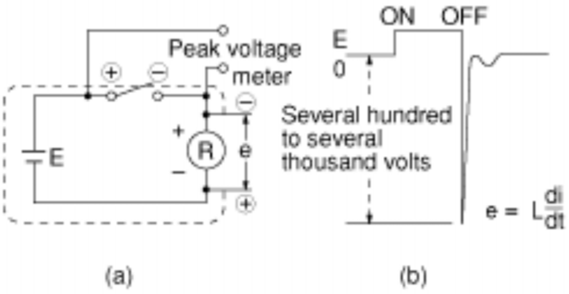


**Figure 6-1 –** Example of counter emf and actual measurement on a peak hold meter

In Fig. 6-1(a), an emf (e = -L di/dt) with a steep waveform is generated across the coil with the polarity shown in Fig. 6-2(b) at the instant the inductive load is switched off. The counter emf passes through the power supply line and reaches both contacts.
Generally, the critical dielectric breakdown voltage at standard temperature and pressure in air is about 200 to 300 volts.

Therefore, if the counter emf exceeds this, discharge occurs at the contacts to dissipate the energy (1/2Li$^2$) stored in the coil. For this reason, it is desirable to absorb the counter emf so that it is 200V or less. Actual measured values of counter emf are as below.

| **Nominal coil voltage** | **DC6V** | **DC12V** | **DC24V** |
|---|---|---|---|
| **NR relay (single stable)** | 144V | 165V | 188V |
| **NF 4 relay** | 410V | 470V | 510V |

### 6.1.2 Component Failures

#### 6.1.2.1 The PECU cover & Acrylic plastics

Analysis has been carried out on the covers of some of suppliers units. In this case, the direct/hemispherical transmission of small samples of the covers of 30 PECU's that had been in service for periods up to 10 years was determined. As can be seen in Fig. 6-2 the loss in transmission of the covers with age behaved, as would be expected, in an exponential manner. The loss in transmission is consistent with a radiation damage explanation: the number of scattering or absorbing centers in the cover being proportional to time, the dose being considered approximately constant. An investigation into the exact cause of this aging process will always be ongoing.

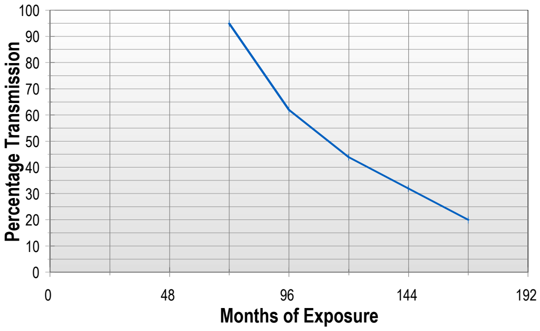


**Figure 6-2 -** Percentage transmission loss with aging

There is now some evidence that the aging process is not caused by UVA radiation alone. Whether the aging process involves the effects of UVA and UVB radiation alone or in combination with the annealing processes that may occur during temperature cycling is not known. It is common practice for plastic and paint manufacturers to rely mainly on

outdoor exposure tests to test their materials for environmentally induced change in optical properties, rather than to rely on laboratory simulations. There are now materials available, such as polymethyl metacrylate, which can be expected to maintain their transmission characteristics over a number of years. Manufacturers' testing of such materials under outdoor exposure conditions, in both the UK and India, indicate that they may exhibit negligible loss of transmission after five years of operation, despite some evidence of transmission loss and recovery over shorter time scales.
The ageing effect of the sun on plastics is well documented. UV radiation, the worst culprit here can cause certain plastics to discolour and crack. For this reason most manufacturers use acrylic polymers for the photocell domes. However, technical literature indicates that if acrylic plastics are inadvertently stressed during the manufacturing process that this invisible defect may manifest itself as mysterious surface cracking at some future time. It is therefore important that the dome does not fit too tightly onto the base otherwise crack may form, thereby facilitating moisture ingress, or worse still, the dome may come adrift completely.

## 6.2 Functional Failures

### 6.2.1 Lifetime Requirements

#### 6.2.1.1 Lifetime of existing PECU’s

It is possible to illustrate the lifetime and failure characteristics of a batch of old PECU’s, and to draw some conclusions as to the reasonable lifetime that could be demanded from the next generation of PECU’s.
There is some technical literature giving the results that a European based company carried out on a bulk change of 3,000 PECU’s. These were sorted into groups according to year of manufacture. Although the rate of installation of PECU’s during the 10 years was approximately constant, the 3,000 samples removed may not have been totally randomly selected. Indeed, either there was a tendency to over-sample units manufactured in on specific year or else some batch of units for that year was unusually reliable. Despite this, it is possible to fit an exponential curve to the data to describe the fall-off in survivors Fig.6-3, and from this fitted curve to deduce that the average life of the units was about two years. This can be compared with a user estimate that, in practice, the lifetime of thermal units is nearer to three years.

The survivors in this exercise were not complete failures; but many were partial failures, in that they no longer met the photometric specifications and certainly did not meet the requirements of the user. At dusk, many of these units switched on so late as to cause a safety hazard, and switched off so late as to increase burning hours to an unacceptable level.

Some data on the photometric performance of these switches is summarised in Fig. 6-5. For this analysis, an "acceptable" switch ON level is defined as 40 to 70 lux, representing over 20% variation on the rated switch-on level of 55 lux for these units.

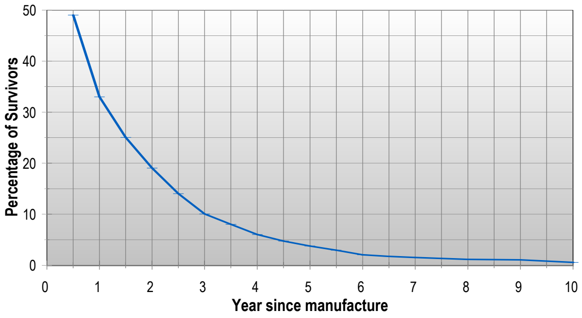


**Figure 6-3 -** Exponential curve fitted to plots of % of survivors Vs age from year of manufacture. The slope of the fitted curve indicates a two-year average lifetime.

An even wider "acceptable" switch OFF range of 80 to 140 lux was defined. Less than 10% of the units were still switching ON within this "acceptable" ON range, whilst about 12% were still switching OFF at "acceptable" levels. Of particular concern to the user was the high proportion of units (over 40%) which switched OFF at over 300 lux.

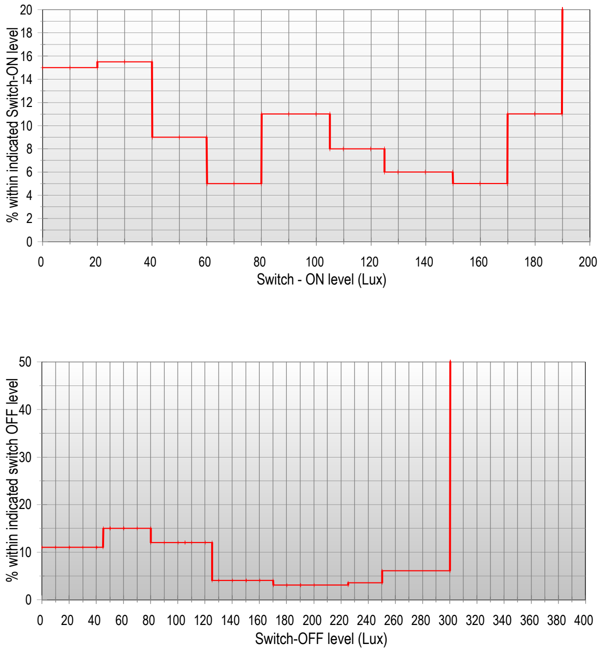


**Figure 6-5 -** Performance Switch-ON and Switch-OFF levels of thermal PECU's manufactured in 1982, '84 and '86, and removed from service in 1987. 'Acceptable' switch-ON and level 40-70 lux. 'Acceptable' switch-OFF level 80-140 lux.

#### 6.2.1.2 The user's lifetime requirement

It can be seen from the paragraphs above that the older generation of PECU’s tested suffered from an unacceptably short life and their switch-ON/OFF levels were likely to deviate by unacceptable amounts. We in South Africa can use this knowledge to develop new PECU’s which would have lives in excess of six years whilst maintaining acceptable photometric performance. We need to examine the role that two crucial components that contribute to this unreliable and variable behaviour before indicating the alternatives.

### 6.2.2 **Stability of the sensing circuitry**

Apart from the mechanical considerations in (i) and (i) above, the calibration and stability of the cell should be carefully studied.

In thermal switching units, a light-dependent resistor/diode/transistor generates a current that is generated by the amount of light falling on it. Silicon photodiodes or phototransistors have the capability of converting incident photons into charge carriers with an efficiency of 60 to 80%. For example, the responsivity of a typical photodiode would be of the order of 0.5 amps per watt of incident radiation in the visible range. Illuminance of 70 Lux at 555nm corresponds to 70/683 watts/m2 which would give a current of about 0.2 microamps in a photodiode of 4mm2 surface area. Despite such small detectable current, photodiodes (and/or phototransistors) must be considered because of their high reliability, low cost, lack of measurable degradation in time, good linearity and generally well proven characteristics in both on-ground and space applications. However, to gain the full advantage of the photo detector reliability, it must be incorporated in suitable circuitry. This circuitry must provide amplification and discrimination, and be unaffected by changes in temperature, supply voltage and other external variables over a wide range. This leads to a requirement for a high quality transformer and regulated DC supply to power a signal processing circuit, with stable reference resistors to provide the calibration level. Unfortunately, silicon photo detectors have higher sensitivity in the red and near IR than CdS cells. To approximate the V(l) curve they require to be fitted with filters.

### 6.2.3 **Choosing the Detector for your Unique Light Sensing Application**

The choice of photo-electric sensor has a huge impact upon longevity and switching level performance. Traditional cadmium sulphide cells (CdS) have a spectral response that closely matches the photopic response of the human eye, but their parameter shift with ageing has resulted in them being replaced by silicon photo-electric detectors.

#### 6.2.3.1 **Abstract**

How do you decide what detector to use for your light sensing application? The choices can seem overwhelming: photodiodes, phototransistors, photodarlingtons, photomultiplier tubes, photoresistors, integrated circuits, various hybrids and even thermopiles. This application note provides insights on selecting the best approach for your ultraviolet, visible and near-infrared light sensing applications. Specific application needs considered include:

light source spectral
characteristics optical
power mating
electronics packaging
constraints

- image size
- signal-to-noise ratio
- frequency bandwidth
- cost

#### 6.2.3.2 **Available Light Sensing Options**

Light sensing applications vary widely from specialized scientific instrumentation that needs to detect individual light particles (photons) to systems that control high speed welding and cutting lasers that produce kilowatts of optical power. Fortunately, there are sensors for almost any application imaginable: from a photomultiplier tube which gives a large voltage pulse for every photon it detects, to cooled thermopiles that absorb kilowatts of power providing a thermocouple voltage proportional to the optical power absorbed. The following describes the most popular light sensing technologies. Their characteristics are summarized in Table 6-2.

| **Electrical Characteristics** | **Photo Multiplier tubes** | **Photodiodes** | **Photo-transistors** | **CdS Photocells** | **Other Photoconductors** | **Integrated Circuits** | **Hybrids** | **Sensor Electronics Assembly** |
|---|---|---|---|---|---|---|---|---|
| **Available Wavelengths (µm)** | 0.2 - 0.9 | 0.2 - 2.0 | 0.4 - 1.1 | 0.4 - 0.7 | 2 - 15 | 0.2 - 1.1 | 0.2 - 15 | 0.2 - 15 |
| **Performance-to-cost ratio** | Fair | Good | Excellent | Excellent | Fair | Fair | Fair | Good |
| **Sensitivity** | Excellent | Very Good | Very Good | Very Good | Very Good | Very Good | Very Good | Very Good |
| **Linearity** | Good | Excellent | Good | Good | Good | Good | Good | Good |
| **Ambient Noise Performance** | Fair | Very Good | Very Good | Very Good | Very Good | Excellent | Excellent | Excellent |
| **Dynamic range** | Very Good | Excellent | Very Good | Good | Good | Very Good | Very Good | Very Good |
| **Stability** | Very Good | Very Good | Good | Poor | Fair | Very Good | Very Good | Very Good |

**Other Characteristics**

| **Electrical Characteristics** | **Photo Multiplier tubes** | **Photodiodes** | **Photo-transistors** | **CdS Photocells** | **Other Photoconductors** | **Integrated Circuits** | **Hybrids** | **Sensor Electronics Assembly** |
|---|---|---|---|---|---|---|---|---|
| **Produceability** | Fair | Excellent | Fair | Poor | Fair | Very Good | Very Good | Very Good |
| **Cost** | High | Low | Very Low | Very Low | High | Medium | High | Medium |
| **Ruggedness** | Poor | Excellent | Excellent | Excellent | Excellent | Good | Very good | Excellent |
| **Physical Size** | Large | Small | Small | Small | Small | Small | Medium | Medium |
| **Ease of Customisation** | Poor | Easy | Fair | Fair | Poor | Poor | Poor | Fair |
| **Cost of Customisation** | Very High | Low | Medium | Low | High | Very High | High | Medium |

***Figure 6-2 –*** *Comparison of light sensor characteristics*

#### 6.2.3.3 Photodiode Sensors

The spectral response describes the sensitivity of the photosensor to optical radiation of different wavelengths. This is important because only a small part of the optical radiation spectrum is visible.

It is possible to construct a semiconductor diode to produce a current proportional to the incident light level. The currents generate are small and need careful amplification by a circuit that compensates for thermal effects. The fundamental physics of semiconductor junctions means that silicon photodiodes have significant sensitivity to light outside the visible spectrum.

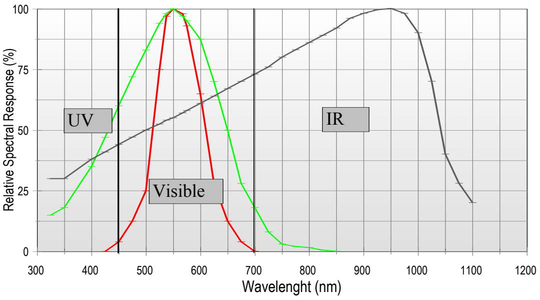


***Fig 6-7*** *- Comparison of filtered and unfiltered photodiode sensitivity with eye sensitivity detectors. [Red] - V Photoptic curve, [Black] -Bare Silicon photodiode, [Green] - silicon photodiode with filter*

Filters can take a number of forms, but are usually bulk-coloured glass slips added to the photodiode assembly during manufacture.

A variant of the above is to add a filter that blocks all visible light, so that the photodiode is only sensitive to Infra-red light. This can be incorporated into a PECU that is only sensitive to IR, and virtually insensitive to visible light. See Fig 6-7. This means that the PECU can be used where it is partially illuminated by visible light, often produced by the light that is being controlled by the PECU. This type is typically used in bollards, where the PECU is incorporated into the base compartment and is illuminated by visible light from the lamps within the base reflected from the inside of the cover. This PECU is insensitive to this light, and operates by sensing the IR component of daylight transmitted through the cover.

There are three cautionary notes:

- Such PECU's can only be used with light sources that generate virtually no IR (incandescent lamps generate huge amounts of IR).
- That the PECU, although insensitive to visible light, will still be affected by very high levels of visible light. The arrangement of the PECU within the luminaire should minimise such light.
- The proportion of IR to visible light in daylight varies with weather conditions so the PECU will not switch as accurately as a conventional PECU. An increase in annual burning hours of up to 25% can be expected.

Photodiode sensors can also be incorporated into integrated circuits although the functionality may be limited due to the competing requirements of semiconductor processing for optoelectronics and integrated circuits.

## 7. CONCLUSIONS

### 7.1 Photometric Accuracy

#### 7.1.1 Negative Switching Ratio

**Myth** : Negative Switching Ratio will reduce the energy levels of all municipality street lighting.

**Fact**: Yes, in a perfect world but it must be said "No" not with current level of failures where 90% of PECU's that fail, fail in the "ON" position. These energy savings are negated in this respect. This is explained below.

#### 7.1.1.1 Energy Savings

The national average cost of electricity in the South Africa ranges from R0.29 to R0.30 per kilowatt-hour (kWh). To calculate your average energy costs, use the following formula:-

**Bulb power (Watts) x Streetlight burning time x Cost per kWh/1000 = Cost of Electricity.**

Table 7-1 shows the annual cost of a 400W HPS lamp burning for various hours.

| Burn Time per day | Annual Hours | Annual Cost |
|---|---|---|
| **3 hrs** | 1095 | R131.25 |
| **6 hrs** | 2190 | R262.50 |
| **12 hrs** | 4380 | R525.00 |
| **24 hrs** | 8760 | R1050.00 |

***Table 7-1****: Comparative annual operating costs for a 400W HPS lamp @R0.30/kWh)*

Acceptable number of burning hours for one street light is typically 4380 hours @ R525. When the lamp stays on continuously then the cost is doubled. Negative switching may save 47hours per annum per light which amounts to R5.52 per annum. However, with many other variables which are explained in paragraph 7.1.2 below, this small saving may not be realized.

#### 7.1.2 Very accurate switching levels

**Myth** : Very accurate switching levels are required.

**Fact**: NO. Many factors affect the switching levels and these levels are influenced by atmospheric conditions, such as clouds, rain, fog, mist etc. PECU's misjudge the ambient levels and leads to switch ON even during the day.

The **Effect of dust** present in the general atmosphere and the high degree of the same in busy streets, factories etc will accumulate on the sensor window and will make the switch to behave erratically allowing the PECU's performance to drift on account of dust.

The **Effect of Shades** such as trees will block a major portion of sunlight in the midday its effect in the dawn and dusk times will be very less in view of the fact that light will be reaching from all directions of the sky almost with the same intensity. But however a tree shade will have an impact in terms of a slight shift in the timing of operation of the PECU. The real difference in terms of time may be as low as 1 second to a high of 5 minutes.

The **Sky at Dusk or Dawn** does not behave in any easily described manner. Its colour and its angular luminance distributions are highly variable. The sky colour can vary from predominantly red near the horizon, to white or even blue at the zenith. One is aware of these and even more exotic colours and angular distribution changes which nature displays under the sorts of ever changing mixed cloud conditions that can occur. Amounts of light are measured in a metric term known as Lux. Daylight is a mixture of colours of different frequencies. The amount of light reflected from any object determines how bright it appears. Think of how much brighter people and object appear on snow than on dark, less reflective backgrounds. The sunny snow scene would have a very high lux level, whilst dusk is a low lux level. All the above add to an almost impossible task of achieving these levels.

**Solar radiation** causes the rapid ageing of certain plastics with loss of transmission and electronic components become overexposed resulting in poor sensitivity resulting in incorrect switching levels.

### 7.1.3 Photometric Properties

**Myth**: The photometric properties of the perfect PECU should approach that of the perfect luxmeter against which it is normally compared.

**Fact**: NO. The present state of luxmeters permits a fairly precise (±5% or better) which matches the sensor to the V(l) curve at many visible wavelengths. Many municipalities call for PECU's to have an accuracy of ±10% or better. This is not easily achievable and there is no point in insisting on the photometrical perfect PECU if

i. the cost is prohibitive, or
ii. these photometric properties are not stable enough to be maintained over its usable lifetime.

The photometric accuracy of the PECU will depend on the investment made in the effort to match the V(l) curve. Photo detector/filter combinations are available at prices from R18 to R2250 depending on the quality of fit to the V(l) curve.

### 7.2 Lifetime Requirement

**Myth**: The PECU's have a lifespan of 10 years or more.

**Fact**: NO. Tests have proven that the average lifetime of a PECU is three years. Long life will require the sourcing of high reliability components. Employing new technology to improve performance and increase life will have an effect on the cost of the unit. Individual components have their minimum unit costs; e.g., a transformer for these applications could cost R20-00 to R30-00, and analogue components R4-00 to R5-00, etc. components which will be more expensive. Thus, those who specify the technical requirements of the current generation PECU's will also determine the order of magnitude of their cost.

### 7.3 Final Conclusions

Technology is now available which will enable a PECU to operate for up to six (6) years without failing because of relay arcing and wear, or without causing the unit to overheat.

The combination of using good quality technology for switching to prevent contact welding with stable sensor circuitry (adding filters) and good design will ensure a more reliable product but with increase in unit cost.

**Cost of Operation**

The cost of light is not only reflected in the cost of the light bulb itself, but in the installation and the electricity the bulb uses. Electricity accounts for the greatest share at approximately 80% to 88% of the cost. The cost of labour to install the bulb is approximately 8% while the cost of the bulb is around 4% of the total cost. Purchasing the most reliable efficient PECU with the longest life possible will save a great deal of time effort and money and energy.

In the South African scenario municipalities must ensure that the PECU's that are purchased is waterproof and the design is sound.

Streetlights switching levels should be set within reasonable levels and not choosing unrealistic levels. Photosensor sensitivity doesn't match human visual sensitivity Photosensors react to optical radiation, including visible light, ultraviolet radiation and infrared radiation. Humans, however, do not see or react to ultraviolet or infrared radiation. Photosensors with a broad spectral response (i.e., sensitivity to optical radiation of different wavelengths) often respond as if more daylight is in a space than actually exists. This can lead to problems where precise switching or dimming levels are required.

Good quality relays must be incorporated within the design. This will contact welding which in turn reduce unacceptable levels of burning hours. This effort will ultimately ensure municipalities try and meet the needs of the Kyoto Protocol for future generations.

Finally, a major consideration must be to ensure the lifetime of the PECU meets the 6-10 year period without failing rather than focusing on how accurately and consistently the load is controlled.

Keep the design simple.

## 8. GLOSSARY

**Candela**

The Systeme International d'Unities (SI) of luminous intensity. One candela is one lumen per steradian. Formerly, candle.

**Footcandle (fc)**

A measure of illuminance in lumens per square foot. One footcandle equals 10.76 lux, although for convenience 10 lux commonly is used as the equivalent. A unit of illuminance equal to 1 lumen per square foot.

**Illuminance**

light arriving at a surface, expressed in lumens per unit area; 1 lumen per square foot equals 1 *footcandle*, while 1 lumen per square meter equals 1 *lux*.

**Illumination**

The process of using light to see objects at a particular location.

**Lumen (lm)**

A unit measurement of the rate at which a source produces light. The sources light output rating expresses the total amount of light emitted in all directions per unit time.

**Luminance (L)**

The photometric quantity most closely associated with the perception of brightness, measured in units of luminous intensity (candelas) per unit area (square feet or square meter).

**Luminous flux**

the time rate of flow of light.

**Lux, (lx)**

a unit of illuminance equal to 1 lumen per square meter.

**Nanometer (nm)**

a unit of length equal to $10^{-9}$ meters; commonly used as a unit of wavelength.

**Power factor (PF)**

The ratio of active power (in watts) to apparent power (in rms volt-amperes), power factor is a measure of how effectively an electric load converts power into useful work. Power factor (PF) is calculated using the equation PF = (active power) / [(rms voltage) x (rms current)]. Phase displacement and current distortion both reduce power factor. A power factor of 0.9 or greater indicates a high power factor ballast.

**Spectral power distribution (SPD)**

A representation of the radiant power emitted by a light source as a function of wavelength.

**Transmission**

the process by which incident flux leaves a surface or medium on a side other than the incident side, the characteristics of many materials such as glass, plastics and textiles.

**Capacitor**

A device used in electric circuitry to temporarily store electrical charge in the form of an electrostatic field. In lighting, a capacitor is used to smooth out alternating current from the power supply.

**Cosine distribution**

A property of a light source such that its luminous intensity in a particular direction is proportional to the cosine of the angle from the normal to the source.

**Infrared radiation**

Any radiant energy within the wavelength range of 770 to 106 nanometers is considered infrared energy. (1 nanometer = 1 billionth of a meter, or 1 X $10^{-9}$ m).

**Intensity (luminous intensity)**

Total luminous flux within a given solid angle, in units of candelas, or lumens per steradian.

**Irradiance**

The density of radiant flux incident on a surface.

**Kelvin**

Color temperature is measured in degrees Kelvin, which indicates hue of a specific type of light source. Higher temperatures indicate whiter, "cooler" colors, while lower temperatures indicate yellower, "warmer" colors.

**Photopic**

Vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to a luminance of at least 3.4 cd/$m^2$.

**Steradian (sr)**

A unit of measure equal to the solid angle subtended at the center of a sphere by an area on the surface of the sphere equal to the square of the sphere radius.

**Wavelength (λ)**

The distance between two corresponding points of a given wave. Wavelengths of light are measured in nanometers (1 nanometer = 1 billionth of a meter, or 1 X $10^{-9}$ m)

**Zenith**

In the lighting discipline, zenith is the angle pointing directly upward from the luminaire, or 180°. Zenith is opposite nadir. In astronomical usage, zenith is the highest point in the sky, directly above the observation point.