MR16 LED Retrofit Lamps:
Quality, Consistency and Reliability

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Abstract

Light-emitting diode (LED) MR16 lamps have recently become part of the residential lighting market, bringing with them a new lighting paradigm. Consumers previously accustomed to halogen MR16 technology must now select suitable LED replacements based on their photometric information. In the wake of stories of exaggerated lumen outputs and inaccurate marketing literature, this research takes a snapshot of MR16 LED residential lighting in New Zealand to evaluate its status.

Forty-eight readily available products (six repetitions of eight types) were tested in Massey University's integrating sphere. Initial investigations focused on baseline photometric values to determine whether claims of halogen equivalency were justified and if manufacturers’ photometric information was valid. Lamp quality was checked using ENERGY STAR as a basis, and variation across each six-lamp sample was checked to determine whether consistency could be assured to the consumer.

The effect of heat on LEDs was investigated through a 6,000 hour test. This saw groups of lamps running continuously in both downlights and free air in a simulated residential installation in Auckland, New Zealand. As well as analysing whether such mounting arrangements caused different levels of non-recoverable deterioration over time, the study also considered the general behaviour of all lamps over the test period.

The study had mixed results, and revealed that care must be taken when purchasing MR16 LED lamps in New Zealand due to these varied levels of quality.

Significantly, one lamp type was found to mechanically deteriorate over time such that it proved a fire risk. This was exacerbated by high temperature and the lamps mounted in downlights deteriorated 2,000 hours before their free air equivalents showed signs of similar behaviour.

With 25% of the lamps sampled in the study shown to be seriously flawed, it is clear that appropriate regulation is required in order to ensure that MR16 LED lamps sold in New Zealand are fit for purpose.

The study concludes by suggesting further areas for research which were limited by time constraints. All of these proposed investigations would enrich the existing findings.

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Acronyms and Abbreviations

$\Delta u'v'$	Colour difference recorded as the change in (u', v') coordinates on the CIE 1976 diagram.
AC	Alternating Current
ANSI	American National Standards Institute
CA	"Closed Abutted" rating of heat can which, under the now superseded downlight code, allowed ceiling insulation to be abutted to the luminaire
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	Correlated Colour Temperature
CFL	Compact Fluorescent Lamp
CIE	International Commission on Illumination
CRI	Colour Rendering Index
DC	Direct Current
DOE	U.S. Department Of Energy
D_{uv}	Colour difference recorded as the change in (u, v) coordinates on the CIE 1960 diagram.
EECA	Energy Efficiency and Conservation Authority
HEEP	Household Energy End-use Project
IESANZ	Illuminating Engineering Society of Australia and New Zealand
IESNA	Illuminating Engineering Society of North America
IR	Infra-red
K	Kelvin
KEMA	Consultancy company (now known as DNV KEMA)
LED	Light-emitting diode
LM-79	LM-79-08 Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products
LM-80	LM-80-08 Approved Method: Measuring Lumen Maintenance of LED Light Sources

lm/W	Lumens per Watt
MEPS	Minimum Energy Performance Standards
MR	Multifaceted Reflector
NEMA	National Electrical Manufacturers Association
NGLIA	Next Generation Lighting Industry Alliance
nm	Nanometre
P-N	Positive-Negative
R_9	Saturated red value used for colour rendering
R_a	General colour rendering index
SDCM	Standard deviation of colour matching
SSL	Solid-state lighting
T_j	Junction temperature
TM-21	TM-21-11 Projecting Long Term Lumen Maintenance of LED Light Sources

1 Introduction

In today's world energy efficiency is extremely topical, as Governments seek ways to reduce the burden placed on their power generation resources. Lighting is responsible for approximately one fifth of the world's electricity consumption (Dowling, 2007). Of this, McKinsey and Company (2011) estimate that incandescent lighting accounts for over 52 percent of the general market. Curbing the use of incandescent lamps therefore presents itself as a valuable way of reducing energy use. With this in mind, some countries such as Australia have fast-tracked the phase out of inefficient incandescent lamps through specific legislation (Australian Government Department of Resources Energy and Tourism, n.d.). New Zealand followed suit until public outcry at the perceived removal of consumer choice led to a policy u-turn in 2008 (Brownlee, 2008).

Recent advancements in LED lighting have provided viable replacements to incandescent lamps and many retrofit lamps are now available through retail outlets. Not long ago this market penetration was merely a pipe dream. As recently as 2005 a study by Brown, Nicol and Ferguson (2005) concluded that the poor efficiencies and low luminous outputs of LED retrofit lamps made them unsuitable as direct replacements.

While these innovative lamp types are now available in the marketplace, the public's buy-in to this technology is key to its success. It is important that LEDs do not follow in the footsteps of compact fluorescent lamps (CFLs) which have been plagued with end-user rejection despite large publicity drives (Siminovitch & Papamichael, n.d.). Siminovitch and Papamichael were disappointed to note that a North American campaign had resulted in only a 10-15% uptake of CFLs in homes which was "embarrassing compared to the vast amounts of time, energy and public investment sunk into the effort" (Siminovitch & Papamichael, n.d., p. 1).

This is reflected in the New Zealand market, where the Electricity Commission was involved in subsidising approximately five million CFLs in an effort to increase their acceptance (Hawke, 2012). Yet Hawke (2012) stated in a subsequent Regulatory Impact Statement that problems with consumer confidence remained. Problems cited by Hawke included those with quality, performance, poor perception of possible energy savings and health concerns (due to mercury content). In addition, Hawke commented that only limited (and often inaccurate) information was available to the consumer in order for a reliable comparison to be made between products.

Siminovitch and Papamichael (n.d.) mentioned similar concerns but also recognised that one of the problems was lamp life and that this could be affected by heat. It was found that a build-up of heat in luminaires such as downlights caused failure of the CFLs' integral electronic ballasts, resulting in overall lamp failure.

The issue of heat in downlights is of similar concern for LED technology as it is well known that LEDs are affected by heat, resulting in poor performance (DiLaura, Houser, Mistrick, & Steffy, 2011). To this end, it is vitally important to photometrically evaluate LEDs over time in a New Zealand environment. This will ensure that the public is given accurate information on LED lamps so that their product expectations are realised.

The quality of LED lamps is not regulated in New Zealand and anecdotal evidence suggests that the available products are of variable quality (Edmunds, 2013). The purpose of this research is to evaluate MR16 LED product available on the New Zealand market in order to provide consumer satisfaction and avoid a repeat of the CFL experience. This includes not only benchmark data but also the performance of the lamps over time.

2 Literature Review

2.1 Introduction

When researching LED lighting it quickly became apparent that the recent exponential growth of the LED industry translated to rapidly outdated reference material. There were, therefore, two quite distinct arms of background reading, these being journal articles and industry literature. Journal articles, while vital to providing an in-depth background knowledge of the subject matter, often contain dated and superseded material. It therefore became necessary to turn to the industry itself and investigate the latest technology that it had to offer, through websites and magazines. In particular, LEDs Magazine and the U.S. Department of Energy (DOE) were beneficial for obtaining up-to-the-minute information. LEDs Magazine is a well respected magazine by the PenWell Corporation and is now produced in both print form and as a free PDF download (http://ledsmagazine.com/). The DOE is at the forefront of development in the LED area, through initiatives such as its CALiPER[1] program and administration of the L prize[2] (http://www1.eere.energy.gov/buildings/ssl/).

Other sources include the Next Generation Lighting Industry Alliance (NGLIA) which is comprised of members of the LED lighting community in the United States (Next Generation Lighting Industry Alliance, n.d.). Together with the DOE, the NGLIA has been overseeing a working group seeking to provide advice to the wider LED community, including standards bodies (Next Generation Lighting Industry Alliance, 2011).

Organisations such as the Illuminating Engineering Society of North America (IESNA), the American National Standards Institute (ANSI) and the U.S. based National Electrical Manufacturers Association (NEMA) have also been invaluable sources of information.

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[1] See Section 2.14.1 for more details.

[2] The L prize is a competition sponsored by the U.S. Department of Energy which rewards innovations in solid-state lighting technology. The inaugural prize was awarded in 2011 for a 60W incandescent replacement. At the time of writing, the PAR38 replacement lamp category is underway (U.S. Department of Energy, 2013e).

Due to New Zealand's relatively small size, statistical information such as lighting market share is limited. The most recent comprehensive study for the New Zealand residential lighting industry was by KEMA and dates back to 2007 (KEMA, 2007). This was based on information found at the time, plus information sourced from prior studies. Given modern advancements, such as the proliferation of LED lighting technology since that time, it is a fair assumption that this report is largely outdated. Thus reputable international sources have been used in conjunction with local knowledge, to draw reasonable conclusions on the state of the lighting market in New Zealand.

2.2 Halogen MR16 Lamps

Incandescent lamps produce light through the process of incandescence, whereby electricity passing through a tungsten filament causes it to heat up and produce visible radiation (Pritchard, 1999). Over time the filament material can evaporate and deposit onto the inner surface of the glass bulb (Coaton & Marsden, 1997). Halogen lamps overcome the problem of bulb blackening by utilising halogen elements which combine with the evaporated tungsten and aid in depositing it back onto the filament (Julian, 2003). This allows for a smaller form factor than traditional incandescent lamps. The McKinsey Report of 2011 noted that halogen lamps had a 12 percent worldwide market share (10% by value) (McKinsey & Company, 2011).

A subset of halogen lamps is the MR16 lamp which is suggested to account for "perhaps one billion sockets around the world" (Peters, 2012, p. 39). This lamp type combines a halogen lamp capsule with a reflector system and has a front cover. The cover acts to absorb ultra-violet radiation and provides safety in case the capsule explodes (Julian, 2003). The MR16 designation refers to the reflector shape; this being a Multifaceted Reflector with a diameter of 16 eighths of an inch. A typical lamp is illustrated in Figure 2.1.

Figure 2.1 Typical halogen lamp

Initially used in slide projectors, MR16 lamps are commonly used for applications such as display and accent lighting (NLPIP, 2002). Though up-to-date figures are not available (see Section 2.1), a quick scan through any property sales pages (e.g. http://www.trademe.co.nz/property) reveals that these lamps are often found in a New Zealand domestic setting.

Halogen MR16 lamps produce a large amount of heat whereby nearly 90% of the radiation produced is in the infrared region (Paget, Lingard, & Myer, 2008). This leads to low efficacies[3] of approximately 8-20lm/W (Paget et al., 2008).

Due to the nature of the incandescent process, halogen MR16 lamps have continuous spectral power distributions like those shown in Figure 2.2 and Figure 2.3. These spectra illustrate the two typical types of halogen MR16 lamp which utilise either aluminium (Figure 2.2) or dichroic (Figure 2.3) reflectors. Dichroic ("cool beam") technology removes most of the heat from the light beam by allowing it to transfer through the back of the reflector (Kitsinelis, 2011). Spectral analysis has revealed that dichroic lamps tend to have a diminished red region of the spectrum and a higher CCT as a by-product. This is illustrated in Figure 2.3.

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[3] *Efficacy* is used to describe the relationship between the electrical input and the lumen output. It is measured in lumens per watt (lm/W).

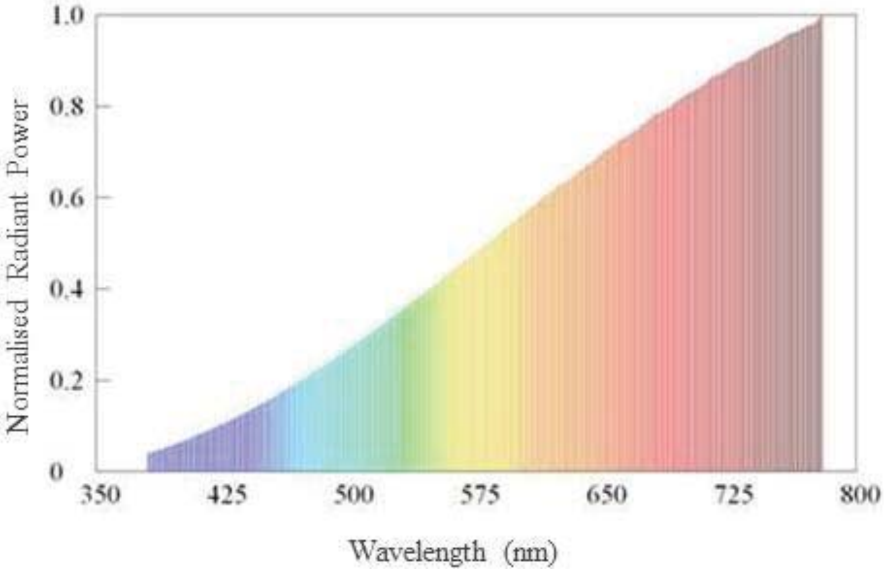

Figure 2.2 Typical spectrum of a halogen MR16 lamp with an aluminium reflector

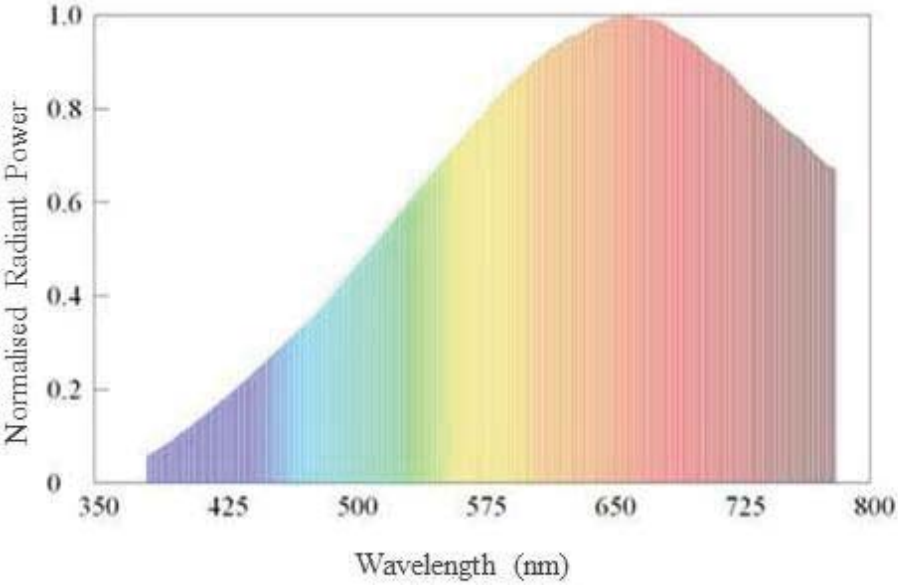

Figure 2.3 Typical spectrum of a halogen MR16 lamp with a dichroic reflector

Figure 2.4 shows the two categories of MR16 lamps, which are easily identified by their different lamp bases. The lamp on the left is designed for mains operation (230V in New Zealand) and utilises a GU10 twist-lock lamp base. The lamp on the right has a GU5.3 base which is designed for low voltage operation through a transformer. This study is based on 12V low voltage[4] lamps.

Figure 2.4 Typical 230V (left) and 12V (right) MR16 halogen lamps

Low voltage MR16 lamps have shorter, thicker filaments than their 230V counterparts, which leads to advantages such as greater physical resilience (Najmi, 2012). Paget et al. (2008) note that the majority of MR16 halogen lamps are low voltage.

The low voltage MR16 form factor is defined by ANSI C78.24-2001 which stipulates specific lamp dimensions (ANSLG - National Electrical Manufacturers Association, 2001). This enables lamps to be freely interchanged between luminaires.

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[4] While 12V is defined as *extra-low* voltage in some literature (e.g. the National Appliance and Equipment Energy Efficiency Program (2005)), the term *low voltage* will be utilised in this report. This is consistent with many of the reference documents used (e.g. Paget et al. (2008), Southern California Edison (2009)).

2.3 LED Replacement Lamps

With the advent of more reliable LED technology, MR16s are increasingly available as LED retrofit lamps. These purport to be a direct replacement for halogen MR16 lamps in terms of both physical size and lumen output but with far superior life and efficacy.

Unlike their halogen counterparts, LEDs produce light through a process known as electroluminescence. This process involves passing an electric current through a solid-state diode[5]. The diode consists of a P-N (positive-negative) junction which produces visible radiation under forward bias through the recombination of electrons and holes (Poplawski, 2011). This process is shown in Figure 2.5, where an LED with zero bias is shown on the left and forward bias on the right. The temperature at the junction (T_j) is crucial to the success of this operation and will be discussed further in Section 2.7.

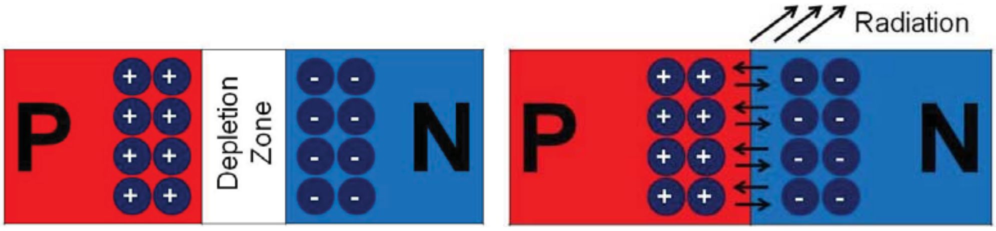

Figure 2.5 Electroluminescence (based on a diagram by Poplawski (2011, p. 6))

LEDs are comprised of a crystalline epitaxial layer deposited on a large wafer of base substrate (Howland & Pierson, 2013). This wafer of material is then scribed and sliced into small rectangles known as dice (singular die) or chips (DiLaura et al., 2011). Following the addition of electrical connections, a phosphor is applied if required[6] and the product is then encapsulated to make a complete LED “package” (Lithonia Lighting, 2010). An example is illustrated in Figure 2.6.

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[5] Due to this method of light production, LEDs fall under the category of *solid-state lighting* (SSL).

[6] Phosphor application is discussed in Section 2.4.

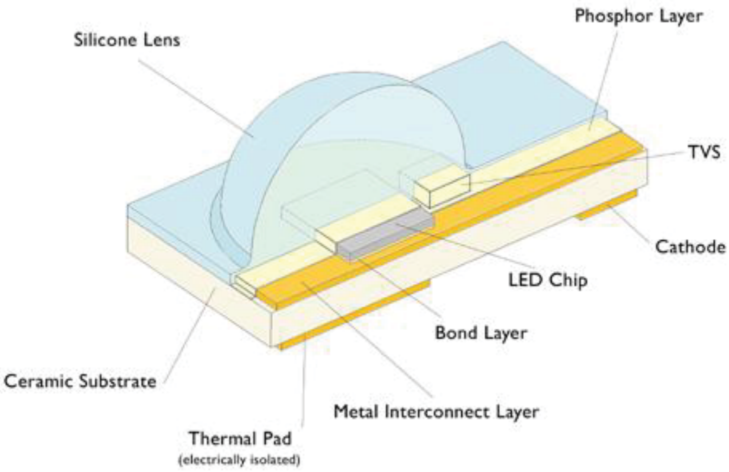

Figure 2.6 Example of LED package (Philips, 2013, p. 1)

Multiple LEDs can be used in combination to produce the necessary lumen output for a particular lamp. One example is shown in Figure 2.7, though many combinations are possible.

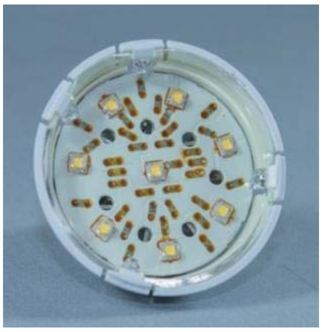

Figure 2.7 Example of multiple LED packages

In addition to the LED package(s), retrofit LED lamps are made up of the lamp housing, an integral driver and a thermal solution such as a heat sink (Van Driel, Yuan, Koh, & Zhang, 2011). Drivers are electronic devices which provide an interface between the input power supply and the LEDs (DiLaura et al., 2011). Heatsinks will be discussed in Section 2.8.

In the past, misunderstanding has caused manufacturers to calculate the lumen output of their lamp based the performance of the individual LED packages (Saula, 2011). Narendran (2011, p. 3) warns that the performance of an LED package in isolation does not reflect its performance in the lamp system “since the design of the system, its thermal management and its installation environment will all have an effect on light output, life, and color”.

He adds that “the average efficacy of an LED lighting system is approximately 60% of the bare LED package’s efficacy”. Thus an LED lamp’s performance cannot be judged by summating the individual LED outputs but by holistically considering the combined system.

Despite their MR16 designation, LED replacement lamps do not require a multifaceted reflector to provide their optics as the LEDs are highly directional by nature (Southern California Edison, 2009). This is evident in Figure 2.7 where the LEDs can be seen to be mounted onto a flat white board. The shape of the lamp is therefore a legacy of the halogen form factor, to enable direct replacement of the LED lamps into existing halogen luminaires.

LEDs that have departed from the MR16 form factor have proven problematic in the past. Figure 2.8 shows an installation in an existing public building in Auckland where LED replacement lamps had been used in chandeliers. Two brands of lamps clearly exceeded the length requirements and were protruding from the mirrored bases of the luminaires.

Figure 2.8 Retrofit lamps with poor form factor

2.4 Production of White Light

LEDs are, by nature, monochromatic light sources (Schubert, 2010), whose emitted wavelength depends on “the band gap energy of the materials forming the P-N junction” (Poplawski, 2011, p. 6). Therefore white light needs to be created through engineering techniques. These include the use of colour mixing and various phosphor techniques (Bürmen, Pernu, & Likar, 2008). At present, a blue LED in combination with phosphors is typically utilised, with the blue light being produced by Gallium Nitride (GaN) (Benya, 2012). Figure 2.9 shows a typical spectrum for an LED lamp which produces white light in this manner. The large peak on the left is a direct result of the blue LED while the wavelengths on the right are a result of the phosphor coating.

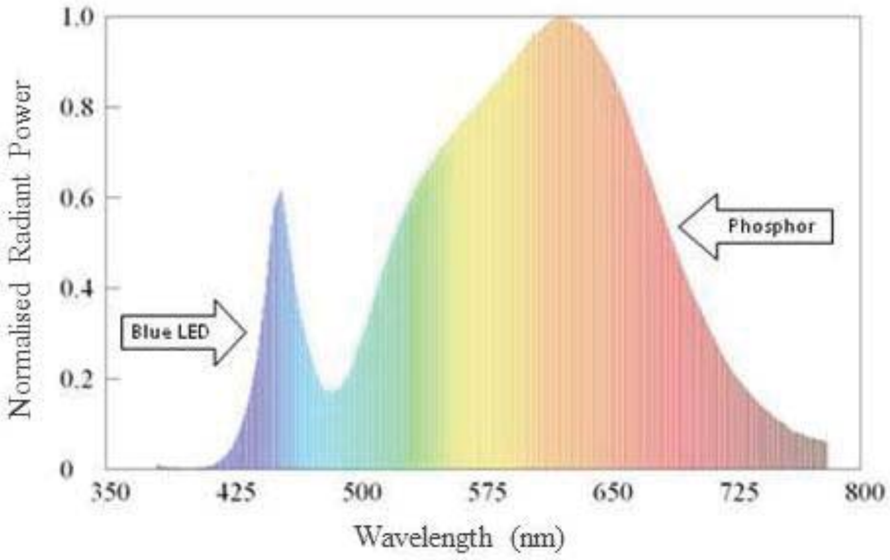

Figure 2.9 Example of LED spectrum produced by blue LED combined with phosphors

Different manufacturers use small variations within the basic LED framework to optimise their designs. For example, some may choose to include a layer of phosphor over the chip while others embed the phosphor into the encapsulant (Meneghini, Tazzoli, Mura, Meneghesso, & Zanoni, 2010). The substrate used is also manufacturer dependent and is commonly sapphire or silicon carbide (Benya, 2012). A more recent innovation is the use of GaN (Benya, 2012).

Recent developments include the addition of discrete orange LEDs in order to improve colour rendering (Dyble, 2011). One such spectrum is shown in Figure 2.10 which illustrates the extra spike introduced by the orange LED.

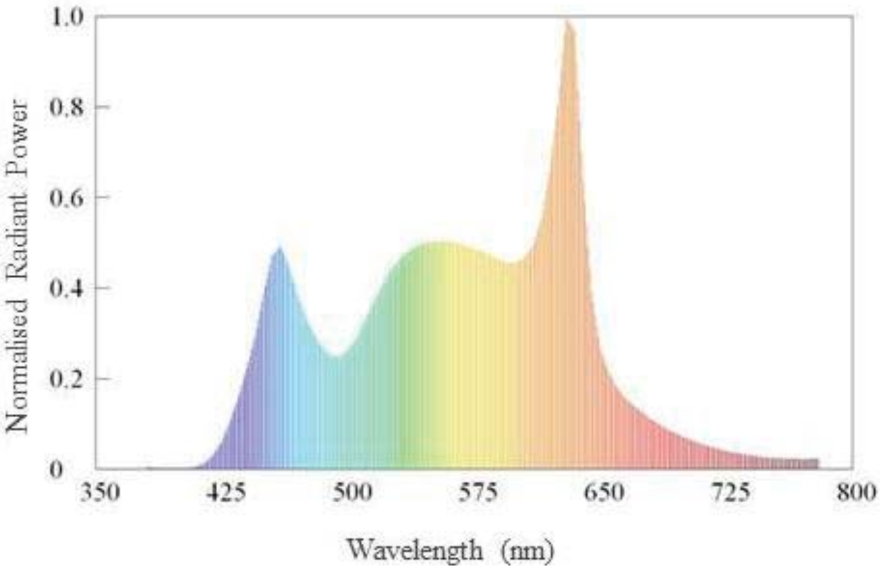

Figure 2.10 Spectrum of LED module with discrete orange LEDs

2.5 Colour Appearance of LED Replacement Lamps

2.5.1 Colour and the CIE Diagram

In photometry, colour is linked to the CIE diagram which has had various incarnations since its first introduction in 1931 (Coaton & Marsden, 1997). Figure 2.11 shows this first representation, which uses (x,y) coordinates to identify colours.

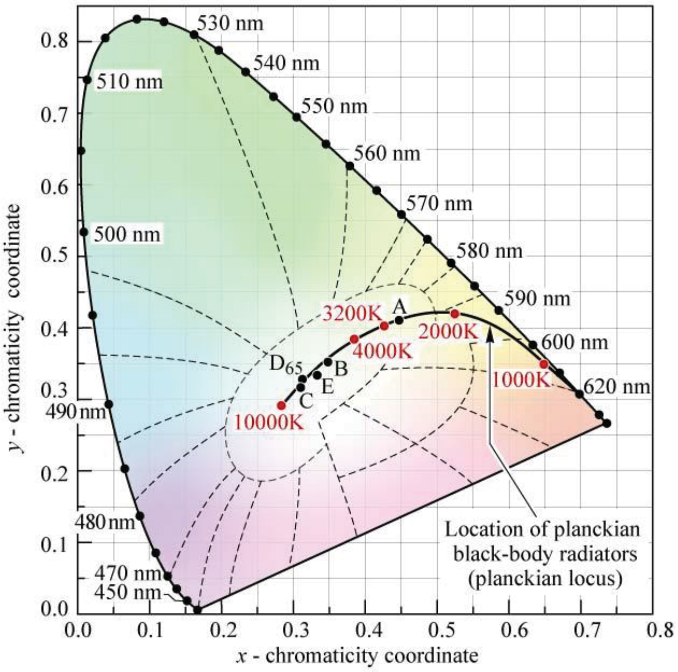

Figure 2.11 Chromaticity diagram (1931) showing black body locus (Schubert, 2010, p. 308)

The outer horseshoe shaped curve indicates pure spectral colours, while the non-spectral purples are shown as a straight line at the bottom. At the centre of the diagram is a curve known as the *black body* (or *planckian*) locus. This shows the colour emitted by a theoretically perfect black body radiator when it is heated to different temperatures (measured in Kelvin). Perhaps counterintuitively, a higher colour temperature denotes a *cooler* (more blue) light and vice versa (Coaton & Marsden, 1997). Incandescent lamps can be described in terms of colour temperature in Kelvin as their coordinates lie close to the blackbody locus (Julian, 2003).

Correlated colour temperature (CCT) is used to describe *white* lamps that are not incandescent in nature and therefore do not fall in close proximity to the black body locus. In this case the nearest point on the blackbody locus is used to describe the colour of the light source (Julian, 2003). Lamps are often incorrectly described by their *colour temperature* when the term *correlated colour temperature* should be used.

The perpendicular deviation from the blackbody locus is measured as D_{uv} which is based on the CIE 1960 (u, v) diagram (U.S. Department of Energy, 2012). A positive D_{uv} indicates a shift to the green side of the CIE diagram, whereas negative D_{uv} denotes a shift towards pink as illustrated in Figure 2.12.

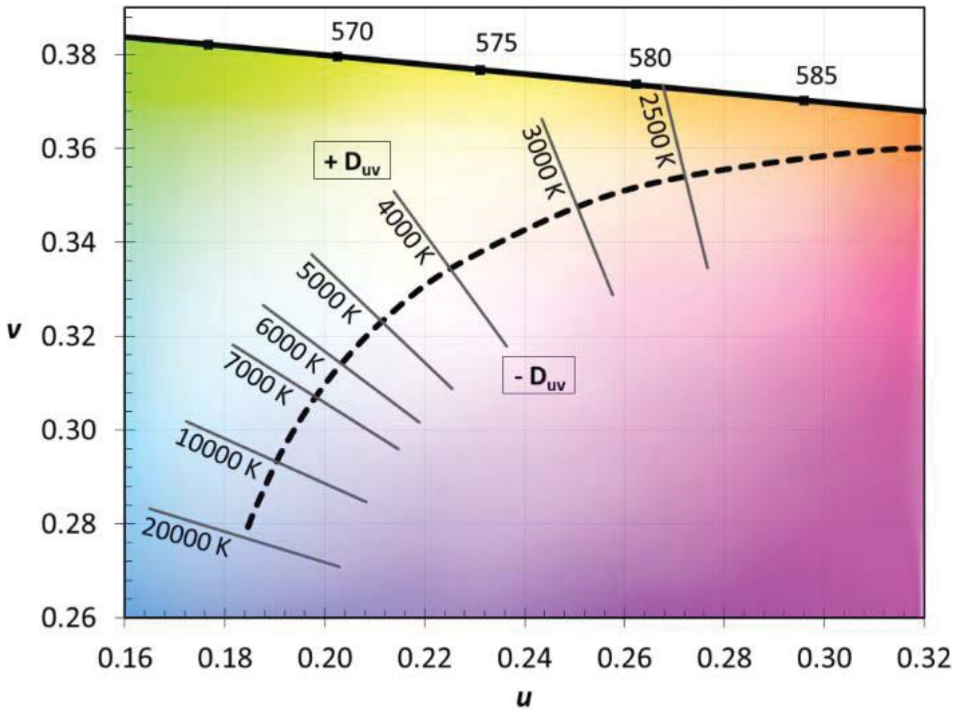

Figure 2.12 Close-up of CIE 1960 (u, v) diagram, showing CCT lines and D_{uv} (Royer, Tuttle, Rosenfeld, & Miller, 2013, p. 3)

Therefore, depending on which side of the black body locus they fall, two lamps can have the same CCT while displaying different colour characteristics (DiLaura et al., 2011).

The more recent CIE 1976 diagram is also used to denote colour change as the greater uniformity of this diagram results in a more suitable product (American National Standard Lighting Group, 2008). Thus, colour difference is frequently recorded as the change in (u', v') which is denoted as Δu'v'. This does not convey the *direction* of the colour shift but merely indicates that a shift of a certain magnitude has occurred (Royer et al., 2013).

This report will use (x, y), (u, v) and (u', v') when appropriate.

2.5.2 Correlated Colour Temperatures of Lamps

The colour temperature of incandescent lamps is restricted to approximately 2800K – 3400K which is defined by the maximum efficacy available in relation to the melting point of the filament (Murdoch, 2003). This gives incandescent lamps a *warm* colour appearance.

LEDs are not limited in this manner and a wide range of CCTs is available. However, due to very small tolerances in the manufacture of semiconductors, a plant cannot be set up to do a run of say 4000K chips as “the properties of the LEDs may vary significantly within single production runs and even on the same wafer” (Philips, 2009, p. 7). Thus a process known as *binning* is used. This tests the LEDs after manufacture to determine which colour category they fall into as defined by the quadrangles shown in Figure 2.13 from ANSI C78.377 (American National Standard Lighting Group, 2008). These correspond to the 7-step MacAdam ellipses which are commonly used for compact fluorescent lamps (DiLaura et al., 2011)[7].

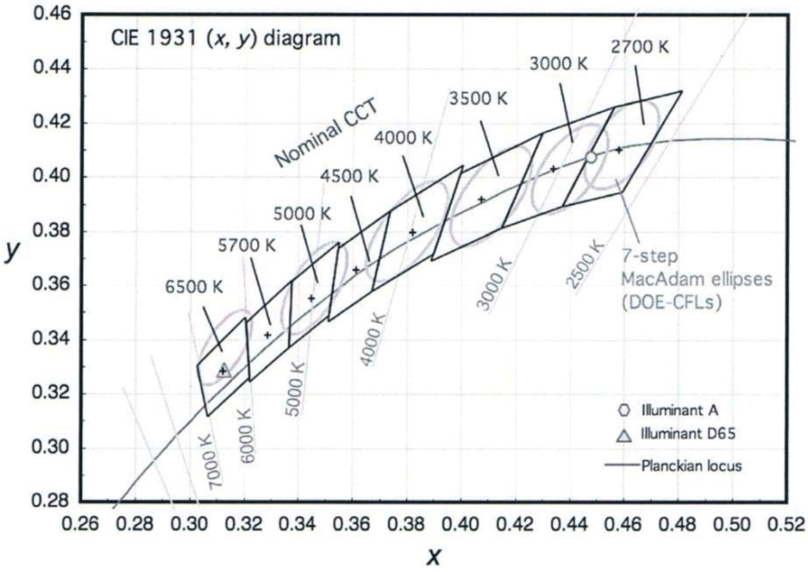

Figure 2.13 Quadrangles used to specify CCT of LEDs (American National Standard Lighting Group, 2008, p. 12)

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[7] MacAdam ellipses encompass a small group of colours that a majority of the population would perceive as being the same (Schubert, 2010). These ellipses are defined in MacAdam’s paper of 1943 entitled “Specification of small chromaticity differences” (American National Standard Lighting Group, 2008). In photometry, the term *standard deviation of colour matching* (SDCM) is also used, where a MacAdam ellipse represents one SDCM (Royer et al., 2013). Thus two lamps with different chromaticity coordinates can be described as having a difference of “x” number of steps (Royer et al., 2013).

Some companies prefer to have more stringent binning than ANSI with tighter controls. These enable lamp manufacturers to have more precise consistency in colour. An example is shown in Figure 2.14 which shows Cree's neutral and warm white sub-binning categories for one of their products. This is overlaid with the larger ANSI requirements.

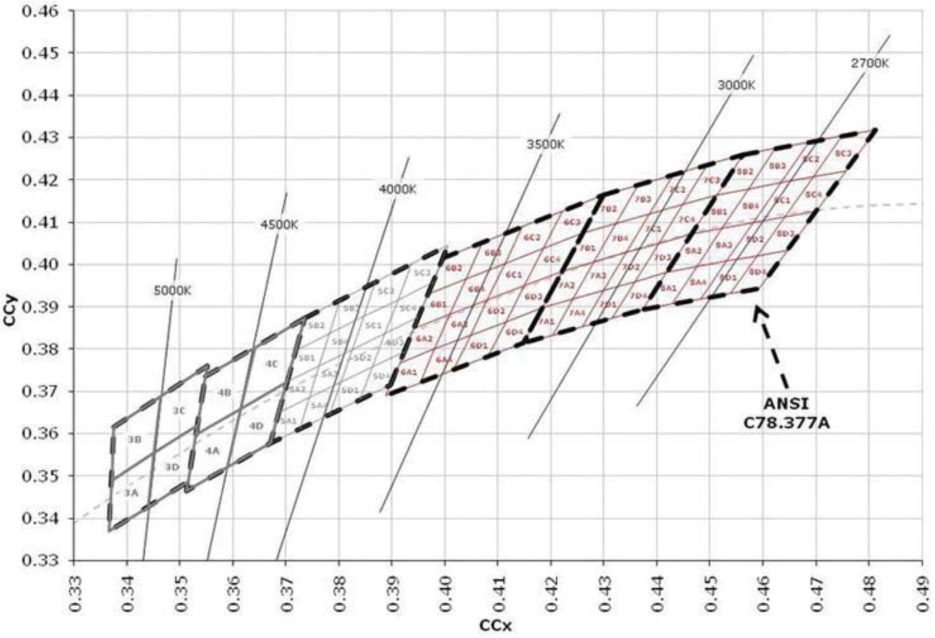

Figure 2.14 Cree's standard neutral and warm white chromaticity regions (Cree, 2013, p. 12)

Cree notes that the tightness (and therefore quality) of the bin is directly related to cost (Cree, 2010). It is therefore possible for lamp manufacturers to use *name brand* chips that are of a lesser tolerance in order to give credence to their product. In addition, some manufacturers have reportedly used their highest quality LEDs for photometric testing, only to use lesser LEDs for bulk manufacture (Southern California Edison, 2009). Unfortunately the consumer is unaware of this information and could be dissatisfied when the quality of the product doesn't meet their expectation.[8]

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[8] Another cause for concern is the incorporation of chips from credible manufacturers into "poorly engineered products" (Next Generation Lighting Industry Alliance, 2011, p. 3). The consumer could again be misled into thinking that name brand chips translate into a quality product. Unfortunately this is not always so.

In a recent document it was queried whether the tight tolerances used by some manufacturers are actually required, given that the limits imposed by ANSI are based on those used for existing lamp technologies which have been accepted and used for some time (Royer et al., 2013). Royer et al., postulated that strict limits may not be required for general lighting but that the tolerances are being driven by the high precision available with LED technology.

2.5.3 Colour Preferences

Due to the incandescent sources used, residential lighting in New Zealand has traditionally been warm coloured. With the advent of LED lighting there is perhaps more scope to change to different CCTs. It is well known that lamp colour selection tends to follow geography, such that warm coloured light is preferred by the European market with Asian consumers preferring the opposite (McKinsey & Company, 2011). Pritchard (1999) noted that colour selection is also determined by the nature of the task. He mentioned, for example, that cooler colours are used for the higher illumination levels required by the working environment. In contrast, warmer appearances are suitable for leisure activities such as entertaining. EECA’s Energywise website recommends warm coloured light for residential living spaces (EECA Energywise, n.d.).

2.6 Colour Rendering

It is possible for two lamps to have the same CCT and yet display colours quite differently due to their spectral power distributions (Murdoch, 2003). The colour rendering index (CRI) addresses this issue and provides an indication of how *true* the colours of an object are when illuminated by a certain light source (Schubert, 2010). The test process involves measuring a set of 14 objects under a reference illuminant and then under the test lamp (Davis & Ohno, n.d.). The resultant CRI is a number up to 100, with a score of 100 denoting perfect colour rendering (Schubert, 2010). The objects (denoted R1 to R14) represent medium-saturated colours, highly saturated colours, a skin tone and a green leaf (Ohno, 2005). These are shown in Figure 2.15.

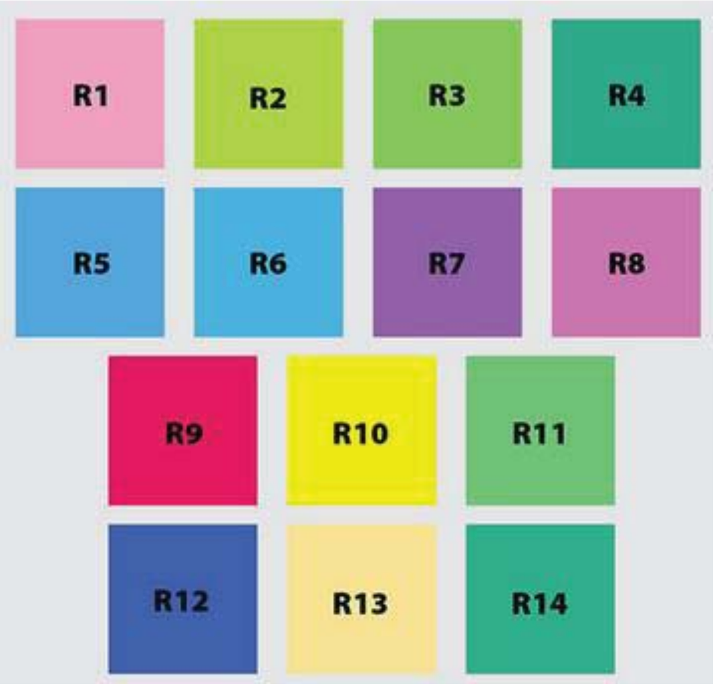

Figure 2.15 Representation[9] of the colours used to calculate CRI (EYE Lighting International of North America Inc., 2014, p. 1).

Due to their correlation to the planckian locus, incandescent sources such as MR16 halogen lamps have high values of CRI and therefore provide colour rendering that is superior to all other man-made light sources (Schubert, 2010).

The deficiencies of this CRI test are well established (American National Standard Lighting Group, 2008) and other measures of colour rendering are presently being postulated (Davis & Ohno, n.d.), however it is still used in the absence of international consensus to an alternative (Ohno, 2005). The saturated red R_9 value is singled out as important by some lighting standards as this colour tends to be particularly difficult (Ohno, 2004).

The *general CRI* (R_a) is an alternative to CRI and considers only the first eight test samples. This is the most commonly used colour rendering benchmark (Pritchard, 1999), such that when *CRI* is mentioned in reference to SSL standards such as LM-79 and ENERGY STAR, it is typically referring to R_a (American National Standard Lighting Group, 2008). This report will do likewise.

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[9] Note that the colours depicted throughout this report are indicative only, due to inaccuracies in printing processes.

2.7 Heat in LED Lamps

Though some LEDs have been specifically designed to produce infrared (IR) radiation, such as for television remote controls (Schubert, 2010), *white light* LEDs have negligible IR in the light stream (DiLaura et al., 2011). This fact has caused some to believe that LEDs do not produce any heat whatsoever, which is incorrect. Of the input energy, some 15-25% is converted into visible radiation which leaves 75-85% to be converted into heat (U.S. Department of Energy, 2007). Unlike incandescent sources, which can remove heat through radiation into the environment (Arik et al., 2010), LEDs must use a combination of conduction and convection to remove their heat to the surrounding air (NLPIP, 2003).

It is well established that temperature plays a key role in the deterioration of LEDs and the removal of heat from the junction is key (Dong & Narendran, 2009). High temperatures affect qualities such as lumen output, CCT and life, causing both recoverable and non-recoverable losses (Cree, 2004). Cree (2004) uses the example of lumen output to illustrate a recoverable loss; low lumen outputs are caused by elevated junction temperatures and are easily reversed by cooling the LED. Non-recoverable losses however occur over time due to physical changes in the LED package and cause permanent degradation (Meneghini et al., 2010).

This study will focus on non-recoverable losses. Many factors are at play here, often at a microscopic level. Meneghini, Trevisanello, Meneghesso and Zanoni (2008) have noted that the complexities of the LED structure make it difficult to pinpoint the exact cause of degradation. For example, heat induced degradation of the silicone encapsulant could be at fault (Tuttle, 2012) or perhaps browning of the phosphor (Meneghini et al., 2010). As LED packages are not generic devices, their construction and therefore failure mechanisms will vary from manufacturer to manufacturer (Philips, 2004). However, while the exact mechanism for deterioration is often not clear, the net effects of excessive heat are made obvious through shortened life and reduced performance (Dong & Narendran, 2009).

2.8 Heat Removal Methods

Various methods are employed to remove heat from the LED junction, both at the package and system level (Dong & Narendran, 2009). The two main system techniques used are active (e.g. fan) and passive heatsinks (Christensen, Ha, & Graham, 2007), with the latter being the most predominant (Arik et al., 2010). Dong et al (2009) note that passive techniques commonly employ fins which increase the area for heat transfer to occur. The thermal conductivity and emission coefficient of the fin material is instrumental in achieving optimum levels of heat removal (Philips, 2009), with aluminium commonly used (Cheng, 2007). It has been said anecdotally (for example in Charlston's blog (Charlston, 2013)) that mass is an indicator of lamp quality, by inferring that a larger quantity of aluminium translates into a more effective heatsink. However other factors can also affect the efficiency of heat extraction, such as the physical location of the fins (Dong & Narendran, 2009) and their orientation (Philips, 2009). Given the many variables, heatsinks vary between manufacturers and indeed between applications, with no *one size fits all* solution (Cree, 2004).

2.9 Typical Lamp Temperatures

Some research has focused on the effects of extreme temperatures on LEDs (e.g. Trevisanello et al. (2008)) and confirmed a correlation between these factors and performance. Denicholas (2011, p. 65) noted that this does not necessarily predict what will happen in reality and stated that for "several families of LEDs from various suppliers, the actual lumen-depreciation curves have been shown to be significantly shallower than those predicted by accelerated, high-temperature testing."

Until recently, LED data was typically given for a junction temperature of 25˚C (LEDs Magazine, 2011). Some manufacturers (for example Philips (2011) and Cree (2011)) saw this as an unrealistic representation of actual operating temperature and now choose to bin at 85˚C. Research suggests that junction temperatures can be as much as 80°C to 100°C at room temperature (Saula, 2011). It can therefore be deduced that LEDs in downlights could have junction temperatures at levels higher than even the 85˚C value used to represent a real world scenario, though data is scarce in this area.

2.10 Efficacy

Efficacy is a key element in the success of LED sources. However, with the push for energy efficiency, it is important to note that this criterion should not be taken in isolation to judge superiority. Narendran (2004) uses the example of a monochromatic amber LED which has been shown to have an efficacy of over 100lm/W yet is unsuitable as a general light source due to its colour. Therefore other items such as colour must also be considered.

Unlike the incumbent halogen lamps, efficacy varies greatly for LED products and wattage does not translate directly to light output (Saula, 2011). Efficacy values have steadily been improving as illustrated in Figure 2.16. This shows the DOE's figures for omni-directional lamps tested under their CALiPER and LED Lighting Facts programs in 2008-2009 (when entries for the L prize competition were first received) and late 2012 (U.S. Department of Energy, 2013e). Where the L Prize target was once out on its own, new products can now match or better this value.

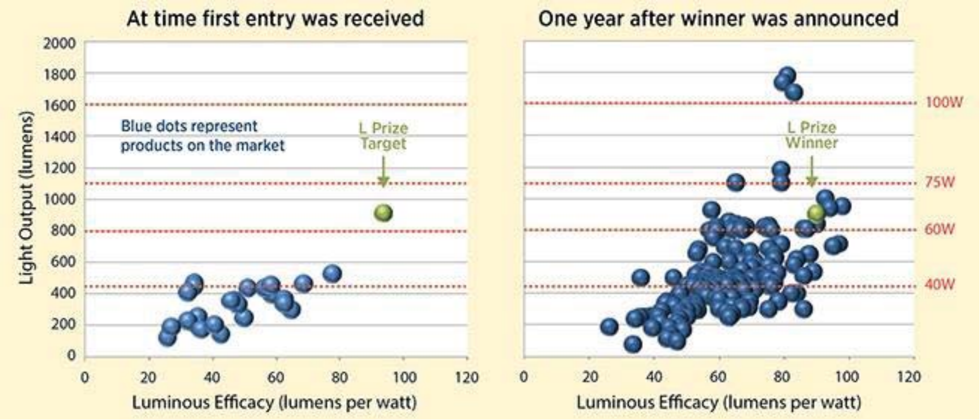

Figure 2.16 Omni-directional lamps tested under the DOE's CALiPER and Lighting Facts programs in 2008-2009 (left) and 2012 (right) (U.S. Department of Energy, 2013e, p. 1)

Lamps with higher values of CCT (i.e. *cooler* light) generally have higher efficacies due to "differences in quantum efficiencies" (U.S. Department of Energy, 2012, p. 2)

2.11 Power Supply

Low voltage MR16 halogen lamps require transformers to step down New Zealand’s 230V AC mains voltage to the lower voltage required by the lamps (typically 12V AC (National Appliance and Equipment Energy Efficiency Program, 2005)). Two main types of transformer are used. These are either an older style magnetic transformer or a more modern electronic transformer (Paget et al., 2008). While the form factor of LED MR16 lamps makes them a direct alternative to halogen in terms of size, Paget et al. (2008) note that a retrofit replacement can be hampered by problems with the existing halogen transformers. For example, electronic transformers were designed to carry a minimum load but, given their increased efficacy, LED lamps are typically under this threshold (Najmi, 2012). The net result, as stated by Najmi (2012) and reported anecdotally through suppliers (D. Holm, personal communication, May 24, 2011), is problems with flicker, hum, and in some cases a failure to start. To avoid these issues, specialised DC LED converters can be utilised in place of existing halogen transformers (D. Holm, personal communication, May 24, 2011), as LED MR16 lamps can operate on either AC or DC supply (Whitaker & Owen, 2010).

Transformer loading problems aside, reference documents give conflicting information over the difference in performance using AC and DC power supplies. Whitaker and Owen (2010) indicated that there was a large performance difference between the two different supplies, with AC operation reducing light output by some 30% when compared to DC. Meanwhile Paget, Lingard and Myer (2008) noted in a CALiPER report that the differences between AC and DC were insignificant.

2.12 Life

As it is unusual for LED packages to fail catastrophically (Royer, 2014), end-of-life is regarded as the point where the light output has reduced to 70% of its initial value (Narendran & Gu, 2005). The Lighting Research Center (2005) notes that this value is generally considered acceptable as it is “close to the threshold for detecting gradual reductions in light output… [and is] considered acceptable by the majority of occupants within a space” (Lighting Research Center, 2005, p. 4).

While it could be expected that improved technology results in longer lamp life, the figures given by manufacturers have decreased over time. Research suggests that this is due to increased awareness of the complexities involved. For example, in 2004 lamp life was commonly given as 100,000 hours, based on laboratory testing of *individual* LEDs (Hong & Narendran, 2004). However it is now known that evaluation of *system* performance is key (see Section 2.3). A 2011 Next Generation Lighting Industry Alliance report notes that this 100,000 hour figure is "gradually giving way to the realization that there is little consistency, very little published data and few hard facts around so-called luminaire lifetime numbers" (Next Generation Lighting Industry Alliance, 2011, p. 3).

While the life time of the LED system is typically referred to on the basis of light output, it should be recognised that component failure (such as driver malfunction) also plays a part in the life of the installed lighting (Next Generation Lighting Industry Alliance, 2011).

Colour shift is also a consideration in LED lifetime. However, at the time of writing, no standard exists to define acceptable levels of colour shift (Royer et al., 2013). Royer et al. note that ENERGY STAR (see Section 2.13.1) is "perhaps the only industry-wide criterion for color shift" (Royer et al., 2013, p. 6). The NGLIA points out that colour is seen as a lesser consideration than lumen output as the latter is a safety aspect and colour could be seen as merely aesthetic (Next Generation Lighting Industry Alliance, 2011).

At the time of writing, journal database searches found little information on the life of MR16 lamps when used at everyday temperatures.

2.13 Performance Standards

Standards New Zealand works closely with its Australian counterpart, such that the majority of lighting standards in New Zealand are joint publications (Standards New Zealand, n.d.). However no LED standards exist in either Trans-Tasman country and international sources are typically used. Some key references are discussed in the upcoming sections.

2.13.1 ENERGY STAR

In New Zealand, Minimum Energy Performance Standards (MEPS) have been imposed on linear and compact fluorescent lamps. These standards state the minimum allowable values of certain lamp characteristics in order for a lamp to be sold in New Zealand. The same is not true for LEDs and presently no standard exists. EECA's website states that this is predominantly due to the regulatory process involved in bringing such a standard into force (EECA, 2012).

Though LED MEPS are not available, EECA provides the ENERGY STAR program in New Zealand. This scheme provides branding to energy efficient products in New Zealand (EECA, 2012). Products that comply with all of the ENERGY STAR requirements are able to register to carry the New Zealand ENERGY STAR mark (EECA, 2011). The program is based on the North American equivalent of the same name (EECA, 2012).

The abbreviated ENERGY STAR criteria that are relevant to this study are listed in Table 2.1. Note that these are based on ENERGY STAR's required sample size of 10 units per model (5 base-up and 5 base-down).

Table 2.1 Relevant ENERGY STAR requirements for MR16 LED lamps (EECA, 2011, pp. 3, 10 & 11)

Criteria Item	**ENERGY STAR Requirements**		
Correlated Color Temperature (CCT) and D_{uv}	Lamp must have one of the following designated CCTs (per ANSI/NEMA/ANSLG C78.377-2008) consistent with the 7-step chromaticity quadrangles and D_{uv} tolerances listed below. At least 9 of the 10 samples must meet specification.		
	Nominal CCT	Target CCT (K) and tolerance	Target D_{uv} and tolerance
	2700K	2725 ± 145	0.000 ± 0.006
	3000K	3045 ± 175	0.000 ± 0.006
Colour Maintenance	The change of chromaticity over the minimum lumen maintenance test period (6000 hours) shall be within 0.007 on the CIE 1976 (u’, v’) diagram. 9 out of 10 lamps must meet specification.		
Colour Quality (Colour Rendering Index or CRI)	Minimum CRI (R_a) of 80. In addition, the R_9 value must be greater than 0. Average of 10 samples must meet specification; none lower than 77.		
Minimum Luminous Efficacy	40 lm/W. 9 out of 10 lamps must meet specification.		
Lumen Maintenance	Average of 10 samples must be ≥91.8% at 6,000 hours.		
Note: ENERGY STAR requires low wattage lamps to operate at 25ºC between lumen maintenance measurements.			

ENERGY STAR also measures colour spatial uniformity and minimum centre beam intensity, both of which are beyond the scope of this report. The document also notes that the lamp envelope should not exceed the incumbent product in terms of diameter and length as defined in ANSI C78.24.

Though ENERGY STAR was adopted by New Zealand in 2011, only three MR16 lamps are currently listed on the EECA website as having reached compliance (EECA, 2014). Of these, two are 12V and for the other the voltage is not clear.

2.13.2 NEMA

In 2012 the North American National Electrical Manufacturers Association published requirements similar to ENERGY STAR as their “Suggested Minimum Performance Requirements” (National Electrical Manufacturers Association, 2012). Their efficacy requirement was less stringent however, with only 25 lm/W required for a small lamp diameter such as the MR16 lamp. Other small changes included the sample size in some instances (6 No. were used compared to 10 No. required by ENERGY STAR). In addition, colour maintenance was not mentioned.

2.13.3 LM-79-08 Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products

Procedures for the photometric testing of complete LED products (i.e. lamps and luminaires) are given in LM-79-08 (*Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*) which is a standard produced by the Illuminating Engineering Society of North America (Illuminating Engineering Society, 2008a). This has been widely adopted amongst the international LED community. Testing to this standard results in outputs which include:

- Total luminous flux
- Spectral power distribution
- Luminous efficacy
- Colour characteristics

This testing is carried out at 25˚C ± 1˚C.

2.13.4 LM-80-08 Approved Method: Measuring Lumen Maintenance of LED Light Sources

LM-80-08 (*Approved Method: Measuring Lumen Maintenance of LED Light Sources*) is also produced by the IESNA and specifies the method for measuring lumen depreciation of LED packages, arrays and modules (Illuminating Engineering Society, 2008b). Complete lamps and luminaires are not yet included, though work on these is presently in progress (Royer et al., 2013). Thus the standard is not directly useful to this experiment, though it does provide helpful background information.

The testing method attempts to simulate actual operating conditions that the LEDs are subject to by elevating temperatures to 55˚C, 85˚C and another temperature chosen by the manufacturer. Testing is carried out “for at least 6,000 hours with data collection at a minimum of every 1000 hours” (Illuminating Engineering Society, 2008b, p. 4).

While LM-80 recognises that colour stability should be tested, it does not provide guidelines on acceptable limits (Royer et al., 2013).

2.13.5 TM-21-11 Projecting Long Term Lumen Maintenance of LED Light Sources

The long life and rapid development of LEDs combine to create a dilemma: how can a lamp be tested fully before the technology had advanced to the next level? TM-21-11 (*Projecting Long Term Lumen maintenance of LED Light Sources*) sought to address this issue by using data collected via LM-80 to predict lumen depreciation by way of mathematical functions (Illuminating Engineering Society of North America, 2011). Owing to its baseline being LM-80 (which excludes complete lamps) this document is not useful for this particular study, though it makes an interesting reference.

2.13.6 Standards Under Development

Due to the fast-moving pace of the SSL industry, new standards are constantly being developed. Two such standards that are of interest to this study are IES-LM-84 (*Method for Measuring Lumen Maintenance of LED Lamps, Light Engines, and Luminaires*) and IES-TM-28 (*Prediction of Lumen Maintenance of LED Lamps and Luminaires*) (U.S. Department of Energy, 2014). Owing to the timing of this report, it is not possible to provide an overview of these standards or other documents under development.

2.14 LED Studies

The following sections detail LED studies which are relevant to this investigation. Key findings are presented to provide a basis for comparison.

2.14.1 CALiPER

CALiPER stands for *Commercially Available Light-Emitting Diode (LED) Product Evaluation and Reporting*. This testing is performed on behalf of the DOE which uses independent laboratories to evaluate SSL products (Pacific Northwest National Laboratory, 2010b). It has produced numerous LED reports through its different investigative arms. Those with specific relevance to this study are discussed in turn in the following paragraphs.

2.14.1.1 CALiPER Benchmark Reports

CALiPER *benchmark* reports focus on baseline data for a particular type of LED application and compares them to their more traditional counterparts (U.S. Department of Energy, 2013d). A total of three reports have been produced since these began in 2008 (U.S. Department of Energy, 2013c). These consider LED replacements for MR16 lamps, linear fluorescent lamps and a combination of A-type[10] and decorative lamps.

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[10] Common household lamp shape; defined in ANSI C78.20-2003.

Of interest to this research is the November 2008 MR16 investigation which analysed ten lamps at zero hours at a temperature of 25˚C (Paget et al., 2008). The testing evaluated standard photometric qualities of luminous flux, efficacy, directionality (beam angle), CCT, CRI, power, dimming and form factor against a typical 20W MR16 halogen lamp[11].

The 2008 testing found that LED lumen output figures at that time (29-159 lumens) could not match their 20W halogen counterparts and were not suitable as direct replacements.

2.14.1.2 CALiPER Summary Reports

CALiPER *summary* reports detail the preliminary testing carried out on LED products at zero hours. These are intended to give a snapshot of the market at a given time (U.S. Department of Energy, 2013d) and investigate the standard LM-79 metrics (e.g. light output, efficacy, CCT, CRI) together with additional comparisons as appropriate. These rounds of testing began in 2006 and were updated on an ad hoc basis until 2011 (U.S. Department of Energy, 2013a).

A tally indicates that a total of 22 MR16 lamp types have been investigated since its inception (Pacific Northwest National Laboratory, 2007, 2008a, 2008b, 2008c, 2009a, 2009b, 2009c, 2010a, 2010b). These lamps ranged in wattage from 1W to 9W and had CCTs of 2620K to 6381K.

The tests found that lumen output and efficacy consistently improved over time (Pacific Northwest National Laboratory, 2010b). In the Round 4 report of 2008 it was noted that none of the lamps provided lumen output equivalent to a 20W halogen lamp (Pacific Northwest National Laboratory, 2008a). This milestone was soon reached in 2009 (Pacific Northwest National Laboratory, 2009b) though none of the MR16 LED replacement lamps tested in the CALiPER summary reports matched or surpassed the lumen output of a 35W halogen lamp (Pacific Northwest National Laboratory, 2010b).

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[11] It is not stated whether the test procedure outlined in LM-79 was followed, however this is likely, given that the standard was approved by the IES Board of Directors nearly a year previous (Illuminating Engineering Society, 2008a) and that the CALiPER studies had been using a draft version of LM-79 up to that point (Sandahl, Cort, & Gordon, 2014).

From Round 8 onwards, CALiPER summary reports highlighted areas where the LED MR16 lamps did not meet ENERGY STAR requirements. Initially, only deficiencies in power factor and CRI were recorded though light output, efficacy and CCT were included from Round 9.

The CALiPER summary reports typically investigated two or more samples with a view to investigating variability, though this was rarely discussed. Round 3 mentioned that two products “exhibited significant variation in light output, efficacy and color qualities between 2 units” (Pacific Northwest National Laboratory, 2007, p. 15) but did not provide substantiating figures, nor confirm whether the lamps were MR16 or of another type. Round 4 mentioned substantial variation between two samples of an MR16 lamp, including a 28.2% variation between the two values of efficacy (Pacific Northwest National Laboratory, 2008a), however no explanation was given for this difference.

Round 3 of the CALiPER investigation regarded lamps with photometric properties within ±10% of manufacturers’ claims as acceptable (Pacific Northwest National Laboratory, 2007). On that basis, ±10% will also be deemed acceptable by this report.

The CALiPER summary reports repeatedly noted that actual lumen outputs did not meet manufacturers’ claims (e.g. (Pacific Northwest National Laboratory, 2008a, 2009b, 2010b)).

2.14.1.3 CALiPER Application Summary Reports

Since 2012 the CALiPER summary reports discussed in Section 2.14.1.2 have focused on specific applications or product types (U.S. Department of Energy, 2013d) and are now called *application* summary reports. MR16 lamps have not yet featured in these reports (U.S. Department of Energy, 2013a, 2013b). The latest study is on LED PAR38 lamps which has increased in scope to include new measures of:

- Beam, shadow and colour quality (report produced October 2013)
- Flicker, dimming and power quality (pending)
- Stress testing (pending)
- Lumen and chromaticity maintenance (pending)

(U.S. Department of Energy, 2013b)

2.14.1.4 CALiPER Exploratory Studies

The CALiPER program lists their *exploratory* studies as being more in-depth investigations that focus on particular areas of LED technology (U.S. Department of Energy, 2013d). Testing for 12V MR16 retail replacement lamps was carried out in 2011 which specifically investigated lamps available to the general public (Pacific Northwest National Laboratory, 2011). This was prompted by the realisation that not all lamps reviewed in the CALiPER summary reports were available through retail outlets (Pacific Northwest National Laboratory, 2011). A total of 11 MR16 lamp types were sampled, though no distinction was made between 12V and mains (120V in North America) lamps.

The study noted that most of the lamps were close to the claimed values of lumen output and CCT, but none were able to meet claims of equivalency (such as *equivalent to a 35W incandescent*). It was found that four of the lamp types produced lumen outputs close to that of a 20W halogen MR16 lamp while the others fell short.

Testing was also undertaken after 1,000 hours of operation and found that one MR16 lamp type had reduced in light output by 57%. The report does not state where the lamps were mounted during the 1,000 hours burning time, so it is not known whether they were at elevated temperatures during that time.

The study investigated three samples per lamp type, though product variability is not mentioned in the report.

A similar study was carried out in 2012, though it looked only at 120V MR16 lamps (Pacific Northwest National Laboratory, 2012) which are not relevant to this study.

2.14.1.5 CALiPER Summary

All of the CALiPER studies provided good baseline data and analysis, however they fell short in some areas with regard to this study. These shortcomings include:

- variability between the lamps in each sample was rarely discussed,
- few studies considered long-term testing,
- clear distinction was not made between 12V and 120V lamps in some cases,
- the lamps had different CCTs which is known to affect efficacy.

2.14.2 GATEWAY Demonstrations

The DOE uses its GATEWAY program to demonstrate LED lighting used in real situations and typically investigates initial performance and payback, rather than monitoring performance through life (Royer et al., 2013). However, of the projects listed on the DOE website, two have considered MR16 lamps over extended periods of time. One of these, at the Smithsonian American Art Museum (Washington, DC), is ongoing but has already noted changes in lumen output and lamp colour with time (Miller & Rosenfeld, 2012).

Royer et al. (2013) noted that the Smithsonian project did not record initial baseline readings for future comparisons as the project did not have monitoring of long-term performance as an initial goal. Thus readings were only taken once a problem with colour shift had been identified and comparisons could only be made against new lamps. It was therefore noted that their data should be treated with caution.

The other MR16 GATEWAY study is of particular note and has produced some interesting findings since its inception in 2010. The project was based at the InterContinental Hotel (San Francisco, California) and included MR16 lamps in confined luminaires (Miller & Curry, 2012). These were run 24/7 in various locations within the Hotel and were tested periodically during this time[12]. The study found that lamps in completely enclosed luminaires operated 18.3°C higher than those in free air, while a 12.1°C temperature

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[12] The study states that two sample lamps were tested after 1,000 hours, 3,000 hours, 6,000 hours and 9,000 hours (Miller & Curry, 2012). It is not clear whether the same two lamps were tested each time.

differential was recorded between those same luminaires with their cover glass removed and lamps in free air (Miller & Curry, 2012). It was postulated that browning of the lamps' plastic parts after 9,000 hours was attributable to these elevated temperatures. High levels of lumen degradation were also noted at that time. Issues with lamp strobing after 9,000-13,000 hours were deemed to have likely been caused by driver problems.

While providing interesting insight, it appears that these two studies monitored only one MR16 brand each and tested only two samples of these brands. In addition, while temperature differentials were noted, photometric comparisons were not made between lamps in free air and those enclosed in luminaires. Therefore, it is not possible to draw conclusions as to the effect that elevated temperatures played on lamp deterioration.

2.14.3 Southern California Edison

A 2009 study by Southern California Edison investigated a sample of 40 individual lamps over a period of 4,872 hours (Southern California Edison, 2009). Thirty-six of the lamps were commercially available with the remainder being prototype models. One sample of each lamp type was used and all were mounted on a track at an average temperature of 76.6˚F (24.8˚C). This temperature was not consistent throughout the experiment due to the close proximity of windows. Figure 2.17 is a photograph taken from that study which shows the window in the bottom left corner of the frame.

Figure 2.17 Illustration taken from report by Southern California Edison (Southern California Edison, 2009, p. 47)

Figure 2.17 also highlights that the lamps appear to have two different orientations with some raised up approximately 45 degrees and some down by the same margin. None appear to be in the usual operating position which could affect the function of the heatsink (Illuminating Engineering Society, 2008a). It could be questioned whether one orientation was favoured over the other and confounded the experimental results.

The data collected included the photometric quantities of luminous flux, CRI and CCT as well as connected load and efficacy. These were measured after initial turn-on (30 seconds) and various (unspecified) times thereafter to 25 minutes run time. Testing was carried out fortnightly (approximately) until the end of the project. All lamps were on 24 hours a day, 7 days a week.

Qualitative tests were also performed to judge the light distribution of each lamp including intensity distribution and chromaticity aberrations across the beam.

LM-79 was in its infancy at the time of the above testing and it is clear that the standard’s test procedures have not been followed. For example, all benchmark tests were carried out after 25 minutes instead of the stabilisation period outlined in LM-79. This could lead to spurious readings. The report itself notes that the lamps changed lumen output during this time, one up to 19%. It is not known if they had stabilised after 25 minutes.

The study found that the lumen output for the lamps under test fell well below that of a 35W halogen. In addition, none that claimed to have a lumen output equivalent to a 20W halogen were able to meet this claim. It was also reported that in some cases the lumen output claimed by the manufacturer was higher than the actual value found in the laboratory. Light output was found to deteriorate over time, with seven of the commercially available lamps falling below 70% light output by the end of the experiment. All of the prototype lamps also failed in this manner. The report made no mention of possible reasons for this degradation. It was noted that some lamps experienced a radical shift in CCT and CRI while others remained stable.

3 Experimental Aims

Background research has revealed claims of exaggerated lumen outputs, dubious equivalencies, excessive product variability and high levels of lumen depreciation. In addition, little is known of how MR16 LED lamps are likely to behave in the temperatures found in a typical New Zealand home.

All of these items need to be addressed in order to ensure that satisfaction is provided to New Zealand consumers. This leads to the six experimental aims of this study.

3.1 Aim 1 – Halogen Equivalency

As noted in Section 2.3, LED MR16 retrofit lamps have been designed as a direct one-for-one replacement for their halogen counterparts. Yet reports by CALiPER and Southern California Edison (see Section 2.14) suggest that retrofit lamps cannot match the lumen output of halogen lamps. This leads to the first experimental aim:

> **Experimental Aim 1**
> To determine whether the MR16 LED lamps in a sample of 48 (six repetitions of eight types) from the New Zealand market are equivalent to their halogen counterparts in terms of lumen output.

3.2 Aim 2 – Manufacturers' Claims

Domestic users are accustomed to purchasing halogen lamps based on their wattage, with the knowledge that a higher wattage produces more light. Contrast this with LED technology, where lumen output is no longer related to wattage (see Section 2.10). The purchaser must now examine product literature to determine the output of the LED lamp. In the same way consumers, once familiar with the narrow colour range of halogen lamps, need to examine manufacturers' information to select their LED colour choice (see Section 2.5.2). There is much more potential for variability between LED products than halogen lamps and it is vital that information is presented accurately to users. As Section 1 suggests, this is key to consumer uptake of LED lamps in New Zealand. The second experimental aim is thus:

Experimental Aim 2
To determine whether the product labels provided by MR16 LED lamp manufacturers (same sample as Experimental Aim 1) quote valid figures.

3.3 Aim 3 – Baseline Lamp Quality

Even if manufacturers' information is correct, the consumer is not guaranteed a quality product unless those figures meet a certain standard in the first place. CALiPER used ENERGY STAR as a benchmark for quality from Round 8 onwards (see Section 2.14.1.2) and this study will do likewise. This leads to the third experimental aim:

Experimental Aim 3
To determine whether MR16 replacement lamps available in New Zealand (same sample as Experimental Aim 1) meet ENERGY STAR requirements.

3.4 Aim 4 – Consistency Within Type

The Southern California Edison study (see Section 2.14.3) focused on one lamp sample per type which did not allow for analysis of variation within type. CALiPER (see Section 2.14.1) used two or more lamp samples per type, however little was mentioned on how the photometric properties varied across these samples. Consistency is key in order to provide the consumer with a reliable product. The fourth experimental aim is therefore as follows:

Experimental Aim 4
To investigate the photometric variation between six repetitions of LED MR16 product (same sample as Experimental Aim 1) to test for consistency.

3.5 Aim 5 – Effect of Heat

It is well established that temperature is critical to the success of an LED (see Section 2.7).

It is difficult to translate experimental findings into a typical New Zealand situation where MR16 lamps are often utilised in downlights. Southern California Edison used lamps in free air at an average temperature of 24.8˚C. CALiPER did not specifically mention temperature data though 25˚C is assumed based on CALiPER's adherence to ENERGY STAR[13]. Section 2.9 notes that other studies have focussed on extreme temperatures which do not reflect running temperatures found in an average New Zealand home.

No study translates well to LEDs installed in downlights in New Zealand's temperate climate. Therefore, the fifth experimental aim is as follows:

Experimental Aim 5
To investigate if the heat build-up in a typical New Zealand downlight installation affects the long term attributes of MR16 retrofit lamps when compared to those same lamps mounted in free air (same sample as Experimental Aim 1).

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[13] ENERGY STAR requires a minimum of 25ºC ambient air temperature between lumen maintenance measurements for low wattage lamps.

3.6 Aim 6 – Lighting Quality Over Time

The final experimental aim carries on from Section 3.3. Retrofit lamps need to be able to maintain quality over their lives and not be overcome by non-recoverable losses. This leads to the sixth experimental aim:

Experimental Aim 6
To investigate whether energy efficiency and longevity are achieved at the expense of photometric outputs, such as a shift in CCT or significant lumen depreciation (same sample as Experimental Aim 1).

All of these elements will combine to build a picture of LED MR16 replacement lamps that are available in the New Zealand market.

4 Methodology

In order to address the six problem statements, a controlled experiment was carried out in the Lighting Laboratory at Massey University's Albany (Auckland) Campus. The laboratory was situated in a building of similar construction to a typical New Zealand house. The building was representative of a New Zealand home by virtue of being a single level timber-framed building with timber cladding, a timber floor and a tiled roof[14] (French, Camilleri, & Isaacs, 2007).

A lighting test rig was mounted abutted to the ceiling within the laboratory and open to the roof space above. This allowed seasonal variation of temperature within the test ceiling space, in order to mimic the conditions that may be experienced in an actual domestic environment. The rig housed a selection of LED lamps in downlights and free air. The lamps were on at all times except for brief moments when they were removed from the test rig for photometric testing. This testing occurred at the commencement of the study and every 1,000 hours thereafter to a total of 6,000 hours.

Testing followed LM-79 methodology as closely as practicable (see Section 4.9) and was carried out in a 1.5 metre diameter integrating sphere. Temperatures were recorded at all times within the laboratory space, ceiling space and in selected luminaires. The total time elapsed since lamp turn-on was monitored by a meter integral to the test rig to ensure that the lamps had not been off due to power failure when not under observation.

Further details are noted in the following sections.

4.1 Lamps

4.1.1 General

Due to space limitations in the test rig, the sample size for this experiment was limited to 48 No. MR16 LED lamps. This sample consisted of six repetitions of eight types. Six of the lamp types were selected by an independent agency, with the remainder sourced to match the agency's

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[14] This representation is drawn from a comprehensive study of New Zealand homes, entitled the "Household Energy End-use Project". The project is discussed in more detail in Section 4.6.1.1.

selection criteria. The final selection of lamps represented both well-known and lesser-known brands, and ranged in price from just over $20 to $100+ per unit. All were readily available to the New Zealand public at the time of purchase (2010-2011).

Due to the fast moving nature of the LED industry, there was a chance that the lamps would not be available by the time the investigation was over. However the lamp types were considered representative of a snapshot of LED MR16 lighting at the time.

While LED lamps are available in a variety of CCTs (2700-6500K+), the lamps chosen were all of a warm CCT and fell within the range of 2700-3000K. This narrow colour range suited the purpose of the study, which was to examine lamps put forward as direct replacements for halogen lamps (see Section 2.5.2). With the exception of one type, for which no designation was given, all lamps had *flood* beam patterns. ANSI C78.379 (2006) defines this as a beam angle of 25 degrees or more. Three types were 3 watts while the remainder fell within a range of 5.5-6.5W. Despite this range in wattages, five lamp types claimed equivalency with a 35W halogen.

Six samples of each type were purchased in order to enable monitoring of variance within the group and allow any spurious results to be identified which may have been caused by manufacturing defect or the use of so-called hero lamps[15]. The sets of lamps also allowed for scenarios such as catastrophic lamp failure. Three of the lamps were installed in free air and three were installed into downlights. After this decision was made, CALiPER testing also adopted a three-lamp test procedure (Pacific Northwest National Laboratory, 2011) which validated this sample size. LM-79 also recommends a multi-lamp approach as LED sources tend to have larger variation between lamps than their more traditional counterparts (Illuminating Engineering Society, 2008a).

As this report is not a product appraisal, brand name data will not be published. Each lamp type within the experiment was given unique letter of identification from A to H. Each of the lamps within type was then numerically labeled from 1 to 6. The photographs in the figures following have been altered to remove identifying labels from the lamps.

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[15] Hero lamps are lamps which outperform their counterparts, for reasons unknown (Whitaker & Owen, 2010).

4.1.2 Form Factor

In order to fit within standard MR16 household luminaires, LED MR16 retrofit lamps must have the required halogen form factor as stipulated in ANSI 78.24 (2001). Figure 4.1 below shows a typical halogen lamp of standard size to the left of the picture, alongside the test samples.

Figure 4.1 Lamps used in the experiment compared to a typical halogen lamp (on left)

Figure 4.1 shows that some lamps were bigger than their halogen counterpart. This did not present a problem for the experiment and all lamps fitted within the downlights. However, as illustrated in Section 2.3, it could be problematic in other installations where a tighter fit is required.

Two of the test lamp types exceeded the maximum lengths stipulated in ANSI C78.24. The standard specifies a maximum of 46mm from the rim to the end of the pins, (dimension "M" in Figure 4.2) and 38.4mm from the rim to the end of the neck (dimension "N" in Figure 4.2). One of the non-complying lamps is shown in Figure 4.3, with the dimensions depicted by black tape. These infringements, however minor, may cause problems in existing luminaires.

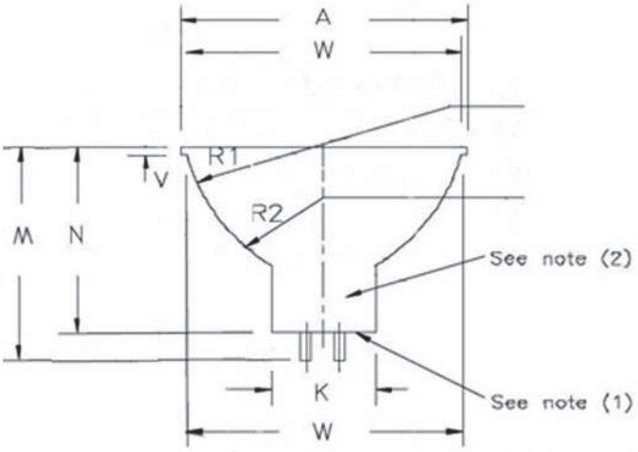

Figure 4.2 Standard dimensions of a 12V MR16 lamp (Miller & Curry, 2012, p. A3); amended by the author to include dimension M

Figure 4.3 Lamp type that exceeds maximum length; measurements that exceed ANSI maximum dimensions are shown in black

4.1.3 Physical Similarities

Another issue is one of physical similarity between products that are different at the chip level. Figure 4.4 shows two of the test lamp types which looked very similar. The cardboard packages for the two lamps were also alike, with exactly the same dimensions and identical lamp support inserts. The packaging also had very similar wording such as the advice on safety. This was of interest as the lamps were from companies who are not typically associated with each other.

Figure 4.4 Different types of lamp with physical similarities

It could be speculated that one lamp design was copied from the other or that they were manufactured at the same plant and then labeled differently. When this was queried with one of the lamp suppliers, they indicated that companies sometimes use the same mass-produced bodies (name withheld[16], personal communication, May 30, 2012). Given the complexities of optimising LED chips against heatsinks (see Section 2.8), it is questionable whether mass-producing bodies is wise. By using generic bodies for different chip architectures, the ability of the lamp to remove heat to the surrounding air may be compromised.

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[16] This name has been withheld to preserve the anonymity of the study.

These lamp types were monitored to investigate whether the physical similarities extended to a photometric match. This is discussed in Section 7.5.

4.1.4 Materials

The lamp housings were constructed of either metal or plastic, the exact properties of which are unknown. The lamps were characteristically lighter or heavier depending on the material of their housing. The two extremes are shown in Figure 4.5, with the plastic-based lamp on the left weighing an average of 23.6g across the six samples[17]. Conversely, the metal lamp on the right weighed 62.1g.

Figure 4.5 Different lamp housings

By comparison, a typical halogen lamp weighed 37.0g. It was not clear whether the added weight of the LED heatsinks would place undue mechanical stress on the luminaire, though Narendran (2011) noted that this has not typically been a problem.

4.1.5 LEDs and Drivers

Aside from the two lamps with the similar housings, the various lamp types had quite different chip placements and phosphor treatments. These are illustrated in Figure 4.6.

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[17] Scales: UWE brand; SC Series; SC-600; 600x0.2g; Serial Number A2845

Figure 4.6 Different lamp types

The use of different methodologies to achieve the same result is quite different from halogen lamps which are aesthetically similar across brands. The different layouts could affect the intensity and glare of the light source, however these items are beyond the scope of this investigation.

It follows that the different lamp types could contain different driver electronics, though analysis of driver componentry remains outside the scope of this report.

4.1.6 Seasoning

The lamps were initially tested at zero hours (i.e. with no seasoning[18]) as per Section 4 of LM-79 (Illuminating Engineering Society, 2008a).

4.2 Luminaires

The lamps in free air were mounted in ceramic lamp holders mounted on an aluminium extrusion on the side of the test rig as shown in Figure 4.7.

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[18] Some lamp types are seasoned for a period of time prior to testing to allow for the lamp operation to settle (DiLouie, 2008). This is also known as *burn-in.*

Figure 4.7 Example of lamp mounted in ceramic holder in free air

The downlight used was a “DL-66” type as shown in Figure 4.8. These were installed with CA rated heat cans, and were selected as they are commonly used in existing residential installations in New Zealand (C. Williams, personal communication, May 15, 2012).

Figure 4.8 Example of downlight used (excluding heat can)

The CA rating allowed for thermal insulation to be abutted to the recessed luminaire (Manager of Standards and Safety, 2001). While this rating has been superseded by Amendment A to AS/NZS 3000, the new code was still very much in its infancy at the time of the investigation (effective from 10 May 2012) (Energy Safety, n.d.). The majority of houses in New Zealand are likely to contain luminaires from the old code for many years to come. As LED replacement lamps are designed for retrofitting into existing installations, it was appropriate to model a pre-May 2012 domestic ceiling space.

The lamp holders provided with the luminaires were replaced with the same ceramic type used for the lamps in free air, to provide consistency and remove a variable from the experiment.

All lamps were operated in the base-up orientation and luminaire clearances were maintained according to manufacturer's instructions.

4.3 Power Supply Used

The same model Vossloh Schwabe 12V DC LED converters were used for all lamps in the experiment to ensure consistency. The converters were selected on the advice of Derek Holm, the General Manager of Vossloh Schwabe Deutschland GmbH (Auckland) (D. Holm, personal communication, May 31, 2011). Holm advised that the industry was (at that time) experiencing problems with AC transformer compatability, and selected 12V DC LED converters to avoid these issues.

As the focus of this study is on lamps, analysis of the converter componentry remains outside the scope of this report.

4.4 Test Rig Construction

The downlights were installed into a mock-up of a residential ceiling which was housed in Massey University's specialist lighting laboratory in Auckland, New Zealand. The ceiling panel was 2.4 metres by 1.2 metres in size, allowing space for all 48 lamps.

In order to provide authenticity, the ceiling panel was built to industry best-practice by a registered builder to model a New Zealand setting as closely as possible. Thus the main ceiling panel was of plasterboard construction with timber ceiling battens and the ceiling space was thermally insulated. The rig protruded down 250 mm into the laboratory and was open to the actual ceiling space of the laboratory. This provided seasonal temperature variation in both the test room and the ceiling space.

The rig housed both the LED lamps in downlights and the "bare" LED lamps in free air, which were mounted on the side of the rig as shown in Figure 4.9.

Figure 4.9 Test rig set up in laboratory showing lamps in downlights and free air

Each lamp was assigned a position and remained in that position throughout the experiment.

4.5 Test Rig Location

The test rig was housed in Massey University's specialist lighting laboratory. This room is housed in a single level timber-framed building with weatherboard cladding, a tiled roof and carpet over a timber floor. According to HEEP[19] figures, this corresponds to a typical New Zealand house which has the following qualities:

- timber frame with weatherboard or brick veneer cladding (75% of HEEP sample)
- a timber (60%) or concrete (30%) floor
- a long-run steel roof (61%) or tiles (22%)
- typically stand-alone with one level (71%) or two levels (26%)
- carpet covering living areas of concrete slab floors (66%) and suspended timber floors (57%)

(French et al., 2007, p. 1)

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[19] HEEP standards for "Household Energy End-use Project" and is discussed in more detail in Section 4.6.1.1.

This adds further credibility to the study rather than the alternative of perhaps a room in a multi-storied building of concrete construction.

Like most New Zealand homes (French et al., 2007), air conditioning was not present except for isolated working days when the laboratory was maintained at approximately 25°C for photometric testing to be undertaken.

The laboratory contained a window which was thermally insulated at all times. The rig was installed at the opposite end to the window and was not in any direct draughts or sun light.

4.6 Temperature

Seven thermocouples allowed for constant monitoring of the ceiling, room and luminaire temperatures, to provide an accurate picture of the various environments. These were placed as follows:

- 2 x ceiling space directly above the lighting rig
- 2 x room at high level in the vicinity of the free air lamps
- 3 x randomly selected luminaires. These were mounted above the lamps inside the heat cans, adjacent to but not touching the lamp

Data collection commenced on 7 August 2012. Temperatures were recorded using a HIOKI 8430-20 data logger at one minute intervals. One hour averages were taken of this minute-by-minute data and transferred to Microsoft Excel for analysis.

4.6.1 Baseline Temperature Data

Temperatures reached in the laboratory were recorded in order to confirm that the laboratory representation of a real New Zealand domestic situation was valid.

4.6.1.1 Mean Room Temperature

The most recent relevant large scale mean household room temperature data is from the *Household Energy End-use Project* (HEEP). This project collected, amongst other things, living room temperatures of approximately 400 homes throughout New Zealand over a period of ten years (Isaacs et al., 2010). The final HEEP report of 2010 stated that the study had produced the first analysis of New Zealand household temperatures since the Household Electricity Survey of the early 1970s (Isaacs et al., 2010).

HEEP gave figures of mean winter (June – August) and summer (December – February) Living Room temperatures for two different time periods. The data is summarised in Table 4.1, with actual data from the lab also shown. This indicates that a difference of only 2.2˚C to 3.9˚C was evident, with HEEP data reading slightly lower than the experimental data.

Table 4.1 Comparison of laboratory mean day and mean night temperatures with HEEP reference

	Mean Day (9:00am–5:00pm) Temperature (ºC)		**Mean Night (5:00pm–11:00pm) Temperature (ºC)**	
	Summer	**Winter**[20]	**Summer**	**Winter**[20]
Actual Data (Auckland)	25.5	19.7	26.1	20.0
HEEP Data (National)	21.8	15.8	23.1	17.8
Difference	3.7	3.9	3.0	2.2

These differences were to be expected as HEEP utilised data from throughout New Zealand, whereas the laboratory was based in Auckland, in the upper part of the North Island. Data from the National Institute of Water and Atmospheric Research (NIWA) suggests that Auckland's average temperature is typically 2.8˚C higher than the national average (NIWA, 2013). As this is similar to the differences noted in Table 4.1, it could be deduced that the temperatures reached in the laboratory were fairly representative of the temperature in New Zealand homes.

4.6.1.2 Maximum Temperature

As HEEP did not report temperature data for the ceiling space, an unpublished study by Massey University was utilised as a comparison for this experiment. The study recorded temperatures in the ceiling cavities of 30 Auckland homes in the summer of 2008/2009 (M. Boulic, personal communication, January 30, 2014). Temperature readings for the unpublished study were taken at approximately 150-200mm above the ceiling which is similar to the location of the thermocouples in this experiment. The data is summarised in Table 4.2, with the actual data from the laboratory also shown. This indicates that the maximum ceiling temperature recorded in this experiment was aligned with the Massey University unpublished data, though it falls at the lower end of that data set. The maximum temperature reached

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[20] Note that full winter data is not available as the investigation commenced in August 2012 (southern hemisphere mid-winter) and was completed prior to winter 2013.

in the laboratory could therefore be said to be consistent with that reached in an Auckland house.

Table 4.2 Comparison of laboratory maximum ceiling space temperature with Massey University Reference

	Maximum Temperature in Ceiling Space with Tiled Roof (˚C)
Actual Data	38.0
Unpublished Data from Massey University (30 Houses)	Mean 44.2; Range 34.0 – 61.0

4.6.2 Maximum and Minimum Temperatures

The overall maximum and minimum temperatures recorded for each of the seven thermocouples are listed in Table 4.3. These corresponded to summer highs and winter lows as expected.

Table 4.3 Overall maximum and minimum temperatures for the experiment (°C)

	Free Air 1	**Free Air 2**	**Downlight 1**	**Downlight 2**	**Downlight 3**	**Ceiling 1**	**Ceiling 2**
Min	14.1	14.9	32.6	34.0	27.5	8.9	8.3
Max	31.1	31.2	54.0	52.7	55.1	38.0	36.6

It is interesting to note that the literature for some of the retrofit lamps prohibited operation in *ambient* temperatures over 40˚C. The data in Table 4.3 shows that while this temperature was not exceeded in the ceiling cavity, the conditions in the downlights themselves were well above this. It is questioned whether the manufacturer based the 40˚C maximum on scientific testing, or it was simply a blanket statement to perhaps limit their obligations under warranty. This poses a potential problem to the consumer, as though Table 4.3 indicates that temperatures will exceed this threshold, it is hard to easily verify this prior to installation.

4.6.3 Seasonal Variation

Figure 4.10 shows the maximum, minimum and average temperatures measured in the downlights and free air across the seasons. Auckland has a "warm temperate maritime climate" (Gosai, Salinger, & Dirks, 2009, p. 522) which is evidenced below by the small changes in temperature throughout the year.

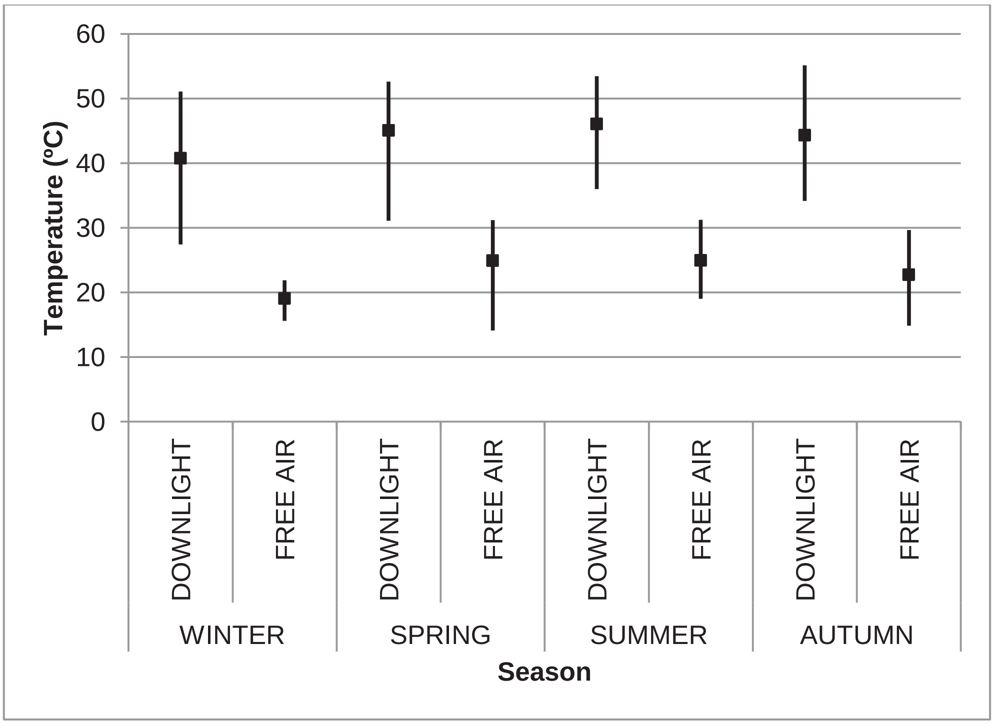

Figure 4.10 Temperatures by season – average and range

4.6.4 Temperature Differential

Analysis of the temperature data indicated that the air adjacent to the lamps in downlights was approximately 21˚C hotter than that adjacent to their free air counterparts. This trend was consistently observed throughout the year, though extreme highs and lows did occur as shown in Figure 4.10.

4.7 Time Frame

LM-80 states the minimum time frame for testing lumen maintenance as 6,000 hours (Illuminating Engineering Society, 2008b) which equates to just over 8 months of continuous use. While the LM-80 standard is not used for lamp testing, it is a useful benchmark. The test period was therefore chosen to be 6,000 hours on that basis. ENERGY STAR also uses a 6,000 hour timeframe for testing lumen depreciation (EECA, 2011) which provided further support for this decision. While this period of time was, by necessity, considerably shorter than the 50,000 hours (5 years+) life claimed by some manufacturers, it was envisaged that indicative trends would become apparent within this interval.

Testing was performed every 1,000 hours in accordance with Section 7.1 of LM-80 (Illuminating Engineering Society, 2008b).

In order to complete the experiment in the shortest timeframe possible, the test rig was left running at all times. The total time run was monitored by an hours-run meter (Omron H7ET) which was integral to the test set-up.

4.8 Test Parameters

Testing was based on LM-79, though strict adherence was not always possible due to the equipment available (see Section 4.9). The departures from LM-79 were not considered to affect the outcome of the experiment.

A temperature of 25˚C ± 1˚C was used for all testing lamps, whether they had been in downlights or free air. This means that only the difference in *non-recoverable* losses was under test (see Section 2.7). To test otherwise would require specialised equipment to measure performance characteristics while the lamps were in-situ. While it would be useful to investigate recoverable losses in the future, this fell outside the scope of the study.

4.9 Photometric Equipment

A 1.5 metre diameter Sensing SPR-600M integrating sphere was used for photometric testing. This meets the guideline given in LM-79 for a minimum 1 metre diameter for compact lamps (Illuminating Engineering Society, 2008a).

The same 12V DC LED converter was used for all testing.

A 2π configuration[21] was used for all testing, with the lamp mounted in the sphere's side-plate. LM-79 notes that "2π geometry…is acceptable for SSL products emitting light only in forwards direction" (Illuminating Engineering Society, 2008a, p. 5). However the associated diagram in the standard shows the lamp mounted in the *top* of the sphere, rather than the side. This demonstrates LM-79's requirement that the lamp's position in the sphere should model its ordinary burning position as lamp orientation could alter heat dissipation. Due to the equipment available, top-mounting was not possible and so the sphere's side-plate was utilised. While this would seem to contravene LM-79, a report by Navigant Consulting (2010) notes that by aiming the test lamp to the bottom of the sphere in this manner, the area of least reliability (owing to dust build up) is being utilised. In addition, CIE84-1989 recommends sphere-wall mounting for strongly directional lamps such as LEDs (Commission Internationale de l'Eclairage, 1996). Trials of other directional lamp types in both 4π and 2π geometries suggested that this would not significantly alter the photometric readings and the side-plate mounting was seen as acceptable for the experiment. As further validation for this mounting configuration, a recent report prepared for the LED Systems Reliability Consortium and the U.S. Department of Energy by RTI International noted a similar arrangement was used for their experiment (RTI International, 2013).

This set-up is shown in Figure 4.11, where the sphere is shown on the left and a close-up of a lamp in position is shown on the right. In order to preserve consistency, the lamps were always installed into the sphere in the same orientation (typically brand-name-up).

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[21] 2π geometry refers to when the test lamp is mounted on the side of the integrating sphere and emits light into the sphere through a port. 4π geometry has the test lamp at its centre.

Figure 4.11 Integrating sphere used for testing (J.P. de la Chaumette, personal communication, August 9, 2013); close up of side-plate is shown on the right

The sphere was calibrated using an omni-directional incandescent lamp which is traceable to Hangzhou Zhejiang University Sensing Instruments Co., Ltd. While LM-79 states that forward emitting standard lamps should be used for 2π calibration, this was not possible with the equipment available. Navigant Consulting (2010) observed that an omni-directional lamp could introduce measurement errors but noted that it is more of an issue for narrow-beam lamps than the flood beam lamps of this investigation.

In combination with the integrating sphere, photometric measurements were made by a spectroradiometer (Sensing SL-300) which is the preferred detector of LM-79. The spectroradiometer had a range of 380nm to 780nm and scanned at 5nm intervals.

The following photometric outputs were recorded and used for analysis of the six experimental aims listed in Section 3:

- Total luminous flux
- Spectral power distribution
- Luminous efficacy
- Colour characteristics (including CCT, D_{uv}, CRI, R_9 and chromaticity coordinates)

5 Halogen Equivalency

5.1 Benchmark

In order to establish a comparison between LEDs and their halogen counterparts, it is important to determine the typical lumen output of a halogen lamp. A large number of data sources were considered when establishing a halogen benchmark. These included product brochures and results from laboratory testing. Details of these investigations are given in the upcoming sections.

5.1.1 Product Catalogues

Product catalogues were found to vary greatly, listing multiple lumen outputs for a 35W lamp. The DOE found a similar variation in their 2008 CALiPER benchmark report, where they considered a large quantity of 20W MR16 halogen lamps. Their report established an average of 278 lumens from manufacturers' data with a range of 130-400 lumens (Paget et al., 2008).

5.1.2 Laboratory Data

The Southern California Edison study appeared to utilise data collected from their laboratory in their comparisons (Southern California Edison, 2009). This information was only given in graph form rather than tabulated in the report. Reading from the graph, it can be deduced that a figure of approximately 415 lumens was used for a 35W lamp and 250 lumens for a 20W lamp. CALiPER's 2008 benchmark testing meanwhile found a range 172-352 lumens for 20W lamps, with an average of 263 lumens (Paget et al., 2008). A later CALiPER report noted a range of 500-603 lumens for 35W lamps (Pacific Northwest National Laboratory, 2010b). A further report, by Navigant Consulting Europe, noted values of 500-700 lumens for 35W lamps with IRC technology (Navigant Consulting Europe Ltd, 2010).

5.1.3 MEPS

Given the variation in lamp output demonstrated in Sections 5.1.1 and 5.1.2, it was decided to utilise Australia's MEPS scheme as a halogen benchmark. Australia's scheme was used as New Zealand does not presently regulate incandescent lamps (see Section 1). MEPS requirements for incandescent lamps are given in Equation 5.1.

Initial efficacy: Average value shall be $\geq (2.8 \ln(L) - 4.0)$

Where $\ln(L)$ is the natural logarithm of the measured initial luminous flux (in lumens)

Equation 5.1 (Commonwealth of Australia E3 Equipment Energy Efficiency, n.d.)

As efficacy is a measure of lumens per watt, Equation 5.1 can be utilised to determine the minimum lumen output for each standard halogen lamp wattage. This information is given in Table 5.1.

Table 5.1 Minimum lumen output as determined by Australian MEPS[22]

Lamp Power (watts)	Minimum Lumen Output (lumens)
10	85
20	223
35	462

A comparison of all reference data is included in Table 5.2.

Table 5.2 Comparison of lumen output figures discussed in Section 5.1

Lamp Power (watts)	Product Catalogues (CALiPER)	Laboratory Data			MEPS
		Southern California Edison	CALiPER	Navigant Consulting Europe	
10	-	-	-	-	85
20	130-400 (278 av)	~250	172-352 (263 av)	-	223
35	-	~415	500-603	500-700	462

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[22] The calculation methodology used in this report for MEPS minimum lumen outputs has been verified by Lighting Council Australia (O. Manley, personal communication, January 13, 2014).

Table 5.2 indicates that the MEPS figures are at the lower end of the data ranges collected via product catalogues and through laboratory tests. This makes sense, as MEPS are based on *minimum* performance standards, with the expectation that lamps in Australia will be able to at least reach this standard. Thus in order for LEDs to be a viable replacement, they must at least make these minimum standards.

5.2 General Luminous Flux Equivalency

Of the eight lamp types, five claimed equivalency to a 35W halogen lamp in their literature[23]. These lamps (Types A, B, D, E and G) are shown in Figure 5.1 and are rated against the Australian MEPS minimum (see Section 5.1.3).

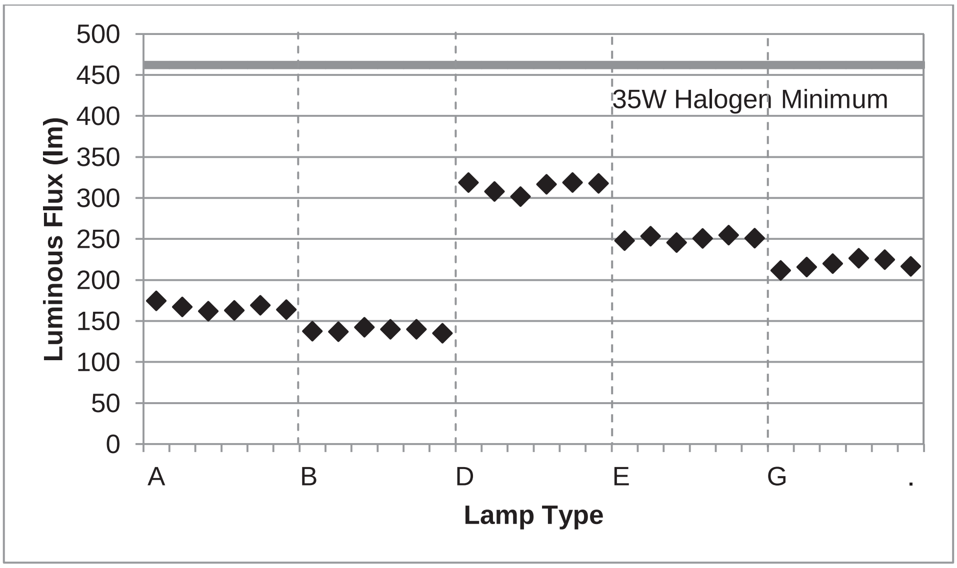

Figure 5.1 Luminous flux at zero hours (for Types A, B, D, E and G) versus the 35W halogen MEPS minimum

It can be seen that all five lamp types fall well short of the 462 lumen minimum set for 35W halogen lamps by MEPS. The 10W and 20W halogen MEPS minimums are overlaid onto the same data in Figure 5.2. It can now be seen that Type D and Type E are above the 20W halogen minimum, with Type G straddling the cut-off line. Type A and Type B fall short of the 20W

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[23] It is noted that in two cases disclaimers were given to diminish responsibility for the accuracy of the equivalency claims.

minimum requirement and are only suitable as replacements for 10W halogen lamps.

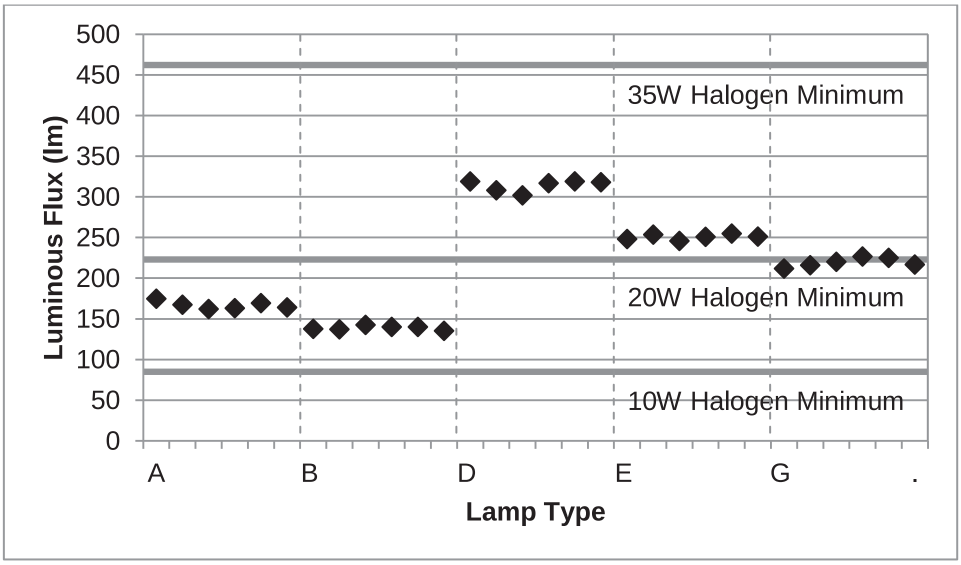

Figure 5.2 Luminous flux at zero hours (for Types A, B, D, E and G) versus the halogen MEPS minimums

The above information illustrates that purchasers hoping to replace their 35W halogen lamps with *equivalent* LED types may be disappointed.

While the other lamp types did not state halogen equivalency in their literature, it is interesting to see the type of lamp that they are likely to replace. To this end, Figure 5.3 shows all lamp types against the MEPS minimum requirements. For clarity, the average lumen value for each lamp type is used.

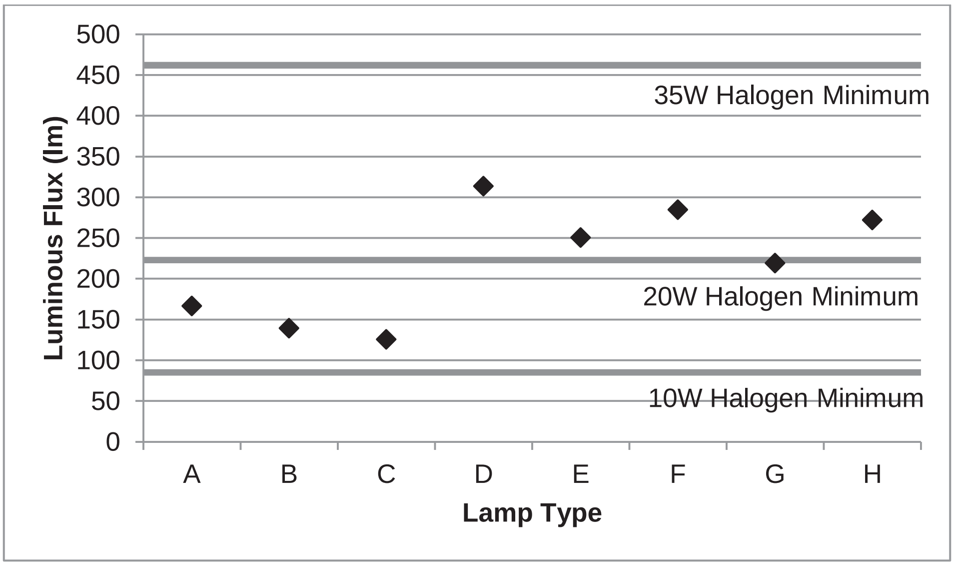

Figure 5.3 Average luminous flux at zero hours versus the halogen MEPS minimums

Figure 5.3 shows that Types A, B and C are only suitable as 10W halogen lamp replacements while the others are able to replace 20W halogens (though Type G is borderline). None of the lamps are suitable to replace 35W halogen lamps, which is a common wattage used in New Zealand homes.

Type C had the poorest lumen output. At an average of 125 lumens, these were only producing 27% of the required 35W halogen minimum. Type D was the closest to 35W but still only reached 68% of the required halogen output.

5.3 Summary of Halogen Equivalency

Five of the lamp types claimed that they had lumen outputs equivalent to a 35W halogen lamp but all failed to meet the Australian MEPS criterion. None of these lamp types were therefore able to perform to the standard claimed in their literature and are not suitable as one-for-one replacements. This agreed with the CALiPER exploratory study for 12V MR16 retail replacement lamps which noted that none of the samples in their study were able to meet claims of equivalency. This failure to meet expectation could lead to a poor consumer experience and limit their acceptance of LED MR16 products.

All lamp types were then compared to MEPS minimums to determine which halogen lamp type they were likely to replace. Types A, B and C were only able to replace 10W halogen lamps while the others were all suitable as 20W halogen lamp replacements (though Type G was borderline). This agreed with findings from the CALiPER and Southern California Edison reports which noted that none of the lamps in their studies were able to produce a lumen output that matched or surpassed a 35W halogen lamp. Given that 35W halogen lamps are a common wattage in New Zealand homes, these low figures are disappointing and will limit the utilisation of these LED lamps.

Without the benefit of photometric testing, the consumer would not be aware of the discrepancies in claimed and actual halogen equivalency. This highlights the need for accurate product labeling, which will be discussed further in Section 6.5.

6 Manufacturers' Claims

Some of the lamp types list photometric properties in the manufacturer's literature. This section evaluates whether these lamps are able to live up to the manufacturer's claims. A tolerance of ±10% is used which is based on Round 3 of CALiPER (see Section 2.14.1.2).

6.1 Luminous Flux

Of the eight lamp types, only three advised values of luminous flux[24] in their literature. Table 6.1 shows the quoted values of luminous flux for Types A, E and F against their actual output at zero hours.

Table 6.1 Comparison of lumen output claimed on product labels with actual initial lumen output

Lamp Type	Claimed Lumen Output (lumens)	Actual Initial Lumen Output - Average (lumens)	Actual Initial Lumen Output - Range (lumens)
A	178	166.6	162.0 – 174.6
E	255	250.6	245.7 – 254.7
F	300	284.8	270.7 – 313.2

In all cases, the average lumen output was slightly lower than that claimed by the manufacturer with none of the Type A or E lamps meeting expectation. The maximum difference was for a Type F lamp which had a lumen output that was 9.8% lower than claimed. Type F was the only lamp type to exceed the value stated by the manufacturer, though only one lamp in that sample performed as claimed. Despite these disparities, all lamps were within the designated ±10% tolerance.

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[24] Note that this is different from lumen *equivalence* (e.g. *equivalent to a 35W halogen*), though both metrics are measured in lumens.

6.2 Correlated Colour Temperature

Six of the eight lamp types had CCTs listed in their literature and one was listed as *warm white* which C78.376 describes as 3000K (American National Standard Lighting Group, 2001). These values are summarised in Table 6.2.

Table 6.2 CCT values listed in literature

Lamp Type	**Claimed CCT(K)**
A	3000
B	Warm White
C	3000
D	2700
E	3000
F	3000
G	2800

Comparisons are made for each CCT in the following sections.

6.2.1 3000K Lamps

Figure 6.1 shows the CCT data recorded at the initiation of the investigation for each 3000K rated lamp, with the ±10% tolerance shown as a grey band. Types A, B and C all fall close to the 3000K line whereas Types E and F are above the line. Type F had the greatest variation from the stated 3000K value, with values of up to 11.1% higher than stated. The values for CCT will be analysed further in Section 7.2 to determine whether they fit within specified ENERGY STAR tolerances.

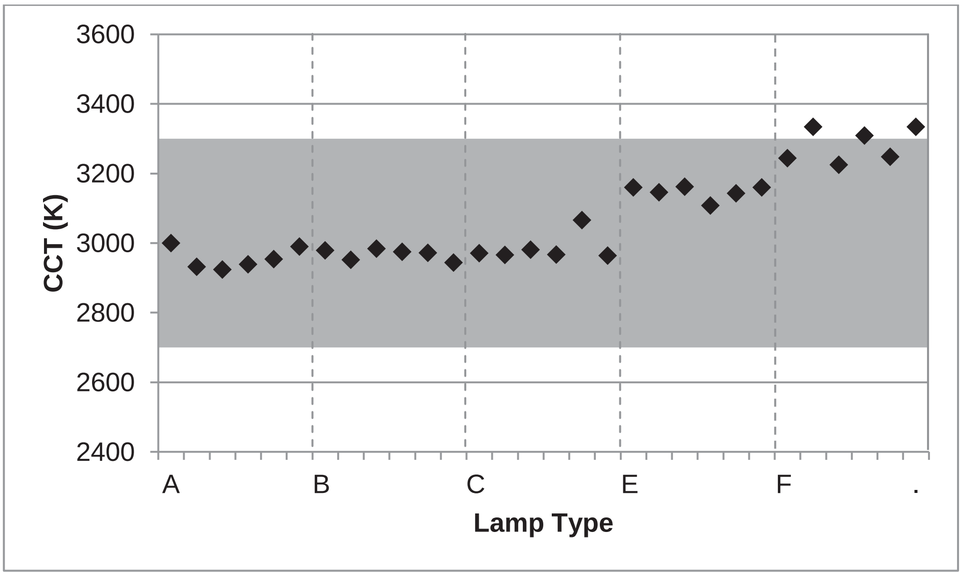


Figure 6.1 CCT at zero hours for 3000K lamps

6.2.2 2700K and 2800K Lamps

Figure 6.2 and Figure 6.3 consider the CCT for the Type D and Type G lamps which claim to be 2700K and 2800K respectively. In all cases the lamps are easily within the ±10% tolerance, with the maximum differences being 1.7% (Type D) and 5.4% (Type G) from the values stated by the manufacturer.

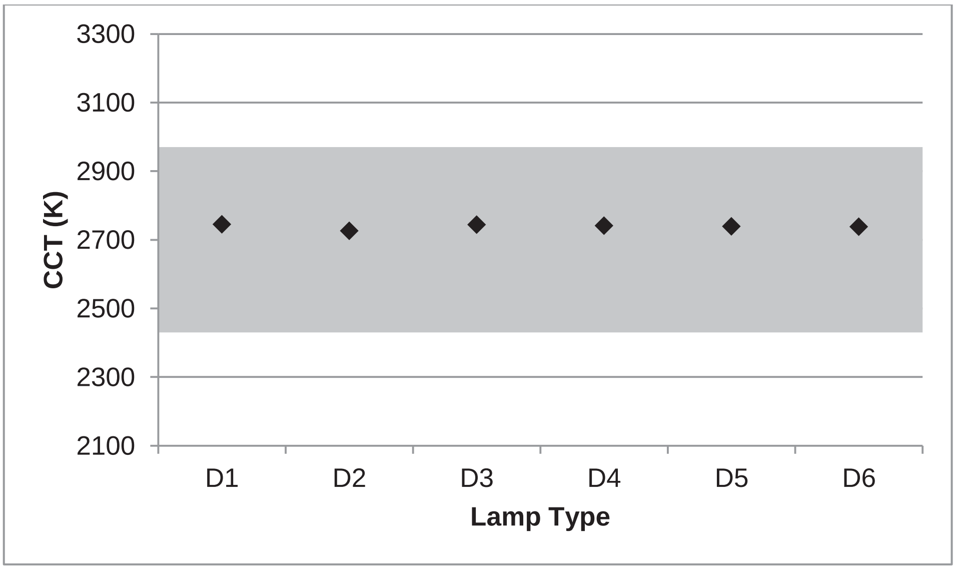


Figure 6.2 CCT at zero hours for 2700K lamps

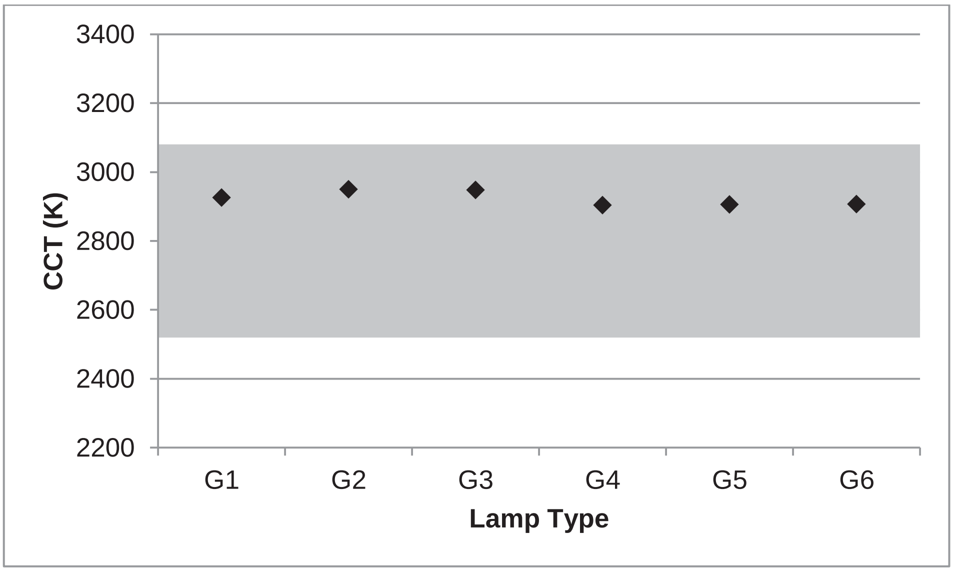


Figure 6.3 CCT at zero hours for 2800K lamps

6.3 Colour Rendering Index

CRI was listed on three of the products' labels, and these values are summarised in Table 6.3. Testing found that Types A and G exceeded their stated CRI values in all but one case, however Type F lamps fell well short by up to 26.3%.

Table 6.3 Comparison of CRI stated in literature with actual CRI

Lamp Type	Claimed CRI	Actual Initial CRI - Average	Actual Initial CRI – Range
A	85	86.9	84.2 – 88.3
F	70	52.4	51.6 – 52.9
G	82	82.4	82.0 – 82.7

6.4 Efficacy

Types A and F were the only lamps to advise efficacy values on their respective product labels. These are listed in column 2 of Table 6.4 against the efficacy values found in this study. It is important to note that the recorded values included LED converter losses which will result in lower figures than for the bare lamps themselves. These values will be used for making comparisons elsewhere in this report as the same LED converter was consistently used. However in order to compare against the values given by the manufacturer, the luminous flux has also been divided by the stated lamp wattage to provide an estimated efficacy for comparison. These comparisons are detailed in Table 6.4.

Table 6.4 Comparison of efficacy stated in literature with actual initial efficacy

Lamp Type	Claimed Efficacy (lm/W)	Actual Initial Efficacy incl. LED Converter: Average (lumens)	Actual Initial Efficacy incl. LED Converter: Range (lumens)	Estimated Initial Efficacy excl LED Converter: Average (lumens)	Estimated Initial Efficacy excl LED Converter: Range (lumens)
A	57	40.2	38.2 – 41.3	55.5	54.0 – 58.2
F	50	41.5	39.5 – 44.9	47.5	45.1 – 52.2

Even with LED converter losses taken into consideration, efficacy in both cases was typically lower than expected though still fell within the ±10% tolerance (5.3% maximum for Type A and 9.8% maximum for Type F). Further studies where LED converter losses are excluded would be required to confirm this result.

6.5 Summary of Manufacturers' Claims

Figure 6.4 summarises the information given in Sections 6.1 to 6.4. Within the sample group, 90% of the values fell within the ±10% tolerance chosen for this experiment and two thirds of the values fell within a tighter 5% tolerance.

This is in line with the 2011 CALiPER exploratory study which noted that most of the lamps in their investigation had lumen outputs that were close to those claimed.

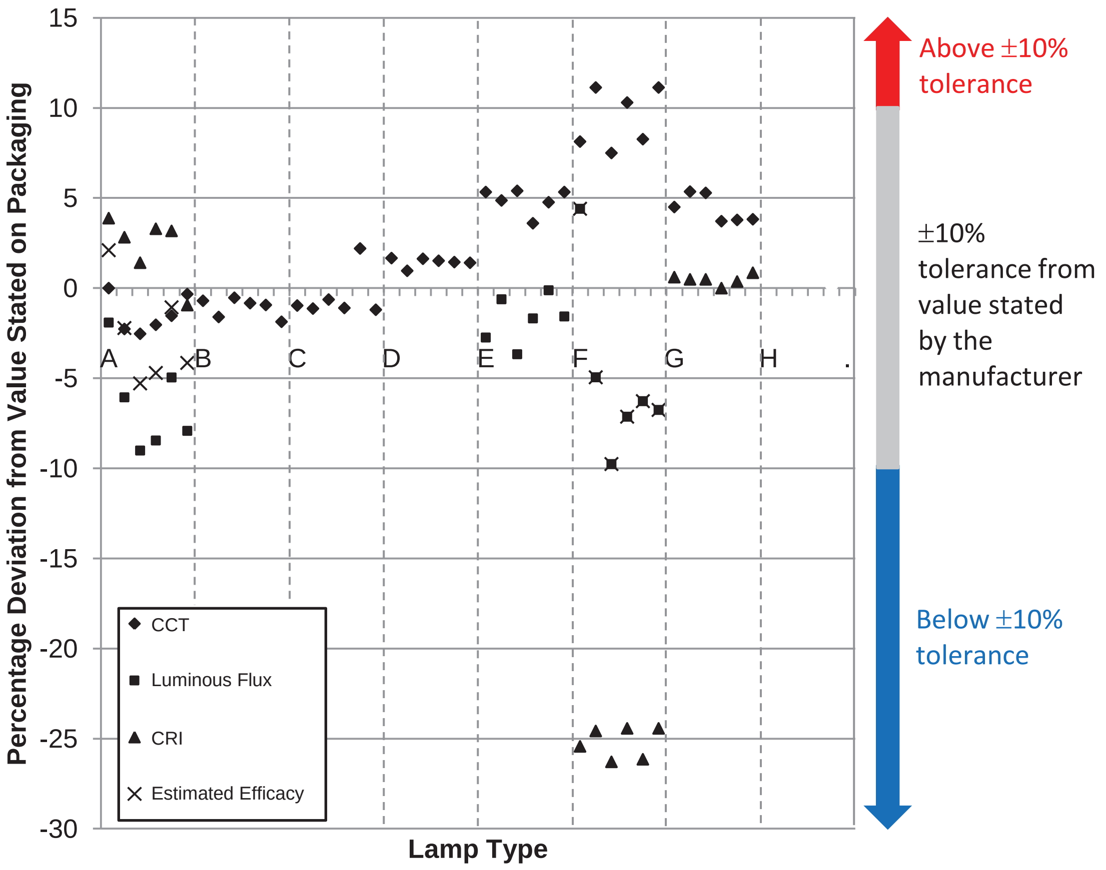
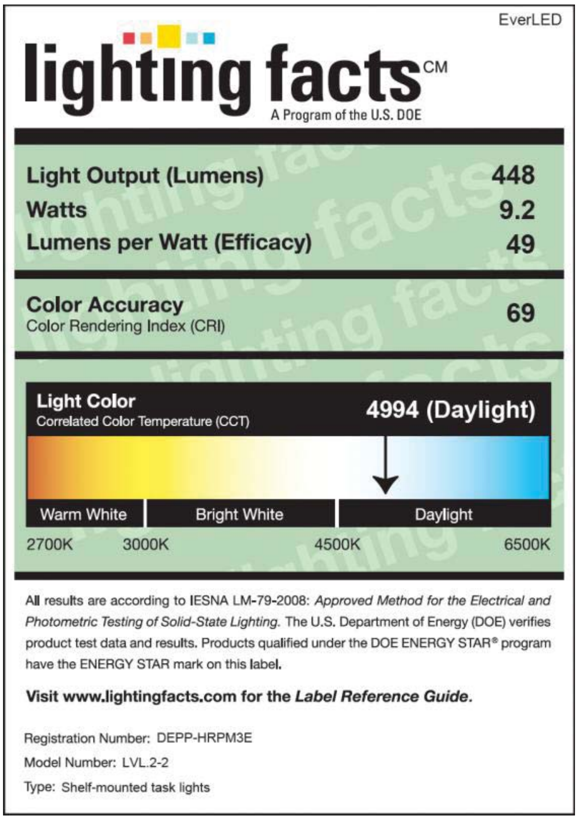


Figure 6.4 Comparison of all lamp types against manufacturers' claims

The data points that fell outside of the 10% tolerance were all attributed to the CCT and CRI of the Type F lamps. This highlights problems with product labeling in the present New Zealand LED market. There is little accountability for incorrect product information, as it is difficult for consumers to easily verify that the data given on the product labels is flawed. Recognising this issue in the United States, the U.S. Department of Energy introduced a voluntary program called *LED Lighting Facts* in 2008 (U.S. Department of Energy, 2013f) . This sought to provide accurate, independently verified, information to consumers through a standard label (LED Lighting Facts, 2014). A sample is shown in Figure 6.5.



EverLED

lighting facts CM

A Program of the U.S. DOE

Light Output (Lumens)	**448**
Watts	**9.2**
Lumens per Watt (Efficacy)	**49**
Color Accuracy Color Rendering Index (CRI)	**69**
Light Color Correlated Color Temperature (CCT)	**4994 (Daylight)**

All results are according to IESNA LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting*. The U.S. Department of Energy (DOE) verifies product test data and results. Products qualified under the DOE ENERGY STAR® program have the ENERGY STAR mark on this label.

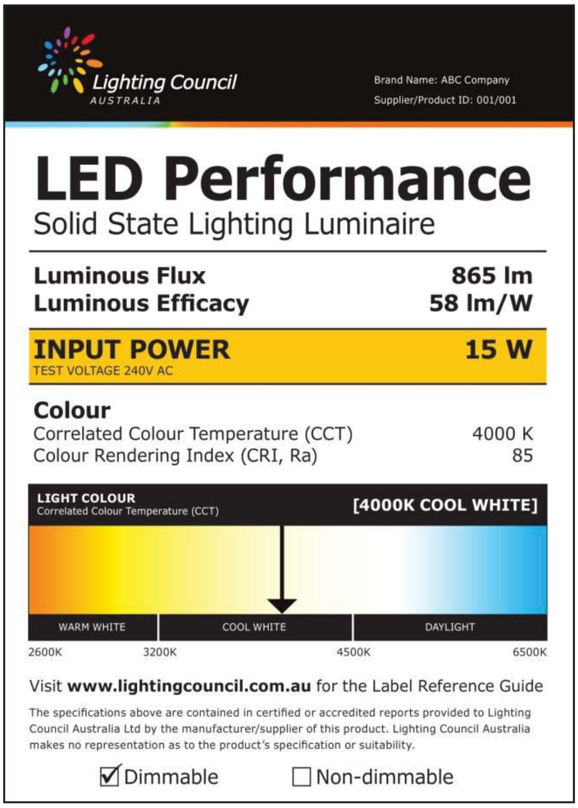
Visit www.lightingfacts.com for the *Label Reference Guide*.

Registration Number: DEPP-HRPM3E
Model Number: LVL.2-2
Type: Shelf-mounted task lights

Figure 6.5 Sample Lighting Facts label for U.S. Department of Energy (EverLED, 2014, p. 1)

To ensure that the products are an accurate representation of lamps available to the consumer, these are obtained through independent agents rather than supplied direct from the manufacturer (LED Lighting Facts, 2014).

Lighting Council Australia has endorsed a similar label, which is shown in Figure 6.6.



Lighting Council
AUSTRALIA

Brand Name: ABC Company
Supplier/Product ID: 001/001

LED Performance
Solid State Lighting Luminaire

Luminous Flux	**865 lm**
Luminous Efficacy	**58 lm/W**
INPUT POWER TEST VOLTAGE 240V AC	**15 W**

Colour

Correlated Colour Temperature (CCT)	4000 K
Colour Rendering Index (CRI, Ra)	85

LIGHT COLOUR
Correlated Colour Temperature (CCT)
[4000K COOL WHITE]

WARM WHITE
COOL WHITE
DAYLIGHT
2600K
3200K
4500K
6500K

Visit **www.lightingcouncil.com.au** for the Label Reference Guide

The specifications above are contained in certified or accredited reports provided to Lighting Council Australia Ltd by the manufacturer/supplier of this product. Lighting Council Australia makes no representation as to the product's specification or suitability.

☑ Dimmable ☐ Non-dimmable

Figure 6.6 Sample Lighting Facts label for Lighting Council Australia (B. Douglas, personal communication, January 13, 2014)

The Lighting Council Australia label is only available to members of that body, and is based on information supplied by the participants of the program (Lighting Council Australia, n.d.), rather than product procured by independent agents.

New Zealand does not yet utilise such labeling, though Lighting Council New Zealand has indicated that this topic is under discussion (B. King, personal communication, December 30, 2013). A program such as those adopted by the United States and Australia would reduce the inaccuracies that are currently presented on the products' cardboard packaging.

A possible downfall of the labels is that the consumer may still consider purchasing a lamp based on wattage, on the mistaken assumption that a higher wattage produces more light. This is particularly true of the Australian label, which places greater emphasis on wattage by highlighting it, to the detriment of other values. It is important that the consumer's focus is shifted from wattage over to luminous flux and efficacy. A promotional drive to aid understanding in this area would be beneficial, as consumers need to learn to think in these new terms. Such advertising could include the use of comparison charts showing the lumen outputs of common halogen wattages as a guide to equivalent LED purchase.

7 Baseline Lamp Quality

As discussed in Section 2.13.1, ENERGY STAR is a useful benchmark to evaluate whether the lamps are quality products. This will therefore be used for each lamp type to see whether it complies with ENERGY STAR requirements. Note that variation within each lamp type will not be considered as this will be discussed in Section 8.

Several ENERGY STAR tests may have provided further information on the performance of the lamps but fell outside of the scope of this study due to the equipment or time required to fulfil them. Thus items such as colour spatial uniformity, minimum centre beam intensity and rapid-cycle stress tests have not been considered. It should also be noted that ENERGY STAR's required sample size of 10 units per model (5 base-up and 5 base-down) has not been adhered to due to the sample size of this experiment.

7.1 Luminous Flux

Rather than listing a minimum lumen output for new lamps at zero hours, ENERGY STAR uses another lighting metric known as minimum centre beam intensity. Intensity values were not within the scope of this investigation and this data was not recorded. ENERGY STAR does however state lumen *maintenance* which will be discussed in Section 12.1.

7.2 Colour Appearance

Table 7.1 summarises the performance characteristics for correlated colour temperature as noted in ENERGY STAR. Rather than using the quadrangles defined as (x, y) coordinates in ANSI C78.377 (see Section 2.5.2), ENERGY STAR uses CCT and D_{uv} to define these limits.

Table 7.1 ENERGY STAR CCT and D_{uv} requirements for MR16 LED lamps (EECA, 2011, p. 3)

Criteria Item	**ENERGY STAR Requirements**		
Correlated Color Temperature (CCT) and D_{uv}	Lamp must have one of the following designated CCTs (per ANSI/NEMA/ANSLG C78.377-2008) consistent with the 7-step chromaticity quadrangles and D_{uv} tolerances listed below). At least 9 of the 10 samples must meet specification.		
	Nominal CCT	Target CCT (K) and tolerance	Target D_{uv} and tolerance
	2700K	2725 ± 145	0.000 ± 0.006
	3000K	3045 ± 175	0.000 ± 0.006

As 2800K is not a designated CCT under ENERGY STAR, the Type G lamps failed to meet the requirements. In addition, as the Type H lamps did not list a CCT they could not be evaluated. The other lamp types are detailed in the following sections.

7.2.1 Correlated Colour Temperature

The correlated colour temperature for Type D lamps, which purport to be 2700K, ranged from 2726K to 2745K. This is within the 2725 ± 145K tolerance listed in ENERGY STAR.

Figure 7.1 shows the initial CCT data for the lamps claiming to be 3000K with the ENERGY STAR requirements show as a grey banded region. This shows that all lamps except Type F met the requirement.

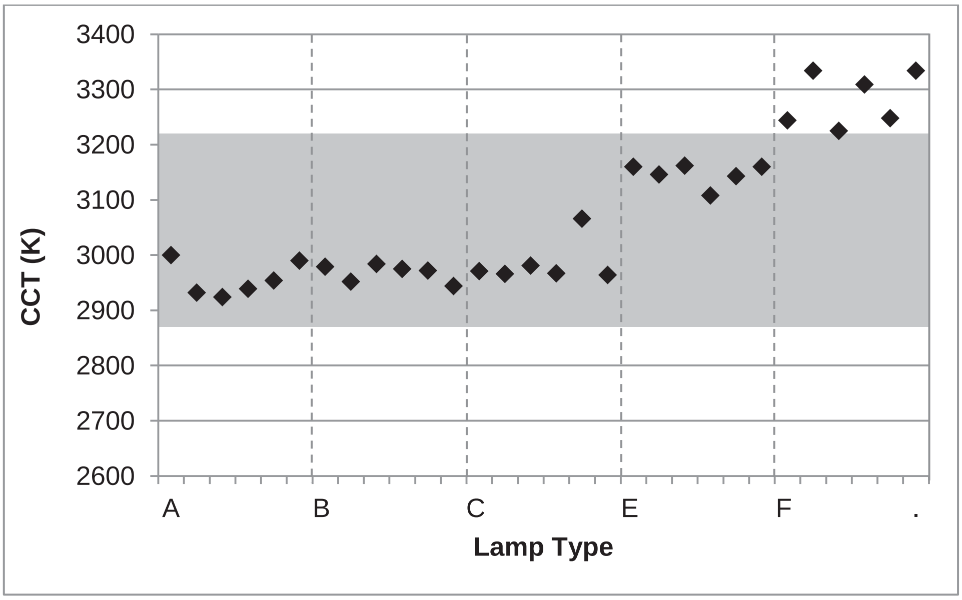


Figure 7.1 CCT at zero hours for 3000K lamps

7.2.2 D_{uv}

All 2700K and 3000K lamps had D_{uv} values that fell within the ± 0.006 ENERGY STAR tolerance. This is illustrated in Figure 7.2 with the ENERGY STAR tolerance shown as a grey band.

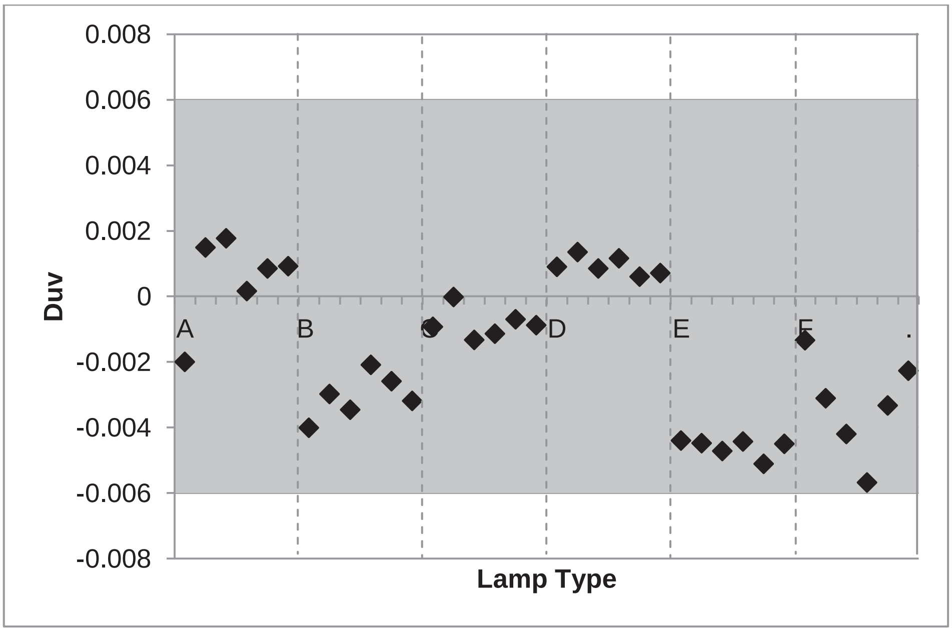


Figure 7.2 D_{uv} at zero hours for all 2700K and 3000K lamps

Most of the 2700K and 3000K lamps had a negative D_{uv} which has a slightly purple/pink hue. Type A and Type D lamps typically had a positive D_{uv} which gives a more yellow/green colour appearance. Further discussion on consistency within type is in Section 8.2.2.

7.2.3 Spectra

Figure 7.3 shows typical spectral data for each of the 3000K lamps at the commencement of the investigation, with one lamp of each sample shown. This shows that the combination of LEDs and phosphors work in different ways to produce a target CCT.

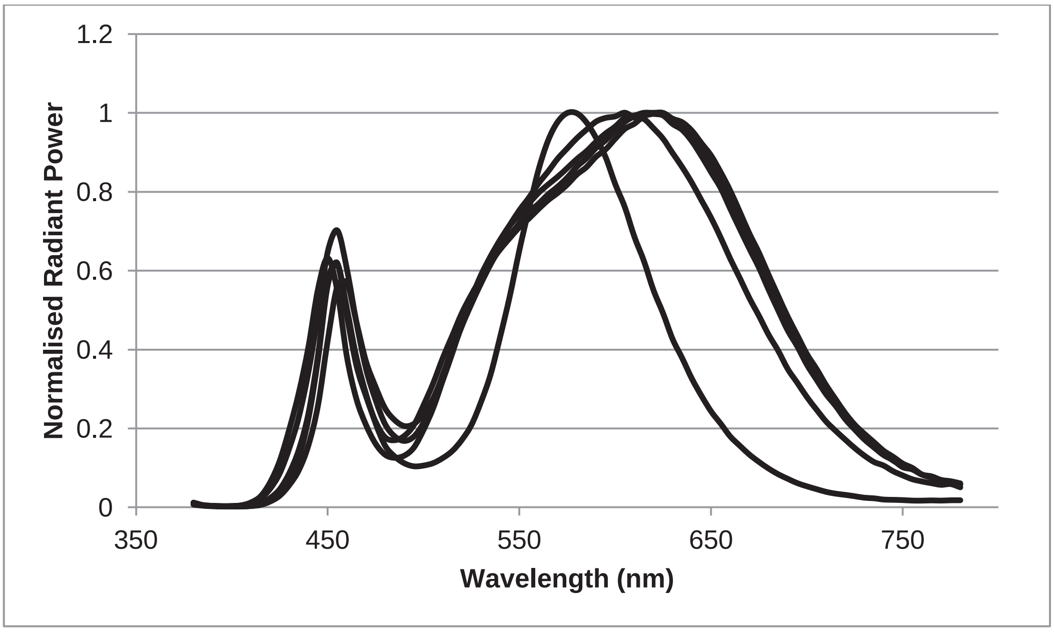


Figure 7.3 Spectra for all 3000K lamp types

It follows that spectral differences may result in different colour appearances and may render objects quite differently. This level of detail would not be widely known to the general public. It reiterates the difficulties encountered when replacing a well-known incumbent product with a lesser understood equivalent. Purchasing a 3000K LED lamp does not guarantee that the colour will match another 3000K lamp. While the tolerances set by ENERGY STAR go some way to provide matching product when viewed by the average observer, there will be some manufacturers who choose not to be part of this optional scheme. Therefore it is possible for installations to have adjacent “3000K” lamps from different manufacturers that each display a slightly different hue. How these spectral differences relate to colour rendering is discussed in Section 7.3.

7.3 Colour Rendering

7.3.1 General CRI

ENERGY STAR requires a minimum CRI of 80. Figure 7.4 shows that all lamp types met this requirement with the exception of Type F. Type E complied only marginally, with the samples ranging from 80.2 to 81.6.

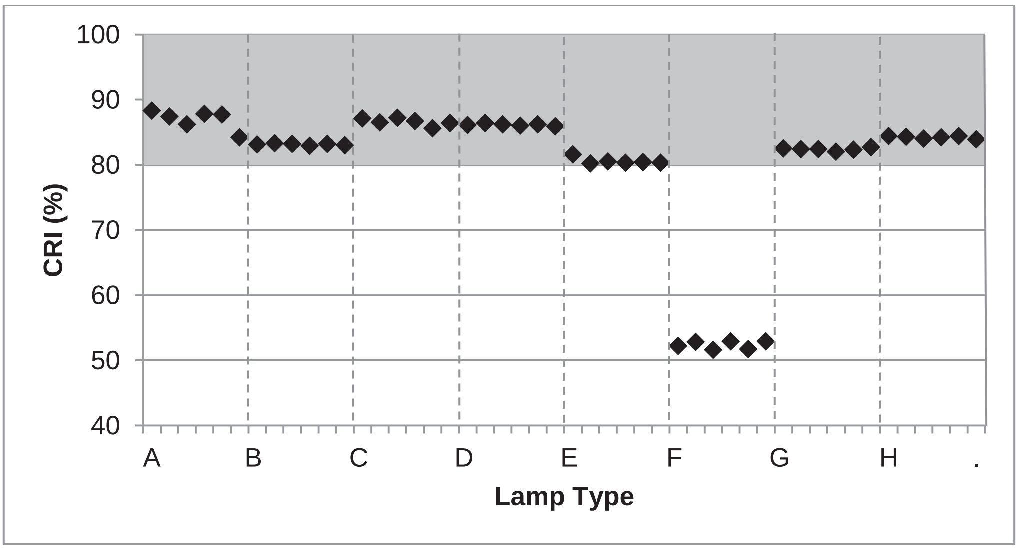


Figure 7.4 CRI at zero hours

The Type F lamps therefore had both poor CCT *and* unacceptable CRI.

7.3.2 R_9

In addition to the general CRI requirement, ENERGY STAR notes that the R_9 value must be greater than zero[25]. With the exception of Type F again, all lamp types were able to meet this requirement. This is illustrated in Figure 7.5, where the ENERGY STAR requirement is shown as the banded area.

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[25] As noted in Section 2.6, R_9 is not included in the R_a value.

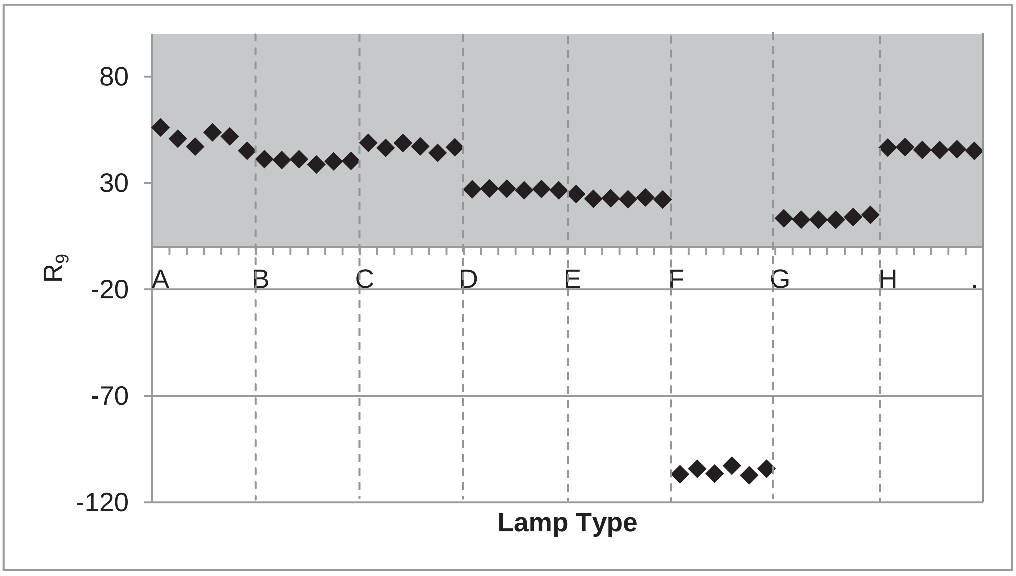

Figure 7.5 R_9 values at zero hours

The failure of Type F lamps to meet the ENERGY STAR requirement means that red coloured objects could suffer in their appearance. Figure 7.6 illustrates the approximate effect of four lamp types with different R_9 values when illuminating a red colour sample.

R_9 = 100 R_9 = 74 R_9 = 31 R_9 = -214

Figure 7.6 Approximate effect of four lamp types with different R_9 values, when illuminating a red colour sample (U.S. Department of Energy, 2012, p. 3); adapted by the author for clarity

7.4 Efficacy

ENERGY STAR requires a minimum luminous efficacy of 40lm/W for MR16 LED lamps[26]. Figure 7.7 shows the initial efficacy values for all lamps, including LED converters. The ENERGY STAR requirements are shown as a grey banded area. Type D was easily above this threshold with Types A, E and F generally achieving the standard. Types B, C, G and H were all below

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[26] 9 out of 10 lamps must meet specification.

the standard. As noted in Section 6.4, these figures are lower than the bare lamps themselves due to LED converter losses.

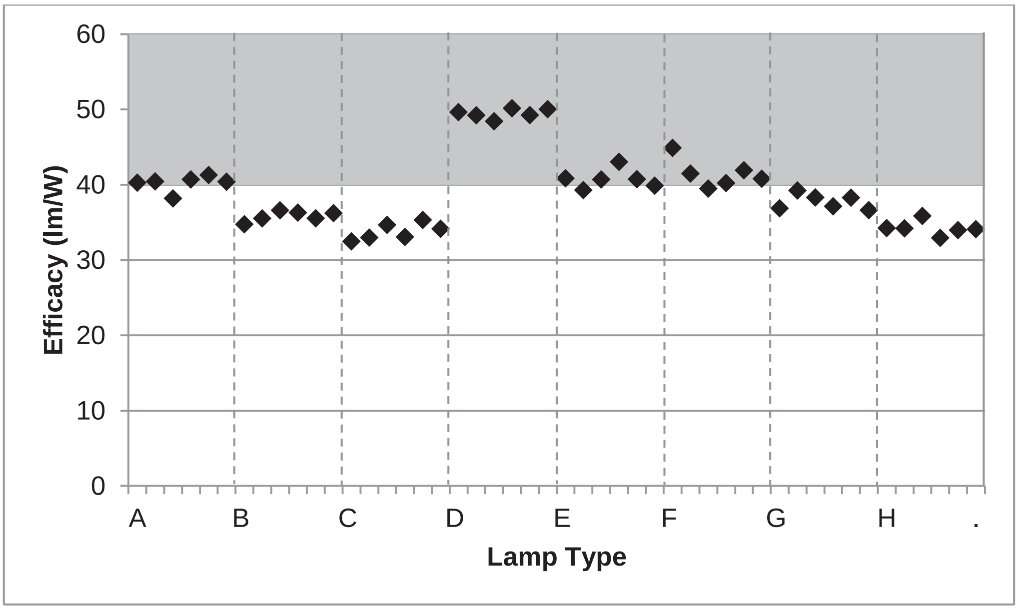

Figure 7.7 Efficacy at zero hours (including LED converters)

Figure 7.8 shows the efficacy values on the basis of recorded lumens divided by wattage given by the lamp manufacturer. While the values are only an approximation, they indicate the efficacy values without LED converters.

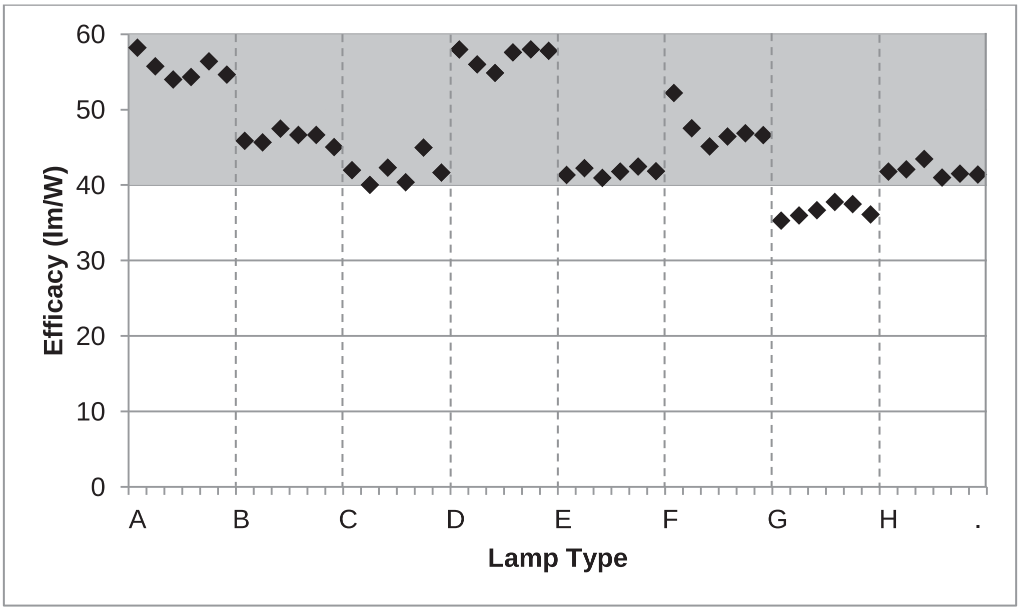

Figure 7.8 Estimated efficacy at zero hours (excluding LED converters)

While a simplistic method of calculation was used, Figure 7.8 indicates that the majority of the marginal lamps met efficacy requirements when the LED converter losses were eliminated. Some however were very close to falling under the ENERGY STAR threshold and Type G remained under the minimum requirement.

7.5 Physical Similarities

Section 4.1.3 noted that two lamps were of very similar physical appearance, and queried whether one design was copied from the other or that they were produced at the same manufacturing plant before being given different branding.

Photometric testing revealed that the two lamp types had different properties. This raises an interesting point for the consumer who is accustomed to replacing *like for like*. If an unfamiliar lamp fails, they are likely to take the lamp or its cardboard packaging with them to the store in order to find a replacement. The identical form factors and cardboard packaging, coupled with the similar wording, could lead the purchaser to believe that they have the same product. Yet the lamps had different spectral properties and therefore different colour appearances.

7.6 Summary of Baseline Lamp Quality

A summary of all of the lamps is shown in Table 7.2 which highlights all lamps that met or surpassed the ENERGY STAR benchmark in grey. Note that luminous flux is not detailed as it is not included in ENERGY STAR.

Table 7.2 Compliance with ENERGY STAR

	A	B	C	D	E	F	G	H
CCT	✓	✓	✓	✓	✓	✗	✗	N/A
D_{uv}	✓	✓	✓	✓	✓	✓	✗	N/A
CRI	✓	✓	✓	✓	✓	✗	✓	✓
R_9	✓	✓	✓	✓	✓	✗	✓	✓
Estimated Efficacy	✓	✓	✓	✓	✓	✓	✗	✓

Table 7.2 shows that all lamps passed ENERGY STAR requirements with the exception of Type F and Type G. Type F failed in CCT, CRI and R_9, while Type G had estimated efficacy values that were lower than required. Type G also listed a CCT that was not one of those designated by ENERGY STAR and therefore also failed on CCT and D_{uv}. As Type H did not list a CCT value, its colour properties were unable to be tested.

While Table 7.2 shows which lamps passed or failed ENERGY STAR, it does not show by what margin. Figure 7.9 therefore illustrates the ENERGY STAR requirements together with the actual lamp data. Note that CCT is not shown, as not all lamps were in the same colour class and therefore cannot be directly compared.

All data values in Figure 7.9 have been averaged across type and normalized in order to provide appropriate scaling. This means that ‘1’ is the maximum value recorded in each data set.

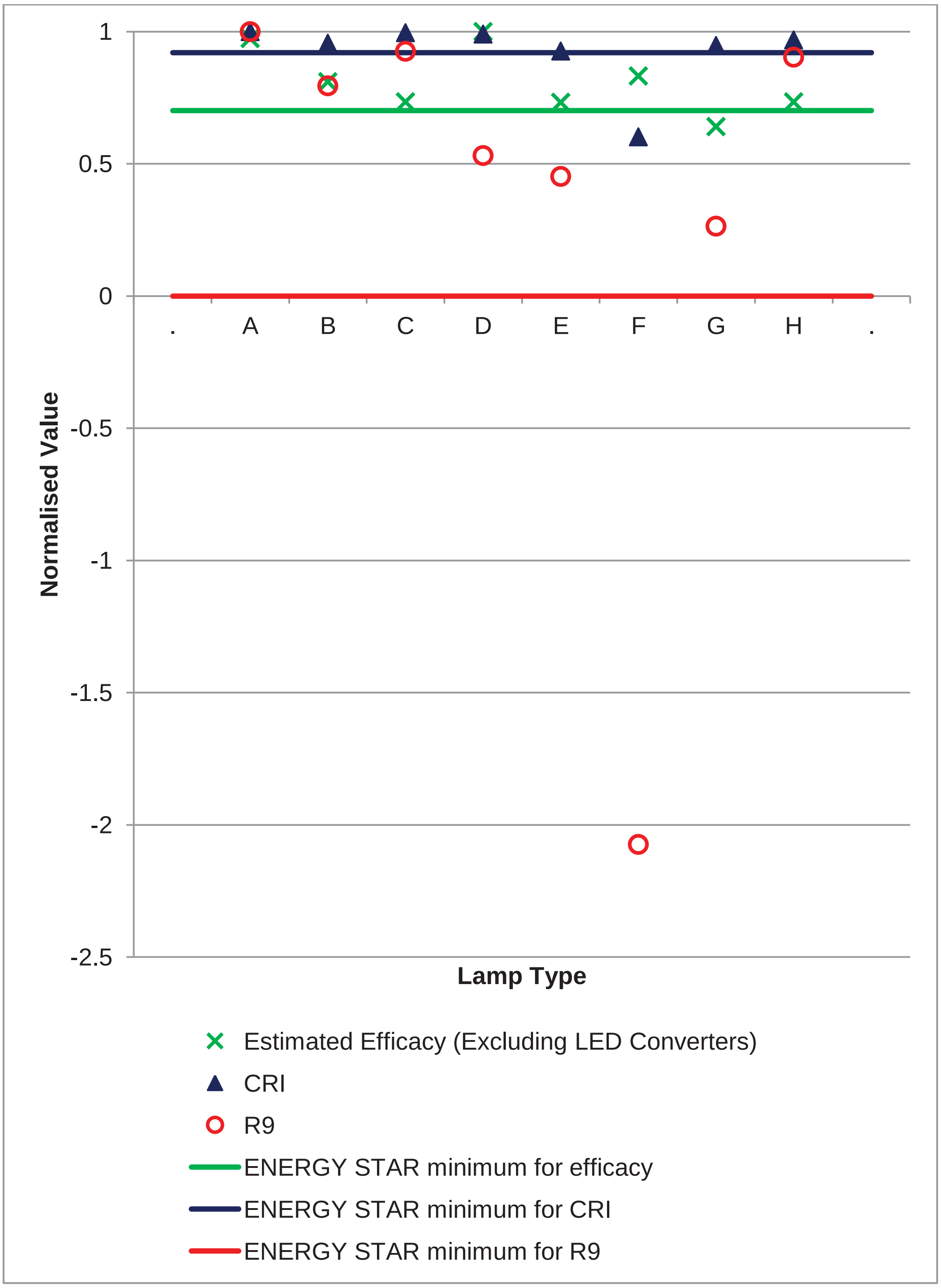

Figure 7.9 Comparison of all lamp types against ENERGY STAR

Figure 7.9 demonstrates that Type A performed consistently well for the ENERGY STAR criteria tested in this experiment[27]. Other lamp types had their own strengths and weaknesses. The CALiPER summary reports noted similar variation, with one particular lamp in Round 8 performing well

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[27] It is noted that Type A lamps had a lower lumen output than other lamp types which does not show here due to the absence of a luminous flux ENERGY STAR metric. The minimum centre beam intensity value required by ENERGY STAR fell outside of the scope of this study.

compared to the other lamps under test (Pacific Northwest National Laboratory, 2009b).

While it is commendable that most lamps fulfilled the ENERGY STAR requirements, this information is not conveyed to the consumer as none of the lamps in this study had been registered to carry the ENERGY STAR mark. An increased uptake of the ENERGY STAR program would ensure that a range of quality products is easily identifiable on New Zealand shop shelves.

It is also important that poor product is removed from the New Zealand market. A MEPS program, similar to that already used for CFL lamps in New Zealand, could be a way of achieving this goal. EECA's website advises that this is under consideration (EECA, 2012).

8 Consistency Within Type

This section considers the initial variability noted within each set of six samples per lamp type. Consistency across the six samples within each type is key, to assure the consumer of a quality product. Note that benchmark quality will not be considered as this was previously discussed in Section 7.

Consistency within a sample of MR16 lamps is rarely mentioned in the studies already referred to, though ENERGY STAR metrics often allow for one out of the ten samples to fail the specification. Round 4 of CALiPER noted a 28.2% difference between two samples of an MR16 LED product (Pacific Northwest National Laboratory, 2008a). A review of DOE testing variability and repeatability noted that the LED products in their study had an average of 4% variation between two units for the metrics of lumen output and efficacy (Paget, 2009). Paget noted that this figure included all LEDs in their test with replacement lamps showing a higher degree of variation than luminaires with integral LEDs. On this basis, 4% could be seen as an ambitious comparison.

8.1 Luminous Flux

Figure 8.1 shows the average luminous flux and the range across each lamp type. Type F was the most inconsistent sample with a 42.5 lumen range (13.6%). All other lamps had ranges of 3.6% (Type E) to 11% (Type C).

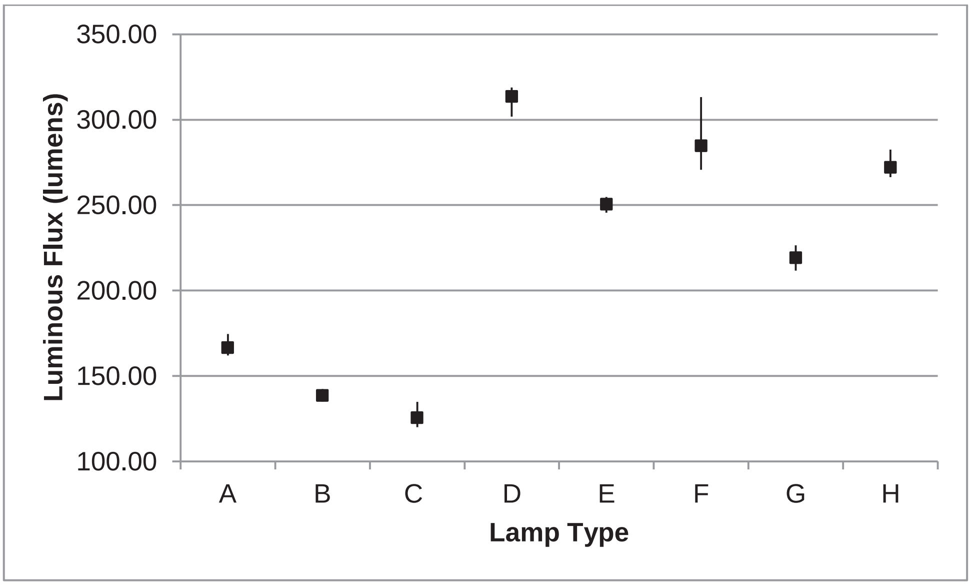

Figure 8.1 Luminous flux at zero hours – average and range across six samples

8.2 Colour Appearance

8.2.1 Correlated Colour Temperature

The variation of CCT within lamp samples is illustrated in Figure 8.2.

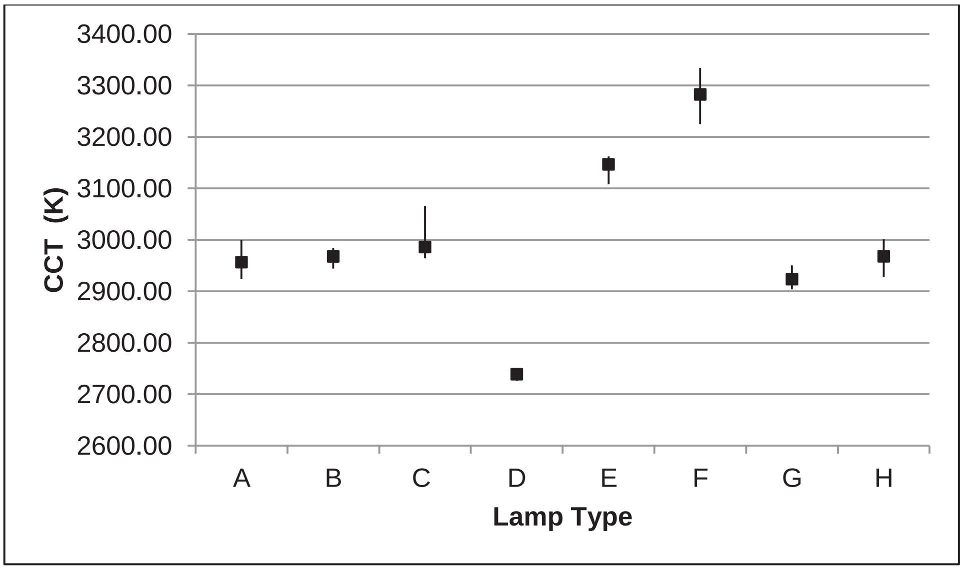

Figure 8.2 CCT at zero hours – average and range across six samples

Again, it was lamp Type F which had the largest range with a difference of 109K (3.3%) between the two extreme samples. This was equalled by Type C which also had a (3.3%) variation. The remaining lamp types had a difference of between 0.7% (Type D) and 2.5% (Type A and Type H). All lamp types fell within two standard deviations from the mean with the exception of Type C. This indicated a spurious result as it was expected that 95% of the sample population would fall within two standard deviations of the mean (B. Jones, personal communication, February 10, 2014). The CCT values for Type C lamps were therefore investigated further and are presented in detail in Figure 8.3.

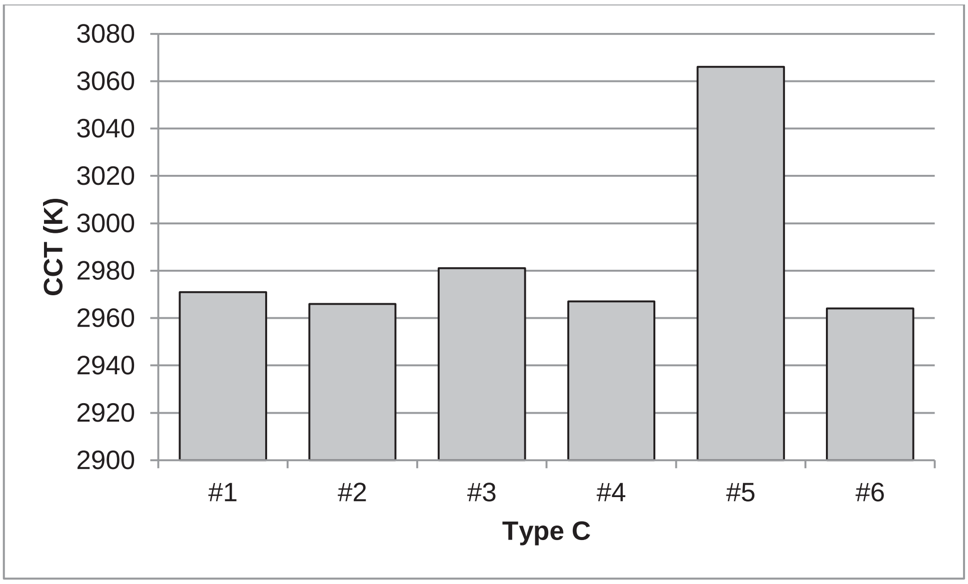

Figure 8.3 CCT at zero hours for Type C lamps

Figure 8.3 shows that one lamp out of six that was at fault. Figure 8.4 illustrates this variation by showing an overlay of the six Type C lamp spectra on top of each other. The arrowed portion of the spectra shows the aberration.

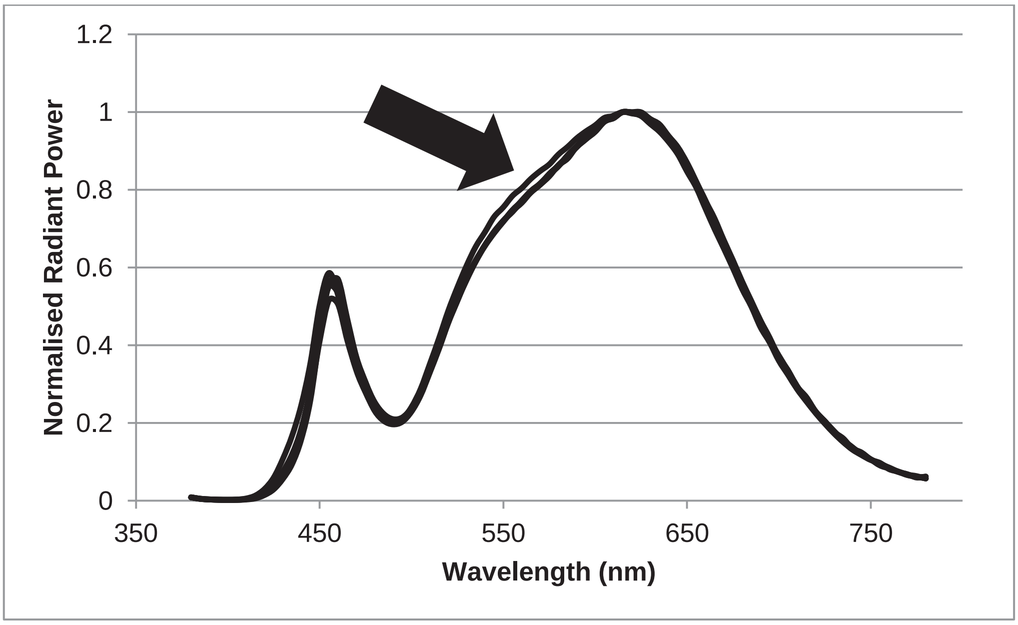

Figure 8.4 Variation across Type C

While Type F lamps fell within the 95% statistical test, they also had a higher range than other lamp types as shown in Figure 8.5.

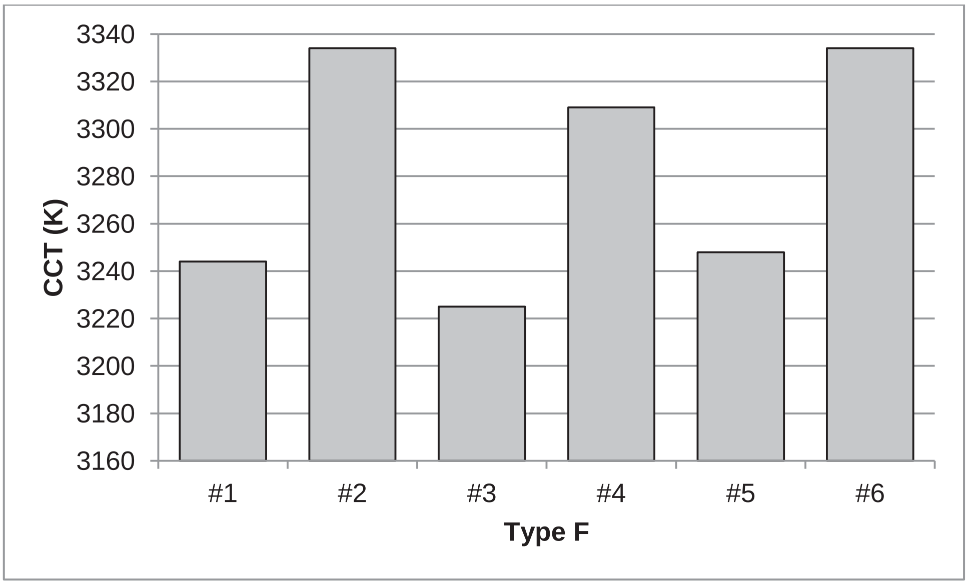

Figure 8.5 CCT at zero hours for Type F lamps

These variations in CCT are illustrated in Figure 8.6 where the arrow again indicates differences between the spectra of the six lamps.

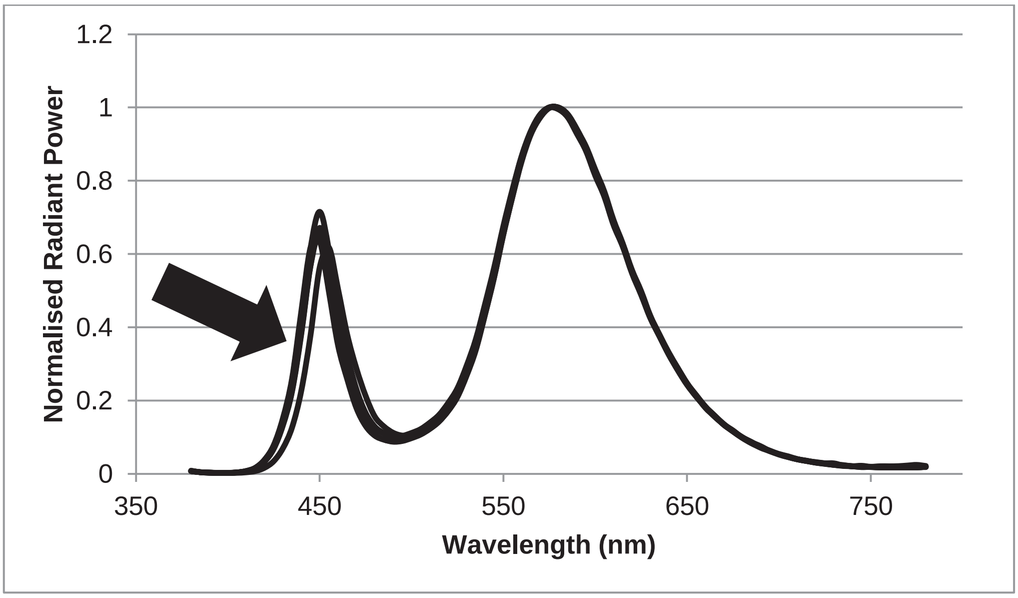

Figure 8.6 Variation across Type F

This is contrasted with the Type D lamp which is shown in Figure 8.7. Type D displayed very little variation across the six lamps sampled.

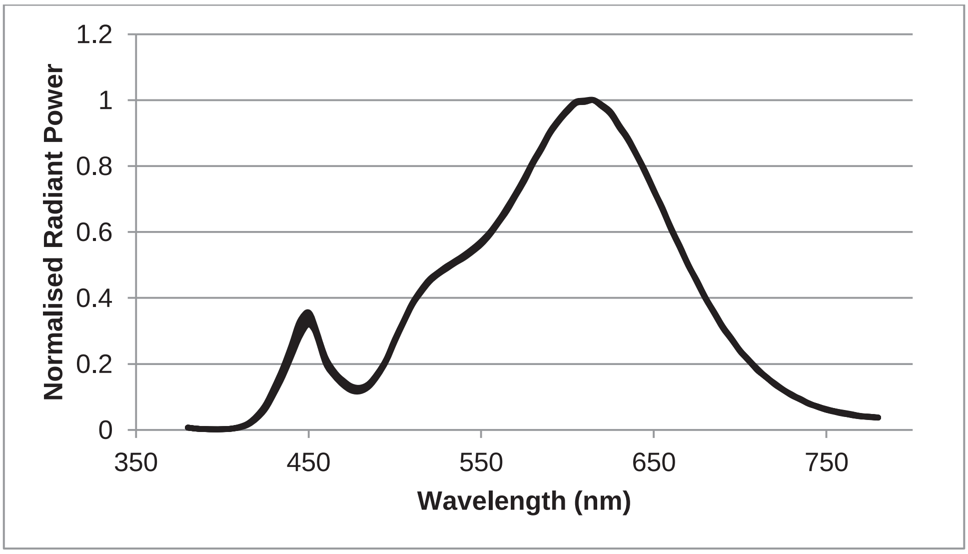

Figure 8.7 Variations across type (Type D)

8.2.2 D_{uv}

Figure 8.8 shows the variation in D_{uv} values across the lamp types.

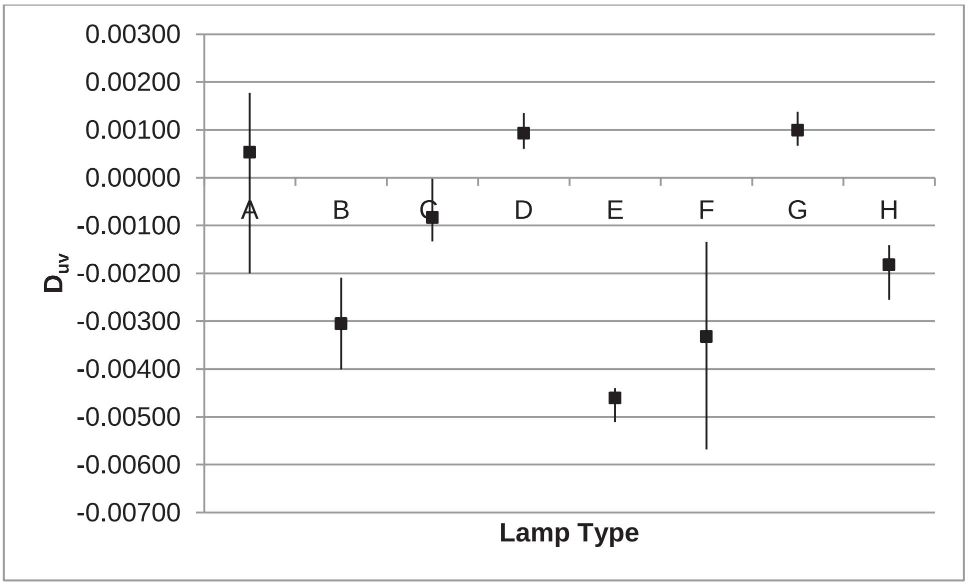

Figure 8.8 D_{uv} at zero hours – average and range across six samples

Type E and Type G showed the most consistency with both lamp types having a range of 0.00071. Type D followed slightly behind with a range of 0.00075. Type A had a range of 0.00377 and is shown in detail in Figure 8.9.

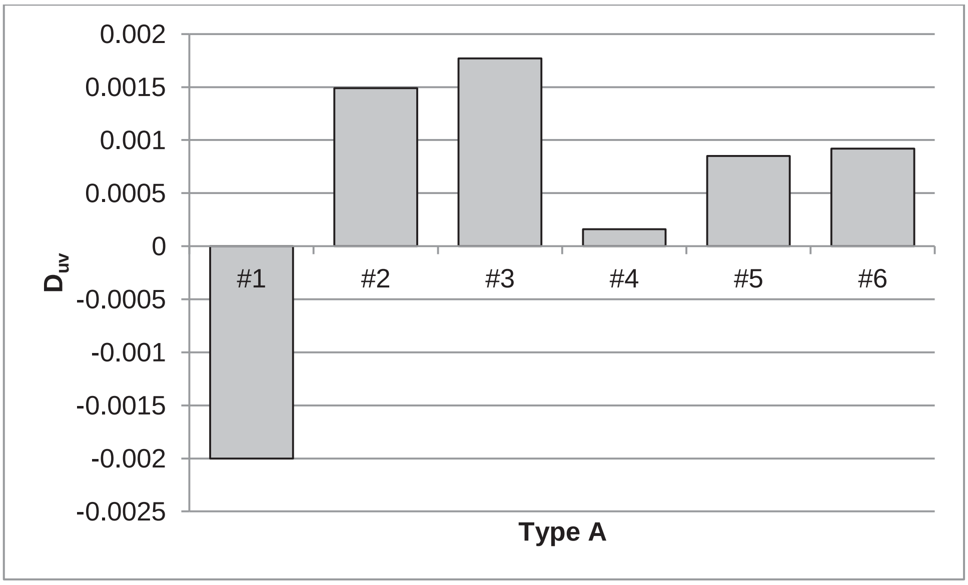

Figure 8.9 D_{uv} values at zero hours for Type A lamps

Figure 8.9 shows that Type A had one lamp that fell in negative D_{uv} while the others were positive. Thus five of the lamps take on a slightly purple/pink tinge while the other one is slightly green/yellow (Csuti & Harbers, n.d.).

Type F lamps had the greatest range of the lamp types as shown in Figure 8.10. This once again highlights the slightly larger tolerances of the Type F lamps.

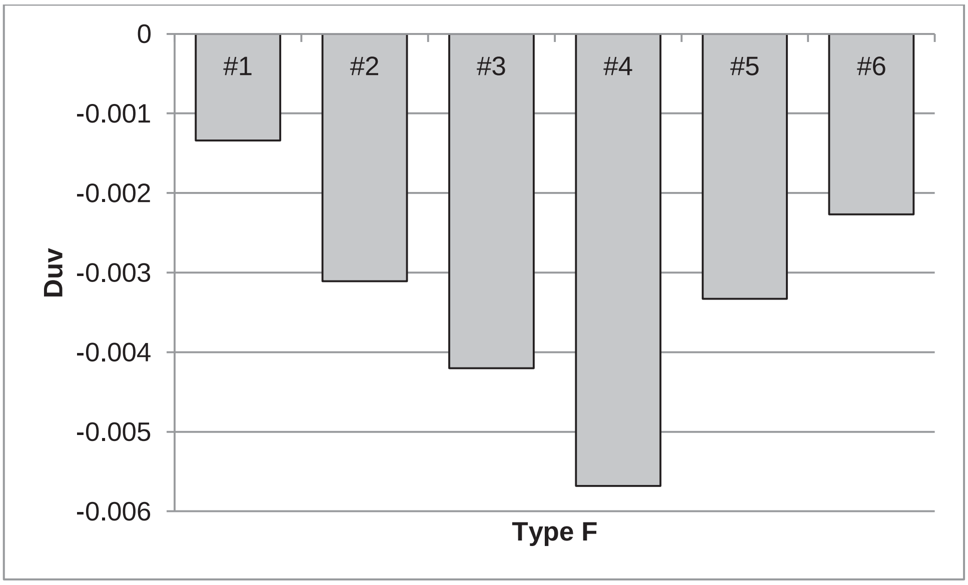

Figure 8.10 D_{uv} at zero hours for Type F lamps

8.3 Colour Rendering

8.3.1 General CRI

Figure 8.11 shows the CRI for the various lamp types. Type A was found to have the highest range though this was only 4.1 (4.6%). All other lamps had ranges from 0.5% (Type B) to 2.5% (Type F).

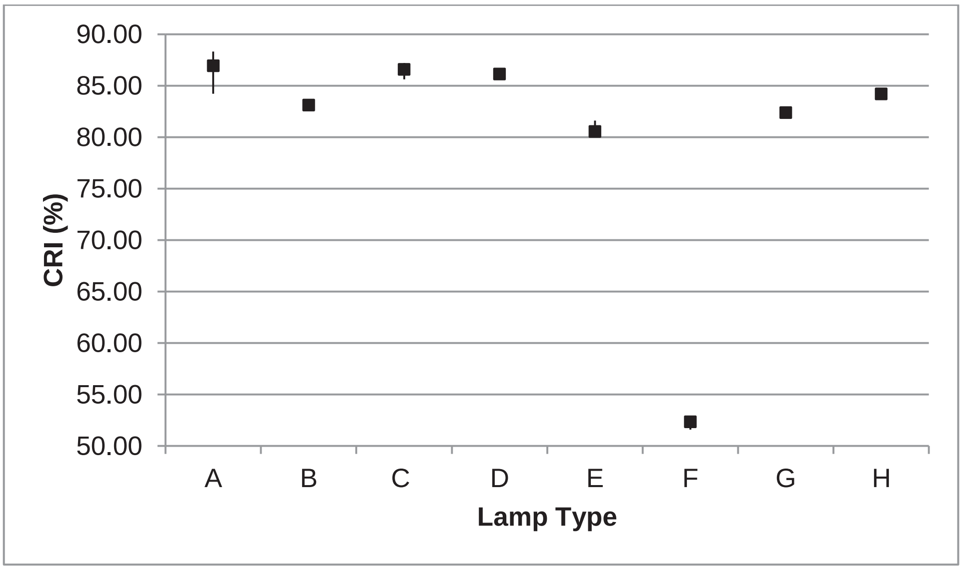

Figure 8.11 CRI at zero hours – average and range across six samples

8.3.2 R_9

As well as having the largest range in CRI, Type A lamps were similarly varied across R_9 with a range of 10.9 (19.5%). The other lamp types had ranges of 3.2% (Type D) to 15.4% (Type G). These are shown in Figure 8.12.

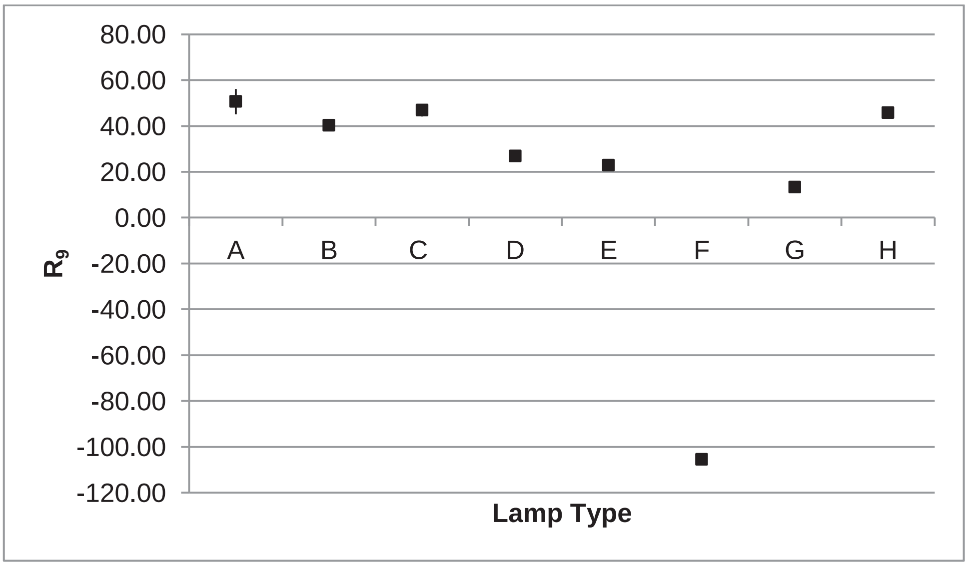

Figure 8.12 R_9 values at zero hours – average and range across six samples

8.4 Efficacy

The variation of efficacy across each lamp sample is shown in Figure 8.13.

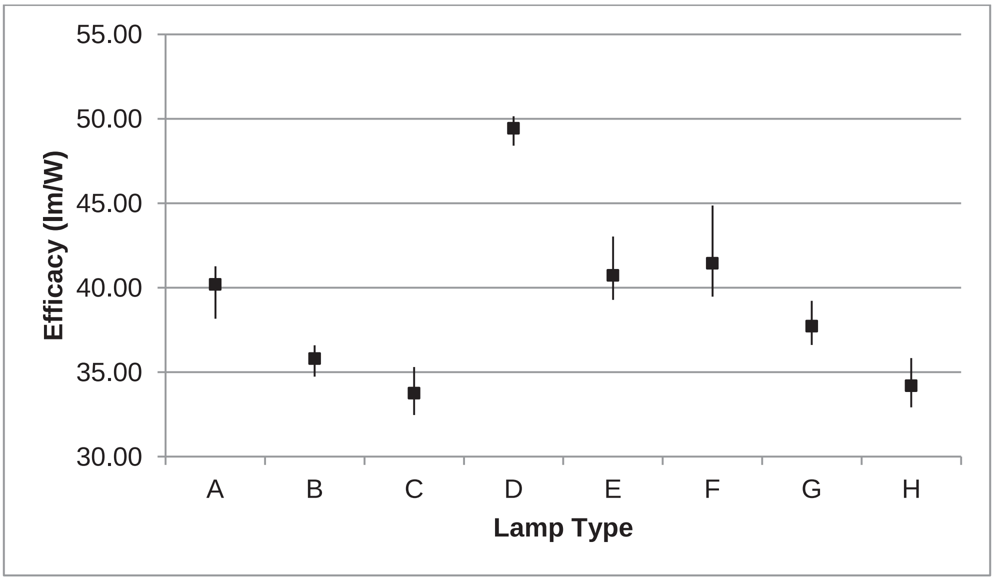

Figure 8.13 Efficacy at zero hours (including LED converters) – average and range across six samples

In this case it was the Type F lamps which had the largest variation across type with a range of 5.4 lm/W (12.0%). Type D meanwhile had a range of only 3.4%.

8.5 Physical Differences

While all of the lamps within type were of the same form factor, as they used the same factory casts, it was noticed that one lamp (Type A #3) had frosted material on the front as opposed to the other five in the sample that had clear covers.

Type A #3 was closely monitored to detect whether the frosted material affected the performance of the lamp, and is discussed further in Section 12.6.

8.6 Summary of Consistency Within Type

Table 8.1 summarises the consistency within each type for the four main metrics. The colours indicate consistency, where green shows the most consistent products (0-5%), orange shows mid-range consistency (5-10%) and red shows the least consistent (10-15%).

Table 8.1 Consistency of lamp types

	A	B	C	D	E	F	G	H
Flux	🟧	🟧	🟥	🟧	🟩	🟥	🟧	🟧
CCT	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
CRI	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Efficacy	🟧	🟧	🟧	🟩	🟧	🟥	🟧	🟧

Table 8.1 indicates that Type D and Type E were the most consistent lamps, with three of the four metrics having ranges within the 0-5% band and Type F was the least consistent.

Figure 8.14 shows the average ranges across the four areas and reveals that Type D had an average range of 2.5% while Type E averaged 3.9%.

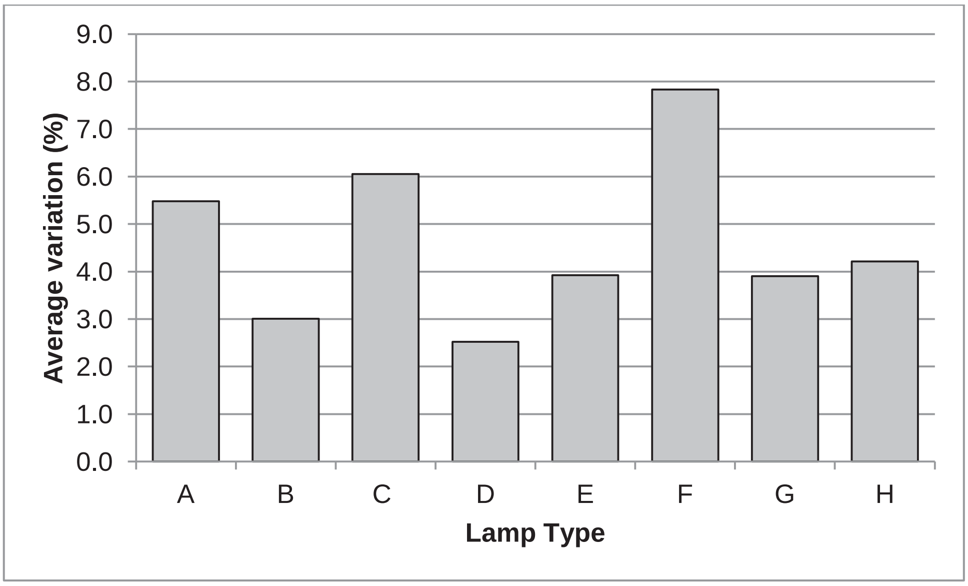

Figure 8.14 Average variation between highest and lowest value in lamp sample across four metrics (flux, CCT, CRI and efficacy)

It was noted above that a 2009 CALiPER report listed an average of 4% variation between two units for the metrics of lumen output and efficacy. This figure included both replacement lamps which showed a higher degree of variation, and luminaires with integral LEDs. By contrast, this experiment found an average variation of 7.5% (efficacy) and 7.3% (lumen output) between the highest and lowest of the six lamps in each sample for those same metrics. In addition, an average variation of 2.1% was found for CCT and 1.6% for CRI.

The consistencies noted within a majority of the lamp samples indicate that it may be possible to reduce sample size in the future. However the larger tolerances of the Type F lamps highlight that some samples contain anomalies. Further research is required to determine a suitable lamp sample size.

9 Additional Initial Findings

9.1 Electrical Compatibility

Though compatibility of LED lamps with different power supplies does not form one of the experimental aims, three additional lamps were purchased in order to investigate the compatibility problems noted in Section 2.11. These lamps were all of the same type, and were kept separate from the main investigation so that the main test data was not compromised.

Product labels indicated that the test lamps could be used with both AC and DC input voltages and did not mention potential problems with electronic transformers. The three lamps were tested using three supplies, these being 12V magnetic and electronic AC transformers, as well as a 12V DC LED converter.

The three lamps all functioned with the LED converter and the magnetic transformer. Two of the lamps also worked for the electronic transformer, but the third flickered and would not stabilise. This confirmed the compatibility issues and highlighted that it can sometimes be specific to a single lamp rather than across type. In order to meet ENERGY STAR requirements, manufacturers must include information on transformer compatibility to the consumer including a web address for up-to-date information (EECA, 2011).

9.2 Lumen Output for AC and DC Operation

The three additional lamps also offered the opportunity to check AC versus DC operation in terms of light output as it had been mentioned that AC operation reduced light output (see Section 2.11).

It was found that there was no significant difference in lumen output between AC and DC operation for the three additional lamps under test, which agrees with the findings of Paget et al. (2008). It is noted however that the AC magnetic transformer introduced extra losses.

9.3 Summary of Additional Initial Findings

The issues with compatibility highlight that clear information must be provided to consumers to ensure that an appropriate transformer is selected for each individual lamp type. Consumers also need to be aware that different types of transformers have different losses.

10 Interim Trends

There were issues with two lamp types prior to the conclusion of the full 6,000 hour testing. These are detailed in the following sections.

10.1 Type H Lamps

The Type H lamps posed a serious safety issue not long after the commencement of the experiment. These 6.5W lamps had the highest power rating in the investigation. After 1,000 hours all three Type H lamps mounted in downlights were discoloured and bulging at their bases[28] while emitting a burning smell. As the three lamps in free air did not display the same behaviour, it was concluded that the elevated air temperature in the downlights caused catastrophic failure of the lamps.

This occurred over the winter months when the maximum temperature recorded in the ceiling was 26.9˚C and was 11.1˚C lower than the summer high. This raises very real concerns over the safety of the Type H lamps while operating in the warmer months of the year in downlights. The sales literature for these lamps did not prohibit use in downlights. There is a strong possibility that consumers could install them into their ceilings for the quoted 25,000 hour life and not check on them thereafter.

Owing to this serious fire risk, the distributor of these lamps was advised. The three lamps used in the experiment were judged to be unsafe and removed from the experiment while their *free air* counterparts remained in place. These lamps were frequently inspected to ensure that they did not exhibit similar behaviour to the three lamps in downlights.

After 3,000 hours the three lamps in free air were also found to have discoloured. Though these had not deteriorated to the same extent as the lamps in downlights, they were seen as a potential fire risk and removed from the experiment. This confirmed that the lamps were a risk regardless of temperature and mounting type. The distributor was again advised of this development. It is not known whether these lamps are still being sold, however they are not shown on the manufacturer’s website. An internet

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[28] It was not possible to photograph the discolouration without revealing text on the product and thus destroying the anonymity of this study.

search found no mention of the lamps being recalled or withdrawn from the market due to safety concerns.

As noted in Section 2.14.2, browning of the lamp plastic was also noted after 9,000 hours in the InterContinental Hotel GATEWAY demonstration (Miller & Curry, 2012). The study postulated that this degradation was heat induced.

After the 3,000 hour test period, lumen maintenance for the Type H lamps in free air was an average 97.1% which is well above the 70% figure typically used to determine lamp life (Narendran & Gu, 2005). This demonstrates that LED lamp life cannot be simply based on light output as component failure also plays a part.

It is of note that Type H was the most expensive lamp type used in this study. This implies that the consumer cannot necessarily use price-point as an indicator of quality.

10.2 Type F Lamps

The Type F lamps experienced mechanical failure of a different kind whereby some of their casings were found to have cracked after 3,000 hours. This behaviour was not restricted to the lamps mounted in downlights as may perhaps have been expected from the higher ambient temperatures. As these did not pose a fire risk, the lamps remained in place and were closely monitored. Figure 10.1 and Figure 10.2 show the extent of this degradation on one Type F lamp. Figure 10.1 shows the degradation after 3,000 hours and Figure 10.2 shows further degradation after 6,000 hours. Four of the six Type F lamps were cracked to varying extents. Two lamps were mounted in downlights and two in free air.

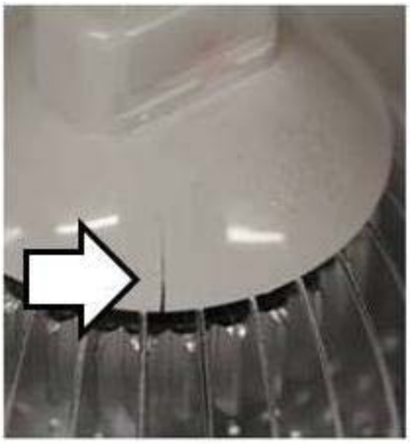

Figure 10.1 Example of Type F cracks after 3,000 hours

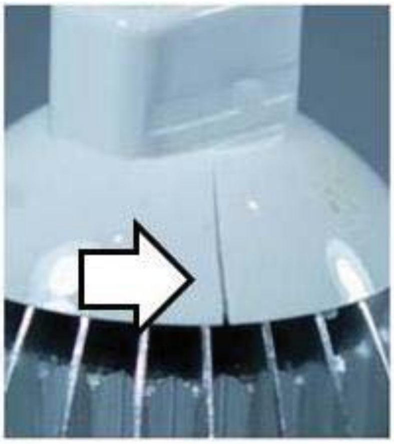

Figure 10.2 Example of Type F cracks after 6,000 hours

10.3 Summary of Interim Trends

The fire risk posed by the Type H lamps raises serious questions over the long-term safety of MR16 LED lamps, and is a worrying outcome. It is unlikely that consumers will check these after installation, resulting in the lamps' deterioration passing undetected until it is too late.

The mechanical deterioration of both Type H and Type F lamps demonstrated that component failure can also play a part in lamp life. Thus, as noted in Section 2.12, life cannot be simply measured based on the time to reach 70% lumen maintenance.

Type H was the most expensive lamp type in this study, while Type F was mid-range. It can therefore be concluded that price is not necessarily an indicator of lamp quality. The consumer would be unwise to make a purchasing decision on price alone.

11 Effect of Heat

One of the experimental objectives was to observe the effect of elevated temperatures on lamps in downlights compared to lamps in free air. The average temperature in the sample luminaires over the experimental period was recorded to be 43.2°C which was 20.4°C above average room temperature. It was postulated that these elevated temperatures would translate into accelerated degradation of the lamps in downlights. In other words, after 6,000 hours the lamps in downlights would have a lower lumen output and significantly altered CCT compared to their free air counterparts.

It is important to note here that some lamp types did depreciate more than others and this will be addressed in Section 12. Section 11 merely investigates the effect that *elevated temperature* had on deterioration.

11.1 Catastrophic Failure

Except for the six Type H lamps which were removed for safety reasons, all lamps were still performing after 6,000 hours and no catastrophic failures occurred. Thus there was no difference in catastrophic failures between lamps in downlights and those in free air. All LED converters maintained output throughout.

11.2 Luminous Flux

Figure 11.1 shows the percentage deterioration of luminous flux for the three lamps mounted in downlights versus the three lamps mounted in free air.

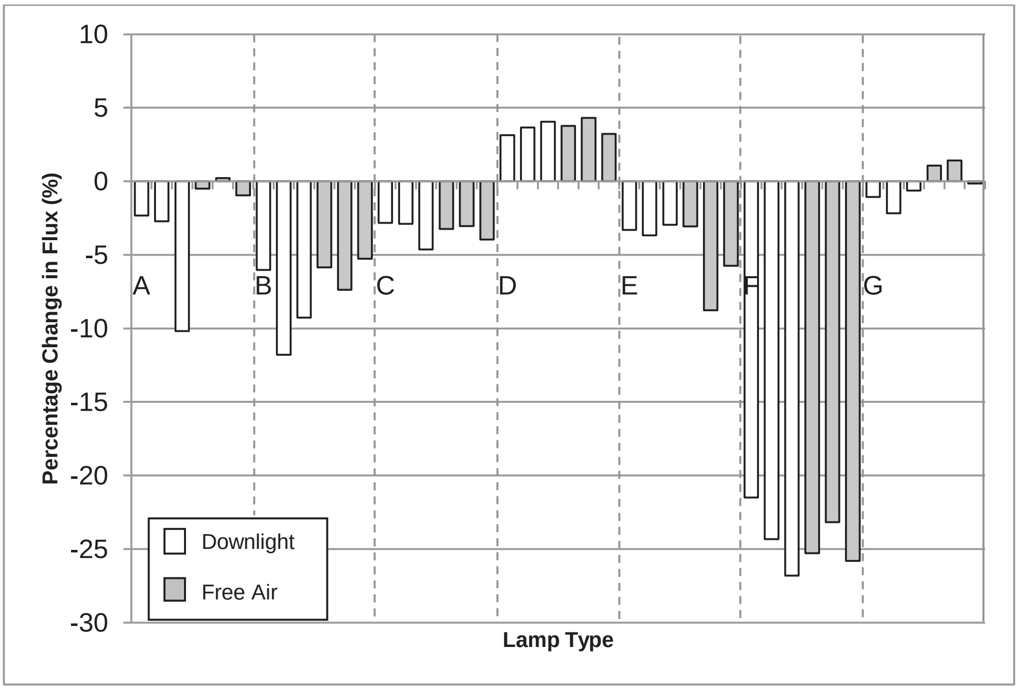

Figure 11.1 Percentage change in flux from zero hours to 6,000 hours

Figure 11.1 indicates that some lamps performed better than others but there was no overall difference between lamps in free air and those in downlights. To confirm this, two way ANOVA testing was performed on the following null hypotheses:

- Ho1: There was no difference in change in flux between the two lamp locations
- Ho2: There was no difference in change in flux between the lamp types

(B. Jones, personal communication, February 10, 2014)

The testing found the following statements to be true:

- Ho1: There was no difference in change in flux between the two lamp locations
- Ha2: There *was* a difference in change in flux between the lamp types

Therefore it can be concluded that there was no difference in the lumen output data between the lamps mounted in downlights and those in free air over 6,000 hours. It can also be concluded that the different lamp types deteriorated at different rates. This will be discussed further in Section 12.1.

11.3 Correlated Colour Temperature

Figure 11.2 shows the actual percentage change in correlated colour temperature across all of the samples.

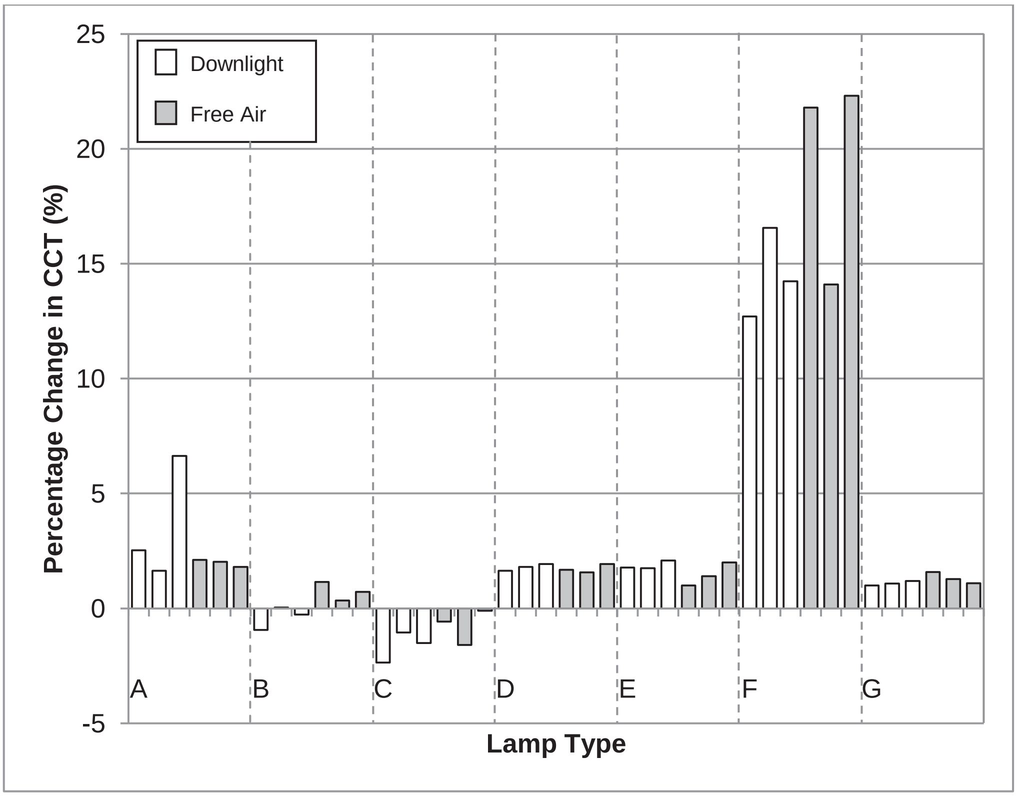

Figure 11.2 Percentage change in CCT from zero hours to 6,000 hours

As with the luminous flux results discussed in Section 11.2, it appeared that the lamps in downlights performed no better or worse than those in free air though some lamp types experienced more change than others. Two way ANOVA testing using the same methodology as Section 11.2 (B. Jones, personal communication, February 10, 2014) confirmed this to be true.

11.4 Summary for Effect of Heat

Temperature data in Section 4.6.4 showed a temperature differential of approximately 21˚C was typically maintained between the lamps mounted in downlights and those in free air for this experiment. It was therefore postulated that the lamps in downlights would deteriorate faster than those in free air, due to their higher ambient temperatures. This was true of the Type H lamps, where (as noted in Section 10.1) the housings of the lamps in downlights consistently discoloured before the equivalent lamps in free air. However such differences were not apparent in the other lamp types. Section 11.2 showed that there was no statistically significant difference in lumen deterioration between the two groups of lamps over a 6,000 hour period in an Auckland ceiling. Nor was a statistically significant difference recorded in CCT over the same period.

It is not known why the results from this experiment differed from previous knowledge that LEDs are negatively affected by heat with higher temperatures resulting in higher levels of degradation (Tuttle, 2012). One hypothesis is that the difference in temperatures was not extreme enough to produce different results in the two mounting positions. Research by Meneghini et al. (2010) found that white LEDs produced significantly different levels of depreciation with a 20˚C temperature differential. However their experiment used ambient temperatures of 80˚C and 100˚C, compared to the extreme highs of 31.2˚C and 55.1˚C recorded for the two lamp groups in this experiment. In addition, Meneghini et al. placed the LEDs under current stress which may have contributed to the degradation levels. Section 2.9 noted research by Denicholas (2011) which suggested that laboratory testing at high temperatures produced deeper curves than those found in reality. It is postulated that Denicholas' findings were reflected in this experiment.

In order to further compare this experiment with a larger pool of research, there may be value in using special methodologies to indicate *junction temperatures* in all of the lamps in future studies.

12 Lighting Quality Over Time

One of the aims of this investigation was to determine whether the LED lamps' impressive efficacies and life spans were at the expense of lighting quality over time. This tradeoff could be in CCT shift or significant lumen depreciation. As per Section 7, ENERGY STAR will be used as a basis for determining whether lamps were maintaining a high standard of light output and colour stability.

In Section 11 it was shown that (with the exception of Type H) there was no significant difference in deterioration between the lamps mounted in downlights and those in free air. On that basis, the following section will draw no distinction between lamps in downlights and those in free air, and expect all lamps within the sample to meet the ENERGY STAR requirements.

12.1 Luminous Flux

Table 12.1 summarises the performance characteristics for lumen maintenance as required by ENERGY STAR.

Table 12.1 ENERGY STAR requirements for lumen maintenance (EECA, 2011, p. 11)

Criteria Item	ENERGY STAR Requirements
Lumen maintenance	Average of 10 samples must be ≥91.8% at 6,000 hours.

Note that ENERGY STAR requires that low voltage lamps operate at 25ºC between lumen maintenance measurements. Owing to the nature of this experiment, which included the aim of investigating the effects of seasonal temperatures in a typical New Zealand home, the room temperature was lower than this value at times. However research on the negative effects of high temperatures (see Section 2.7) suggests that this should favour lumen maintenance and therefore the results in this section would be slightly more favourable than they would have been had the air temperature been maintained at 25 ºC.

Figure 12.1 shows the lumen maintenance for all lamps (excluding Type H) after 6,000 hours. Type F was the worst performing lamp type and all lamps of this type fell well beneath the 91.8% ENERGY STAR threshold which is shown as a grey band. The lowest value for Type F lamps was 73.2% with an average across the six lamps in the sample of 75.5%. The product label for the Type F lamps stated that 70% lumen maintenance would be reached after 35,000 hours. It is questioned whether this is a reasonable claim for lamp life given that the figures were close to this value after only 6,000 hours. This highlights the need for manufacturers to test their luminaires over time, to ensure that life claims can be substantiated. This should be 6,000 hours at the very least, as required by LM-80 (Illuminating Engineering Society, 2008b) and ENERGY STAR (EECA, 2011).

In addition to the Type F lamps, four other lamps (Type A #3, Type B #2 and #3, and Type E #5) fell just short of the ENERGY STAR requirement. Of note, some lamps (most distinctly Type D) exceeded 100% lumen maintenance, which means that they increased lumen output over time. LM-79 states that this phenomenon is possible in the first 1,000 hours but does not discuss increased lumen output beyond that point.

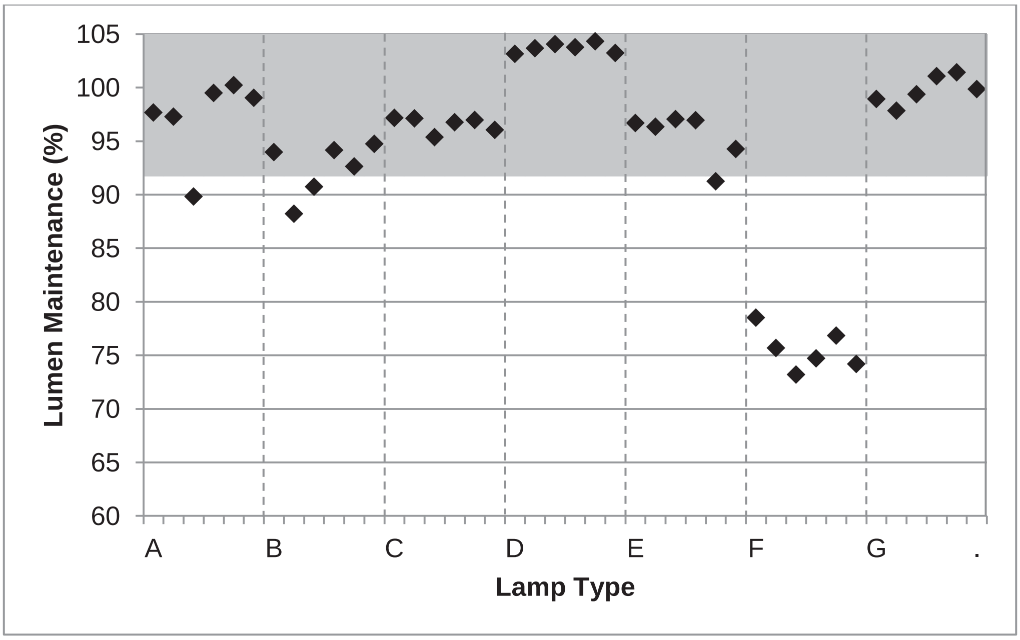

Figure 12.1 Lumen maintenance at 6,000 hours

12.2 Colour Appearance

12.2.1 Correlated Colour Temperature

Colour consistency is particularly important to the consumer. They need confidence that if one of their lamps fails, they will be able to buy a matching lamp. This will not be possible if the other remaining lamps have markedly changed CCT. Figure 12.2 shows the percentage change in colour over the 6,000 hour test period. Positive numbers indicate a shift towards the blue end of the spectrum, whereas negative numbers show a shift towards the red end.

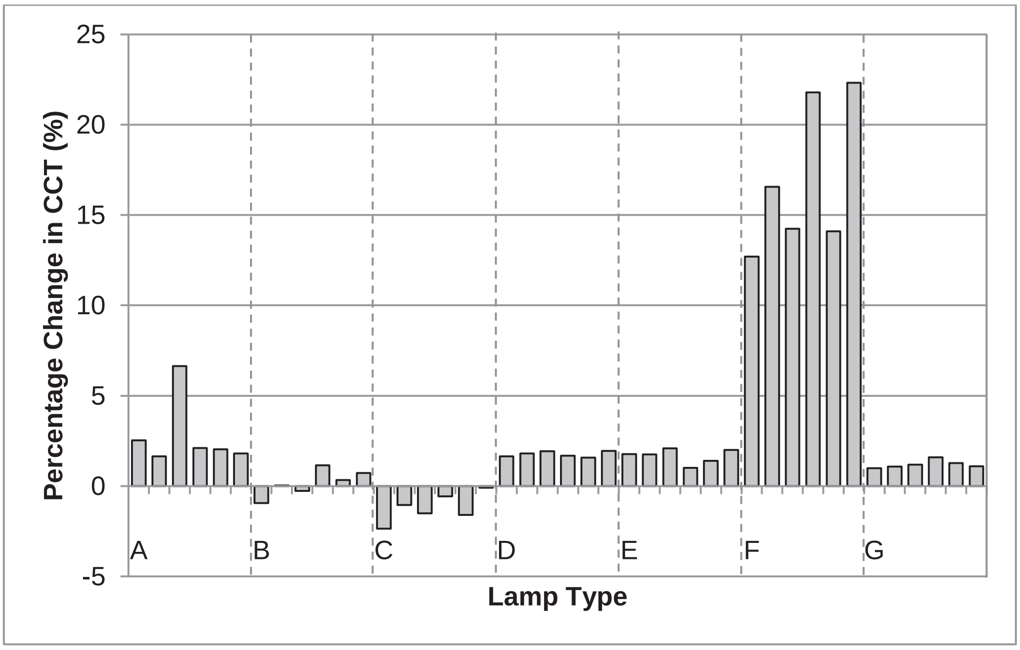

Figure 12.2 Percentage change in CCT from zero hours to 6,000 hours

This illustrates that most lamps increased slightly in CCT and became more *blue* in appearance. Type B lamp samples had a mix of increase and decrease though these values were small. Type C lamps consistently became slightly redder in appearance. The Type F lamps experienced the greatest change in CCT, with the worst lamp changing from 3334K to 4078K. It is not possible to determine how this considerable change in CCT measures up against ENERGY STAR as a criterion for CCT maintenance is not given. ENERGY STAR instead focuses on the change in chromaticity coordinates which is discussed next.

12.2.2 Δu’v’

ENERGY STAR stipulates that “the change of chromaticity over the minimum lumen maintenance test period (6000 hours) shall be within 0.007 on the CIE 1976 (u’,v’) diagram”[29] (EECA, 2011, p. 3). This metric is denoted as Δu’v’. As stated in Section 2.5.1, Δu’v’ does not indicate the direction of the colour shift.

Initially the raw data from the integrating sphere did not give (u’,v’) coordinates, thus it was necessary to convert (u, v) values to (u’, v’) using the transformations given in Equation 12.1 and Equation 12.2.

$$u' = u$$

Equation 12.1 (Ohno, 2011)

$$v' = \frac{3}{2}\, v$$

Equation 12.2 (Ohno, 2011)

This was rectified in a later software update that was installed after the 4,000 hour testing.

Royer et al. (2013) noted that colour difference on the (u’ v’) diagram can be measured as the Euclidean difference between two sets of coordinates. Thus the Pythagorean formula can be applied (Deza & Deza, 2013) to find Δu’v’. This can be written as Equation 12.3.

$$\Delta u'v' = \sqrt{(u'_{6000\,hours} - u'_{0\,hours})^2 + (v'_{6000\,hours} - v'_{0\,hours})^2}$$

Equation 12.3

Figure 12.3 shows the Δu’v’ values for each lamp from initiation of the investigation to 6,000 hours run, with the ENERGY STAR requirement shown in grey.

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[29] 9 out of 10 lamps must meet specification.

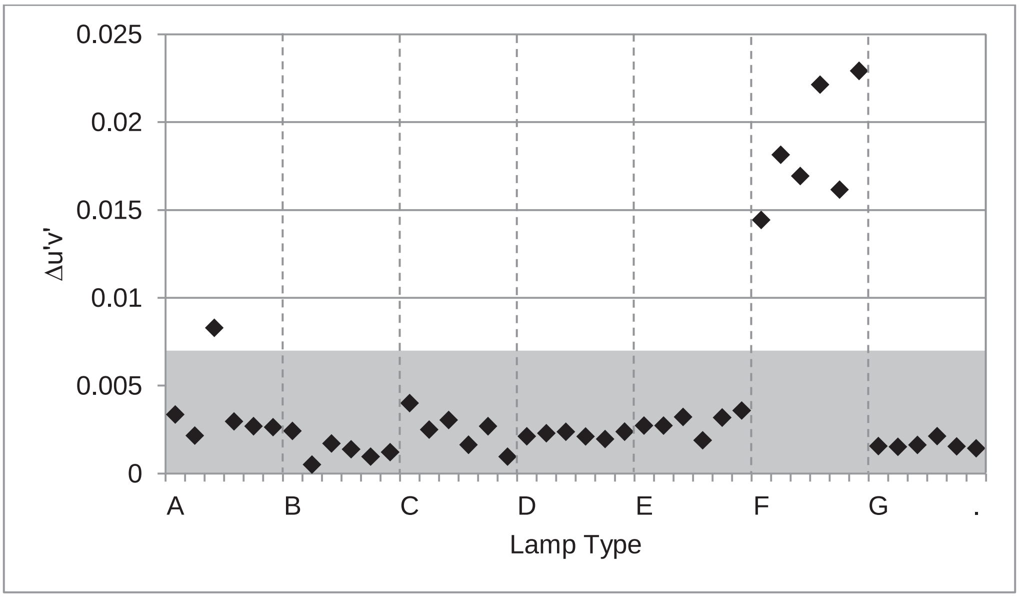

Figure 12.3 Δu'v' after 6,000 hours

Most lamps exhibited a change of under 0.007 which meets ENERGY STAR.

The Type A #3 lamp warranted further investigation due to its higher change. Figure 12.4 illustrates the change in chromaticity. While this was still within the bounds of the NEMA 3000K quadrangle, it fell short of ENERGY STAR.

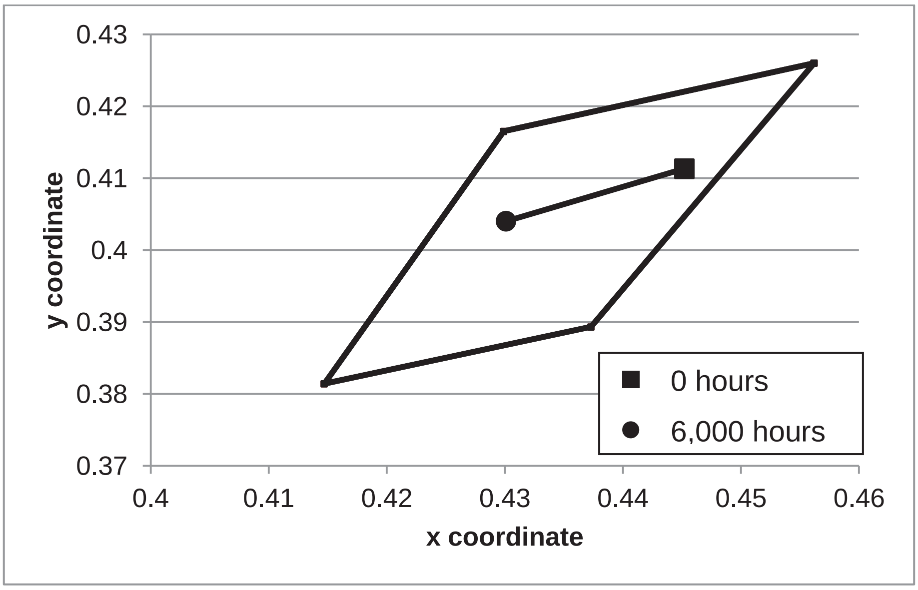

Figure 12.4 CCT change for the Type A #3 lamp

It is postulated that this change was due to a difference in the Type A #3 lamp envelope which is discussed further in Section 12.6.

The Type F lamps consistently had ∆u'v' values that were notably higher than the ENERGY STAR requirement and had changed by as much as 0.0229.

Figure 12.5 illustrates the change in Type F lamps and shows how their chromaticity has shifted even further from the 3000K tolerance quadrangle for SSL lamps.

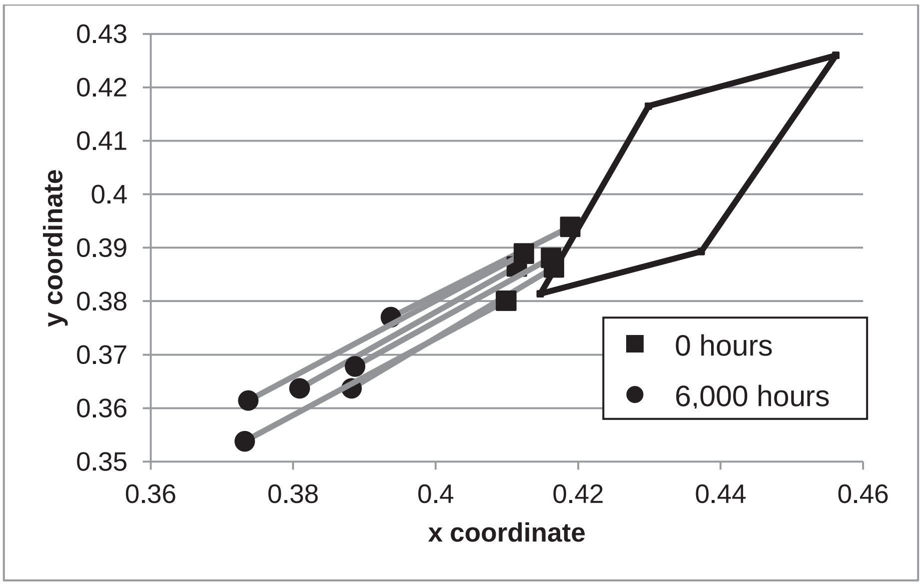

Figure 12.5 CCT change for Type F lamps

As noted in Section 12.2.1, the lamp with the highest deviation commenced the experiment with a CCT of 3334K and increased to 4078K over the 6,000 hour period. Figure 12.6 illustrates this shift by showing the spectra at zero hours and every 1,000 hours thereafter.

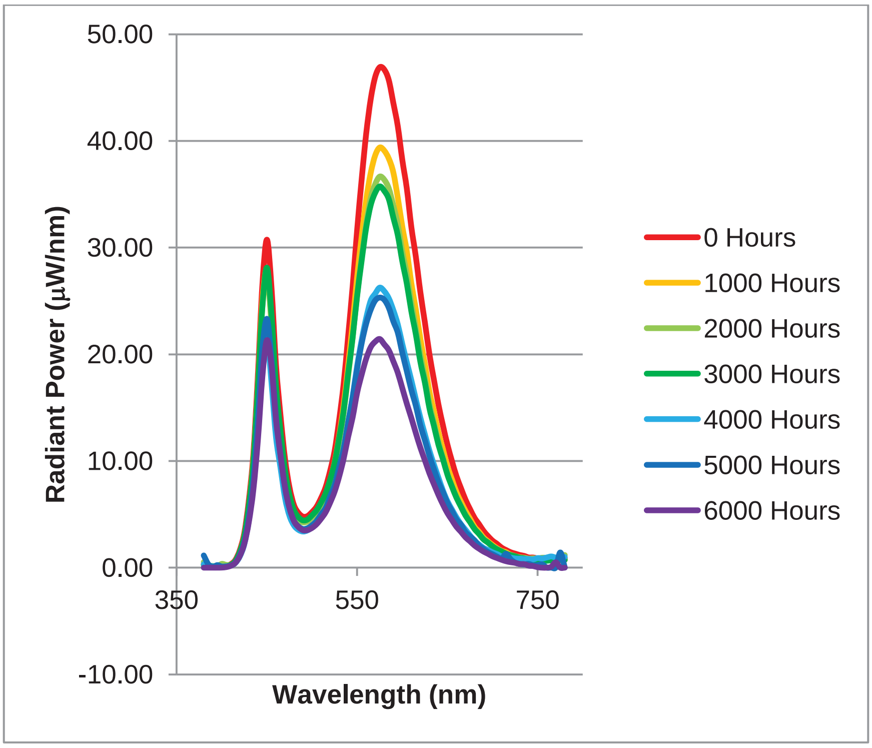

Figure 12.6 Comparison of Type F spectra at zero hours up to 6,000 hours

It can be observed in Figure 12.6 that the ratio between the blue peak and the phosphor contribution was high at zero hours. This ratio gradually decreased, such that the blue peak was more prominent in the spectrum at 6,000 hours and gave a more *blue* CCT. Meneghini et al. (2010) found a similar spectral response when testing under thermal stress at an ambient temperature of 140˚C. The results from this test are shown in Figure 12.7.

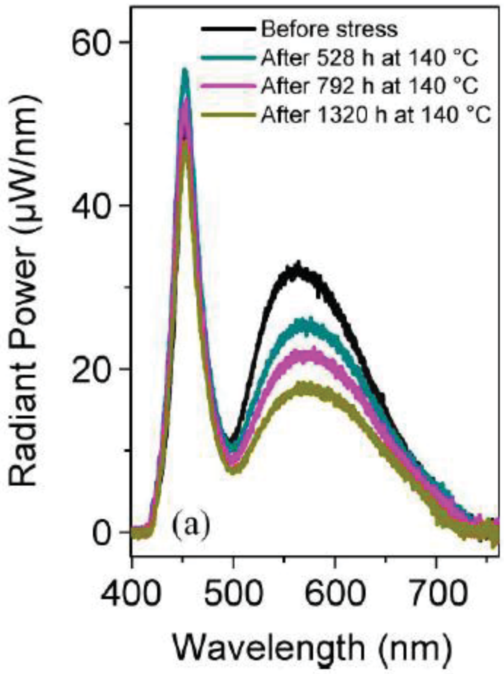

Figure 12.7 Spectral power distribution from a study by Meneghini et al. (Meneghini et al., 2010, p. 115)

The research by Meneghini et al. (2010) suggested that this type of change is indicative of browning of the encapsulation material, resulting in a shift towards the blue end of the spectrum. They also noted that "partial carbonization of the reflective surface of the package" (Meneghini et al., 2010, p. 115) could also be at play, with both factors resulting in altered blue and yellow peaks.

The effect of this colour shift to the consumer is illustrated in Figure 12.8 with the lamp on the left indicating the initial colour of the lamp and the final state shown on the right.

Figure 12.8 Representation of Type F lamp CCT at zero hours (left) and 6,000 hours (right)

As noted earlier, this colour shift raises problems for the householder. Compared to the stated rated life of 35,000 hours for this particular lamp type, 6,000 hours is a relatively short time period. If the consumer needed to add a new lamp to an existing fitout, it would not match the existing installation. If the pattern of degradation continued, colour matching would become more and more of an issue as time went on. Though lumen depreciation is used to measure LED lamp life, the Type F lamps illustrate that CCT is also an important consideration.

By contrast, Figure 12.9 shows the colour shift of the Type G lamps which had a maximum shift of only 0.002.

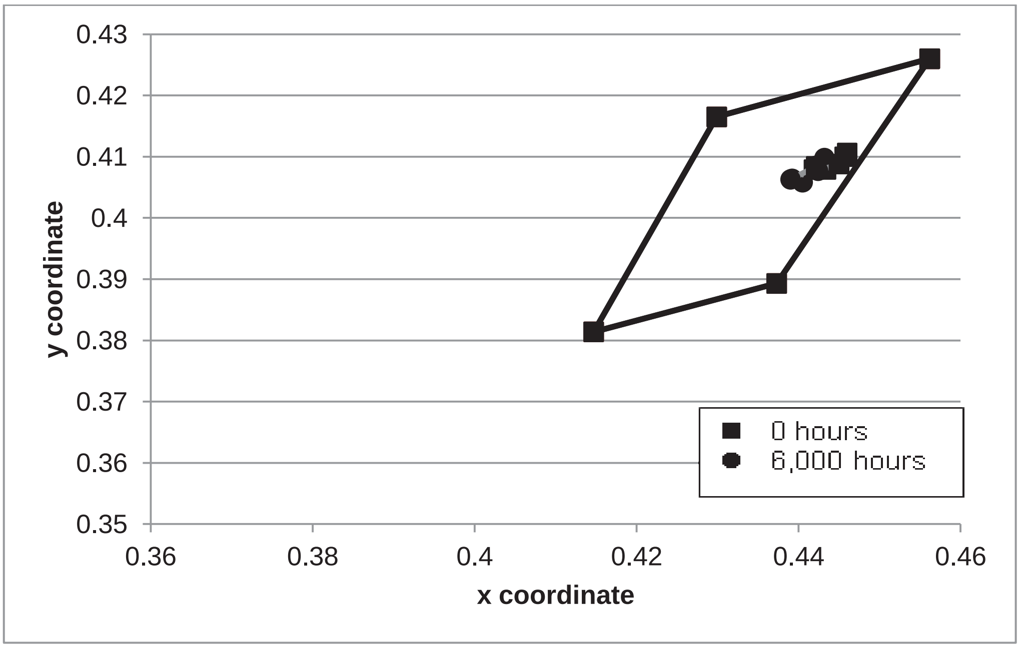

Figure 12.9 CCT change for Type G lamps

12.3 Colour Rendering

ENERGY STAR does not require the shift in CRI to be measured. However it is listed here to provide an insight into the change in colour rendering over time.

12.3.1 General CRI

For the majority of the lamps, CRI changed insignificantly over time. Type F lamps however improved noticeably by up to 12.9%. These changes are shown in Figure 12.10.

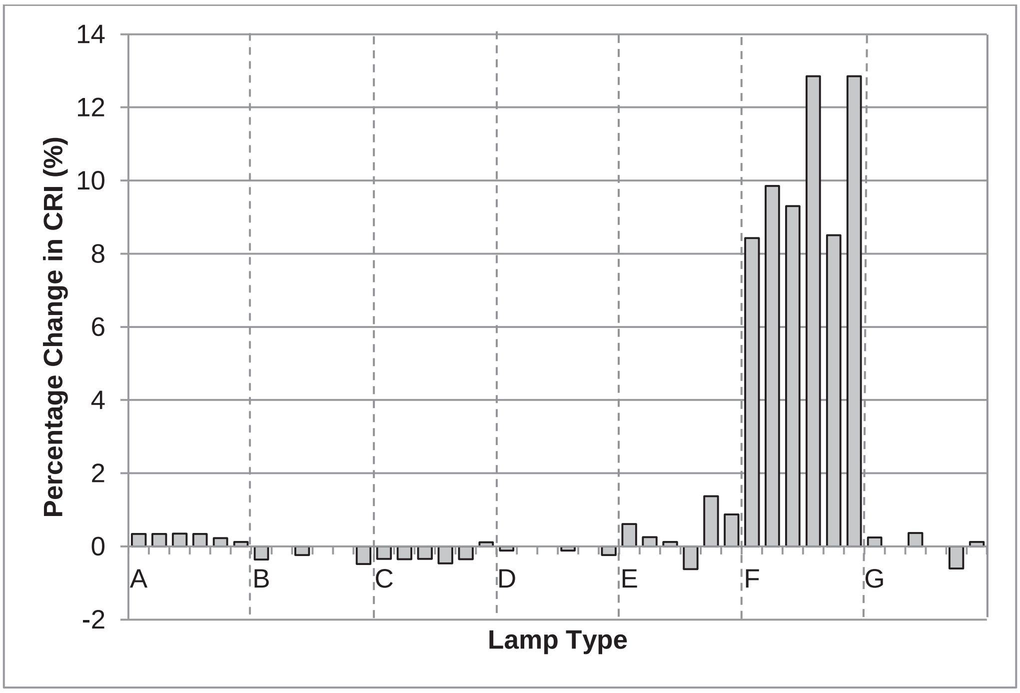

Figure 12.10 Percentage change in CRI from zero hours to 6,000 hours

Section 7.3.1 noted that CRI values for the Type F lamps fell short of the ENERGY STAR requirement. After 6,000 hours their CRI values had shifted up towards the ENERGY STAR acceptable limits. Even so, the lamps still failed to meet the requirement. This is shown in Figure 12.11 where the ENERGY STAR requirement is shown in grey.

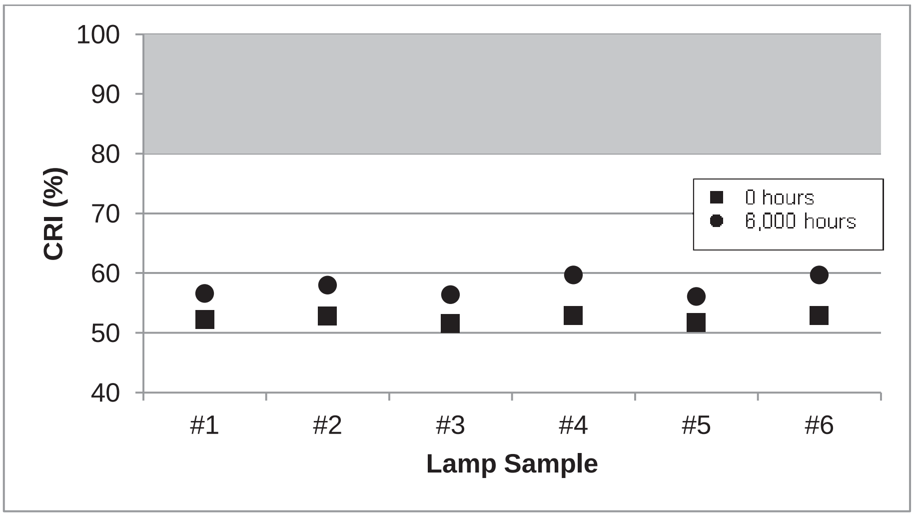

Figure 12.11 CRI change for Type F lamps

12.3.2 R_9

Figure 12.12 illustrates that most of the lamps had improved R_9 values over time.

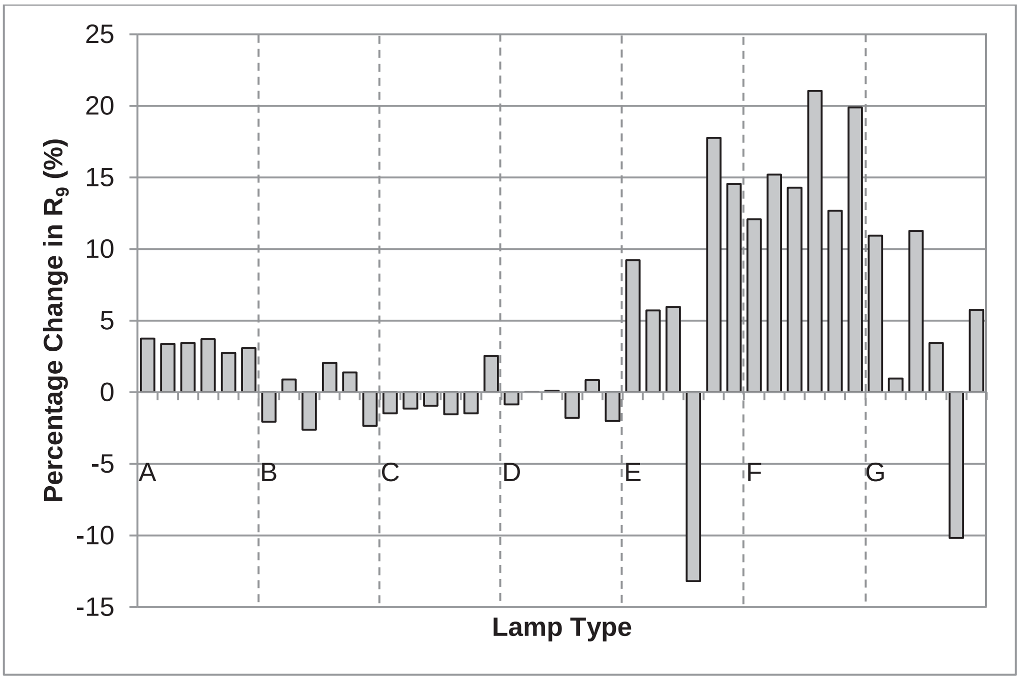

Figure 12.12 Percentage change in R_9 from zero hours to 6,000 hours

Type F lamps increased by as much as 21.0%, though its R_9 figures remained negative. It is not clear whether this would make much difference to the observer however, as the U.S. Department of Energy (2012, p. 3) notes that "the color space used in the CIE Test-Color Method often causes color shifts in the red region to be exaggerated".

12.4 Efficacy

A CALiPER study noted that efficacy values typically followed the lumen maintenance values (Paget, 2010). In other words, power usage stayed consistent throughout and the reduced lumen output values resulted in reduced efficacy. This experiment found a similar result which is illustrated in Figure 12.13.

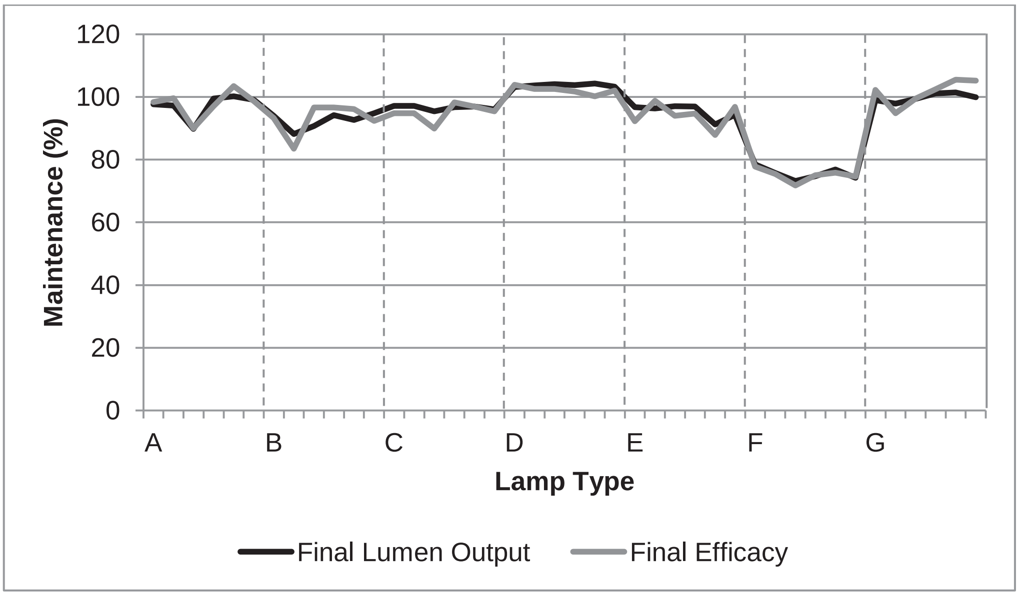

Figure 12.13 Lumen maintenance and efficacy maintenance at 6,000 hours

12.5 Lamp Quality Versus Mass

Section 2.8 noted that mass could be an indicator of lamp quality by deducing that a more effective heatsink is afforded through a larger quantity of aluminium. On that basis, a heavy lamp could be expected to have a smaller change in luminous flux due to its effective removal of heat from the junction. Figure 12.14 indicates that this was true in some respects for this experiment. The lamp with the lowest weight suffered the most degradation, with the other lamp types mostly in the ±5% region. It is important however to remember that many factors are at work in LED degradation and mass will not be the only cause of this change.

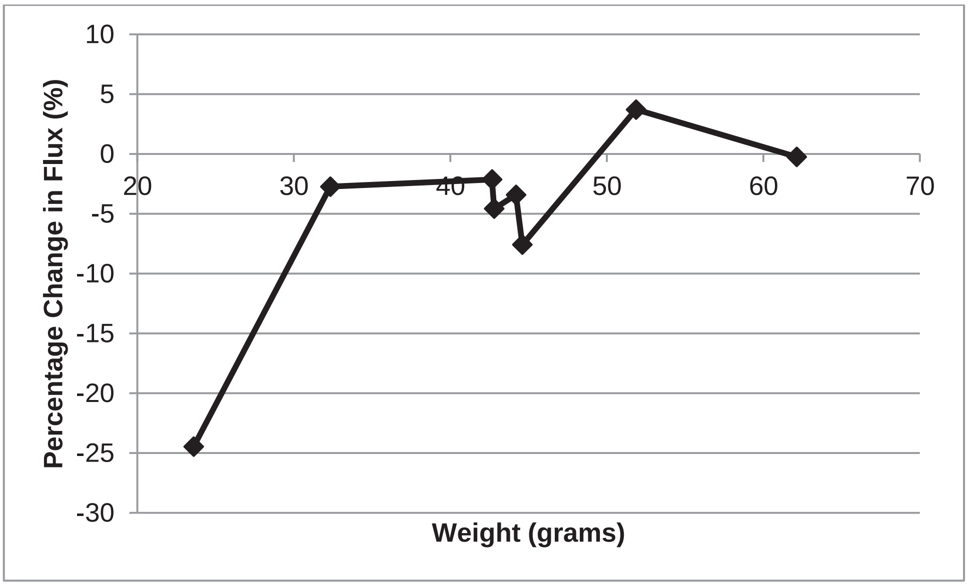

Figure 12.14 Percentage change in flux (zero hours to 6,000 hours) versus weight.

A report by the DOE (2013g) from the 2013 LIGHTFAIR International in Philadelphia noted that new design methods are leading to LED products becoming smaller and lighter. Therefore the perceived correlation between weight and quality, as indicated in this study, is changing as technology improves.

12.6 Lamp Envelope

Section 8.5 noted that one of the lamps (Type A #3) differed from the other Type A lamps as it had translucent rather than clear material at the front. This lamp was monitored to determine whether the material affected the photometric properties of the lamp. Figure 12.15 shows the initial values of luminous flux for the six Type A lamps. While the Type A #3 lamp initially had a lower light output than the other lamps in the sample, this was only marginal.

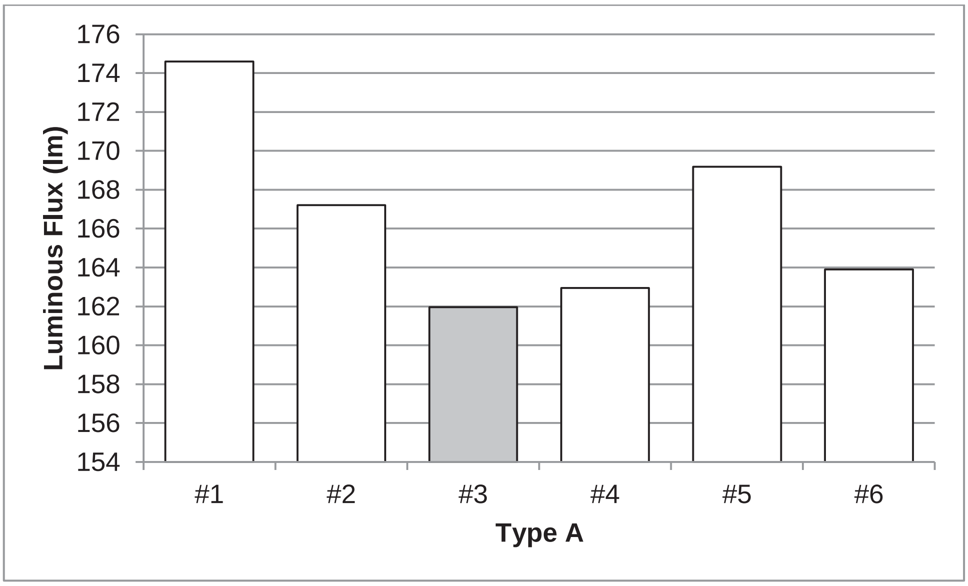

Figure 12.15 Luminous flux at zero hours for Type A lamps

Figure 12.16 shows that the lumen output of the frosted lamp (Type A #3) had depreciated more than its counterparts over 6,000 hours.

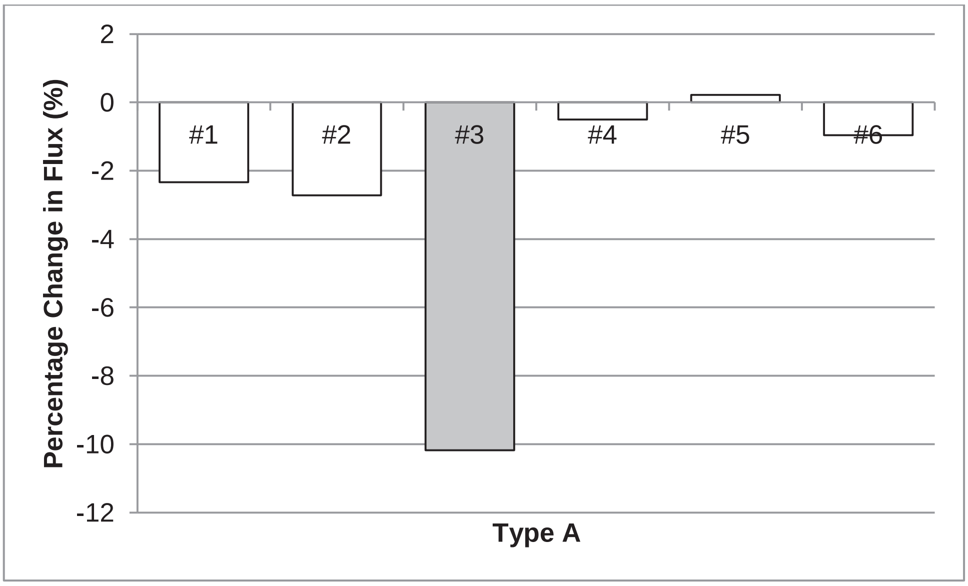

Figure 12.16 Percentage change in flux from zero hours to 6,000 hours for Type A lamps

Heightened deterioration was also encountered for CCT (see Figure 12.2) and ∆u'v' (see Figure 12.3). It is not possible to isolate the frosted material as the cause of this without further testing, however it may have contributed to the degradation. Further investigations would therefore be required to substantiate these theories.

12.7 Summary of Lighting Quality Over Time

Figure 12.17 shows the change in the photometric qualities of each lamp after 6,000 hours. A value of zero indicates no change. Positive figures show that the photometric quality in question has increased over time. The converse holds for negative values. Note that CCT is shown as the metric for colour in this case, as $\Delta u'v'$ cannot be shown as a percentage.

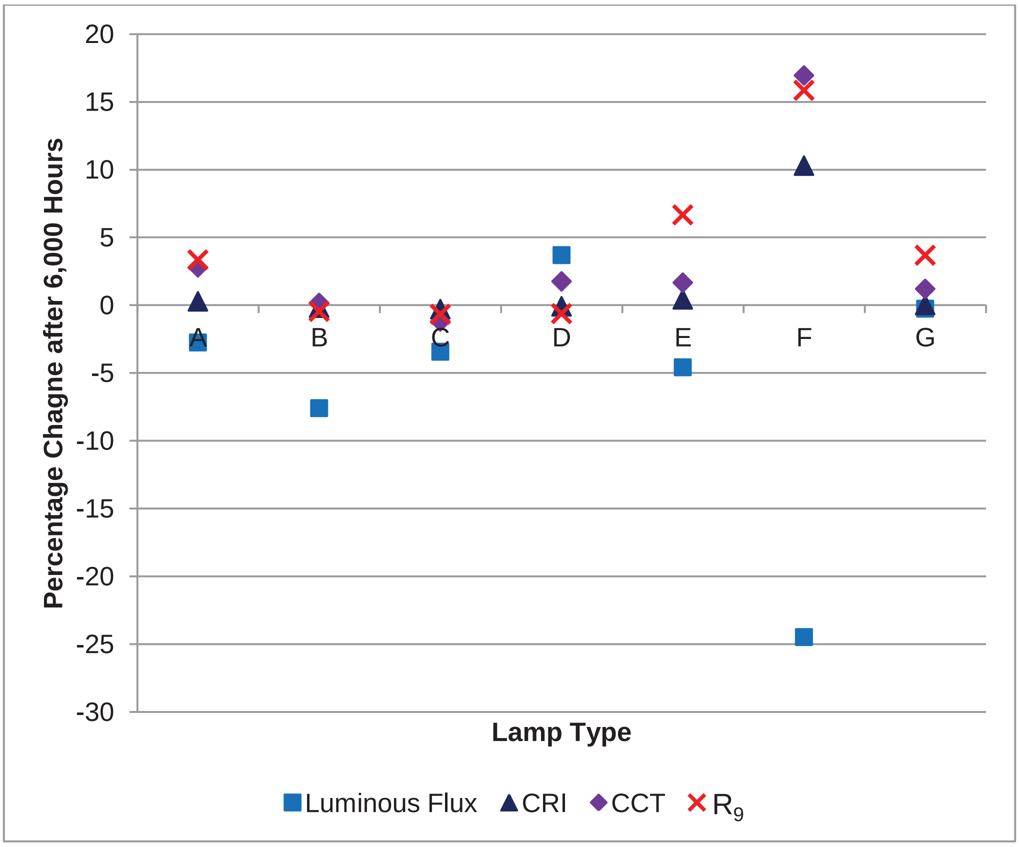

Figure 12.17 Change in photometric qualities of all lamp types after 6,000 hours

Figure 12.17 highlights that most lamp types had less than 5% change after 6,000 hours. Type B and Type E had slightly larger changes in lumen output and R_9 respectively though these were still less than 8% from the figures recorded at zero hours.

Given that most lamps exhibited less than 8% change over 6,000 hours, it could be questioned whether the test period was long enough to detect photometric deterioration. The 6,000 hour time period was selected based on LM-80 (see Section 4.7), as a test method for measuring the lumen maintenance of LED lamps does not presently exist. As noted in Section

2.13.6, IES-LM-84 (*Method for Measuring Lumen Maintenance of LED Lamps, Light Engines, and Luminaires*) is presently under development and may provide further guidance on testing duration. The little variation noted above for most of the lamps indicates that a longer test period than 6,000 hours may be appropriate.

Type F displayed marked changes after 6,000 hours with increases in CRI and CCT of up to 12.9% and 22.3% respectively. The increase in CRI is commendable, as this brought the Type F lamps up to a CRI average of 57.8. This was an improvement on its average CRI value of 52.4 at zero hours, though the lamps still failed to meet ENERGY STAR requirements. The significant increase in CCT was disappointing and could be noticeable if new lamps were introduced into an existing installation. Though lamp life for LED lamps is typically measured in terms of lumen maintenance, this illustrates that CCT maintenance is also an important consideration.

The average value for lumen maintenance after 6,000 hours was 75.5% for Type F lamps with one lamp falling to only 73.2%. As end-of-life for LED lamps is regarded as the point where the light output has reduced to 70% of its initial value, the Type F lamps could be considered to be nearing the end of their useful lives at this point. As this deterioration occurred after only 6,000 hours, the claimed lamp life of 35,000 hours is questionable.

Though the lumen maintenance figures for Type F lamps were low compared to other lamp types in this experiment, they were not as extreme as some lamps in the 2009 Southern California Edison study. In that study, twelve lamps fell below 70% light output in a shorter time period. In addition the 2011 CALiPER exploratory study noted that one lamp type reduced to only 43% light output after 1,000 hours. Thus, while the Type F lamps performed poorly compared to others in this study, they out-performed some earlier lamp models.

Type F lamps also had increased R_9 values of up to 21.0%, though this increase may not be noticeable to the average observer due to inconsistencies in the CIE Test-Colour Method.

13 Conclusions

To conclude, each of the experimental aims are discussed in turn.

13.1 Aim 1 – Halogen Equivalency

Experimental Aim 1

To determine whether the MR16 LED lamps in a sample of 48 (six repetitions of eight types) from the New Zealand market are equivalent to their halogen counterparts in terms of lumen output.

Australian MEPS requirements were used as a benchmark to determine equivalency with halogen lamps. The results shown in Section 5 demonstrate that none of the lamp types in this study were able to meet the MEPS minimum requirement for 35W halogen lamps. Based on MEPS minimums, five lamp types were suitable as 20W halogen lamps though one type was borderline. The remaining three lamp types were only suitable as 10W halogen replacements.

The comparatively low lumen outputs for the LED products will limit their utilisation and render them unsuitable as direct replacements for the 35W halogen lamps that are popularly used in New Zealand homes.

Five lamp types claimed to be 35W halogen equivalents on their product labels but were all found to be lacking. This agreed with a CALiPER exploratory study which noted likewise. This failure to meet consumer expectation could limit acceptance of LED MR16 lamps.

13.2 Aim 2 – Manufacturers' Claims

Experimental Aim 2

To determine whether the product labels provided by MR16 LED lamp manufacturers (same sample as Experimental Aim 1) quote valid figures.

Section 6 investigated whether the information presented in the manufacturers' literature on the lamps was accurate. Of the photometric values tested, 90% were found to be within 10% of the values given on the product labels.

CALiPER summary reports noted that lumen output in particular had been overstated in their study timeframe (2007-2010), though this appeared to have been rectified by the time of the CALiPER 2011 exploratory study. The three lamp types tested for luminous flux in this investigation were found to be within 10% of the values stated in their literature.

The largest deviation from the advertised values was shown by Type F. This was particularly true for CCT and CRI. Testing showed that CCT was up to 11.1% more than that shown on the product labels while they underperformed by up to 26.3% in CRI.

From the data tested, it can be concluded that the information presented on the lamp labels in the test sample is generally accurate. The Type F lamps are an exception to this. With the rapidly changing LED market, it is not possible to know whether the products presently available in the New Zealand market are better or worse than those tested. Without the benefit of photometric testing, consumers will not be aware of inaccurate claims. A labeling program, such as those utilised by the U.S. Department of Energy and Lighting Council, Australia would ensure that accurate information is imparted to consumers. This could be accompanied by a promotional drive to introduce consumers to necessary terminology such as *luminous flux* and *efficacy*. It is important to shift emphasis away from the use of wattage as a predictor of light output.

13.3 Aim 3 – Baseline Lamp Quality

Experimental Aim 3

To determine whether MR16 replacement lamps available in New Zealand (same sample as Experimental Aim 1) meet ENERGY STAR requirements.

The values given in Section 7 determined that all lamp types passed ENERGY STAR requirements with the exception of Type F and Type G. Type F failed in the colour properties of CCT, CRI and R_9, while Type G failed in efficacy, though efficacy was estimated due to LED converter losses. Type G also failed in CCT, as it listed a value that is not designated by ENERGY STAR. Type H did not list a value for CCT and was not able to be evaluated for this metric.

Though Type F failed in colour, it outperformed other lamp types in terms of estimated efficacy. It was thus found that the eight different lamp types had their own strengths and weaknesses. Type A lamps performed consistently well for the ENERGY STAR criteria tested in this experiment.

The CALiPER summary reports noted a similar trend with one particular lamp in Round 8 consistently functioning at a high level when compared to the other lamps under test.

While it is commendable that most lamps in this study complied with ENERGY STAR, it is important that this information be conveyed to the consumer. None of the lamps in this study carried the ENERGY STAR mark, as none had been registered under the program. It is therefore important that manufacturers are encouraged to register with ENERGY STAR in order for quality to be recognised. It is equally important that poor product is removed from New Zealand shop shelves, by way of a program such as MEPS.

13.4 Aim 4 – Consistency Within Type

Experimental Aim 4

To investigate the photometric variation between six repetitions of LED MR16 product (same sample as Experimental Aim 1) to test for consistency.

Data given in Section 8 showed that the lamp samples had an average variation of 7.5% (efficacy), 7.3% (lumen output), 2.1% (CCT) and 1.6% (CRI) between the lowest and highest lamp.

Type F proved to be the least consistent lamp type of the eight tested whereas Type D was the most consistent.

Though product consistency was rarely mentioned in the other studies referred to in this report, a value of 4% average variation between two units was given for lumen output and efficacy in a 2009 report. However the report included both replacement lamps and integral luminaires. It was noted that replacement lamps showed a higher variation though the exact figure is unknown.

The general consistencies noted above indicate that it may be possible to reduce sample size in the future. However the larger tolerances of the Type F lamps highlight that anomalies exist. Further research is required to determine a suitable lamp sample size.

13.5 Aim 5 – Effect of Heat

Experimental Aim 5

To investigate if the heat build-up in a typical New Zealand downlight installation affects the long term attributes of MR16 retrofit lamps when compared to those same lamps mounted in free air (same sample as Experimental Aim 1).

The results noted in Section 10 revealed that heat exacerbated the deterioration of Type H lamps, where the lamps in downlights consistently discoloured after a shorter time than the equivalent lamps in free air.

As noted in Section 11, there was no statistically significant difference in lumen deterioration between the remaining seven lamp types mounted in downlights and those in free air over a 6,000 hour period in an Auckland ceiling. CCT was also measured over the same period with no significant difference recorded between the two test groups.

The findings for lamp Types A-G are contrary to previous knowledge that LEDs are negatively affected by heat with higher temperatures resulting in higher levels of degradation. While reasons for this disparity are unknown, it is postulated that laboratory testing at extreme temperatures under electrical current stress produced different data to that found in reality.

In order to further compare this experiment with a larger pool of research, there may be value in using special methodologies to indicate *junction temperatures* in all of the lamps in future studies.

13.6 Aim 6 – Lighting Quality Over Time

Experimental Aim 6

To investigate whether energy efficiency and longevity are achieved at the expense of photometric outputs, such as a shift in CCT or significant lumen depreciation (same sample as Experimental Aim 1).

Lighting quality over time was analysed in Section 12. With the exception of Type F, all lamps exhibited less than 8% variation after 6,000 hours. Given that most of the lamps in the sample exhibited little variation, it could be questioned whether the 6,000 hour test period was long enough to detect photometric deterioration. As noted in Section 4.7, the 6,000 hour time period was selected based on LM-80, as a test method for measuring the lumen maintenance of LED lamps does not presently exist.

IES-LM-84 (*Method for Measuring Lumen Maintenance of LED Lamps, Light Engines, and Luminaires*) is presently under development (see Section 2.13.6) and may provide further guidance on testing duration. The little variation noted for most of the lamps indicates that a longer test period than 6,000 hours may be appropriate.

Type F showed clear changes after the test period, with an increase in CRI of up to 12.9%. This improved the average figure for CRI from 52.4 at zero hours to 57.8 at 6,000 hours however the lamps still failed to meet ENERGY STAR requirements. CCT also increased in Type F lamps and this change of up to 22.3% could cause problems with future colour matching of lamps. Of all the lamp types tested, lumen maintenance also suffered the greatest change for Type F lamps, with one lamp falling to only 73.2%. As this value is close to the 70% figure normally used as end-of-life for LED lamps and was reached after only 6,000 hours, the claimed 35,000 hour lamp life is highly questionable.

Type F lamps suffered the most change but their lumen maintenance figures were not as poor as values noted in previous studies by CALiPER and Southern California Edison.

13.7 Additional Findings

In addition to the findings listed in Sections 13.1 to 13.6, other observations were made which do not fit into the conclusions previously given. These are listed below.

- Two of the test lamp types exceeded the form factor set by ANSI C78.24 and could cause installation problems in existing luminaires;
- Two seemingly unrelated lamp types looked physically similar which could lead the consumer to believe that they are the same product;
- Difficulties were encountered when using one lamp (from a set of additional test lamps) with an electronic transformer;
- There was no noticeable difference in light output figures for a set of test lamps under AC and DC operation;
- All six Type H lamps had to be removed from the experiment due to a potential fire risk;
- Four Type F lamps experienced cracks in their casings after 3,000 hours, which became worse as the experiment progressed.

13.8 Final Conclusion

This investigation began with the statement:

> *The purpose of this research is to evaluate MR16 LED product available on the New Zealand market in order to provide consumer satisfaction and avoid a repeat of the CFL experience.*

This report has shown that the unregulated New Zealand market contains flawed lamps which could severely taint consumer's acceptance of MR16 LED lamps. Of the eight lamp types studied, two (25%) were shown to be seriously flawed.

The Type H lamps were of particular concern, due to the fire risk that they presented. This could have a catastrophic outcome for the consumer, who is unlikely to check on the lamps after installation. The resulting deterioration could therefore continue undetected until it was too late. As Type H was the most expensive lamp type used in this study, it is concluded that price is not necessarily an indicator of lamp quality. The consumer would be unwise to purchase on price-point alone.

The Type F lamps performed poorly on a number of levels, both at project initiation and over time. The lamps failed to meet many of the photometric claims made on their product labels, and proved to be the most inconsistent product of the eight types tested. After time, the lamps not only deteriorated rapidly in output, they also underwent mechanical failure and started cracking.

The other six lamp types under test showed that while improvements have been made since similar studies began in 2007, it is clear that each product has its own strengths and weaknesses.

The fact that 25% of the lamps sampled in this study were seriously flawed illustrates that care must be taken when purchasing LED lamps in the unregulated New Zealand market. At present it is difficult for the consumer to differentiate good product from bad. Research shows that a quality chip brand is not necessarily indicative of a quality product, due to the possible use of low tolerance binning (Cree, 2010) and "poorly engineered products" (Next Generation Lighting Industry Alliance, 2011, p. 3).

An increased uptake in ENERGY STAR would aid the purchaser in procuring a quality product, however it would not prevent poor product from being sold. Appropriate methodology needs to be developed in order to remove these poor performing options from New Zealand shop shelves. A program such as MEPS would satisfy this requirement.

Labeling based on independent testing, such as the process utilised by the *LED Lighting Facts* program, would provide accurate information to the consumer. However, it relies on the consumer being fluent in photometric terminology. An accompanying advertising program would be beneficial to ensure that consumers understand the implications of the data presented to them, such that they learn to stop relying on wattage as the sole determinant of light output.

The CFL experience highlighted that consumer understanding is vital to acceptance of new product. Problems encountered with initial quality and performance of MR16 LED lamps could be mitigated by using the steps noted above. These can be summarised as:

- Encourage the uptake of ENERGY STAR, to facilitate the identification of quality product
- Use appropriate means (such as MEPS) to remove poor product from shop shelves
- Provide accurate photometric information to the consumer through the use of standardised product labels

Long-term quality and performance is harder to quantify, and is not addressed by the above recommendations. This report utilised the common metric of lumen maintenance, which is also used in ENERGY STAR. As noted in Section 2.13.6, a formal method for measuring the lumen maintenance of lamps is presently under development, and will be issued as IES-LM-84. It is envisaged that this new standard will test lamps at different temperatures for significant periods of time, in the same vein as LM-80-08. On that basis it could be assumed that potential problems with mechanical failure, such as those noted for Type F and Type H, will be identified at the testing stage. Other measures such as colour maintenance are sure to follow in due course.

As noted above, work is required in order to ensure that MR16 LED lamps are accepted by consumers and do not follow the same path as CFLs. In the meantime, while appropriate regulation is not in place, it is essential that consumers seek advice from reputable lighting specialists in order to select a suitable product that is fit for purpose.

14 Further Study

This investigation has revealed a number of areas which would benefit from additional study. These are listed as follows.

14.1 Recoverable Losses

Though the lamps in this study were divided into two groups mounted in downlights and free air, they were all tested at 25˚C. This identified non-recoverable losses which caused permanent damage to the lamps. However literature states that losses can also be *recoverable*. Cree (2004) noted that lumen output decreases with increased junction temperature but recovers once the LED cools down. This means that the lamps may have produced less light and/or had undesirable colour qualities from recoverable losses while mounted in the test rig.

Future testing could record the light output while the lamps are running in the test rig to ascertain whether recoverable losses are causing a drop in luminous flux or producing unacceptable colour outputs. These could both contribute to an acceptable installation for the consumer.

14.2 AC versus DC

The various issues regarding powering LEDs through AC transformers have already been discussed. Three lamps used various 12V AC transformers and a 12V DC LED converter to determine whether they produced less luminous flux.

Future testing could run additional lamps on a selection of different supplies to note whether these result in differing outputs or rates of degradation over time.

14.3 Temperature

While the lamps were mounted in the test rig, it was noted that one lamp was very unstable in that it changed temperature quickly. One other lamp maintained a very stable temperature output and was not affected by the small fluctuations in the ambient conditions. Further study could investigate the temperatures of all lamps as this study was restricted to just three lamps, given the size of the data logger used.

In addition, some lamps took a long time to stabilise in the integrating sphere, while others maintained a very constant output. Further research could identify whether there were links to the temperature data noted above and the stabilisation time in the integrating sphere.

A further study could also provide an indication of the junction temperatures in the differing lamp types. This would allow further comparison with a larger set of data.

14.4 Catastrophic Failure

While there were issues with possible fire risk and cracking of plastic, none of the lamps experienced catastrophic failure. Nor did it appear that any of the individual LEDs within the lamps had failed. By continuing to run the test rig further, suspect lamps could be tested to destruction.

14.5 CALiPER Studies

Section 2.14.1.3 noted that CALiPER has recently extended its studies to include reports on the following topics:

- Beam, shadow and colour quality
- Flicker, dimming and power quality
- Stress testing
- Lumen and chromaticity maintenance

(U.S. Department of Energy, 2013b)

Future testing could also include some or all of these. This report has focused on lumen and chromaticity maintenance. However the first three items would provide an interesting annexure, as quality lighting is measured in more than lumen and chromaticity maintenance alone.

14.6 Mechanisms of Deterioration

Type F lamps experienced both mechanical and photometric deterioriation. Further research could closely examine the mechanisms behind the deterioration of the Type F lamps over time. This could extend to include the degradation of the materials found within *all* of the lamps sampled.

14.7 Design

Section 4.1.5 noted that the various lamp types had a diverse mix of LED types and layouts. It follows that the integral drivers could have different designs. Future study could analyse the different lamp designs and consider this in relation to other findings.

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