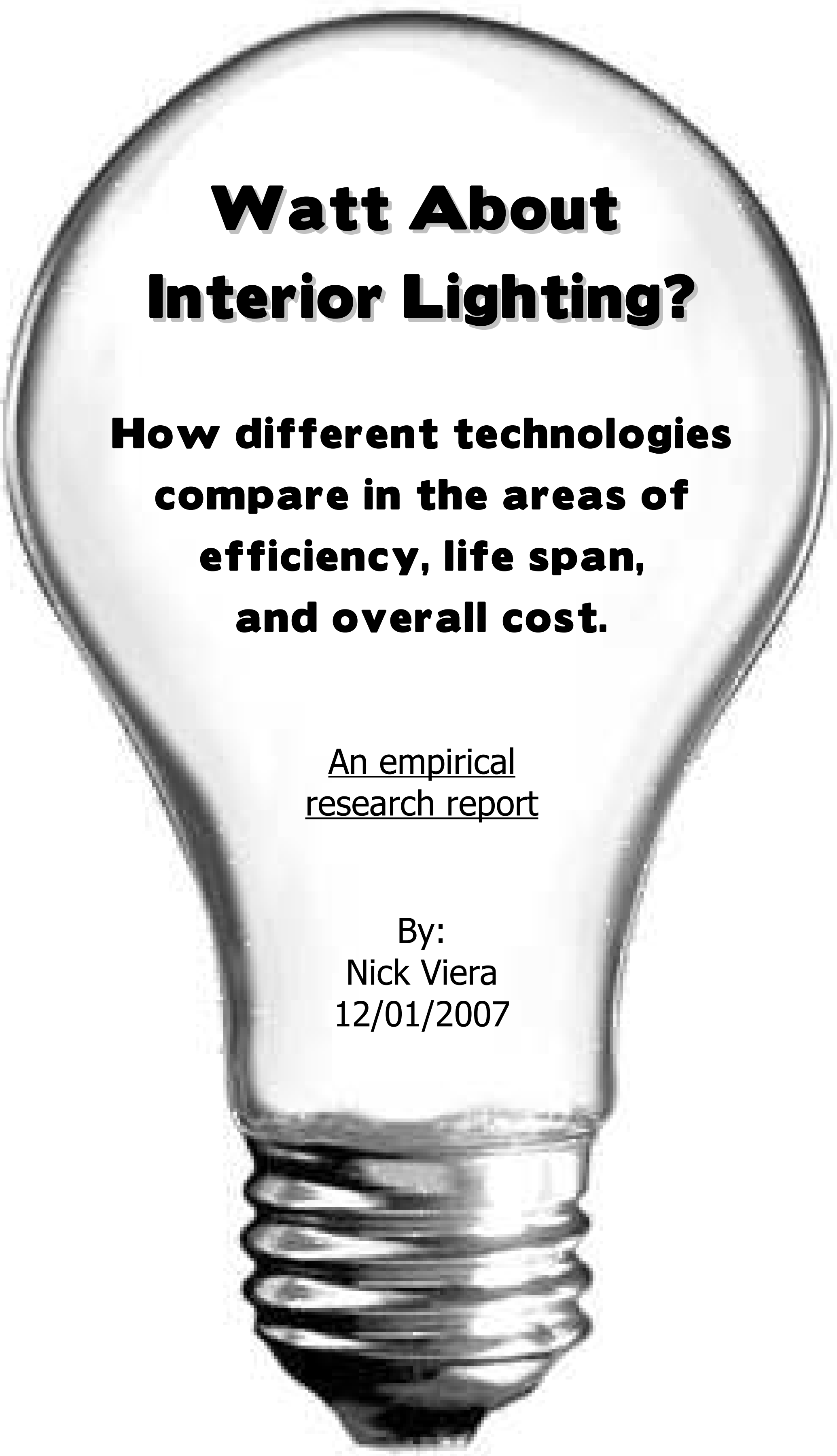

Watt About Interior Lighting?

How different technologies compare in the areas of efficiency, life span, and overall cost.

An empirical
research report

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Abstract

Ever since its invention and successful commercialization, electric lighting has been one of the single most crucial technologies for sustaining modern civilization as we know it. Due to its frequent and wide-spread use, indoor lighting is one of the main sources of energy-and thus-financial waste in buildings across the world. Such waste is usually the result of the use of inefficient and/or improperly used lighting technologies.

For these reasons common indoor lighting technologies were studied by the author in order to determine the strengths and weaknesses of each technology, especially regarding the energy efficiency of each technology. The study also took into consideration cycle life, initial cost, operating cost, and light quality of the studied lighting technologies. The study focused on incandescent, halogen, linear and compact fluorescent, cold-cathode fluorescent, and metal halide lighting technologies, which make up the vast majority of indoor lighting used today.

Literature review and practical research both suggested that metal halide and linear fluorescent lighting are the most efficient and longest-lived technologies of those studied, with metal halide lighting having a slight advantage over linear fluorescent in most applications. In addition, the study suggested that incandescent lighting was the least efficient and shortest-lived technology, closely followed by halogen lighting. Lastly, compact fluorescent and cold-cathode fluorescent lamps were neither as efficient and long-lived as metal halide lamps nor nearly as inefficient and short-lived as incandescent lamps.

The study shows how much energy and money can be pointlessly wasted due to the selection of inefficient lighting technologies... and it also shows the great potential for saving money while helping conserve energy by selecting modern, efficient lighting technologies whenever possible. For many years lighting has been treated like an afterthought, where poorly-planned and/or low quality lighting installations have become commonplace in buildings across the world. However, with some extra planning and care, indoor lighting can be selected and installed which will not only save building owners and operators money, but will improve the indoor atmosphere, reduce waste, and help bring us closer to living in a truly sustainable world.

Introduction

Ever since its invention and successful commercialization, electric lighting has been one of the single most crucial technologies for sustaining modern civilization as we know it. Yet, despite its significant role in virtually everyone's lives, electric lighting has also become one of, if not the most taken-for-granted technologies in use today.

This is unfortunate because the quality, efficiency, and performance of lighting can have a huge impact on people's mood, energy, checkbook, and overall lifestyle. Thus making good, well-informed decisions when selecting lighting technologies can ensure that the lighting is economical and practical, yet provides the best possible environment for its users.

For these reasons common indoor lighting technologies were studied by the author in order to determine the strengths and weaknesses of each technology, especially regarding the efficiency of each technology. The aforementioned study consists of two major components, a comprehensive literature review, and an empirical research project. These two components together allow the author to present results obtained both from theoretical and practical study of indoor lighting technologies.

Literature Review

Scope

This literature review examines the energy efficiency, life-cycle expectancy, and overall performance of the primary lighting technologies which are used by the billions to provide interior lighting around the world. Specifically, this paper focuses on “medium” scale lighting, defined here as lamps and fixtures in the 40 to 200W power range, which are commonly found in residential and commercial buildings. Such lighting accounts for as much as 40% of all the electricity used in commercial buildings [4][20], and 10% of all the electricity used in homes [8][7].

This lighting belongs to the following lighting categories: resistive, fluorescent & high intensity discharge (HID), and (to a much lesser extent) solid-state. Currently, the most common lamp and lighting system types in use are incandescent, halogen, linear fluorescent, compact fluorescent (CFL), and metal halide. Solid-state Light Emitting Diodes (LEDs) are beginning to gain acceptance and become practical interior lighting sources, but are currently not up to par with the aforementioned lighting types, and will not be discussed in this paper.

Incandescent: Seasoned veteran of lighting

The oldest and still one of the most widely used types of lighting is the venerable incandescent lamp, first made into a practical source of illumination by Thomas Edison in 1879. Incandescent lamps, being resistive devices, rely on heating their filaments from 2000 to 3500 degrees Kelvin (1700 to 3200 degrees Celsius) in order to emit light [14][11]. This severe heating of the filament accounts for incandescent lamps' greatest flaw as well as their greatest asset.

The flaw is that the process of powering the filament emits far more heat energy than light energy. The average incandescent lamp wastes over 95% of its consumed energy as heat and is thus only about 2 to 3% efficient at producing light [14]. These numbers translate to the average incandescent lamp, of the 40 to 200W range, having a luminous efficacy of about 12 to 18 lm/W (lumens per Watt), depending on the size of the lamp [15][14]. Since these lamps waste so much energy as heat, not only are they expensive to operate directly due to their high electricity usage, but they are also expensive to operate indirectly because their excess heat generation increases the loading of air conditioners and other climate control systems.

The greatest assets of the incandescent lamp are very low production costs, easy full-range dimming, and comparatively good temperature tolerance, allowing it to operate in almost any environment. In addition, incandescent lamp filaments are black body radiators, which have the unique property of generating light quite uniformly across the visible and infrared spectrum. Thus incandescent lamps typically produce a very balanced light output with a color rendering index (CRI) rating of 100, approximately equivalent to sunlight [14]. Lastly, the resistive design of incandescent lamps ensures that they operate with a unity power factor of 1.00, which is a bonus for applications where power factor is strictly regulated.

Modern incandescent lamps, such as those depicted in Figure 2.1, have been perfected to last significantly longer than their crude predecessors, however even modern lamps still suffer from a comparatively short life span. In fact, incandescent lamps, with a life span of 1,000 to 2,000 hours, are the shortest-lived lamps of any modern lighting technology [11]. This makes them problematic and expensive for use in applications where lamp replacement is difficult and/or labor intensive. In addition, the lives of incandescent lamps are further reduced by external factors such as high ambient temperature and vibration.

Figure 2.1: An Assortment of modern incandescent lamps. From left to right: A-lamp, flame, tubular, G25 globe, R20 reflector, and PAR38 reflector.

While incandescent lamps do provide some useful benefits such as excellent quality of outputted light, and low manufacturing and thus low purchasing cost, their very dismal efficiency, efficacy, and life span make them an economically poor choice for all but the harshest of interior lighting applications.

Halogen: Best of the worst

In an effort to make incandescent lighting technology more efficient, and generally better, research done throughout the 1950s led to the first practical halogen lamps in 1959 [17]. Halogen lamps are essentially nothing more than refined incandescent lamps, but their utilization of halogen gases within the lamp allows them to operate more efficiently and have a longer life expectancy than their incandescent counterparts. As Figure 3.1 shows, modern halogen lamps are available in many shapes and sizes to facilitate easy replacement of their incandescent predecessors.

Despite being slightly more efficient than standard incandescent lamps, halogen lamps remain comparatively inefficient amongst modern lighting. Luminous efficacies for halogen lamps are in the 16 to 24 lm/W range, with efficiencies of 3 to 4% depending on lamp size and whether the lamp is standard or quartz halogen [18][8]. Also, while halogen lamps produce less overall heat (due to their higher efficiency), the lamps themselves operate at much higher temperatures than standard incandescent lamps, making them a much greater fire hazard, and leading to their banning in certain areas and applications [12].

Figure 3.1: An Assortment of modern halogen lamps. From left to right: A-lamp, BT-15, Midbreak, PAR16 reflector, and low-voltage lamps: MR-16 reflector and T4 bi-pin.

Light output of halogen lights is similar in spectrum to incandescent lamps, as halogen lamps also act as black body emitters. As a result, halogen lamps also have a high CRI rating while producing light with a cooler color temperature then incandescent lamps, an attribute which is said to make them seem brighter than they are. Halogen lamps are also excellent emitters of short-wave ultraviolet (UV) light, which can pose a serious health risk in many indoor and/or close-proximity applications. Thus most halogen lamps made for such use utilize filters to block the UV radiation, which causes a slight reduction in luminous efficacy, but allows halogen lamps to produce less UV then standard incandescent lamps [12].

The place where halogen lamps really do outshine standard incandescent lamps, however, is life span. Typical life span for halogen lamps is roughly double that of incandescents, giving them a typical life span of 2,000 to 4,000 hours [12]. Longer life means halogen lamps are better suited for applications where lamp changing is difficult and/or expensive, and the money saved with fewer replacements will help offset some of the money wasted due to halogen lamps' relatively low efficiency.

These improved characteristics, as well as the other features that halogen lamps inherited from their incandescent counterparts, namely simplicity, unity power factor, simple full-range dimming, environmental robustness, and low purchase price, make halogens the best choice of lamps from the resistive lighting category; the worst category with respect to economics and efficiency.

Linear Fluorescent : Most underrated lighting

Linear fluorescent lamps have been around longer than halogen lamps, with the first practical fluorescent lamp being invented in 1927 and the lamps first appearing on the market in 1938 [2]. Yet despite this technology's age, fluorescent lights saw a much slower adoption and have remained less popular than halogen and incandescent lamps in residential applications, historically being only truly appreciated in the commercial/industrial world.

This is undoubtedly due to the limitations and nuances of early fluorescent tubes and their associated ballasts and starters... systems which struggled for decades with poor cold climate operation, slow warm-up times, poor color temperature, low CRI, humming, and noticeable flickering inherited from the 60Hz AC line power [10]. The good news is that modern T8 and T5 fluorescent lighting systems have evolved the technology to the point of extremely reducing or eliminating all of these nuances which plagued legacy T10 and T12 fluorescent systems. Figure 4.1 displays the currently available fluorescent tube sizes.

Despite all of the early growing pains experienced by fluorescent lighting, one area where the technology always excelled was efficiency. This holds true today, where linear fluorescent lighting remains one of the most efficient forms of lighting in existence. Where legacy T12 systems with magnetic ballasts typically had efficacies around 50 to 60 lm/W, modern, average-quality (25 to 54W) T5 and T8 fluorescent systems with electronic ballasts achieve 80 to 92 lm/W. In addition, top-of-the-line "high performance" T5 and T8 systems can achieve efficacies as high as 95 to 102 lm/W [5][10][9]. These numbers translate to fluorescent lighting system luminous efficiencies from 7 to 15% efficient [10].

Thus even the worst fluorescent lighting systems destroy resistive lighting in the war for highest efficiency. However, fluorescent lighting systems are unable to achieve the perfect unity power factor of resistive lamps. Although they can achieve a power factor as high as 0.99, average fluorescent ballasts have power factors of 0.80 to 0.95, which could require external power factor correction systems to be used with large lighting installations [10].

Figure 4.1: An Assortment of Linear fluorescent tubes. From left to right: T4 bi-pin, T5 bi-pin, T6, T8 bi-pin, T8 recessed contact (R17d), T12, T8 U-tubes.

Despite the added complexity and higher component count of fluorescent lighting systems versus simple resistive lighting, fluorescent lights have been able to achieve long life spans. Linear fluorescent tubes have typical life spans of 10,000 to 25,000 hours, while ballast systems can last 20 years or more [8]. The result is that fluorescent lights are excellent for use in applications where lamp or fixture replacement would be difficult and or expensive.

However, fluorescent lights are not black body radiators like resistive lamps are, and as a result the quality and spectrum of emitted light is extremely dependent on the type and quality of phosphors used in the lamps. Typical fluorescent lamps output light with color temperatures in the 3000 to 6500K range, with the 4100K "cool white" color temperature historically being the most widely used. In addition, most lamps only achieve CRI ratings of 70 to 78 [5][9]. For applications where lighting quality is very important, fluorescent lamps are available with higher quality halophosphate or triphosphor coatings which can achieve CRI ratings of 80 to 99 [5][10].

These characteristics of fluorescent lighting, as well as other improvements of the technology (i.e. dimming capability, instant starting, etc), have given fluorescent lighting a big boost and finally allowed it to become a dominant technology in both the commercial and residential worlds. And for good reason as, despite relatively high initial cost, modern fluorescent lights ultimately save money directly and indirectly through lower operating and maintenance costs, while providing light quality comparable to or exceeding that of other technologies.

Compact Fluorescent: Efficiency meets style

Linear fluorescent lighting was the undisputed winner when it came to efficiency and low lifetime cost, but its large form factor and inelegant shape make it hard to use in applications where space is limited or where square or rectangular shapes don't fit the aesthetics of the space. The invention of the compact fluorescent lamp (CFL) in 1972 and successful commercialization in the 1980s made it possible to use fluorescent technology in almost every application [7][17]. CFLs operate just like linear fluorescent lamps; some require external ballasts, while many are manufactured with integral ballasts and starting systems which reside in the base of the lamp.

CFLs, while using efficient fluorescent technology, are usually less efficient than their linear counterparts, mainly due to smaller, cheaper ballast and starting systems being used. In addition, the ballast and lamp are usually packed tightly into the same package, causing the operating temperature of the components to be higher than that of externally-ballasted fluorescent lamps, which also causes a slight reduction in efficiency [7]. Average CFLs in the 9 to 30W range are 7 to 9% efficient, which translates to a luminous efficacy of 45 to 65 lm/W [7] [3]. Like linear fluorescents, CFLs operate at much lower temperatures than resistive lamps, meaning they put less load on air conditioning and climate control systems, and are less of a fire hazard then hotter-burning lamps.

As is evident from Figure 5.1, modern CFLs come in many shapes, sizes, and tube styles, providing a variety of aesthetics. Special dimmable, 3-way, motion-activated, and photocell CFLs are now available. Thus, CFLs are usable and accepted in many more applications than linear fluorescents, and now can be used virtually everywhere an incandescent or halogen lamp is used. In addition, the quality of light emitted from a CFL is similar to linear fluorescents, with color temperatures from 2700 to 6500K available, in addition to colored and UV “blacklight” CFLs. Special high-quality and full-spectrum CFLs can be had to provide the best light quality with CRI ratings as high as 96, where the average CFL has a CRI of 80-85 [7].

Figure 5.1: An Assortment of modern CFLs. From left to right: Self-ballasted lamps: Spiral, A-lamp, R20 reflector, Quad. Discreet (non-ballasted) lamps: Quad PL, Circline

Furthermore, CFLs, like linear fluorescents, are capable of very long life spans. Average CFLs are made to last 6,000 to 10,000 hours, while higher-quality CFLs can last as long as 15,000 hours, approaching the life span of linear fluorescent lamps [7]. Thus CFLs are also good candidates for applications where lamp and fixture maintenance is difficult or expensive to carry out.

However, CFLs also share the same main drawbacks as linear fluorescent tubes. Their relatively high initial cost and containment of trace amounts of mercury make it more difficult to purchase and dispose of them than the simpler resistive lighting technologies. Yet, these issues are being worked out as manufactures continue to find ways to reduce the production costs of CFLs, and as manufactures and governments improve and enforce the infrastructure to make proper disposal of CFLs easy and efficient. In addition, the fact that CFL life span continues to be improved means that CFLs will have to be purchased and disposed of less frequently, which also helps to reduce the impact of the aforementioned issues.

Metal Halide: High density, high intensity

Throughout the 20th century, as the fluorescent lamp was being perfected, consecutive work was going into mercury vapor lamps, a promisingly efficient High Intensity Discharge (HID) technology. However, the main drawback of mercury vapor lamps was their poor light quality and blue-green light spectrum. In an attempt to make the mercury vapor light better, the first practical metal halide lamps were invented in the 1950s and successfully commercialized in 1962 [17]. Since its creation, the metal halide lamp has rivaled mercury and sodium vapor lamps for the HID market, and as a result is now widely available in a variety of form factors, depicted in Figure 6.1.

Figure 6.1: An Assortment of metal halide lamps. From top-left to bottom-right: Tubular, EDxx series, PAR30 reflector, T7 double-ended, and T6 bi-pin.

Metal halide lamps, like fluorescent lamps, need ballasts and starters to operate, and are surprisingly efficient lighting systems. Metal halide systems are most efficient in large formats, and as a result haven't been very popular in the residential market, where lower power lamps are used [4]. Average metal halide lamps in the 50 to 400W range are as much as 24% efficient, and have efficacies of 65 to 115 lm/W, depending on lamp size, with smaller lamps peaking at about 90 lm/W [4][19][15]. Thus large format metal halide systems are the most efficient kind of mainstream lighting currently being used indoors.

In addition to high efficiency, metal halide systems produce higher quality light then other HID technologies. Typical metal halide lamps produce light with a color temperature in the 3000 to 20000K range, and with CRI ratings of 65 to 90 [19]. Like fluorescent lamps, metal halide lamps are also available in special colors such as blue, green, aqua, and pink. Metal halide lamps typically last 15,000 to 20,000 hours and ballasts can last as long as 30 years [13].

Despite their high energy efficiency, metal halide lamps operate at very high temperatures of about 1,090 degrees Celsius internally, making them problematic for certain applications, and a more likely fire hazard. In addition, their chemistry makes it hard to guarantee a specific color temperature, and the color temperature of their light shifts with lamp age. Lastly, like all HID lamps, metal halide lamps have a warm-up time of as long as 5 minutes, and cannot be restarted until the lamp has sufficiently cooled after being powered off, a process which typically takes up to 10 minutes [19].

Even with these limitations, the high efficiency and very acceptable light quality of metal halide systems have made them the standard HID lighting technology for indoor applications. Some metal halide systems are now available with even more features, such as advanced lamp management, dimming capabilities, and instant restart designs [13]. In addition, the relatively high initial cost of the systems continues to fall as they find their way into new applications, including greater acceptance in the residential market and in fiber optics [15].

Literature Review Results

Based on the energy efficiency, life expectancy, and relative cost research done during this literature review, metal halide lighting systems are the most efficient lighting technology. In addition, linear fluorescent lighting systems are the technology with the longest life, while incandescent lamps remain the technology with the lowest initial cost. Overall, the data gathered during this literature review suggests that metal halide and linear fluorescent lighting are the best choices for most interior lighting applications. This information is presented in Table 7.1 below:

Table 7.1: Quick comparison of interior lighting technologies

Lighting Type	Luminous efficacy	Life expectancy	Relative initial cost
Metal Halide	65 to 115 lm/W	15000 to 20000 hours	$$$$
Linear Fluorescent	50 to 105 lm/W	10000 to 25000 hours	$$$
Compact Fluorescent	45 to 65 lm/W	6000 to 15000 hours	$$
Halogen	16 to 24 lm/W	2000 to 4000 hours	$$
Incandescent	12 to 18 lm/W	1000 to 2000 hours	$

Empirical Research Project

Scope

The goal of the empirical research project part of this study was to collect data representative of the real-world operational characteristics of the lighting technologies discussed in the literature review. Due to time constraints for the project and the gathering of tested lamps from many sources, lamp cycle life and initial cost were not tested as part of this project.

The lighting technologies tested were incandescent, halogen, linear fluorescent, compact fluorescent, and cold-cathode fluorescent (CCFL) lamps. CCFLs, though not a technology discussed in the literature review, were tested during this research project due to their similarities to CFLs, rapidly increasing use, and the fact that test lamps were readily available at the time of the research.

However, the total number of lamps/systems tested during the course of this project was twenty rather than just one of each of the five technologies listed above. This was done to collect more data for the lamp technologies tested, making it possible to average the results and to provide some insight as to how scale of the technology affects its efficiency characteristics.

Expected Results

Since this research project was done in conjunction with the literature review to form a single, comprehensive study, the results were expected to generally agree with the literature review. However the results were not expected to agree completely due to the probability of errors and inconsistencies during testing, as well as other factors that make the practical world non-ideal when compared to the theoretical world. Thus, it was expected that the project would follow the literature review in suggesting that metal halide and linear fluorescent lighting are the indoor lighting technologies with the best efficiency and longest cycle life.

Materials and Equipment

To make this project possible, basic test equipment was needed to gather data, as well as the actual lamps and related systems/accessories needed to perform testing on. The lamps/systems which were ultimately obtained for testing were as follows (sorted by technology):

- Incandescent
    - 40W frosted standard type A lamp
    - 60W frosted standard type A lamp
    - 100W frosted standard type A lamp
    - 135W clear standard type A lamp
    - 300W clear type PS25 lamp
- Halogen
    - 60W frosted type BT-15 lamp
    - 120W type PAR38 reflector lamp
- Cold-Cathode fluorescent
    - 3W linear lamp + electronic inverter
    - 5W type A lamp w/ integral electronic inverter

- Linear fluorescent
    - (2x) 14W type T5 24” lamps + electronic ballast
    - (1x) 17W type T8 24” lamp + electronic ballast
    - (2x) 17W type T8 24” lamps + electronic ballast
    - (1x) 25W type T8 36” lamp + electronic ballast
    - (2x) 25W type T8 36” lamp + electronic ballast
- Compact fluorescent
    - 7W globe lamp w/ integral electronic ballast
    - 9W spiral lamp w/ integral electronic ballast
    - 13W spiral lamp w/ integral electronic ballast
    - 23W spiral lamp w/ integral electronic ballast
    - 42W spiral lamp w/ integral electronic ballast
- Metal halide
    - 70W type ED17 lamp + pulse-start magnetic ballast

The equipment used for the actual testing of the lamps/systems consisted of both commercially manufactured equipment as well as several custom-made pieces of equipment. All equipment and materials used are as follows and as represented in figure 9.1:

- Air-tight light box (custom-made)
- Digital relative illuminance (light) meter (custom-made)
- Sight Saver™ Analog illuminance (light) meter
- TruTemp® Digital combination thermometer and timer
- Extech 42525A digital hand-held Infrared Thermometer
- P3 Kill A Watt™ P4400 digital energy, power, power factor, frequency, voltage, and current combination meter
- In-line switch and extension cord
- Safety glasses

Figure 9.1: From left to right: Sight Saver™ light meter, Kill A Watt™ digital combination meter, TruTemp® digital thermometer and timer.

Testing of each lamp/system for the project consisted of a specific procedure carried out using a constant test setup. This setup consisted primarily of a custom-made light box, which consisted of two interconnected halves. See Appendix A for details about the construction of the light box.

The test lamps and any associated parts (ballast, etc) were placed in one side of the box, one lamp/system at a time. All compact/round lamps other than the metal halide lamp were placed horizontally on top of a metal electrical box in the center of one box half. The metal halide lamp was placed in the center of one box half, in an upright (base-down) position. Lastly, the linear fluorescent lamps were tested lying centered across the long side of one box half.

The other side of the box housed test-equipment parts. The sensor for the custom-made light meter was placed slightly off-center on the bottom of this half of the box, and the commercial light meter was placed right next to it, and underneath a "window" cut into the top of the box, to allow the meter to be read from the outside. Also, the temperature probe of the thermometer/timer was mounted in the side-wall of the half of the box in which the light meters resided. Figure 10.1 shows the setup during the test of a CFL.

The location of the light meters and temperature sensor was designed so as to be relatively far from the light sources, and not in direct line-of-sight of them. This was done in order to help make the specific optical and thermal properties of the different light sources less noticeable to the sensors. The only tool which took measurements in sight of the light sources was the infrared thermometer, which was aimed at the center of each light source, through a second "window" in the top of the light box.

Lastly, outside of the box resided several other pieces of equipment. The actual electronic circuit board and meter for the custom-made light meter, as well as the main part of the digital thermometer/timer were located just outside of the box in a readable location. In addition, the Kill A Watt energy meter was placed just outside of the light box. Then, the light source being tested was plugged into a switch box and extension cord which were plugged into the Kill A Watt, providing an easy way to turn on and off the light source. The overall test setup (excluding the infrared thermometer) is shown in Figure 10.2.

Figure 10.1: The location of all equipment inside of the light box during a typical test.

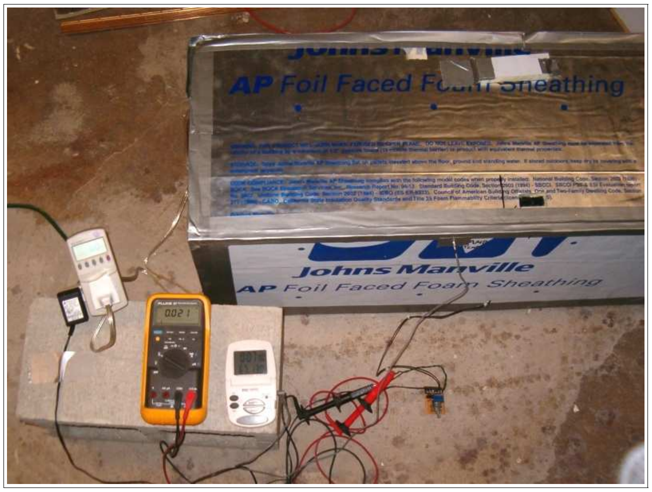

Figure 10.2: The overall test setup for the empirical research project.

Test Procedure

The procedure for gathering data for each lamp system consisted of the following routine:

1. Turning on all test equipment
2. Measuring the temperature of the light box. The constant starting temperature was chosen as 64°F. If the box temperature was less than 64°F, then the box was heated up to 64°F. Note that due to the location of the light box in a cold room, the initial temperature never exceeded the 64°F base temperature.
3. Placing the lamp/system to be tested in the light box (as detailed in the *Test Setup* section on page 10) and plugging the lamp/system into the switch outside of the box.
4. Setting the timer to 7 minutes; the chosen constant run time for all tests.
5. Simultaneously starting the timer counting down while turning on the lamp/system being tested using the external switch.
6. Immediately recording the initial power consumption and illuminance of the light/system under test on the test data sheet (included in *Appendix C*).
7. Watching during the test for the peak power consumption, power factor, and illuminance of the light/system under test, and recording this data on the test data sheet.
8. Waiting for the timer to time out and then recording the final temperature of the light box on the test data sheet.
9. Using the infrared thermometer to look into the light box to find the average hottest temperature of the lamp/system under test and then recording it on the test data sheet.
10. Shutting off the lamp/system under test and opening the top of the light box to expel excess heat.
11. Waiting for the light box to cool to 66°F, then replacing the current lamp/system with the next lamp/system to be tested.
12. Starting the next round of testing (from step 4) as soon as the light box finished cooling back to the base temperature of 64°F.

Test Data and Calculations

After running all 20 tests, the test data sheet was entered into a computer and cleaned up for better presentation. In addition, several calculations were performed on the test data in an attempt to quantify characteristics of the lamp/systems that were not directly measurable. These characteristics included total lamp/system luminous flux (lumens/Watt), waste heat energy expelled (Joules), waste heat power (Watts), and relative light-to-heat efficiency ratio. The equations used to derive these values are discussed below.

Total lamp/system luminous flux was not directly measurable as a part of this project due to the need of an integrating light sphere to correctly measure it. However, because the light box and relation of the light source to the light meters was kept constant during this project, luminous flux can be approximated by multiplying the value of each lamp's illuminance by a constant.

For this project, the constant was derived using the data from the testing of the 13-Watt CFL as the base metric for deriving the constant. It is known from the lamp manufacturer's specifications that this lamp produces a peak luminous flux of 900 lumens. The custom-made light meter registered the same lamp as having a relative illuminance of 2.66 lols, the relative unit of measure defined for the custom-made light meter (see Appendix B for more information). Thus, the constant for the box was found using Equation 12.1, after which the approximate luminous flux could be found using equation 12.2. Using these Equations, the light box constant K_{LB} for this project was determined to be 338.35.

$$K_{LB}=\frac{900}{E_V}$$

Where: K_{LB} = Light box constant
E_V = Relative illuminance (lol)

Equation 12.1: Light box constant equation.

$$F=E_V*K_{LB}$$

Where: F = Luminous flux (lumen)
E_V = Relative illuminance (lol)
K_{LB} = Light box constant = 338.35

Equation 12.2: Equation for approximating luminous flux.

The next value computed for each lamp/system was the waste heat energy expelled by each lamp/system into the light box during the test, in Joules. These values were computed using Equation 12.4. In order to calculate the mass of air in the light box, Equation 12.3 first had to be used. The volume of the light box used for this project was found to be 0.09409 m^3. Also, the average power expelled as heat by each lamp/system was calculated using Equation 12.5.

$$m=\rho*V_{LB}$$

Where: m = Mass of air in the light box (g)
ρ = Density of typical room air = 1168 g/m^3
V_{LB} = Volume of light box (m^3) = 0.09409 m^3

Equation 12.3: Equation for finding the mass of the air in the light box.

$$Q=C_P*m*(T_f-T_i)$$

Where: Q = Total heat energy expelled (J)
C_P = Specific heat capacity of air ≈ 1.012 $Jg^{-1}K^{-1}$
m = Mass of air in the light box (g)
T_f = Final ambient temperature of light box (°C)
T_i = Initial ambient temperature of light box (°C)

Equation 12.4: Heat energy released into the light box during testing.

$$P=\frac{Q}{t}$$

Where: P = Power dissipated as heat (W)
Q = Total heat energy expelled (J)
t = Time of test (sec) = 7 min = 420 sec

Equation 12.5: Average power dissipated as heat by each lamp/system.

Inconsistencies and Error

Inconsistencies and sources of error are inevitable during the course of any research. Though attempts were made to minimize sources of error as much as possible, this project was not entirely error-free.

The main inconsistencies encountered during this project were that the ambient temperature in the testing room wasn't able to be held constant, and that the AC line voltage used to power the lamps/systems was not constant. The temperature swing of the testing room could create error in the heat output measurements taken due to greater or less heat being lost through the walls of the light box. The AC line voltage swing could also create error in all measurements due to the electrical properties of the lamps/systems and thus their greater or lesser creation of light, heat, and different power factor due to line voltage changes. Both of these issues could be resolved thorough the use of additional equipment.

Another inconsistency of the test setup was the location of the lamp/system withing the light box and the specific optical properties of each lamp being tested. The light box was designed in such a way as to minimize the effects of imperfect lamp placement and differing lamp optical properties, however its design was not perfect and thus some inconsistency remained.

The main source of error was caused by both light meters. The commercial light meter was an inexpensive, low-quality unit which appeared to be somewhat sensitive to temperature changes. The custom-made light meter was also sensitive to temperature changes, though not as much as the commercial light meter. Thus, the accuracy of measurements obtained from the light meters was not ideal as the temperature in the light box would change drastically during testing. The only feasible way to solve this issue would be to use higher quality meters which are less sensitive to temperature changes.

Other sources of error were inevitably caused by other test equipment, none of which is perfect. For example, the digital thermometer and the Kill A Watt energy meter aren't perfect devices and thus their readings contain some margin of error. In addition, the infrared thermometer's design and the accuracy with which it was aimed at the light source both create a certain margin of error in its readings.

Despite these sources of error and inconsistencies, the data recorded during the project testing still provides decent numbers with which to relatively compare the various lamps/systems which were tested.

Research Project Results

After analyzing the project test data, conclusions can be drawn from the data as to which lighting technologies were most efficient as well as what the effects of scale have on the different technologies.

The efficacy data from the project testing shows that the incandescent and halogen lamps had the lowest efficacies, and thus were least efficient at producing light. It also shows that the CFLs and CCFLs had the highest efficacies, and thus were the most efficient at producing light. Finally, the data placed the linear fluorescents and metal halide lamp in the middle of the efficacy distribution. Overall this data agrees with the literature review information, with the only large discrepancy being the metal halide lamp, which scored significantly lower efficacy during the test than what was expected based on the literature review. However, this is likely due to inconsistencies and error created during testing, as discussed in the previous section.

The waste heat and heat efficiency data from the project testing relates well to the efficacy data discussed above. It shows that the incandescent and halogen lamps expelled the most heat energy during testing, while the CFLs and CCFLs produced the least heat. In addition, it too shows the linear fluorescent and metal halide lamps in the middle of the scale. This pattern similarily applies to the heat efficiency data, which was calculated as a light-to-heat production ratio. Thus, the lower the value of the heat efficiency ratio, the less efficient the lamp/system, and vice-versa.

Lastly, although the peak lamp surface temperature data recorded during the tests doesn't necessarily affect the efficiency and efficacy data, it is important. From a safety factor, this data shows which lamps/systems burn the hottest, increasing the risk of fire and burns. Likewise, it also shows which lamps/systems burn the coolest, reducing fire hazard associated with their use, and making them suitable for use in temperature-sensitive applications.

Conclusion

The literature review and empirical research project very much agree that incandescent and halogen lamps don't have anything to offer in the way of efficiency or life span. Efficiency and life span have a notably negative effect on long-term operation and maintenance costs. Since incandescent and halogen lamps have nothing beneficial to offer with respect to these criteria, they cannot be recommended for use in any general lighting application. Their use should instead be limited only to those applications in which no other current lighting technology can feasibly exist... for example ovens and other environments where extreme temperatures are present.

On the other hand, both the literature review and project agree that fluorescent lighting (compact or linear) is generally the technology which provides the most “bang for the buck,” being both quite efficient and long-lived. In addition, although metal halide lighting didn't perform nearly as well as expected during the project testing, it still performed decently. Coupled with the research gleaned from the literature review, metal halide is still a very promising and increasingly efficient technology, though it is a significantly better performer in large-scale/high-power formats then it is in small-scale formats. For this reason metal halide remains a technology worth pursuing.

In conclusion, the research as a whole suggests that fluorescent and metal halide lighting are the technologies best suited for general lighting use in the present day. Since research indicates that these technologies continue to get more efficient and generally better the longer they've been out on the market, they should remain excellent technologies throughout the near future as well. However, there is no way to claim that any single lighting type is outright the best lighting technology because many important factors related to the application must be considered. The best lighting type for one application could very well be the worst for another application. The good news is that due to the variety of lighting technologies on the market today, there are many choices available to the lighting installer, designer, specifier, and/or end user, so that they may get the type of lighting that suits them best. For the indoor lighting market in particular, the refinement of and greater shift towards fluorescent and HID technologies will help ensure that the future is illuminated by superior, efficient lighting to help move us towards total energy sustainability.

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Appendix A: Custom Light Box Design

The main piece of equipment used for the empirical research project was a custom-made light box. The box was constructed of typical 1/2" rigid-foam board insulation. The foam board was cut with a box cutter so that the interior size of the light box was: 37.50" long, 12.25" wide, and 12.50" tall. The box was held together with duct tape, and the top of the box utilized duct tape to form a "hinge" along one of its long edges. The central divider was held into the box mainly by friction due to its tight fit. The box sides and bottom were installed with the reflective-side of the foam board facing inward, while the top was installed white-side inward, in order to maximize light diffusion over the meters.

To add the finishing touches to the box, a hole was cut in one of the sides to allow the wiring for the lamps to exit. In addition, two "windows" were cut in the top of the box: one covered with clear tape so it could be seen through without letting heat out of the box, and the other covered by a "flap" of foam, "hinged" to the box with duct tape. Lastly, joints and other areas of the box which would be close to the hot lamps were covered with a layer of reflective foil tape. This was done in an attempt to reflect additional heat away from the structural duct tape. Figures 17.1-17.4 show the light box.

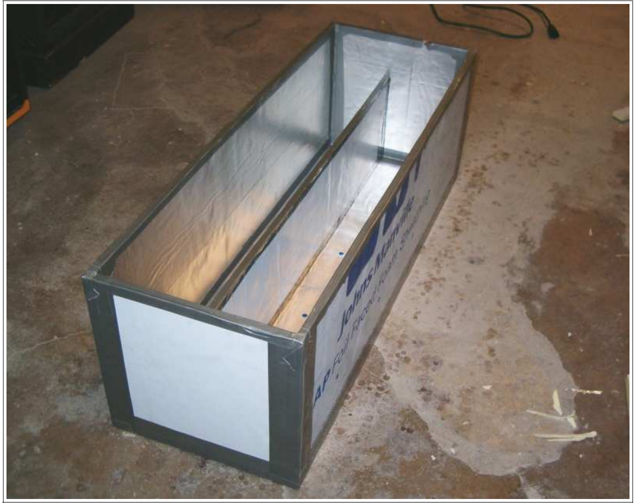

Figure 17.1 Side view of the constructed light box without the top attached.

Figure17.2 Top view looking down into the light box without the top attached.

Figure 17.3 Light box with attached lid, prepared to run a test on a CFL.

Figure 17.4 Light box with lid closed, and test equipment powered up for a test run.

Appendix B: Custom Light Meter Design

This appendix provides detailed information regarding the custom light meter designed and built for this empirical research project. This light meter was built and used along side a commercial light meter to help verify relative measurements and provide a “second opinion” of sorts. This light meter design is based around a simple Cadmium Sulfide (CdS) cell, which is essentially just a photosensitive resistor. CdS cells typically have little to no resistance in the presence of bright light and high to infinite resistance when in complete darkness. The design of this light meter incorporates a common CdS cell as one of four resistors which form a Wheatstone voltage-dividing bridge. The output voltage of this bridge is read using a voltmeter, and it is this measurement which is used as the metric for estimating relative light output; in this case 0V is complete darkness, and 12V is the meter's upper limit under extremely bright illumination. This meter has been calibrated off of the commercial light meter so that 1V is roughly equal to 100 Lux, however the linearity of this meter or the commercial meter isn't guaranteed.

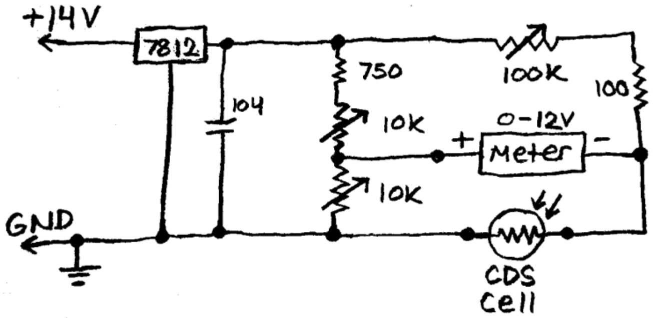

Figure 18.1 Circuit Schematic for the light meter based around a CdS sensor and bridge.

Figure 18.2 (right) All components of the light meter: AC-DC converter, CdS cell, main circuit board, digital voltmeter.

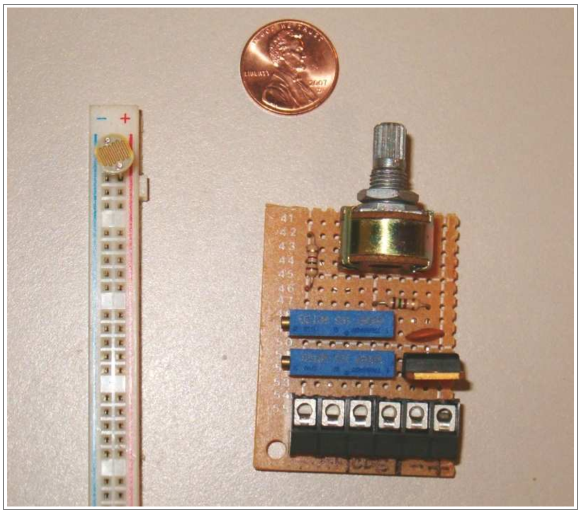

Figure 18.3 Top view of the main light meter circuit board and CdS sensor.

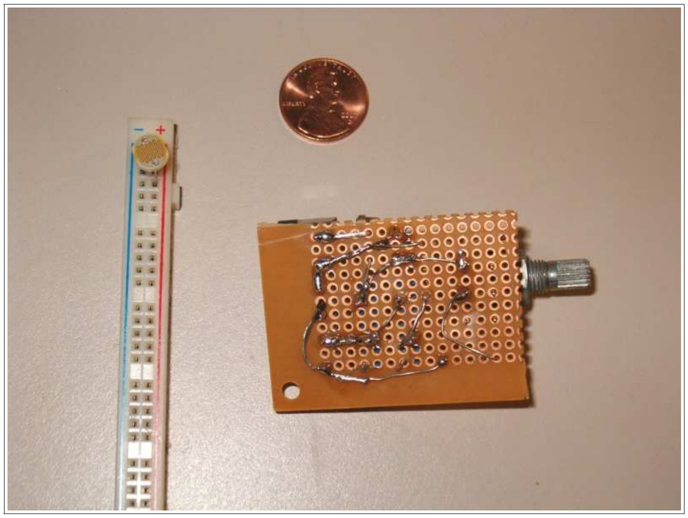

Figure 18.4 Bottom view of the main light meter circuit board and CdS sensor

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Run #	Lamp		System Power (W)			Power Factor	Illuminance		Luminous flux		Final Temperature		Waste Heat		Efficiency	
	Technology	Type	Spec.	Initial	Peak		Initial	Peak	Equivalents		Box	Lamp	Joules	Watts	Luminous	Heat
1	Halogen	BT-15	60	62	61	1.00	400 lx	400 lx	2.88 lol	974 lm	33.3 °C	195 °C	1735.11	4.13	16.0 lm/W	0.56
2	Incand.	A	135	123	123	1.00	500 lx	500 lx	3.54 lol	1198 lm	50.6 °C	260 °C	3654.35	8.7	9.7 lm/W	0.33
3	Incand.	A	60	53	54	1.00	300 lx	300 lx	2.49 lol	842 lm	34.4 °C	177 °C	1862.40	4.43	15.6 lm/W	0.45
4	Incand.	A	40	37	36	1.00	200 lx	200 lx	2.11 lol	714 lm	29.4 °C	176 °C	1306.27	3.11	19.8 lm/W	0.55
5	CFL	Spiral	42	35	37	0.56	400 lx	850 lx	4.30 lol	1455 lm	27.8 °C	95 °C	1120.90	2.67	39.3 lm/W	1.30
6	CFL	Spiral	23	20	22	0.65	300 lx	550 lx	3.47 lol	1174 lm	23.3 °C	96 °C	626.57	1.49	53.4 lm/W	1.87
7	CFL	Spiral	13	12	14	0.67	125 lx	400 lx	2.66 lol	900 lm	21.1 °C	94 °C	379.40	0.9	64.3 lm/W	2.37
8	CCFL	A	5	2	3	0.94	25 lx	100 lx	0.99 lol	335 lm	18.9 °C	45 °C	132.23	0.31	111.7 lm/W	2.53
9	CFL	Globe	7	4	5	0.67	25 lx	150 lx	1.41 lol	477 lm	18.9 °C	60 °C	132.23	0.31	95.4 lm/W	3.61
10	Fluorescent	T5	(2) 14	27	30	0.99	425 lx	750 lx	4.13 lol	1397 lm	26.1 °C	46 °C	935.52	2.23	46.6 lm/W	1.49
11	Fluorescent	T8 (700)	25	24	28	0.91	350 lx	750 lx	3.88 lol	1313 lm	23.9 °C	40 °C	688.36	1.64	46.9 lm/W	1.91
12	Fluorescent	T8 (800)	17	18	20	0.80	350 lx	500 lx	3.17 lol	1073 lm	23.9 °C	40 °C	688.36	1.64	53.6 lm/W	1.56
13	Fluorescent	T8 (700)	(2) 25	39	45	0.98	650 lx	1000 lx	4.65 lol	1573 lm	26.7 °C	42 °C	997.32	2.37	35.0 lm/W	1.58
14	Fluorescent	T8 (800)	(2) 17	28	31	0.92	500 lx	750 lx	3.92 lol	1326 lm	25.0 °C	42 °C	811.94	1.93	42.8 lm/W	1.63
15	Metal Halide	ED17	70	40	79	0.83	15 lx	2500 lx	5.79 lol	1959 lm	29.4 °C	195 °C	1306.27	3.11	24.8 lm/W	1.50
16	CCFL	Linear	3	4	4	0.59	15 lx	65 lx	0.64 lol	217 lm	18.3 °C	36 °C	70.44	0.17	54.1 lm/W	3.07
17	CFL	Spiral	9	7	8	0.62	100 lx	250 lx	2.07 lol	700 lm	18.9 °C	80 °C	132.23	0.31	87.5 lm/W	5.30
18	Incand.	A	100	94	93	1.00	700 lx	700 lx	3.84 lol	1299 lm	43.9 °C	235 °C	2912.86	6.94	14.0 lm/W	0.45
19	Incand.	PS25	300	300	301	1.00	2500 lx	2500 lx	6.18 lol	2091 lm	88.9 °C	325 °C	7917.98	18.85	6.9 lm/W	0.26
20	Halogen	PAR38	120	117	116	1.00	600 lx	600 lx	3.46 lol	1171 lm	40.6 °C	192 °C	2542.11	6.05	10.1 lm/W	0.46

Table 19.1 Complete test data from the empirical research project testing.