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Overview of LED Lighting for Refrigerated Display Merchandisers

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ABSTRACT

Conventional fluorescent lighting used to illuminate products within refrigerated merchandisers can account for as much as 30 percent of the energy consumed by a case. Solid-state lighting using LEDs presents a substantial opportunity to reduce both direct electrical and indirect power consumption (i.e., load capacity) of commercial refrigerated display merchandisers.

The transition from linear T-8 fluorescent lamps to LED luminaires is not straightforward and requires careful consideration of a number of criteria when designing or implementing solid-state lighting fixtures into display merchandisers. These factors include the directionality and usable light of an LED luminaire, thermal management of the LED lamps, power supplies (drivers), Correlated Color Temperature (CCT), color quality, useful life (L_{70}) of the luminaire, and dimming control of the light output. This report looks at these factors and their effect on design and selection of LED luminaires.

1. INTRODUCTION

Fluorescent lighting technology, now used for product illumination in commercial refrigerators for nearly seventy years, has begun to plateau in terms of efficacy (light output per unit of power input) and reliability. As the standard lighting option for decades, fluorescent tubes have reached efficacies of 90 lumens/watt (at room temperature) and color rendering indices (CRI) as high as 85 – 90. Along with the positive attributes of fluorescents, the negatives for end-users include fragile lamps containing mercury, UV and IR light emission, poor performance in cold ambient conditions, average rated lives of only 18,000 to 24,000 hours, high-voltage power at startup, and the heat given off by the lamps.

The need for more energy efficient and more robust lighting systems is apparent. Ready to fill that need, Solid-State Lighting (SSL) systems with white light LEDs are improving rapidly and will eventually displace fluorescent technology as the industry standard for merchandiser lighting.

In general, there are two approaches to generating white light with LEDs: 1. mixing monochromatic red, green and blue sources, and 2. using phosphors to “down-convert” ultraviolet or blue LEDs to a mixture of colors which produces a white appearance (DiMaio et al., 2006). This paper will focus on the latter, which is the more widely used method. These blue chip + phosphor white light LEDs were first introduced commercially in the mid-1990s. Since that time, the technology has progressed in terms of performance, decreased in cost and recently has reached the point of commercial viability.

2. LED BASICS

Light emitting diodes, or LEDs, are semiconductor devices designed to emit a narrow band of light when electrically biased in the forward direction. From 1968, when the first commercial red LEDs were introduced at 0.001 lumens/LED, until the mid-1990s, LEDs were used exclusively as electronic indicating devices (Martin, 2001). Then in 1996, Nichia Corporation demonstrated the first high-brightness blue LED using an indium gallium nitride (InGaN) semiconductor material. By mixing this blue light with yellow light, created by adding a rare-earth phosphor on top of the diode, a white light was created.

Advances in semiconductor and phosphor technology have allowed the brightness and efficiency of these blue + phosphor LEDs to become a source of light, not for indication, but for general illumination in a myriad of

applications. In fact, LED technology has improved so rapidly over the past 40 years that a “law” (analogous to Moore’s Law for integrated circuits) now exists. Haitz’s Law, named for Roland Haitz, a now-retired scientist from Agilent Technologies, forecasts that every 10 years the amount of light generated by an LED increases by a factor of 20, while the cost per lumen falls by a factor of 10 (Graydon, 2007).

Figure 1 below shows a cut-away of a typical high-power LED and some of the components which are combined to make a package.

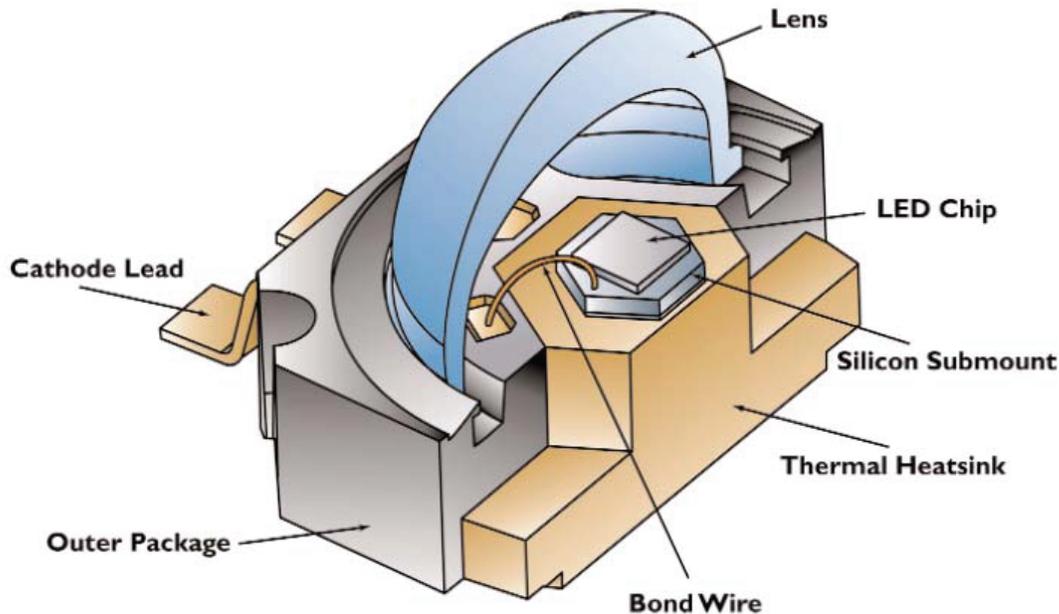


Figure 1: Cut-away of a typical white LED package (courtesy of Lumileds)

3. CORRELATED COLOR TEMPERATURE

Correlated Color Temperature (CCT) is a measure of the color appearance of a white light source. CCT is measured on the Kelvin absolute temperature scale. For example, a light source with a CCT of 3500K will appear the same color as a blackbody radiator heated to a temperature of 3500K. White lighting products are most commonly available from 2700K (warm white) to 5000K (cool white).

Until recently, white LEDs were available mostly in very high CCTs, often 5000K or above, which appear very blue to an observer. As semiconductor technology, package design, and phosphor mixtures have improved, warmer CCT LEDs, as low as 2700K, have become widely available.

4. COLOR QUALITY

Color quality of a white light source is most often quantified with a measure known as the Color Rendering Index (CRI or R_a). As defined by the Illuminating Engineering Society of North America (IESNA), CRI is a measure of the degree of color shift that objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source, of comparable color temperature (Rea, 2000).

To determine the CRI rating of a specific lamp, eight standard color samples are illuminated by a reference light source defined as having a CRI of 100, which very closely matches the test lamp in color temperature. The chromaticity of the samples under the reference source is calculated. The test lamp is then used to illuminate the same samples. All “shifts” in chromaticity between the two tests are tabulated, and the results are averaged to arrive at a single CRI number for the test lamp. Since the CRI of a lamp is related to the reference source of similar color

temperature, comparing the CRIs of lamps with different correlated color temperatures (CCT) provides no useful information (<http://www.lrc.rpi.edu/education/learning/intro.asp?mode=terminology>). That is, CRI may be compared only between light sources of equal CCT.

CRI has been used to compare incandescent, fluorescent and High-Intensity Discharge (HID) lamps for over 40 years. However, last year the International Commission on Illumination (CIE) recommended that CRI should not be used with white light LEDs. CIE Technical Report 177:2007, Color Rendering of White LED Light Sources, states, “The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the color rendering rank order of a set of light sources when white LED light sources are involved in this set,” (“LED Measurement Series: Color Rendering Index and LEDs,” 2008, p.1).

The CIE is currently developing a new metric for solid-state light sources to address the specific shortcomings of CRI in relation to white light LEDs. In the meantime, CRI can still be considered as one data point in evaluating white LED products and systems. However, it should not be used to make product selections in the absence of in-person and on-site evaluations (“LED Measurement Series: Color Rendering Index and LEDs,” 2008, p.2).

5. LUMEN DEPRECIATION

All electric light sources experience a decrease in the amount of light they emit over time, a process known as lumen depreciation. For example, incandescent filaments evaporate over time and the tungsten particles collect on the bulb wall. In fluorescent lamps, photochemical degradation of the phosphor coating and accumulation of light-absorbing deposits cause lumen depreciation. High-quality linear fluorescent lamps (T8 and T5) using rare earth phosphors will lose about 5 percent of initial lumens at 20,000 hours of operation.

At some point, each of these lamps will experience a failure (e.g., a broken filament) and will “burn out.” The average rated life (of a light source) is usually defined as the number of hours when 50 percent of a large group of lamps have failed. However, unlike incandescent, fluorescent or HID lamps, LEDs are solid-state devices and do not burn out, but instead experience a decrease in light output over time. The Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC), recommends defining useful life of LEDs as the point at which light output has declined to 70 percent of initial lumens, which is abbreviated as L_{70} (“Lifetime of White LEDs,” 2007, p.1-2).

To address the discrepancy in definitions of rated life, the IESNA is currently developing a life testing procedure for LED products. The title of this draft procedure is LM-80: Approved Method for Measuring Lumen Depreciation of LED Light Sources. The proposed method involves operating the LED component or system at rated current and voltage for 1,000 hours as a “seasoning period.” This is necessary because the light output actually increases during the first 1,000 hours of operation for most LEDs. Then the LED is operated for another 5,000 hours. The radiant output of the device is measured at 1,000 hours of operation; this is normalized to 100 percent. Measurements taken between 1,000 and 6,000 hours are compared to the initial (1,000 hour) level. If the L_{70} level has not been reached during the 6,000 hours, the data is used to extrapolate that point (“Lifetime of White LEDs,” 2007, p.2).

When evaluating the projected lifetime of LED products the following questions should be addressed:

- Does the LED manufacturer publish thermal design guidance?
- Does the lamp design have any special features for heat sinking/thermal management?
- Does the fixture manufacturer have test data supporting life claims? If so, what procedure was used for these tests?
- What life rating methodology was used (e.g. L_{70})?
- What warranty is offered by the manufacture and does the warranty cover lumen depreciation?

6. THERMAL MANAGEMENT

Since white light LEDs do not emit IR radiation, a large portion of the input power to the device is converted to heat, which must be removed through conduction and convection, see Table 1. The single biggest factor affecting the useful life (i.e., the L_{70} life based on lumen depreciation) of an LED is the junction temperature within the semiconductor chip. Therefore, proper thermal management is absolutely vital to the success and longevity of an LED lighting system. Without it, the rate of lumen depreciation will increase, shortening the useful life of the LEDs.

According to Cree's guidelines on thermal management of their XLamp devices, junction temperature of an LED is primarily affected by three parameters:

- Ambient temperature of the LED's immediate surroundings
- Thermal path between the LED junction and ambient conditions
- Power dissipated by the LED

Table 1: Power conversion for white light sources

	Incandescent* (60W)	Fluorescent* (Typical linear cool white)	Metal Halide†	LED‡
Visible Light	8%	21%	27%	15-25%
IR	73%	37%	17%	0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	15-25%
Heat (Conduction + Convection)	19%	42%	37%	75-85%
Total	100%	100%	100%	100%

* IESNA Handbook

† Osram Sylvania

‡ Varies depending on LED efficacy. The US Department of Energy's SSL Multi-Year

Program Plan (Mar 2006) calls for increasing extraction efficiency to more than 50% by 2012.

The following guidelines should be followed when designing lighting systems using high-power LEDs:

- The most important consideration for successful thermal design is to minimize the amount of heat that needs to be removed. It is important to separate the LED drive circuitry from the LED board so that the heat generated by the driver will not contribute to the LED junction temperature.
- The next most effective strategy is to minimize the ambient temperature inside the fixture. This goal is achieved by paying attention to several design parameters such as a conservative packaging design that does not allow the upper limit on overall system power density to be reached. Maintaining clear and clean airflow paths for natural convection cooling is vital as well.
- Enhancing thermal conductivity between the heat sinks and the LED is very preferable for thermal management. Even though the heat removal from the heat sink is via convection, the path from the LED to the heat sink depends upon conduction.
- Finally, the orientation of the LED PCB/heat sink should be considered carefully. If possible, it is important to position the board/heat sink so that the plane is vertical. If the board plane is horizontal, it will block the formation of air convection currents and substantially reduce the cooling capability of the system, ("Cree XLamp Thermal Management," 2006, p.1).

7. ADVANTAGES AND TRADE-OFFS OF LED LIGHTING

7.1 Advantages of LEDs

LEDs have a number of advantages versus other forms of lighting including incandescent, fluorescent and high-intensity discharge (HID).

- Directional light emission – able to direct light where it is needed without the use of reflectors.
- Small in size – can be very compact and low-profile.
- Durable – no breakable glass or filaments.
- Cold temperature operation – performance improves in the cold due to lower junction temperature within the diode. DOE testing of an LED refrigerated case light measured 5 percent higher efficacy at -5°C, compared to operation at 25°C (“LED Application Series: Using LEDs to Their Best Advantage,” 2008, p.3).
- Instant on – require no “warm up” time.
- Rapid cycling capability – lifetime not affected by frequent switching on and off.
- Controllability – compatible with electronic controls to change light levels and color characteristics.
- No IR or UV emissions – LEDs intended for lighting do not emit infrared or ultraviolet radiation.
- No hazardous substances – do not contain mercury and are able to meet the RoHS directive.
- Low voltage – can easily be configured to operate at safe, low DC voltages such as 12V or 24V.
- Long life – properly designed LED luminaires with good thermal management can have useful lives (L_{70}) of 50,000 hours or more.

7.2 Trade-offs for LEDs

A number of trade-offs must be considered when selecting white LEDs to be used in a luminaire. As shown in Table 2, as CCT decreases, the efficacy of the device will also decrease. It is also true that an increase in heat output from the device (whether the result of driving it at a higher current or from poor thermal management) will cause the efficacy of the LED to decrease and its life to be shortened. A careful balance between CCT, color quality and luminous output should be reached when designing or selecting an LED luminaire for illumination in retail displays.

Table 2: Trade-offs for white LEDs

Color Temperature (CCT)	↓	Efficacy (Efficiency)	↓
Color Quality	↑	Efficacy (Efficiency)	↓
Heat Output	↑	Efficacy (Efficiency)	↓
Heat Output	↑	Life / Durability	↓

8. IMPLEMENTATION OF LEDS INTO DISPLAY MERCHANDISERS

The transition from linear T-8 fluorescent lamps to LED luminaires is not straightforward and requires careful consideration of a number of criteria when designing or implementing solid-state lighting fixtures into display merchandisers.

8.1 Vertical Glass-Door Merchandisers

Vertical glass-door merchandisers, often called “reach-ins,” are the first style of commercial refrigerator to begin to see widespread use of LED lighting systems. Due to their relatively common shape, size and configuration across different manufacturers, reach-ins present one of the easier applications in which LED lighting systems can be utilized.

However, before selecting an LED light fixture for a reach-in merchandiser, special attention should be paid to the geometry within the case. Specifically, the most important relationship is the distance between the face of the product stocking area (i.e., the front of the shelves) and the mullions, where the light fixtures are typically mounted. Depending on the depth of the shelves and of the overall merchandiser, this distance can vary from as little as 3 inches (76 mm) to as much as 7 inches (178 mm) or more. The smaller this distance is, the more difficult it will be

for the LED luminaire to provide even illumination level across the front of the shelves. This problem is particularly prevalent in narrow-footprint reach-in cases.

8.2 Vertical and Semi-Vertical Open Multi-Deck Merchandisers

A second type of high-volume merchandiser used in supermarkets is the vertical or semi-vertical open multi-deck style, often used for dairy, meat and produce products. Due to the massive variety of shapes and sizes available, these cases present more of a challenge when using LED luminaires in place of traditional linear fluorescent lamps.

Items to consider when designing or selecting LED shelf light fixtures:

- Need to work with both horizontal and down-tilted shelving configurations.
- Good color quality may be vitally important, especially in red meat merchandisers.
- A wide angle of light discharge may be required to light the top of products evenly on deep shelves.
- Shelf fixtures may be exposed to water, corrosive cleaning agents, and acidic food substances.

Items to consider when designing or selecting LED canopy light fixtures:

- Canopy lighting system must have enough flexibility to evenly illuminate products as close as 12 inches (0.30 m) and as far as 60 inches (1.52 m) away.
- Canopy lighting system must have enough flexibility to evenly illuminate products in vertical merchandisers with air curtain angles of nearly 90 degrees as well as semi-vertical merchandisers with air curtain angles as steep as 45 degrees or less, see Figure 2.
- Must have enough light output to adequately illuminate products as far as 60 inches (1.52 m) away.
- Good thermal management of the LEDs is required because the luminaire may not be mounted inside the refrigerated zone of the merchandiser.

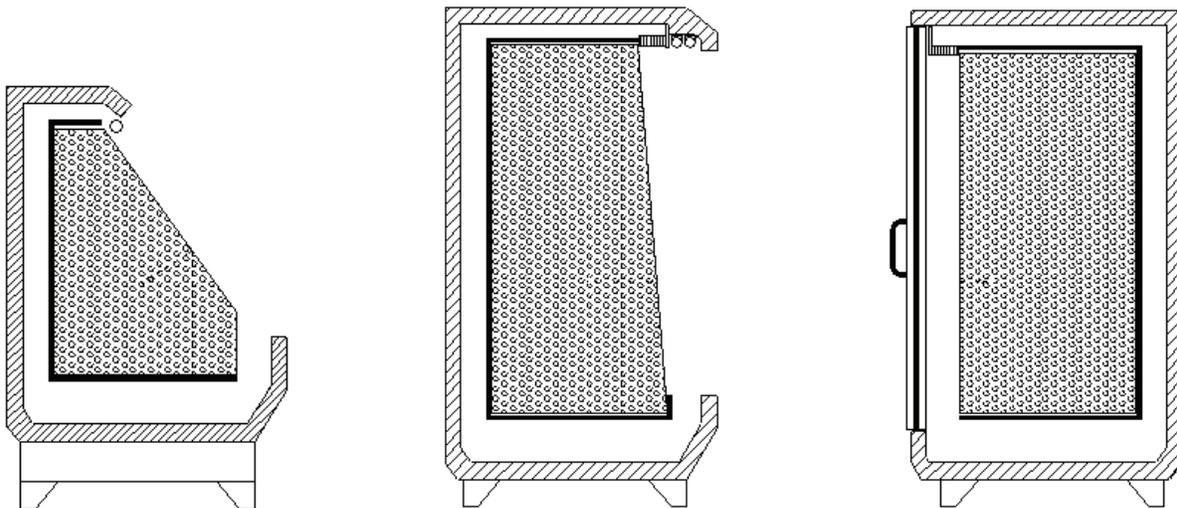


Figure 2: Cross-sections, from left to right, of a semi-vertical open merchandiser, a vertical open merchandiser, and a vertical glass-door merchandiser.

9. ENERGY ANALYSIS

Table 3: Example of an ARI Standard 1200 energy comparison of two 5-door “reach-in” merchandisers, one with vertical T-8 fluorescent lighting and the other with vertical LED lighting

Item Number	Informational Item	Data	Data
1	Commercial Refrigerated Display Merchandiser Model Number	5-Door Reach-in Case	5-Door Reach-in Case
2	Adjusted Dew Point, °F [°C]	-14 (-25.5)	-14 (-25.5)
3	Q _{rt} , Load Capacity, Btu/h [kW]	6109 (1.790)	5578 (1.635)
4	Length, ft [m]	12.78 (3.895)	12.78 (3.895)
5	Refrigerated Volume, ft ³ [m ³]	135.3 (3.831)	135.3 (3.831)
6	Total Display Area, ft ² [m ²]	65.4 (6.08)	65.4 (6.08)
7	Commercial Refrigerated Display Merchandiser Test Voltage, V	120	120
8	Commercial Refrigerated Display Merchandiser Evaporator Dew Point Temperature, °F [°C]	-11 (-23.9)	-11 (-23.9)
9	Integrated Average Temperature of Product Simulators, °F [°C]	0.0 (-17.8)	0.0 (-17.8)
10	Compressor Energy Consumption, CEC, kW·h [kW·h] per day	19.04	17.43
11	Fan Energy Consumption, FEC, kW·h [kW·h] per day	2.93	2.93
12	Light Energy Consumption, LEC, kW·h [kW·h] per day	8.65	4.91
13	Condensate Evaporator Pan Energy Consumption, PEC, kW·h [kW·h] per day	0.00	0.00
14	Anti-condensate Energy Consumption, AEC, kW·h [kW·h] per day	6.47	6.47
15	Defrost Energy Consumption, DEC, kW·h [kW·h] per day	3.37	3.37
16	Calculated Daily Energy Consumption, CDEC, kW·h [kW·h] per day	40.46	35.11
17	CDEC/Refrigerated Volume, kW·h/ft ³ [kW·h/m ³] per day	0.30	0.26
18	CDEC/Total Display Area, kW·h/ft ² [kW·h/m ²] per day	0.62	0.54
19	Other Loads, Notes:	T-8 Lighting	LED Lighting

	Cost of Electrical Power, USD/kWh	\$0.11	\$0.11
	Annual Energy Cost per Year for a Single 5-Door Reach-in Case, USD	\$1,624.53	\$1,409.53
	Energy Cost Savings per Year for a Single 5-Door Reach-in Case, USD		\$215.00

10. CONCLUSIONS

When designing or selecting LED luminaires for use in refrigerated display merchandisers, consider the following parameters to help ensure success:

- Correlated Color Temperature – select a CCT appropriate to the application even if it means a slightly lower light output from the luminaire.
- Color quality – in addition to CRI, always evaluate the color quality of the luminaire in the setting it will be used.
- Lumen depreciation – be aware that the light output of the LEDs will dim over time and design or select the system to account for that fact.
- Thermal management – proper thermal management of LEDs will increase their useful life.
- Advantages and disadvantages of LEDs – design or select luminaires to take advantage of the benefits of LEDs and be aware of the trade-offs between CCT, color quality, brightness and efficacy inherent in LED devices.
- Application – be sure that the light dispersion characteristics of the LED luminaire are well-suited to the merchandiser they are used in.

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