Energy-Efficient Lighting Alternative for Commercial Refrigeration

Final Report

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NOTICE

Abstract

A field study was conducted to evaluate the use of white LED lighting systems inside commercial freezers found in supermarkets. The goals of the study were to:

- improve the light uniformity and visibility of merchandise inside supermarket freezers
- evaluate shoppers' lighting preferences for supermarket freezers
- demonstrate the benefits of LED lighting technology in refrigerated display cases used in groceries, florists, retail, and convenience stores
- compare the energy usage of LED lighting technology with traditional fluorescent technology in this application
- monitor product sales under new and traditional lighting

In May 2004, two similar, four-door supermarket freezers, one with white LED lighting and the other with traditional linear fluorescent lighting, were installed at a full-service supermarket located in the Albany, N.Y., metropolitan area. The LED lighting system used in this prototype freezer consisted of 1-watt phosphor-converted white LEDs with an average efficacy of 25 lumens per watt (lm/W). The study included the following:

- photometric and power measurements of the LED-lighted freezer and a similar fluorescent-lighted freezer
- surveys of shoppers and their preferences for freezer lighting
- monitoring and analysis of sales for the test freezer cases

Surveys showed that shoppers preferred the LED freezer over the fluorescent freezer, even when the LED lighting was dimmed to a light level 25% lower than that of the fluorescent freezer. A sales analysis showed that the lighting did not affect sales.

Using current white LED light sources with an average efficacy of 45 lumens per watt (lm/W), an LED lighting system dimmed to a level that maintains shopper satisfaction would save 14 W over fluorescent lighting in a four-door freezer similar to the one tested in this study. When LEDs reach the U.S. Department of Energy target of 150 lm/W, LED-lighted freezers will be significantly more energy efficient than fluorescent-lighted freezers. Considering their longer life, ruggedness, and varied control features, LEDs are a better choice for supermarket freezer case lighting than fluorescent lamps.

Keywords: LED, light-emitting diode, freezer, refrigerator, supermarket

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Table of Contents

Executive Summary

Commercial refrigerators and freezer cases account for nearly half of a supermarket's annual electricity costs (Southern California Edison, n.d.). Interior case lighting accounts for 21% to 26% of the electricity required to operate refrigerated and freezer display cases in supermarkets (U.S. Department of Energy 1996).[1] Nearly all commercial refrigerators and freezers use linear fluorescent lamps to light the interior of the cases. Although fluorescent lamps provide superior energy efficiency in many lighting applications, their use in commercial refrigeration is not ideal. Fluorescent lamps in this application provide poor performance, wasted light, and uneven lighting on the products. These problems are a result of ineffective lamp operation at cold temperatures, the lack of optics to direct the light, and poor configuration and mounting location within the freezers.

Alternative lighting technologies may provide better solutions to the limitations found with fluorescent lamps in this application. One such technology is the light-emitting diode (LED), a type of solid-state lighting. Solid-state lighting has become a major focus in the lighting industry because of its potential for energy savings and its flexibility to create innovative designs not possible with traditional lamps. LEDs do not suffer the same drop in light output under cold temperatures as fluorescent lamps. The current luminous efficacy (the amount of light per watt of energy used) of some high-power white LEDs—45 lumens per watt in 2006—is similar to the application efficacy of fluorescent lamps in commercial refrigeration. LEDs also can be customized to provide several distributions of light to provide more even lighting across freezer shelves. These differences mean that LEDs potentially can provide more efficient lighting.

To fully understand the effects and operation of LED lighting in commercial refrigeration, the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute conducted a field study at an Albany, N.Y., metropolitan area supermarket. The LRC investigated the use of white LEDs inside supermarket freezers. The goals of the study were to:

- improve the light uniformity and visibility of merchandise inside supermarket freezers
- evaluate shoppers' lighting preferences for supermarket freezers
- demonstrate the benefits of LED lighting technology in refrigerated display cases used in supermarkets, florists, retail, and convenience stores
- compare the energy usage of LED lighting technology with traditional fluorescent technology in this application
- monitor product sales under new and traditional lighting

Based on a previous laboratory study and light level measurements of freezers at the field study store, the LRC developed the illuminance requirements for the freezer lighting. The LRC worked with LED systems manufacturer GELcore and freezer manufacturer Tyler Refrigeration to build a prototype four-door, supermarket-style freezer outfitted with white LED lighting. The prototype freezer and a matching fluorescent-lighted freezer were installed at a Price Chopper supermarket. Compared with some other supermarkets in the area, this particular store had a

[1] The electricity consumption reported by the U.S. Department of Energy is for supermarket display cases available at the time of that report. Consumption may differ now because of better efficiencies for compressors and other refrigerator components.

higher average light level; thus, the freezer case lighting for the prototypes had to be set higher so that the merchandise inside the cases would appear bright.

At the beginning of the project in 2003, it was known that white LEDs at that time would not provide an energy-efficient solution compared with traditional fluorescent lamps. However, the LRC expected that by the completion of the study, white LED efficacy would reach a higher level, making them more energy efficient.

Power measurements made at the Tyler Refrigeration facility of the prototype LED and fluorescent freezers showed that energy consumption was higher for the LED lighting system operated at both 100% and 50% control voltage. Decreasing the control voltage by 50% reduced the light level by approximately 30%. Calculated kilowatt hours per door per day were 14.04 kWh for the fluorescent freezer, 16.56 kWh for the LED freezer at 100%, and 14.98 kWh for the LED freezer at 50%.

Over the course of a year, the LRC conducted two human factors investigations to evaluate shoppers' preferences for lighting inside supermarket freezers. The first investigation was a survey of shoppers at the field study store. Shoppers were asked about their opinions of each of the prototype freezers and their preferences for one over the other. Opinions and preferences were gathered through a questionnaire that asked about the appearance of merchandise and the overall brightness, comfort, and evenness of the freezer lighting. Shoppers rated the freezers with the LEDs at both full light output and dimmed. The fluorescent-lighted case remained at full light output at all times. (The average illuminance level of the LED case at full light output was approximately 14% lower than the fluorescent case due to system differences and possible contributions from ambient lighting.)

Overall, shoppers highly rated the LED freezer on all questions asked. At full light output, 86% of shoppers stated that they preferred the LED freezer lighting over all other freezer lighting in the aisle. When the LEDs were dimmed, shoppers still preferred the LED freezer lighting, with 68% saying they liked it the most. Although the LED freezer had a lower average illuminance level than the test fluorescent freezer, shoppers said the LED freezer was brighter. The even illuminance uniformity and higher correlated color temperature (CCT) of the LED lighting likely contributed to shoppers' perceptions that the LED freezer was brighter. This indicates that light levels within a freezer case could be reduced for added energy savings if the distribution and uniformity are even across the freezer shelves and products.

The second human factors investigation was an analysis of product sales from each prototype freezer case. During the course of the study, the position of the freezers was switched to collect sales of the same products under each type of lighting. The sales analysis showed that the sales activity inside the LED-lighted freezer increased during the analysis period. However, it was unclear whether this increase was the result of the lighting or of a multiple-package sale ("10 for $10") offered by the store at that time. To answer this question, sales at a similar store in the Albany area were analyzed and compared. The analysis of the sales increase at the field study store indicated that the increase was due to the multiple-package sale and that the LED lighting did not affect sales.

The potential exists now for LED lighting in commercial refrigeration to match or even surpass fluorescent lighting in terms of shopper satisfaction. It is believed that shoppers in this study showed greater preference for the LED freezer because of its better illuminance uniformity. In this study, it is believed that better uniformity allowed the LED freezer to have a lower average light level than the test fluorescent freezer, yet appear brighter and more appealing. At no time did the illuminance levels inside the LED freezer match or exceed the light levels inside the test fluorescent freezer, yet surveys showed that for each condition, shoppers preferred the LED case over the fluorescent case. The perception of higher brightness for the LED freezer could also have been a result of the color temperature of the LEDs; the 5500 kelvin (K) LEDs used were "cooler" or "bluer" in color appearance than the fluorescent lamps at 3500 K. At a dimmer light level, LEDs are at a "threshold" efficacy where they fall slightly below the energy consumption of fluorescent lighting without sacrificing shopper satisfaction. Using current LED light sources (45 lm/W), a dimmed LED lighting system has a savings of 14 W over fluorescent lighting in a four-door freezer similar to the one used in this study.

1. Introduction

Commercial refrigerators and freezer cases account for nearly half of a supermarket's annual electricity costs (Southern California Edison, n.d.). Interior case lighting accounts for 21% to 26% of the electricity required to operate refrigerated and freezer display cases in supermarkets (U.S. Department of Energy 1996).[1] Interior lighting is required to display merchandise and assist shoppers with viewing and selecting food products, with linear fluorescent lamps supplying the needed illumination. Although fluorescent lamps provide superior energy efficiency in many lighting applications, their use in commercial refrigeration is not ideal. Fluorescent lamps in this application provide poor performance, wasted light, and uneven lighting on the products.

The light output of a linear fluorescent lamp varies with the ambient temperature of the space. At normal room temperature (25°C), linear fluorescent lamps provide a luminous efficacy of 90 lumens per watt (lm/W) or greater. However, at colder temperatures, their efficacy and light output drops dramatically due to a decrease in mercury vapor pressure (Rea 2000). A temperature drop to 7°C—the temperature of a typical beverage display case—will reduce fluorescent light output by nearly 25% (Raghavan 2002). Positioning and the lack of optics are also drawbacks to using fluorescent lamps in commercial refrigeration. Linear fluorescent lamps are typically mounted vertically behind the door hinge along one or both sides of the door. In this position, optics may or may not be used to redirect the light onto the products. Poor configuration within the freezer or refrigerator case can waste light and create an uneven (non-uniform) illumination across the display shelves. With only one or two light sources, merchandise closer to the lamp(s) are often more brightly lit, while those farther away appear darker. This creates an unappealing display and viewing difficulties for shoppers. Overall, the system efficacy of the fluorescent lighting under typical refrigerator temperatures drops by half to approximately 40-45 lm/W in this application (Raghavan 2002; Raghavan and Narendran 2002).

Fluorescent lamps also produce radiant heat, contributing to the heat gain inside refrigerators and freezers and increasing the energy consumption needed for cooling. More than 40% of a fluorescent lamp's input energy is given off as dissipated heat; only 21% is converted to light (Rea 2000). LEDs have greater heat dissipation; however, the heat generated by LEDs is mainly conducted. Therefore, with proper thermal management, LED heat can be conducted outside the freezer, whereas radiant heat from fluorescent lamps cannot be controlled.

Past research has explored new methods and equipment to project fluorescent lighting deeper and more evenly inside refrigerator and freezer cases (Hed 1996; Joseph 1999; McGovern 1994; Saraiji 1999; Severloh 1995). These techniques consider issues of poor distribution and limited visibility, but they do not address energy consumption or luminous efficacy. Alternative lighting technologies may provide better solutions to the limitations found with fluorescent lamps in this application. One such technology is the light-emitting diode (LED), a type of solid-state lighting.

[1] The electricity consumption reported by the U.S. Department of Energy is for supermarket display cases available at the time of that report. Consumption may differ now because of better efficiencies for compressors and other refrigerator components.

Solid-state lighting has become a major focus in the lighting industry because of its potential for energy savings and its flexibility to create innovative designs not possible with traditional lamps. LEDs have traditionally been found in "indicator" applications, such as traffic signals and exit signs, but are now moving toward the general illumination market—an important advance for the future of solid-state lighting technology. The U.S. Department of Energy reports that if certain price and performance targets are met over the next 20 years, solid-state lighting could decrease national energy consumption for lighting by 29% and save consumers more than $125 billion on electric bills from 2005 to 2025 (U.S. DOE, 2003; U.S. DOE, 2004).

In the last ten years, white LEDs have experienced major advances in light output (lumens per package), luminous efficacy (lumens per watt), life, and color. These advances have made white LEDs a more plausible option for many general lighting applications. White LEDs are currently found in mostly niche general lighting applications, such as task and under-cabinet lighting.

LEDs offer several key advantages for commercial refrigeration:

- **LED light output and efficacy are not affected by cold temperatures.** Cold temperatures have a negative impact on the mercury vapor pressure inside fluorescent lamps. At low temperatures, the mercury vapor pressure decreases, reducing light output from the lamp (Rea 2000). LEDs, however, are known to maintain or improve their light output when operating under colder temperatures. Research also suggests that LEDs may last longer than their rated life when operated under colder temperatures. Figure 1a shows light output versus ambient temperature for a 58 W T8 fluorescent lamp, a typical lamp found inside supermarket freezers (Sylvania n.d.). Figure 1b shows light output as a function of junction temperature for high-power Luxeon LEDs (Philips Lumileds Lighting 2006). Junction temperature refers to the temperature of the p-n junction within the semiconductor chip. This is where LED light is created and emitted. The temperature of the p-n junction is the primary factor affecting LED light output and life. Junction temperature is calculated from the ambient temperature, the forward current and forward voltage, and the thermal resistance from the junction to the ambient environment.

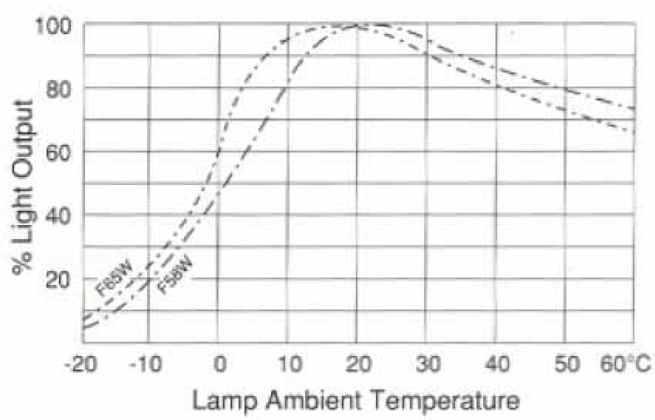

Figure 1a. The percentage of light output versus ambient temperature for a 58 W T8 fluorescent lamp. (Graph reprinted from Sylvania Fluorescent Lamps Technical Manual, p. 25).

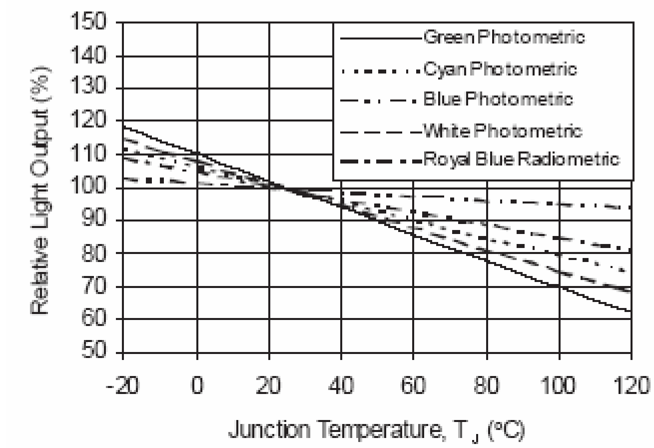

Figure 1b. The percentage of light output versus junction temperature for Luxeon high-power LEDs. (Graph reprinted from Luxeon Emitter Technical Datasheet DS25, p. 9).

- **White LEDs provide luminous efficacies near levels produced by fluorescent lamps under cold temperatures.**
  Commercial LED packages now available (2006) on the market typically have luminous efficacies of 40-45 lm/W—approximately the same application efficacy (the amount of lumens per watt of energy utilized for illuminating the merchandise) as fluorescent lamps used in commercial refrigeration. Laboratory prototypes of white LEDs have demonstrated luminous efficacies of 65-100 lm/W (LEDs Magazine 2006; Narendran et al. 2005; U.S. Department of Energy 2006), equal to the rated efficacy of fluorescent lamps operating at room temperature and twice the efficacy of fluorescent lamps found in commercial refrigeration. These prototypes are likely to become commercially available in the next three to five years.

- **LEDs offer multiple illuminance distributions to provide more efficient illumination.**
  An array of LEDs running vertically along the door of a freezer case can contain LEDs with two or more different illuminance distributions. Multiple distributions allow some LEDs to direct light onto the products, while others to provide general illumination within the case. A linear fluorescent lamp is restricted in its ability to provide a customized distribution, limiting the effectiveness of the interior case lighting and potentially reducing visibility. Alternatively, the size and shape of LEDs allow them to be mounted onto shelves to provide light to the face of the merchandise without much waste.

- **LEDs produce little radiant heat.**
  LEDs produce very little radiant heat compared with fluorescent lamps. Therefore, the loss of perishable goods from heat gain caused by radiant heat can be reduced.

- **LEDs offer flexible lighting configurations.**
  Because LED lighting systems can be configured to any shape, refrigerator and freezer display cases can be redesigned into other geometric shapes for visual appeal and more efficient cooling.

A previous Lighting Research Center laboratory study explored the potential use of white LEDs inside commercial refrigerators (Raghavan 2002; Raghavan and Narendran 2002). The researchers developed a prototype refrigerator lighting system using shelf-mounted LEDs with the goals of minimizing wasted light, producing uniform illumination for the merchandise, and potentially providing energy savings. Also studied were people's preferences for refrigerator lighting. Illuminance measurements of a modified refrigerator showed that the LED lighting system produced a more uniform illumination on the displayed products than did the original fluorescent lighting system. A survey showed that subjects strongly preferred the LED lighting over traditional fluorescent lighting in this application. Light distribution was found to be the most important factor influencing people's preferences for refrigerator lighting. Figure 2 shows the subject preference ratings from this study.

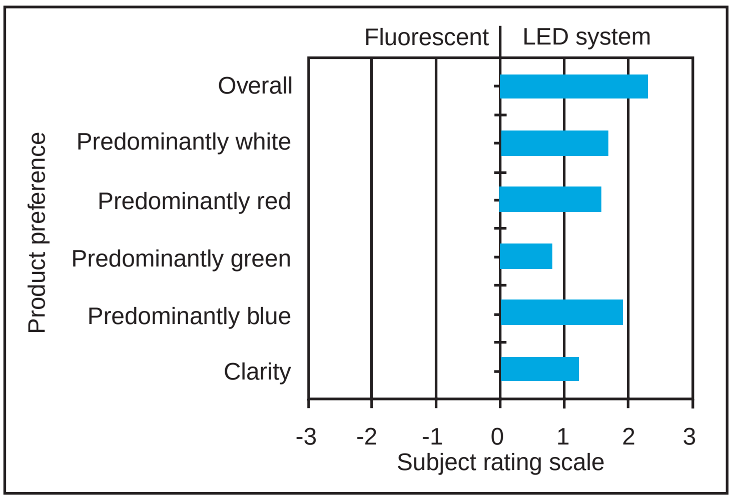

Figure 2. Results of a human factors laboratory experiment to rate preferences for LED vs. fluorescent lighting in commercial refrigerator cases. Mean preference rating shown. On the horizontal axis, scores to the left of zero are for the display case with fluorescent lighting; scores to the right of zero are for the display case with LED lighting.

The previous study was limited by the laboratory environment and the small number of subjects participating in the human factors survey. In order to fully understand the effects of LED lighting inside commercial refrigerators and freezers, a larger field study was necessary. Such a study was undertaken and is described in this report.

2. Project Goals

To build upon prior laboratory results, the LRC conducted a field study at an Albany, N.Y., metropolitan area supermarket to investigate the use of white LEDs inside commercial refrigeration, and specifically, supermarket freezers. The goals of the study were to:

- improve the light uniformity and visibility of merchandise inside supermarket freezers
- evaluate shoppers' lighting preferences for supermarket freezers

- demonstrate the benefits of LED lighting technology in refrigerated display cases used in supermarkets, florists, retail, and convenience stores
- compare the energy usage of LED lighting technology with traditional fluorescent technology in this application
- monitor product sales under new and traditional lighting

3. Freezer Lighting System Development, Testing, and Installation

3.1 Field study location and existing freezer lighting

Price Chopper is a chain of 115 full-service supermarkets located throughout New York state and greater New England. The field study was conducted at the Price Chopper located on Altamont Avenue in Rotterdam (Schenectady), N.Y.

Like most large supermarkets, Price Chopper dedicates at least one aisle of the store to frozen foods. The majority of its frozen foods are displayed inside upright freezer cases with glass doors that swing open. Price Chopper's existing freezer cases are illuminated with five-foot (1.5 m) T8 fluorescent lamps, 58 watts with a color rendering index (CRI) of 80 and a correlated color temperature (CCT) of 3500 K.

3.2 Developing illuminance level recommendations

Illuminance levels on the face of displayed products are critical to customers. Not only can lighting attract customers, but it also allows them to evaluate the quality and appeal of a product. The Illuminating Engineering Society of North America (IESNA) provides lighting recommendations for retail and merchandise displays, but does not provide guidelines specific to grocery freezer cases. IESNA's recommended illuminance level for retail displays is 500 lux (IESNA 2001), but freezer cases cannot rely upon this guideline. Higher illuminance levels are needed to counteract the veiling reflections that appear on the glass doorfronts, which can impede a clear view of what is inside without opening the door.

Illuminance distribution and the uniformity of light are also important to consider when lighting displayed merchandise (IESNA 2001). Previous research has shown that people prefer a large area of uniform illuminance in the task area (Boyce 1979), that the uniformity of illuminance should be within 30% of the average illuminance (Saunders 1969), and that several distributed light sources create better uniformity than one large source (Huang 1999). Previous LRC research of refrigeration lighting suggested that LEDs, as small light sources distributed along shelves, can provide better illuminance distribution and uniformity on the face of products inside refrigerated cases than fluorescent lighting (Raghavan 2002; Raghavan and Narendran 2002).

Price Chopper prefers its stores to be more brightly lit than typical grocery stores. Vertical illuminance measurements of the freezers at the Altamont Avenue Price Chopper ranged from 1500 lux to more than 3000 lux. Overall, the freezer cases showed light level variations near 40%. The non-uniformity of light levels across a freezer unit were easily noticeable.

On the basis of illuminance measurements taken of existing freezers at Price Chopper, discussions with Price Chopper about its illumination preferences, and previous studies of LEDs in commercial refrigeration, the LRC recommended that illuminance levels inside the prototype LED-lighted freezer match approximately with other fluorescent lighting systems for freezers. Specifically, the LED freezer should match closely with the fluorescent-lighted case that Tyler would also be building for this study. Shopper surveys and sales analyses would be conducted comparing these two test cases side by side; therefore, the light levels should be similar.

3.3 Freezers and lighting systems

3.3.1 Prototype LED-lighted freezer

The LRC worked with LED system manufacturer GELcore and freezer manufacturer Tyler Refrigeration to design and build a commercial, four-door, supermarket freezer modified with a white LED lighting system.

GELcore developed the lighting system for the freezer unit. Tyler Refrigeration and Price Chopper decided upon the freezer type and style, and Tyler shipped this new freezer to GELcore for the lighting system installation.

The LED lighting was attached to the mullions running the length of each side of the doors. The lighting system consisted of 1-watt Luxeon cool-white (5500 K) LEDs with batwing and lambertian distributions. Optics also were used to direct light onto the center regions of the shelves. Manufacturer's ratings for these white LEDs were 25 lm/W. Each door of the freezer unit was illuminated with 102 LEDs (51 LEDs on each mullion on either side of the door). The lighting system included a dimmer to reduce light levels for the dimming portion of the study. A 10-watt cooling fan on each mullion was also installed. Figure 3 shows the LED freezer and its lighting systems in the laboratory.

Figure 3. The LED freezer (left); close-up of the LED lighting system (center); close-up of the LED freezer interior (right).

3.3.2 Prototype fluorescent-lighted freezer

In addition to the LED freezer, Tyler Refrigeration built an identical unit with a fluorescent lighting system. This unit would be used as a comparison model to the LED freezer. The lighting system was custom made by Tyler and consisted of five-foot, 58 W SLI Luxline Plus 835 T8 lamps, 3500 K CCT, with a polished aluminum reflector and a molded, wraparound, prismatic lens. One lamp with a clear sleeve was mounted on the sides of each door, for a total of five lamps for the 4-door unit. The lighting system used rapid-start electronic ballasts manufactured by Anthony International. The lighting system power was 72.6 W per door on average.

3.3.3 Laboratory illuminance measurements of the prototype freezers

GELcore completed illuminance measurements of the prototype LED freezer, which were compared to illuminance measurements from Tyler's prototype fluorescent-lighted freezer. Measurements in the laboratory were taken at ambient air temperature.

Figure 4 compares the results on a given shelf in the unit. The horizontal red lines indicate the recommended upper and lower specification limits, and the yellow line is the mean of these. These limits are ± 30% of the average light output of the fluorescent lighting system measured. The LED system illuminance is within these limits and more uniform than the illuminance of the fluorescent system. Better uniformity may permit the light level of the LED system to be lower without changing shoppers' perceptions. This concept would be tested during the field study.

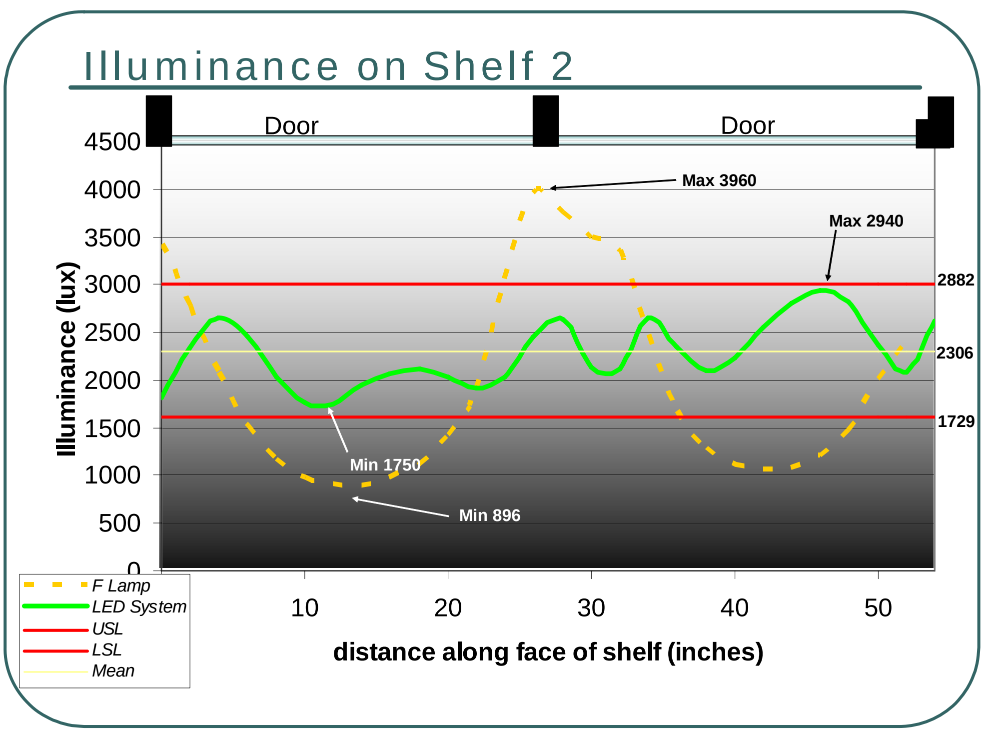

Figure 4. Illuminance levels across a given shelf of the LED case and the prototype fluorescent case. Horizontal red lines show the upper and lower specification limits, and the yellow line is the mean of these. (Figure courtesy of GELcore.)

3.3.4 Laboratory power measurements of the prototype freezers

Tyler conducted an energy assessment of both prototype freezers in March 2004 at its laboratory. Tyler's tests compared the energy usage and lighting loads of its freezer with fluorescent lighting against the same freezer with LED lighting at 100% control voltage (10V) and 50% control voltage (5V). All tests followed ASHRAE testing guidelines. Table 1 provides the energy data.

Energy consumption was higher for the LEDs operated at both 100% and 50% control voltage. Decreasing the control voltage to half of the normal level (10V to 5V) reduced the light level by approximately 30%. The higher consumption was not a major concern because of the LED freezer's prototype status. The LEDs used in this prototype, built in 2003, had a luminous efficacy of approximately 25 lm/W. LEDs at the time of this report (September 2006) had an efficacy of 45 lm/W. Future improvements in LED technology will certainly allow LEDs to compete with fluorescent lamps in the application.

During testing, Tyler found that the mullion fans in the LED freezer were causing sweating on the outer doors. These fans were initially designed to control the temperature of the LEDs. However, Tyler found that the fans were not necessary because the LEDs remained cool enough from the refrigeration alone, so the fans were not used once the unit was installed.

Table 1. Energy calculations for the fluorescent freezer, LED freezer at 100% control voltage, and LED freezer at 50% control voltage.

TYLER ENERGY COMPARISONS PLATFORM CASE - KWH/DOOR/24 HRS			
	Fluorescent	**LED 100%**	**LED 50%**
Btuh per door	**1528**	**1701**	**1602**
Evap temp at case (°F)	-22	-22	-22
Unit sizing temperature (°F)	-25	-25	-25
Energy Efficiency Rating	6.41	6.41	6.41
Fan watts per door	45	45	45
Door glass anti-sweat watts per door	59	59	59
Door perimeter anti-sweat watts per door	79.6	79.6	79.6
Main Frame anti-sweat watts per door	71.6	71.6	71.6
Light watts per door	**69.8**	**148**	**97.5**
Defrost+drain htr watts per door	1040	1040	1040
Defrost frequency	1	1	1
Defrost length (minutes)	30	30	30
KILOWATT CONSUMPTION			
Compressor kWh	5.72	6.37	6.00
Fan kWh	1.08	1.08	1.08
Door glass anti-sweat kWh	1.42	1.42	1.42
Door perimeter anti-sweat kWh	1.91	1.91	1.91
Main frame anti-sweat kWh	1.72	1.72	1.72
Light kWh	1.68	3.55	2.34
Defrost kWh	0.52	0.52	0.52
kWh/Door/Day	**14.04**	**16.56**	**14.98**

3.4 Price Chopper installation

The LED and fluorescent test freezers were installed side by side at the Altamont Avenue Price Chopper in May 2004. Figure 5 and Figure 6 show the LED freezer and a close-up of the LED lighting system. Figure 7 shows the test fluorescent freezer. Figure 8 shows the existing freezers in the supermarket aisle. Figure 9 shows the LED freezer's side mullion lighting dimmed.

Figure 5. The LED freezer installed at Price Chopper.

Figure 6. Close-up of the LED lighting system.

Figure 7. The fluorescent freezer installed at Price Chopper.

Figure 8. Existing freezers at Price Chopper.

Figure 9. The LED freezer's side mullion lighting dimmed.

A series of pilot studies were conducted to evaluate the appearance of the new freezers and to test the survey design. After the installation, three inconsistencies were noted by LRC research specialists and by shoppers between the test freezers and the existing freezers in the supermarket aisle.

First, the number of shelves inside the freezers did not match with the existing freezers at the store. Extra shelves were installed in both test freezers to make their appearance uniform with the other freezers in the aisle.

Second, the narrow footprint of the test freezers forced the shelves to sit close to the door and to the lighting system. As a result, the aluminum shelving material combined with the narrow beam spread of some of the LEDs created glare across the front edge of the shelves. To correct this problem, the LRC installed matte white shelf covers inside the LED freezer. A pilot study was conducted at the store with and without the white shelf covers to evaluate shoppers' preferences. Surveys showed that while the white covers cut the glare considerably, shoppers preferred the LED freezer case without them. The white covers were left on for the primary survey period, however. Although the fluorescent case did not use the same covers, this difference would not produce a confounding effect because of the lower ratings found with the white covers in the pilot study.

Third, the top shelf of the LED freezer appeared much darker than the rest of the freezer interior. GELcore created additional LED light strips for the top shelves to increase the light level in that section. Each light strip consisted of 12 lambertian Luxeon LEDs. A pilot study showed that when the LED side mullions were dimmed, the top row of LEDs provided a boost in shopper preference. Figure 10 shows the installation of the top row of LEDs inside the freezer.

Figure 10. The top row of LEDs added to the freezer.

3.4.1 Field location illuminance measurements – October 2004

Vertical illuminance measurements were taken in October 2004 for the LED freezer and the test fluorescent freezer. Measurements were taken on the face of the products at the front edge of the shelves. These measurements were taken at six points across each shelf for each door. Table 2 shows the average for all doors and shelves combined for each prototype freezer case measured at full light output.

The average illuminance for all shelves in the LED case was 2470 lux at full light output. The average illuminance for the test fluorescent freezer case was 2871 lux. The average illuminance within the LED case at full light output (100%) was 14% lower than the average illuminance within the fluorescent case. This difference could be due to the ambient lighting inside the store. Since the LEDs were already at their maximum and the fluorescent case did not have dimming capabilities, it was not possible to adjust the lighting of the two test cases to similar levels. Also, the two types of lighting provided completely different illuminance profiles within the cases. The fluorescent case had very high illuminance levels near the lamps and very low values at the middle of the glass door, but the LEDs had a much more even illuminance across the door, as seen in Figure 11 below.

Table 2. Average illuminance measurement for all shelves and doors at each measurement point inside the LED freezer (100% light output) and the test fluorescent freezer.

Measurement point	LEDs at 100%	Fluorescent
	E (Lux)	E (Lux)
1	2779	5980
2	2242	1744
3	2575	1048
4	2620	1083
5	2173	2064
6	2430	5305
Average	**2470**	**2871**

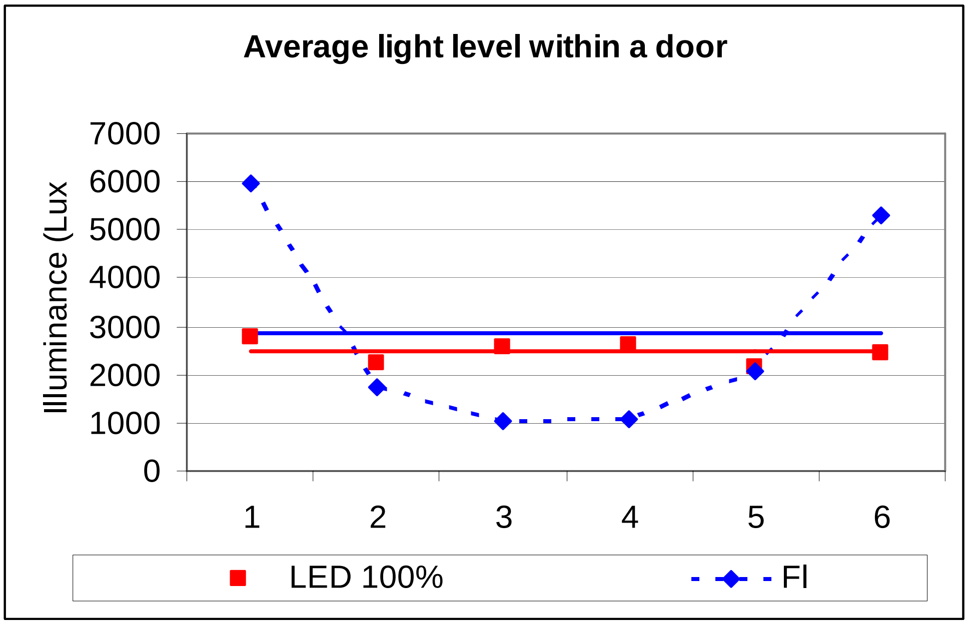

Figure 11. The average uniformity of each lighting system across a freezer door. Straight lines indicate the average illuminance for a given lighting system.

After the first field survey was completed with LEDs operating at the 100% level, a second field survey was conducted using a dimmed light level. Because the dimming control was not precise, it was not possible to reduce light levels to exactly 80%, as desired. By changing the potentiometer and measuring the light level inside the freezer, a 86% light level was finally reached. Table 3 shows the average illuminance measurements. The average illuminance within the LED case at the dimmed level was 2148 lux, approximately 85% of the initial value. At this point, the dimmed LED case on average had a 25% lower light level than the test fluorescent case. Figure 12 shows the average uniformity of each lighting system.

Table 3. Average illuminance measurement for all shelves and doors at each measurement point inside the LED freezer at 100% light output and at dimmed light output, and for the test fluorescent freezer.

Measurement point	LED at 100%	LED dimmed	Fluorescent
	E (Lux)	E (Lux)	E (Lux)
1	2779	2321	5980
2	2242	1985	1744
3	2575	2264	1048
4	2620	2267	1083
5	2173	1984	2064
6	2430	2066	5305
Average	**2470**	**2148**	**2871**

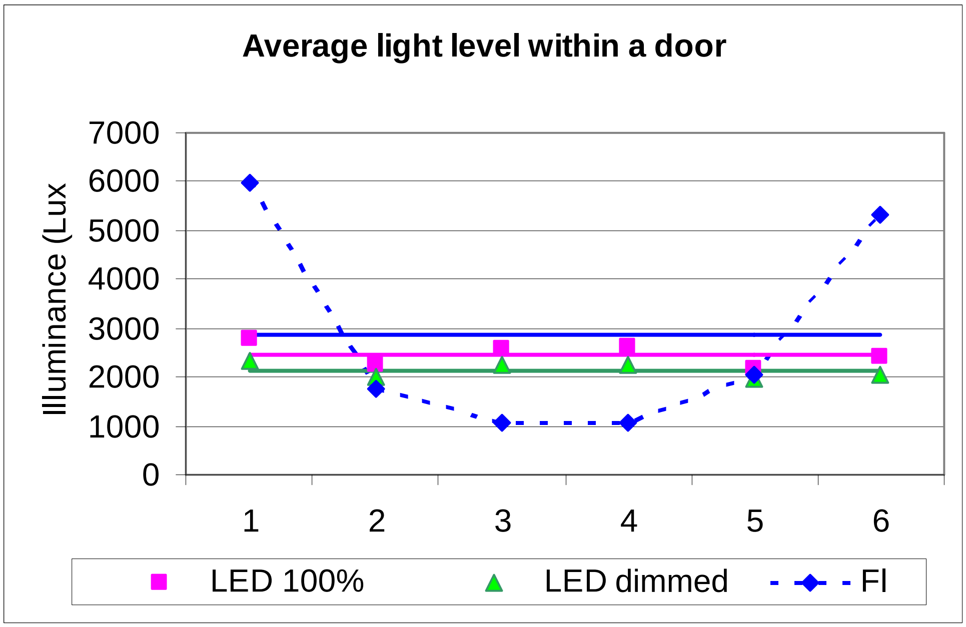

Figure 12. The average uniformity of each lighting condition across a freezer door. Straight lines indicate the average illuminance for a given lighting system.

3.4.2 Field location illuminance measurements – July 2005

Vertical illuminance measurements of the LED freezer were taken again in July 2005. At this time, the position of the side-by-side freezer cases were switched in order to collect and analyze sales of the same products under both LED and fluorescent lighting. These illuminance measurements were compared with those taken in October 2004 to determine whether any degradation of the LEDs had occurred. Table 4 shows the average illuminance measurements for all doors and shelves combined for each type of freezer case.

Table 4. Average illuminance measurement for all shelves and doors at each measurement point inside the LED freezer (100% light output) and the test fluorescent freezer after switching positions of the two freezers.

Measurement point	LED at 100%	Fluorescent
	E (Lux)	E (Lux)
1	1899	6051
2	2061	2190
3	2314	1069
4	2549	1112
5	2264	2411
6	2168	5578
Average	**2209**	**3068**

When the light levels were measured again after switching the two freezer cases, it was noticed that the average light level inside the LED case was 10% lower than before, and the average light level within the fluorescent case was 10% higher. The illuminance values are shown in Figure 13 and Figure 14. This difference could be the result of relamping the fluorescent case or from the ambient lighting in the store. In the worst case, the LEDs depreciated 10% during the one-year period. It is difficult to pinpoint exactly when the light levels changed. As a result, when the final field survey was conducted, the illuminance level inside the LED case measured 28% lower than the illuminance level inside the test fluorescent case.

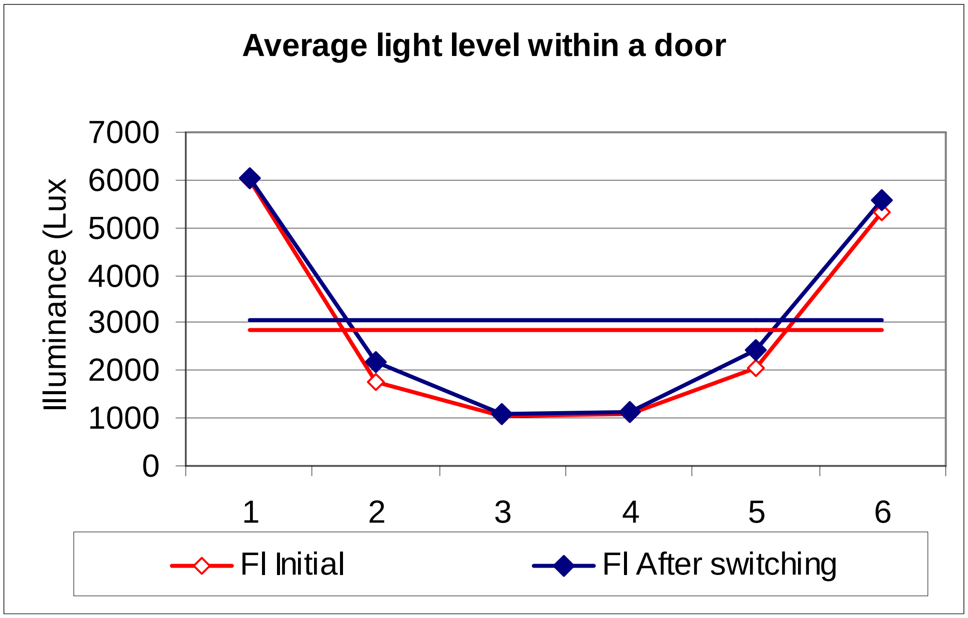

Figure 13. Illuminance levels of the test fluorescent freezer at each measurement point before and after switching the location of the freezer cases.

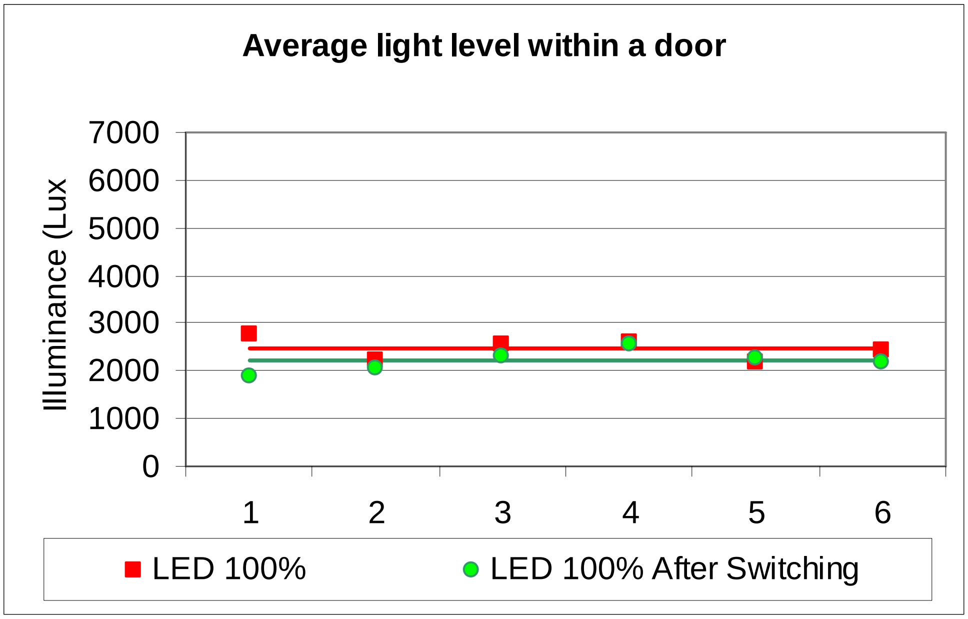

Figure 14. Illuminance levels of the LED freezer at each measurement point before and after switching the location of the freezer cases.

4. Field Evaluation

After the freezer configuration and survey were finalized, the primary field study began. The field study included the following activities:

- survey of shoppers' opinions and preferences
- monitoring and analysis of product sales for the test freezer cases

4.1 Experimental conditions

Survey and sales data were collected for combinations of two lighting conditions and two freezer positions.

Two lighting conditions were tested: LEDs at 100% light output, and side mullions dimmed (top row LEDs remained at 100% light output). Light levels were maintained at 100% for the test fluorescent freezer and the existing freezers throughout the study. The LEDs were dimmed to determine whether lower light levels would be acceptable, as a means of saving energy.

Two different freezer positions also were used. During the course of the field study, the position of the side-by-side freezer cases were switched in order to collect and analyze sales of the same products under both LED and fluorescent lighting. At Price Chopper's request, the case positions were switched in order to maintain the physical location of the food products within the supermarket aisle. The first set of data was collected with the LED freezer on the right. The freezer positions were then switched, and a second set of data was collected with the LED freezer on the left.

4.2 Shopper survey

One major goal of this study was to understand shoppers' preferences for the lighting of freezer cases. Therefore, a survey was designed to collect shoppers' opinions of the LED freezer, the test fluorescent freezer, and the existing fluorescent freezer cases in the supermarket. Approximately 100 surveys were collected for three experimental conditions: LEDs at 100% light output, LEDs dimmed, and LEDs at 100% light output after the freezer position switch. A survey of LEDs dimmed after switching freezer positions was not conducted because of time and budget constraints.

An LRC employee waited in the frozen food aisle and randomly approached shoppers to fill out a survey. Shoppers were offered lottery tickets as incentive for their participation. They were not informed about the type of lighting in the freezers or the purpose of the study.

The first part of the survey asked shoppers to rate the lighting in both test freezers for attractiveness, comfort, and quality. For each of the test freezers, shoppers were asked:

1. How eye-catching is the case?
2. How clearly can you see the merchandise in the case?
3. How accurately can you see the colors of the merchandise in the case?
4. How appealing does the lighting make the merchandise look?
5. How comfortable is the case to look at?
6. How bright is the lighting of the case?
7. How even is the lighting of the case?
8. Overall, how much do you like the lighting of the case?

Shoppers could select one answer from the following choices: "Not at all," "A little," "More," or "Very much."

In the second part of the survey, shoppers were asked to compare the LED freezer, the test fluorescent freezer, and existing freezers located in the same aisle. They were asked:

1. Which lighting do you prefer?
2. Which lighting is more eye-catching?
3. Which lighting makes the merchandise more appealing?
4. Which lighting is more even?
5. Which lighting looks brighter?
6. Which lighting is more comfortable to look at?
7. Which lighting shows the colors of the merchandise better?
8. Which lighting lets you see the price tags more clearly?
9. Which lighting do you like more?

See Appendix A for a copy of the survey.

4.3. Shopper survey results

4.3.1 LED freezer at 100% light output

Figure 15 shows the percentage of responses from 108 subjects to each survey question about the LED freezer at 100% light output. Overall, 90% of shoppers said they liked the lighting of the LED freezer (ratings of "More" and "Very much").

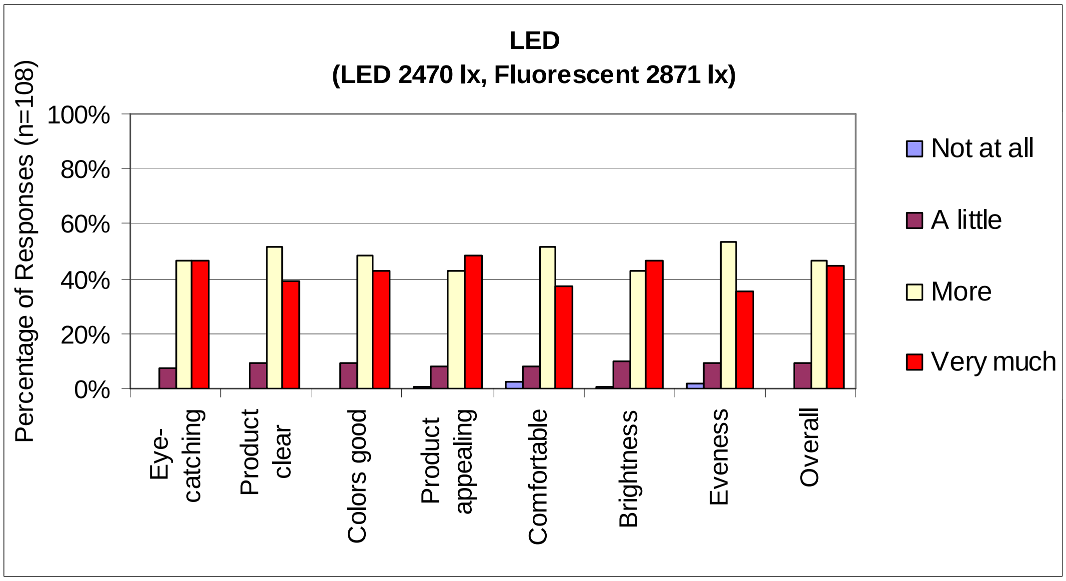

Figure 15. Subject ratings of the LED freezer at 100% light output.

Figure 16 shows the percentage of responses from 108 subjects to each survey question about the test fluorescent freezer. Overall, 51% of shoppers said they liked the lighting of the test fluorescent freezer (ratings of "More" and "Very much").

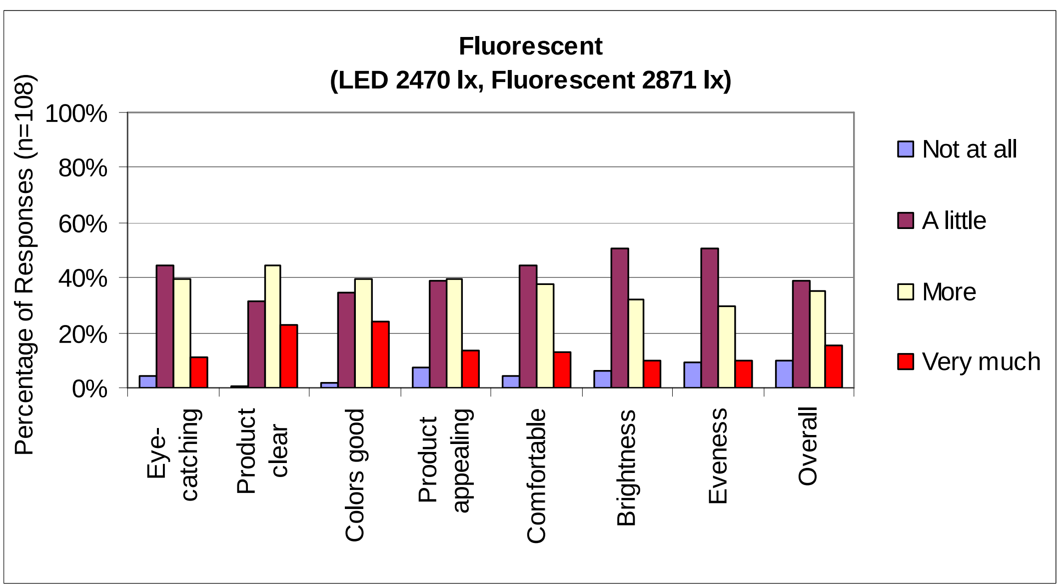

Figure 16. Subject ratings of the test fluorescent freezer.

Figure 17 shows the percentage of responses from 108 subjects to each survey question where they were asked to compare the LED freezer at full output, the test fluorescent freezer, and the existing freezers in the supermarket aisle. Subjects overwhelmingly preferred the LED freezer, with 86% of subjects selecting the LED freezer as the one they liked the most. Less than 1% of subjects chose the existing freezers as the option they liked the most.

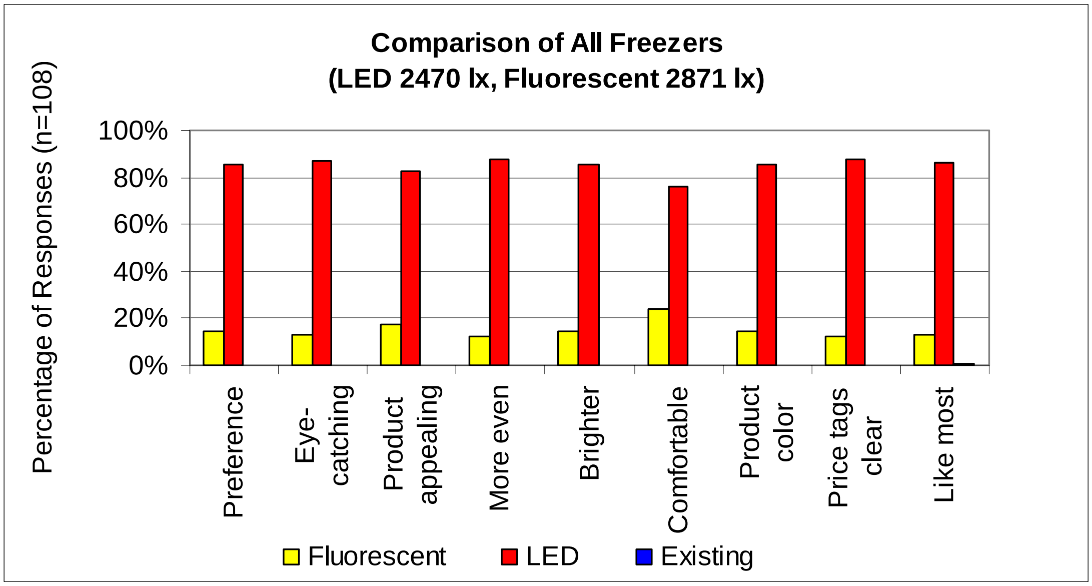

Figure 17. Subject ratings comparing the LED freezer, the test fluorescent freezer, and existing freezers in the supermarket aisle.

4.3.2 LED freezer at dimmed light output

Figure 18 shows the percentage of responses from 94 subjects to each survey question about the LED freezer at a dimmed light output. Overall, 79% of shoppers said they liked the lighting of the LED freezer (ratings of "More" and "Very much").

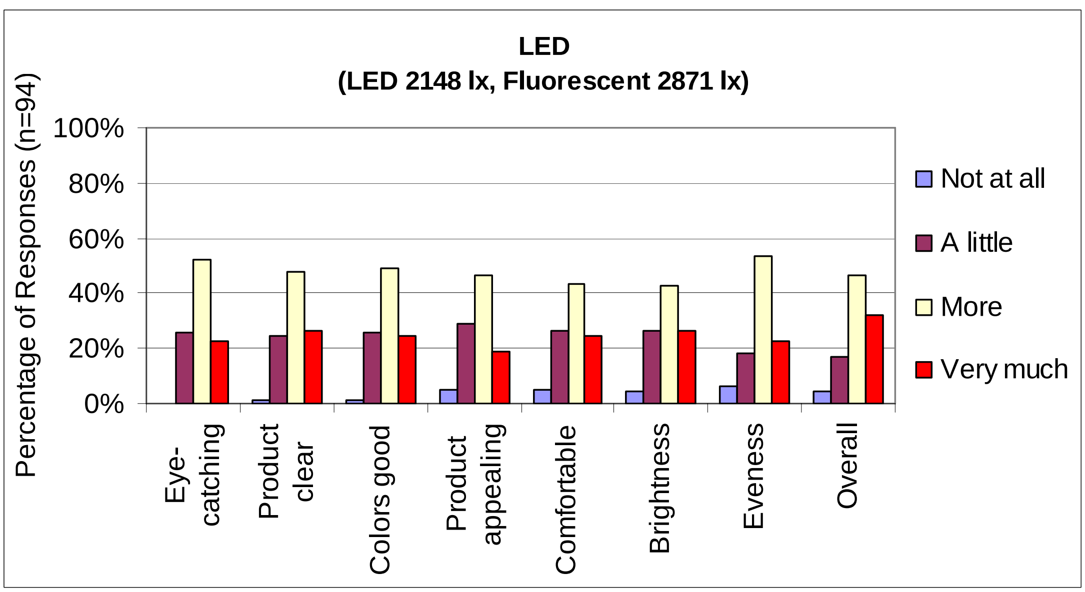

Figure 18. Subject ratings of the LED freezer dimmed.

Figure 19 shows the percentage of responses from 94 subjects to each survey question about the test fluorescent freezer. Here again, 51% of shoppers said they liked the lighting of the test fluorescent freezer (ratings of “More” and “Very much”).

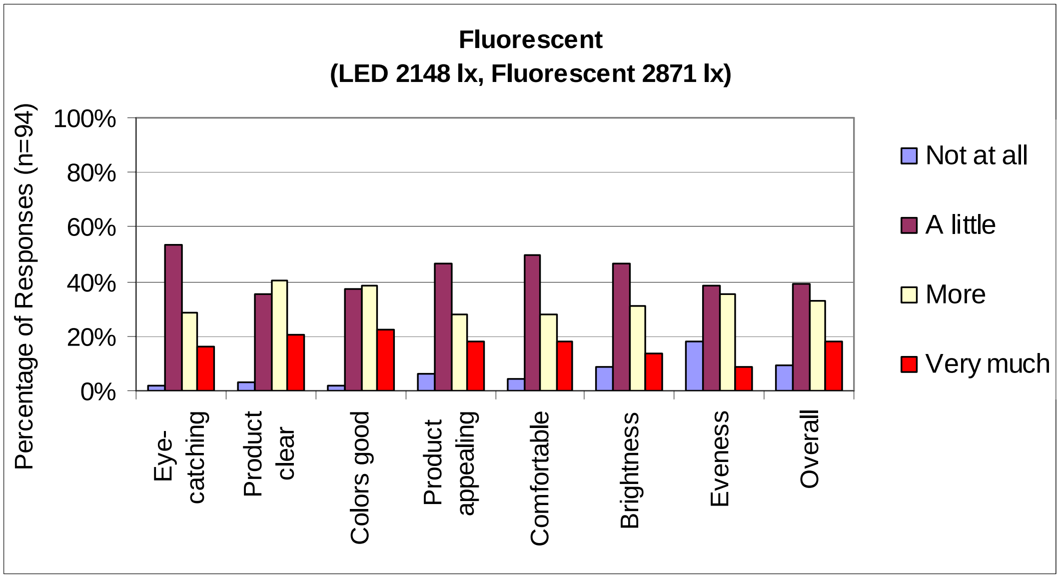

Figure 19. Subject ratings of the test fluorescent freezer.

Figure 20 shows the percentage of responses from 94 subjects to each question where they were asked to compare the LED freezer dimmed, the test fluorescent freezer, and the existing freezers in the supermarket aisle. Even at a lower light level, subjects still preferred the LED freezer over the test fluorescent freezer, with 68% of subjects selecting the LED freezer as the one they liked the most. The existing freezers were not selected as a preferred option on any question.

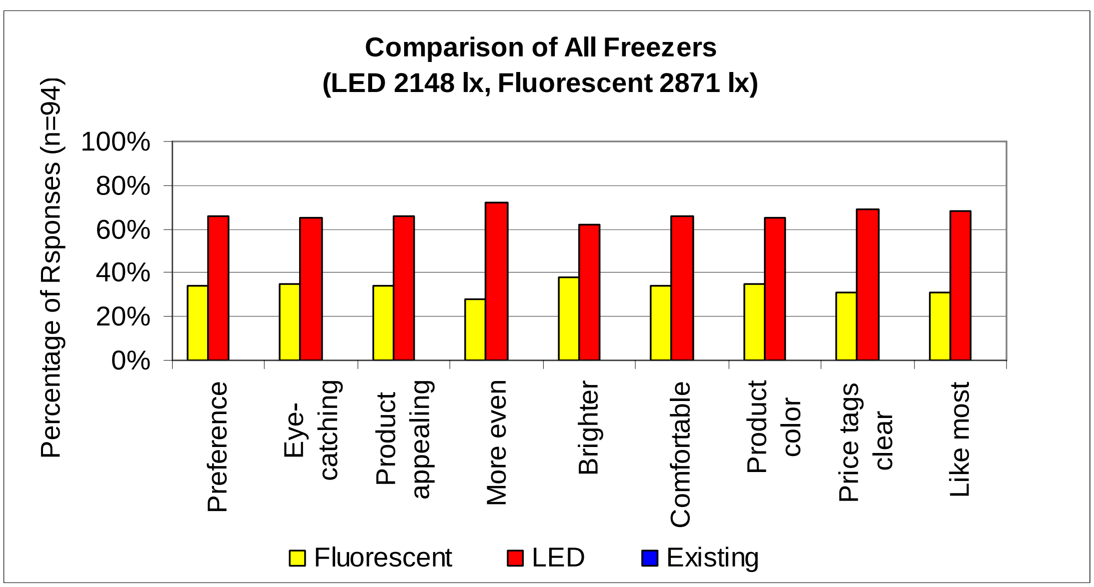

Figure 20. Subject ratings comparing the LED freezer dimmed, the test fluorescent freezer, and existing freezers in the supermarket aisle.

4.3.3 LED freezer at 100% light output, after position switch

Figure 21 shows the percentage of responses from 109 subjects to each survey question about the LED freezer at 100% light output after the positions of the two test freezers were switched. Overall, 87% of shoppers said they liked the lighting of the LED freezer (ratings of “More” and “Very much”).

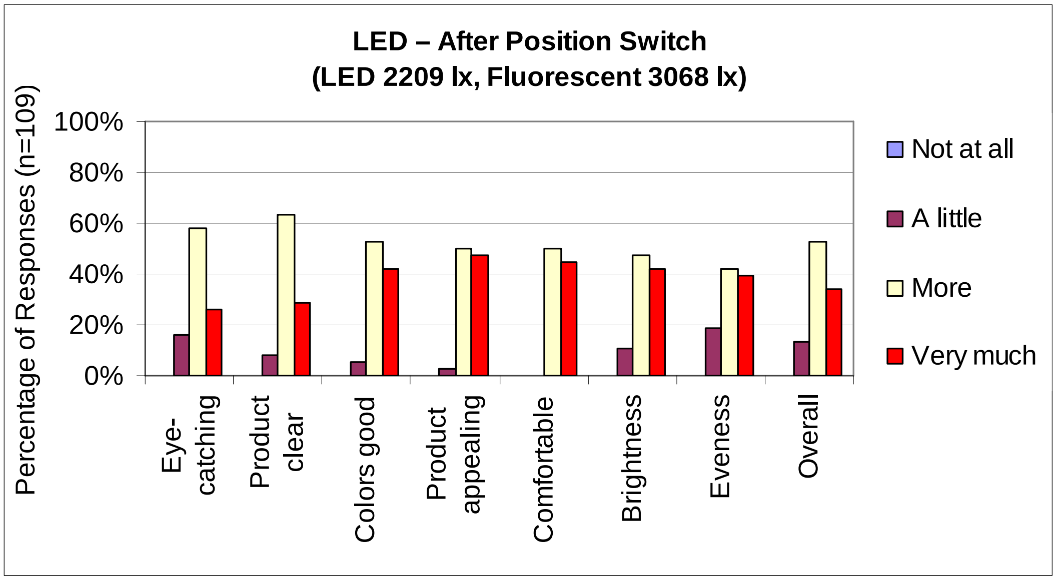

Figure 21. Subject ratings of the LED freezer at 100% light output after switching freezer positions.

Figure 22 shows the percentage of responses from 109 subjects to each survey question about the test fluorescent freezer after the positions of the two test freezers were switched. Overall, 53% of shoppers said they liked the lighting of the test fluorescent freezer (ratings of “More” and “Very much”).

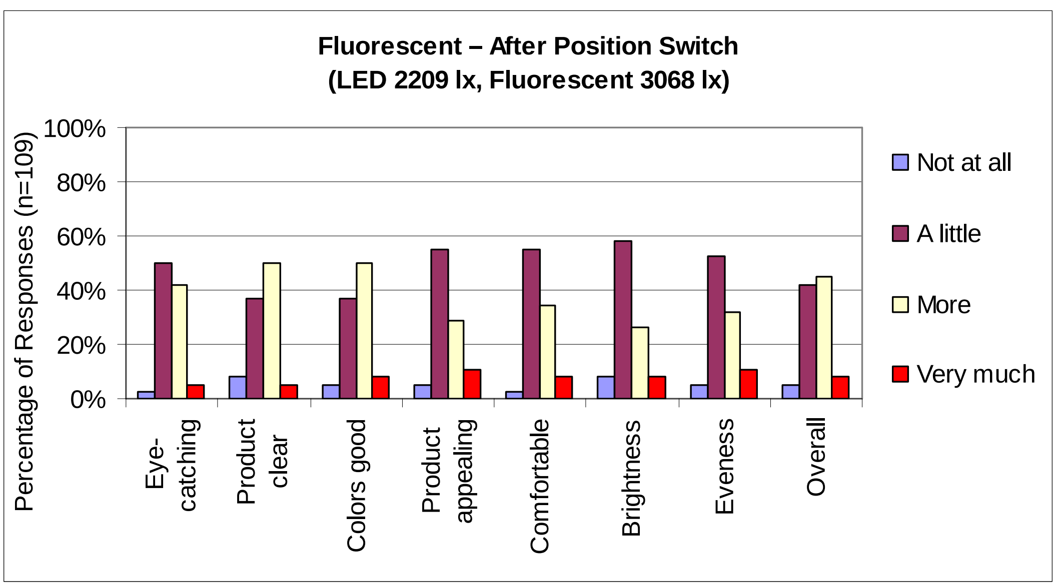

Figure 22. Subject ratings of the test fluorescent freezer after switching freezer positions.

Figure 23 shows the percentage of responses from 109 subjects to each survey question where they were asked to compare the LED freezer, the test fluorescent freezer, and the existing freezers in the supermarket aisle after the positions of the two test freezers were switched. Subjects overwhelmingly preferred the LED freezer, with 95% of subjects selecting the LED freezer as the one they liked the most. The existing freezers again were not selected as a preferred option on any question.

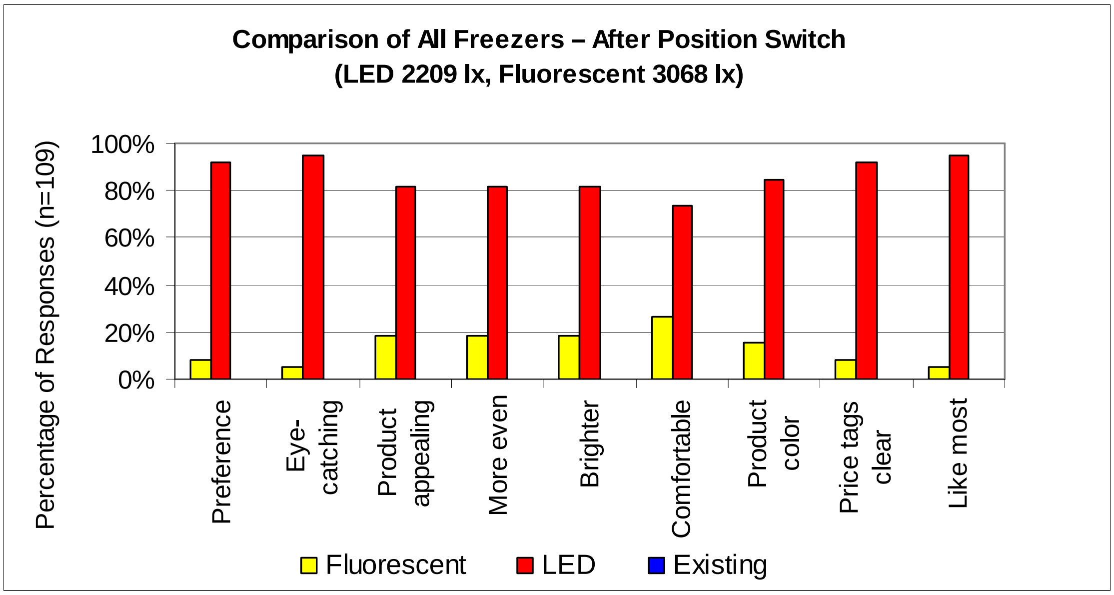

Figure 23. Subject ratings comparing the LED freezer, the test fluorescent freezer, and existing freezers in the supermarket aisle after switching freezer positions.

4.4 Sales analysis

To evaluate the potential effect of freezer lighting on product purchases, sales data were collected for the products displayed in each of the test cases for each experimental condition. Time periods for the analysis corresponded to specific four-week sales periods defined by Price Chopper. The test freezer units were installed in May 2004 (05-Period 1; 05 refers to the fiscal year 2005 for the store). The left-hand freezer case under study in the experimental store is referred to as Case #1, and the right-hand freezer is referred to as Case #2. Starting in the 05 fiscal year, Case #1 had new fluorescent lighting (using the traditional lighting method), and Case #2 had LED lighting. The positions were switched during the 06 fiscal year starting in 06-Period 6, with LED lighting in Case #1 and new fluorescent lighting in Case #2. Products in each freezer case were different. Sales data were analyzed up to 06-Period 13.

Sales data from two freezer cases from a comparison, control store were also analyzed. These freezers contained the same products as Case #1 and #2 in the experimental store and are also referred to here as Case #1 and #2 for the control store. Sales data were analyzed in terms of units sold and in terms of dollar value sold.

4.5. Sales analysis results

To avoid potential confounding caused by reporting errors in either the total dollar sales or units sold data from the grocery store, an average price for each product during each sales period was calculated by dividing the total dollar sales for that product by the units of that product sold. Observation of these average price data showed that generally, prices remained largely constant or increased gradually but slightly over the three-year analysis timeframe. Occasionally, there were very large fluctuations in the calculated average price for a single period that exceeded a standard deviation of the average price throughout the entire timeframe. Because there was no way to determine whether the total dollar sales or the units sold data were incorrectly reported, causing such a large price fluctuation, both types of data were excluded from subsequent analysis of total dollar sales and units sold for each product. Very few data (less than a few percent for each case) were excluded using this procedure, and there were no systematic patterns found that would have affected the subsequent results.

Sales data for a total of 59 products (30 in Case #1 and 29 in Case #2) were analyzed. Figure 24 shows, as an example, the total sales data (in units sold) for the 29 products in Case #2 in each store (experimental and control). Units sold are in arbitrary units to protect the stores' confidential sales data.

Because of potential impacts of yearly variations (holidays, seasonal items, etc.) on sales, only data from the three fiscal years where the same times of the year were available for all three conditions were analyzed. In other words, since there were no data for LED lighting in Case #1 of the experimental store for Periods 1 through 5, these periods were not studied in other fiscal years. The analysis included Periods 6 to 13 in fiscal years 04 through 06. Comparisons were made of the sales in Case #1 and Case #2 and each store across fiscal years using two-tailed, paired t-tests (i.e., comparing sales of each product brand with itself). The results indicated that while there were some examples of sales (both in units and dollar value) increasing and decreasing significantly from the 04 fiscal year to the 05 and 06 fiscal years, these changes were largely paralleled in the corresponding cases in both stores. Some instances of sales changing in one store but not in another occurred, but sales never increased in one store while decreasing in another.

A similar analysis was performed comparing the three periods before and after the transitions in lighting to determine whether there might have been short-term changes in product sales at these times for Cases #1 or #2 in the experimental store. Again, changes in sales (units and dollar values) largely tracked one another across the experimental and control stores and did not point to a large impact of lighting on sales (e.g., at no time did sales in one store increase while sales in the other store decreased).

Figure 24 does show a brief increase in sales for Case #2 in the experimental store during 05-Periods 4 and 5, after the lighting had been switched to the LED system. This increase appeared to be largely due to a special offer in the experimental store with one particular brand of frozen food product. In fact, removing the data from just the top three selling items of this particular brand resulted in a much smaller increase, as illustrated in Figure 25. For this reason, it seems unlikely that the lighting was the cause for this temporary increase.

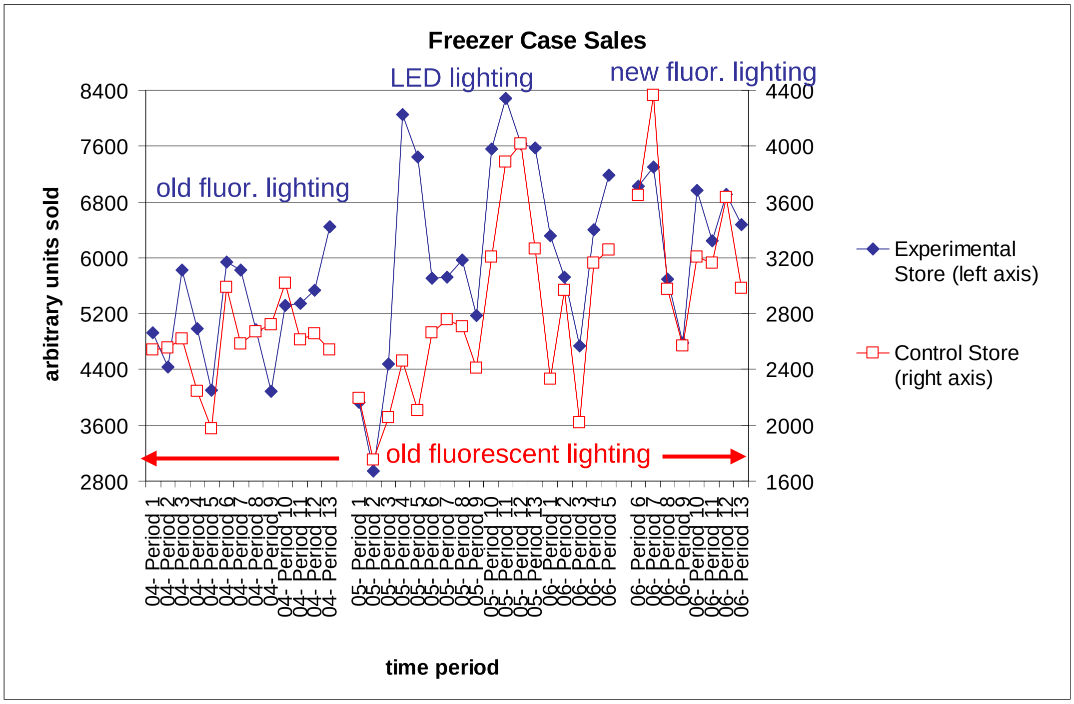

Figure 24. Sales data (total units sold for all products, in arbitrary units) for Case #2 in the experimental and control stores. Absolute sales values differ in volume (note two ordinate scales), but trends are similar across the stores.

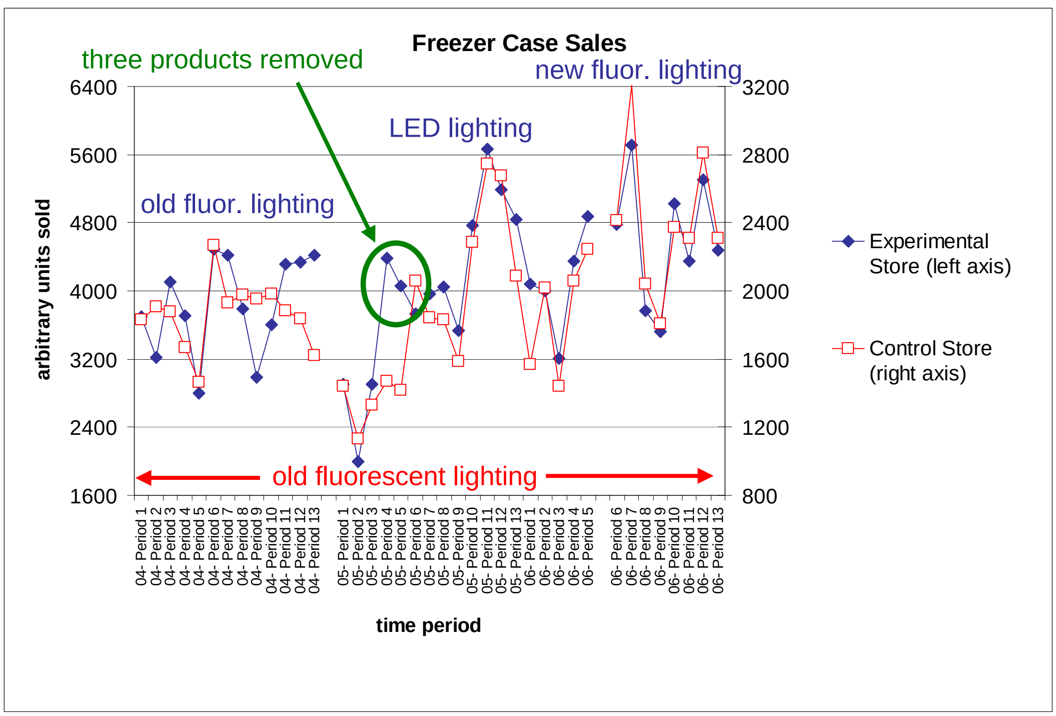

Figure 25. Sales data (total units sold for all products except three, in arbitrary units) for Case #2 in the experimental and control stores. Absolute sales values differ in volume (note two ordinate scales), but trends are similar across the stores. The large increase in 05-Periods 4 and 5 is much smaller compared to that in Figure 24.

5. Human Factors Lab Study – Relamping Criteria Development

A separate human factors laboratory study was completed to understand how well people perceive differences in illumination levels when viewing two lighted spaces side by side. This study was prepared to develop relamping criteria for the LED freezer lighting system. For more information about this study, see Appendix B.

6. Discussion

Results of the in-store survey indicate that shoppers preferred the LED freezer lighting over the test fluorescent lighting and over the existing freezers, even when dimmed. Shoppers rated the lighting of the LED freezer as being brighter, even though the average illuminance inside the case at full light output was 400 lux (14%) lower than that of the test fluorescent freezer (see Table 3). When dimmed, the LED freezer was still considered somewhat brighter at an illuminance more than 700 lux (25%) lower than that of the test fluorescent freezer. The even illuminance uniformity and higher CCT of the LED lighting likely contributed to shoppers' perceptions that the LED freezer was brighter. While the average illuminance level of the fluorescent freezer was higher, the uneven distribution led to areas at the center of each glass door that were roughly half of the average LED light level in the same location. Because the center of the door is where products are most visible, this may have led to the increased brightness perception of the LED freezer. Further, this finding indicates that light levels within a freezer case could be reduced for added energy savings if the distribution and uniformity are even across the freezer shelves and products.

An interesting finding of the survey was that shoppers did not select the existing Price Chopper freezers as a preference on any question. The reason for this may be the lower illuminance levels measured on the product face inside these cases. The existing Price Chopper freezers showed significantly lower illuminances at full light output (average 1725 lux) compared with the LED and test fluorescent cases at full light output (2470 lux and 2871 lux, respectively). This difference is likely a result of the different footprint and geometry inside the case. The shelves inside the Price Chopper existing cases sit 9 inches back from the light mullions, compared with 4 inches back for the test freezers. A smaller footprint was selected for the test freezers in this study because the grocery industry expects that supermarkets will move toward purchasing these types of freezers in the future to save floor space.

6.1 Energy savings potential for LEDs in commercial refrigeration

The potential exists now for LED lighting in commercial refrigeration to match or even surpass fluorescent lighting in terms of shopper satisfaction. We believe that shoppers in this study showed greater preference for the LED freezer because of its better illuminance uniformity. In this study, we believe that better uniformity allowed the LED freezer to have a lower light level than the test fluorescent freezer, yet be deemed brighter, more even, more appealing, and more comfortable. At a dimmer light level, LEDs are now at a "threshold" efficacy where they fall slightly below the energy consumption of fluorescent lighting without sacrificing shopper satisfaction. Table 5 shows an energy usage comparison of fluorescent lighting, LEDs used in this field study, and LEDs as they stand at the time of this report.

The argument for energy savings with LEDs rests on shopper preference rather than illuminance. At no time did the illuminance levels inside the LED freezer match or exceed the light levels inside the test fluorescent freezer, yet surveys showed for each condition that shoppers preferred the LED case over the fluorescent case. However, it is important to note that the preferences stated in this study may not apply to other store installations or to other freezer case configurations. The freezers used in this study had smaller interiors, which brought the luminaires closer to the products. Not all freezer cases are restricted to this size and configuration; therefore, fluorescent may be more uniform and thus more acceptable to shoppers in certain case configurations. Additionally, these energy calculations assume the use of a 58 W fluorescent lamp, the standard for most fluorescent-lighted freezers. However, some supermarkets use freezers with 40 W lamps. In this case, the energy consumption from fluorescent would be lower than stated in Table 5. It may be possible, however, to use fewer LEDs to create an energy argument against the reduced-wattage fluorescent freezer.

Table 5. Energy usage comparison of LED and fluorescent lighting in commercial refrigeration.

	Field Study Light Sources (2003)	Current Light Sources (2006)
LED luminous efficacy	25 lm/W [a]	45 lm/W [a]
LED lighting system watts, 4-door freezer – 100% light output	652 W [b]	362 W [d]
LED lighting system watts, 4-door freezer – Dimmed	496 W [b]	276 W [d]
Fluorescent lighting system watts, 4-door freezer (100% light output, 58 W per lamp, 5 lamps)	290 W [c]	290 W [c]
Energy savings with dimmed LEDs	–206 W	14 W

[a] Luminous efficacy of light source stated by manufacturer, not system efficacy.
[b] Lighting system watts were measured
[c] Lighting system watts were calculated
[d] Estimated by dividing the measured field study wattage by 1.8, the ratio of 2003 LED luminous efficacy to 2006 LED luminous efficacy.

7. Market Transformation

At the present time, a number of market transformation activities for the lighting of commercial refrigeration are taking place. In 2005, GELcore began promoting an LED lighting retrofit kit for refrigerated display cases. GELcore markets the product as providing 75% light level uniformity across packages, 50,000-hour life, and no relamping for a decade. While GELcore mentions the possibility of saving energy through dimming, it makes no overall claims of energy savings. GELcore's product specifications show that a 65-inch system has a power of 76 W and produces 1800 lm (GELcore n.d.).

Nualight also began marketing an LED lighting system for upright freezers in 2005. Nualight's system can be installed during freezer construction or as a retrofit. Nualight claims its product consumes 40% less energy, produces more than 1400 lux at the center of the door, and has a life greater than 50,000 hours. Nualight's product specifications show that a 65-inch system has a power of 50 W and produces 1836 lm (Nualight n.d.).

Three other companies provide LED lighting kits for this application, including Everbrite Lighting Technologies (n.d.), Leotek Electronics (n.d.), and Permlight (n.d).

Wal-Mart is testing a wide range of energy-saving building systems at two experimental stores in McKinney, Texas, and Aurora, Colo., including LED lighting for its grocery cases and jewelry cases (Wal-Mart n.d.). These stores are open to the public.

7.1 Interviews with major supermarket chains

Five supermarket chains and major retailers with full-scale supermarkets inside their stores were contacted at the end of 2005 and in early 2006 in order to learn more about their expectations for freezer case lighting. These chains were interviewed about their stores' freezer light levels and lamp maintenance needs, and their awareness of new LED lighting technology. Interviews took place with an energy manager at the corporate headquarters of each chain.

Most said that fluorescent lighting technologies provide sufficient light levels inside freezer cases. Expectations and standards for freezer and ambient light levels varied widely among the chains. One supermarket reported that its new stores will feature lower ambient light levels and more accent lighting. Under low ambient light levels, freezer lighting may be considered a type of accent lighting to draw shoppers for a closer look. Another chain dismissed the value of illuminance measurements, noting that it makes its decisions of light levels on the basis of subjective evaluation.

Most supermarkets reported that they currently use 58 W fluorescent lamps in their freezer cases. One chain is even more aggressive, as it is satisfied with a 40 W lamp.

Energy usage from freezers is a primary concern for supermarkets, though one noted that energy savings should not be at the expense of customer satisfaction. The same chain also said it is interested in moving the market toward LEDs, as part of its commitment to cut greenhouse gas production from its business.

According to these energy managers, maintenance is important but secondary to energy; most reported no serious lighting maintenance issues or concerns with their current freezers. None reported problems with heat gain from fluorescent lamps or food spoilage.

Most of the supermarket chains contacted were in the process of reviewing LED lighting for their refrigerator and freezer cases, as well as for other in-store lighting uses. Many are currently running their own field studies on the use of LEDs in freezer cases.

Supermarkets have a strong interest in LED lighting, particularly as the efficacy and intensity of LEDs increase. One supermarket reported that it would be interested in combining a dimming

LED system with a motion detector. Another liked that LEDs are small enough to be well shielded, thus producing less glare than fluorescent lamps. None reported any objections to LED color appearance in their field studies.

With the exception of one chain, most interviewed had not yet found a satisfactory solution with the LED products currently available. Overall, their major concerns at this time with LEDs are optical qualities, energy, and cost. The one chain that is moving forward with LEDs in its refrigeration and freezer cases said it is expanding the use of doors on its cases, rather than having open cases. Closed-door cases require their own lighting systems, whereas open cases can take advantage of the ability to mount lighting in non-refrigerated conditions. In this instance, the efficacy of fluorescent technologies remains superior to LEDs. If stores trend toward enclosing more refrigerated merchandise behind glass doors, the value of LED lighting will increase.

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Appendix A

RPI Lighting Research Center Refrigerator Case Lighting Study

The Lighting Research Center wants your opinions of the lighting in the two refrigerator cases in front of you. For completing this survey, you will receive an Instant-Win™ lottery ticket. There are no right or wrong answers; your responses should simply reflect your opinions. Please be sure to answer all questions.

Demographics

How old are you?
- 20 years or younger
- between 21 and 40 years
- between 41 and 60 years
- above 60 years

What is your gender?
- Male
- Female

Please answer the questions below by checking ONE of the four boxes next to each question.

LEFT Refrigerator Case

	Not at All	A Little	More	Very Much
How eye-catching is the case?				
How clearly can you see the merchandise in the case?				
How accurately can you see the colors of the merchandise in the case?				
How appealing does the lighting make the merchandise look?				
How comfortable is the case to look at?				
How bright is the lighting of the case?				
How even is the lighting of the case?				
Overall, how much do you like the lighting of the case?				

RIGHT Refrigerator Case

	Not at All	A Little	More	Very Much
How eye-catching is the case?				
How clearly can you see the merchandise in the case?				
How accurately can you see the colors of the merchandise in the case?				
How appealing does the lighting make the merchandise look?				
How comfortable is the case to look at?				
How bright is the lighting of the case?				
How even is the lighting of the case?				
Overall, how much do you like the lighting of the case?				

Date:

Continue Other Side

Left = L or F

COMPARE All Refrigerator Cases

Please rank (1st, 2nd or 3rd) all of the refrigerators on the following qualities.

	Left	Right	Other Store Cases
Which lighting do you prefer?			
Which lighting is more eye-catching?			
Which lighting makes the merchandise more appealing?			
Which lighting is more even?			
Which lighting looks brighter?			
Which lighting is more comfortable to look at?			
Which lighting shows the colors of the merchandise better?			
Which lighting lets you see the price tags more clearly?			
Which lighting do you like more?			

COMMENTS

Please write any of your opinions about the refrigerator lighting.
Make sure to indicate which refrigerator (LEFT or RIGHT) that you are commenting about.

Date: Thank you for completing this survey Left = L or F

Appendix B

Human Factors Lab Study – Relamping Criteria Development

A separate human factors laboratory study was completed to understand how well people perceive differences in illumination levels when viewing two lighted spaces side by side. This study was prepared to develop relamping criteria for the LED freezer lighting system.

Twelve subjects viewed two side-by-side cabinets lighted with RGB LED systems set at 3000 K CCT. The cabinets were viewed with either empty (white) interiors or stacked food packages (Fig. A-1 and Fig. A-2). Two horizontal illuminance levels (300 lux and 500 lux) were selected as reference illuminances. At the beginning of each experimental session, the light levels in each cabinet were set at identical illuminances. During the course of the session, the light level in the reference cabinet remained constant while the level in the other cabinet changed in incremental steps. Subjects looked away from the cabinet during light level changes. Subjects compared the lighting of the two side-by-side cabinets at each step and stated whether they saw a light level difference between the cabinets and whether the difference was acceptable.

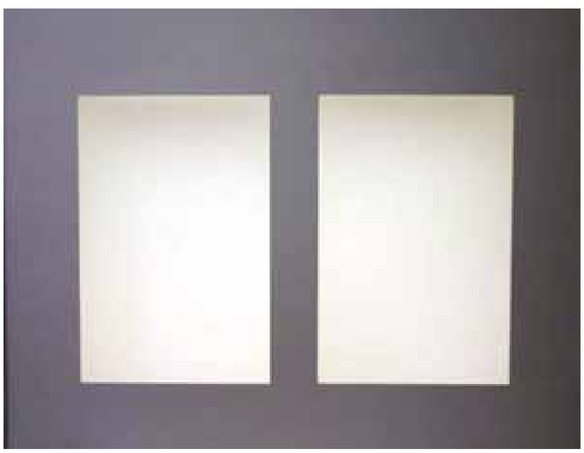

Fig. A-1. Example of the white background.

Fig. A-2. Example of the colored background using stacked frozen food packages.

Results

Subjects compared two side-by-side lighted compartments and stated whether they saw a light level difference between the compartments and whether the difference was acceptable. Figure A-3 depicts the overall results. The results indicate that for a stocked freezer case (colored background) with a 300 lux illuminance, the subjects generally did not detect a light level difference until the illuminance reached a 32% reduction. Additionally, they were willing to accept up to a 39% light level reduction from the original 300 lux illuminance. At higher light levels, the subjects generally detected light level reductions more readily. For the same freezer case with a 500 lux illuminance, the subjects noticed a light level difference at a 27% reduction and were willing to accept up to a 29% reduction.

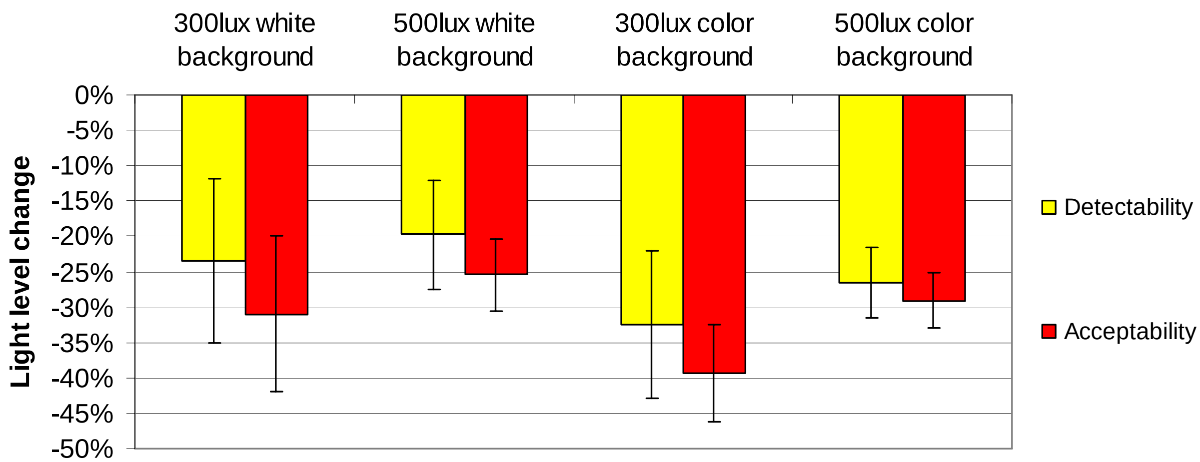

Fig. A-3. Detectability and acceptability of light level changes at different reference illuminance levels and backgrounds.

Regardless of the type of visual background, the subjects were generally more sensitive to light level changes when starting with a high reference light level. The visual background also affected the subjects' detection and acceptance of light level changes, with subjects being generally more sensitive to light level changes under a white background than under a colored background.

From these results, it is reasonable to conclude that a 30% reduction from the initial light level is a good estimate for when the lighting system should be replaced. In other LED life tests, the LRC has found that high-flux white LEDs last approximately 30,000 hours before their light level drops by 30%.