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ABSTRACT

The rapid development of high brightness light emitting diodes (LEDs) has triggered many applications, especially in the area of display lighting. This paper focuses on the application of white LEDs in refrigerated display cases. The fluorescent lighting presently used in commercial refrigerators is inefficient in the application and also it provides poor lighting for merchandising. A laboratory human factors experiment was conducted to assess the preference for the different lighting systems, namely, fluorescent and LED. Two refrigerated display cases, one with the traditional fluorescent lighting system and the other with a prototype LED lighting system, were placed side-by-side in a laboratory setting. Illuminance measurements made within the two display cases showed that the lighting was more uniform with the LED system compared to the traditional fluorescent system. Sixteen human subjects participated in this study and rated their preference for the two lighting systems. The results show that human subjects strongly preferred the display case with the LED lighting. The authors of this manuscript believe a field study would be greatly beneficial to further confirm these results and to understand the relationship between preference and sales. Considering the luminous efficacy of white LEDs presently available in the marketplace, it is possible to develop a LED based lighting system for commercial refrigerators that is competitive with fluorescent lighting system in terms of energy use. The LED based lighting would provide better lighting than traditional fluorescent lighting.

Key Words: LED, White light LED, Display Lighting, refrigerated display cases, uniformity and preference.

INTRODUCTION

Supermarkets spend nearly half their annual electric cost for refrigeration [1]. Studies have shown that lighting accounts for about 15% of the total energy consumed by commercial refrigerators [2]. Although in this document it is referred to as refrigerators, it includes both refrigerators and freezers. Linear fluorescent lamp is the most commonly used light source in commercial refrigerators. In general linear fluorescent lamp is considered energy efficient in applications because as a light source it has very high luminous efficacy. Rea and Bullough in 2001 showed that high light source efficacy does not mean high application efficacy [3]. Figure 1 shows how the light output of a fluorescent lamp varies as a function of ambient temperature [4]. The light output of a T8 linear fluorescent lamp could drop more than 25% when the ambient temperature reduces from room temperature, 25^{o}C, to refrigeration temperature, 7^{o}C. In the case of freezers the light output could drop even more. In addition the linear fluorescent lamp is typically mounted near the door hinge with poor optics to redirect the light towards the displayed products. As a result only about 60% of the light is directed towards the displayed products and the rest is wasted. Therefore, of the 2800 lumens produced by a typical T8 fluorescent lamp with electronic ballast, only about 1260 lumens is eventually utilized for lighting the products. As a result in the refrigerator lighting application the efficacy of a T8 fluorescent lamp reduces to 40 lumens per watt (lpw), which is much less than the rated source efficacy, 90 lpw. Another drawback of fluorescent lighting is that it does not provide for visually appealing merchandise displays. As shown in Figure 2, the lighting within the display case is very uneven. In most supermarket display cases it is difficult to see the products that are set behind. This is because the products in the front obstruct the light and cast heavy shadows.

Considering the energy consumption issue and the poor lighting in commercial refrigerated display cases, it appears that there is an opportunity for alternate lighting technologies. Surveying the past literature it became evident that very little work has been done in the area of refrigerator lighting. The few that is out there have either looked at using optics with the existing fluorescent systems to get the light distributed deeper into the shelves [5-7] or using remote source illumination systems to better distribute the light [8-9].

Although these techniques may address the poor lighting issue they do not address the energy consumption issue. Over the past few years a new light source technology, light emitting diode (LED), has been rapidly developing. This new light source technology holds promise for energy savings, low maintenance, and better lighting for the target application. Therefore the goal of the study presented in this manuscript was to investigate the use of white light LEDs for commercial refrigerator lighting applications.

Although LEDs were invented during the later part of 1960's it is only after the mid 1990's when the white light LEDs were developed it became a potential light source for general lighting applications [10]. The initial white LEDs came in the standard 5 mm configuration, typically used for indicator lighting applications. Each of these LEDs produced very little flux, less than a lumen, and their efficacy was less than 10 lpw. Furthermore, these 5 mm white LEDs degraded very rapidly and did not hold up to their long life promise [11]. Aggressive product development programs within manufacturing organizations have led to new commercial white LED packages suitable for illumination applications. These illuminator LEDs have larger lumen package, 120 lumens, and high luminous efficacy values, of the order of 24 lpw [12]. Also these devices have much less lumen depreciation compared to the traditional 5 mm-white LEDs [11]. Industry experts are predicting the white light LEDs to reach 50 lpw by 2005 and 100 lpw by 2010 [13]. Hence a distributed LED system can be a good alternative to the existing fluorescent lighting system.

EXPERIMENT

As mentioned earlier the goal of this study was to investigate the use of white light LEDs for commercial refrigerator lighting applications. A laboratory human factors experiment was conducted to assess the preference for the different lighting systems, namely, fluorescent and LED.

Two refrigerated display cases were used in the experiment. Both units had a 4-foot 32-watt 6500K T8 fluorescent lamp. The rated light output for this lamp was 2700 lumens at room temperature, 25° C. Initially one of the refrigerators was turned on and the light output was continuously monitored until the temperature inside the case reached its steady state value (7^{o}C). The light output of the fluorescent lamp dropped 25% when the refrigerator reached its operating temperature (7^{o}C). This corresponds to about 2200 lumens at 7° C for the fluorescent lamp.

The second refrigerator was retrofitted with a prototype LED lighting system that had two types of LEDs. The first was a linear array of 5 mm white LEDs, 2 feet long. The second was a high flux illuminator that had densely packed semiconducting elements. Two of these high flux LEDs were mounted on a flat aluminum plate. The availability dictated the use of these particular LED packages. Figure 5 illustrates the LED lighting system formed using the two types of white LEDs. Two such fixtures were mounted to the bottom side of each shelf, one in the front close to the glass door and the other half way between the glass door and the back wall. The total flux produced by the LED lighting system was about 1200 lumens and the CCT was about 5300 K. The number of LEDs used here was based on attaining 500 lux, which is the recommended vertical illuminance on the face of the displayed products [14].

As shown in Figure 3, both display cases were filled with products typically found in supermarkets. Both display cases were placed side-by-side in a laboratory setting. The two cases visually looked the same under the same lighting. The ambient light level in the surrounding area was kept at 530 lux, which is similar to the illuminance levels in the isles of supermarkets where refrigerated display cases are kept [15]. Illuminance measurements were made at multiple points across the shelves for both display cases, one with the fluorescent lighting system and the other with the LED lighting system. The shelves were partially filled with products while taking illuminance measurements. The point of measurement and the arrangement of products within the shelves were kept the same for both the cases.

Human Factors Experiment

Two refrigerated display cases, one with the traditional 4-ft T8 fluorescent lighting system and the other with the prototype LED lighting system, were placed side-by-side in a laboratory setting. All subjects were screened for deficiencies in color vision prior to starting the experiment. Each subject viewed the two display cases simultaneously and rated their preference on a 1 to 3 scale. The questions asked to the subjects were based on the overall clarity, overall preference and preferences for four individual products placed on the shelves. The four products had different packaging and they were predominantly white, red, blue and green in color. Rating of zero indicated no preference, 1 indicated little preference, and 3 indicated high preference. The time for making the subjective judgments was not restricted, however, most subjects rated their preferences within 1 minute.

The first experimental condition observed and rated by human subjects was the null test, in which both display cases were lit by the fluorescent lighting system and had identical product arrangement and light levels. Figure 8 illustrates the results of the null test. Statistical analysis of this data showed no significant preference for either display case, thus the null condition was verified. In the second experiment subjects rated their preference for the display cases lit by the fluorescent and LED lighting systems; the results are illustrated in Figure 10. Statistical analysis of this data showed significant preference for the display case with the LED lighting system. This indicated that human subjects strongly preferred the display case with the LED lighting system.

Table 1 summarizes the parameters of the two lighting conditions. The lighting in the two display cases, one with the fluorescent and the other with LEDs, had two main differences, namely, the light distribution and CCT. Both these parameters could have had an impact on the subjective rating.

	Fluorescent	**LED**
Lighting system	Single large light source	Many small distributed light sources
Illuminance range	200 to 1200 lux	550 to 650 lux
CCT	6500 K	5300 K
CRI	86	82

Therefore to understand the impact of CCT on subject rating, both display cases were lit by fluorescent lamp. In one of the cases the light was made warm, similar to the CCT of the LED system, using a thin sheet of theatrical gel. The subject rating results for this experiment is illustrated in Figure 9. Statistical analysis of this data showed no significant preference for either display case. This indicated that on an average the human subjects had no preference for the two CCT conditions used here. Therefore form the three experiments it appears that the lighting distribution had the highest impact on peoples' preference.

Table 2 summarizes the light output characteristics and energy use of linear fluorescent and LED lighting systems. The table also shows projected energy use in 2005 and 2010 for LED lighting systems. It appears even at the present time a properly constructed LED lighting system for refrigerators would have similar energy consumption as a fluorescent system. With the proposed advancements in the efficacy of white LEDs one can expect future LED equipped commercial refrigerators to have better lighting with less energy consumption.

Lighting system	**Light output (Lumens at 7°C)**	**System Efficacy (Lumens/watt)**	**Energy use (KWhr)**	**Energy Savings**
32 Watt Fluorescent	2200	68	0.76	
LED in 2002[12]	1200	32	0.91	-18 %
LED in 2010[13]	1200	100	0.28	62 %

Table 2: System efficacy and energy use projections.

SUMMARY

A laboratory human factors experiment was conducted to assess the preference for the different lighting systems, namely, fluorescent and LED. Two refrigerated display cases, one with the traditional fluorescent lighting system and the other with a prototype LED lighting system, were placed side-by-side in a laboratory setting. Illuminance measurements made within the two display cases showed that the lighting was more uniform with the LED system compared to the traditional fluorescent system. Sixteen human subjects participated in this study and rated their preference. The results show that human subjects strongly preferred the display case with the LED lighting. The authors of this manuscript believe a field study would be greatly beneficial to further confirm these results and to understand the relationship between preference and sales. Considering the luminous efficacy of white LEDs presently available in the marketplace, it is possible to develop a LED based lighting system for commercial refrigerators that is competitive with fluorescent lighting system in terms of energy use. The LED based lighting would provide better lighting than traditional fluorescent lighting. Since the LEDs are still in their development phase, at the present time they are much more expensive than fluorescent systems. However, with the proposed advancements one can expect lower cost for future LED lighting systems.

ACKNOWLEDGMENTS

Authors gratefully acknowledge the financial support of the U.S. Department of Energy/Oak Ridge National Laboratories/Foster Miller. We thank Carrier Corporation for donating the refrigerators, B/E Aerospace Inc. for providing the LED arrays, and Opto Technology Inc. for supplying the high flux LEDs.

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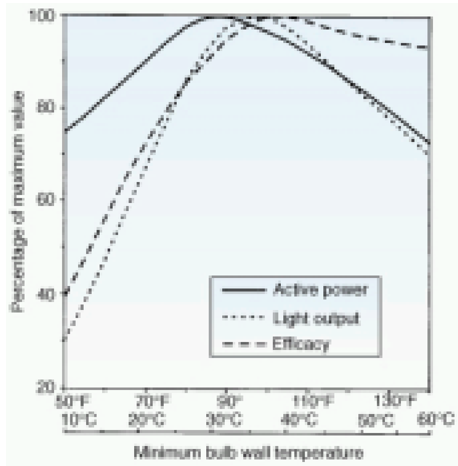
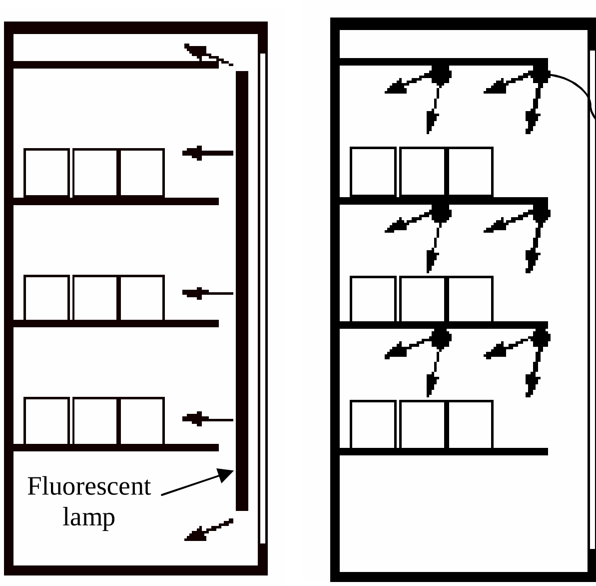


Figure 1: Light output versus ambient temperature curve for a typical fluorescent system [4].

Figure 2: A typical supermarket refrigerator. The picture clearly shows the non uniform light distribution.

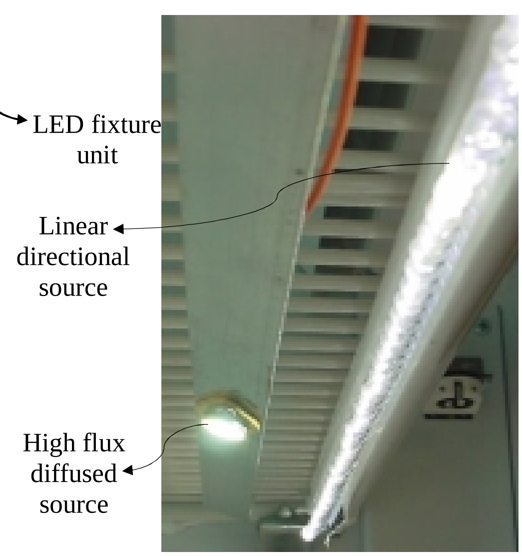
Figure 3: Refrigerated display cases with florescent lighting on the left and LED lighting on the right.



Cross section

Cross section

Figure 4: Schematic showing the light distribution with florescent lighting on the left and LED lighting on the right.



LED fixture unit inside the refrigerator

Figure 5: Arrangement of the LED fixture

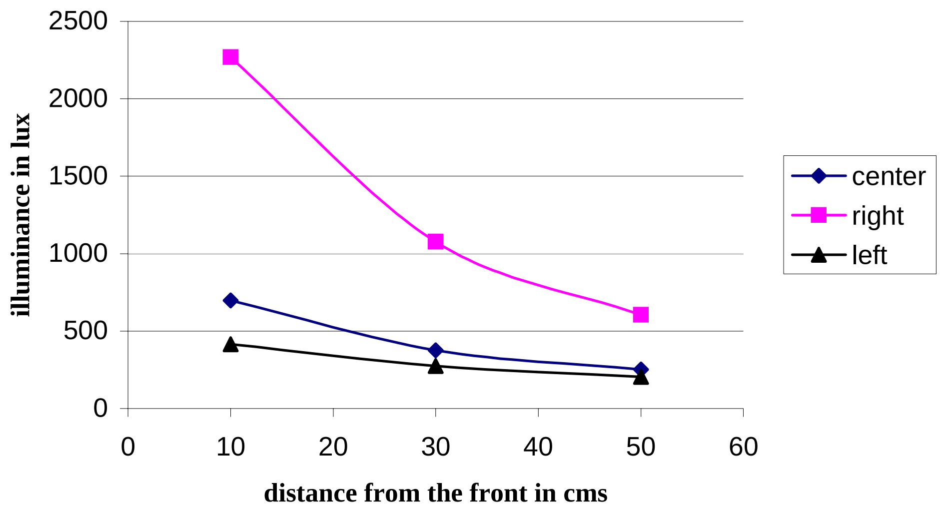


Figure 6: Illuminance with distance for fluorescent lighting

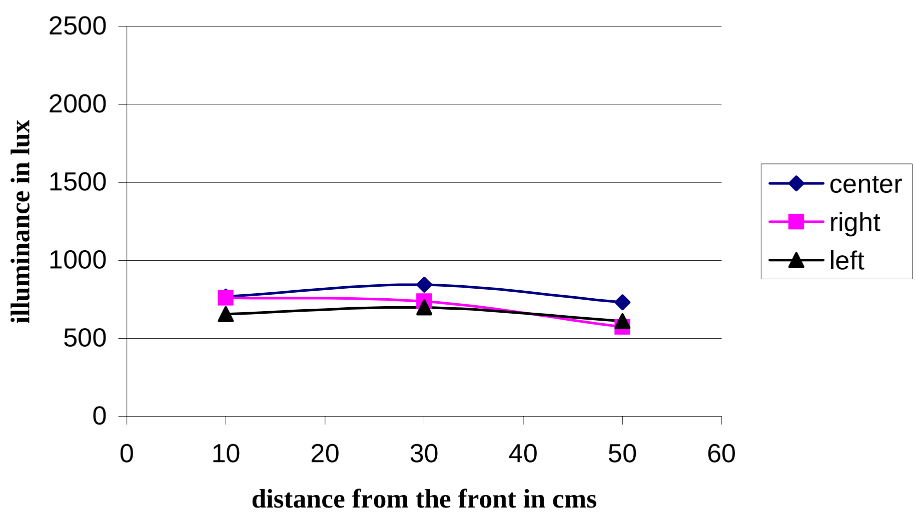


Figure 7: Illuminance with distance for distributed LED lighting

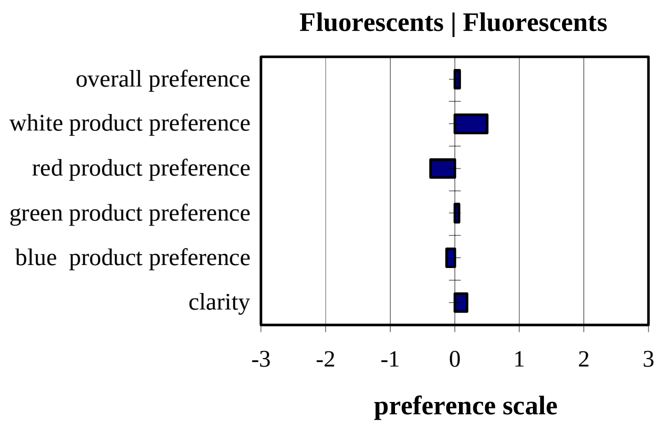


Figure 8: Null test results

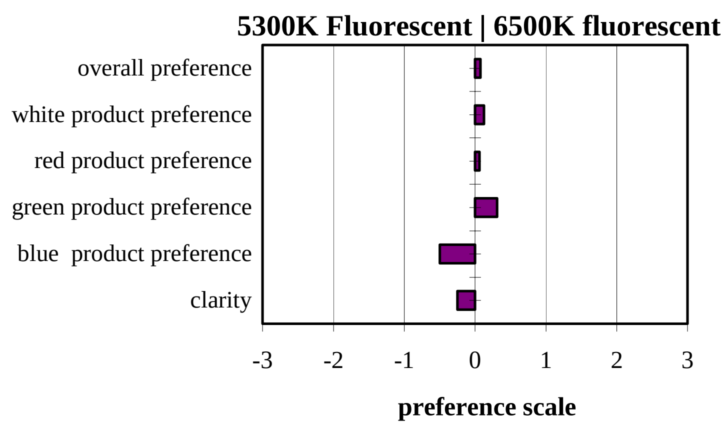


Figure 9: Color temperature test results

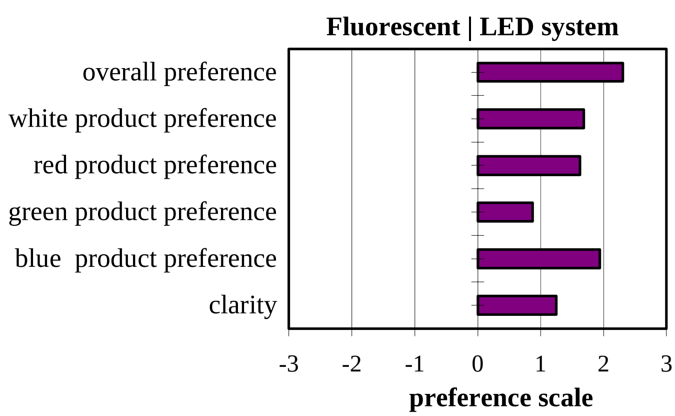


Figure 10: System comparison test results