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Light-Emitting Diode Taxiway Edge Light Photometric Evaluation

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16. Abstract

The Federal Aviation Administration Airport Safety Technology Research and Development Subteam initiated a long-term study of light-emitting diode (LED) taxiway edge lights. The purpose of this study was to determine and evaluate the photometric performance, durability, and reliability of LED taxiway edge light fixtures. LED taxiway edge lights degrade in intensity over time reducing the visibility to pilots. When this occurs, the LED light must be replaced. However, the exact time to replace the fixture to obtain the highest cost effectiveness is unknown.

The goal of this project was to determine how the intensity changes with time and when the lights should be replaced. To do this, 24 LED taxiway edge lights and 6 incandescent lights were installed in a test bed; the latter were used as a baseline for the test.

The test objectives were to (1) determine the electrical characteristics of an airfield circuit with LEDs, (2) evaluate the photometric performance of LED taxiway edge light fixtures compared with incandescent taxiway edge light fixtures, and (3) evaluate the maintenance required over time.

It was determined that the photometric performance of the LED taxiway edge light fixtures was significantly better than the incandescent taxiway edge light fixtures. The average photometric intensity of the incandescent taxiway edge light fixtures deteriorated to 43% in 2 years, while the average photometric intensity of the LED taxiway edge light fixtures deteriorated to 77% in 2 years. The research found that some manufacturer’s electronic circuit boards had difficulty setting to the correct intensity that was selected. LED taxiway edge lights, in addition to having a better deterioration rate than incandescent taxiway edge light fixtures, also have a higher-average photometric intensity after 2 years of operation than the incandescent taxiway edge light fixtures.

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LIST OF ACRONYMS

A	Amps
AC	Advisory Circular
CCR	Constant current regulator
FAA	Federal Aviation Administration
kVA	Kilovolt amp
kW	Kilowatt
LED	Light-emitting diode
MTTF	Mean time to failure
THD	Total harmonic distortion

EXECUTIVE SUMMARY

The Federal Aviation Administration Airport Safety Technology Research and Development Subteam initiated a long-term study of light-emitting diode (LED) taxiway edge lights. The purpose of this study was to determine and evaluate the photometric performance, durability, and reliability of LED taxiway edge light fixtures. LED taxiway edge lights degrade in intensity over time reducing the visibility to pilots. When this occurs, the LED light must be replaced. However, the exact time to replace the fixture to obtain the highest cost effectiveness is unknown.

The goal of this project was to determine how the intensity changes with time and when the lights should be replaced. To do this, 24 LED taxiway edge lights and 6 incandescent lights were installed in a test bed; the latter were used as a baseline for the test. All light fixtures were connected in series to a constant current regulator (CCR). All light fixtures were operated 24 hours a day, 7 days a week.

The test objectives were to (1) determine the electrical characteristics of an airfield circuit with LEDs, (2) evaluate the photometric performance of LED taxiway edge light fixtures compared with incandescent taxiway edge light fixtures, and (3) evaluate the maintenance required over time.

It was determined that the photometric performance of the LED taxiway edge light fixtures was significantly better than the incandescent taxiway edge light fixtures. The average photometric intensity of the incandescent taxiway edge light fixtures deteriorated to 43% in 2 years, while the average photometric intensity of the LED taxiway edge light fixtures deteriorated to 77% in 2 years. The research found that some manufacturer’s electronic circuit boards had difficulty setting to the correct intensity. LED taxiway edge lights, in addition to having a better deterioration rate than incandescent taxiway edge light fixtures, also have a higher-average photometric intensity after 2 years of operation than the incandescent taxiway edge light fixtures.

INTRODUCTION

PURPOSE.

The Federal Aviation Administration (FAA) Airport Safety Technology Research and Development Subteam initiated a long-term study of light-emitting diode (LED) taxiway edge lights. The purpose of this study was to determine and evaluate the photometric performance, durability, and reliability of LED taxiway edge light fixtures. The tests were conducted over a 2-year period, between July 2005 and September 2007. The data collected were compared to the performance of the baseline incandescent taxiway edge light fixtures.

BACKGROUND.

Numerous airports throughout the United States have installed LED taxiway edge lights under federally funded Airport Improvement Programs. The goals were to:

- Reduce maintenance cost. The lifetime of an LED lamp is significantly longer than the lamp currently used in incandescent, halogen, or quartz fixtures. LED taxiway edge light fixtures may provide significant maintenance cost savings if the mean time to failure (MTTF) of the LED fixture is significantly longer than the incandescent fixture. This is because (in terms of labor and materials) LED fixtures are expensive to replace.

- Reduce power consumption. LED taxiway edge lights consume significantly less power than incandescent taxiway edge light fixtures. This may result in a reduction of general power consumption which, in turn, may result in significant cost savings.

- Improve photometric longevity. The installation of LED taxiway edge lights would be advantageous if the photometric intensity of the LED taxiway edge light fixtures deteriorated more slowly than the incandescent taxiway edge light fixtures.

The initial cost of installing LED taxiway edge lights was higher than for incandescent taxiway edge light fixtures. Additionally, when an LED taxiway edge light fixture goes out, the entire fixture must be replaced, unlike incandescent taxiway edge light fixtures, which only require the lamp to be replaced. Thus, not only is the initial cost of installing the LED taxiway edge light fixtures higher, its replacement cost is higher as well. In order for the LED taxiway edge light fixtures to be more cost-effective, they must outperform the incandescent taxiway edge light fixtures by a significant margin.

OBJECTIVES.

The objectives of this study were to

- determine the electrical characteristics of an airfield circuit with LEDs.

- test and evaluate the photometric performance of the LED taxiway edge light fixtures compared to the baseline incandescent taxiway edge light fixtures.

- evaluate the LED taxiway edge light fixture maintenance requirements.

RELATED DOCUMENTS.

- Advisory Circular (AC) 150/5340-30D, "Design and Installation Details for Airport Visual Aids," September 30, 2008.

- AC 150/5345-46C, "Specification for Runway and Taxiway Edge Light Fixtures," September 26, 2006.

- AC 150/5345-10F, "Specification for Constant Current Regulators and Regulator Monitors," June 24, 2005.

- FAA LED Engineering Brief 67B, "Light Sources Other Than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures," AAS-100, March 2007.

EVALUATION APPROACH

A field test bed was installed on a paved pad at the Atlantic City International Airport. Figure 1 shows the test bed configuration used for the LED taxiway edge light fixtures. There were 30 taxiway edge light fixtures spaced evenly in four rows with each row composed of fixtures produced by four manufacturers. Twenty-four LED taxiway edge light fixtures were installed in the field test bed, and six incandescent taxiway edge light fixtures were installed to provide a baseline for the performance of the LED taxiway edge light fixtures.

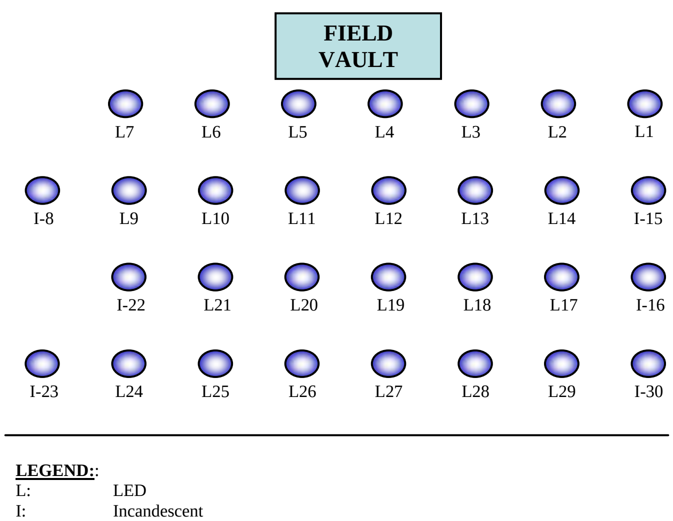


Figure 1. Schematic of Test Bed Used for LED Taxiway Edge Light Fixtures

Four manufacturers supplied LED taxiway edge light fixtures. One manufacturer's set of fixtures completely failed and was removed from the test. The manufacturers are referred to as manufacturer 1, 2, and 3. Each manufacturer supplied eight LED taxiway edge light fixtures. Six incandescent taxiway edge light fixtures were also tested for comparison.

The results of the LED taxiway edge light fixture measurements were compared against one another and the incandescent fixture baseline measurements. These measurements included photometric output, chromaticity coordinates, and electrical characteristics of the circuit.

The light fixtures were connected in series to a 5-step constant current regulator (CCR). The LED taxiway edge light fixtures were operated 24 hours a day, 7 days a week. For 6 days, the CCR was set to step 3 at a current of 4.1 amps (A). For 8 hours of 1 day, the LED taxiway edge light was set to step 5, at a current of 6.6 A. Table 1 shows the CCR data. Each CCR accepted a 240-volt input and could sustain a load of 10 kilowatts (kW).

Table 1. Constant Current Regulators Data

CCR Number	CCR Type	Number of Steps
1	Ferroresonance	5
2	Thyristor	5
3	Thyristor	5
4	Thyristor	5
5	Thyristor	5
6	Thyristor	3

TEST PROCEDURES.

PHOTOMETRIC MEASUREMENTS OF LIGHT FIXTURES. The photometric performance of the light fixtures was tested and evaluated directly after the fixtures were installed. These tests were performed to ensure that the fixtures were installed correctly and to determine the performance of the light fixtures with respect to the appropriate FAA AC and/or Engineering Brief.

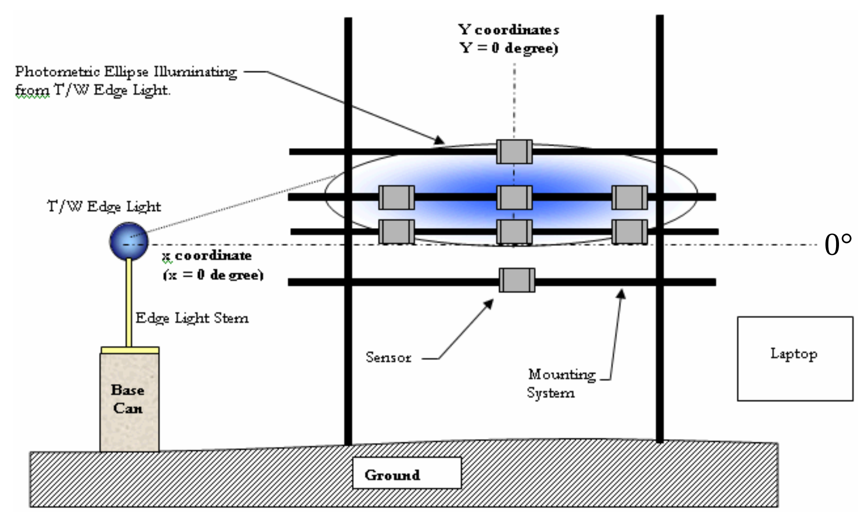
As discussed above, one of the major factors in analyzing the photometric performance of the LED taxiway edge light fixtures was to compare the photometric intensity deterioration of the LED taxiway edge light fixtures with the incandescent taxiway edge light fixtures. The photometric tests were performed 1 month after the verification test (August 2005), 6 months after installation (February 2006), and 2 years after installation (September 2007).

This section details the test procedure used to obtain the photometric measurements of the LED taxiway edge light fixtures. It is understood that the test procedure detailed herein is not equivalent to certification, indoor laboratory test techniques, or procedures because of the many variables that exist in a real-world environment. For example, laboratory tests are performed indoors in a dark room under optimal environmental and circuit conditions. Field tests are performed with ambient light and other variable light sources that can affect the results.

Additionally, in laboratory tests, the LED taxiway edge light fixture is tested by itself and usually energized by a variable power supply. In the field, the fixture is connected to other fixtures and energized via a CCR. The CCR introduces harmonic distortion to the circuit and, thus, affects the performance of the light fixture. The test technique described herein has been proven to furnish good indications of compliance with FAA requirements and with manufacturer's specifications for fixture performance. This system was not developed to challenge the manufacturer's laboratory results, but rather, to test the fixtures under real-life field conditions.

To evaluate the photometric performance of the taxiway edge light fixtures, test equipment that simultaneously measures the photometric intensity from the taxiway edge light at several horizontal and vertical angles was used. Figure 2 shows a schematic of the test setup. New, calibrated Konica-Minolta CL-100 sensors specifically designed for outdoor calibration and measurement of photometric intensity were used. The estimated accuracy of the sensor was approximately 5 to 7 percent. The margin of error for the entire system was no greater than 10 percent. This included distance measurement and data conversion. The sensors were color-corrected and connected to a computer for data acquisition. The sensor mounting system was placed in front of each fixture at a given distance, and the photometric intensity was then measured. It should be noted that the photometric intensity of the fixture was measured at one set of angles directly in front of the fixture. In field tests, it would not be feasible to measure the intensity of the light fixture for 360°.

FAA AC 150/5345-46D states that the minimum photometric intensity of a taxiway edge light fixture shall be no less than 2 candelas. This requirement is true for all angles between 0° and 6° vertically. The sensor array was mounted on an aluminum frame that allowed full sensor adjustment and placement flexibility. As shown in figure 2, the zero horizontal degree is the plane parallel to the ground, cutting the fixture in half.



T/W = Taxiway

Figure 2. Schematic of Field Photometric Sensor Array and Mounting Apparatus

ELECTRICAL CHARACTERISTICS OF THE CIRCUIT. The electrical characteristics of the CCRs were tested to ensure that the CCRs were providing sufficient output current to the light fixtures and that there were no serious deficiencies in the installation of the CCRs. This was important because it determines if any of the deficiencies in LED fixture performances were due to the fixture itself or were a result of deficiencies in the circuit that energized the LED fixture.

The electrical data was obtained by connecting two T-line connectors across the home-run cable, i.e., versatile multi-conductor cable, feeding the first light fixture. Each end of the T-line connector was connected via alligator clips to either a Fluke 43B Amprobe Harmonic Analyzer Scope or a Tektronix TDS 2000 series oscilloscope. The voltage used to perform the calculations was measured by taking the differential voltage between the two connectors, or across the two conductors, feeding each light fixture. The current was obtained by using an Amprobe around one leg of the home-run cable. The margin of error for this technique was within 5% and 10% of the true value, depending on the amount of harmonic distortion in the circuit.

This test setup was used to collect the following data points:

- Input current to the regulator (Iin)
- Input voltage to the regulator (Vin)
- Output current from the regulator (Iout)
- Output voltage from the regulator (Vout)
- Total Power (kilovolt amperes (kVA))
- Reactive power (kVAR)
- Resistive power (kW)
- Power factor (PF)
- Total harmonic distortion (THD) of current
- THD of voltage

This data was used to provide important information regarding the performance of the circuit energizing the light fixture. This information was used to understand whether or not the deficiencies were attributed to the light fixture or to the circuit, or both. It was important to define if the deficiencies found were associated with the fixture itself or with the system as a whole.

MAINTENANCE REQUIREMENTS. The LED taxiway edge light fixtures were operated for a period of 18 months. The work required to maintain these fixtures was tracked, recorded, and analyzed to understand the specific efforts involved to keep the LED taxiway edge light fixtures operational.

RESULTS

ELECTRICAL PERFORMANCE.

ELECTRICAL PERFORMANCE OF THE CCR. Efficiency was calculated as the output load divided by the input load. Ideally, the efficiency would be equal to 1. This would mean the entire input load being drawn from the power distribution system by the CCR was also being used by the fixtures, i.e., no losses.

The average efficiency of the six CCRs on step 1 was approximately 5.62%. It is widely accepted in the industry that ferroresonant CCRs adjust their input load to match the output load. However, at step 1, even the ferroresonant CCR did not have a good efficiency measuring at 6.39%. At step 2, the average efficiency of the CCRs was approximately 8.43%. At step 3, the average efficiency was 18.10%. Based on this, it was recommended to energize the LED taxiway edge light fixtures on the ferroresonant CCR for the remainder of the test period (CCR 1), because it was the most efficient unit.

Table 2 summarizes the efficiency versus the intensity settings over the three test periods (August 2005, February 2006, and September 2007). Note that the efficiency at the lower intensity settings is significantly lower than the higher intensity settings. The CCR should be better matched for the lower intensity settings to ensure optimal power efficiency of the CCR. A detailed list of results from the test periods are shown in appendix A in tables A-1, A-2, and A-3 for the test periods 2005, 2006, and 2007, respectively.

Table 2. Efficiency Versus Intensity Setting Between August 2005 and September 2007

Intensity Setting	Efficiency (9/2007) (%)	Efficiency (2/2006) (%)	Efficiency (8/2005) (%)
1	19	6	7
2	40	16	18
3	77	63	67

Table 3 shows the efficiency of the ferroresonnance CCR for three intensity steps.

Table 3. Average Input Load, Output Load, and Efficiency Versus Intensity Setting

Intensity Setting	Input Load (kVA)	Output Load (kVA)	Efficiency (%)
1	4.41	0.47	10.8
2	2.72	0.67	24.8
3	1.40	0.96	69.0

kVA = Kilovolt amps

As shown in table 3, the input load of the circuit using the ferroresonant CCR decreased as the intensity setting was increased. That is, the power consumption of the circuit was higher on the lower intensity settings than on the higher intensity settings. This was attributed to the resistive load present on the circuit of less than 1 kW, which was very low with respect to the size of the regulator (10 kW). At lower intensity settings, the circuit had a difficult time regulating the current to the fixture and consumed more power than necessary. In actual airport designs, the regulator size would be comparable to the load. Nevertheless, since the taxiway edge lights are usually energized at the lower intensity steps, the higher consumption at these lower intensity settings reduces the power savings typical for LED taxiway edge lights. This phenomenon held true for all three test periods.

HARMONIC DISTORTION. At step 2, all CCRs had voltage or current harmonic distortion greater than 10%. Generally, it is recommended to maintain the level of harmonic distortion of the system below 10%. High harmonic distortion on the circuit results in a deterioration of the lifespan of certain electronic components, such as the electrical mechanism that regulates the photometric output of an LED taxiway edge light fixture. A decrease of the lifespan of the electronic mechanism may result in an increase in the amount of deficient fixtures, which will result in increased maintenance costs.

Table 4 summarizes the input harmonic distortion versus the intensity settings over the three test periods (August 2005, February 2006, and September 2007) for the ferroresonant CCR that had the lowest THD figures. The harmonic distortion of the input current during September 2007 is significantly higher than the input current harmonic distortions measured in February 2006 and August 2005. The higher harmonic distortion measured during September 2007 was attributed to one of the manufacturer's fixtures that did not remain functional for the entire test period. Subsequent investigation revealed that the cause of the deficient fixture was a deficient electronic circuit board that regulates the current to the LED driver. The electronic circuit board typically introduces an inductive load to the circuit, which increases the harmonic distortion.

Table 4. Total Harmonic Distortion Versus Intensity Setting Between August 2005 and September 2007

Intensity Setting	Input Current THD (9/2007)	Input Current THD (2/2006)	Input Current THD (8/2005)
1	30.5	9.5	9.3
2	50.8	12.7	11.5
3	85.6	27.2	32.3

PHOTOMETRIC PERFORMANCE.

The photometric test data on the taxiway edge lights was compared to the following criteria:

- Minimum Candela Requirement. FAA AC 150/5345-46D states that the minimum candela output for a taxiway edge light shall be 2 candelas at the highest intensity setting. All the LED taxiway edge light fixtures passed this requirement.

- Maximum Candela Requirement. Engineering Brief 67B specifies that the maximum candela output for LED taxiway edge light fixtures at any one angle at the highest intensity setting cannot be greater than three times the minimum candela output at any one angle. The data is shown in appendix B.

A ratio of the photometric data was calculated for each light fixture at each angle over the three test periods. The goal of this test was to measure the deterioration of the photometric performance of the fixtures over time and to determine if the LED taxiway edge lights perform better than the incandescent taxiway edge light fixtures.

A detailed list of the results from the photometric measurements taken between August 2005 and September 2007 is given in tables B-1 through B-8 of appendix B.

INTENSITY DEGRADATION. Table 5 compares the average photometric data for each light fixture between August 2005 and September 2007. Note that the photometric intensity for the LED taxiway edge lights measured in 2007 was 77% when the fixture was new in 2005. The photometric intensity for the incandescent taxiway edge light fixtures measured in 2007 was 43% when the fixture was new in 2005. That is, the LED taxiway edge light fixtures' light intensity deterioration rate over time was significantly less than the incandescent taxiway edge light fixtures.

Table 5. Average Photometric Intensity and Deterioration Over Time

Type	Manufacturer	Average Intensity (8/2005)	Average Intensity (2/2006)	Average Intensity (9/2007)	Ratio of Intensities (2/2006) (8/2005)	Ratio of Intensities (9/2007) (8/2005)
LED	1	6.33	6.11	5.17	0.97	0.82
LED	1	7.17	6.22	5.63	0.87	0.79
LED	1	8.21	7.79	6.33	0.95	0.77
LED	1	6.78	6.21	5.30	0.92	0.78
LED	1	5.77	4.97	4.28	0.86	0.74
LED	1	7.30	6.58	5.65	0.90	0.77
LED	1	7.85	7.29	6.08	0.93	0.77
LED	1	6.76	6.13	5.78	0.91	0.86
LED	2	3.48	3.11	2.80	0.89	0.86
LED	2	5.14	4.97	4.03	0.97	0.78
LED	2	4.41	3.87	3.57	0.88	0.81
LED	2	4.60	3.90	2.93	0.85	0.64
LED	2	4.94	4.33	3.40	0.88	0.69
LED	2	6.80	5.74	5.37	0.84	0.79
LED	2	6.56	5.25	4.75	0.80	0.72

Table 5. Average Photometric Intensity and Deterioration Over Time (Continued)

Type	Manufacturer	Average Intensity (8/2005)	Average Intensity (2/2006)	Average Intensity (9/2007)	Ratio of Intensities (2/2006) (8/2005)	Ratio of Intensities (9/2007) (8/2005)
LED	2	5.57	4.55	4.13	0.82	0.74
LED	3	11.18	9.31	---	0.83	---
LED	3	12.24	10.07	---	0.82	---
LED	3	9.46	6.15	---	0.65	---
LED	3	10.61	5.98	---	0.56	---
LED	3	13.23	5.63	---	0.43	---
LED	3	12.21	9.20	---	0.75	---
LED	3	9.61	5.35	---	0.56	---
LED	3	10.53	3.87	---	0.37	---
INCAN	---	9.95	6.98	3.91	0.70	0.39
INCAN	---	6.56	3.40	2.55	0.52	0.39
INCAN	---	5.12	4.05	2.72	0.79	0.53
INCAN	---	9.50	4.94	3.86	0.52	0.41
INCAN	---	5.06	3.37	2.30	0.67	0.45
INCAN	---	7.97	6.62	---	0.83	---

INCAN = Incandescent

Note: Between February 2006 and September 2007, one of the manufacturer's fixtures became deficient and was excluded from the photometric evaluation.

AVERAGE PHOTOMETRIC INTENSITY. The average photometric intensity for each type of light fixture compared over the test period is provided in table 5. Note that while the incandescent taxiway edge light fixtures started with a photometric intensity higher than the LED, the LED taxiway edge light fixtures had an average photometric intensity greater than the incandescent lights after the test period due to the deterioration rate.

CHROMATICITY. There are specific FAA requirements for the color of LED taxiway edge light fixtures. Figure 3 shows the Commission Internationale de l'Eclairage (CIE) Laboratories color requirements for each type of fixture detailed in MIL-C-25050A. Each colored wedge corresponds to the specific color requirement for that type of fixture. The blue wedge corresponds to the chromaticity requirements for blue taxiway edge lights. A detailed listing of the numerical values of the 1931 CIE Chromaticity coordinates for the light fixtures tested appears in table C-1 of appendix C.

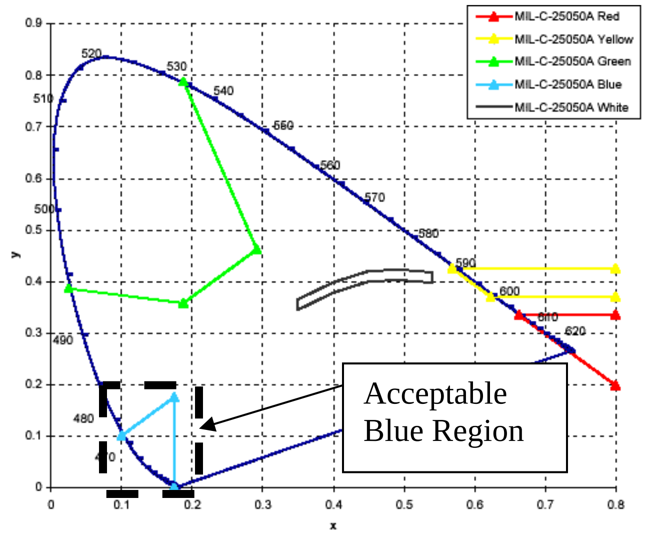


Figure 3. Chromaticity Requirements for Taxiway Edge Lights

Figure 4 shows that, in general, the chromaticity of the LED taxiway edge light fixtures over time remained more consistent than the incandescent taxiway edge light fixtures. Additionally, the LED taxiway edge light fixtures had a more consistent chromaticity between each fixture within the type of manufacturer. Fixtures that have similar chromaticity provide a clearer, more homogeneous color to the pilot. The LED taxiway edge light fixtures provide a more consistent visual cue than the incandescent taxiway edge light fixtures.

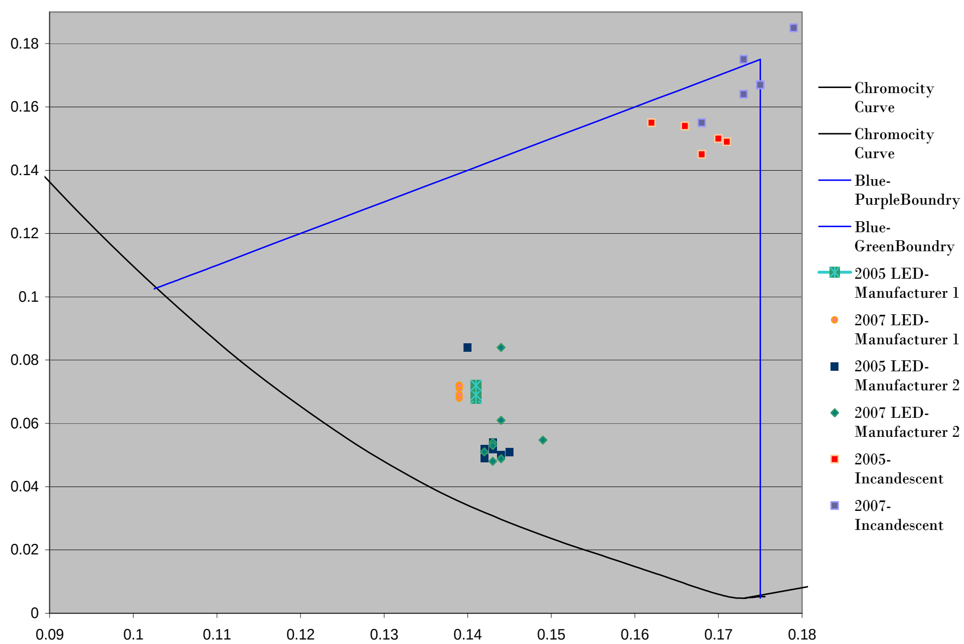


Figure 4. Chromaticity Data Collected From Taxiway Edge Light Fixtures

PHOTOMETRIC PERFORMANCE VERSUS OUTPUT CURRENT. Engineering Brief 67B provides criteria for photometric output across the three CCR output current steps. Specifically, it states that the measured minimum cannot be more than three times the minimum required intensity. Additionally, it specifies that the ratio between the photometric intensity at step 3 and step 2, as well as the ratio of the photometric intensity at steps 3 and 1, need to be within a specific requirement, as shown in table 6. Since the output current of CCR 1 for the three steps is 6.58, 5.12, and 4.10 A, respectively, the photometric output at the multiple steps are compared to the intensity ratios detailed in rows one, three, and five of table 6, respectively.

Table 6. Intensity and Brightness Ratios for Various Output Current Steps

Category	Output Current (Amps)	Minimum Brightness (%)	Maximum Brightness (%)
1	6.6	100.00	N/A
2	5.5	30.00	51.00
3	5.2	25.00	45.00
4	4.8	10.00	19.00
5	4.1	5.00	10.00
6	3.4	1.20	3.00
7	2.8	0.15	1.65

N/A = Not available

A detailed analysis of the photometric intensity versus the various output current steps was performed during the first site visit. This test was repeated for three select fixtures to determine if the current stepping changed significantly over time.

The photometric intensity ratios versus the input current steps are summarized in table 7.

Table 7. Brightness Ratios for Various Output Current Steps

Step	Output Current (Amps)	Minimum Brightness (%)	Maximum Brightness (%)	Fixture A Brightness Relative to Maximum (%)	Fixture B Brightness Relative to Maximum (%)	Fixture C Brightness Relative to Maximum (%)
5	6.6	100.00	N/A	---	---	---
4	5.2	25.00	45.00	~23	~28	~18
3	4.1	5.00	10.00	~10	~12	~4.8

N/A = Not available at highest step setting

Fixture A was an incandescent fixture. Fixtures B and C were LED taxiway edge light fixtures. It is worth noting that, in general, the LED taxiway edge light fixtures (plus or minus 2% error of measurement) met the brightness ratios.

While the fixtures generally passed this requirement, there were several light fixtures that exhibited a drop in the photometric intensity at step 2, bringing it to step 1 levels. This was caused by these light fixtures misinterpreting the current setting of step 2 of the CCR for step 1 current setting levels. This may have had an adverse affect on the performance of the fixtures. This phenomenon also existed during the initial test and may be caused by the LED taxiway edge light electronic mechanism working to read the current of the primary series. Additional tests are required to determine the significance of this effect.

MAINTENANCE PERFORMANCE.

Between August 2005 and September 2007, all the LED taxiway edge light fixtures remained energized and did not require replacement, with the exception of the deficient light fixtures from a single manufacturer. Because the manufacturer's light fixtures failed in mass, they were removed from the maintenance performance analysis.

Between August 2005 and September 2007, one incandescent light fixture (fixture 30) became deficient.

At the time of this writing, it is too early to provide statistically significant data to determine if the LED taxiway edge light fixtures were more reliable than the incandescent taxiway edge light fixtures. Additional study is required to determine this result.

SUMMARY

PHOTOMETRIC PERFORMANCE OF LED TAXIWAY EDGE LIGHT FIXTURES.

The LED taxiway edge light fixtures performed significantly better than the incandescent taxiway edge light fixtures in photometric tests. While the photometric intensity of the incandescent taxiway edge light fixtures deteriorated to 43% in 2007 compared to measurements taken in 2005, the photometric intensity of the LED taxiway edge light fixtures deteriorated to only 77% in 2007 compared to 2005. Figure 5 shows the average photometric performance over time for each type of light fixture. The LED taxiway edge lights, in addition to having a better deterioration rate than incandescent taxiway edge light fixtures, also have a higher-average photometric intensity after 2 years of operation than the incandescent taxiway edge light fixtures.

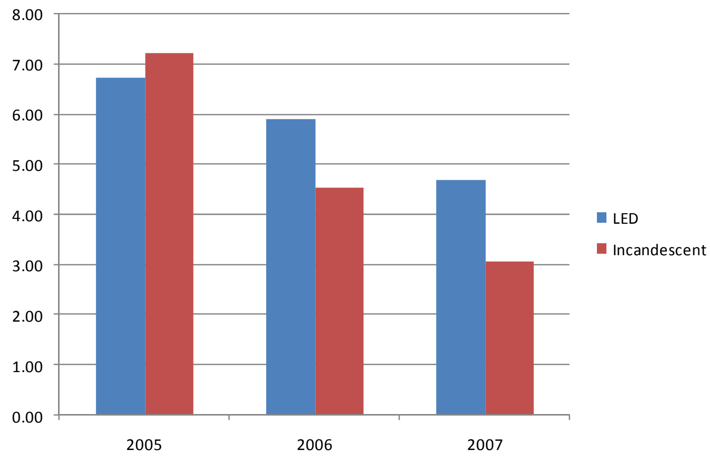


Figure 5. Average Photometric Intensity for Each Type of Light Fixture Versus Time

CHROMATICITY OF LED TAXIWAY EDGE LIGHT FIXTURES.

There are specific FAA requirements for the color or chromaticity of the blue LED taxiway edge light fixtures. All the LED taxiway edge light fixtures met the FAA chromaticity requirements. In addition, the LED taxiway edge light fixtures showed better consistency within one manufacturer's fixture than incandescent taxiway edge light fixtures. Refer to figure 4 for the chromaticity diagram and specific information for incandescent and LED taxiway edge light fixtures. Moreover, the light fixture chromaticity for the LED taxiway edge light fixtures remained consistent from one year to the next. Similar chromaticity provides a clearer and more homogeneous signal due to the condensed spectral content and greater saturation of the LED taxiway edge light fixture-emitted light chromaticity.

FIXTURE RELIABILITY.

Failures were confined to fixtures supplied by a single manufacturer. All failed LED taxiway edge light fixtures installed at the test bed became deficient between 2006 and 2007. Prior to that date, the electronic circuit board that regulates the current intensity for these fixtures experienced problems. Since the fixtures failed in mass, they were removed from the fixture reliability analysis. Therefore, only one incandescent taxiway edge light fixture failed between 2005 and 2007. However, this sample size was not sufficient to clearly state the MTTF for each light fixture.

INPUT LOAD.

The input load, measured in kW, is the amount of power the CCR consumes from the power distribution system. In general, the circuit should consume more power as the intensity setting increases from step 1 to step 3. However, the input load of the circuit was shown to decrease as the intensity setting increased. That is, the power consumption of the circuit was higher on the lower intensity settings than at higher intensity settings. This behavior was attributed to the lower intensity settings of the CCR, where the CCR had a more difficult time regulating the current to the fixture and consumed more power than necessary. Since the taxiway edge lights were usually energized at the lower intensity steps, the higher consumption at these lower intensity settings reduced the power savings typical for LED taxiway edge lights. This phenomenon held true for all three test periods.

CONCLUSIONS AND RECOMMENDATIONS

The following are conclusions and recommendations for this effort.

- Electrical characteristics of airfield circuits with light-emitting diodes (LED)

    - A recommendation should be added to Engineering Brief 67B stating that the LED taxiway edge light fixtures be installed on a ferroresonant constant current regulator (CCR) if practicable. This should improve the overall efficiency of LED taxiway edge light fixtures as well as reduce harmonic distortion, thereby improving the overall performance of the fixtures.

    - It is recommended that designers be made aware of CCR performance under low loads, which may occur when retrofitting LED taxiway edge light fixtures into an existing circuit. Input load may be higher at the lower intensity settings unless the CCR is sized and tapped appropriately for the known low-load condition. CCR manufacturers have started to produce low-load CCRs whose resistive load capacity is on or about 2 kW. A broad range of CCRs should be considered based on airport design recommendations and calculations of load presented in Advisory Circular 150/5340-30D, Appendix 6, which provides guidance on this issue.

- Photometric performance of the LED taxiway edge light fixtures compared with the baseline incandescent taxiway edge light fixtures.

    - The LED taxiway edge light fixtures performed significantly better than the incandescent taxiway edge light fixtures. While the photometric intensity of the incandescent taxiway edge light fixtures deteriorated to 43% of the intensity in 2 years, the photometric intensity of the LED taxiway edge light fixtures deteriorated to 77% of the intensity in 2 years. LED taxiway edge light fixtures, in addition to having a better deterioration rate than incandescent taxiway edge light fixtures, also had a higher-average photometric intensity after 2 years of operation than the incandescent taxiway edge light fixtures.

- Recommendations of the maintenance requirements over time

    - The mean time to failure (MTTF) of any product is usually measured by its weakest component. One of the major advantages of LED taxiway edge light fixtures is the inherent longevity of the LED light engine. However, unlike incandescent taxiway edge light fixtures, the LED taxiway edge light fixtures are equipped with an internal electronic circuit that regulates the output current. The data herein suggests that the electronic mechanism regulating the photometric output may be the system's weakest component and may make the LED fixture's MTTF actually shorter than an incandescent fixture. Additionally, there is evidence that suggests the electronic circuit board might have difficulty performing intensity setting regulation over time. Therefore, it is recommended that the following requirements be added to Engineering Brief 67B:

- The manufacturer of the LED taxiway edge light fixture shall provide in the fixture cut-sheets the MTTF data for the electronic mechanism regulating the photometric output across the multiple output current steps.

- The manufacturer of the LED taxiway edge light fixture shall perform additional production tests, as proposed in the following wording:

  <u>3.2 Production Test at Different Output Currents</u>. Alternative light sources must be energized for a minimum of 4 hours, at all intensity steps. The fixtures shall be continuously stepped across all the output current steps in equal time increments for the 4-hour period. The manufacturer shall verify that no failures exist in the alternative light source circuitry and that the photometric output is changing in accordance with the output current. Any failure of the alternative light source after burn-in will be cause for rejection.

APPENDIX A—ELECTRICAL DATA

Table A-1. Electrical Characteristics of Taxiway Edge Light Circuit Measured in August 2005 on a Ferroresonant Constant Current Regulator

Step	Input to CCR Data					Output to CCR Data					Calculations		
	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Input Load (KVA)	Output Load (KVA)	Efficiency
1	232.4	18.5	0.25	1.3	9.3	72.6	4.10	0.75	19.9	6.9	4.30	0.30	6.9%
2	232.9	11.1	0.39	1.4	11.5	89.6	5.19	0.79	19.2	18.1	2.59	0.47	18.0%
3	233.7	4.7	0.92	1.3	32.3	112.2	6.58	0.92	6.2	4.3	1.11	0.74	66.6%

Table A-2. Electrical Characteristics of Taxiway Edge Light Circuit Measured in February 2006 on a Ferroresonant Constant Current Regulator

Step	Input to CCR Data					Output to CCR Data					Calculations		
	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Input Load (KVA)	Output Load (KVA)	Efficiency
1	239.6	19.4	0.24	1.7	9.5	73.1	4.12	0.75	21.1	12.7	4.64	0.30	6.5%
2	239.7	11.9	0.37	1.6	12.7	90.2	5.22	0.80	17.5	4.7	2.85	0.47	16.5%
3	240.4	4.9	0.91	1.5	27.2	113.0	6.61	0.91	6.4	2.9	1.19	0.75	63.0%

Table A-3. Electrical Characteristics of Taxiway Edge Light Circuit Measured in September 2007 on a Ferroresonant Constant Current Regulator

Step	Input to CCR Data					Output to CCR Data					Calculations		
	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Voltage (V)	Current (A)	True Power Factor	Voltage %THD	Current %THD	Input Load (KVA)	Output Load (KVA)	Efficiency
1	238.2	18.0	0.16	1.1	30.5	198.8	4.11	0.26	55.2	22.9	4.29	0.82	19.1%
2	239.4	11.4	0.27	1.3	50.8	209.3	5.20	0.30	50.9	19.4	2.73	1.09	39.8%
3	239.4	7.9	0.52	1.2	85.6	222.7	6.59	0.39	17.7	49.6	1.90	1.47	77.2%

APPENDIX B—PHOTOMETRIC DATA

Table B-1. Data for Light Fixtures 1 Through 15 Measured in August 2005

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	L-1 (cd)	L-2 (cd)	L-3 (cd)	L-4 (cd)	L-5 (cd)	L-6 (cd)	L-7 (cd)	I-8 (cd)	L-9 (cd)	L-10 (cd)	L-11 (cd)	L-12 (cd)	L-13 (cd)	L-14 (cd)	I-15 (cd)
-3	+1	5.50	5.88	6.92	6.71	3.98	7.33	7.08	13.66	5.90	2.15	3.41	2.75	2.33	3.03	13.09
0	+1	5.18	6.05	7.05	6.48	3.75	7.52	7.23	16.08	5.98	2.13	3.03	2.78	2.23	2.77	9.47
3	+1	4.75	5.93	7.52	6.03	3.68	7.06	7.50	12.38	6.06	2.38	2.83	2.65	2.18	2.40	9.47
-3	+3	7.57	7.85	9.10	7.67	7.08	7.88	8.73	7.80	7.57	4.55	7.08	5.53	6.53	7.03	4.14
0	+3	7.38	8.10	9.03	7.48	7.12	7.79	8.63	9.29	7.50	4.55	6.24	5.60	6.45	6.43	3.48
3	+3	6.95	7.90	9.05	7.02	7.08	7.18	8.48	7.28	7.28	4.38	5.72	5.25	6.35	5.95	3.38
0	+6	6.98	8.45	8.77	6.05	7.73	6.35	7.30	3.14	7.01	4.23	7.68	6.30	6.10	6.95	2.87
	Summary Data															
	AVG.	6.33	7.17	8.21	6.78	5.77	7.30	7.85	9.95	6.76	3.48	5.14	4.41	4.60	4.94	6.56
	MIN VALUE	4.75	5.88	6.92	6.03	3.68	6.35	7.08	3.14	5.90	2.13	2.83	2.65	2.18	2.40	2.87
	MAX VALUE	7.57	8.45	9.10	7.67	7.73	7.88	8.73	16.08	7.57	4.55	7.68	6.30	6.53	7.03	13.09
	MIN > 2 CD	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	MAX < 3*MIN	Pass	Pass	Pass	Pass	Pass	Pass	Pass	N/A	Pass	Pass	Pass	Pass	Pass	Pass	N/A

Table B-2. Photometric Data for Light Fixtures 16 Through 30 Measured in August 2005

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	I-16 (cd)	L-17 (cd)	L-18 (cd)	L-19 (cd)	L-20 (cd)	L-21 (cd)	I-22 (cd)	I-23 (cd)	L-24 (cd)	L-25 (cd)	L-26 (cd)	L-27 (cd)	L-28 (cd)	L-29 (cd)	I-30 (cd)
-3	+1	6.98	5.15	4.75	4.58	14.95	13.50	15.40	6.25	15.29	11.15	18.80	11.04	7.15	5.88	10.22
0	+1	7.69	5.43	4.78	4.83	14.43	13.69	12.73	8.65	13.65	10.00	20.89	10.07	6.98	5.87	7.59
3	+1	9.46	6.78	4.60	4.28	12.66	13.19	17.46	9.70	12.70	9.05	22.90	8.70	6.52	5.65	9.72
-3	+3	2.68	6.58	8.80	7.08	10.55	12.46	5.64	2.43	6.56	14.26	7.48	17.47	13.50	15.35	8.21
0	+3	2.90	6.90	8.33	7.08	10.76	12.79	5.61	2.83	7.01	13.04	8.56	17.22	13.70	14.90	7.50
3	+3	3.39	8.20	7.94	6.25	9.80	13.43	7.15	2.75	7.16	11.75	9.23	15.03	13.05	13.88	9.81
0	+6	2.73	8.55	6.73	4.90	5.08	6.64	2.50	2.82	3.87	5.02	4.74	5.93	6.39	12.17	2.73
	Summary Data															
	AVG.	5.12	6.80	6.56	5.57	11.18	12.24	9.50	5.06	9.46	10.61	13.23	12.21	9.61	10.53	7.97
	MIN VALUE	2.68	5.15	4.60	4.28	5.08	6.64	2.50	2.43	3.87	5.02	4.74	5.93	6.39	5.65	2.73
	MAX VALUE	9.46	8.55	8.80	7.08	14.95	13.69	17.46	9.70	15.29	14.26	22.90	17.47	13.70	15.35	10.22
	MIN > 2 CD	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	MAX < 3*MIN	N/A	Pass	Pass	Pass	Pass	Pass	N/A	N/A	Fail	Pass	Fail	Pass	Pass	Pass	N/A

Table B-3. Photometric Data for Light Fixtures 1 Through 15 Measured in February 2006

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	L-1 (cd)	L-2 (cd)	L-3 (cd)	L-4 (cd)	L-5 (cd)	L-6 (cd)	L-7 (cd)	I-8 (cd)	L-9 (cd)	L-10 (cd)	L-11 (cd)	L-12 (cd)	L-13 (cd)	L-14 (cd)	I-15 (cd)
-3	+1	5.32	5.70	6.54	6.07	3.55	7.21	6.58	11.10	5.50	2.09	3.04	2.49	2.21	2.84	5.01
0	+1	5.12	5.27	6.01	6.08	3.40	7.26	6.61	12.20	5.37	2.10	2.84	2.36	2.12	2.34	4.35
3	+1	4.68	5.15	6.74	5.75	3.62	6.85	6.85	10.85	5.17	2.34	2.30	2.18	2.01	2.08	4.27
-3	+3	5.99	6.55	8.02	6.86	5.75	5.65	7.83	5.65	6.37	3.49	6.10	5.33	5.22	6.54	2.93
0	+3	6.33	7.29	8.60	6.80	6.25	6.16	7.63	2.52	6.89	3.74	6.18	4.81	5.12	5.45	2.72
3	+3	6.18	7.02	8.31	6.03	6.15	6.16	7.84	3.98	6.77	3.67	5.31	4.91	5.64	5.65	2.45
0	+6	6.27	6.59	8.41	5.85	6.10	6.30	7.19	2.54	6.84	3.55	6.92	5.02	4.98	5.44	2.06
Summary Data																
	AVG.	6.11	6.22	7.79	6.21	4.97	6.58	7.29	6.98	6.13	3.11	4.97	3.87	3.90	4.33	3.40
	MIN VALUE	5.77	5.15	6.74	5.75	3.40	5.65	6.58	2.52	5.17	2.10	2.30	2.18	2.01	2.08	2.06
	MAX VALUE	6.33	7.29	8.60	6.86	6.25	7.34	7.84	12.20	6.89	3.74	6.92	5.33	5.64	6.54	5.01
	MIN > 2 CD	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	MAX < 3*MIN	Pass	Pass	Pass	Pass	Pass	Pass	Pass	N/A	Pass	Pass	Pass	Pass	Pass	Pass	N/A

Table B-4. Photometric Data for Light Fixtures 16 Through 30 Measured in February 2006

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	I-16 (cd)	L-17 (cd)	L-18 (cd)	L-19 (cd)	L-20 (cd)	L-21 (cd)	I-22 (cd)	I-23 (cd)	L-24 (cd)	L-25 (cd)	L-26 (cd)	L-27 (cd)	L-28 (cd)	L-29 (cd)	I-30 (cd)
-3	+1	5.75	4.62	4.39	3.17	14.58	9.56	9.50	5.11	9.29	6.63	6.08	8.21	3.45	2.62	9.12
0	+1	5.54	4.67	4.35	3.06	13.87	9.64	8.11	5.41	9.48	7.16	5.99	8.40	3.47	2.47	6.21
3	+1	7.88	5.80	4.29	2.89	11.45	9.39	6.64	4.43	9.13	7.50	5.53	8.14	3.33	2.49	8.25
-3	+3	2.11	6.54	5.42	5.89	5.99	11.65	2.41	2.12	3.46	5.17	5.69	10.64	6.57	4.55	7.12
0	+3	2.05	6.40	6.05	6.35	7.20	11.87	2.48	2.10	4.03	5.63	6.02	11.77	7.23	5.14	6.57
3	+3	2.86	5.88	6.05	5.98	7.56	12.85	3.12	2.33	4.20	5.07	5.66	11.67	7.05	5.06	7.21
0	+6	2.19	6.24	6.22	4.49	4.54	5.54	2.35	2.12	3.45	4.69	4.45	5.59	6.35	4.74	1.86
Summary Data																
	AVG.	4.05	5.74	5.25	4.55	9.31	10.07	4.94	3.37	6.15	5.98	5.63	9.20	5.35	3.87	6.62
	MIN VALUE	2.05	4.62	4.29	2.89	4.54	5.54	2.35	2.10	3.45	4.69	4.45	5.59	3.33	2.47	1.86
	MAX VALUE	7.88	6.54	6.22	6.35	14.58	12.85	9.50	5.41	9.48	7.50	6.08	11.77	7.23	5.14	9.12
	MIN > 2 CD	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail
	MAX < 3*MIN	N/A	Pass	Pass	Pass	Fail	Pass	N/A	N/A	Pass	Pass	Pass	Pass	Pass	Pass	N/A

Table B-5. Photometric Data for Light Fixtures 1 Through 15 Measured in September 2007

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	L-1 (cd)	L-2 (cd)	L-3 (cd)	L-4 (cd)	L-5 (cd)	L-6 (cd)	L-7 (cd)	I-8 (cd)	L-9 (cd)	L-10 (cd)	L-11 (cd)	L-12 (cd)	L-13 (cd)	L-14 (cd)	I-15 (cd)
-3	+1	5.07	4.95	6.32	5.94	2.16	6.12	5.62	5.54	4.83	2.05	2.59	2.05	2.05	2.25	4.01
0	+1	4.82	4.87	5.86	5.42	3.34	5.54	5.87	6.20	5.19	2.02	2.65	2.21	1.98	2.12	3.25
3	+1	4.29	4.93	5.90	4.25	2.64	5.22	6.23	6.40	4.89	2.21	2.09	2.01	1.84	1.89	3.34
-3	+3	5.38	5.64	6.01	5.64	4.64	5.22	6.48	3.64	5.80	3.21	6.01	4.91	2.99	4.86	2.12
0	+3	6.01	5.95	6.95	5.54	5.51	5.89	6.41	1.91	6.74	3.54	5.03	4.71	3.91	3.83	1.98
3	+3	5.40	6.87	6.56	5.41	5.76	5.64	5.98	2.09	6.54	3.33	4.88	4.54	3.89	4.21	1.45
0	+6	5.18	6.21	6.73	4.87	5.94	5.90	5.94	1.60	6.45	3.21	4.96	4.59	3.88	4.67	1.68
	Summary Data															
	AVG.	5.17	5.63	6.33	5.30	4.28	5.65	6.08	3.91	5.78	2.80	4.03	3.57	2.93	3.40	2.55
	MIN VALUE	4.29	4.87	5.86	4.25	2.16	5.22	5.62	1.60	4.83	2.02	2.09	2.01	1.84	1.89	1.45
	MAX VALUE	6.01	6.87	6.95	5.94	5.94	6.12	6.48	6.40	6.74	3.54	6.01	4.91	3.91	4.86	4.01
	MIN > 2 CD	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Pass	Pass	Pass	Pass	Fail	Fail	Fail
	MAX < 3*MIN	Pass	Pass	Pass	Pass	Pass	Pass	Pass	N/A	Pass	Pass	Pass	Pass	Pass	Pass	N/A

Table B-6. Photometric Data for Light Fixtures 16 Through 30 Measured in September 2007

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	I-16 (cd)	L-17 (cd)	L-18 (cd)	L-19 (cd)	L-20 (cd)	L-21 (cd)	I-22 (cd)	I-23 (cd)	L-24 (cd)	L-25 (cd)	L-26 (cd)	L-27 (cd)	L-28 (cd)	L-29 (cd)	I-30 (cd)
-3	+1	4.32	4.56	3.69	2.66	---	---	7.10	3.74	---	---	---	---	---	---	DEF.
0	+1	4.51	4.36	4.09	2.87	---	---	6.12	3.64	---	---	---	---	---	---	DEF.
3	+1	3.95	5.64	3.94	2.74	---	---	5.84	2.98	---	---	---	---	---	---	DEF.
-3	+3	1.84	6.21	5.12	4.90	---	---	2.10	1.54	---	---	---	---	---	---	DEF.
0	+3	1.65	6.24	5.46	5.90	---	---	2.05	1.65	---	---	---	---	---	---	DEF.
3	+3	1.34	4.98	5.51	5.50	---	---	1.84	1.34	---	---	---	---	---	---	DEF.
0	+6	1.45	5.59	5.43	4.32	---	---	1.98	1.21	---	---	---	---	---	---	DEF.
	Summary Data															
	AVG.	2.72	5.37	4.75	4.13	---	---	3.86	2.30	---	---	---	---	---	---	DEF
	MIN VALUE	1.34	4.36	3.69	2.66	---	---	1.84	1.21	---	---	---	---	---	---	0.00
	MAX VALUE	4.51	6.24	5.51	5.90	---	---	7.10	3.74	---	---	---	---	---	---	0.00
	MIN > 2 CD	Fail	Pass	Pass	Pass	---	---	Fail	Fail	---	---	---	---	---	---	Fail
	MAX < 3*MIN	N/A	Pass	Pass	Pass	---	---	N/A	N/A	---	---	---	---	---	---	N/A

Table B-7. Ratio of Photometric Output Measured (September 2007/August 2005) for Fixtures 1 Through 15

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	L-1 (cd)	L-2 (cd)	L-3 (cd)	L-4 (cd)	L-5 (cd)	L-6 (cd)	L-7 (cd)	I-8 (cd)	L-9 (cd)	L-10 (cd)	L-11 (cd)	L-12 (cd)	L-13 (cd)	L-14 (cd)	I-15 (cd)
-3	+1	0.92	0.84	0.91	0.89	0.54	0.84	0.79	0.41	0.82	0.95	0.76	0.75	0.88	0.74	0.31
0	+1	0.93	0.80	0.83	0.84	0.89	0.74	0.81	0.39	0.87	0.95	0.87	0.79	0.89	0.76	0.34
3	+1	0.90	0.83	0.79	0.71	0.72	0.74	0.83	0.52	0.81	0.93	0.74	0.76	0.85	0.79	0.35
-3	+3	0.71	0.72	0.66	0.74	0.66	0.66	0.74	0.47	0.77	0.70	0.85	0.89	0.46	0.69	0.51
0	+3	0.81	0.73	0.77	0.74	0.77	0.76	0.74	0.21	0.90	0.78	0.81	0.84	0.61	0.60	0.57
3	+3	0.78	0.87	0.72	0.77	0.81	0.79	0.71	0.29	0.90	0.76	0.85	0.86	0.61	0.71	0.43
0	+6	0.74	0.73	0.77	0.81	0.77	0.93	0.81	0.51	0.92	0.76	0.65	0.73	0.64	0.67	0.59
	Summary Data															
	AVG.	0.83	0.79	0.78	0.78	0.74	0.78	0.78	0.40	0.85	0.83	0.79	0.80	0.70	0.71	0.44

Table B-8. Ratio of Photometric Output Measured (September 2007/August 2005) for Fixtures 16 Through 30

		Fixture Photometric Data														
Horizontal Angle (Degrees)	Vertical Angle (Degrees)	I-16 (cd)	L-17 (cd)	L-18 (cd)	L-19 (cd)	L-20 (cd)	L-21 (cd)	I-22 (cd)	I-23 (cd)	L-24 (cd)	L-25 (cd)	L-26 (cd)	L-27 (cd)	L-28 (cd)	L-29 (cd)	I-30 (cd)
-3	+1	0.62	0.89	0.78	0.58	---	---	0.46	0.60	---	---	---	---	---	---	N/A
0	+1	0.59	0.80	0.86	0.59	---	---	0.48	0.42	---	---	---	---	---	---	N/A
3	+1	0.42	0.83	0.86	0.64	---	---	0.33	0.31	---	---	---	---	---	---	N/A
-3	+3	0.69	0.94	0.58	0.69	---	---	0.37	0.63	---	---	---	---	---	---	N/A
0	+3	0.57	0.90	0.66	0.83	---	---	0.37	0.58	---	---	---	---	---	---	N/A
3	+3	0.39	0.61	0.69	0.88	---	---	0.26	0.49	---	---	---	---	---	---	N/A
0	+6	0.53	0.65	0.81	0.88	---	---	0.79	0.43	---	---	---	---	---	---	N/A
	Summary Data															
	AVG.	0.54	0.80	0.75	0.73	---	---	0.44	0.49	---	---	---	---	---	---	N/A

APPENDIX C—CHROMATICITY DATA

Table C-1. Chromaticity Measurements Measured in 2005 and 2007

Fixture Number	Manufacturing	2005 x Coordinates	2005 y Coordinates	2007 x Coordinates	2007 y Coordinates	Difference x Coordinates	Difference y Coordinates
L1	1	0.141	0.070	0.139	0.071	0.002	0.001
L2	1	0.141	0.070	0.139	0.072	0.002	0.002
L3	1	0.141	0.068	0.139	0.068	0.002	0.000
L4	1	0.141	0.071	0.139	0.072	0.002	0.001
L5	1	0.141	0.071	0.139	0.069	0.002	0.002
L6	1	0.141	0.069	0.139	0.072	0.002	0.003
L7	1	0.141	0.072	0.139	0.072	0.002	0.000
I8	Incandescent	0.171	0.149	0.168	0.155	0.003	0.006
L9	1	0.141	0.072	0.139	0.072	0.002	0.000
L10	2	0.142	0.049	0.144	0.048	0.002	0.001
L11	2	0.143	0.054	0.143	0.053	0.000	0.001
L12	2	0.144	0.050	0.144	0.051	0.000	0.001
L13	2	0.144	0.050	0.143	0.0488	0.001	0.001
L14	2	0.145	0.051	0.143	0.0547	0.002	0.004
I15	Incandescent	0.170	0.150	0.173	0.164	0.003	0.014
I16	Incandescent	0.168	0.145	0.175	0.167	0.007	0.022
L17	2	0.140	0.084	0.142	0.084	0.002	0.000
L18	2	0.143	0.052	0.144	0.054	0.001	0.002
L19	2	0.142	0.052	0.149	0.061	0.007	0.009
L20	3	0.145	0.044	---	---	---	---
L21	3	0.144	0.051	---	---	---	---
I22	Incandescent	0.162	0.155	0.173	0.175	0.011	0.020
I23	Incandescent	0.166	0.154	0.179	0.185	0.013	0.031
L24	3	0.144	0.045	---	---	---	---
L25	3	0.145	0.045	---	---	---	---
L26	3	0.144	0.046	---	---	---	---
L27	3	0.145	0.044	---	---	---	---
L28	3	0.144	0.048	---	---	---	---
L29	3	0.144	0.048	---	---	---	---
L30	Incandescent	0.146	0.045	Off	Off	N/A	N/A