Pacific Gas and Electric Company

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Emerging Technologies Program

Application Assessment Report # 0701

LED Low-Bay Garage Lighting
South San Francisco, California

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Preface

Energy Solutions provided monitoring, data collection, and data analysis services for an LED Low-Bay Garage Lighting Demonstration project under contract to the Emerging Technologies Program of Pacific Gas and Electric Company. The project replaced low-bay metal halide fixtures of 175 lamp-watts with new low-bay LED Fixtures from Lighting Science Group Corporation of nominal 85 watts and 6,000K color temperature.

Acknowledgements

This project was funded by the Emerging Technologies Program of Pacific Gas and Electric Company. Energy Solutions would like to gratefully acknowledge the direction and assistance of Pacific Gas and Electric Company, the Lighting Science Group Corporation, and Boston Properties for their participation and support of this project.

Executive Summary

The LED Low-Bay Garage Lighting Demonstration project studied the applicability of low-bay LED fixtures in a parking-garage installation. Low-bay metal halide (MH) fixtures were replaced with new low-bay LED fixtures in a parking garage located in South San Francisco. Light quality and intensity, and electrical power measurements were taken. Economic costs were then estimated, and qualitative satisfaction was determined from interviews with the property managers.

The average illuminance level was slightly increased after the installation of the LED fixtures. The maximum uniformity ratio (a ratio of the brightest spot to the dimmest) decreased, suggesting a more uniform light spread. However, the average illuminance near the darkest wall decreased which the property managers identified as a potential concern.

TABLE ES-I: ILLUMINANCE LEVELS

Measured Circuits	Average Illuminance (fc)	Max Illuminance (fc)	Min Illuminance (fc)	Average Near- Wall Illuminance (fc)
Pre-Installation	5.0	22	.22	1.6
Post-Installation	5.6	28	.38	1

An average LED fixture drew 87.5 watts, 115 watts less than an average MH fixture (202 watts). In order to provide satisfactory illumination and uniformity for this particular application, two LED fixtures were required to replace one MH fixture. This resulted in final savings of 27 watts per MH fixture replaced.

TABLE ES-II: POTENTIAL DEMAND AND ENERGY SAVINGS

Fixture Type	Average Power (W)	Power Savings (W)	Annual Energy Savings (kWh)
Metal Halide Fixture	202.0	-	-
2 LED Fixtures	174.8	27.25	238.71
Full Garage (1250 LED Fixtures)	109,242	17,031	149,194

The LED fixtures were assumed to have zero maintenance cost over the course of their expected useful life (50,000 hours, or 5.7 years with continuous operation). When maintenance savings were combined with energy savings, the resulting total annual savings were approximately $70, over one year of operation per MH fixture replaced. In a new construction setting, where these fixtures are installed in place of MH fixtures, the total incremental cost is estimated at $689 per MH fixture replaced. This corresponds to a simple payback period for the LED fixtures of roughly 10 years. In a retrofit setting, the incremental cost is $832, corresponding to a simple payback period of roughly 12 years.

Table ES-III: Estimated Simple Payback

	Metal Halide (per Fixture)	LED (2 Fixtures)	LED Full Garage (1250 Fixtures)
Annual Savings	-	$68.40	$42,749
Incremental Cost (New Construction)	-	$688.83	$430,519
Simple Payback (Years, New Construction)	-	10.07	10.07
Incremental Cost (Retrofit)	-	$831.93	$519,956
Simple Payback (Years, Retrofit)	-	12.16	12.16

For this particular case-study, these payback periods are longer than the 50,000-hour expected useful life of the LED fixtures. To achieve a simple payback of less than 5.7 years under current conditions, the cost of the LED fixture needs to decline to approximately $150 in a retrofit scenario or $225 in a new construction scenario.

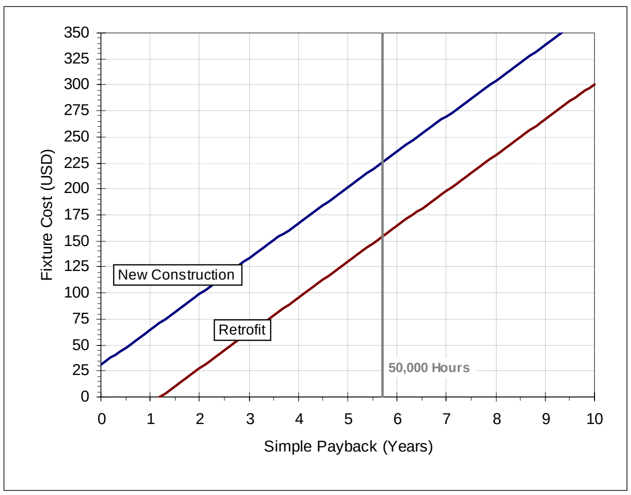

Figure ES-1: Estimated LED Fixture Payback

Although the results of this assessment indicate a relatively long payback period for LED low-bay garage lighting under current conditions, LED technology is advancing at such a rate as to make these fixtures more economical in the future. Predictions from the manufacturer indicate that within 2 to 3 years, a low-bay LED fixture may be available that will provide a payback on the order of 3 years. This is supported by current trends in LED pricing declines and advancements in LED performance. In addition, utility incentives could help in the short-term to make the fixtures cost-effective for customers, and thus encourage energy savings.

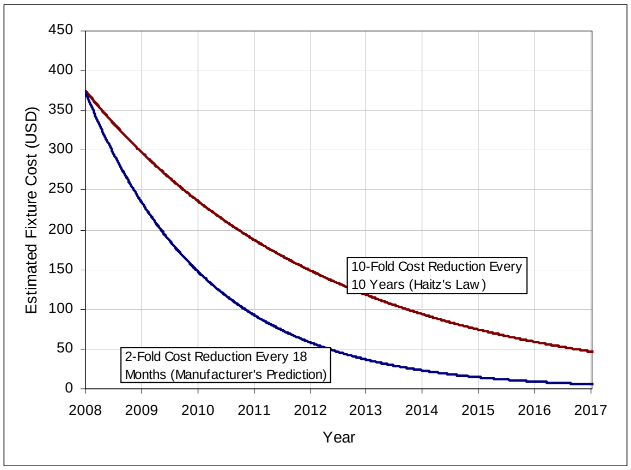

FIGURE ES-2: ESTIMATED FUTURE LED FIXTURE COST[1]

[1] See 'Economic Performance' section

Project Background

Project Overview

The LED Low-Bay Garage Lighting Demonstration project studied the applicability of low-bay light-emitting-diodes (LED) fixtures in a parking-garage installation. Low-bay metal halide (MH) fixtures were replaced with new low-bay LED fixtures in a parking garage located in South San Francisco. The applicability of the technology was determined by light output, energy and power usage, economic factors, and qualitative satisfaction. The feasibility of potential future LED fixtures in the same application was also assessed.

The LED Low-Bay Garage Lighting Demonstration project was conducted as part of the Emerging Technologies Program of Pacific Gas and Electric Company. The Emerging Technologies program "is an information-only program that seeks to accelerate the introduction of innovative energy efficient technologies, applications and analytical tools that are not widely adopted in California…. [The] information includes verified energy savings and demand reductions, market potential and market barriers, incremental cost, and the technology's life expectancy."[2]

Technological Overview

At the time of this assessment, LEDs are showing promise in outdoor settings due to the general directionality of outdoor installations and less stringent requirements for color consistency. One such application is low-bay fixtures, such as those found in parking garages. Currently, parking garages are normally illuminated with MH, high-pressure sodium, or linear fluorescent lights. LEDs have the potential for long life, reduced maintenance, high color rendition, reduced fixture size and operating cost, and lower energy usage than other technologies. Currently however, the initial cost of LEDs is much higher than alternative light sources.

Information from the US Department of Energy suggests the technology is changing at a rapid pace. Overall, the performance of LED fixtures seems to be advancing at a rate of approximately 35% annually.[3] Therefore, readers of this assessment are encouraged to note that while this particular demonstration may not have met the host customer's requirements for further investment, advances in this field are occurring so quickly that this or another manufacturer may have a product under development that will soon meet the host customer's performance and investment criteria.

Market Overview

A report by Navigant Consulting in 2002 estimates that lighting makes up approximately 22% of IOU kWh sales on a national scale. The study further estimates that lighting for parking accounts

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[2] Pacific Gas and Electric Company (2006). Program Descriptions, Market Integrated Demand Side Management, Emerging Technologies. *PGE2011*

[3] Based on lumen output per LED. See 'Economic Performance' section

for roughly 4% of kWh sales for lighting.[4] Using kWh sales figures from a 2006 study,[5] the total consumption in PG&E's service territory for lighting is calculated to be on the order of 21,500 GWh in 2002, with a resulting 860 GWh for parking. Although these figures are not exclusively for parking lot lights, and do not include parking structures that are integrated into other buildings, they give an idea of the significant potential that exists for savings.

[4] Navigant Consulting, Inc. (2002). "US Lighting Market Characterization, Volume I".

[5] Itron Inc., et al (2006). "California Energy Efficiency Potential Study".

Project Objectives

The objectives of the project were to examine electrical, lighting, and economic performance of low-bay LED fixtures as compared to MH fixtures in a parking garage application. The potential electrical demand and energy savings were measured in terms of instantaneous wattage and estimated annual kWh usage. Quantitative lighting performance was determined by average illuminance, uniformity, and correlated color temperature (in Kelvin). Qualitative lighting performance was judged by the satisfaction and concerns of interested parties. Finally, economic performance was calculated as simple-payback for substitution in a new construction setting or replacement in a retrofit setting, accounting for fixture life-span, maintenance costs, and electrical costs.

Methodology

Host site information

The facility selected for this demonstration was a private parking garage in South San Francisco, California. The facility contains approximately 625 existing MH fixtures, and is open to the exterior and therefore has ambient daylighting for parts of the structure. The test area within the structure was chosen to minimize ambient daylighting.

Monitoring Plan

The Monitoring Plan called for initial, pre-installation and post-installation field visits to the parking structure.

The initial field visit was intended for familiarization with the parking facility, and to gather general base-line information.

The pre-installation field visit occurred after initial field visit and prior to installation of the LED fixtures. It was intended to document the existing condition of the lighting system. The MH lamps had been replaced as a part of routine maintenance approximately 3.5 months (roughly 2,500 hours of continuous operation) prior to the pre-installation visit. This represents 25% of the 10,000 hour rated life of the lamps, corresponding to an estimated 25% lumen depreciation.[6] All light measurements were taken after dusk. The measurements were taken on a 10'x10' grid for the entire test area (the area in which LED fixtures were installed), and on a 2'x2' grid for 10' out from a single fixture. For measurement locations and geometry, see Appendix A. Measurements were taken consistent with Appendix B. The specific outcomes of the pre-installation field visit are listed below:

1. Pre-installation on-site photographs, Appendix C.
2. Pre-installation power, illumination and correlated color temperature readings, Appendix D.

The post-installation field visit was intended to document the condition of the lighting system after the installation of the LED fixtures. It occurred approximately 2 weeks after the equipment installation, and after the lamps had at least 100 burn hours. Burn hours were based on the confirmed installation date and the average daily burn times, and measurements were taken at the same locations where they were taken for the pre-installation visit. Specific outcomes of the post-installation field are:

1. Post-installation on-site photographs, Appendix C.
2. Post-installation power, illumination and correlated color temperature readings, Appendix D.

The following monitoring equipment used in the execution of this Monitoring Plan was obtained from the Pacific Energy Center:

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[6] Osram Sylvania (2003). "Product Information Bulletin, COMPACT METALARC and COMPACT SUPER METALARC". *HID032R3*

Light Output
Li-Cor Light Meter, Model: LI-250 with LI-COR Photometric Sensor, Model: li-210sa

Correlated Color Temperature Meter
Konica Minolta Chroma Meter, Model CL-200

Power Meter
Summit Technology Power Sight 3000 Meter (PS3000) kit with Clamp on Voltage Probes, and Clamp-on Current Probes, Model: HA10

Project Results

Electrical Demand and Energy Savings

Power measurements were taken over 2 visits. The data result from short-term averages of two complete circuits in the test garage, one originally with 13 MH fixtures, and one circuit originally with 14 'emergency' MH fixtures. The 'emergency' fixtures contained, in addition to the standard lamps, a quartz bulb for illumination only when the primary lamp was out. This did not affect the electrical demand of the fixtures. Eight LED fixtures were installed in each circuit, replacing 4 MH fixtures. This 2-for-1 replacement was necessary to provide satisfactory illumination levels and lighting distribution.

Annual energy and savings figures were estimated based on replacing 625 MH fixtures, corresponding to a garage with 5 floors and 125 fixtures per floor. This would correspond to 1250 replacement LED fixtures.

The LED fixtures used an average of 87.4 watts per fixture, slightly higher than the rated 85 watts. The average installed MH fixture used 202 watts. As a result, the demand savings per replaced fixture was approximately 27.25 watts, or 17 kW for 625 fixtures.

The garage fixtures are on continuously, amounting to annual savings of 239 kWh per replacement, or 149,194 kWh for 625 fixtures.

Table I: Measured Power Demand and Estimated Energy Usage

Measured Circuits	Metal Halide Fixtures	LED Fixtures	Total Power (W)	Annual Energy (kWh)
Pre-Installation	27	0	5,455	47,786
Post-Installation	19	16	5,237	45,876

Table II: Potential Demand and Energy Savings

Fixture Type	Average Power (W)	Power Savings (W)	Annual Energy Savings (kWh)
Metal Halide Fixture	202.0	-	-
2 LED Fixtures	174.8	27.25	238.71
1250 LED Fixtures	109,242	17,031	149,194

Lighting Performance

ILLUMINANCE

Illuminance levels were measured on a 10-foot grid for the entire test area, and on a 2-foot grid for a single fixture. The average measured illuminance for the MH installation was 5.0 foot-candles, with the LED fixtures increasing this value to 5.6 foot-candles. The maximum and minimum levels measured for the MHs were 22 and .22 foot-candles, respectively. The ratio of these two values is known as the uniformity ratio, and in this case is 100:1. The Illuminating Engineering Society of North America recommends a minimum light level of 1 foot-candle and a maximum uniformity ratio for parking garages of 10:1. For the LED fixtures, these values were 28 and .38 foot-candles, with a slightly improved uniformity ratio of approximately 78:1.

Due to stated customer concerns regarding lighting levels along walls,[7] an average near-wall illuminance was calculated. This was done using measurements of south-wall lighting levels as representative. In addition, a "fixture-to-wall" ratio was calculated as the average amount of light along the strip directly under the southern fixtures divided by the average near-wall lighting level. For the MH fixtures, the average near-wall illuminance was 1.6 foot-candle, with a fixture-to-wall ratio of 5.1:1. For the LED fixtures, these values were 1 foot-candle and 15:1.

TABLE III: ILLUMINANCE LEVELS

Measured Circuits	Average Illuminance (fc)	Max Illuminance (fc)	Min Illuminance (fc)	Uniformity Ratio	Average Near-Wall Illuminance (fc)	Fixture-to-Wall Ratio
Pre-Installation	5.0	22	.22	100:1	1.6	5.1:1
Post-Installation	5.6	28	.38	78:1	1	15:1

Due to the layout of the test area, measurements were not necessarily taken directly under fixtures.[8] Consequently, qualitative results were obtained by assuming a constant light output from all fixtures, with a varying amount of background light. These results, shown below, give an idea of the light levels throughout the entire test areas.

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[7] See 'Customer Acceptance' section.

[8] See Appendix A

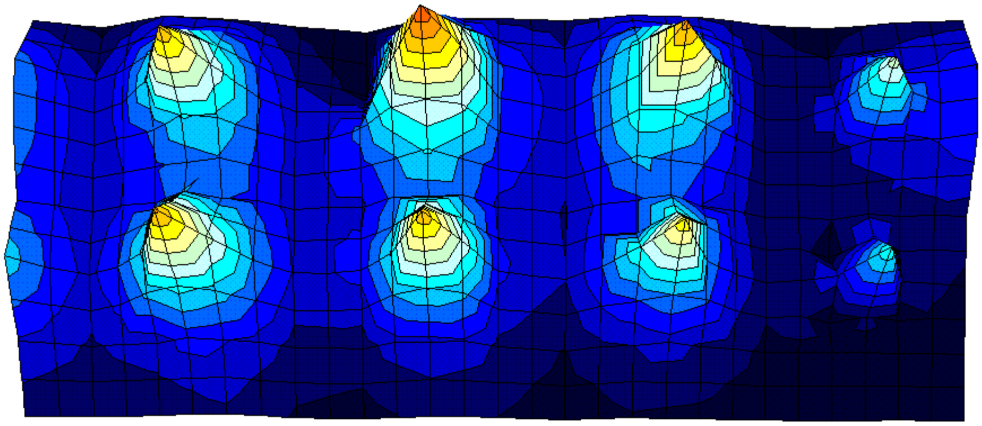


FIGURE 1: PRE-INSTALLATION LIGHTING DEPICTION

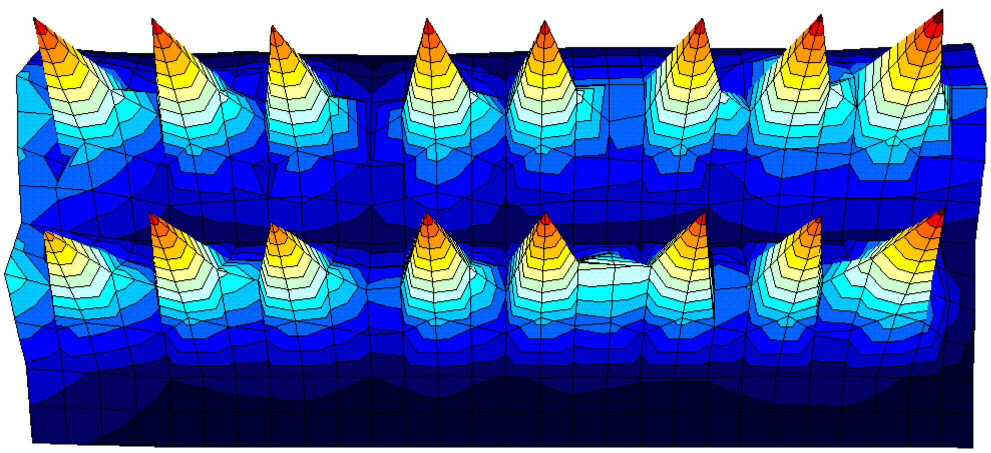


FIGURE 2: POST-INSTALLATION LIGHTING DEPICTION

CORRELATED COLOR TEMPERATURE

The correlated color temperature directly under the MH lamps was measured as 4761K during the day, and 4672K at night. This temperature was qualitatively consistent throughout the test area. The color temperature of the LED fixtures varied, with fixtures generally falling into two qualitative categories. Measurements under representative sample of the higher color-temperature fixtures indicated an average color temperature of 6917K. Under the other fixtures, the average color temperature was 5484K. See the below picture for an indication of this difference. This is likely a result of binning, and could be mitigated by mixing LEDs from different bins in a single fixture.

FIGURE 3: POST-INSTALLATION COLOR TEMPERATURE

CUSTOMER ACCEPTANCE

Due to circumstances resulting from previous lighting problems in the garage, concerns of the garage property managers with the new lights were such that no survey could be issued to garage tenants. However these concerns, along with other feedback from the property managers, are sufficient to give an idea of the qualitative performance of the lighting.

Prior to this project, there had been concerns at the garage regarding the amount of light reaching the area between the front of cars and the walls. These concerns were such that for a time female patrons refused to park in the garage. In response, the property managers replaced the old MH lamps, which had depreciated in lumen output, with new MH lamps. This was sufficient to alleviate the problem. As a result the property managers followed a lamp and capacitor replacement schedule for the MH lamps to maintain minimum lighting levels.

Upon installation of the LED fixtures, the conclusion of the property managers was that the amount of light reaching that space was reduced enough to reintroduce the previous problem. The decision was then made not to revisit this issue by distributing a survey to the tenants. The concerns of the property managers are supported by the measured fixture-to-wall ratio of lighting levels, which was roughly 3 times larger for the LED fixtures.

Outside of this concern, the lighting levels from the LED fixtures were deemed by the property managers to be sufficient, with good quality of light. The light was said to be "sharper," allowing details such as the floor texture to be more easily seen, and giving a feeling of more light. The smaller size of the LED fixtures compared to the MH fixtures also reduced glare because they were completely hidden by the horizontal ceiling-beams. The color variation among the LED fixtures was of small concern to the property managers, although they noted that the color from the fixtures was such that the colors of cars were generally harder to distinguish.

Overall, the property managers indicated that they were happy with the LED fixtures other than the amount of light reaching the walls of the garage. The wall lighting concern however, was such that they plan to eventually re-install the previous MH fixtures.

Economic Performance

Economic performance was evaluated primarily by simple payback of the LED fixtures versus the MH fixtures. To calculate this, current energy and materials costs were assumed while taking into account maintenance cost and energy cost.

To estimate energy cost, a 2007 PG&E E-19 rate schedule was used. This is the rate schedule under which the parking garage operated, and was deemed the most economical. The key features of the E-19 rates include time-of-use metering and a demand charge. Based on 12 months of billing data, the garage paid an average of $0.11566 per kWh after taxes.

Maintenance costs for MH fixtures were calculated on an annualized basis, assuming MH lamps replaced every year. This is a shorter life (8,760 hours) than the rated 10,000 hours, however this was the replacement cycle used by the host customer to maintain desired illuminance levels. The host customer also replaces ballast capacitors for the MH fixtures roughly once every 2 years, so this too was incorporated.

Due to uncertainties in future LED fixture costs, LED fixture replacement was not incorporated into maintenance estimates. Normally this cost could be annualized, effectively saving money each year toward eventual fixture replacement. Since this was not done, if a fixture has a calculated simple payback period longer than its useful life, it will not have recouped the initial investment.

Two economic scenarios were evaluated: a new-construction scenario and a retrofit scenario. In the new-construction scenario, the LED fixtures are assumed to be installed in place of metal-halide fixtures. In the retrofit scenario, the LED fixtures are assumed to replace metal-halide fixtures upon planned replacement of both MH lamp and MH capacitor.

TABLE IV: ANNUAL FIXTURE COSTS

	Annual Maintenance Cost	Annual Energy Cost	Total Annual Cost
Metal Halide (per Fixture)	$40.83	$204.70	$245.53
LED (2 Fixtures)	$0	$177.13	$177.13
Metal Halide (625 Fixture)	$25,520	$127,937	$153,458
LED (1250 Fixtures)	$0	$110,709	$110,709

TABLE V: NEW CONSTRUCTION ECONOMICS

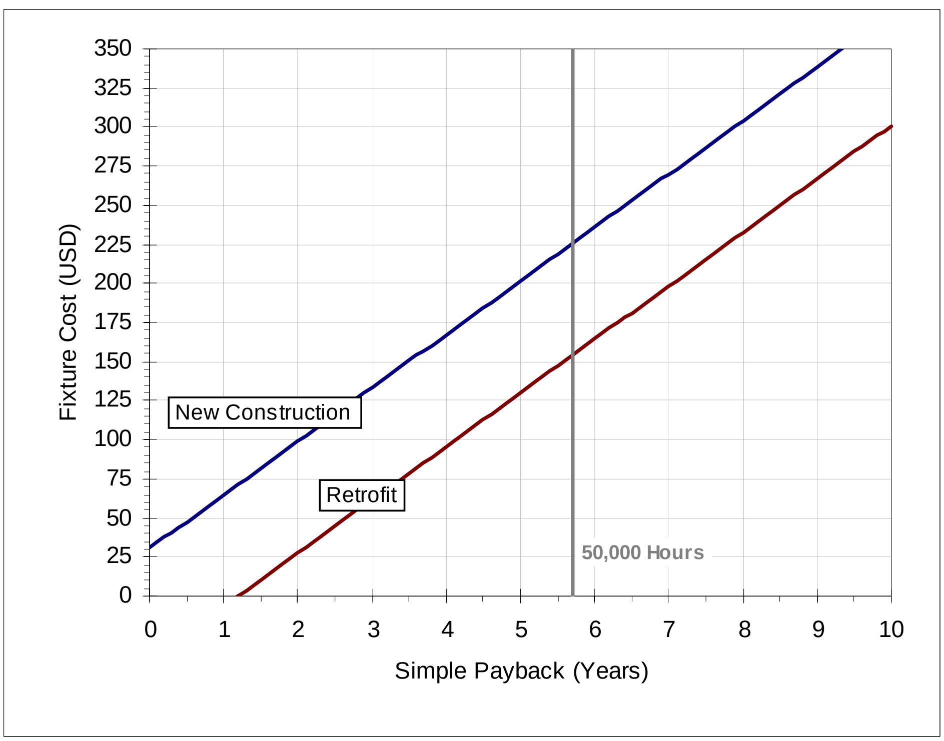
	Initial Investment	Incremental Cost	Annual Savings	Simple Payback (Years)
Metal Halide (per Fixture)	$196.85	--	--	--
LED (2 Fixtures)	$885.68	$688.83	$68.40	10.07
Metal Halide (625 Fixture)	$123,031	--	--	--
LED (1250 Fixtures)	$553,550	$430,519	$42,749	10.07

TABLE VI: RETROFIT ECONOMICS

	Initial Investment	Incremental Cost	Annual Savings	Simple Payback (Years)
Metal Halide (per Fixture)	$53.75	--	--	--
LED (2 Fixtures)	$885.68	$831.93	$68.40	12.16
Metal Halide (625 Fixture)	$33,594	--	--	--
LED (1250 Fixtures)	$553,550	$519,956	$42,749	12.16

For the MH fixtures, maintenance accounted for roughly 20% of the total annual cost, with energy costs accounting for the remaining 80%. As previously noted, maintenance costs for the LED fixtures were effectively assumed to be zero, so the energy costs accounted for 100% of the annual cost.[9] This is because the only predicted maintenance for the LED fixtures was eventual fixture replacement due to lumen depreciation.

Cost curves were generated showing requisite LED fixture costs for simple paybacks under 10 years with the existing 2-for-1 replacement factor, as well as a theoretical 1-for-1 replacement. The 1-for-1 cost curve assumes the same amount of total energy required for the replacement (i.e. the 1 fixture uses 175 watts).[10]



[9] See Appendix E1. 1,2

[10] See Appendix E1. 3,4

FIGURE 4: ESTIMATED 2-FOR-1 FIXTURE PAYBACK (ASSUMING NO MAINTENANCE)

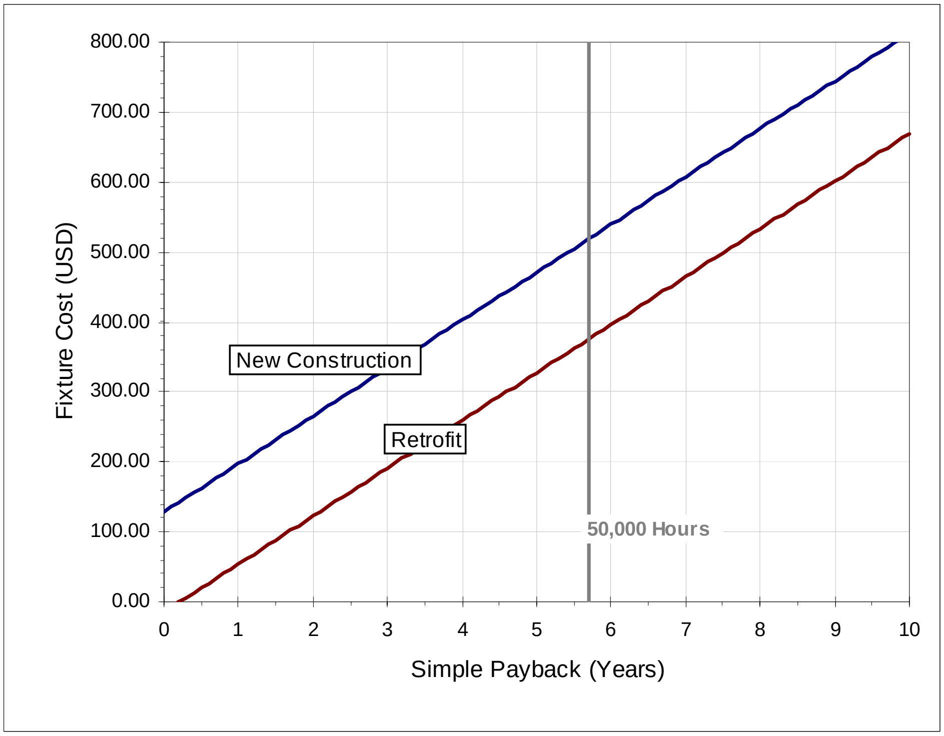


FIGURE 5: ESTIMATED 1-FOR-1 FIXTURE PAYBACK (ASSUMING NO MAINTENANCE)

If the LED fixtures are to be replaced at the current price of $375 at the end of their rated life (every 50,000 hours), the annualized maintenance cost is approximately $133 per year for two fixtures. This nearly doubles the annual cost of the fixtures, causing the annual cost of the LED fixtures to be greater than that of the MH fixtures. The main factors driving this high annual maintenance cost are the fixture cost and the 2-for-1 replacement factor.

Haitz's Law predicts that the light output of LEDs increases by a factor of 20 every 10 years, while the cost decreases by a factor of 10 over the same period of time. This has held approximately true since the late 1960's.[11] If fixture cost is assumed to decrease at a rate consistent with Haitz's law, the LED fixture cost in late 2013 (the end of their rated life, if installed now) would be approximately $100. The annualized cost of replacement would then be roughly $37 /year, resulting in annual savings of $31.30 /year, and simple payback of 22 years based on the same initial investment.[12] Simple paybacks calculated in this way are applicable beyond a single lamp cycle, although depending on future lamp costs they may begin to lose applicability beyond two lamp cycles.

[11] Steele, Robert V (2006). "The story of a new light source." Nature Photonics 1, 25 – 26. *10.1038/nphoton.2006.44*

[12] See Appendix E2

In recent years technological improvements have begun to exceed the pace of Haitz's law; in communications with the manufacturer, it was indicated that in the near future prices may decrease by as much as a factor of 2 every 18 months. If this remains the case, an equivalent fixture could be expected to cost on the order of $200 in 2 years.

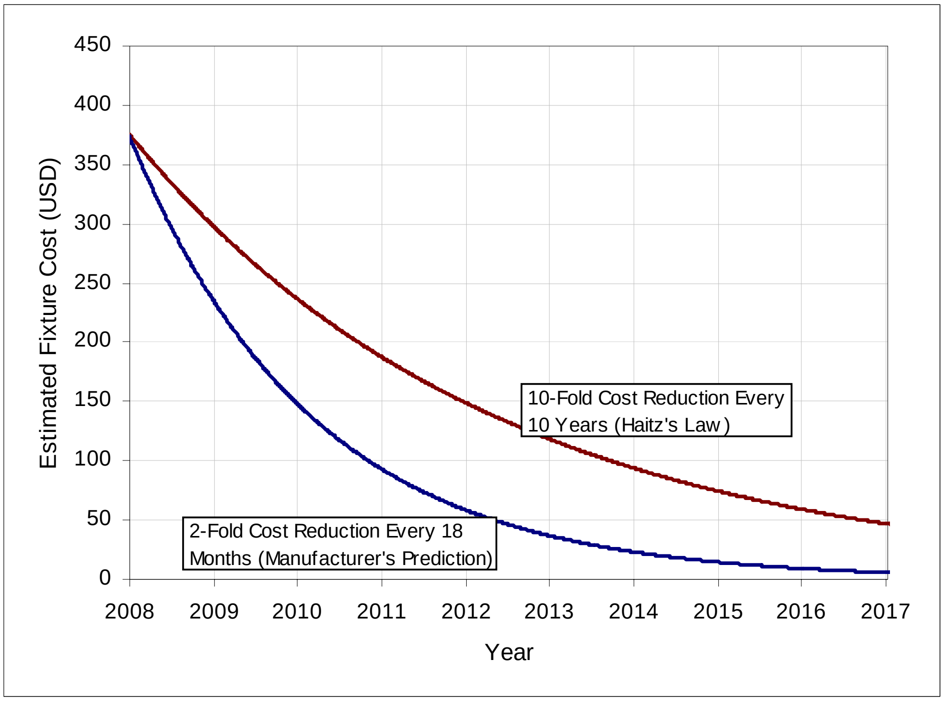


FIGURE 6: ESTIMATED FIXTURE COST[13]

In addition, the manufacturer predicted that further technological improvements would be such that a 1-for-1 fixture could be available in 6 to 9 months. It was indicated that this fixture could have equivalent performance to the tested 2-for-1 replacement, and cost roughly $450. If this advancement were then followed by a 2-fold reduction in price in 18 months, the result would be a product capable of achieving on the order of a 3-year simple payback by mid-2009.

It should be noted that the economic viability of the LED fixtures is sensitive to the specific application. This includes both the alternative lighting scenarios considered and the estimated maintenance costs. In the case studied, the existing MH lighting system was relatively efficient, representing current best practice. In other applications where the existing lighting system is not as efficient, LED lighting may be more cost effective. In addition, maintenance estimates in this report were based on information from the host customer. This included group re-lamping, which reduces maintenance time and a pay rate of $35/ hour. The assumed maintenance time is 5 minutes for a lamp, and 15 minutes for a lamp and capacitor.

An alternate maintenance scenario is shown in Appendix E3, in which MH lamps are individually replaced at assumed failure (end of rated life). The assumed maintenance time for this scenario is 15 minutes for a lamp, and 30 minutes for a lamp and capacitor. In addition, a pay rate of $70

[13] Steele (2006).

/hour, twice that indicated by the host customer, was used to provide an upper bound for maintenance costs. This has the effect of considerably reducing simple payback periods for LED fixtures.

Discussion

The installed 85 watt LED fixtures provided sufficient general illumination to be a practicable replacement for 175 watt MH fixtures on a 2-for-1 basis. The LED fixtures provided a slight overall increase in illumination, as well as an increase in uniformity, over the MH fixtures. The power required by the LED fixtures to provide this illumination, even with the 2-for-1 replacement, was less than that of the MH fixtures. There were concerns specific to the test site however, which caused the fixtures to be less feasible in the particular application. Specifically, the illumination near the walls in front of parking spaces was of great concern, and was reduced by the LED fixtures. It should be noted that a 2006 study indicated that a lens optic can be effectively used to provide greater light dispersion, potentially addressing this problem.[14] Additionally, lighting distribution will vary in situations where the arrangement or installation of the fixtures is different from this particular application.

Despite the energy savings of the LED fixtures, the fixture costs in this case were such that they were not economical as judged by simple payback. In order to achieve a 2-year simple payback during new construction, these fixtures could cost a maximum of around $99, or $202 for a 5-year payback.

Future advancements to significantly reduce fixture cost or to allow a 1-for-1 replacement would make the fixtures more economical. If a 1-to-1 replacement factor could be achieved, a fixture of equivalent efficacy to those installed for this test (~175 watts to replace a 200 watt MH fixture) would have a 2-year simple payback with a fixture cost of $266. A 5-year simple payback could then also be achieved at $471 per fixture. Communications with the manufacturer indicated that a fixture providing equivalent performance in a 1-for-1 replacement scenario may be available in 6-9 months, costing roughly $450.

Advancements in LED efficacy will also aid in improving the economic performance of LED fixtures by increasing energy savings. The same 2006 study indicated that a 121-LED fixture could be designed with proper optics to meet IESNA standards for parking garages. They show that this fixture would directly replace a 200 watt metal-halide fixture, and use an estimated 142 watts.[15] Such a fixture would have a 2-year payback at approximately $332, and a 5-year payback at roughly $637.

With the rapid development of LED technology, this is not out of the realm of possibility in the relatively near-term. Utility incentive programs could help to bring the price down to this level for the consumer even sooner.

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[14] Peck, John P. and C. Vishno Shastry (2006). "LED Light fixture for parking garages." Proc. Of SPIE Vol. 6337. *63371D*

[15] Ibid.

Conclusion

Exterior LED lighting, such as that demonstrated in this project, has great potential for energy savings. Although the specific fixtures tested in this project did not prove an economic replacement for the previously installed MH fixtures, the economic viability of LED fixtures in general is continually improving as the technology advances. Further consumer adoption of LEDs for general lighting could also provide a positive feedback cycle with technology advancement, as more research money is invested. Utility incentive programs, if they are able to bring prices down to an economical level for consumers, have the potential to help spur this cycle.

Appendix A: Facility and Monitoring Layout

APPENDIX A1: FACILITY AND MONITORING LAYOUT

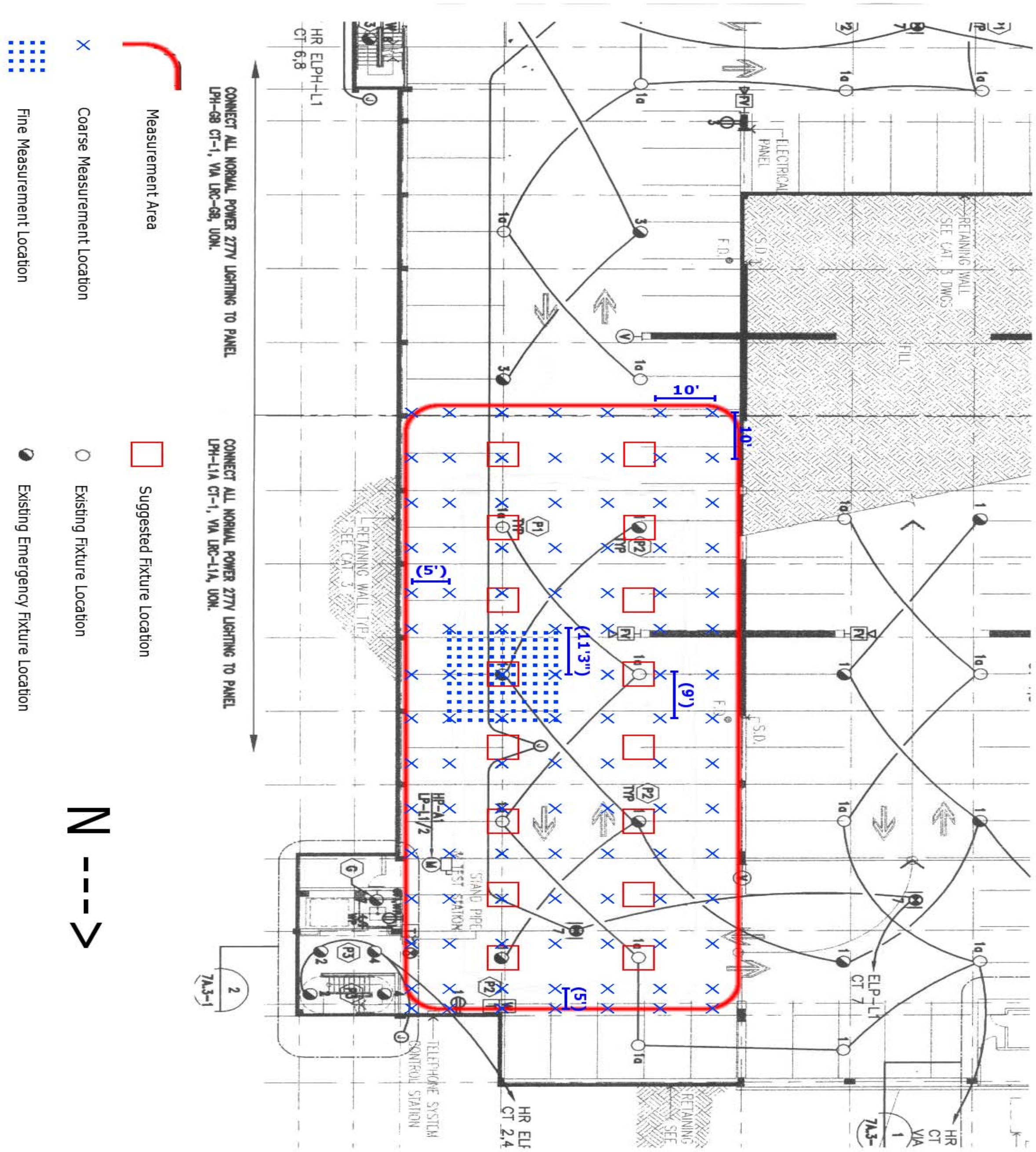


Figure A1.1: Floor-Plan and Measurement Layout of Testing Area.

APPENDIX A2: FIXTURE LOCATIONS

Table A2.i: Estimated Pre-installation Fixture Locations.

Fixture Number (clockwise from SW corner)	Fixture Type	Reference Point	Approximate Distance from Reference Point to Light
1	Metal-Halide	C2	69"N, 55"E
2	Metal-Halide	G2	0"N, 55"E
3	Metal-Halide	J2	46.5"N, 55"E
4	Metal-Halide	M2	45.5"N, 55"E
5	Metal-Halide	C5	69"N, 0"E
6	Metal-Halide	G5	0"N, 0"E
7	Metal-Halide	J5	46.5"N, 0"E
8	Metal-Halide	M5	45.5"N, 0"E

Table A2.ii: Estimated Post-installation Fixture Locations.

Fixture Number (clockwise from SW corner)	Fixture Type	Reference Point	Approximate Distance from Reference Point to Light
1	"Blue" LED	A2	100"N, 55"E
2	"Green" LED	C2	69"N, 55"E
3	"Green" LED	E2	27.5"N, 55"E
4	"Green" LED	G2	0"N, 55"E
5	"Blue" LED	H2	76"N, 55"E
6	"Green" LED	J2	46.5"N, 55"E
7	"Blue" LED	L2	3"N, 55"E
8	"Green" LED	M2	45.5"N, 55"E
9	"Blue" LED	A5	100"N, 0"E
10	"Blue" LED	C5	69"N, 0"E
11	"Green" LED	E5	27.5"N, 0"E
12	"Blue" LED	G5	0"N, 0"E
13	"Green" LED	H5	76"N, 0"E
14	"Green" LED	J5	46.5"N, 0"E
15	"Green" LED	L5	3"N, 0"E
16	"Green" LED	M5	45.5"N, 0"E

Appendix B: Data Collection Form

Low Bay Parking Garage LED Fixture
Field Collection Form

Page: 1 of 5
Pre-installation date ______
Post-installation date ______
Light Status Meter ______
Light Output Meter ______
Power Meter ______

Location: Parking Garage at 631 Gateway, SSF

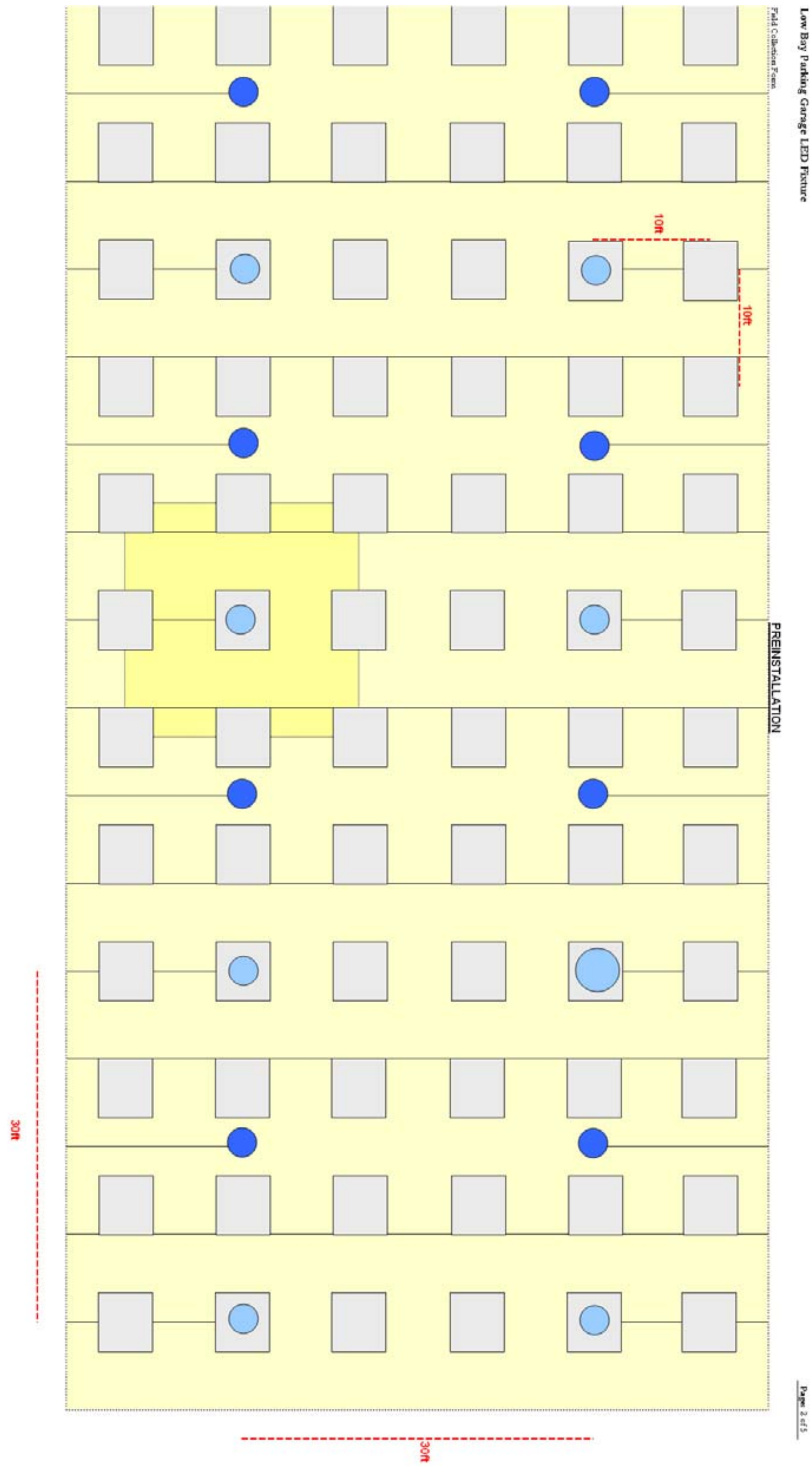
Pre-installation Test Team: ______

Post-installation Test team: ______

FIXTURE	FOOTCANDLES	Color Temp (K)	NOTES
Type	At Ground on Grid (Attached)	Of Light In Space (midway)	
Standard Fixture:			Kim Lighting PGL4 Sylvania M175/U/Med
Pre-installation Value	Pages 2, 3		
Post-installation Value	Pages 4, 5		
Delta Value			
Emergency Fixture:			
Pre-installation Value	Pages 2, 3		
Post-installation Value	Pages 4, 5		
Delta Value			

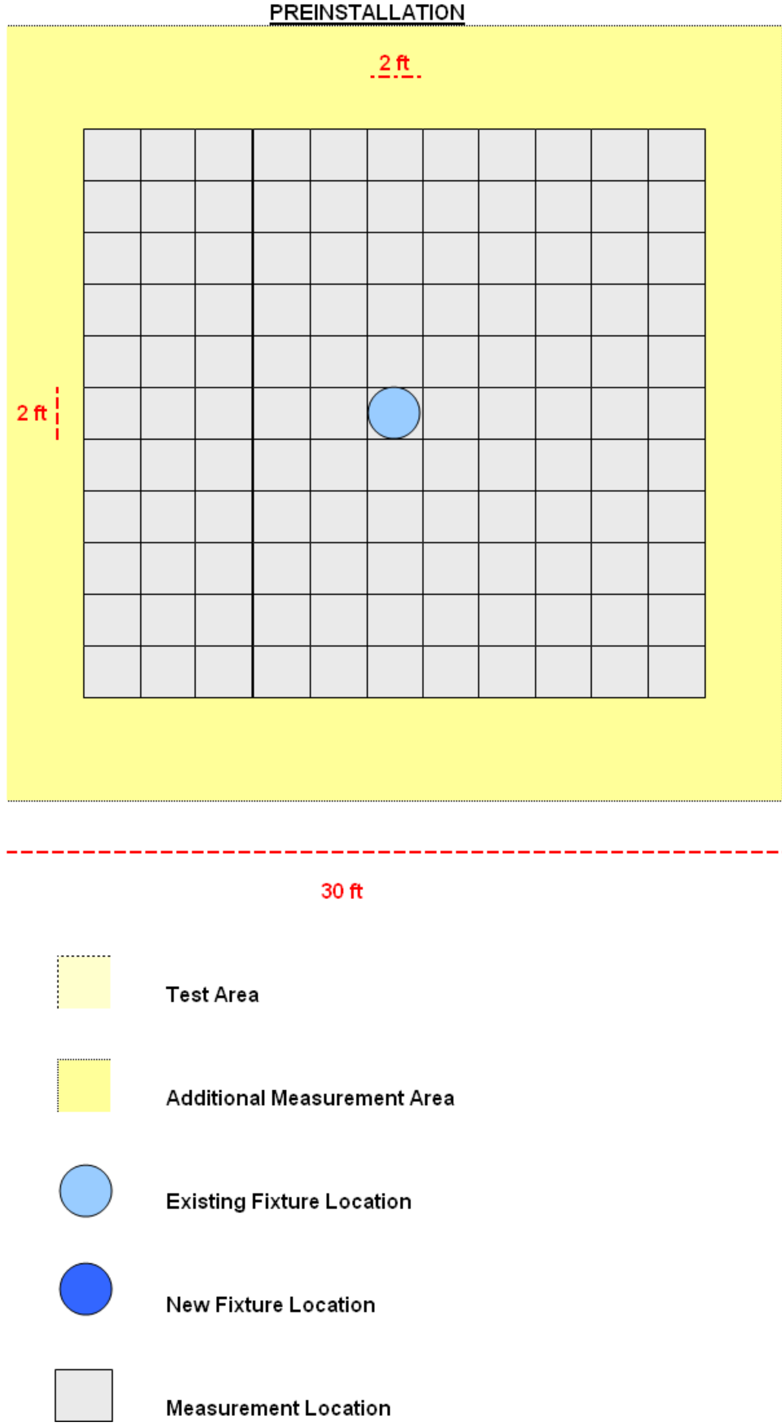
LIGHTING CIRCUIT	RMS WATTS	RMS VOLTAGE	RMS CURRENT (A)	NOTES
Circuit 1: ______				
Pre-installation Value				
Post-installation Value				
Delta Value				
Circuit 2: ______				
Pre-installation Value				
Post-installation Value				
Delta Value				

LIGHTING CIRCUIT	NUMBER OF FIXTURES				
	Std HID	Emerg. HID	Std LED	Emerg. LED	NOTES
Circuit 1: ______ Pre-installation Value Post-installation Value					
Circuit 2: ______ Pre-installation Value Post-installation Value					



Low Bay Parking Garage LED Fixture
Field Collection Form
PREINSTALLATION
10ft
10ft
30ft
30ft
Pages 2 of 5

PREINSTALLATION



Appendix C: Site Photographs

APPENDIX C1: PRE-INSTALLATION PHOTOGRAPHS

APPENDIX C2: POST-INSTALLATION PHOTOGRAPHS

Appendix D: Monitoring Data

APPENDIX D1: PRE-INSTALLATION DATA

APPENDIX D1.1: POWER DATA

Table D1.1.i: Averaged Pre-installation Power Measurements. (Measured with Summit PS3000 and HA-1000, last calibrated 6/9/2007; ambient temperature 68˚F)

Circuit (Code)	**M-H Fixtures**	**LED Fixtures**	**Voltage (v)**	**Current (a)**	**Power (w)**	**Power Factor**
1 (ELPH-L1)	14	0	283.3	10.1	2813	0.98
1a (LPH-L1A)	13	0	283.7	9.6	2642	0.97

APPENDIX D1.2: CORRELATED COLOR TEMPERATURE DATA

Table D1.2.i: Pre-installation Correlated Color Temperature Measurements. (Measured with Minolta CL-200, last calibrated 7/24/2006; daytime ambient temperature 68˚F; nighttime ambient temperature 58˚F)

Ambient Conditions	Measurement Location	Color Temperature (K)
Daytime	E4	4241
Nighttime	E4	4191
Daytime	F4	4701
Nighttime	F4	4511
Daytime	G5	4761
Nighttime	G5	4672
Daytime	I7	4608
Nighttime	I7	4672

APPENDIX D1.3: ILLUMINATION DATA

Table D1.3.i: Illumination over Entire Test Area. (In lux; measured with Minolta CL-200, last calibrated 7/24/2006 and LI-COR LI-250 with PHOTOMETRIC, calibrated against Minolta CL-200; ambient temperature 68˚F)

Reference Coordinates (ft)	**A** (-61.25)	**B** (-51.25)	**C** (-41.25)	**D** (-31.25)	**E** (-21.25)	**F** (-11.25)	**G** (0)	**H** (9)	**I** (18)	**J** (27)	**K** (36)	**L** (45)	**M** (54)	**N** (63)	**O** (68)
1 (40)	29.10	13.50	40.60	33.30	15.60	2.40	36.20	34.60	30.90	41.67	38.11	20.00	11.41	24.71	29.74
2 (30)	94.00	43.20	106.30	121.80	39.00	4.10	204.50	82.60	49.50	129.85	108.28	27.75	27.43	61.05	80.42
3 (20)	93.50	44.70	84.10	115.70	51.50	86.10	159.60	81.00	48.10	134.35	100.95	25.13	25.23	54.45	76.86
4 (10)	73.70	42.60	68.30	81.30	50.50	56.00	88.00	55.60	38.10	76.55	58.54	25.02	20.73	30.05	28.37
5 (0)	113.70	53.60	125.10	168.60	59.50	66.80	240.10	65.40	40.73	141.06	96.13	27.96	51.10	32.88	16.75
6 (-10)	57.40	36.60	47.10	61.80	31.40	28.60	53.50	35.30	18.95	40.10	36.44	14.45	14.34	12.56	8.27
7 (-15)	25.90	22.20	29.70	36.50	17.60	13.30	25.00	19.90	-2.20	18.11	15.49	7.33	5.34	7.43	2.82

Table D1.3.ii: Illumination over Detailed Test Area. (In lux; measured with Minolta CL-200, last calibrated 7/24/2006; ambient temperature 68˚F)

Reference Coordinates (ft)	**A** (-10)	**B** (-8)	**C** (-6)	**D** (-4)	**E** (-2)	**F** (0)	**G** (2)	**H** (4)	**I** (6)	**J** (8)	**K** (10)
1 (10)	55.1	60.3	69.7	79.8	87.2	88.8	86.2	82.7	72.6	65.9	57.1
2 (8)	55.1	63.1	78.2	89.1	106.7	112.2	107.9	94.6	80.5	65.7	56.2
3 (6)	59	66.7	85.3	111.2	127.4	137.6	129.2	119.3	89	70.9	58.8
4 (4)	64.1	75	112.5	124	163.6	184	165.1	123.5	102.4	75.1	61.2
5 (2)	61.4	79.2	121.8	144.9	179.2	198.7	173.3	141	105.8	86.2	64.1
6 (0)	58.5	79.1	122.9	146.7	160.4	232.8	164.3	158.2	116.2	95.5	63.6
7 (-2)	57.1	80.6	125.1	144.4	183.3	159.1	163.3	144.2	114	83.9	61.7
8 (-4)	54.3	71.3	116	125.8	149.1	141	138.5	117.5	102.1	71.5	55.8
9 (-6)	47.4	59.3	83.9	107.2	111.4	106.8	105.2	95.2	75.9	60.6	49
10 (-8)	39	48.9	65.6	73.3	73.8	73	70.3	66.3	62	49.6	41.5
11 (-10)	31.7	38.5	50.9	56.3	50.6	50.8	50.5	46.5	48.4	41.2	30.4

APPENDIX D2: POST-INSTALLATION DATA

APPENDIX D2.1: POWER DATA

Table D2.1.i: Averaged Pre-installation Power Measurements. (Measured with Summit PS3000 and HA-1000, last calibrated 6/9/2007; ambient temperature 67˚F)

Circuit (Code)	**M-H Fixtures**	**LED Fixtures**	**Voltage (v)**	**Current (a)**	**Power (w)**	**Power Factor**
1 (ELPH-L1)	10	8	283.2	9.7	2695	0.98
1a (LPH-L1A)	9	8	284.2	9.1	2542	0.98

APPENDIX D2.2: CORRELATED COLOR TEMPERATURE DATA

Table D2.2.i: Pre-installation Correlated Color Temperature Measurements. (Measured with Minolta CL-200, last calibrated 7/24/2006; daytime ambient temperature 67˚F; nighttime ambient temperature 58˚F)

Ambient Conditions	Measurement Location	Color Temperature (K)
Daytime	E4	4837
Nighttime	E4	4760
Daytime	F4	4873
Nighttime	F4	4801
Daytime	G5	6979
Nighttime	G5	6918
Daytime	I7	4703
Nighttime	I7	4874

APPENDIX D2.3: ILLUMINATION DATA

Table D2.3.i: Illumination over Entire Test Area. (In lux; measured with Minolta CL-200, last calibrated 7/24/2006 and LI-COR LI-250 with PHOTOMETRIC, calibrated against Minolta CL-200; ambient temperature 58˚F)

Reference Coordinates (ft)	**A** (-61.25)	**B** (-51.25)	**C** (-41.25)	**D** (-31.25)	**E** (-21.25)	**F** (-11.25)	**G** (0)	**H** (9)	**I** (18)	**J** (27)	**K** (36)	**L** (45)	**M** (54)	**N** (63)	**O** (68)
1 (40)	26.40	12.80	8.80	15.50	10.10	6.10	9.20	13.80	24.30	25.30	23.00	21.80	18.00	27.30	34.10
2 (30)	112.20	119.90	68.80	81.10	110.00	48.50	113.60	55.30	89.80	92.30	65.40	145.00	108.20	83.10	83.30
3 (20)	104.20	114.30	54.20	76.70	94.40	55.30	116.40	46.60	79.60	68.80	56.40	101.30	85.10	80.90	71.00
4 (10)	84.30	44.00	26.70	28.70	34.10	25.35	31.70	27.60	28.70	29.70	25.20	35.10	33.90	33.40	25.70
5 (0)	138.10	257.70	101.00	148.30	277.80	88.10	302.60	82.50	168.60	157.80	90.40	294.20	184.20	88.30	20.70
6 (-10)	53.50	37.40	20.40	23.40	25.90	19.60	25.40	18.50	23.80	21.00	20.70	26.10	27.10	19.10	8.90
7 (-15)	27.40	17.80	9.10	10.00	9.20	7.70	8.70	8.00	9.20	8.10	8.80	10.70	11.00	10.50	4.10

Table D2.3.ii: Illumination over Detailed Test Area. (In lux; measured with Minolta CL-200, last calibrated 7/24/2006; ambient temperature 58˚F)

Reference Coordinates (ft)	**A** (-10)	**B** (-8)	**C** (-6)	**D** (-4)	**E** (-2)	**F** (0)	**G** (2)	**H** (4)	**I** (6)	**J** (8)	**K** (10)
1 (10)	24.6	25.1	27.4	29.6	31.8	32.3	32.8	31	26.6	26.2	27
2 (8)	31.3	31.1	35.4	41.6	46.7	48.2	48.3	40.7	34.7	33.6	35.3
3 (6)	42	40.8	48.8	63	80.4	84.7	78.9	62.6	50.2	45.9	49.1
4 (4)	54.9	52.7	67.6	99.1	136.7	150.8	131.8	94.9	67	59.9	68.6
5 (2)	67.37	64.2	89.4	142	213.8	247.6	209.1	136.6	87.3	73.8	89
6 (0)	72.7	69.9	98.9	165.9	260.4	303.2	247.3	153.8	97.2	79.8	97.7
7 (-2)	68.5	64.7	89.2	143.6	221.4	251	211.9	140.2	85	74	88.2
8 (-4)	55.4	53.3	70.8	100.2	142.3	149.1	141.9	102.1	71.5	58.8	70.4
9 (-6)	40.6	40	47	62	80	81.6	81.4	64.6	50.5	44	48.7
10 (-8)	28.4	26.3	32.8	38.5	45.5	43.6	46.6	40.7	33	30.5	33.2
11 (-10)	19.4	18.9	21.1	23.4	24.4	23.9	24.4	24.3	21.8	20.5	21.9

Appendix E: Additional Economic Data and Scenarios

APPENDIX E1: ADDITIONAL ECONOMIC DATA

APPENDIX E1.1: 2-FOR-1 REPLACEMENT, NEW CONSTRUCTION

Metal Halide Fixtures

Maintenance		
Lamp Replacement		
Replacement Frequency	1.00	/yr
Replacement Cost	25.00	$/lamp
Replacement Time	0.083	hr/replacement
Pay Rate	35.00	$/hr
Annual Cost	27.92	$/yr
Capacitor Replacement		
Replacement Frequency	0.50	/yr
Replacement Cost	20.00	$/capacitor
Replacement Time	0.167	hr/replacement
Pay Rate	35.00	$/hr
Annual Cost	12.92	$/yr
Fixture Installation		
Installation Frequency	0.00	/yr
Installation Cost	129.01	$/part
Installation Time	1.94	hr/installation
Pay Rate	35.00	$/hr
Annual Cost	0.00	$/yr
Total Maintenance Cost:	40.83	$/yr

Energy		
Demand	202.04	w
Usage	1769.84	kWh
Rate	0.1157	$/kWh
Annual Cost	204.70	$/yr
Total Energy Cost:	204.70	$/yr

TOTAL ANNUAL COST: $245.53

LED Fixtures

Maintenance		
Fixture Installation		
Installation Frequency	0.00	/yr
Installation Cost	375.00	$/fixture
Installation Time	0.17	hr/installation
Pay Rate	35.00	$/hr
Annual Cost	0.00	$/yr
Total Maintenance Cost:	0.00	$/yr

Energy		
Demand	87.41	w
Usage	765.75	kWh
Rate	0.1157	$/kWh
Annual Cost	88.57	$/yr
Total Energy Cost:	88.57	$/yr

TOTAL ANNUAL COST: $88.57

Payback

Initial Installation	67.84	$
Replacement Factor	2.00	for 1
Incremental Cost	688.83	$
Annual Savings	68.40	$
Simple Payback	10.07	years
2 Year Payback	98.98	$ Repl. Cost
5 Year Payback	201.58	$ Repl. Cost

APPENDIX E1.2: 2-FOR-1 REPLACEMENT, RETROFIT

Metal Halide Fixtures

Maintenance		
Lamp Replacement		
Replacement Frequency	1.00	/yr
Replacement Cost	25.00	$/lamp
Replacement Time	0.083	hr/replacement
Pay Rate	35.00	$/hr
Annual Cost	27.92	$/yr
Capacitor Replacement		
Replacement Frequency	0.50	/yr
Replacement Cost	20.00	$/capacitor
Replacement Time	0.167	hr/replacement
Pay Rate	35.00	$/hr
Annual Cost	12.92	$/yr
Fixture Installation		
Installation Frequency	0.00	/yr
Installation Cost	129.01	$/part
Installation Time	1.94	hr/installation
Pay Rate	35.00	$/hr
Annual Cost	0.00	$/yr
Total Maintenance Cost:	40.83	$/yr
Energy		
Demand	202.04	w
Usage	1769.84	kWh
Rate	0.1157	$/kWh
Annual Cost	204.70	$/yr
Total Energy Cost:	204.70	$/yr
TOTAL ANNUAL COST:	$245.53	

LED Fixtures

Maintenance		
Fixture Installation		
Installation Frequency	0.00	/yr
Installation Cost	375.00	$/fixture
Installation Time	0.17	hr/installation
Pay Rate	35.00	$/hr
Annual Cost	0.00	$/yr
Total Maintenance Cost:	0.00	$/yr
Energy		
Demand	87.41	w
Usage	765.75	kWh
Rate	0.1157	$/kWh
Annual Cost	88.57	$/yr
Total Energy Cost:	88.57	$/yr
TOTAL ANNUAL COST:	$88.57	

Payback

Replacement Labor	67.84	$
Replacement Factor	2	for 1
Incremental Cost	831.93	$
Annual Savings	68.40	$
Simple Payback	12.16	years
2 Year Payback	27.43367521	$ Repl. Cost
5 Year Payback	130.031688	$ Repl. Cost

APPENDIX E1.3: 1-FOR-1 REPLACEMENT, NEW CONSTRUCTION

Metal Halide Fixtures

Maintenance		
Lamp Replacement		
Replacement Frequency	1	/yr
Replacement Cost	25	$/lamp
Replacement Time	0.0833	hr/replacement
Pay Rate	35	$/hr
Annual Cost	27.9155	$/yr
Capacitor Replacement		
Replacement Frequency	0.5	/yr
Replacement Cost	20	$/capacitor
Replacement Time	0.1667	hr/replacement
Pay Rate	35	$/hr
Annual Cost	12.91725	$/yr
Fixture Installation		
Installation Frequency	0	/yr
Installation Cost	129.01	$/part
Installation Time	1.94	hr/installation
Pay Rate	35	$/hr
Annual Cost	0	$/yr
Total Maintenance Cost:	40.83275	$/yr
Energy		
Demand	202.037037	w
Usage	1769.844444	kWh
Rate	0.1157	$/kWh
Annual Cost	204.6996283	$/yr
Total Energy Cost:	204.6996283	$/yr
TOTAL ANNUAL COST:	$245.53	

LED Fixtures

Maintenance		
Fixture Installation		
Installation Frequency	0	/yr
Installation Cost	450	$/fixture
Installation Time	0.1667	hr/installation
Pay Rate	35	$/hr
Annual Cost	0	$/yr
Total Maintenance Cost:	0	$/yr
Energy		
Demand	174.8296703	w
Usage	1531.507912	kWh
Rate	0.115659672	$/kWh
Annual Cost	177.1337031	$/yr
Total Energy Cost:	177.1337031	$/yr
TOTAL ANNUAL COST	$177.13	

Payback

Initial Installation	67.84	$
Replacement Factor	1	for 1
Incremental Cost	320.99	$
Annual Savings	68.40	$
Simple Payback	4.69	years
2 Year Payback	265.8073504	$ Repl. Cost
5 Year Payback	471.003376	$ Repl. Cost

APPENDIX E1.4: 1-FOR-1 REPLACEMENT, RETROFIT

Metal Halide Fixtures

Maintenance		
Lamp Replacement		
Replacement Frequency	1	/yr
Replacement Cost	25	$/lamp
Replacement Time	0.0833	hr/replacement
Pay Rate	35	$/hr
Annual Cost	27.9155	$/yr
Capacitor Replacement		
Replacement Frequency	0.5	/yr
Replacement Cost	20	$/capacitor
Replacement Time	0.1667	hr/replacement
Pay Rate	35	$/hr
Annual Cost	12.91725	$/yr
Fixture Installation		
Installation Frequency	0	/yr
Installation Cost	129.01	$/part
Installation Time	1.94	hr/installation
Pay Rate	35	$/hr
Annual Cost	0	$/yr
Total Maintenance Cost:	40.83275	$/yr

Energy		
Demand	202.037037	w
Usage	1769.844444	kWh
Rate	0.1157	$/kWh
Annual Cost	204.6996283	$/yr
Total Energy Cost:	204.6996283	$/yr

TOTAL ANNUAL COST:	$245.53

LED Fixtures

Maintenance		
Fixture Installation		
Installation Frequency	0	/yr
Installation Cost	450	$/fixture
Installation Time	0.1667	hr/installation
Pay Rate	35	$/hr
Annual Cost	0	$/yr
Total Maintenance Cost:	0	$/yr

Energy		
Demand	174.8296703	w
Usage	1531.507912	kWh
Rate	0.115659672	$/kWh
Annual Cost	177.1337031	$/yr
Total Energy Cost:	177.1337031	$/yr

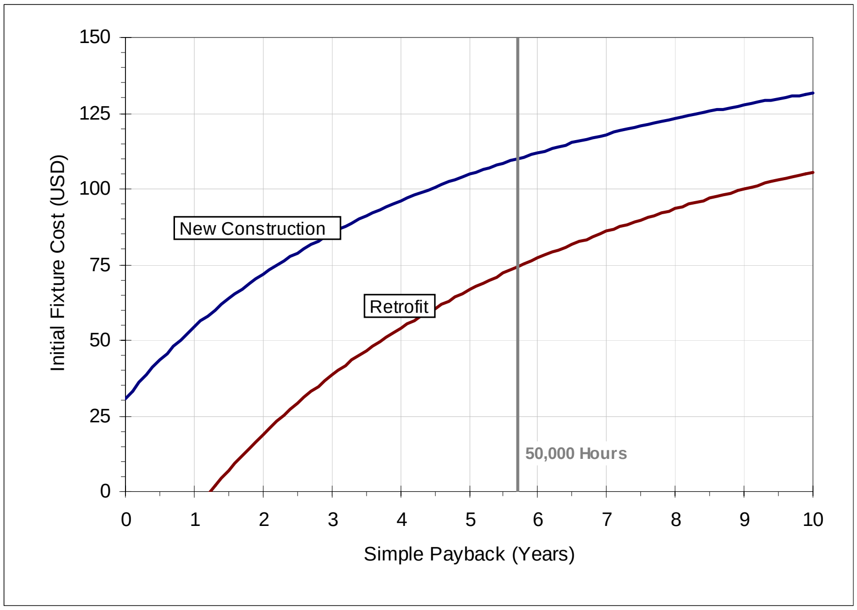
TOTAL ANNUAL COST	$177.13

Payback

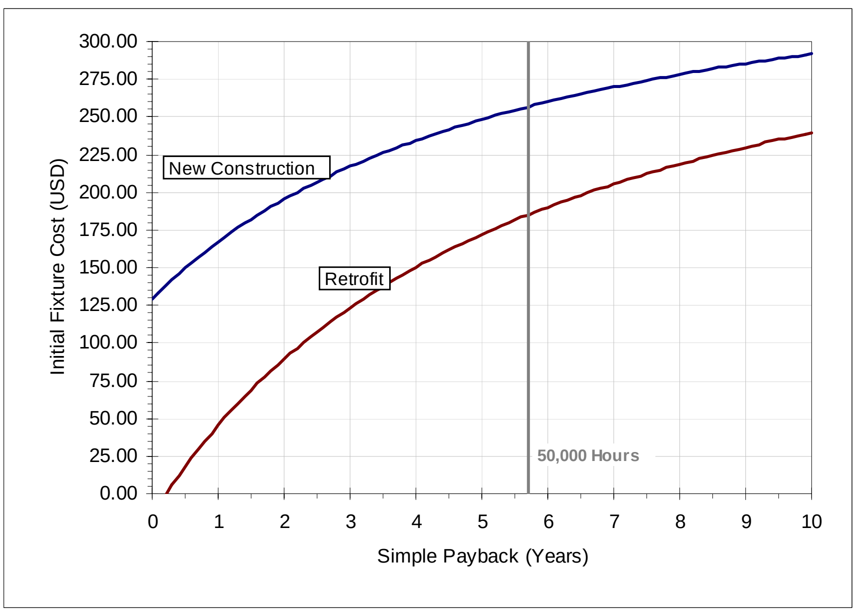
Replacement Labor	67.84	$
Replacement Factor	1	for 1
Incremental Cost	464.09	$
Annual Savings	68.40	$
Simple Payback	6.79	years
2 Year Payback	122.7073504	$ Repl. Cost
5 Year Payback	327.903376	$ Repl. Cost

APPENDIX E2: ADDITIONAL ECONOMIC FIGURES

APPENDIX E2.1: 2-FOR-1 SIMPLE PAYBACK CURVE WITH $100 FIXTURE REPLACEMENT

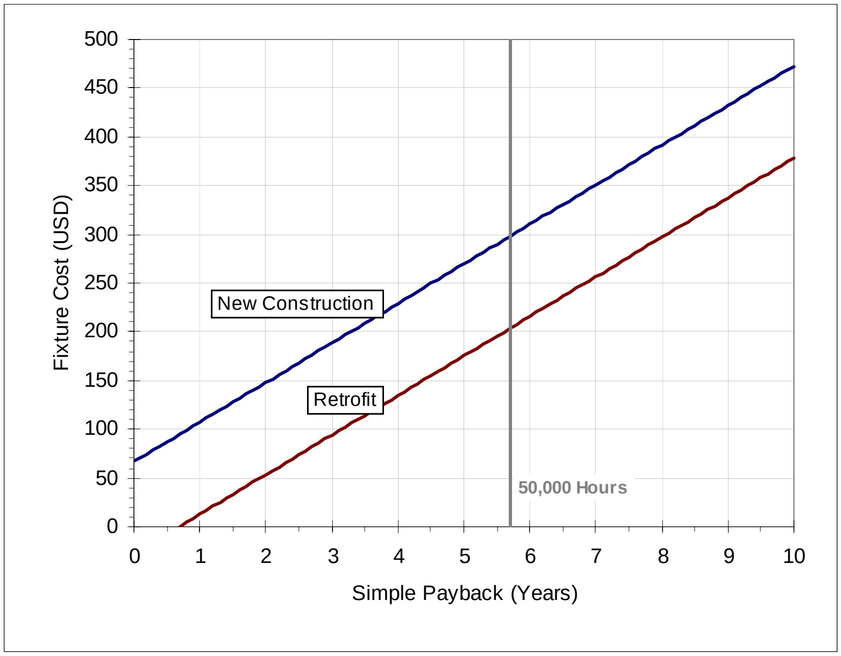


APPENDIX E2.2: 1-FOR-1 SIMPLE PAYBACK CURVE WITH $100 FIXTURE REPLACEMENT

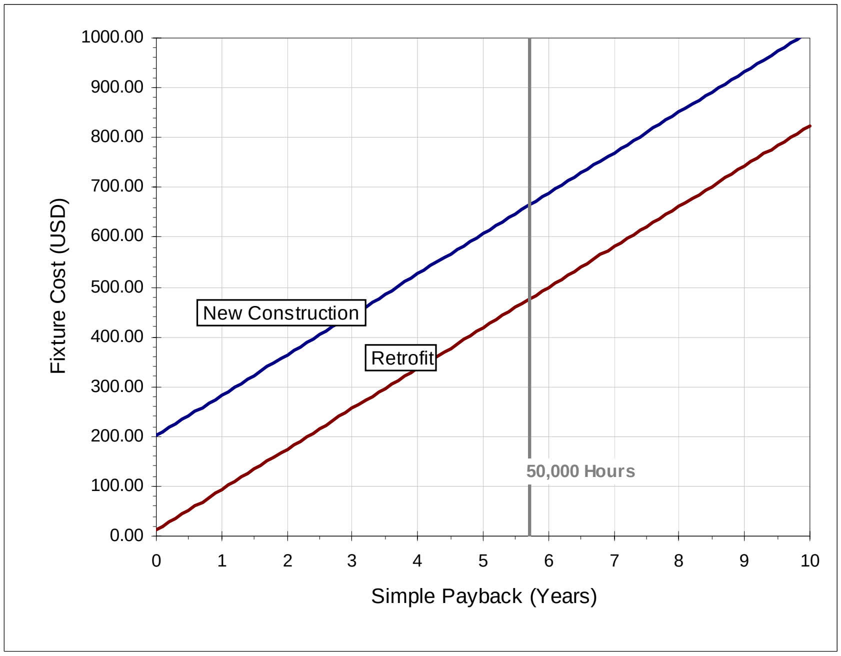


APPENDIX E3: ECONOMIC FIGURES WITH INDIVIDUAL RE-LAMPING AND INCREASED LABOR COSTS

APPENDIX E3.1: 2-FOR-1 FIXTURE REPLACEMENT



APPENDIX E3.2: 1-FOR-1 FIXTURE REPLACEMENT



Appendix F: Laboratory LED Fixture Test Results (California Lighting Technology Center)

LSG Parking Lot Fixture

Lighting Science Group LED – Measurements taken after 30 minutes

- Total Lumen Output ~ 3068.457 Lumens
- CCT ~ 4875 K
- CRI ~ 76.1
- AC Wattage ~ 81.2 W
- Source Efficacy ~ 37.79 L / W

RESEARCH • INNOVATION • PARTNERSHIP

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