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Doug Crawford, Carl Gould, Michael Packer, Francis Rubinstein, and Michael Siminovitch

Lighting Research Group
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

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Abstract

This paper describes the results of a photometric and energy analysis that was conducted on a new light guide and sulfur lamp system recently installed at the U.S. Department of Energy's Forrestal Building. This novel system couples two high lumen output, high efficiency sulfur lamps to a single 73 m (240 ft.) hollow light guide lined with a reflective prismatic film. The system lights a large roadway and plaza area that lies beneath a section of the building. It has been designed to completely replace the grid of 280 mercury vapor lamps formerly used to light the space. This paper details the results of a field study that characterizes the significant energy savings and increased illumination levels that have been achieved. Comparisons to modeled HID lighting scenarios are also included.

Introduction

In October, 1994, the Department of Energy announced the unveiling of a new light guide and sulfur lamp lighting system at their Washington D.C. Forrestal building. The new sulfur lamp system, designed by Fusion Lighting of Rockville, MD, was coupled to a single hollow light guide, designed by Dr. Lorne Whitehead, Associate Professor of physics at the University of British Columbia. The coupled system was installed in October 1994 as a replacement lighting system for the existing 175 W mercury HID lamps. The existing HID system consists of a grid of 280 separate lamps and fixtures illuminating the exterior plaza. We conducted a photometric and energy assessment of both the existing mercury HID lighting system and the new sulfur lamp/light guide system. This paper presents an analysis of these results and includes performance comparisons to hypothetical installations of new mercury HID and metal halide lighting systems.

Site Description

The exterior plaza of the Forrestal building is predominantly a pedestrian walkway with a bisecting roadway. In the test area, the 10.3 m (34 ft.) ceiling of the plaza houses 280 175 W mercury HID fixtures. Four fixtures are recessed within the corners of each of the square concrete coffers covering the ceiling (Figure 1). Forrestal facility records indicate that approximately ten years ago, the existing 175 W mercury HID lamps were placed in fixtures intended for the PAR type reflector lamps of a previous system. Several years later, the Forrestal plaza floor was retrofitted with thin concrete pavers on top of a thin, waterproof membrane. The fragility, and subsequent loading limitations, of the pavers and membrane makes lamp and fixture maintenance a labor intensive process. Consequently, minimal lamp maintenance has occurred, resulting in low illumination levels on the plaza floor.

The new sulfur lamp/light guide system, installed at the site, consists of two 5,900 W, microwave driven sulfur lamps[1] optically coupled to each end of a single 73 m (240 ft.) prismatic film lined light guide.[2] The light guide is positioned along the long central axis of the plaza and is suspended just below the ceiling girders.

Figure 1. Forrestal Plaza, U.S. Department of Energy

Methods

Horizontal illuminance levels were measured with Tektronix J17 illuminance meters on a regularly spaced grid beneath the central region of the plaza. The grid contained 343 measurement points on 3 m (10 ft.) centers over a 33.5 m (110 ft.) by 82.3 m (270 ft.) region (eight points omitted due to physical obstructions). The grid was centered to the north and south boundaries of the plaza ceiling and to the east/west positioning of the light guide. All measurements were taken at night to reduce ambient lighting and baseline data was taken with both lighting systems off. A random sampling of 30 data points was taken for both lighting system measurements to ensure reproducibility.

Energy consumption for the measured mercury system and the sulfur lamp system were determined by data provided by Fusion Lighting and the Forrestal facility staff. Estimates of materials, maintenance requirements, and their associated costs were based on information provided by Fusion Lighting, Forrestal facility staff and Frank Florentine, lighting designer of the National Air and Space Museum and on calculations performed by researchers at LBL.

Results

The sulfur lamp/light guide system provides an average illuminance of 137 lux over the work plane with an 11.8 kW power load. The existing mercury HID lighting system provides an average illuminance of 33.7 lux with a 49.0 kW power load (Table 1). At the average Forrestal energy rate of 5.5¢/kWh, the sulfur lamp/light guide system will save nearly $9,000 each year in energy costs, while providing four times the light level.

Table 1. Measured Forrestal Illuminance

	Total System Power (Watts)	Total Lumens on Workplane	Workplane Area (m^2)	Coefficient of Utilization (workplane lumens/ total lamp lumen output)	Average Illuminance (lux)
Mercury system	49,000	92,961	2,760	0.09*	33.7
Sulfur lamp system	11,800	378,000	2,760	0.42	137.0

* C.U. calculated from measured system performance

As outlined in the site description, numerous factors contribute to the significant differences in illuminance levels and power consumption between the two lighting systems. Because of the dilapidated condition of the Forrestal building's previous lighting system, it does not offer a completely meaningful photometric comparison to the performance of the new sulfur lamp/light guide system. For this reason, hypothetical scenarios have been developed that represent the likely performance of two other feasible lighting designs (Table 2). One scenario characterizes the expected photometric results had the Forrestal's existing, poorly maintained mercury HID system simply been retrofitted with new mercury lamps and appropriate fixtures. A second scenario presents the predicted performance of what would have been an energy-efficient retrofit alternative to the sulfur lamp/light guide system; 100 W metal halide fixtures surface mounted in the centers of the concrete ceiling coffers, which currently each house four 175 W recessed mercury lamps in their corners.

Table 2. Forrestal Scenarios

Parameters (footnote)	**Case 1** Measured Mercury System	**Case 2** New Mercury System	**Case 3** New Metal Halide System	**Case 4** Sulfur Lamp System
Initial lamp lumens(1)	7,000	8,500	8,000	450,000
Lumen depreciation factor (2)	0.60	0.89	0.75	0.92
Fixture efficiency(3)	0.27	0.50	0.77	0.7
Fixture dirt depreciation factor(4)	0.55	1	1	1
Light pipe efficiency(5)	N/A	N/A	N/A	0.6
Ceiling factor(6)	0.63	0.68	0.95	1
Number of lamps(7)	239	280	70	2
Total lumens on work plane(8)	92,961	720,188	307,230	347,760
Work plane area (sq. m.)(9)	2,760	2,760	2,760	2,760
Average illuminance (lux)(10)	33.7	261.0	111.3	126.0
Lamp power (Watts)(11)	175	175	100	5900
Ballast power (Watts)(12)	30	30	27	N/A
Total system power (kW)(13)	49.00	57.40	8.9	11.8
Source efficacy (lumens/W)	34.0	41.5	63.0	76.3
Coefficient of utilization(14)	0.17	0.34	0.73	0.42
Lumens/Watt over work plane	1.90	12.50	34.6	29.5

Footnotes:

1) Initial lamp lumens
Case 1: H39KC-R175/WDX.
Case 2: H39KC-175/DX.
Case 3: M57-175/U.
Case 4: Fusion Lighting.

2) Lumen Depreciation Factor
Case 1: IES Handbook, 1993.
Cases 2-3: Mean lumens, manufacturer specs.
Cases 4: Fusion Lighting, system maintenance factor.

3) Fixture Efficiency
Case 1: Estimate based on fixture/lamp combination.
Cases 2 & 3: IES Handbook, 1993.
Case 4: Fusion Lighting, August 9, 1994.

4) Fixture Dirt Depreciation
Case 1: IES Handbook, 1993.
Cases 2-4: Nominal depreciation, regularly maintained.

5) Light Pipe Efficiency
Cases 1-3: No effect.
Case 4: Total lumens out of light pipe/total lumens from fixture.

6) Ceiling Factor (coffer loss)
Cases 1-3: LBL calculation based on light distribution from fixture in relation to ceiling cavity geometry.
Case 4: No effect.

7) Number of Lamps
Case 1: 239 lamps (# of lamps operational during measurements).
Cases 2: 280 lamps (4 lamps per coffer).
Case 3: 70 lamps (2 lamps per coffer).
Case 4: 2 lamps.

8) Total Lumens on Work Plane - Cases 1-4: Factors 1-6 multiplied by number of lamps.

9) Work Plane Area - Equal for all cases, 29,700 s.f.

10) Average Footcandles over Workplane - Total Footcandles/Work Plane Area

11) Lamp Power Consumption
Cases 1-2: 175 watts, lamp only.
Case 3: 100 watts, lamp only.
Case 4: 5900 watts, total power per lamp system.

12) Ballast Power -
Cases 1 - 3: Ballast manufacturer data.
Case 4: No factor, inclusive in factor 11.

13) Total System Watts Consumed -
Cases 1 - 3: (Lamp Power + Ballast Power) x # of lamps.
Case 4: Lamp Power x 2 lamps.

14) C.U. approximated as:
Cases 1-3: Fixture efficiency X ceiling factor.
Case 4: Fixture efficiency X light pipe efficiency.

Case 1 - The 'measured mercury' system is the pre-existing mercury HID lighting system at the Forrestal plaza. The lighting installation is approximately eight years old and has been poorly maintained. Many of the lamps are quite old resulting in significant lumen depreciation. The fixtures have not been cleaned regularly and being in an outdoor location with nearby car traffic, optical losses have resulted. Compounding the inefficiencies of the system, the 175 W mercury HID lamps are housed in fixtures originally designed for reflector style PAR lamps resulting in a poor fixture efficiency. The lamp fixtures are recessed within low reflectivity concrete coffers roughly 10.3 m (34 ft.) above the plaza floor. The installation has 280 lamp fixtures in place, however,41 lamps were burned out at the time of measurement, leaving only 239 operational lamps.

Case 2 - The 'new mercury system' is a hypothetical lighting scenario which models relamping of the pre-existing 175 W mercury HID's with new mercury lamps of the same wattage. Complete relamping would raise the number of operational lamps from 239 to 280. This retrofit scenario also includes replacing the existing PAR lamp reflectors with ones appropriate for an HID downlight application. This would result in not only a higher fixture efficiency but, as well, an improved ceiling factor as a result of a more suitable flux distribution.

Case 3 - The 'new metal halide system' is a hypothetical scenario that would utilize seventy 100 W metal halide fixtures surface mounted to the center of each of the concrete ceiling coffers currently housing the existing mercury system. This scenario not only utilizes a more efficacious source but, as well, improves the optical efficiency of the system. By surface mounting rather than recessing the metal halide lamps, and by bringing them to center, rather than to the corners of the low reflectivity ceiling coffers, the coefficient of utilization is significantly enhanced.

Case 4 - The 'sulfur lamp system' is the existing sulfur lamp/light guide system as installed by Fusion Lighting and measured by LBL's Lighting Research Group. The system consists of two 5900 W microwave driven sulfur lamps optically coupled to both ends of a single 73 m (240 ft.) prismatic hollow light guide spanning the central length of the Forrestal plaza.

Discussion

The Forrestal plaza provided an ideal location to demonstrate the advantages of the sulfur lamp/light guide system over the existing 280 lamp mercury HID system. However, our analysis shows that a properly designed metal halide lighting system would currently exceed the system efficacy of the sulfur lamp/light guide demonstration system.

It is shown by case 2, that simply relamping the mercury system and providing appropriate fixtures is not an ideal scenario. While efficiency is improved by using new lamps and appropriate fixtures, this system would provide an unnecessarily high level of illumination with subsequently unwarranted energy consumption. This leads to the thought that the relamping could be more appropriately done with 100 W lamps rather than with the 175 W lamps of the original design. It is calculated that this system would provide an average work plane illuminance of 122.7 lux and require 35.0 kW of electrical power.

While the 100 W mercury system would supply a more reasonable illumination level, its energy consumption would still be greater than necessary. This inefficiency can be ameliorated with a retrofit that uses a more efficacious source and a better optical configuration as is achieved by the case 3 scenario.

Although conventional HID lighting systems are capable of illuminating large areas at energy consumption rates comparable to the sulfur lamp/light guide system, initial costs and annual maintenance costs must also be considered.

The dual sulfur lamp – 73 m light guide demonstration system was installed for a total cost of approximately $100,000. Annual maintenance requirements for this system can be separated into two components; light guide maintenance and light source maintenance. The light guide's exterior surface is smooth plastic, that can simply be hosed down from the plaza floor. Costs for cleaning are site specific, yet the labor required to maintain the light guide portion of system is estimated to be no greater than one man-day each year. The sulfur lamps themselves are engineering prototypes, therefore, the annual maintenance requirements are unknown. LBL researchers estimate the labor costs will add an additional one man-day per year with nominal material costs.

A replacement HID lighting system of 280 mercury lamps and fixtures is estimated to cost over $500,000 for materials and labor. A reconfigured lighting system of 70 metal halide lamps placed in the center of each ceiling coffer is estimated to cost near $450,000 for materials and labor. These figures were based on the Means cost guide. Labor is the cost driver in these two scenarios, and remains so for the annual maintenance requirements of multiple lamp lighting systems.

The high ceiling and fragile floor of the Forrestal plaza requires special equipment and procedures for lamp maintenance. Forrestal facility staff estimate that annual maintenance for a 280 lamp system would require 18 man-days in labor costs in addition to any material costs for lamp or ballast failure. Comparatively, a 70 lamp system would require roughly 5 man-days plus materials for annual maintenance.

Summary

The sulfur lamp/light guide lighting system installed in the plaza of DOE's Forrestal building demonstrates a novel lighting system which has provided significantly increased illumination levels and reduced energy consumption over the pre-existing mercury HID lighting system. A properly designed metal halide lighting system would exceed the efficacy of the prototype sulfur lamp/light guide system with nominal differences in maintenance costs. A main advantage of installing the sulfur lamp/light guide system in this scenario is the incurred initial costs. An HID lighting system retrofit at the Forrestal building would be very labor intensive, thus making its initial costs well above that of the demonstration prototype.

Lighting systems, like the sulfur lamp/light guide, that utilize a small number of high lumen sources coupled to a low maintenance distribution system, are ideal for areas with restrictions on access to the light sources.[1] Additionally, the linear source aspect of the light guide aids in reducing glare by emitting light over a large region, rather than from concentrated point sources. It is important to consider that a comparison between a state-of-the-art metal halide system to an engineering prototype does not take into account advances in technology currently under way. In examining the source efficacies (Table 2), note that the sulfur lamp is operating at 73.6 lumens per plug watt.[3] Recent developments in sulfur lamp technology indicate that a 1000 W sulfur lamp is now operating at 100 lumens per plug watt. With this increased source efficacy, a sulfur lamp/light guide system would exceed the performance of a new metal halide lighting system.

We anticipate further development of sulfur lamps coupled to light guide distribution systems through collaborative efforts between Fusion Lighting, Dr. Whitehead and researchers at LBL's Lighting Research Group. Future directions include increasing the lamp to light guide coupling efficiency, increased light source efficiency and enhanced fixture efficiency.

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