Lighting Retrofit Monitoring for the Federal Sector - Strategies and Results at the DOE Forrestal Building

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Pacific Northwest Laboratory (PNL), the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP), and Potomac Electric Power Company (PEPCO) have been conducting short-term monitoring studies at the Forrestal Building, headquarters of the DOE, since 1990. These studies were an integral part of the Shared Energy Savings (SES) lighting retrofit project completed in 1993. The overall goal of the project was to reduce electricity consumption at the Forrestal Building. One objective of the project was to use the building as a model for other federal SES lighting retrofit efforts.

A complete short-term monitoring strategy in support of the SES project was developed. The strategy included baseline measurements of electrical consumption, performance measurements of proposed retrofits, and post-retrofit measurements of electricity consumption. Measurements included power consumption, power harmonics, and lighting levels. The results show a 56% reduction in electrical power consumed for lighting, as well as improved power quality and increased lighting levels.

Introduction

The Forrestal Building, U.S. Department of Energy (DOE) headquarters in Washington, D.C., was considered in late 1989 for a shared energy savings (SES) demonstration. The SES project was to focus on improvement of lighting systems in the building to reduce energy costs. The proposed SES project would not only retrofit the Forrestal Building's aging lighting systems (vintage mid-1960s) with newer energy-efficient lights, but would also serve as a major demonstration project for the rest of the federal sector.

The Forrestal Building was constructed in the late 1960s and occupied in the early 1970s. It appears as three separate structures on a connecting paved courtyard that includes a roadway. The structures are often referred to as the North, South, and West buildings. The buildings contain 1.7 million gross square feet, of which 1.14 million square feet are occupiable assigned areas.

The building is air-conditioned by fan coil units on the perimeter and air-handling units serving the interior zones. The units are provided with hot water for heating and chilled water for cooling. Both the hot and chilled water are supplied to the building by a General Services Administration (GSA) central distribution system that serves a number of federal buildings in the heart of Washington, D.C. Because of the building's connection to a district heating and cooling source, graphic representations of its electrical consumption typically show the classic "hat-shaped" load profiles often associated with lighting and plug loads. These profiles show minimal seasonal variation.

The building electrical systems are powered by a single 13.2-kV service entrance from Potomac Electric Power Company (PEPCO). Electricity is provided to building systems through five nominal 480/277-V, three-phase, four-wire switchboards. More than 80 transformers are distributed throughout the building to provide 11 O-V service to plug and appliance circuits. Most of the lighting is 277-V fluorescent supplied with electricity by 131 panels. The 110-V transformers are fed from a subset of the lighting panels. Common risers makes the lighting energy disaggregation impossible except at the point of delivery (the lighting panels).

Monitoring Strategy

In support of the DOE Federal Energy Management Program (FEMP), Pacific Northwest Laboratory (PNL) conducted energy use monitoring efforts that would (1) assist in the development of the SES request for proposal (RFP) from potential lighting retrofit contractors and (2) provide empirical data that could be used to confirm predicted results. To accomplish these goals, three distinct but integrated monitoring activities were planned:

- baseline monitoring of the existing lighting loads
- performance monitoring of any proposed lighting retrofits
- post-retrofit monitoring of the new lighting loads.

Each of these three activities is discussed in turn below.

Baseline Monitoring

The first step at the Forrestal Building was to establish the baseline lighting loads. The baseline profiles would not only provide prospective bidders some idea of the magnitude of the lighting retrofit, but also provide DOE with an empirical pre-retrofit measurement of the lighting loads that could be used to evaluate the success of the retrofit. A number of different field data collection strategies were proposed, but most were deemed to be unacceptable in terms of cost or extent of disruption to the building occupants. The final decision was to implement a hybrid strategy that combined short-term (24-hour) monitoring of a subset of the 131 lighting panels with a one-time ("snapshot") measurement from each of the remaining panels.

Nine industry standard data loggers were equipped with split-core current transformers; clip-on voltage probes were prewired to each data logger. A common set of data logger parameters was developed for all data loggers, and software macros to streamline data collection and review were developed. The strategy for this monitoring was to install and move the loggers approximately every 24 hours. The loggers were moved during periods of small load variation, which allowed easy and accurate filling of any missing records. The panels selected for monitoring were chosen to provide a good representative sample of the building.

Those panels not monitored with data loggers were subjected to two sets of measurements with industry standard portable hand-held voltage and current meters to evaluate the lighting loads during occupied and unoccupied periods. True root-mean-square (RMS) meters were used to provide accurate measurements for these conditions.

Initial field measurements were taken from May 14 through May 23, 1990, in the Forrestal Building. Data processing took place during summer 1990. Data processing activities included entering the one-time measurements into spreadsheets, subtracting plug transformer loads from total lighting panel loads to yield net lighting panel loads, and creating typical weekday and weekend profiles for the lighting loads. A total of 50 panel profiles were used to create the weekday load, while 9 panels contributed the profile data for the weekend load. The profiles were then adjusted upward by the results of the one-time measurements to account for panels that were not monitored with the data loggers.

The lighting and plug profiles obtained in the baseline monitoring were combined with a series of one-time measurements (provided by DOE staff) of major Forrestal Building equipment loads, to produce an estimated total building profile that could be compared with utility billing data for the building. Details of the building's lighting load baseline measurements were included in the RFP sent to potential lighting retrofit contractors (Stoops et al. 1990; Mazzucchi 1992).

Performance Monitoring of Proposed Retrofits

The second step at the Forrestal Building was to technically evaluate the bids received in response to the RFP. Four contractors bid on the SES contract, and arrangements were made to perform a live test demonstration (LTD) of each contractor's proposed retrofit package. The strategy was to empirically evaluate the contractor's advertised energy savings.

To implement this strategy, a single office in the building was set up as a test room. The office, nominally 10 ft by 15 ft, was equipped with six existing light fixtures specially wired to allow convenient measurement of the lighting load at each fixture. The fixtures were set up to represent the mix of ballasts and tubes believed to be found in the Forrestal Building. Original old ballasts were mixed with newer "energy-saving" ballasts, and a specified mix of 34-W and 40-W T-12 tubes was used. In addition, one fixture was delamped and left with a live ballast while another was delamped and left with no ballast to represent the entire spectrum of fixtures in the building. This specified configuration of the test room provided a baseline against which the proposed retrofits could be evaluated. Figure 1 shows the test room layout.

The RFP explicitly listed three requirements: (1) power consumption must be at least 20% lower than baseline power consumption in the test room; (2) lighting levels at 30 in. above the floor must be at least 50 foot-candles on the work surface and 30 foot-candles in other areas of the

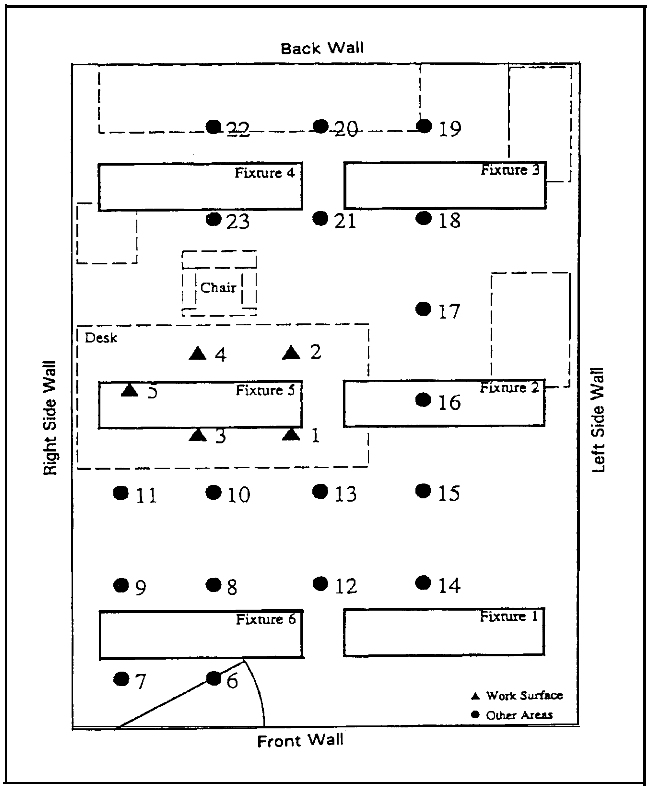

Figure 1. Live Test Demonstration Layout

room; and (3) the retrofit must not degrade any aspect of building performance below current levels. The third requirement was geared primarily toward total harmonic distortion (THD) levels associated with the lighting system.

The process in this phase of the monitoring was to measure the baseline performance of the test room, allow the retrofit contractor to install the proposed retrofit, and repeat the required measurements. Once measurement of the retrofit was complete, the test room was restored to its original configuration and the process was repeated for the next contractor. An additional set of measurements, based on the most energy-efficient technology available to the building maintenance staff, was taken to compare the retrofits with current maintenance practice.

Power measurements were taken with an industry standard data logger configured with 1% tolerance, 5-ampere current transformers, and power transducers. Lighting measurements were taken with an industry standard lighting meter. Power quality measurements were taken with industry standard power quality monitoring equipment.

Two series of tests were conducted, one from March 9 through March 16, 1992, and the other between August 3 and August 6, 1992. The second set was requested by two of the bidders after changes were made to the PEPCO ballast rebate schedule in June 1992. Evaluations included measurement of lighting power consumption for the room as a whole and for each individual lighting fixture, lighting levels at 23 locations in the test room, and power quality. The test process is described in detail in Halverson, Schmelzer, and Parker (1993) and Halverson, Schmelzer, and Harris (1993).

Post-Retrofit Monitoring

The third step at the Forrestal Building was to evaluate the lighting load after the retrofit. A retrofit contractor was selected in November 1992, with the retrofit scheduled for spring and summer 1993. The retrofit was completed in September 1993; post-retrofit monitoring was conducted from October 23 through November 3, 1993. (Because of the office and lighting control configuration in the Forrestal Building, the seasonal impact of daylighting is minimal.) Sixty-five 277-V lighting panels were metered to determine the lighting profile. An additional 64 were given one-time occupied and unoccupied period measurements. (Reconfiguration of the Forrestal Building in the period between the baseline and post-retrofit measurements had resulted in the removal of two electrical panels.) Procedures, equipment, and data processing for the post-retrofit monitoring were similar to those for the baseline monitoring. Because of a lack of new building equipment loads and the addition of a new daycare center in the Forrestal Building complex, no attempt was made to derive an estimated total electrical profile.

Results

Baseline Monitoring

The results of the baseline monitoring were detailed weekday and weekend end-use profiles of the Forrestal Building electrical consumption. These profiles can be combined to give an estimated annual breakdown of electrical usage. Figure 2 shows a typical working day demand profile (based on 15-minute metered end-use data collected during the baseline work).

One of the striking features of Figure 2 is the relatively large portion of the maximum lighting load that occurs 24 hours a day. It is obvious from Figure 2 that a large amount of lighting is left on continuously. One reason for this is a mismatch between switch location and the current office configuration; the lighting fixtures in many offices are controlled by switches in adjacent offices.

Figure 3 shows the estimated weekend profile. Figure 4 shows the annual electrical consumption baseline, with lighting consuming about 33% of the building total, followed by fans at 25% and plug loads at 11%.

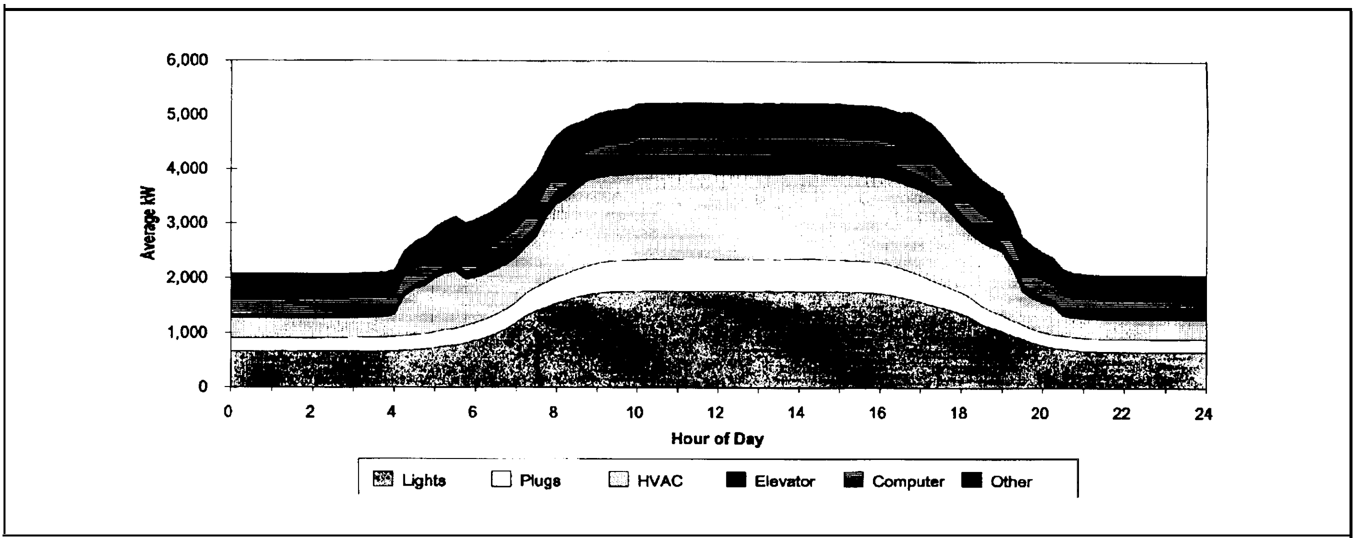

Figure 2. Baseline Weekday Profile

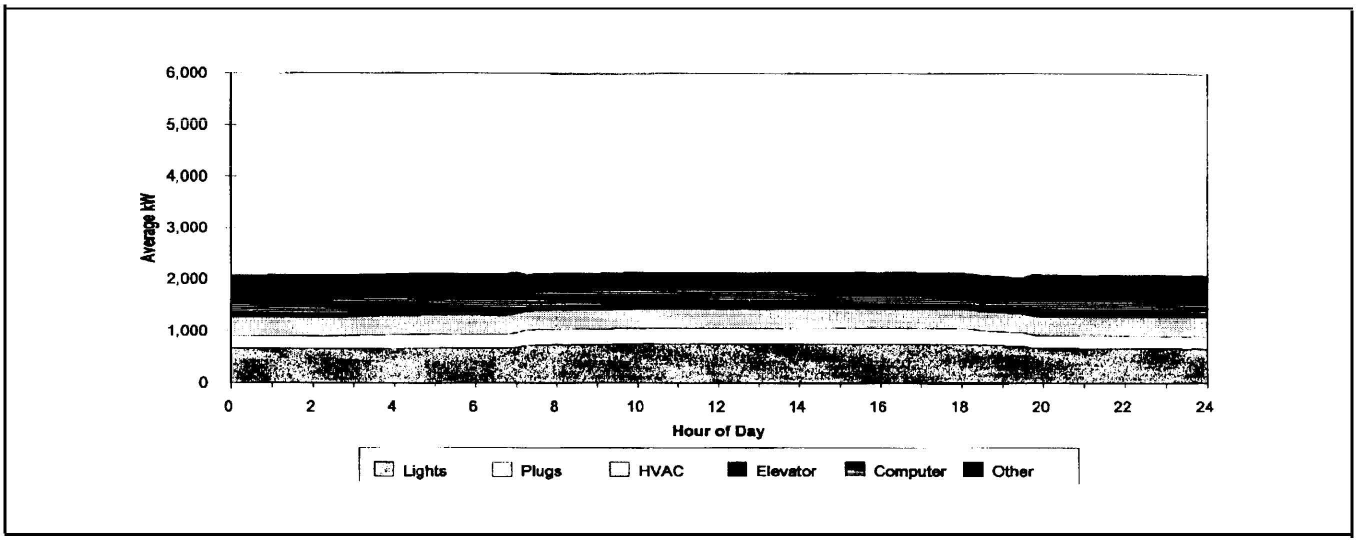

Figure 3. Baseline Weekend Profile

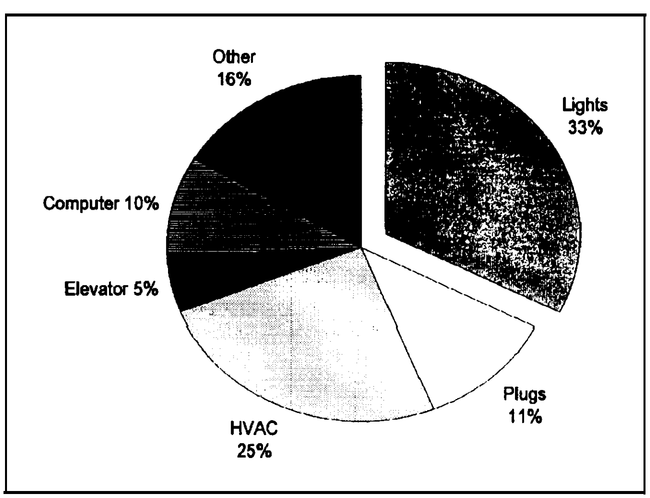

Figure 4. Baseline Annual Electricity Consumption

Performance Monitoring of Proposed Retrofits

The results of the live test demonstrations are a series of tables and figures that compare the proposed retrofit packages with the test room baseline. Table 1 shows the power consumption for each of the proposed retrofit packages evaluated in the LTD. The four contractors are labeled *A, B, C,* and *D,* with the baseline labeled *Base* and the best technology available to the maintenance staff labeled *ESBase* (for energy-saving baseline).

Table 1 also shows the percentage reduction in the lighting power achieved by each potential retrofit. Note that all four of the bidders on the SES contract easily met the requirement to reduce lighting power by at least 20%. All bidders proposed to use T-8 tubes, electronic ballasts, and

Table 1. Live Test Demonstration Energy Reduction Results

Retrofit Option	Demand W	Reduction	Power Density W/ft^2
Base	335	-	2.23
Contractor A	113	66%	0.75
Contractor B	101	70%	0.67
Contractor C	108	68%	0.72
Contractor D	144	57%	0.96
ESBase	285	12%	1.97

silvered reflectors in the retrofit, leading to very similar results for all contractors. The energy-saving baseline available from Forrestal Building maintenance staff consisted of energy-saving magnetic ballasts and 34-W T-12 tubes. This option did not meet the required savings.

Table 1 lists the calculated lighting power density in the test room for each retrofit. For an enclosed office, such as the one used as the test room, federal energy standards for new construction require a maximum lighting power density of 1.3 W/ft^2 (10 CFR 435 1989). It is interesting to note that the proposed retrofits for the Forrestal Building are well below the federally-mandated requirements for new construction.

Table 2 shows the lighting levels achieved for each of the proposed retrofits. Note that all bidders again met the requirements of 50 foot-candles on the work surface and 30 foot-candles in the rest of the room. The energy-saving maintenance baseline did provide the required illumination levels. Figures 5 and 6 provide details of the uniformity of illumination present in the test room, both in the baseline case and for contractor D (the ultimate winner of the SES contract). Comparison of Figures 5 and 6 reveals that the illumination levels of the retrofit are much more even, resulting in a more pleasant environment for building occupants. The improvement in illumination level is attributable to the use of parabolic reflectors in the retrofitted fixtures and to the use of all six fixtures in the retrofit. (As noted before, the baseline case for the test room included two delamped fixtures.)

Again, all proposed retrofits and the energy-saving maintenance baseline met the requirements of maintaining power quality at baseline levels. It is interesting to note that the energy-saving maintenance baseline (employing new magnetic ballasts), with the highest power consumption of the proposed retrofits, by far has the lowest THD of the retrofits. This is the result of the

Table 2. Live Test Demonstration Average Illuminance Results

Retrofit Option	Work Area foot-candles	Other Areas foot-candles
Base	49.1	37.6
Contractor A	61.0	44.7
Contractor B	54.2	38.9
Contractor C	54.6	40.5
Contractor D	58.0	51.3
ESBase	56.6	43.3

higher THD for electronic ballasts in the four retrofit Figure 7 shows the results of the power quality testing performed during the LTD. bids. The high values of THD measured in the test room original baseline reflect the use of very old magnetic ballasts.

Post-Retrofit Monitoring

The results of the post-retrofit monitoring are shown in Figures 8 and 9. Figure 8 shows the estimated post-retrofit weekday lighting profile with the baseline weekday lighting profile superimposed. The estimated savings in peak demand is 53.5% of the total lighting load, with daily consumption reduced 55.4 %. Figure 9 shows the results for the estimated weekend lighting load, with demand savings estimated at 49.6% and consumption savings at 57.4%. On an annual basis, the savings are estimated to be 56.0%. Based on the baseline lighting load, savings of just over 5 million kWh/yr are expected from the retrofit.

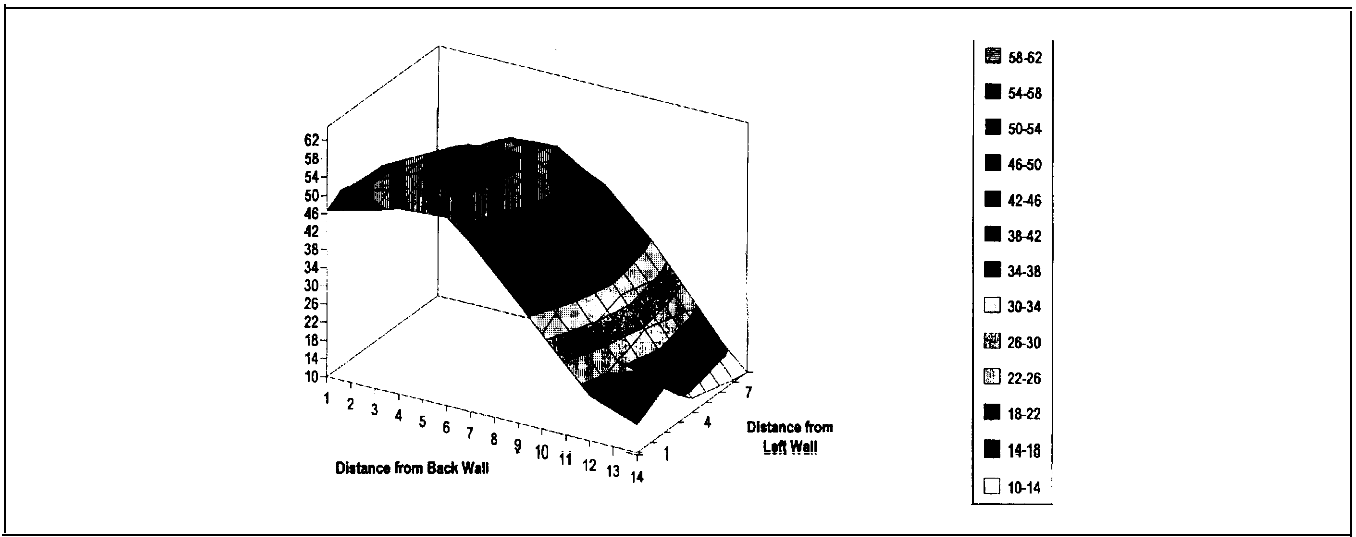

Figure 5. Live Test Demonstration Baseline Illuminance

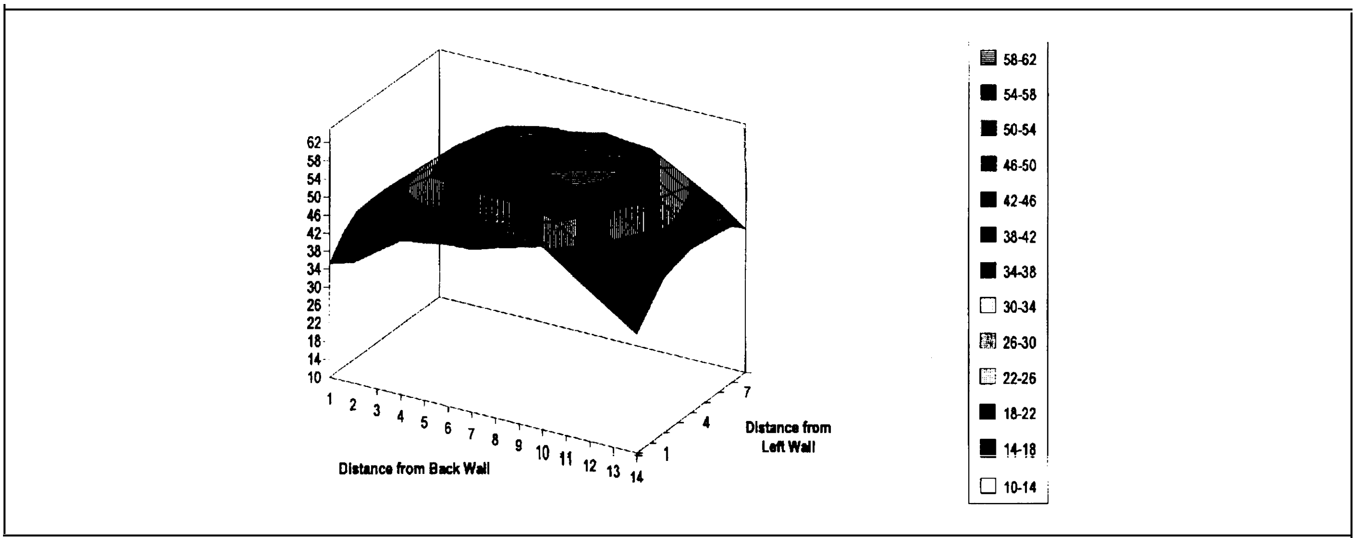

Figure 6. Live Test Demonstration Retrofit Illuminance

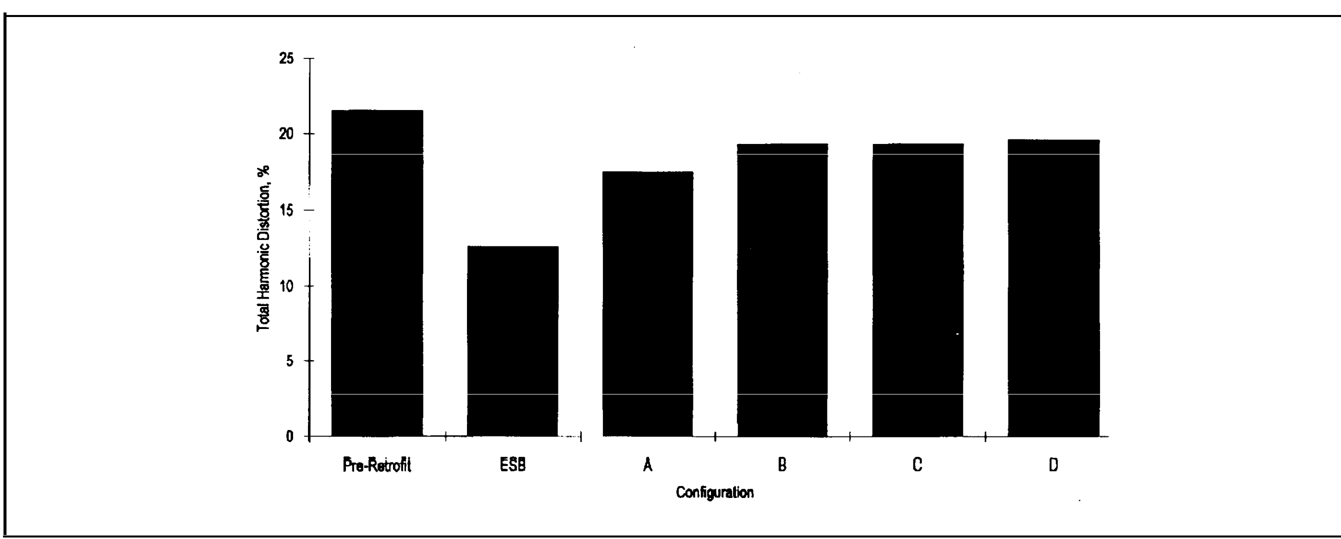

Figure 7. Live Test Demonstration Total Harmonic Distortion

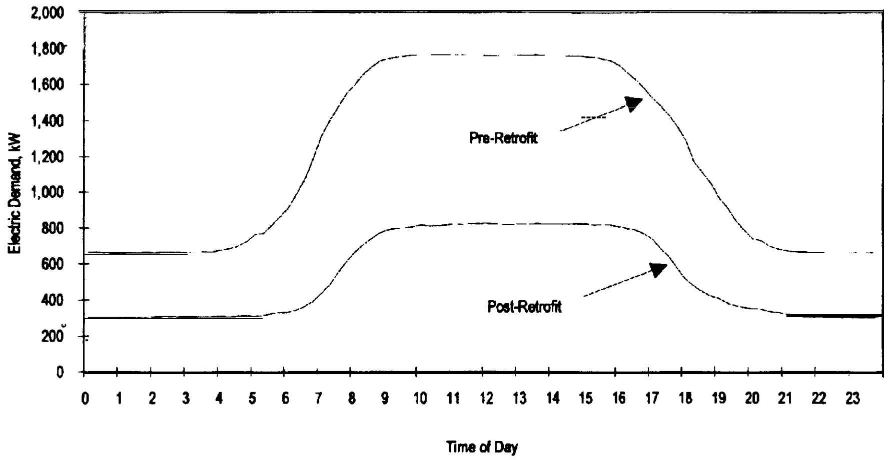

Figure 8. Post-Retrofit Weekday Profile

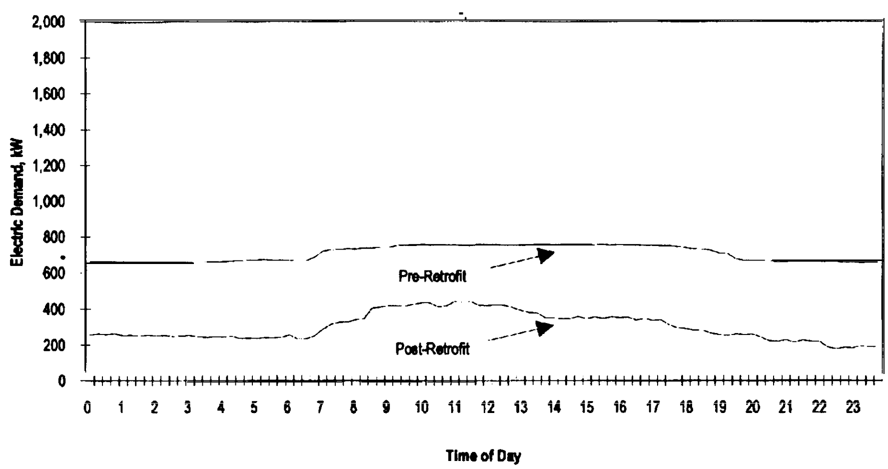

Figure 9. Post-Retrofit Weekend Profile

A separate appraisal of the retrofit savings was made by DOE staff and reported in trade journals (Nelson 1993). This evaluation used detailed fixture audit information, the results of the LTD, and engineering estimates to calculate an estimated 63% annual energy savings and a total savings of just under 5.7 million kWh/yr. These savings included the effects of the lighting retrofit evaluated in the LTD and the effects of • 349 motion sensors that were installed in the Forrestal Building during the retrofit. The general agreement between the LTD results, the post-retrofit monitoring, and the separate evaluation is shown in Table 3.

A comparison of baseline and post-retrofit panel one-time measurements (for panels with one-time measurements in both monitoring periods) also yielded a savings estimate of 63% of the total lighting load.

Table 3. Comparison of Various Retrofit Evaluations

Evaluation	Predicted Annual Savings	
Live Test Demonstration	57%	(without motion sensors)
Post-Retrofit Monitoring	56%	(with motion sensors)
Audit and Calculation	63%	(with motion sensors)

Conclusions

DOE's Forrestal Building in Washington, D. C., successfully awarded a performance-based shared energy savings contract for retrofit of office and hallway lighting systems. Energy savings for the project have been estimated at 63% of the lighting load and independently measured at 56% of the lighting load, yielding an independent and empirical measure of the savings. The estimated and measured savings were also in good agreement with the test results for a typical single office.

The lighting retrofit must be considered a major success for all parties involved. For DOE, the lighting retrofit has led to increased lighting levels and greatly decreased lighting power consumption while maintaining power quality in the building. Anecdotal comments from building occupants indicated great satisfaction with the retrofit. Estimated annual savings to DOE from the lighting retrofit are approximately $400,000. From the utility perspective, the 53.5% reduction in weekday peak lighting electrical demand at the Forrestal Building is sufficient incentive for the activity. Because lighting accounts for approximately a third of the electricity use at the Forrestal, this savings translates to a reduction in peak daily demand of about 1,300 kW.

Finally, the Forrestal Building lighting retrofit represents a major step in the federal government's goal to reduce energy consumption 20% by the year 2000. The building is in many ways typical of the federal building stock, so the Forrestal Building's shared energy savings contract can serve as a model for other federal agencies.

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