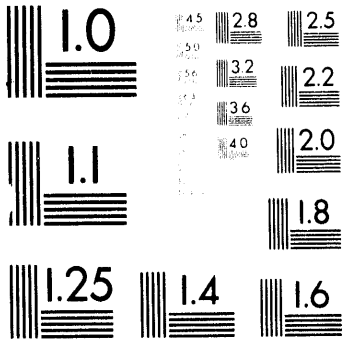
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THE LIVE TEST DEMONSTRATION (LTD) OF LIGHTING RETROFIT TECHNOLOGIES AT THE DOE FORRESTAL BUILDING

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(a) U.S. Department of Energy, Washington, D.C.

The Live Test Demonstration (LTD) of Lighting Retrofit Technologies at the DOE Forrestal Building

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Introduction

The James B. Forrestal Building is a 1.7-million-square-foot office building located in Washington, D.C., that serves as the headquarters building for the U.S. Department of Energy (DOE). In late 1989, a shared energy savings (SES) relighting project was proposed for the Forrestal Building. The proposed project would not only serve to retrofit the Forrestal Building's aging lighting systems (vintage mid-1960s) with newer energy-saving lights, but would also serve as a major demonstration project for the Federal Relighting Initiative operated by the Federal Energy Management Program (FEMP) at DOE.

In 1990, Pacific Northwest Laboratory (PNL)[a] performed the first of three planned metering activities at the Forrestal Building. This activity included establishment of baseline electricity usage at the Forrestal Building and end-use disaggregation of that usage. Usage was broken down into lighting, plug loads (office equipment), HVAC Motor Control Center, elevators, main frame computers, and other loads (cafeteria, telephone system, etc). Since the Forrestal Building is served by district hot water and chilled water, the HVAC electrical loads are primarily fan loads. The results of the baseline work are presented in detail in Stoops et al. (1990) and Mazzucchi (1992).

Figure 1 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 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 on all the time.

A request for proposal (RFP) for the proposed SES lighting retrofit was issued in May 1991. This proposal contained the results of the baseline metering for use by potential bidders and also described the live test demonstration (LTD) that would be required of all qualified bidders. The technical requirements of the LTD are summarized as follows:

- The power consumption of each retrofit must be at least 20% lower than the baseline power consumption in the room when configured as described in the RFP.
- The lighting levels measured at 30 inches above the floor must be at least 50 footcandles on the part of the work surface that is at least 18 inches from the wall and at least 30 footcandles in the other areas of the room.
- The retrofit may not degrade any aspect of building performance below the current levels. This requirement is related primarily to total harmonic distortion (THD) levels associated with the lighting system.

The four contractors proposing on the lighting retrofit project were originally tested between March 9 and March 16, 1992. Changes to the Potomac Electric Power Company (PEPCO) ballast rebate schedule effective June 1992 led to two of the four contractors requesting additional

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

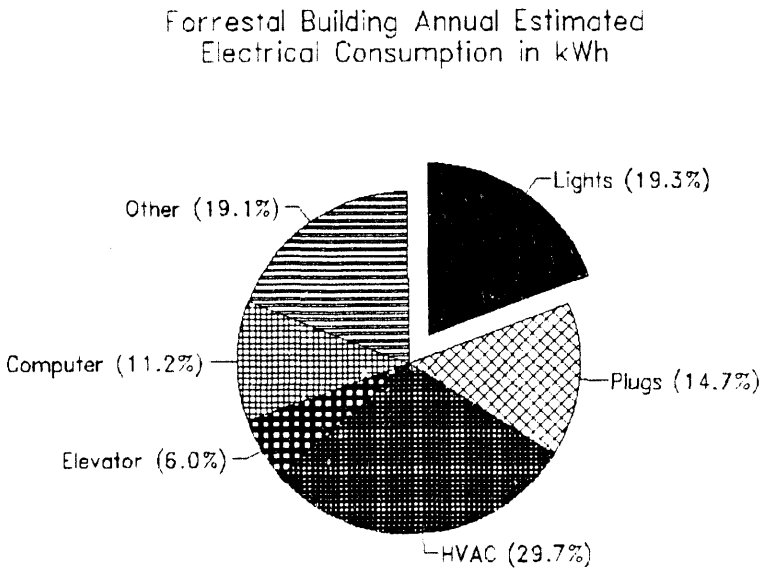

Figure 1. Baseline Annual Electricity Consumptic .

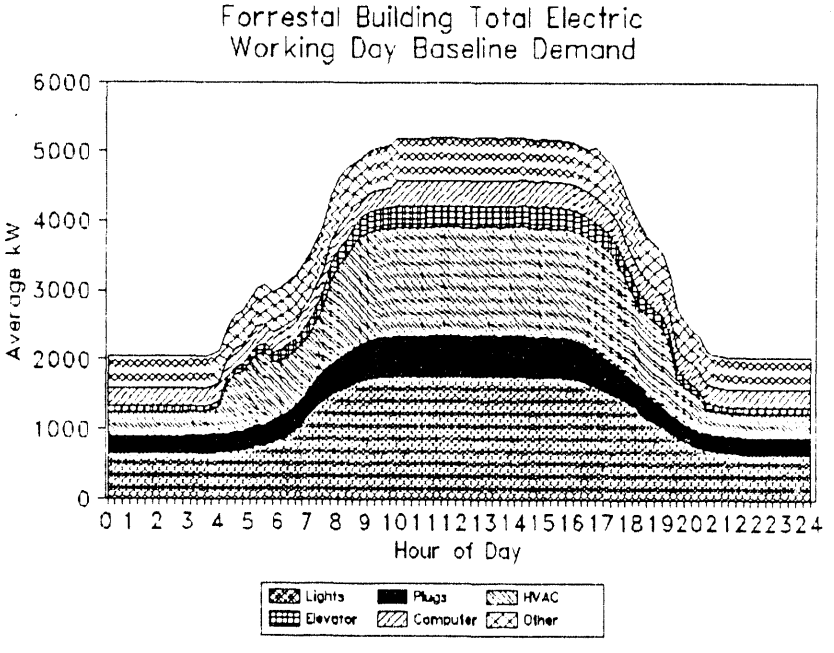

Figure 2. Baseline Working Day Electrical Demand

tests with different products. The retests took place from August 3 to August 6, 1992. The results shown here are from the final retrofit strategies submitted by the contractors.

Evaluations were made of the baseline performance of the room as configured in the RFP, each of the four proposed retrofits, and on a configuration representing the best technology currently available to building maintenance staff. During the test period, the room was unoccupied, but contained office furniture.

Evaluations included measurement of power consumption for the room lighting as a whole and for each lighting fixture in the room. Lighting levels were recorded at five locations on the work surface and 18 locations in the rest of the room. Power quality measurements were also taken on the room lighting system as a whole. Power consumption and lighting level (illuminance) were called out as direct requirements of the RFP. Power quality measurements were taken to ensure that the retrofits did not raise the total harmonic distortion above current levels.

This paper presents the results of the Forrestal Building LTD conducted during March and August 1992. Results are given for illuminance, power consumption, and total harmonic distortion.

Lighting Configurations

The office used for testing (Room 5E-080 in the Forrestal Building) was arranged with furniture as shown in Figure 3. The selected office contained six 2-foot by 4-foot two-tube drop-in light fixtures in a suspended acoustic tile ceiling.

Tests were performed on six different lighting configurations in the office. The six configurations included the baseline configuration (as specified in the RFP), four proposed retrofits (one by each contractor), and a configuration representing the best technology currently available to the building maintenance staff.

The baseline configuration was designed to represent the range and approximate mix of lighting fixture configurations currently found in the Forrestal Building. For the test room, the two lighting fixtures closest to the door (fixtures 1 and 6) were delamped by removing both tubes. Fixture 1 also had the ballast removed, but fixture 6 had a live ballast. Fixtures 2 through 5 each had two T12 tubes installed, with three of the tubes being standard 40W T12 and the other five tubes being "energy saving" 34W T12 tubes. A number of different manufacturer's tubes were used. One of the ballasts was an "energy saving" inductive ballast, but all other ballasts were original ballasts from the mid-1960s.

Four contractors submitted proposals for relighting the Forrestal Building. The retrofits proposed by the four contractors were remarkably similar. The retrofit strategy for all four contractors was to clean the fixtures, relamp the fixture with a single T8 tube, install a reflector, and tandem-wire two or more fixtures with a single electronic ballast. The specific combinations of lamps, ballasts, and reflectors installed by each contractor are given in Halverson, Schmelzer, and Parker (1993).

The only differences between proposed retrofits (aside from differences in the brands of tubes, ballasts, and reflectors chosen) were in the number and location of fixtures that were chosen for retrofit. The RFP for the Forrestal relighting contract specified lighting levels on the work surface and in the remainder of the room, but did not specify how many fixtures had to be illuminated to achieve the lighting levels. The RFP did specify a bonus for lighting all fixtures in each room, but this bonus was offered solely for aesthetic reasons (an illuminated fixture being visually more appealing than a darkened fixture). Three contractors chose to light four of the six fixtures in the LTD test room. The other contractor (ultimately the winning contractor) chose to illuminate all six fixtures in the test room.

At the conclusion of the March measurements, the room was equipped with new lamps and ballasts from existing maintenance supplies. This combination represents the best lighting technology available to the maintenance staff. Included in this combination were "energy saving" 34W T12 tubes and "energy saving" inductive ballasts.

Test Equipment

Power consumption was measured with a Synergistics C180 Survey Meter.[a] The power consumption was determined through the use of 1%-tolerance, 5-amp current transformers (CTs) connected directly to the lighting circuit wiring in the room. Additional power consumption measurements were provided by a Basic Measurement

(a) Synergistics Control Systems, Inc., New Orleans, Louisiana.

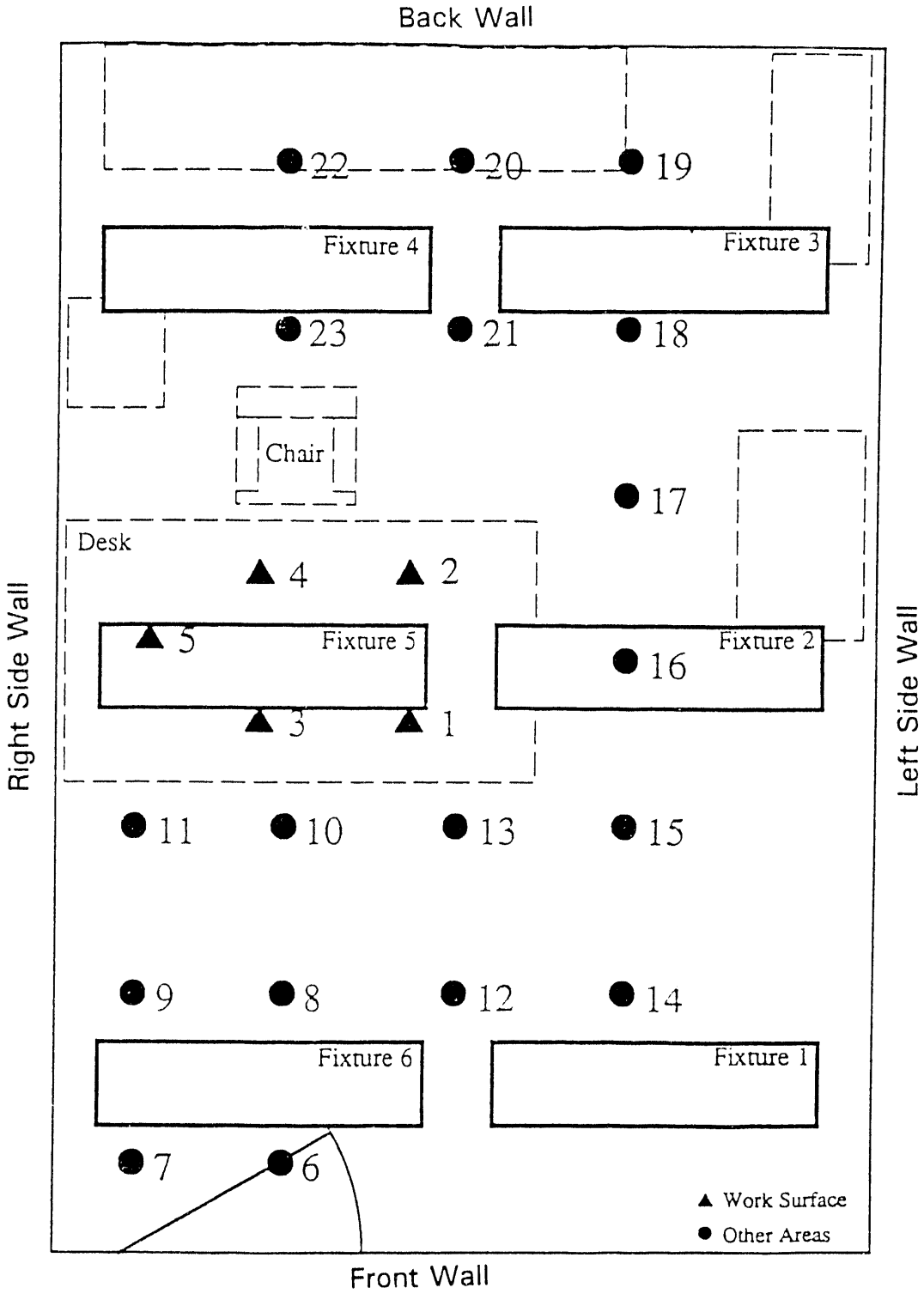

Figure 3. LTD Test Room Layout and Measurement Points

Instruments (BMI) 3060 Power Profiler[a] and by a Synergistics C180E Survey Meter.

The accuracy of the CTs is influenced by the magnitude of the current flowing through the current transformer. To increase the current and accuracy of the measurements, the wire carrying power for each individual fixture was looped through the CT five times. The current flowing in the wire to measure the total lighting power (of all six fixtures) was sufficient without looping through the CT. Due to expected measurement errors, the sum of the six individual circuit measurements is not identical to the single power consumption measurement of the total lighting power. The single total lighting power measurement is the most accurate description of the total lighting power in the room.

Illuminance (lighting level) was measured with a Photo Research LiteMate III® light meter.[b] The photometric accuracy of the instrument is listed by the manufacturer as +/-5%. The instrument was calibrated to National Bureau of Standards (NBS) traceable standards over the range of lighting levels found in the room (0 to 60 footcandles). Additional lighting level measurements during the March tests were provided by a second Photo Research LiteMate III® light meter.

Power harmonics measurements during the March tests were provided by a BMI 3060 Power Profiler equipped with a BMI A-115 Probe. The instrument was calibrated by BMI to factory specifications using NBS traceable standards. Additional power harmonic measurements during the March tests were provided by a Synergistics C180E Survey Meter. Based on comparisons between this instrument and the BMI during the March tests, the C180E was used both as the redundant power and the only THD measurement instrument for the August tests.

Test Procedures

The overall procedure of the test was to allow the contractors to install their proposed retrofit in the test room, conduct the tests outlined below, and then have the contractors restore the room to its original condition. Installation of the retrofit was typically concluded in a single morning, with testing and restoration occurring in the afternoon. All testing was conducted during normal operating hours of the building.

Power consumption was taken continuously throughout the period of testing with a C180 data logger connected directly to the power for room lighting using 1%-tolerance CTs. The test room was specially wired so that all six lighting fixtures were controlled by individual switches. Each fixture was monitored independently and a seventh measurement was taken of all six fixtures at once. Data were collected, read and recorded in real time prior to and during the testing and stored for future analysis on a portable computer. Data analysis was conducted shortly after each test to examine for reasonableness of the test results.

The fundamental illuminance measurement prescribed in the IES Lighting Handbook (IES 1984) is a light level measurement taken in a 2-foot square. There are numerous statistical sampling procedures listed in the Handbook for reducing the number of measurements that must be taken in a large room, but these procedures are used in determining the average illuminance in a room. Since the LTD requirements called for one illuminance level on the work surface and another in the rest of the room, an average room illuminance was not appropriate.

To meet the requirements of the Handbook, the work surface and other areas of the room were laid out in grids of approximately 2 feet (see Figure 3). Grids on the work surface (defined in discussions with DOE staff as the desktop only) were 25 inches by 19 inches and excluded the 18 inches closest to the wall (as required by the LTD). Grids laid out on the floor were 24 inches by 24 inches with the exception of the six points in the entryway near the door. These points were on a 21-inch by 24-inch grid due to the proximity of the door. Grid points were chosen to exclude locations deep in

(a) BMI, Inc., Foster City, California.
(b) Kollmorgen Instruments Corp., Chatsworth, California

corners or in between pieces of office furniture. The decision to exclude deep corners was consciously made after discussion with DOE staff. The resulting grid represents the areas of the room where occupant activity can be reasonably expected, other than the work surface. A map of all lighting level measurement locations is shown in Figure 3.

Discussions with DOE staff led to a decision to interpret the lighting level requirements as averages for the appropriate areas. Thus, the 30-footcandle requirement for the other areas of the room was taken as the average of the 18 light level measurements in the other areas. The 50-footcandle requirement for the work surface was taken as the average of the four desktop measurements that were at least 18 inches from the wall. All lighting retrofits were allowed to warm up for 1 hour prior to measurement.

Power harmonic measurements in the August test were taken continuously throughout the period of testing with a C180E data logger equipped with 1%-tolerance CTs. Additional power harmonics measurements in the March tests (only) were provided by a BMI Power Profiler equipped with calibrated probes. The main interest in this measurement was the total harmonic distortion.

Results

The results of the Forrestal Building LTD are summarized below. The four proposed retrofits, the baseline configuration of the room as described in the RFP, and a baseline representing the best technology currently available to the building maintenance staff (energy saving baseline [ESBase]) are compared.

Illuminance Results

Illuminance levels for each of the 23 locations in the room are shown in Table 1. Table 2 shows a number of statistics related to average illumination in various areas of the room. (See Figure 3 for locations of each measurement.) Note that the lamps used during the August testing of contractors C and D were not burned-in for the required 100 hours prior to testing. This will result in illuminance measurements for these two contractors being somewhat higher than what would be measured if the protocols in the LTD were followed. Therefore, a "derating" factor of approximately 1 to 2% should be applied to these illuminance measurements. Applying this derating factor results in lamps that, under the LTD test conditions, should produce at least 51 footcandles on the desktop and at least 31 footcandles in the rest of the room.

All proposed retrofits met the illuminance requirements of the LTD. Both the 50 footcandles on the work surface and the 30 footcandles in the other areas of the office were easily achieved by all proposed retrofits. This indicates that it should be possible to specify higher lighting levels in future RFPs and still achieve desired power reductions.

It is interesting to note that the baseline (Base) illumination almost met the LTD requirements for the work surface and met the other room illumination requirements, while the energy saving baseline (ESBase) met all illumination requirements of the LTD. Merely cleaning the lenses for the baseline case would likely have provided about 4 to 5 additional footcandles of illumination and would have allowed the baseline to meet the requirements of the LTD. There was no requirement in the LTD that the baseline illumination levels would in fact meet the LTD requirements.

In terms of uniformity of illumination on the work surface (as measured by the ratio of the minimum to maximum illuminance values on the work surface), all proposed retrofits exceed both the baseline (Base) and the energy saving baseline (ESBase). In the other areas of the room, only contractor B failed to improve the uniformity of illumination over baseline values. Uniformity of illumination is not a requirement of the LTD, however, so this calculation is for information purposes only.

Figure 4 shows a contour plot of the lighting levels in the test room during the baseline measurements. Figure 5 shows a contour plot of the lighting levels in the test room during testing of the winning contractor. Comparison of these two

Table 1. Illuminance Measurements, Footcandles

	Contractor						
	Location	A	B[a]	C[b]	D[b]	Base	ESBase[c]
Desktop	1	61.4	54.4	55.3	60.2	47.2	55.2
	2	61.2	58.3	55.0	60.1	53.1	62.0
	3	60.7	50.3	54.3	56.1	44.3	51.4
	4	60.5	53.7	53.6	55.7	51.7	57.8
	5	55.0	45.6	48.3	47.7	41.7	47.3
Floor	6	39.4	18.3	39.9	44.4	20.0	23.0
	7	36.1	13.7	34.3	36.2	16.1	18.8
	8	49.9	20.2	44.6	49.5	23.2	27.4
	9	46.2	17.4	41.5	43.2	19.9	23.3
	10	50.8	31.9	46.7	57.1	35.7	40.3
	11	47.4	29.1	43.5	50.6	30.9	35.4
	12	44.3	21.5	41.6	53.6	25.7	30.1
	13	48.8	35.3	44.4	60.4	38.2	44.2
	14	36.7	24.2	33.0	51.7	24.0	29.2
	15	44.2	35.2	39.6	58.0	36.5	42.3
	16	56.6	53.6	31.6	58.1	46.4	54.5
	17	46.6	51.1	43.9	57.4	51.8	60.2
	18	37.9	54.3	33.8	54.4	51.1	59.2
	19	31.3	57.5	27.4	45.3	46.0	54.0
	20	41.1	62.6	35.9	47.3	50.3	57.9
	21	47.8	58.1	40.9	56.2	55.6	62.9
	22	47.7	59.9	40.7	46.3	50.3	56.0
	23	52.5	56.4	45.9	53.8	54.7	60.9

(a) Contractor B chose not to clean fixtures for the March LTD. This would have likely increased the measured lighting levels by an estimated 4 to 5 footcandles (based on measurements with clean fixtures in the test room).

(b) Contractors C and D did not use tubes with 100 hours of burn-in during August testing. Illuminance measurements should be reduced 1-2% to account for this.

(c) ESBase measurements were taken in both March and August but only March measurements are presented here. August measurements were about 2% lower due to the extended period of use.

Table 2. Illuminance Statistics, Footcandles

	Contractor					
Statistic	A	B[a]	C	D	Base	ESBase
Work Area[b] Average	61.0	54.2	54.6	58.0	49.1	56.6
Other Area[c] Average	44.7	38.9	40.5	51.3	37.6	43.3
Work Min	60.5	50.3	53.6	55.7	44.3	51.4
Work Max	61.4	58.3	55.3	60.2	53.1	62.0
Other Min	31.3	13.7	27.4	36.2	16.1	18.8
Other Max	56.6	62.6	51.6	60.4	55.6	62.9
Work Ratio	0.99	0.86	0.97	0.93	0.83	0.83
Other Ratio	0.55	0.22	0.53	0.60	0.29	0.30

(a) Contractor B chose not to clean fixtures for the March LTD although this would have increased the measured lighting levels by an estimated 4 to 5 footcandles.
(b) *Work Area* is defined as locations 1 through 4 (see Figure 3). Location 5, while still on the desktop, is within 18 inches of the wall.
(c) *Other Area* is defined as locations 6 through 23.

plots shows that illumination levels in the test room were not only higher but also more uniform after the retrofit.

Power Consumption Results

The average load for each of the six fixtures in the room, the sum of the individual fixture loads, the measured total load, and the room total lighting power density (in watts/ft^2 of floor space) are given for each of the four retrofits, the baseline (Base), and the energy saving baseline (ESBase) in Table 3.

Lighting loads and total harmonic distortion for the Base and ESBase configurations were measured only during the March testing. Individual fixture loads were recorded only for those fixtures with ballasts and therefore some of the fixtures in the configurations will have no load listed as noted in Table 3. The total load for the Base case does include the wired but unused ballast in fixture 6.

Comparing the measured total power consumption for each retrofit to the baseline (Base) power consumption of 335 watts gives the percent reduction in power consumption. All proposed retrofits exceeded the requirement of at least 20% reduction in the power consumption of the test room.

Figure 6 compares power consumption on a per-square-foot-basis for each of the lighting configurations measured with current federal energy standards for lighting power density (10 CFR 435). The required 20% reduction in lighting power would have been just sufficient to bring the Forrestal Building down to the 1989 lighting power limits but would not have been sufficient to meet the requirements for 1993. Fortunately, all proposed retrofits have lighting power densities far below current federal standards.

Contractor D chose to lamp all six fixtures (contractors A, B, and C chose to lamp only

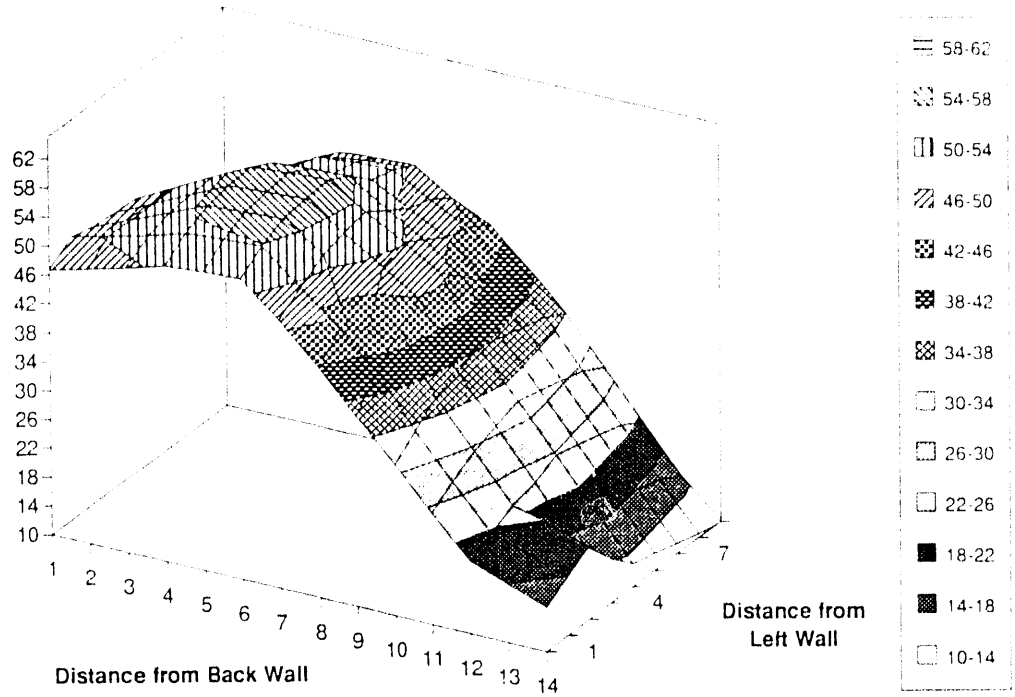

Figure 4. Contour Plot of Baseline (in footcandles)

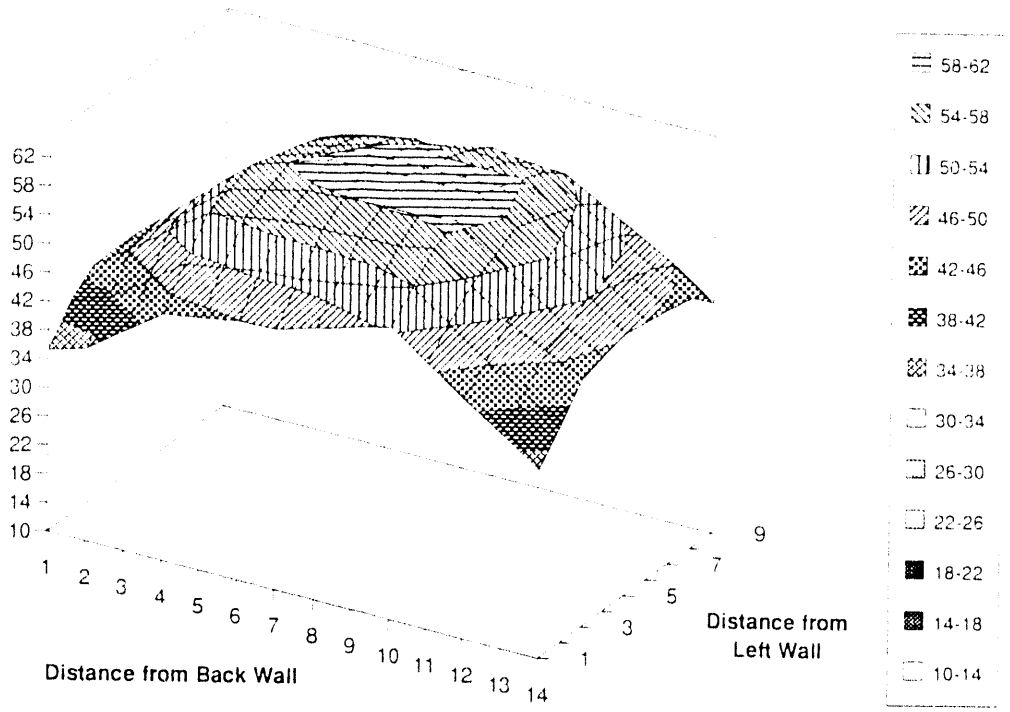

Figure 5. Contour Plot of Retrofit (in footcandles)

Table 3. Power Consumption, Watts

Contractor						
Fixture	A	B	C	D	Base	ESBase
1	0.0	0.0	0.0	50.8	0.0	0.0
2	0.0	0.0	108.0	0.0	86.0	77.4
3	0.0	52.6	0.0	0.0	95.0	70.0
4	0.0	0.0	0.0	94.8	80.8	75.6
5	59.0	51.6	0.0	0.0	69.6	78.8
6	56.6	0.0	0.0	0.0	9.0	0.0
Sum	115.6	104.2	108.0	145.6	340.4	301.8
Measured Total	113	101	108	144	335	295
Watts/ft^2	0.75	0.67	0.72	0.96	2.23	1.97
Percent Reduction	66%	70%	68%	57%	0%	12%

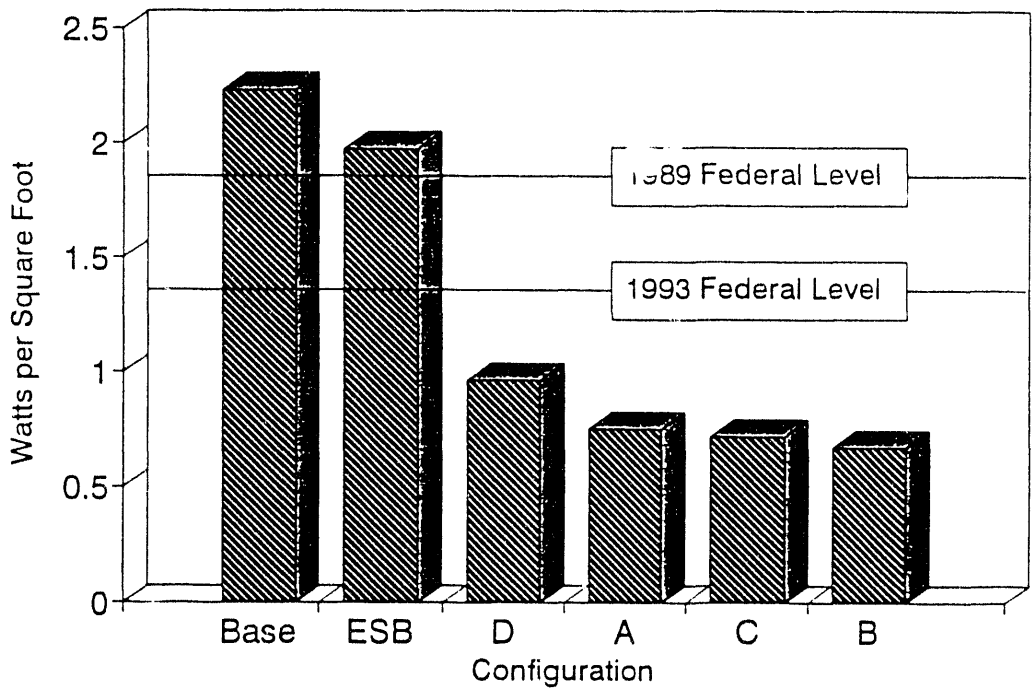

Figure 6. Forrestal Building LTD Lighting Power Density

four) to achieve uniform lighting levels even though the LTD did not require all fixtures to be lit and there was no requirement for uniform lighting levels in the room. The addition of two extra lamps significantly increased the measured total power consumption of this configuration compared with the other three contractors' retrofits. On a per-lit-fixture basis, the energy savings are almost identical among the four contractors.

Power Harmonic Results

Power harmonic measurements for each of the four proposed contractor retrofits plus the baseline and the energy saving baseline are shown in Figure 7. All contractors met the requirement that THD be held to no more than current levels in the test room.

These results are expected due to the age and nature of the ballasts involved. The baseline (Base) configuration contains older inductive ballasts originally installed in the building in 1968. The energy saving baseline (ESBase) configuration contains much newer inductive ballasts with a lower THD. All four contractors installed electronic ballasts, which typically have higher THD than inductive ballasts.

Conclusions

DOE's Forrestal Building in Washington, D.C., has successfully awarded a performance-based shared energy savings contract for retrofit of office and hallway lighting systems. The winning contractor estimates that the retrofit (and associated occupancy sensors) will lead to savings of up to 62% of the power currently used for lighting, with an estimated annual cost savings of $340,000. The retrofit will also increase lighting levels to required levels, while reducing total harmonic distortion on the lighting circuits.

The performance-based shared energy savings approach to lighting retrofits will result in a guaranteed contract to maintain lighting levels and savings for the next seven years. Over the life of the contract, the shared energy savings approach will provide $1 million each for DOE and the contractor.

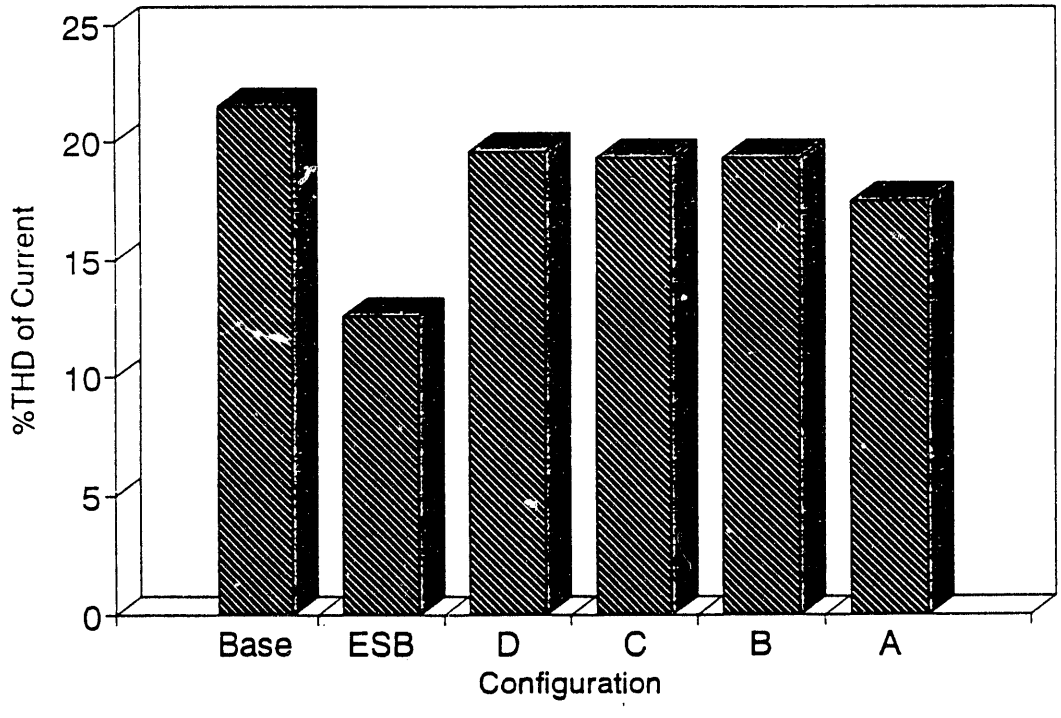

Figure 7. Comparison of THD Levels

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