Evaluation of a Major Lighting Retrofit Project

Charlie Huizenga, Marc D. Colman and Janet E. Smith
Minnesota Building Research Center

A major lighting retrofit project which has been underway for nearly two years presents an opportunity to evaluate the effectiveness of the project as well as its impact on the occupants. The project consists of retrofitting approximately 16 million ft^2 of space in over 200 buildings in a major university. These buildings cover a wide range of size, age, use and occupancy. Fluorescent retrofits include conversions from magnetic to electronic ballasts and from 40W T12 to 32W T8 lamps, assessment of light level and installation of reflectors. Reductions of approximately 9 MW demand and 27,000 MWh/year will be achieved by the end of the project in the December 1992 at a cost of approximately $6,500,000. Annual savings will be nearly $1,500,000 yielding a simple payback of 4.3 years.

An extensive audit process and software have been developed to inventory existing lighting, analyze electrical consumption, and select retrofits meeting both economic criteria and occupant requirements. Emphasis was placed on improving the visual environment of the building occupants as well as saving energy. After the retrofit work has been completed, the building is visited by a project team member who assesses both the technical success of the retrofit and its impact on the occupants of the building. Post-retrofit light levels are measured to quantify the results of changes. Both pre-retrofit and post-retrofit surveys are given to a sample of occupants in an attempt to discover the impact of the retrofit. Statistical models have been developed to compare projected and measured savings for the entire project and work is continuing on individual building models.

Introduction

The University of Minnesota has initiated a major program to increase the energy efficiency of the buildings in the Twin Cities campus. The short term goal of the University Building Energy Efficiency Program (UBEEP) is to increase efficiency by 30% over a five year period ending in 1995. The project includes three parallel activities: a fast payback path, a detailed analysis path, and a design assistance path.

The fast payback path targets energy conservation measures with simple paybacks of less than 4 years and which can be applied to the majority of campus buildings. The major components of this path are lighting retrofits, steam trap and radiator valve repair. In the detailed analysis path, individual buildings are studied in depth to determine changes in operation and cost effective retrofits to the HVAC system and building envelope. In order to be effective, any building energy efficiency program must be able to influence decisions as new buildings and major renovation projects are implemented. The final path of the program, the design assistance path, addresses this issue.

The program was initially funded through a start-up grant from the State of Minnesota, but is currently funded through University bonding. Revenue from the savings generated by the program is used to pay off the bonds, creating in effect a revolving loan fund for energy efficiency projects.

Lighting Retrofit Project

Lighting energy accounts for approximately 25% of the $12,000,000 in annual electricity use on campus. The goal of the lighting retrofit project is to increase the efficiency of lighting systems in each of the buildings on campus by an average of 50% while at the same time improving the quality of these lighting systems. The lighting retrofit program consists of three major components designed to reduce this energy use: fluorescent retrofit, incandescent replacement and improved controls. The focus of this paper will be the fluorescent retrofit. To date, the fluorescent retrofit is over 70% complete and the project is saving approximately $1 million annually. A 60% average reduction in fluorescent lighting use has been achieved in retrofitted buildings.

Fluorescent Retrofit

The fluorescent retrofit program consists of six components:

- replacement of existing magnetic ballasts with electronic high frequency ballasts
- replacement of existing T12 lamps with T8 lamps
- assessment of light level
- use of delamping where applicable
- use of parabolic reflectors where applicable
- use of partial light output ballasts where applicable.

Economic criteria are applied at the project level to avoid "cream skimming"; individual measures which have paybacks longer than the project guidelines are offset by measures which have paybacks shorter than the project guidelines. This approach results in obtaining the greatest overall energy savings within the overall project economic guidelines. The audit process includes an assessment of light levels to identify spaces which are either overlit or underlit. Overlit spaces offer an opportunity for increased savings by delamping or using partial light output ballasts.

Ballasts and Lamps

The potential energy savings of electronic ballasts has been well documented (Verderber and Morse 1988). The economics of such a retrofit is highly dependent on several factors including electric rate structure, ballast installation cost (both material and labor), hours of ballast operation, utility rebate programs, maintenance costs and retrofit life. To take these factors into consideration, life-cycle cost analysis over a 20-year period (consistent with manufacturers stated lifetime of electronic ballasts) was used to examine the economics of the ballast/lamp retrofit. At the start of the project, it was estimated that approximately 150,000 two-lamp magnetic ballasts would be replaced by 90,000 electronic ballasts at a cost of approximately $5.2 million (less a $1 million utility rebate) over a 2-year period. Annual savings were estimated at $1.2 million. The results of this analysis indicated a very favorable Net Present Value of the savings cash stream ($12.2 million) as compared with the Net Present Value of the investment ($4.2 million).

A pilot project was completed in which 237 two-lamp pendant fixtures with 40W T12 lamps and magnetic ballasts were retrofitted with 32W T8 lamps and electronic ballasts. An interesting aspect of this project was the use of four-lamp ballasts in continuous rows of two-lamp fixtures. The ballasts were installed in every other fixture, and the wiring was connected to adjacent fixtures through the existing nipple connection. The use of four-lamp ballasts greatly reduced the capital cost of the retrofit since there is a rather small incremental cost for a four-lamp ballast as compared to a two-lamp ballast. Monitoring was initiated in the pilot project building two months prior to the retrofit. Integrated power, voltage and current were recorded in 15-minute intervals. The monitored data show a post-retrofit reduction in energy use and demand of 41%.

A majority of the ballasts being replaced by the project contain PCBs. The removal of these ballasts will result in avoiding future exposure risks and clean-up costs associated with ballast failures. These ballasts are being disposed of as regulated hazardous waste. One year into the project, the Minnesota Pollution Control Agency (MPCA) ruled that fluorescent lamps should also be treated as regulated hazardous waste under some circumstances. Due to the large number of lamps being removed by the project, this ruling has had a substantial impact on the project. Efforts to reuse and recycle the lamps early in the project had been largely unsuccessful, though one contractor had been able to resell a portion of the lamps. Recycling is currently unavailable in the state, though the ruling by the MPCA will likely result in the initiation of a recycling industry. Lamps are currently being stored with the expectation that recycling will become possible in the near future.

Light Level

Light levels are measured in each space and used to evaluate appropriate retrofits. In spaces which are above established IES-based guidelines (Kaufman 1984), three measures are considered (in order of preference): delamping, reflectors (with delamping), and partial light output ballasts. Delamping of fixtures is obviously the most economical method to reduce light levels and, in spaces where light levels and fixture configurations permit, it is the preferred method. Reflectors are used only in fixtures where they will not have a significant qualitative impact. Partial light output ballasts are used where reflectors are inappropriate and uniform lighting density is required.

Reflectors

Parabolic reflectors can greatly improve the efficiency of existing fixtures (Lindsey 1987). In such a large project, it was necessary to establish criteria for appropriate application of reflectors without evaluating each specific case in great detail. To accomplish this, a bid specification was written in which performance specifications were established with respect to generic applications of reflectors. The predicted performance was based on the reflector conversion efficiency, defined as

$$CE = \frac{Post\text{-}RetrofitLightLevel}{Pre\text{-}RetrofitLightLevel} \times f \qquad (1)$$

where:

CE = conversion efficiency

f = factor to adjust for difference in light output of post-retrofit lamp/ballast combination when compared to pre-retrofit lamp/ballast combination. For this project, f=1.0 was assumed.

Post-Retrofit Light Level and Pre-Retrofit Light Level refer to the light level at a given location within the room at normal working height (30") with clean fixtures and new lamps burned in for a period of 100 hours.

The conversion efficiency must be met in all critical task areas of a space. This enables the specifications to cover both the quantity of light produced by the fixture and the distribution of that light relative to the initial fixture configuration. The conversion efficiencies specified in the project are shown in Table 1.

Table 1. Reflector Conversion Efficiencies

Reflector Conversion	Minimum CE
8 lamps to 4 lamps	75%
6 lamps to 3 lamps	75%
6 lamps to 2 lamps	50%
4 lamps to 2 lamps	75%
3 lamps to 2 lamps	100%
3 lamps to 1 lamp	50%
2 lamps to 1 lamp	75%

A pilot reflector installation was completed in the Architecture building studios which contained 2'x 4' fixtures with six T-12 lamps and three magnetic ballasts. These fixtures were retrofitted with reflectors, three T-8 lamps and a single electronic three-lamp ballast. Energy use in these fixtures went from 276 watts to 88 watts, a reduction of 68%. Light levels were taken before and after the retrofit on a one foot grid at a height of 30". Figure 1 shows the results of these measurements.

Partial Output Ballasts

A significant fraction of the fluorescent lighting on campus is provided by 1'x 4' two-lamp pendant fixtures. These and other fixtures with both a direct and indirect lighting component are not normally appropriate candidates for reflectors since the use of the reflector would result in a significant qualitative change in lighting. In cases where light levels can be reduced (particularly in circulation spaces), partial light output ballasts are utilized to reduce energy consumption. These ballasts provide approximately 75% light output at reduced power consumption.

Ballast Failures

One area of concern with respect to electronic ballasts has been their failure rate (Gould 1987). Recent projects have indicated favorable reliability with most ballasts (Abesamis, Black, and Kessel 1989), but the risk of failure is still perceived by some as a barrier to wide scale implementation. Careful tracking of ballast failures has been implemented in this project to evaluate its impact on project economics.

The overall failure rate 16 months into the project is 0.48%. This figure is based on the installation of 71,000 ballasts from five different manufacturers. The original economic evaluation used an assumption of a 1% annual failure rate during the first 5 years. While the overall failure rate is quite acceptable, four buildings are experiencing considerably higher failures. Each of these buildings have 277 volt lighting circuits and the majority of failures are 4-lamp ballasts from a single manufacturer. Further investigation with the manufacturer has determined that a bad component was used in the ballasts during a limited period of manufacturing that resulted in the premature failures. Those ballasts are now being replaced at the expense of the manufacturer.

Evaluation of Energy Savings

A critical component of the project is measurement of savings due to the retrofits. Electric energy use and demand has been measured at three different scales in this project: hourly monitoring of lighting circuits within a building, monthly meter readings at the building level, and monthly meter readings at the substation level.

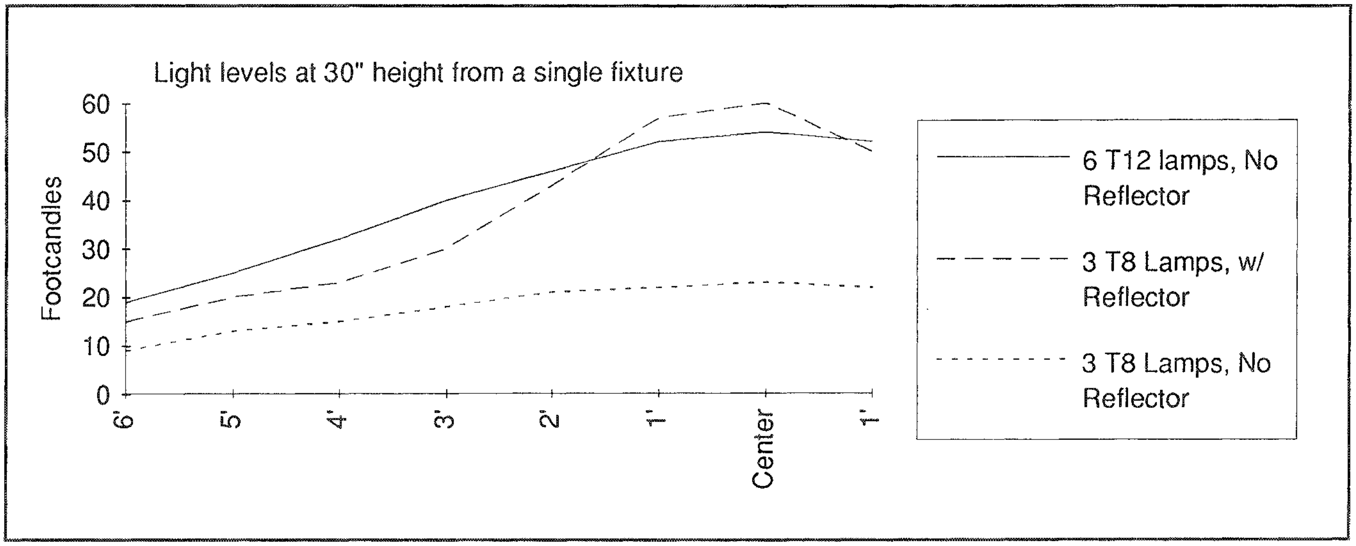

Figure 1. Architecture Building Reflector Test

Detailed Hourly Monitoring

Hourly measurement of electric demand and energy consumption has been made in four buildings using current transformers and a dedicated datalogger. Data collection was initiated prior to the retrofit in each case and continued for a substantial period after the retrofit was completed. Figure 2 shows electric demand for a one week period prior to the retrofit and a one week period after the retrofit. Analysis of the data clearly shows a 40% reduction in energy use and demand, consistent with the projections for the area monitored.

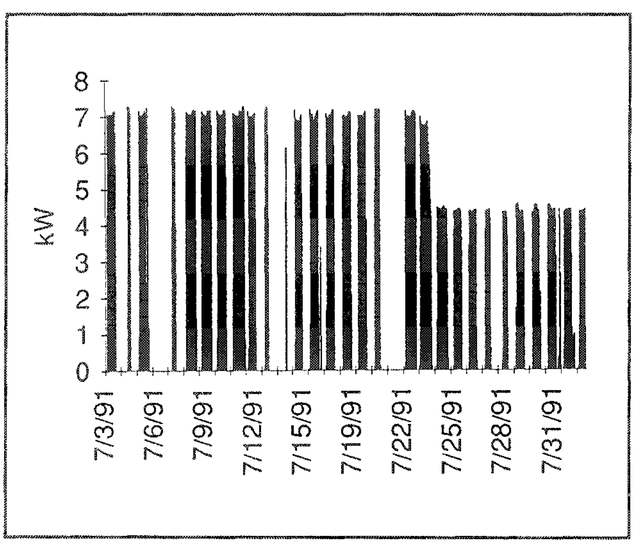

Figure 2. Shops Building Electricity Use

Monthly Building Meter Data

The hourly monitoring is quite effective in demonstrating energy savings, but is somewhat impractical to implement on a wide scale basis. Electric meters are normally read monthly in all campus buildings. Most buildings have at least one meter, some have several meters, and some have meters which record electric use in adjoining buildings. Approximately half of the buildings have demand meters. Historically, little use as been made of this data and consequently its reliability is quite low. Estimated readings, data entry errors, meter multiplier errors and missing data are quite common. One objective of this project is to improve the quality of the monthly meter data.

Recognizing that an important element in strategies toward reducing energy consumption is the development of an understanding of individual building performance, current work is underway in deriving predictive equations based on statistical data analysis techniques primarily involving multiple linear regression. This analysis will provide a basis for evaluating the impact of energy conservation measures on individual buildings. However, preliminary results indicate that several buildings exhibit "flat" consumption profiles which can be evaluated by a direct comparison of a period prior to retrofit with the same calendar months following the retrofit.

An integral component of the audit process is the collection of data relevant to understanding energy consumption patterns. Auditors record estimated hours of operation for each group of lighting fixtures in a space. Combined with an estimate of the type of ballasts within a building, annual lighting energy use and demand is calculated. Based on the specifications of the retrofit installations, a projection of the reduction in lighting energy consumption and demand is calculated.

Table 2 presents a cost-benefit analysis of retrofit installations for 40 selected buildings based on projected savings and actual costs. Projected savings are based on building audit data and the associated retrofit installations to determine annual energy reduction. A cost of $0.058/kWh is used for calculating savings and a discount rate of 7% is assumed for the economic analysis. Table 3 presents an analysis of savings based on a comparison of metered (measured) post-retrofit data with data from the same period prior to the retrofit. The building sample consists of those for which comparison intervals include only late fall and winter, thereby controlling for any variation due to summer air-conditioning use. These savings are compared to estimates derived from audit data in the same manner as in Table 2.

As Table 3 indicates, measured savings are within 4% of the projected savings for the selected buildings. The standard deviation is quite high (27%), but we expect this to drop as more post-retrofit data becomes available. This agreement has resulted in a high degree of confidence that the overall economic criteria determined at the start of the project will be met.

Monthly Campus Wide Meter Data

Unlike the building level meters, data for the substation meters is quite reliable since it serves as the basis for billing by the electric utility. As a final evaluation tool, analysis of this data has been carried out in a similar fashion as the individual building data. The campus is divided into four substations. The East Bank substation will be discussed here. The basis of the model is a baseline energy consumption plus a linear dependence on cooling degree days to account for electric chilling. Rather than a step change model which would be appropriate for a retrofit implemented over a relatively short period of time, the campus model assumes a constant rate of change in energy use and demand due to the retrofit work, and adds a linear growth term to adjust for increasing campus electric use.

$$E + A + \beta(CDD) + G\cdot(t) + S\cdot(t') + ae \qquad (2)$$

where:

E = energy use (MWh/day)
A = baseline energy use (MWh/day)
ß = coefficient for cooling degree day term (MWh/day/°F)
CDD = cooling degree days for selected reference temperature
G = coefficient for growth term (MWh/day/month)
t = time since start of pre-retrofit period (months)
S = coefficient for retrofit savings term (MWh/day/month)
t' = time since start of retrofit (0 if prior to retrofit start) (months)
æ = stochastic disturbance term to account for unexplained behavior (assumed mean of 0).

A cooling degree day reference temperature of 55°F was determined to give the best statistical fit to the data.

The general least squares method was used to generate the values for the model shown in Table 4 for the East Bank campus based on three years of monthly data preceding the start of the retrofit and 16 months of data since the start of the retrofit work. Although the model has the potential for multi-colinearity, the coefficients G and S have proven very stable over the past several months of data.

The rate of increase of savings as indicated by the model is 2.75 MWh/day/month or an annualized rate of savings of 1,004 MWh/month. As a way of establishing a conservative minimum for the savings, we can make the assumption that no actual growth occurred after the start of the retrofit work. In this case, the rate of savings becomes (S + G), or 1.23 MWh/day/month. Figure 3 shows measured and predicted electricity consumption based on this model for a three-year period.

Based on data as of March 1992, the projected savings of 11,578 MWh/yr is well within the 90% confidence interval of the regression estimate of 16,060 MWh/yr (±8,030 MWh/yr). Data collected over the next few months will be very important in verifying this result.

Table 4 also shows the results of the regression for demand. Using the two models, electric energy cost reduction can be calculated using current electric rates of $0.029/kWh and $6.04/kW-month (average demand charge). Total savings as of March 1992 were $857,000 (±$397,000).

Heating and Cooling Impacts

The impact of a lighting retrofit on heating and cooling loads is quite predictable, yet the impact on heating and cooling energy consumption is much less deterministic.

Table 2. Cost Analysis of Projected Savings for Selected Buildings

Bldg. No.	Gross Area (ft^2)	Annual Pre-Retrofit Consumption Cost Total	Annual Pre-Retrofit Consumption Cost ($\$/ft^2$)	Annual Cost Avoided Total	Annual Cost Avoided ($\$/ft^2$)	Retrofit Cost Total	Utility Rebate ($)	Net Retrofit Cost ($\$/ft^2$)	Dis-Counted Payback (Yrs)	Cost of Conserved Energy[(a)] ($/kWh)
1	33,535	12,400	0.37	2,097	0.063	10,740	2,405	0.249	4.2	0.022
2	57,185	18,195	0.32	4,656	0.081	27,763	6,429	0.373	5.0	0.025
5	90,420	14,318	0.16	5,545	0.061	41,361	9,905	0.348	6.1	0.031
6	29,459	3,895	0.13	1,659	0.056	18,748	3,850	0.506	10.2	0.048
8	56,037	13,330	0.24	4,350	0.078	31,250	7,240	0.428	6.2	0.030
19	47,910	13,581	0.28	4,162	0.087	27,159	5,809	0.446	5.5	0.028
20	190,209	112,039	0.59	18,805	0.099	84,477	38,201	0.243	2.5	0.013
21	33,174	7,806	0.24	1,634	0.049	8,482	1,930	0.198	4.2	0.022
22	111,889	21,990	0.20	7,801	0.070	38,683	10,308	0.254	3.9	0.020
24	7,231	1,215	0.17	150	0.021	2,078	510	0.217	12.9	0.056
31	92,382	27,638	0.30	8,233	0.089	46,252	11,042	0.381	4.7	0.023
33	94,559	86,606	0.92	8,180	0.087	59,820	12,266	0.503	6.5	0.031
36	64,684	21,086	0.33	2,154	0.033	10,226	2,431	0.121	3.7	0.019
40	34,905	5,490	0.16	1,621	0.046	7,935	1,791	0.176	4.0	0.020
44	89,054	50,126	0.56	7,762	0.087	49,625	11,788	0.425	5.1	0.026
46	92,921	34,809	0.37	9,446	0.102	49,860	9,226	0.437	4.6	0.023
51	100,984	38,878	0.38	6,965	0.069	41,257	6,825	0.341	5.2	0.027
53	183,189	25,166	0.14	5,256	0.029	7,712	1,235	0.035	1.3	0.007
57	40,199	4,482	0.36	1,652	0.041	12,970	2,364	0.264	7.1	0.035
60	95,313	68,288	0.72	9,240	0.097	52,529	10,311	0.443	5.0	0.025
62	53,064	17,924	0.34	4,321	0.081	26,272	4,888	0.403	5.5	0.027
71	85,842	13,576	0.16	5,166	0.060	53,194	9,910	0.504	9.6	0.045
73	79,816	27,110	0.34	6,230	0.078	42,236	8,420	0.424	6.0	0.029
79	47,411	49,053	1.03	4,318	0.091	23,362	5,018	0.387	4.7	0.023
96	13,164	3,141	0.24	589	0.045	5,151	1,113	0.307	7.9	0.037
100	50,128	35,619	0.71	1,568	0.031	16,717	2,627	0.281	10.5	0.048
102	21,634	5,327	0.25	1,353	0.063	9,335	2,050	0.337	5.9	0.029
108	201,604	132,937	0.66	45,580	0.226	132,144	30,663	0.503	2.5	0.012
116	41,905	22,655	0.54	2,078	0.050	9,138	981	0.195	4.5	0.021
117	5,617	640	0.11	501	0.089	3,101	564	0.452	5.7	0.027
122	157,726	240,846	1.53	5,474	0.035	70,276	42,040	0.179	5.3	0.028
201	100,408	48,801	0.49	8,187	0.082	53,828	10,880	0.428	5.7	0.028
202	107,074	44,758	0.42	8,849	0.083	62,029	12,632	0.458	6.2	0.030
203	102,200	42,070	0.41	9,612	0.094	38,618	8,050	0.299	3.4	0.017
204	386,517	326,157	0.84	41,827	0.108	233,969	39,962	0.502	5.1	0.025
205	64,291	29,428	0.46	3,799	0.059	21,381	4,485	0.263	4.8	0.024
206	18,990	9,458	0.50	2,993	0.158	8,970	2,100	0.362	2.5	0.012
334	48,870	15,513	0.32	5,358	0.110	24,317	4,856	0.398	3.9	0.020
381	85,619	76,046	0.89	11,096	0.130	77,056	17,071	0.701	5.9	0.029
394	65,076	106,737	1.64	11,855	0.182	49,636	7,539	0.647	4.9	0.019
412	130,566	75,116	0.58	17,403	0.133	73,646	13,701	0.459	3.7	0.019
Total	3,580,619	1,887,140	0.57	323,217	0.091	1,621,067	376,996	0.375	4.5	0.022

(a) $CCE = \frac{\text{Capital Cost} \times d/(1-(1+d)^{-n})}{\text{Annual Energy Savings}}$ (Kooney et al. 1991)

Table 3. Comparison of Measured and Projected Savings for Selected Buildings

Building	Primary Use	Gross Sq Ft^2	Consumption kWh/day Before	Consumption kWh/day After	Measured Savings (kWh/day)	Measured Savings (%)	Predicted Savings (kWh/day)	Ratio: Measured/ Predicted
Eddy Hall	Office/Classroom	33,535	878	730	148	16.9	114	1.30
Morrill Hall	Office	91,992	2,139	1,741	398	18.6	459	0.87
Science Classroom	Lab/Classroom	41,905	989	890	99	10.0	114	0.87
Smith Bookstore	Retail	18,990	646	535	111	17.2	142	0.78
Alderman Hall	Lab/Classroom	65,076	6,752	5,842	910	13.5	657	1.39
Agricultural Engr.	Lab/Classroom	48,870	968	789	179	18.5	238	0.75
Anderson Hall	Office/Classroom	64,291	2,212	2,110	102	4.6	166	0.61
Pillsbury Hall	Office/Classroom	57,185	1,078	889	189	17.5	185	1.02
Shops Bldg.	Office/Lab	89,054	2,813	2,312	501	17.8	336	1.49
Shops Annex	Office/Lab	13,164	153	124	29	19.0	23	1.25
Blegan Hall	Office/Classroom	102,000	2,552	1,989	563	22.1	436	1.29
Classroom Office	Office/Classroom	130,566	4,489	3,831	658	14.7	808	0.81
Food Science	Lab/Classroom	76,046	4,682	4,120	562	12.0	515	1.09
Total		832,674	30,351	25,902	4,449	14.7%	4,193	1.06±2.7

Given a change in load, any corresponding change in energy use is dependent upon the control system and the loading of the equipment. A central steam plant system provides energy for all heating and the majority of cooling at the University. Additional cooling is provided by electric centrifugal chilling and window air conditioners. Assuming the impact on load is entirely reflected in heating and cooling energy use, the campus wide impact was estimated to be an increase in heating costs of $144,000 and a decrease in cooling costs of $84,000. This net increase of $60,000 represents approximately 4% of the estimated lighting energy savings.

In all probability, this analysis overestimates the impact. Many buildings have poor temperature control, particularly in the winter when they tend to overheat. In these buildings, it is unlikely that the full penalty of the lighting retrofit will be seen. In spaces with less than adequate cooling capacity, the reduction in load will result in increased comfort rather than a savings in cooling energy.

Table 4. Regression Coefficients and Predicted Savings for Energy Use and Demand Models

	Energy Use Model Value	Energy Use Model Std. Error	Demand Model Value	Demand Model Std. Error
A	500	8.34	28.0	0.692
β	6.25	0.42	0.40	0.036
G	1.52	0.41	0.14	0.035
S	-2.75	1.08	-0.34	0.090
	$R^2 = 0.87$		$R^2 = 0.77$	
	Savings = 16,060 (±8,030) MWh/yr; $466,000 (±233,000)/yr		Savings = 5.4 MW ±2.3 MW; $391,000 (±164,000)/yr	

Total annual savings = $857,000 ± $397,000

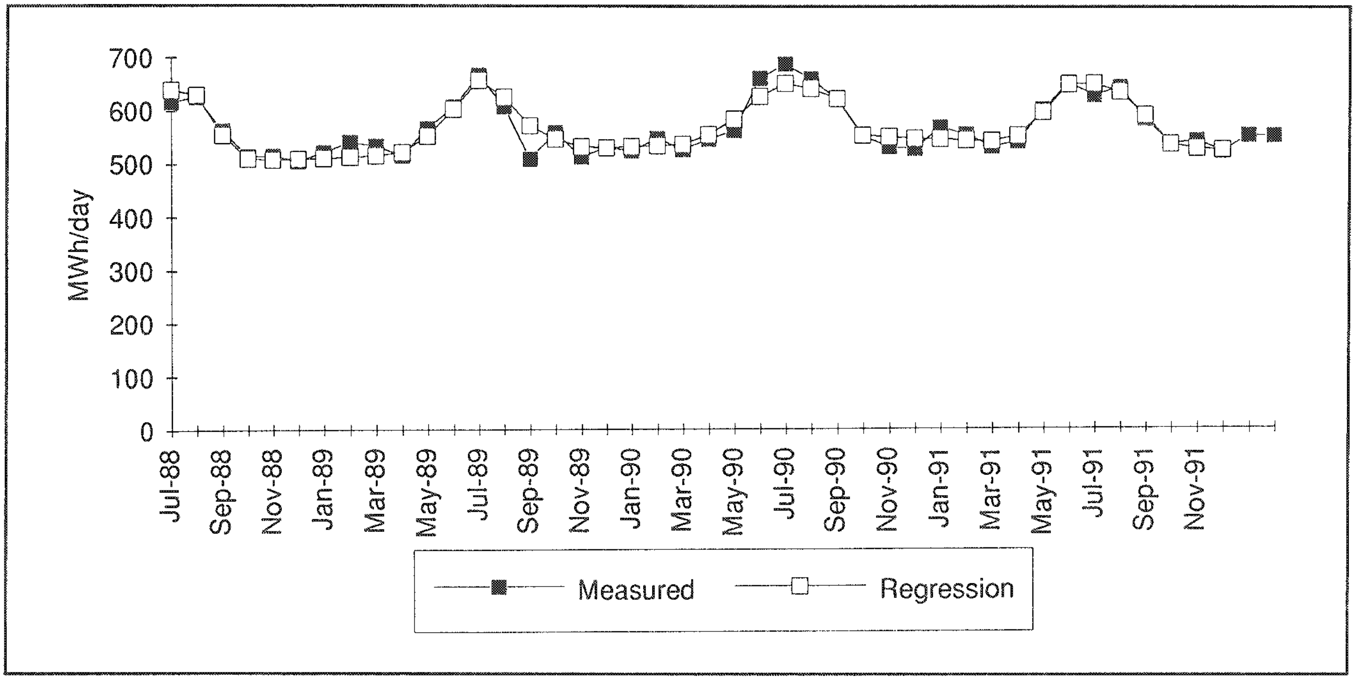

Figure 3. Measured Electrical Energy Use vs Regression Model for East Bank Campus

Audit Design

Optimizing lighting energy use necessitated an audit design and associated requirements of the data base application which integrates several quantitative and qualitative criteria in the evaluation of retrofit options. Confronted with the constraint of a two-year project window, it was imperative to maintain an operational flexibility in response to balancing the need to maintain audit efficiency with that of increasing the level of sophistication in the evaluation process as additional retrofit options were introduced. It was soon realized that, because of resource and time constraints, it might often be necessary to redefine the data collection procedures. Consequently, while the operational requirements of the project often precluded the collection of data at a level of detail desired, it was realized that the effectiveness of the audit could be maintained if a consistent conceptual and logical data base design were maintained.

Audit Procedures

An initial audit design attempted to mathematically model the room light levels using the zonal cavity method. However, because of the exhaustive data on the physical characteristics of a space required and inconsistent initial results, it was concluded that a standardized approach to the measurement and recording of actual light levels in a space would adequately provide a basis for evaluating retrofit options.

The present methodology utilizes a series of measured light levels at a reference work-plane sufficient to determine the range of illumination appropriate for tasks within a given space. A taxonomy based on the IES illuminance categories for lighting design currently contains about 60 classifications of primary functions for the space. A target maintained illuminance value is determined by utilizing the IES recommended values and a consideration of the visual characteristics of the tasks performed within each classification. The Light Level Ratio (LLR), or ratio of the existing light level to the target light level, of each space then becomes one of the major criterion in the determination of the appropriate retrofit.

Data Collection

An initial attempt to inventory lighting fixtures based on the IES luminaire taxonomy was abandoned due to the diversity of fixture types found throughout the University. A general data coding convention has been adopted which includes fixture type (fluorescent, incandescent, high intensity discharge), number of lamps, length, width, lamp shape, light level control, switching levels, etc.

Other related data items include fixture layout, mounting, diffuser type, lamp type and wattage, and fixture condition.

The data set currently includes:

a) fixture attributes: (grouped on several criteria): quantity, type, lamp type and quantity, width, length, switching, diffuser type, layout, hours of operation, peak use.

b) room attributes: use classification, area, light levels, window air conditioners, suitability for daylight controls, work stations.

c) building attributes: voltage, existing ballast percentages, contact/resource individuals, description of recent lighting modifications, any special access and security considerations.

Auditors document building floor plans with the actual light fixture configurations for each space with detailed annotation for recommendations involving delamping, reflector locations, fixture replacement, and any discrepancies due to space modifications. These become an important reference document for the auditor in refining final specifications and a copy is furnished to the contractor.

Retrofit Criteria

The evaluation of retrofit options for any given space involves the application of a set of specific quantitative and qualitative criteria within a framework which allows for an assessment of the appropriateness of measures based on occupant preference and acceptability. Where comparison of existing with target light levels in a space indicates that reductions are possible, subsequent evaluation is based on cost effectiveness criteria incorporating a combination of installation cost and energy usage reductions.

In the early stages of the program stringent guidelines with respect to light levels limited the discretion of the auditor to utilize all retrofit options. With increased sophistication of audit staff and as additional options are added, guidelines have been relaxed so that several combinations of retrofits may be considered. Whereas initially delamping was only allowed in spaces where light levels exceeded twice that of IES recommendations, auditors are now encouraged to consider partial or whole fixture delamping in overlit spaces, especially in areas where critical visual tasks are not performed. Indeed, the economies of tandem wiring bias selection of delamping where reductions are possible.

Parabolic reflectors are the next choice where reduction of light levels is possible. Since vendor bid specifications require that reflectors return a sustained percentage of original illumination, program guidelines are based on the combination(s) of delamping and existing light levels which result in illumination at or above target levels.

Database Design

Since the process of audit implementation design was one of progressive refinement utilizing ongoing auditor feedback and evaluation of procedures, the primary objective of the data base design and the associated processing requirements was to allow for flexibility in adapting to changing operational and processing requirements. A PC based relational data base management system was selected because of its emphasis on 1) data independence from processing requirements; 2) implementation independence from physical storage; and 3) responsiveness to changing information requirements.

The PC implementation also allowed for portability to several remote installations so that data entry could be done at locations accessible and available to the auditor. Installation at 3-5 sites has been maintained throughout the project. The local electric utility, Northern States Power, has supported the project with direct funding and in-kind support consisting of 2 contract personnel with experience in commercial and residential lighting audits. This staffing has been supplemented with student and other temporary positions resulting in an average complement of 4 FTE auditors.

Because of the diversity of experience and background, as well as the need to test the criteria on which the retrofit options could be selected, it was initially necessary to adhere to stringent retrofit selection standards. This required that software applications be designed such that a broad range of user discretion in specifying retrofits be enforced at the systems level.

At successive levels of control, the software provides for:

(1) inclusion of specific retrofit options to be considered;

(2) determination of appropriate retrofit based on programmed application of selection criteria or auditor recommendation;

(3) determination of retrofit based on auditor recommendation subject to evaluation and optimization by program criteria. This enables the user to control the retrofit selection process based on the project implementation plan, the individual skill level of the auditor, or an evaluation of the cost effectiveness of different combinations of retrofits.

Database Details

A great deal of emphasis was placed on validation criteria and integrity constraints defined on database items enforced when values for those data items are captured using screen forms. The forms of validation attached to screen definition consisted of mandatory data values, range specifications, pattern conformity, and conditional enforcement depending on the value(s) of other data items. Experience to date indicates that, given the scale of the project and attendant large volume of data to be collected, the capabilities of the data base management system in defining validation criteria beyond those which are part of data base definition is critical. This requirement not only ensures the integrity of the data, but also is key to the development of a credible relationship with contractors and other field personnel.

Database Reports

Existing report formats are provided for the auditor to review the accuracy and completeness of the data. In addition to presenting a lighting inventory of the building, projections of LLR's based on the auditor's specifications enable the user to optimize recommendations for each space. In addition, detailed reports are available which analyze existing lighting consumption/demand and projections of the impact of the selected retrofits on usage. These projections incorporate ballast-lamp wattage ratings, vendor's specifications, and the local utility's rate structure. Analyses can be done on a room/space, a building, or aggregated on a project level.

Based on the selected retrofit measures, an installation report is then generated which serves as a detailed specification of work. The report includes an assignment of retrofit code(s) on a fixture and room basis which is derived from a schedule of approximately 50 unit price quotes by contractor. This report can then be used as a bid specification for negotiation of contracts or for projecting aggregate building retrofit costs based on existing prices.

The project report presents an electrical energy utilization profile of all audited buildings. Included is installed lighting capacity, consumption, consumption/ft^2, average and peak power densities, annual consumption costs, and calculated projections of these measures based on the proposed retrofit modifications. A summary of the above measures is calculated on a campus-wide level which includes a brief analysis of the project status.

Post-Retrofit Evaluation

An objective of the retrofit project was to preserve or improve the lighting quality of campus buildings while bringing light levels to within IES guidelines. This objective was evaluated in two ways. After the retrofit was complete, the light level was measured in a sample group of spaces. Comparisons were made between the expected results and actual post-retrofit measurements based on the specific retrofit criteria and original light levels. Qualitative information, as perceived by the occupants, was gathered through pre and post-retrofit surveys. This information included: occupant awareness of the retrofit, perceived changes in the lighting characteristics, lighting use patterns in relation to working hours and available daylight, degree of lighting control, and overall satisfaction with the general lighting. Finally, comparisons were made between the quantifiable and qualifiable aspects of the lighting data.

Post-Retrofit Light Level Measurements

A significant part of the evaluation was measuring light levels in spaces six months after the retrofit was complete. These measurements were used to compare the predicted impact of the retrofit with what was seen in the field. Figure 4 shows the correspondence between the pre-retrofit light level, projected light level, and the post-retrofit light level. In general, good agreement was found between expected and actual results, and final light levels were in reasonable agreement with target light levels.

A post retrofit audit of a group of sample spaces yielded interesting results. Based on a lumen depreciation of 10% at 40% of rated life, we would expect light levels to be approximately 10% above target levels immediately after the retrofit. In the case of standard retrofits (one to one replacement of T12 lamps with T8 lamps), light levels increased by 5%, indicating a probable 5% loss in light over the pre-retrofit condition.

Light levels in spaces retrofitted with partial light output ballasts were 26% lower than the pre-retrofit levels rather than the 20% used for recommendations and calculations. On average, these spaces had a LLR of 1.16 after the retrofit, and even after lumen depreciation would be above target light levels.

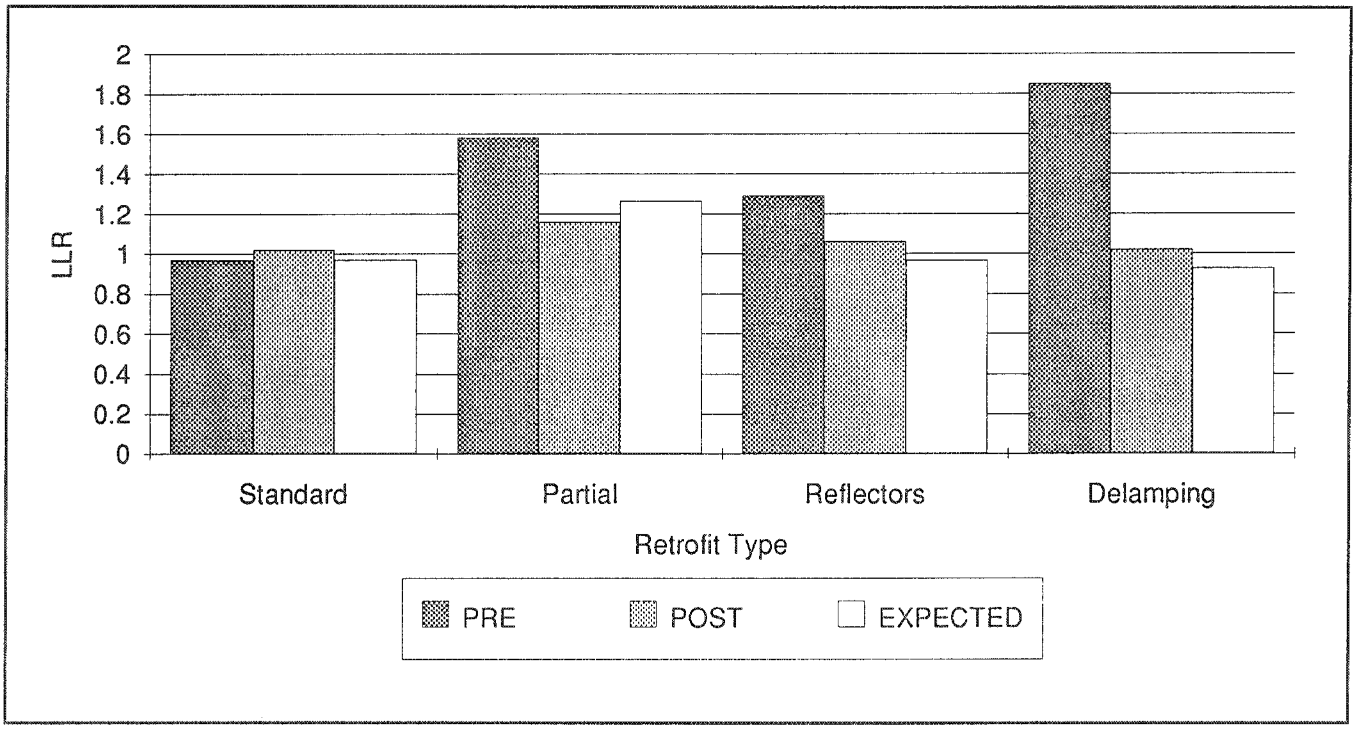

Figure 4. Pre/Post Retrofit LLR Compared to Expected LLR

The light levels in spaces with parabolic reflectors averaged 83% of the initial light levels. The majority of these spaces were conversions from two lamps to one lamp, with a specified conversion efficiency of 75%. Corrected for lumen depreciation, the reflector retrofits appear to be tracking expected performance in the spaces evaluated to date.

There was an 83% correspondence between audit recommendations and contractor installations. Differences between audit recommendations and actual installations included no retrofit taking place, reflectors not installed, standard ballasts installed instead of partial power ballasts, partial power ballasts installed instead of reflectors, and delamping of fixtures instead of reflectors.

Occupant Impact

The goals of the occupant surveys included assessing occupants satisfaction with the lighting in their spaces and the influences that affected that satisfaction. Also of interest was the occupants perception of lighting change. The pre-retrofit survey was distributed close to the time that the audit was being conducted. The post-retrofit survey was distributed approximately two weeks after the retrofit work was completed. Along with comparative lighting questions, this survey was concerned with occupants' reaction to the project as a whole: was the retrofit, in a broad sense, and asset or liability to the University, the environment, the community.

The pre-retrofit survey results were compiled from the responses of two hundred occupants. The data indicated that there was no clear trend between satisfaction with the lighting and room LLR, hours worked, or occupant control of the lighting. Daylight, however, did affect the occupants perception of satisfactory lighting. Figure 5 shows that those occupants that were most satisfied with their lighting had a significant daylight contribution in their space.

Additional pre-retrofit survey results include the following:

- The average LLR of a space with satisfied occupants (a rating of 3 or above) was 0.92, not statistically different than the overall average LLR of 0.90.
- For spaces that receive daylight the average rating for satisfaction was 3.9, well above the overall satisfied rating of 3.0.
- 75% of the occupants have some control over the electric lighting. Of these occupants, 94% have a personal switch in their space and 61% turn the lights on/off once or twice a day while 32% claim to turn

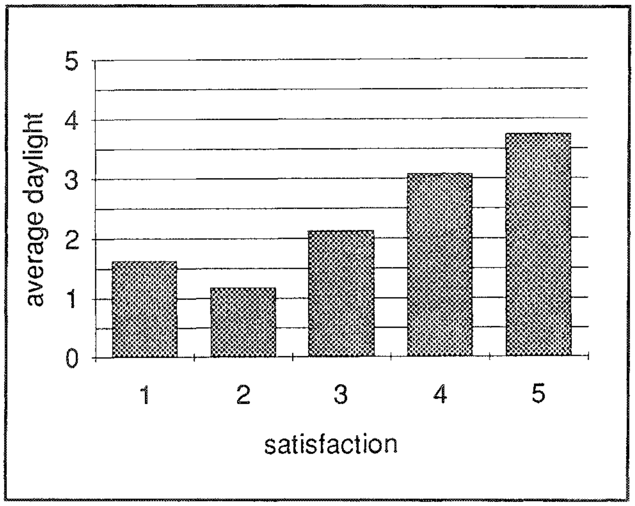

Figure 5. Daylight Related to Satisfaction

the lights out whenever they leave the room. Only one occupant admits to never turning out the lights.

- The most common requested lighting change was for dimming controls. Multiple switching was the second most asked for item. Comments showed that there was also an interest in more "naturally" colored light. In all, 47% of the occupants felt that no change with the lighting was necessary in their work spaces. It was noted, however, that the lighting in the hallways was inconsistent and a bit too dark. This was an area of concern for many of the building users.

The post-retrofit survey was distributed to thirty of the pre-retrofit respondents. Table 5 shows results as occupants rated lighting qualities in their space before and after the retrofit. The responses were scaled from 1 to 5 with 1 being poor or none and 5 being exceptional or excessive. Corresponding with the goals of the project, the numbers show that occupants felt the color of the light had improved (also noted in comment section of the survey) and the noise and flicker had been reduced. Overall satisfaction increased greatly. Questions were raised concerning the waste produced by the project and its evaluation.

Conclusions

Overall, the project has been quite successful in meeting or exceeding the original energy efficiency goals of the project. Feedback from the University community has been positive and communication with the building occupants has been shown to minimize interference with day to day activity. The next phase of the project will include retrofitting the unexpectedly large number of incandescent lamps which were discovered during the auditing process.

Acknowledgments

The authors would like to thank Wang Zhi for his work in developing the statistical data analysis methodology, Darin Jensen for his tracking of installation and ballast failure data, and lighting auditors Jeff Beskar, Mario Monesterio, George Moyzis, Larry Taylor and Darryl Thayer. We would also like to acknowledge Northern States Power for their support of the project, along with the Legislative Commission on Minnesota Resources under grant MNADM/02190-03540.

References

Abesamis, R., P. Black, and J. Kessel. 1989. "Field Experience with High-Frequency Ballasts." University of California at Berkeley, Berkeley, CA.

Gould, M. S. 1987. "Cautious Application of Solid State Ballasts." Proceedings of the 10th World Energy Congress. Association of Energy Engineers, Atlanta, GA.

Kaufman, J. E., ed. 1984. IES Lighting Handbook, 1984 Reference Volume, Illuminating Engineering Society, New York, N.Y.

Kooney, J. G. et al. 1991. "The Potential for Electricity Efficiency Improvements in the U.S. Residential Sector." DOE/DE-AC03-F00098, Lawrence Berkeley Laboratory, Berkeley, CA.

Lindsey, J. L. 1987. "Specular Retrofit Reflectors for Fluorescent Troffers." Southern California Edison Company, Rosemead, CA.

Verderber, R., and O. Morse. 1988. Performance of Electronic Ballasts and Other New Lighting Equipment-Phase II Final Report. Electric Power Research Institute, Palo Alto, CA.

Table 5. Retrofit Survey Results

	Pre-Retrofit		Post-Retrofit	
	Average Response	Standard Deviation	Average Response	Standard Deviation
Amount of light	3.0	0.7	3.3	0.4
Color	2.9	0.7	3.6	0.8
Flicker	1.9	1.1	1.5	0.9
Noise	1.6	0.9	1.3	0.7
Glare	2.3	1.1	1.6	0.9
Daylight	2.7	1.7	2.7	1.7
Satisfaction	3.4	1.1	4.2	0.6
Hrs worked	4.1	1.1	4.1	1.1
Hrs lighted	4.3	1.0	4.3	1.0

1 = poor/none   5 = exceptional/excessive