Projected and Measured Results from an Energy-Efficient Small Commercial Office Building

David J. Houghton, E SOURCE

Small commercial office buildings are often neglected in the pursuit of energy and demand savings. They lack the advantages of large-scale economics, concentrated ownership, and dramatic savings that large buildings provide, and present a challenging diversity of tenants and activities. In this case, efficiency upgrades were initiated by the primary tenant, an energy efficiency company with a stake in demonstrating the technologies and design procedures that it recommends to others.

This speculative office project began with conventional lighting, heating, and cooling systems. By re-specifying key equipment and making subtle changes to the building's design, predicted energy consumption and peak demand were reduced by over half. This paper discusses the energy enhancements to the building, and compares measured results with simulated building performance calculated with the DOE-2.1E computer program.

Building enhancements included daylighting, high-performance glazings, indirect lighting with simple occupancy controls, compressorless evaporative cooling, low-flow water fixtures, tankless water heating, and efficient office equipment. The design team's whole-building focus led to savings in unexpected areas, such as snow melting and fire prevention. Additional building goals were to create a low-toxicity environment with ample occupant control, to provide high levels of ventilation airflow, and to offer an aesthetically pleasing and comfortable space.

Introduction

The Columbine Building is a three-story building that was completed in late 1993. Squeezed onto a narrow lot in downtown Boulder, Colorado, the 12,000-square-foot building is typical of small commercial new construction—for most of the design process, energy efficiency was not a development priority. The developer entered this speculative construction project to make money, not save energy.

When one group of potential tenants—who *was* interested in saving energy—entered the building project, the building's design was nearly complete, but construction had not yet begun. On the condition that the building would be built as an example of energy-efficient construction, the group agreed to lease most of the building for a period of seven years.

The project team then initiated a "design retrofit "-an examination of the existing design for potential energy efficiency improvements. This paper describes the changes that were made, the simulated and measured results of those changes, and some of the lessons learned on the project. The primary goal of the project was to demonstrate practical high-efficiency technologies rather than to save money through reduced energy bills (which was a secondary goal). For this reason, efficiency measures were selected on the basis of engineering judgment, and not subject to economic rankings, although the cost of many of the measures was recorded.

The efficiency measures, simulation results, and measured performance apply to most but not all of the building. The first floor is occupied by a beauty parlor and a sandwich shop, neither of which participated in the project. A single HVAC system supplies the entire building, including the first floor tenants, and is included in all simulated and measured results. Shell improvements such as upgraded windows were applied to the entire building.

Physical Description

The site is long and narrow, oriented on a north-south axis, and bordered on both east and west by existing three-story buildings. The building has 3365 square feet on the first floor, 5370 on the second floor, and 3160 on the third floor, for a total of 11900 square feet. For the purposes of the design retrofit, the overall layout of the building could not be changed. The primary features of the building's shape are a stepped-back third floor and a long light well on the east side that allows some daylight to penetrate to part of the second floor. These features were part of the baseline design.

External Load Reduction: Shell Improvements

The thermal loading of the building is dominated by internal equipment and ventilation rather than shell effects because of contact with adjacent buildings. Boulder's climate is characterized by long, cold, sunny winters, and warm, dry summers. Table 1 shows climatic conditions for Boulder, and Figure 1 shows the cooling loads of the baseline and enhanced building plans. (In this comparison of cooling loads, both calculations include the "enhanced" building shell features. The true baseline cooling loads would have been even higher.) Upgrades to the building shell were important not only for reducing the heating and cooling loads of the structure, but to even out the thermal demands placed on the different HVAC zones. As discussed below, the HVAC unit cannot supply heating and cooling at the same time.

On the exposed wall surfaces of the building, one inch of rigid foam insulation was added over the baseline of fiber-insulated metal-stud 2x4 construction. The baseline roof was already well insulated with R-38 fiberglass batts. The floor below the north part of the second floor is separated from the open-air garage below only by drop-in ceiling tiles. In this area, the insulation was increased from the baseline R-19 to R-30 fiberglass batts.

Table 1. Climatic Conditions in Boulder, Colorado

	Value
Design summer Dry-bulb temperature (DBT)/Mean coincident Wet-bulb temperature (WBT) (1%)	93DBT/59WBT
Design winter DBT (99%)	2°F
Cooling degree-days (base 55)	1938
Heating degree-days (base 55)	3197

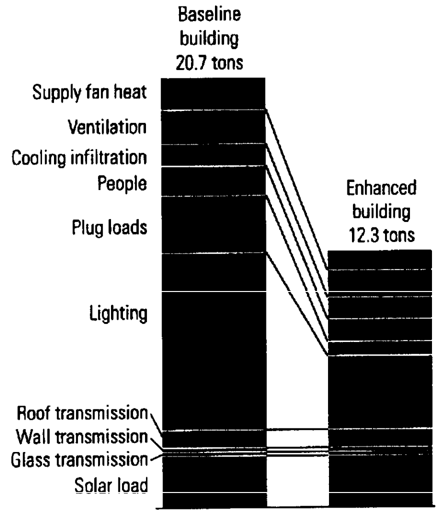

Figure 1. Cooling Load Stacked Bars

The baseline double-pane windows were upgraded to commercially available krypton-filled units with two layers of suspended film. A few special window sizes had to be custom-built locally; these units also had two film layers, but no gas fill. All windows used clad wood frames, and the glazing incorporated thermally-broken edges. Table 2 lists the properties of the windows.

High-performance windows were important in attaining the design goals for several reasons. In addition to reducing thermal loads on the building, the solar shading and high insulation of the windows reduced the need for simultaneous heating and cooling in different building zones. This was particularly important since the building uses a single air conditioning unit to supply zones with much different exposures. The multiple glazing layers also reduce the noise of cars and trucks immediately outside the building.

Internal Load Reduction: Lighting and Office Equipment

The baseline lighting design consisted of numerous 2x4 troffers in a drop ceiling, each with 4 four-foot T12 lamps and magnetic ballasts. The total projected lighting power density before the design retrofit was 2.4 W/ft^2. (At the time, no local building code prevented this power density. Future standards will limit lighting power density for offices in Colorado and other states to ASHRAE 90.1 levels or better.) Through a combination of direct, indirect, and task lighting, the lighting power density was reduced to about 0.8 W/ft^2 connected load, with a design illumination level of 35 maintained footcandles. This figure includes compact fluorescent task lights in the

Table 2. Properties of Windows Used in the Columbine Building

	Baseline	Enhanced
Description	Wood frame, double glass	Wood frame, two glass layers, two layers of suspended film, krypton gas fill, thermal edge break
Total unit U-value	0.49	0.25
Shading Coefficient	0.71	0.43
Solar Heat Gain Coefficient	0.61	0.37
Visible Transmission	0.61	0.48

offices. Downlights in the stairwells and exterior areas were changed from incandescent to compact fluorescent (interior) and metal halide (exterior) units. Occupancy sensors are planned for the individual offices, but were not installed during construction.

The design plug load, originally 1 W/ft^2, was reduced to 0.6 W/ft^2 based on the mix of equipment used by the tenants: notebook computers, non-thermal printers, and some power-management equipment for the desktop computers in use. One large copy machine and one large laser printer were also included in this mix.

The original design included a light well to bring natural light and ventilation to five offices along the north part of the east side of the building. The design retrofit added a 2-foot by 16-foot skylight to the north end of the second floor. This four-foot-deep skylight was oriented on an east-west axis to minimize direct daylight penetration. Automatic daylight controls were not installed near the skylight and light well, so the only energy savings attributable to them is from manual occupant control during daylit periods.

Mechanical Equipment

The original design of the building called for four packaged rooftop air conditioners/gas-fired heaters. Because of the relatively dry Boulder climate (Table 1), the design team selected an indirect/direct evaporative cooling system instead of conventional refrigerative cooling equipment. The tenant's desire to avoid the use of CFC or HCFC-based refrigerants was an additional factor in specifying an evaporative cooler. If refrigerative cooling had been chosen, the load reduction measures would have allowed downsized equipment, which may also have saved peak demand and annual energy consumption. This scenario was not modeled.

Even though evaporative coolers are much simpler than refrigerative cooling units, their cost is higher because each unit is essentially built to custom specifications. Installing four separate units proved to be cost-prohibitive, so a single large unit was specified for the entire building. At peak cooling conditions (93°F dry bulb, 62°F wet bulb), the indirect/direct unit is rated to supply up to 15,000 cfm of air at 57°F. Note that the design peak cooling condition of 62°F wet bulb is higher than the 590 F cited in Table 1. The additional three degrees represents a safety factor that the mechanical engineer insisted upon.

The unit has a 15-hp supply fan, a 5-hp return fan, and a fractional-hp "cooling tower" fan for the indirect evaporative stage. The two primary fans are controlled by variable-frequency drives to reduce energy consumption at off-peak conditions. Comparisons of the peak power demand and annual energy consumption of the baseline (refrigerative) and enhanced (evaporative) systems are shown in Table 3. The DOE-2.1E modeling software was not capable of including the effects of variable-speed operation in the simulation, so the savings predicted are conservative.

The HVAC controls for the building consist of intelligent thermostats connected to a master controller, but no dedicated building energy-management system. The master controller allows scheduling of daily setback times, while the local thermostats allow user-specified "occupied" and "vacant" setpoints. During "vacant" periods, building occupants must manually adjust the thermostat in any direction, which returns the thermostat to "occupied" setpoints for an adjustable period, typically one hour. The system does not directly allow the use of strategies such as night air purging.

Table 3. Comparison of Baseline and Enhanced HVAC Systems

	Baseline Refrigerative	Enhanced Evaporative
Cooling Load (tons)	20.7	12.3
Peak electricity demand (kW)		
Compressor	30.5	0
Supply/return fan	4.5	11
Total	3.5	11
Annual electricity consumption (kWh)		
Compressor	31,811	0
Supply/return fan	15,975	29,631
Total	47,786	29,631

In this project, the tenants acted as commissioning agents, carrying out measurements and ensuring that equipment was installed and operated according to the designer's intent. This required attention to innumerable details; at every stage of construction and startup there were opportunities to derail the low-energy concept that drove the building's "redesign." For example, several electric resistance heaters in the stairwells persistently showed up in the construction documents, even after their removal had been recommended and agreed upon.

In another case, three electric resistance heaters rated at 2 kW each were discovered in the plans-heating the space between the open-air garage's ceiling and the second floor above! The purpose of the heaters was to prevent the garage's fire protection system from freezing. As part of the design retrofit, the heaters were removed, and the garage's sprinkler plumbing was converted to a glycol system.

To meet a local code requirement, the original design called for 20 kW of electric resistance heaters for melting snow on the third floor outdoor decks (total area: 950 sq.ft^2). The design retrofit converted this system to a hydronic system with a small gas-fired boiler.

Results

Figure 2 shows the simulated baseline and enhanced building electricity consumption by end use. The predicted electricity consumption for the enhanced building is 8.25 kWh/ft^2 per year, a 57% reduction from the baseline building's 19.02 kWh/ft^2 per year. Table 4 shows the data for predicted electricity and gas consumption by end use, both in absolute values and normalized per square foot. A key result of the redesign of this building was to shift energy consumption from electricity to gas. Since Colorado's electricity comes primarily from thermal fossil fuel plants, this shift results in a large decrease in the primary fuel required to run the building.

The enhanced building's total site energy consumption figures of 16 kWh/ft^2 per year compare favorably with other buildings, especially considering that nearly half of that consumption is gas burned on-site for space heating. The national average for all buildings is 27 kWh/ft^2 per year, while the average for office buildings is 31 kWh/ft^2 per year (DOE 1989). A study of office buildings in the Washington D.C. area found energy consumption of 2 lkWh/ft^2 per year (Barrar 1992), while a group of eight energy-efficient (but all-electric) office buildings in the northwest had measured consumption of 12 kWh/ft^2 per year, compared to 21 to 22 kWh/ft^2 per year for typical office buildings in the area (Diamond 1992).

Figure 3 shows the predicted and measured electrical consumption of the building for the first three months of operation. Measurements are from utility bills and an on-site 24-channel monitoring system that tracks current, temperature, humidity, and other variables. Despite problems in getting the equipment to operate correctly in the first few months, the electrical consumption of the building is significantly less than the projected baseline energy consumption, and less than the projected enhanced building energy consumption after the first few months.

Although the gas consumption was expected to increase from the baseline building, the measured gas consumption of the building (Figure 4) was much higher than expected for the first three months, after which use declined dramatically. These results are not normalized for actual weather data, but weather conditions over the measured period were not unusual. Observation and monitoring of the building and its subsystems indicate several possible reasons for these results.

The initial occupancy period for any new building is typically fraught with problems, and this building was not an exception. The contractors had difficulty getting the variable-speed fan drives to operate properly, and the lack of tenants on the first floor prevented a full balancing of the air system. The first two months of operation included several tests of the HVAC system controls that adversely affected energy consumption. For example, the gas-fired furnace was turned on and off for testing of the smoke detectors and fan lockout relays, and it took some time to correctly program the occupancy scheduling of the HVAC control system. In addition, some lighting equipment

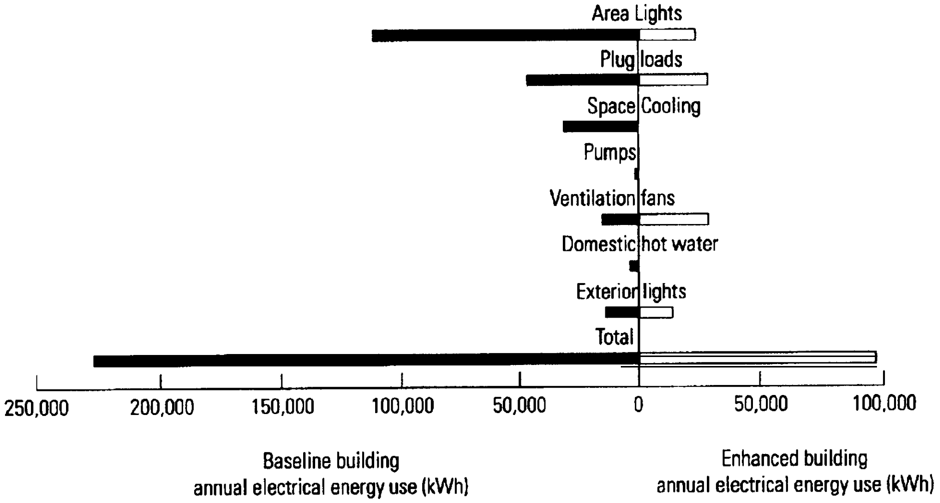

Figure 2. Column Graph of Electricity Use by End Use

Table 4. Energy Consumption by End Use

Electricity consumption	**Annual use (kWh)**		**Annual use (kWh/ft^2)**	
End use	Baseline	Enhanced	Baseline	Enhanced
Area Lights	110783	25060	9.31	2.11
Plug loads	47720	29256	4.01	2.46
Space Cooling	31811	0	2.67	0.00
Pumps	803	0	0.07	0.00
Ventilation fans	15975	29631	1.34	2.49
Domestic hot water	4983	0	0.42	0.00
Exterior lights	14215	14215	1.20	1.20
Total	226291	98162	**19.02**	**8.25**

Gas Consumption	**Annual use (mBtu)**		**Annual use (kwh/ft^2)**	
End use	Baseline	Enhanced	Baseline	Enhanced
Space heating	109.5	293.1	2.70	7.22
Domestic hot water	0	22.6	0.00	0.56
Total	109.5	315.7	**2.70**	**7.78**

Total energy consumption		Baseline	Enhanced
	(kBtu/ft^2-y)	74.12	54.70
	(kWh/ft^2-y)	**21.72**	**16.03**

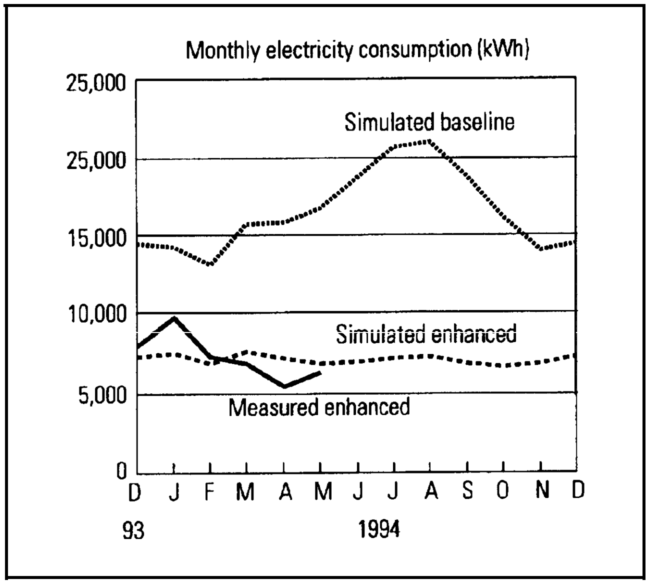

Figure 3. Predicted and Measured Electrical Energy Consumption of the Columbine Building

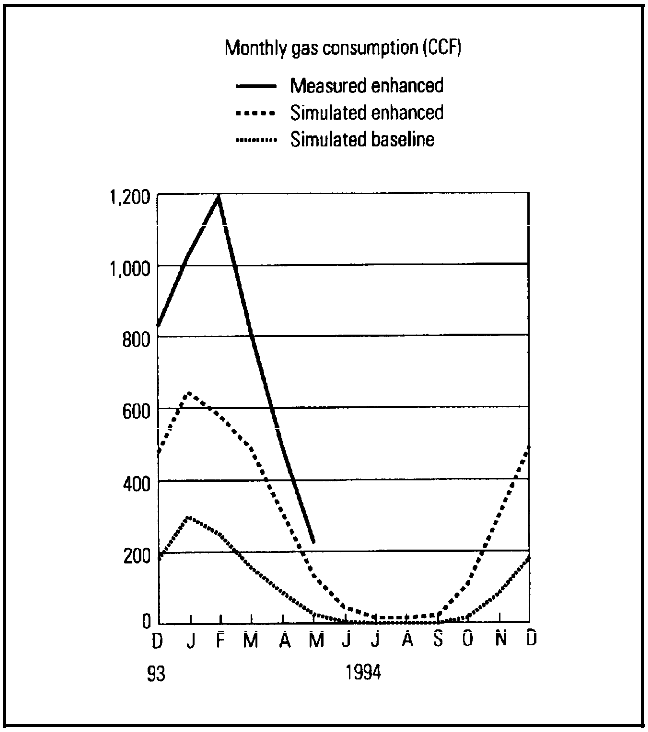

Figure 4. Predicted and Measured Gas Consumption of the Columbine Building

arrived at the site late, and temporary incandescent lighting had to be used for much of December 1993.

Table 5 shows the marginal costs of some of the key upgrades involved in the design retrofit. As noted above, measures were not ranked on cost-effectiveness, but rather on judgments of their ability to save energy and their appropriateness to the task at hand. In this case, costs were high, as all of the items were bid by a sole-source contractor as change orders.

Table 5. Marginal Costs of Efficiency Upgrades

Measure	Marginal Cost ($)
Switch to evaporative cooling system	$34,000
Switch to gas hydronic snowmelt system	$3,800
Upgrade windows	$9,700
Switch to glycol fire protection in garage	$1,200
Upgrade lighting system	$25,000
Savings from downsized electrical panels	($5,400)

Many of the costs shown were arrived at only after rancorous debate with the contractor. For example, the original bid to switch to hydronic snowmelting was $12,700, a marginal cost of $8,600 over the baseline electric resistance heaters. Upon examination, the proposed hydronic system used an expensive snow-detecting sensor to start the boiler, 1,800 feet of piping fed by a 160 Kbtu/h boiler, and included a $875 charge to enlarge the gas piping from 2” to 2-1/2”. The final design had a marginal cost of $3,800, used a simple 12-hour twist timer for control, and 1,000 feet of piping fed by a 75,000 Kbtu/h boiler. By reducing the boiler size, the enlargement of the gas piping was avoided.

In similar fashion, the cost of water treatment for the evaporative cooler was reduced from an initial bid of $7000 to about $500. Downsized electrical breaker switches and transformers provided a capital savings of $5400, but other potential downsizing savings were gobbled up by the change order process. For example, the design team was unable to extract a credit from the contractor for having to run only one gas line to the roof, rather than four lines as the baseline system would have required.

The project coordinators had no control over the selection of the first floor tenants, nor of their choice of lighting and other equipment. Their energy use, especially for the beauty parlor, provides a stark contrast to the efficient spaces above. In two and a half months of operation (mid-March through late May), the 2000-square-foot beauty parlor used about 16 MWh of electricity with a peak demand of 29 kW. Over the same period, the 8800 square feet on the 2nd and 3rd floors, including all external lights, internal hall and stair lighting, *and the entire building's HVAC system,* used about 18 MWh with a peak demand of 20 kW.

Conclusions

Although only seven months of measured data are available, this energy-efficient building appears to be operating according to expectations. Those expectations, based on DOE-2.lE computer simulations, are in turn consistent with other buildings of similar function. More data will be available on the Columbine Building as it is collected, including measured data on electricity consumption by end use.

Acknowledgments

This project was supported by the Colorado Office of Energy Conservation and the Denver Regional Office of the Department of Energy. The author also acknowledges the assistance of E-Cube (computer simulations), Conservation Through Innovation (monitoring system design), Hurd Millwork (windows), and the project developer (Blue Farm Properties).

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