Affordable Housing Through Energy Efficiency

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ABSTRACT

In this paper we evaluate a comprehensive retrofit and rehabilitation effort to improve the comfort, affordability, and energy efficiency of 336 low-income housing units. The units had complete shell retrofits, including new siding, air-infiltration barriers, new windows and doors, and both roof and foundation insulation. In addition, the existing electric-baseboard heating system was replaced with a new gas-fired boiler for each apartment. New programmable thermostats and refrigerators and tenant education were also included in the retrofit package. The evaluation of the project included pre- and post-retrofit utility bill analysis, computer simulation to evaluate the cost and savings of the individual measures, and a comprehensive survey of the residents regarding their comfort, behavior, and satisfaction with the retrofits. The analysis has shown energy savings of more than 20% for the shell measures, with a reduction in utility bills of nearly 50% from the combined measures. The resident survey shows high tenant satisfaction with the retrofits.

INTRODUCTION

The U.S. is currently facing a major housing crisis, one that threatens the loss of hundreds of thousands of low-income housing units across the country. According to the National Low-Income Housing Preservation Commission, by the year 2000, rents of about 650,000 units of federally subsidized housing (HUD 221(d)(3) and 236 Section 8) will be raised to market rates. The units at risk were built in the 1960s and 1970s by private developers under various federal rent-guarantee and mortgage-subsidy incentive programs that are due to expire in the next 10 years. In 1993 alone, the owners of more than 50,000 currently affordable units are likely to prepay the mortgages under which the units were built (National Low-Income Housing Preservation Commission 1988, p.47). After prepayment, the owner has no obligation to continue operating the development as low-income housing.

A key aspect of maintaining the affordability of low-income housing is controlling the costs of energy. Apartment owners lack incentives to make investments in energy-efficiency improvements or even in basic building maintenance because the rent received is more or less fixed, so expenses of energy-efficiency improvements cannot easily be passed on. Inefficient appliances and building shells mean large energy bills, particularly in severe heating climates; for the residents of this housing, high energy costs can compromise affordability (Prindle and Reid 1988). Low-income renters, of course, face the classic "renter's dilemma," in which the landlord has no incentive to make the building energy efficient if the tenants pay for energy, and landlords often lack the capital to make even minor improvements. Even low-income renters receiving energy assistance can face untenable energy bills (Ferrey 1988).

This paper describes a valuable case study that successfully demonstrated how energy efficiency can be a key factor in preserving housing affordability. The project also provides a well-documented example of fuel switching from electric heat to gas—unique in that the conversion to gas was partially paid for by the electric utility.

PROJECT HISTORY

The project is a 336-unit apartment complex in Burlington, Vermont. The units were built in 1969-1970 as subsidized housing under HUD section 221(d)(3), which provided loans to developers to build multifamily housing for low- and moderate-income families. In 1989, the owners announced their intent to pre-pay their HUD loan and convert the apartments to market-level rents. A grass-roots effort was launched to preserve the apartments for low-income families by having a nonprofit organization buy the units. Because utility bills were often higher than rents, the nonprofit organization targeted energy efficiency as a key element in the rehabilitation work planned for the apartments (Northgate and Burlington 1989a, 1989b).

The housing consists of two-story, wood-frame rowhouses, with four to ten houses in each block, which are clustered across the site. There are 36 one-bedroom units, 202 two-bedroom units, and 98 three-bedroom units. The residents are a cross section of the working poor in the region, with more than 80% of the households having at least one wage earner and more than 40% qualifying for low-income (HUD Section 8) housing support; more than 500 children live there.

The major retrofit performed was the replacement of the electric baseboard heating with individual gas-fired boilers that provide both space heating and domestic hot

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water. Additional retrofits included increased levels of insulation in the basements and attics, installation of new exterior siding with infiltration barriers, and the replacement of doors and windows.

In 1990, the U.S. Department of Energy announced that the complex was one of 10 recipients of a competitive solicitation to demonstrate energy conservation in existing buildings. An integral part of the DOE support was to provide a comprehensive evaluation of the project to document the results so that the work could be replicated elsewhere. This paper presents highlights from the project evaluation.

METHODOLOGY

We used three techniques to evaluate the performance of the energy conservation measures: (1) computer simulation of individual apartments to evaluate the individual measures; (2) analysis of the utility bills, pre- and post-retrofit, to determine aggregate, weather-normalized energy savings; and (3) surveys of the residents' satisfaction with the measures.

Determining the Performance of the Individual Measures Through Computer Simulation

We used the DOE-2 building simulation program to determine the energy savings for the individual measures. DOE-2 computes annual energy consumption by simulating the hour-by-hour performance of a building for each of the 8,760 hours in a year. We simulated a block of four one-bedroom units and a block of eight two- and three-bedroom units.

The units were modeled using their design characteristics, which were often considerably better than the actual dilapidated state of the units at the time the retrofits were performed. The input file used these data together with the Typical Meteorological Year (TMY) weather data for Burlington. Additionally, some of the parameters determining the internal loads of the building had to be estimated, such as the occupancy schedules and the domestic hot water loads.

The annual energy consumption for domestic hot water for the one-bedroom apartments was estimated to be 1,278 kWh, without standby and distribution losses. The lights were assumed to have a maximum load of 400 watts and, combined with the lighting schedule, give a result of 967 kWh/year. Refrigerator, cooking, laundry, TV, etc., were assumed to have a maximum load of 2,000 watts. We calculated the energy consumption for this equipment to be 2,628 kWh/year per apartment. We also assumed that there is only one person living in each one-bedroom apartment.

The process of simulating the two- and three-bedroom apartments was similar to the simulation described for the one-bedroom apartments. Retrofit options were the replacement of the electric resistance heating by hydronic thermal distribution systems, installation of infiltration barriers, increased levels of insulation, replacement of doors and windows, and basement insulation.

For the two- and three-bedroom apartments, the consumption profiles and schedules, such as the consumption profile of domestic hot water and schedules for lighting, refrigerator, cooking, laundry, TV, etc., remained the same. The domestic hot water consumption, however, was increased according to the occupancy. For the two-bedroom apartments, we assume a household consumption of 120 liters per day, which translates into an annual energy consumption of 2,556 kWh per apartment. The domestic hot water energy consumption for the three-bedroom apartment accounts for 3,834 kWh if no standby and distribution losses were present. For lighting and equipment, we assumed that the energy consumption does not depend on the number of occupants. Therefore, we kept the maximum load of lighting and equipment at the same value as was used for the one-bedroom apartments. Accordingly, we found 967 kWh/year for lighting and 2,628 kWh/year for refrigerator, cooking, laundry, TV, etc., for each apartment.

Calculation of the Aggregated Energy Savings from the Utility Bills

We collected 12 months of pre-retrofit electricity billing data (June 1989 through June 1990) and 12 months of post-retrofit billing data (September 1990 through Septemyber 1991). In general, the quality of the billing data was high; missing data were relatively few, and we had the advantage that all electricity meters at the site were read on the same days. The electricity data were occasionally missing for one month's reading, and it was often unclear whether the consumption was zero or whether consumption for that billing period was lumped into the following reading. In ambiguous cases, the data were classified as missing; where a reading was clearly skipped, both billing periods were treated as a single data point. In one case, a customer had been overbilled one month and received a refund the next. In this case, the data were adjusted to reflect actual use, i.e., the two bills were spread over both billing periods. These problems affected only 1% to 2% of the data points.

The raw billing data were summarized by apartment size (one-, two-, and three-bedroom) and management-paid meters. Management paid for the electricity for site lighting and for the gas used in vacant apartments.

Calculations were done on the raw data in order to compare energy use from three perspectives—site, source, and delivered energy—and to compare energy costs in the pre- and post-retrofit periods. The analysis followed the following steps:

1. **Site Energy Use** Gas and electricity in the post-retrofit period were combined for each of the 336 apartments.

First, gas use was converted to kilowatthour equivalents at 29.308 kWh/therm (3,412 Btu/ kWh). Since electricity use in the post-retrofit period is less variable than that of gas, electricity data were prorated by day, shifted to correspond to the meter-read dates for gas, and added to the gas use. Figure 1 shows total actual site energy consumption data, pre- and post-retrofit, for both electricity and gas. (These data are not corrected for weather.)

2. **Source Energy Use** Source energy, or primary energy, is a measure of the energy expended to obtain usable energy at the end use; it incorporates into the analysis the overall efficiency of the generation and distribution system. It is a view of energy use from the societal perspective and is useful also for considerations of carbon dioxide emissions and other large-scale environmental impacts of the supply of energy. For the purpose of this analysis, electric system efficiency is estimated to be 31%. This corresponds to a conversion of 10,250 Btu at the source for each kilowatt-hour of billed electricity. Gas is assumed to be 100% efficient in this respect; the consumer explicitly pays for system inefficiencies, since the entire quantity of source energy used appears on the bill.

3. **Delivered Energy Use** To isolate insofar as possible the performance of the rehabilitated building shell, thermal, or "delivered," energy use was calculated using an estimated efficiency for the new heating equipment. In the case of electricity, 100% end-use efficiency is assumed for the electric resistance baseboard heaters that were formerly in use at the complex. In the case of gas, boiler efficiency and distribution losses must be taken into account. The rated efficiency of the boiler units installed is 87%; typical distribution losses might be 4%. Total gas efficiency, then, is estimated at 83%; we ignore the seasonality of distribution losses. Figure 2 shows pre- and post-retrofit consumption in terms of source energy, site energy, and delivered energy.

4. **Energy Costs** Cost information was not taken from actual bills but was calculated from utility rates. Both fuels are billed under tiered rate structures that vary seasonally. Additionally, both fuels underwent rate hikes during the period of analysis. Monthly costs for both fuels for each individual apartment were calculated taking both these complexities into account. Post-retrofit electricity costs were then prorated by day and added to gas costs to determine total energy costs per apartment by billing period in the same way as energy use. Figure 3 shows the costs and site energy consumption per apartment for the pre- and post-retrofit periods.

The raw data were analyzed using the Princeton Scorekeeping Method (PRISM), which normalizes total energy use to a typical meteorological year and identifies the space-heating portion of the normalized annual consumption (Fels 1986). The weather data for the pre- and post-retrofit periods are shown in Figure 4. The pre-retrofit year was colder than the post-retrofit year—6,161 compared to 5,384 heating degree-days (HDD)—due primarily to an unusually cold December, underscoring the importance of weather normalizing the data.

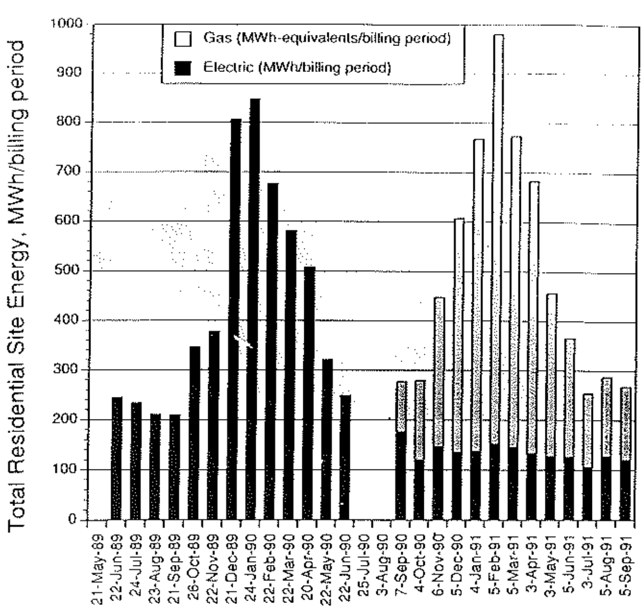


Figure 1 *Total billed energy consumption, pre- and post-retrofit, for monthly billing periods.*

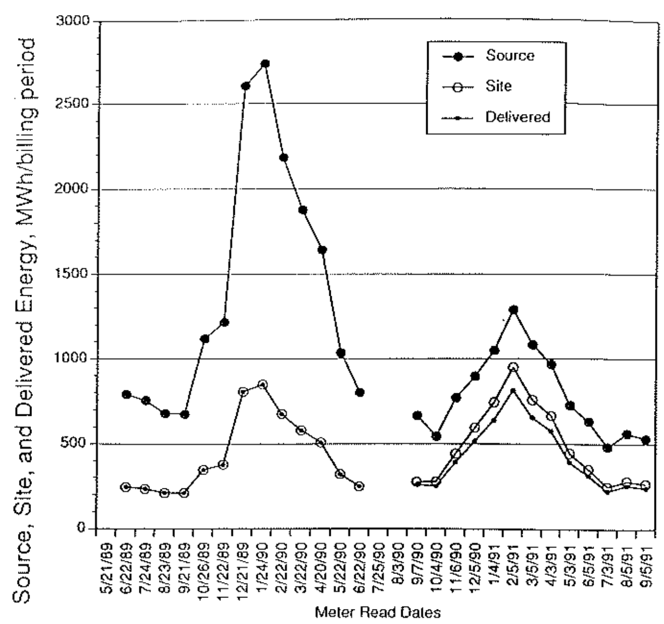


Figure 2 *Energy consumption, pre- and post-retrofit, shown as source energy, site energy, and delivered energy.*

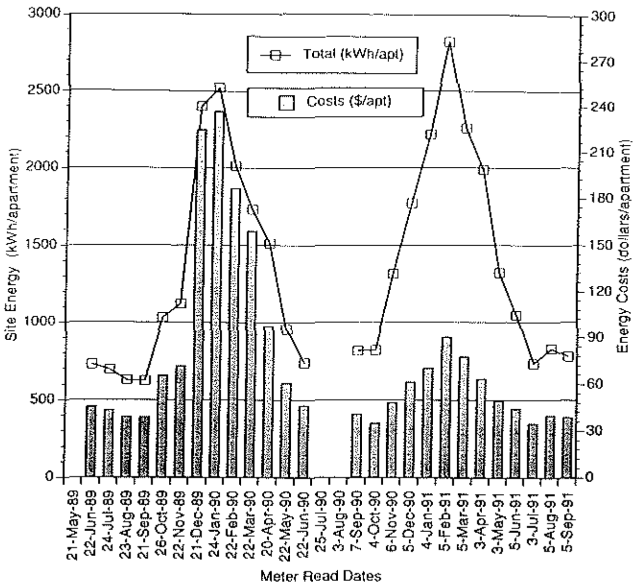


Figure 3 *Residential energy use and costs per apartment.*

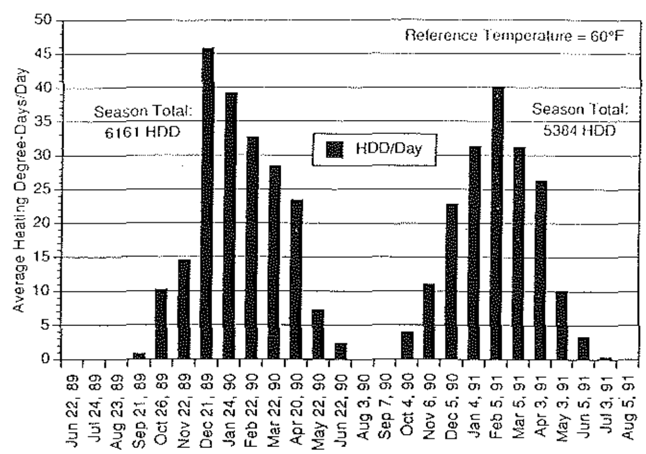


Figure 4 *Heating degree-days (base 60°F) for the pre- and post-retrofit periods.*

The Tenant Satisfaction Survey

In addition to learning about the energy savings due to the retrofits, we also wanted to learn whether the tenants were satisfied with the results. A key goal of the project was to demonstrate that the retrofits would not only save energy but also increase comfort and resident satisfaction.

One-third of the households (100 apartments) were selected at random from the population and were interviewed in person with an 80-question survey. The survey asked the residents about their satisfaction with different aspects of their home before and after the retrofit. Residents were asked about their satisfaction with the inside temperature, draftiness, humidity, hot water temperature and pressure, and the new appliances and thermostat. In addition, they were asked about any changes in their household behavior that might affect their energy consumption. The response rate was 100 percent.

RESULTS

The results of the evaluation are presented in the following three sections, which cover the estimated savings of the individual measures, the aggregate utility bill analysis, and the findings from the tenant surveys.

Estimated Savings for the Individual Measures

The computer simulation calculated an annual space-heating energy consumption for a one-bedroom apartment of 8,050 kWh before retrofit. This value is substantially higher than the 5,868 kWh average heating consumption based on pre-retrofit utility bills. The difference in the energy consumption for space heat of more than 2,000 kWh between the simulation and the billing data is probably due either to the temperatures in the actual apartments being lower than the values assumed in the model or the pattern of only heating parts of the apartments with the electrical heaters rather than the uniform temperatures assumed in the model.

The retrofit of the exterior walls above the basement included an air infiltration retarder and new vinyl siding. The retrofit measure was predicted to reduce infiltration by about 25%, which represents an energy savings of about 3%. Blower door measurements were made on site to determine pre- and post-retrofit airflows at a pressure difference of 50 Pa, but the data proved to be inconsistent and could not be used to calculate infiltration rates. Therefore, the predicted infiltration rates were used in the simulation model.

More cost-effective in terms of energy conservation was the replacement of the old single-pane windows with double-pane insulating glass. The approximately 19% energy savings are based on a reduction of infiltration and the heat transfer through the window. The insulation of the basement walls showed little effect, as the basement was treated as an unconditioned space and the floor is well insulated. Very low outdoor temperatures create basement temperatures close to the freezing point. This retrofit measure will have a greater effect when using a gas-fired boiler, as part of the heat losses of the boiler will heat the basement.

The additional ceiling insulation of approximately one inch, from 10 inches to 11 inches, does not show a significant saving. The insulation level for the pre-retrofit conditions was assumed as specified in the design specification, but there was anecdotal evidence that the cellulose insulation had blown around the attic into piles, reducing its overall effectiveness. Higher ventilation rates in the attic are increasing the energy losses through the ceiling and, therefore, cause a slight increase in energy consumption.

The fuel switching is the most important measure to decrease the energy cost for the buildings. However, due to the lower efficiency of gas boilers and the hydronic thermal distribution system, the site energy consumption for heating and DHW increases about 20%. All measures together produce a decrease of energy consumption of approximately 6%.

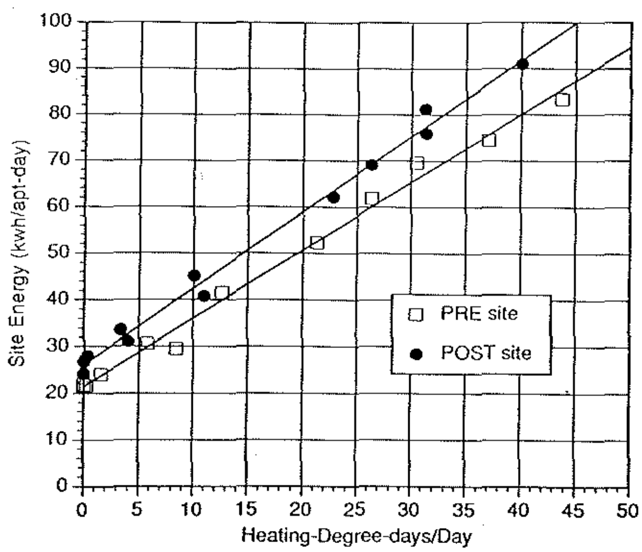
These results are based on the assumption that each apartment is fully heated. The new heating system does not allow for individual room zoning—a single thermostat controls each floor of the apartment. Therefore, we would expect higher heating consumption than with the previous use of the electric baseboard heaters. In order to estimate the savings compared to the zonal heating seen with individual control provided by room thermostats, we have fine-tuned the input data set used for the DOE-2 simulation, using the pre-retrofit utility billing data. The simulation results compare well with the metered data if we assume a room temperature of 60°F. The results of the simulations for the two- and three-bedroom units are similar to the percentage savings in the one-bedroom units.

Aggregate Savings in Utility Bills

The critical issue for the residents was not the reduction in energy use, per se, but the reduction in energy cost. The residents pay for their individual gas and electricity consumption. At the time of the study, residential rates in Burlington were roughly $0.082/kWh for electricity and $0.71/therm (or $.024/kWh) for gas. The reduction in weather-normalized energy costs after the retrofit has been dramatic: the actual utility costs for the average apartment dropped 47%, from $1,278 to $676, and the weather-normalized difference was 45% for the two periods. The largest monthly energy bill in the average apartment declined by 62%, a reduction of $146 per month. Significantly, energy costs per heating degree-day in the post-retrofit period are only one-fourth those during the pre-retrofit period; annual heating costs are $817 and $255 in the pre- and post- periods, respectively (see Figures 5 and 6).

Source energy use was reduced by 41% in the pre- to post-retrofit years, even though site energy increased by 6%. Source energy used for heating was reduced by 60%. The peak month of actual source energy use declined by 52%. Delivered energy, i.e., energy consumption that takes into account the efficiency of the heating equipment, increased slightly (2%) due to the loss of efficiency in the change from electric resistance to gas boilers and the increase in resident comfort levels—we estimate an increase in the interior temperature of 5°F to 10°F.

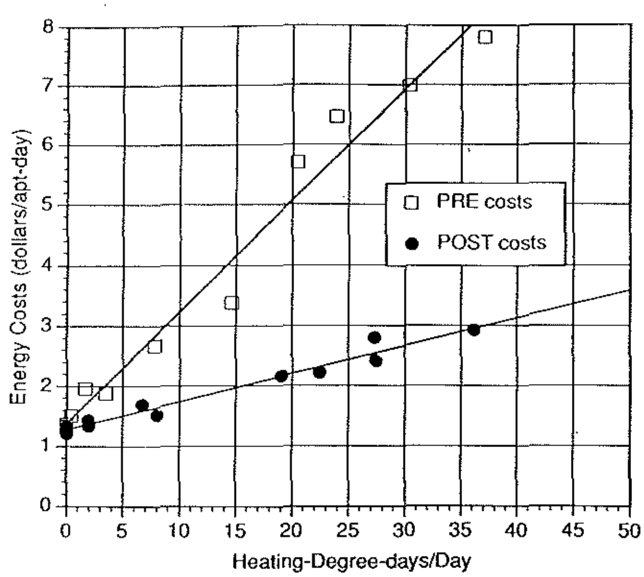
The costs of the energy retrofit measures have been difficult to disaggregate from the total costs of the renovation. The total cost of the building rehabilitation was $8.1 million, of which we estimate $2.1 million was for measures that were specifically for energy improvements, or roughly $6,000 per apartment. The electric utility contributed $267,000 toward the fuel-switching retrofit as part of its long-term effort to move customers off electric heat in order to reduce its winter peak.



PRE:
Base: 21.4 kwh/day (1.24)
Slope: 1.47 kwh/hdd (0.073)
NAC: 16550 kwh/yr (234)
Heat part: 8730 kwh/yr (415)
Ref. Temp: 57.9°F
R-square: 0.99

POST:
Base: 26.1 kwh/day (1.4)
Slope: 1.64 kwh/hdd (0.09)
NAC: 20180 kwh/yr (255)
Heat part: 10650 kwh/yr (470)
Ref. Temp: 60.0°F
R-square: 0.99

Figure 5 *Weather-normalized energy consumption, pre- and post-retrofit.*



PRE:
Base: 1.38 $/day (0.21)
Slope: 0.18 $/hdd (0.018)
NAC: 1322 $/yr (43.8)
Heat part: 817 $/yr (64.5)
Ref. Temp: 51.2°F
R-square: 0.977

POST:
Base: 1.28 $/day (0.068)
Slope: 0.046 $/hdd (0.006)
NAC: 720 $/yr (13.5)
Heat part: 255 $/yr (22.2)
Ref. Temp: 56.1°F
R-square: 0.966

Figure 6 *Energy costs per apartment, pre- and post-retrofit.*

While the utility has expressed satisfaction with the reduction in its winter peak, we have not yet calculated the avoided cost to the utility from the peak reduction, which will require further collaboration with its load-forecasting staff. What we have seen was that the goal of preserving the affordability of the housing was achieved by reducing the residents' utility bills to match the increase in their rents. Not factored into this simple calculation is the enormous increase in occupant comfort and satisfaction. If the occupants had continued to keep the apartments at 60°F post-retrofit, then the energy savings would have been much greater.

Results of the Tenant Surveys

The major finding from the tenant survey was the overwhelmingly positive response from the tenants regarding the retrofits to their apartments. Prior to the retrofits, 84% of the residents said their apartments were too cold, compared to 5% who now say they are too cold. The number of residents who had complained previously of drafts (97%) was reduced to 20% after the retrofit. Uniform temperatures in the apartments had been achieved in 17% of the units prior to the retrofit, compared to 83% of the residents who now report they are able to maintain uniform temperatures. Nearly everyone (98% of the surveyed households) reports that their energy bills have gone down since the retrofits.

The survey also turned up some problems with the retrofits. Perhaps the biggest challenge was the introduction of the new programmable thermostats. An energy specialist met with residents—in some cases several times—to explain the function of the new thermostats. The energy specialist was also able to troubleshoot problems with the new boilers and the installation of the thermostats, more than 50% of which had been incorrectly wired.

Condensation on the windows was another problem reported by the residents after the retrofits were installed. Prior to the retrofits, residents had used humidifiers extensively during the winter due to the dryness caused by the leaky windows admitting cold outside air. The season after the retrofit was not only unusually wet, but some residents continued, through habit, to use their humidifiers. The result was continued condensation on the windows until the residents adapted to the new changes and stopped running their humidifiers.

DISCUSSION

The key to the success of this project has been the demonstration of a major reduction in fuel costs. We have shown that the weather-normalized energy costs are statistically significant, despite the discontinuities introduced by the tiered rate structure, rate changes, and seasonal rate differences. The correlations calculated for the energy costs by the PRISM model are quite high, $r^2 = 0.977$ for the pre-retrofit period and $r^2 = 0.966$ for the post-retrofit period, with standard errors less than 3.5 %.

The base-level energy use and heating slope are similarly defined in terms of dollars. Figure 6 shows in the pre-retrofit period that there is a clear separation between the upper points (representing times of high heating) and the low points (largely nonseasonal or base energy use); the two groups, in fact, seem to lie along two different lines. This is the result of two factors: the tiered rate structure penalizes high electricity users, such as the residents of this complex, during the winter, and seasonal rates are higher in the winter as a disincentive to high energy use during the utility's period of peak demand. There were no rate hikes during the pre-retrofit period. During the post-retrofit period, however, electricity rates went up by 12% in February 1991, and gas rates were raised by 6% in May 1991.

We suspect that the lack of delivered energy savings is due to a substantial "take-back" effect, given that tenants are now paying much less money for much higher comfort levels. The results from the tenant surveys reporting higher indoor temperatures support this finding, but it is difficult to demonstrate the effect from the PRISM model. Figure 5 shows a slight (2°F) increase in the modeled reference temperature, but attributing higher thermostat settings to this finding alone is difficult.

From the survey it is clear that there is now much less zoning of individual rooms for heating. This finding is not surprising in that previously the residents had individual controls on the electric baseboards in each room and they now have one or two thermostats that control entire zones in the house. Consequently, the heated area of each household has increased. The shell retrofit measures (windows and insulation) are consequently providing a significant component of the energy savings, as, without them, the fuel switch might have resulted in much higher heating energy use per apartment.

CONCLUSIONS

The retrofits at a low-income apartment complex have resulted in major cost savings for residents because of fuel switching and the performance of the retrofits. Part of the energy savings is being used to improve the comfort of the residents, both by increasing the interior temperature and in heating the entire house.

The electric utility is happy because of the reduction in its winter peak electricity load and because potentially bill-troubled customers have lowered their bills. Prior to the retrofit, the complex represented 5% of Burlington's residential electric load but accounted for 2% of the utility's households. It now uses less than 2% of the utility's residential load.

The original goal of the community was to preserve the affordability of the low-income housing stock. What the project has demonstrated is that energy efficiency can provide a means for achieving this goal. We hope that the project can serve as a model for housing advocates across the country in showing the linkages between energy efficiency and housing affordability.

ACKNOWLEDGMENTS

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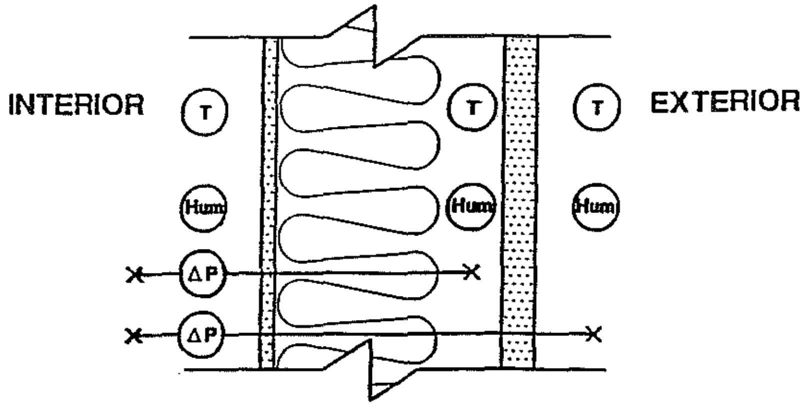

Figure 1 *Instrumentation schematic.*

resistance to airflow are usually, but not always, on the interior side of the insulation as well.

The information needed to assess environmental driving forces on the envelope consist of indoor and outdoor air temperatures, indoor and outdoor humidity levels, and the pressure difference across the envelope. To determine which layer of the wall is resisting these environmental driving forces, one can measure conditions in the cavity, including temperature, humidity, and the pressure difference between indoors and the cavity.

The key to the successful application of envelope performance monitoring is to obtain data for the range of environmental conditions to which that wall or envelope element is exposed. The simplest way of doing this is to collect continuous data for representative periods of time in different seasons. We have found that data collection periods of one or two weeks usually provide adequate temperature, humidity, and pressure variations to provide meaningful results for a particular season. Since so many of Canadian wall performance problems are associated with cold weather, a winter collection period usually proves most valuable, but comparison of winter and summer data has also proved to be enlightening.

A variety of instrumentation and data collection systems have been used to collect these data. A host of temperature sensors provide accurate, reliable performance in field situations, including thermocouples, RTDs, and thermistors.

Pressure transducers to measure the indoor-to-outdoor and indoor-to-cavity pressure differences must be of an appropriate range and bidirectional. While wind forces can create very high pressure differentials over a short term, it is usually the driving forces of long duration, such as stack action or mechanical forces, that cause durability problems. We have therefore found that the most appropriate pressure transducers have a range of -250 to $+250$ Pa (-1.0 to $+1.0$ in. H_2O) with a resolution of at least 1 Pa. Most pressure transducers are subject to significant zero drift, and the monitoring system design or analytical technique must recognize this. There are a number of techniques in which zero drift can be determined and data corrected. For long-term data collection projects, these should be employed. This is not usually necessary for the one- or two-week periods normally used in diagnostic projects *if* it is recognized that there may be some zero drift and the analytical technique works with variations or changes in the pressure differential rather than the absolute values.

Humidity is one of the more difficult things to measure accurately and reliably in the field, especially in freezing and/or condensing conditions. The prime variables required for the analytical techniques are the humidity ratios of the indoor, outdoor, and cavity air. These can be determined from dew-point sensors or calculated from readings of relative humidity and temperature. Both techniques have been used in past projects and both methods have their advantages and disadvantages. Dew-point sensors work very well when properly calibrated but are expensive, bulky (particularly for cavity readings), and require special care and calibration to maintain reliability. Relative humidity sensors are notoriously inaccurate in freezing and condensing conditions. Our experience has shown that either approach can be used, but again, one must use measured humidity as an indicator and look at the patterns of humidity value changes rather than the absolute values.

The most appropriate data acquisition and storage system depends on the specific project. In the original research project in which our techniques were developed, a central data acquisition system collected a whole year's data from a number of sensor locations. However, for most field diagnostic projects, this approach would be expensive and cumbersome. We have therefore developed data acquisition packages to collect data at a single monitoring location. These are based on commercially available data loggers, which are collecting and recording devices that can be downloaded for analysis onto a microcomputer. These units are very compact, relatively inexpensive, and very flexible in their application.

The datalogger modules we use have a 32-kilobyte memory. The data collection interval is set to suit the desired monitoring period. For a two-week period, intervals of 2 to 10 minutes are possible. This data set is post-