ANALYSIS OF ENERGY EFFICIENCY MEASURES IN REHABILITATION OF MULTIFAMILY HOUSING UNITS

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ABSTRACT

An apartment building in Austin, Texas, and one in Boston, Massachusetts, were analyzed to determine the cost-effectiveness of energy efficiency measures. To determine expected energy and cost savings resulting from a set of proposed retrofit measures, hour-by-hour simulations were conducted using the DOE-2.1C building energy analysis computer program. Based on detailed audit data, supplemented by field-measurements in the case of the Austin apartment building, the simulations were run for base case (preretrofit) conditions for each building. Metered electricity and gas consumption was used to calibrate the input data.

A series of proposed retrofit measures was run for each building using the calibrated preretrofit model as the reference. Annual energy and cost savings were calculated separately for each measure and for the combined set of measures. For the Austin building the combined set of 11 measures yielded expected savings of $3,710/year, a 42% savings in site energy. The combination of the 7 measures considered for the Boston building yielded expected savings of $1,292/year, and annual energy savings of nearly 75%. Measured in situ air-conditioner performance for two of the Austin apartments showed EERs of 5.70 and 5.55, indicating an efficiency degradation of 22% and 24%, respectively, after 16 years of operation.

INTRODUCTION

As part of the Multifamily Energy Rehabilita-

(NAHB/RF), the Center for Energy Studies (CES) at The University of Texas at Austin conducted an analysis of energy efficiency retrofit measures for two apartment buildings, an 18-unit complex in Austin, Texas, and a 6-unit complex in Boston, Massachusetts. The purpose of the demonstration program was to determine the effectiveness of energy efficiency measures for each apartment building, as part of the overall rehabilitation of these older multifamily housing units. A comparison of pre- and post-retrofit energy use was not included in the present study.

The project began in March 1986 with pre-retrofit audits of the Austin and Boston complexes. In Austin, the audit was conducted by NAHB/RF staff with the assistance of Planergy, Inc., of Austin, who conducted a preliminary energy analysis. In consultation with the Resource Management Department of the City of Austin and the owner of the building, a set of energy-efficiency retrofit measures was identified. A blower-door infiltration test was conducted on a representative apartment unit by a local contractor.

In May 1986, CES joined the project and conducted a detailed DOE-2 (version DOE-2.1C) building energy analysis computer program simulation of the original building in its pre-retrofit condition[1]. To better characterize key input parameters for infiltration, heat-loss coefficients, and air-conditioner performance, a series of field tests was conducted from July 1986 through March 1987 to measure these parameters in situ. Aggregate utility bills for the complex were used to calibrate the DOE-2 simulation model that was run using historical weather data for the year in which the utility bills were available. Then the 11 proposed retrofit measures were simulated using long-term weather data to determine the energy and cost savings of the retrofit measures. Because the purpose of this study was to determine the potential annual savings of a specified set of retrofit measures, implementation costs and payback periods were not determined.

The analysis of the apartment building in Boston proceeded similarly. However, NAHB/RF personnel audited the Boston apartments in the preretrofit condition; CES staff did not make a site visit, and no field measurements (except infiltration measured by a local contractor) were made to confirm input data.

This paper documents the energy analyses of the retrofit measures for the Austin and Boston apartment buildings. The development of the base case (preretrofit) simulation models is described, as are the air-conditioner performance and co-heating tests conducted at the Austin building. A

measure, and for the aggregate sets of measures, are presented. A detailed documentation of this study is presented in a CES report[2].

DEVELOPMENT OF BASE CASE SIMULATION MODELS

DESCRIPTION OF BUILDINGS IN PRERETROFIT CONDITION

The apartment building in Austin consists of 18 units on two floors of a single building that surrounds a central courtyard. Construction is basically wood frame with single-glazed, horizontal sliding windows with poorly fitting aluminum frames and no screens; thin draperies are available to cover most windows. A mansard roof surrounds the second floor. The exterior is white brick on the outside perimeter; grey wood siding covers the exterior walls facing the courtyard.

The complex contains 12 one-bedroom apartments and 6 two-bedroom apartments, as shown in the floor plan in Figure 1; total floor area is 11,160 ft^2. One-bedroom apartments have floor areas of 565 ft^2; two-bedroom apartments have either 565 or 812 ft^2. The four two-bedroom upstairs apartments on the

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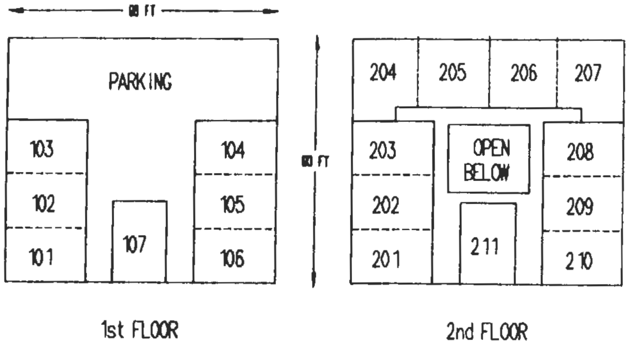

Figure 1 Floor plan of Austin apartments

north side are situated over an exposed parking area; the concrete slab floor is essentially uninsulated. The walls are insulated with R-11 batts and the built-up roof is insulated with R-19 batts, and covered with light-colored gravel.

Each apartment is served by a split system, 1-1/2 ton central air conditioner with the condensing unit mounted on the roof. The evaporator coil for this A/C unit is mounted in the supply plenum of a central forced-air (up-flow) gas furnace rated at 44,000 Btu/h. Hot water is generated in a central gas-fired boiler located in the second-floor utility room.

The apartments in Boston are situated in a 4-story rowhouse. The front (north) and rear (south) walls are fully exposed to the street and alley, respectively. On the east a 3-story building stands 6 inches away. On the west an adjacent 3-story building abuts the apartment building over its front half; the rear half of the west face is exposed. The 6 two-bedroom apartments are arranged on the top three floors; the manager's apartment on the first floor is not part of this study. The front apartments include 516 ft^2 of floor area and the rear apartments 434 ft^2; total floor area for the 6-unit complex is 3,114 ft^2 (see Figure 2 for typical floor plan).

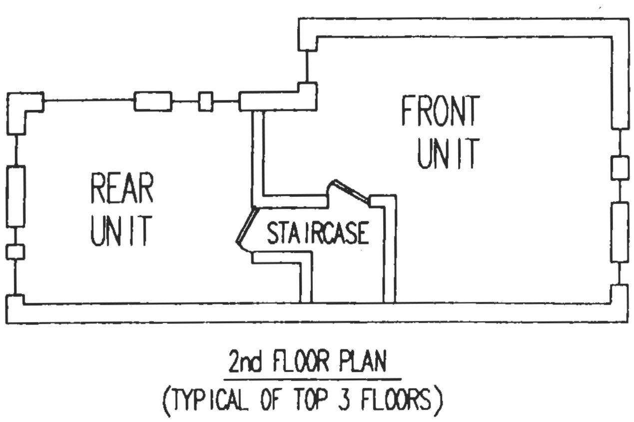

Figure 2 Floor plan of Boston apartments

Construction is wood frame with double-hung, wood-frame, single-glazed windows. All large windows have an aluminum-frame storm sash on the outside, but the bathroom windows have no storm sash. The exterior walls are uninsulated wood frame with dark-colored face brick on the exterior (R-5 walls). The built-up gravel roof is also uninsulated (R-4 roof).

Each apartment is heated by its own combination gas range/heater (25,000 Btu/h); there is no air conditioning. Hot water is supplied from two central, 50-gallon, gas-fired water heaters that supply all apartments.

DOE-2 MODEL: AUSTIN APARTMENT BUILDING

Model Development. The 18 units were combined into 7 thermal zones, with solar exposure being the key consideration. To model accurately the part-load performance of the heating and cooling equipment, 7 systems (serving the 7 zones) were modeled. Each system was sized as a multiple of the individual unit capacities.

The following procedure was used to develop the DOE-2 input for the preretrofit calibration model. Utility data were compiled for each apartment unit. In this calibration, historical weather data for the metered data period were used, and all input data that could be verified were verified by observation or measurement. The comparison of the resulting model with monthly metered data was then used to fine-tune those parameters (such as occupancy schedules) that could not be verified.

First, details of the building design and operation (contstructions, dimensions, shading, heating/cooling system and appliance ratings) were obtained from site energy audits. These data were not changed throughout the analysis. Next, key energy parameters that were known only with a high degree of uncertainty were measured experimentally. These were:

1. Hot water temperature - This was measured at 122°F in apt. #102.

2. Infiltration - Blower door tests conducted by a local contractor indicated infiltration rates of 1.25 air changes per hour (ac/h) at a 10 mph wind speed. However, subsequent coheating tests (see section below) indicated infiltration rates of 1.0 ac/h (at <5 mph wind speed) in the large apartments with exposed floors, and 0.5 ac/h in the small apartments with unexposed floors. Thus rates of 1.25 ac/h for the large units and 1.0 ac/h for the small units were used as the 10 mph wind speed design values in the preretrofit simulations.

3. Air-conditioner efficiency - This was measured for two apartments as described in the field measurement section below.

4. Overall U-value - This was estimated as described in the field measurement section below.

Third, weather and solar conditions for calendar year 1985, the period for which utility records were available, were compiled. Hourly weather data measured at the Austin Airport (about 1/2 mile from the apartment site) were supplemented with hourly global horizontal solar radiation data measured at The University of Texas (about 3 miles from the apartment site)[3]. All calibration simulations used this 1985 weather/solar data set.

Finally, information about apartment vacancy periods was obtained from the apartment manager. These were accounted for in the model by setting thermostats in the vacant apartments at the average outdoor air temperature for the month so that no heating or cooling would be calculated.

Adjustment of Model to Match Metered Data. Once all of the verified data had been incorporated, the model was calibrated to obtain a better match between simulation results and 1985 metered data for the building as a whole. The input parameters chosen for adjustment were those that had a high degree of uncertainty, were not measureable, and had a high impact on the predicted energy consumption of the building.

First, an adjustment was made to match the baseload electric and gas consumption (the average of the three lowest metered monthly usages). The electric baseload (4,700 kWh/month) was matched by scheduling cooling systems off from December through February and by increasing the electric appliance consumption by 20% in each apartment. The gas baseload (28 MBtu/month) was matched by reducing peak hot-water usage by a factor of two from the original estimate (20.5 gal/day per apartment was ultimately used), and by reducing the gas oven consumption by 10%. Occupancy was assumed to be two persons per apartment with a 50% daytime occupancy.

Next, the parameters with the greatest uncertainty were adjusted to achieve a better match to metered data on a monthly basis (heating and cooling load profiles). This included overriding the DOE-2 default curve for furnace part-load performance with one that gave a slightly higher penalty at medium part-load conditions, reducing steady-state furnace efficiency from 65% to 60%, increasing the infiltration rate during swing seasons, and increasing the cooling temperature setpoint from 78° to 79°F (no setforward assumed) for spring and summer months. A heating setpoint of 72°F with no setback was established.

Base Case (Preretrofit) Simulation Results. The process outlined above resulted in a base case DOE-2 input model that predicted metered total energy consumption (electric and fuel) to within 7% on an annual basis for the building as a whole (see Figure 3). However, monthly variations were considerably greater. The complete input listing of the input model is included in 2.

DOE-2 MODEL: BOSTON APARTMENT BUILDING

Model Development. Since there were differing exterior exposures of the individual apartments, each apartment was modeled as a separate zone. Each zone was simulated with its own gas range/heater as the heating plant.

Because no measurements (except infiltration) were made to verify input parameters at the Boston apartment building, data obtained from as-built drawings, supplemented by a report of the detailed preretrofit energy audit conducted by NAHB/RF, were used to define the DOE-2 input. Occupancy schedules (two persons per apartment, 50% daytime occupancy) were estimated from the metered utility data. Blower door infiltration tests were con-

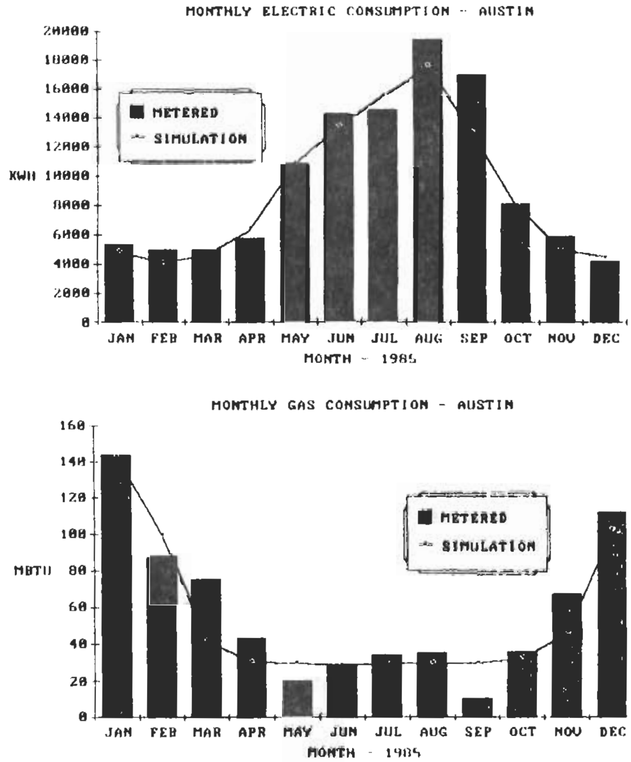

Figure 3 Simulation Results (using 1985 historical weather data) versus 1985 metered data for the Austin apartment building

ducted in the apartments on the second floor by a local contractor. Several tests were made during a summer month yielding nominal preretrofit infiltration rates ranging from 0.8-1.4 ac/h at a simulated 10 mph wind speed. Thus a nominal value of 1.10 ac/h was used in the preretrofit simulation.

Weather data for 1985 from Logan Airport (about 1/2 mile from the apartment site) were used in the preretrofit calibration simulations; no local solar radiation measurements were made. This weather year matched the year for which the metered utility data were available.

A calibration procedure similar to that followed for the Austin apartments resulted in the DOE-2 input model; a complete listing of the model is included in 2. A hot water usage of 8.1 gal/day per apartment was established, as was a 67°F heating setpoint (with no setback).

Base Case (Preretrofit) Simulation Results. The base-case monthly gas consumption profiles are compared with metered gas use for 1985 in Figure 4. Note that although considerable difference exists on a monthly basis, the annual results match within 9%.

FIELD MEASUREMENTS FOR AUSTIN APARTMENTS

AIR CONDITIONER PERFORMANCE MEASUREMENTS

In situ air-conditioner performance measurements were taken in two vacant units in the

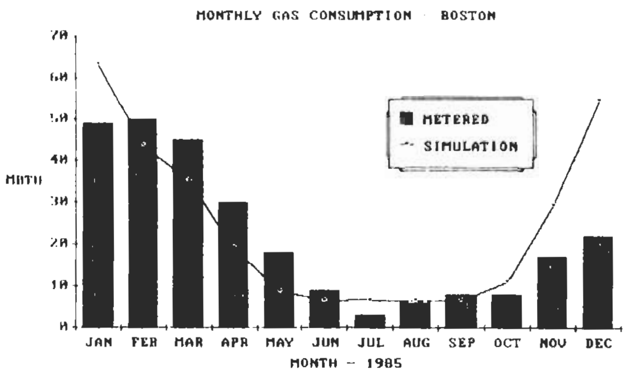

Figure 4 DOE-2 simulation results (using 1985 historical weather data) versus 1985 metered gas data for the Boston apartment building

Austin apartment. The supply air flow rate, cooling rate, and compressor/condensing unit power draw were measured in downstairs apartment 102 (1-bedroom) and in upstairs apartment 206 (2-bedroom). In apartment 102 both full-load (steady-state) and part-load (cycling transient) measurements were made; in apartment 206 only full-load measurements were made. The units were tested in the condition in which they were found; no checks of refrigerant charge were made.

Apartment 102 Measurements. The air conditioner in apartment 102 is a Lennox up-flow gas furnace with a split unit air conditioner whose evaporator coil is mounted in the supply plenum. The compressor and condensing unit are mounted on the roof; the rated cooling capacity is 19,000 Btu/h (nominal 1-1/2 ton) at ARI standard conditions (indoor coil entering air = 80°F DB, 67°F WB, and air to condenser = 95°F DB, 75°F WB). This unit has a rated power input of 2.6 kW (EER = 7.3 Btu/W-h), according to the ARI Unitary Directory, January-March 1968[4], the year in which the unit was installed.

Air from the plenum is ducted in a furred-down ceiling plenum to five supply registers. The supply air flow rate was measured in a configuration as close as possible to the normal flow configuration. Two air-flow-rate measurements were made: one used a pitot tube traverse in a duct extension attached to the supply fan inlet plenum; the other used an Alnor Velometer. Because the furnace filter and the return air grille had to be removed to make the pitot tube measurement, an adjustment to the air flow rate was made to account for the lower pressure drop occurring without these flow restrictions. Details of the measurement procedure are given in 2.

An adjusted flow rate of 573 ft³/min was measured with the pitot tube. A check measurement was made with the Alnor Flow Hood velometer placed over the return air grille. A measured flow rate of 570 ft³/min was obtained, which matches the pitot tube measurement quite closely. A constant supply air flow rate of 570 ft³/min (2,565 lb/h) was used in the subsequent cooling rate calculations.

The cooling rate to the supply air was determined from an energy balance across the evaporator coil:

$$\dot{Q}_c = \dot{m}_a (h_o - h_i) \text{ Btu/h}$$

were $\dot{m}_a$ is the supply air flow rate and h_o and h_i are the coil outlet and inlet enthalpies, respectively. A simultaneous measurement of the combined compressor/condenser fan and supply fan power draw and outside ambient conditions was made to determine the EER (or COP) of the unit[5].

Inlet and outlet enthalpies were measured using wet- and dry-bulb mercury-in-glass thermometers placed in the air stream. Various placements of these thermometers indicated quite uniform conditions across the inlet and outlet flow cross sections. Compressor, condenser fan, and supply fan power draw (including the 13-W refrigerant heater) were measured with current transformers. The supply fan power, measured at 430 W, was considered constant throughout the tests.

Several full-load (steady-state) measurements were made on three separate days in September 1986. The average of these measurements indicated a 16,000 Btu/h cooling capacity, after 16 years of service, showing a degradation of 16% from the rated capacity. Similarly the measured full-load EER of 5.7 is 22% lower than the rated value of 7.3.

To characterize the transient behavior of the air-conditioning unit, a series of cycling tests was conducted in which the unit was turned on for 15 min, then off for 15 min. This pattern was repeated on each of two days. A plot of the temperature-time profiles for the two tests is shown in Figure 5, while the cooling rate, power draw, and EER are plotted in Figure 6. It can be seen that the evaporator coil inlet and outlet temperatures exhibit transient conditions for somewhat longer than 15 min. However, Figure 6 shows that transient conditions persist for the EER for only about 10 min. The data scatter on the cooling rate and the EER is about $\pm$ 20%.

As a check on the moisture removal rate, the condensate flow rate was measured during a steady-state test on September 19. In this test the condensate drain line was opened to fill a beaker over a measured time period. The average of three repeated measurements was 2.61 lb/h. This compares within 7% to the 2.45 lb/h average calculated from the product of the measured air flow rate and the difference between the measured evaporator inlet and outlet humidities.

Apartment 206 Measurements. The air-conditioning unit in apartment 206 is identical to the one in apartment 102. A brief test was conducted in this larger, upstairs apartment on September 24, 1986, to determine the full-load, steady-state cooling performance. Cooling rate and power draw were determined as they were in apartment 102; however, supply air flow rate was measured only using the velometer. An adjusted supply air flow rate of 550 ft³/min (2,475 lb/h) was measured, and a power draw of 370 W was measured for the supply fan.

As with apartment 102, the measured cooling capacity of 16,200 Btu/h is within 15% of the rated capacity. Similarly the measured EER of 5.55 shows a degradation of 25% from the rated value of 7.3.

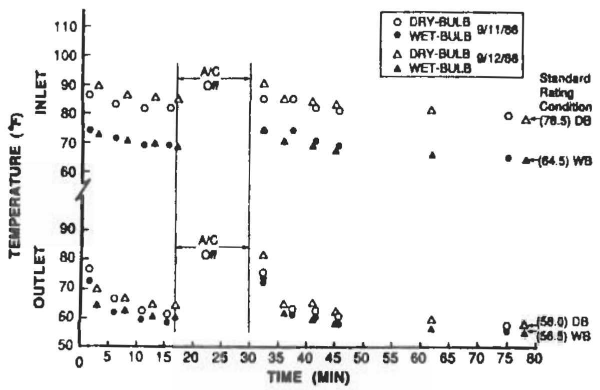

Figure 5 Transient response of air conditioner in apartment 102: Wet- and dry-bulb temperature (Austin)

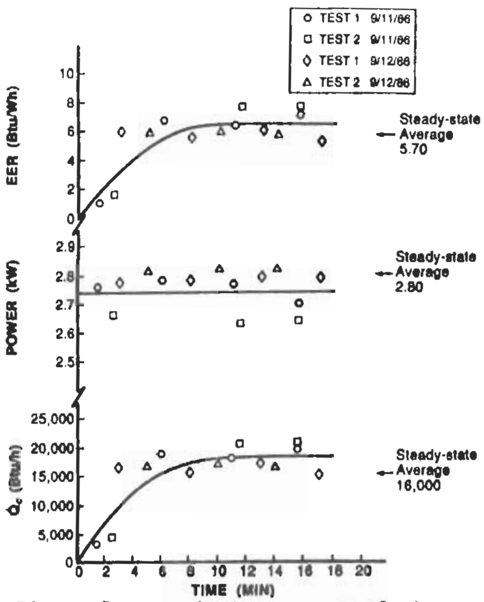

Figure 6 Transient response of air conditioner in apartment 102: Cooling rate, power draw, and EER (Austin)

CO-HEATING MEASUREMENTS

A series of co-heating experiments was conducted in two vacant apartments during March 1987. The purpose of the experiments was to determine the overall heat loss coefficients of representative one- and two-bedroom apartment units. These provide a check on the tabulated envelope conductances, and especially the infiltration rates. Measurements were made in upstairs apartment 206 (2-bedroom, 812 ft²) and upstairs apartment 208 (1-bedroom, 565 ft²).

The co-heating tests consisted of heating the unit to a temperature well above the outside ambient for approximately 12 h at night, during which no solar gains were experienced. Heat is added with metered electric resistance heaters (controlled to be the only energy input to the space) so as to maintain an essentially constant inside ambient temperature. A quasi-steady-state energy balance over the 24-h period gives the overall loss coefficient:

$$UA_o\,(\text{Btu/h-}^\circ\text{F}) = \frac{\sum_{h=1}^{24} Q\ (\text{Btu/h})}{\sum_{h=1}^{24} (T_i - T_o)\ (^\circ\text{F})}$$

This value can then be compared with the calculated UA_o value obtained from tabulated or measured wall, ceiling, floor, and infiltration conductances and areas.

Apartment 206 Measurements. Apartment 206 is exposed on the north and south walls, the ceiling, and through its uninsulated concrete slab floor (located over an open carport); adjacent apartments are to the east and west. Because this vacant apartment was being prepared for remodeling, two of the four windows had no drapes and the carpet had been removed from the floor.

Hourly co-heating energy and indoor/outdoor temperature differences were recorded for the experiment conducted on March 10-11, 1987. Averaged over the 10-h (nondaylight) period, these data yielded a measured UA_o = 276 Btu/h-°F. Tabulated values of the loss components obtained from 6 and based on energy audit data indicate an overall loss coefficient of 278 Btu/h-°F at an infiltration rate of 0.75 ac/h under the calm wind conditions occurring during the tests. Thus a design (10 mph) infiltration rate of 1.0 ac/h was used for the exposed 2-bedroom apartments.

Apartment 208 Measurements. Apartment 208 is smaller than 206 and is buffered by being located above an occupied apartment. It is exposed on the east and west walls, the ceiling, and nearly half of the north wall. Drapes covered all three windows, and the floor was carpeted. Results for the nondaylight period during March 28-April 1 yielded an average overall UA_o = 105 Btu/h-°F. For this apartment, representing unexposed 1-bedroom units, the coheating overall loss coefficient matched the calculated value (using tabulated conductances) at an infiltration rate of 0.5 ac/h under calm wind conditions. Thus 0.75 ac/h was used as the design value.

RETROFIT MEASURE ANALYSIS RESULTS

A set of potential energy-efficient retrofit measures was analyzed for each of the two apartment buildings. To determine the annual energy and cost savings to be expected from the set of potential energy-efficiency measures, each measure was simulated with long-term weather data in DOE-2, and the results were compared with those of the base case preretrofit simulation. Then the combined set of measures was simulated for each of the apartment buildings. The resulting savings are given below.

AUSTIN APARTMENTS

Based on the field measurements of air-conditioner performance at the Austin apartments, the following adjustments were made to the base case (preretrofit) DOE-2 model:

1. Supply air flow set to 570 cfm
2. Supply fan power set to 0.43 kW
3. Cooling capacity set to 16,000 Btu/h
4. Cooling EER set to 5.70

Using this calibrated model the 11 retrofit measures described in Table 1 were simulated using TMY weather data for Austin, Texas.

The annual energy and cost savings predicted by these simulations are summarized in Table 2. This table shows the gas and electric energy and cost savings for each measure, and then the combined set of measures, relative to the pre-retrofit base case. Cost savings are calculated at utility rates of $6.00/10^6 Btu and $0.065/kWh.

The highest percentage of reductions in energy use for the Austin apartments comes from eliminating the gas pilot lights on the furnaces. This result illustrates how even a small energy consumption (500-1,000 Btu/h is typical for pilots) can be significant if its operation is continuous. However, the greatest reduction in energy cost occurs with replacement of the 16-year old air conditioners with high-efficiency models ($1,155/yr).

Floor insulation proves to be a good retrofit option because it addresses one of the weakest components of the envelope: the uninsulated, exposed floor of the second-floor apartments. Thermostat management is usually a very cost-effective energy conservation strategy (if it can be enforced), as the savings in Table 2 indicate, particularly in view of the low installation cost of this measure. Reflective roofs will have signficiant impact only on single-story buildings that are both cooling dominated and have roof loads

Table 1: Austin Retrofit Measures

MEASURE # 1: ....CAULKING & WEATHERSTRIPPING
Apply weatherstripping materials around all doors and windows in all apartments. Apply caulking to seal air leakage areas in the building structural components. Results in infiltration reduction from design value of 1.0 ac/h to 0.75 ac/h, and from 1.25 to 1.0 ac/h in apts 204-207.

MEASURE # 2: ....STORM WINDOWS
Install 1/8" clear insulating glass (2 1/8" panes separated by a 1/2" air space) on exterior windows in all north-, east-, and west-facing apartments. Reduces window U-value 40% and shading coefficient 10%. Also reduces infiltration from 1.0 ac/h to 0.86 ac/h, or from 1.25 to 1.06 ac/h in apts 204-207.

MEASURE # 3: ....SEAL FURNACE CLOSET
Seal around edges/construction joints in air handler enclosure. Install a furnace vent damper that opens only when the furnace is operating. Improves furnace efficiency from 60% to 70%.

MEASURE # 4: ....FLOOR INSULATION
Six-inch fiberglass batts (R-19) added to floor cavity over parking area (north apartments 204, 205, 206, and 207). Decreases overall floor U-value from 0.19 Btu/h-ft^2-°F to 0.04 Btu/h-ft^2-°F. Also reduces infiltration from 1.25 ac/h to 1.15 expected in the affected apartments due to concurrent addition of a vapor barrier.

MEASURE # 5: ....CEILING INSULATION
Rigid board roof insulation (2" thick, R-5.6) added to existing roof surface, then felt paper and tar. Decreases overall roof U-value from 0.04 Btu/h-ft^2-°F to 0.032 Btu/h-ft^2-°F.

MEASURE # 6: ....AUTO NIGHT SETBACK
Install automatic, tamper-proof setback thermostats in all apartments that reduce the heating setpoints from 72°F to 67°F beginning at 10 PM to 7 AM period.

MEASURE # 7: ....AUTO DAY SETFORWARD
Install automatic, tamper-proof setforward thermostats in all apartments that raise the cooling setpoints from 78 to 85°F beginning at 8 AM to 4 PM period (presumed to be unoccupied).

MEASURE # 8: ....LIGHT-COLORED ROOF
Apply coat of light-colored durable paint to roof surface and mansard. Lowers the absorptance of both surfaces from 0.95 to 0.40.

MEASURE # 9: ....SOLAR SCREENS
Install fiberglass mesh solar screens (Shading Coefficient = 0.28) on all east and west windows (excluding windows facing the courtyard).

MEASURE # 10: ....AUTOMATIC PILOT ON FURNACES
Install electronic pilots on all furnaces. Eliminates pilot losses when furnace is not operating (all furnances currently have gas pilots that are left on continuously).

MEASURE # 11: ....HIGH-EFFICIENCY AC
Install high-efficiciency central AC systems (both air- handling units and condensing units) of the same capacity as is currently installed. Base case EER of 5.70 increased to 9.23.

COMBINED MEASURES

All of the above measures were combined into a single retrofit package by incorporating all of the above changes into one simulation. Two modifications were necessary where one or more measures competed for energy savings (addressed the same component of heating or cooling loads):

1. Infiltration impacts of measures 1, 2, and 4 were combined by reducing infiltration to 0.80 ac/h in the north apartments (combination of caulking, storm windows, and floor insulation), and to 0.60 ac/h all other apartments (combination of caulking and storm windows).

2. For combined solar screens and storm windows on east and west windows a shading coefficient of 0.25 was used.

Table 2: Predicted Austin Savings

Measure Number	Description	Annual Energy/Cost Savings						
		Gas (MBtu)	Cost ($)	Elec (kWh)	Cost ($)	Total (MBtu)	Cost ($)	% Energy Saving
1	Caulking & Weatherstripping	49.0	$294	2080	$135	56.1	$429	5.9
2	Storm Windows	53.0	318	2271	148	60.8	466	6.3
3	Seal Furnace Closet	40.5	243	0	0	40.5	243	4.2
4	Floor Insulation	61.3	368	645	42	63.5	410	6.6
5	Ceiling Insulation	9.1	55	691	45	11.5	100	1.2
6	Automatic Night Setback	37.5	225	401	26	38.9	251	4.1
7	Automatic Day Setforward	0	0	8860	576	30.3	576	3.2
8	Light-Colored Roof	-10.57*	-63	3023	196	- .25*	133	0
9	Solar Screens	- 6.1 *	-37	1465	95	-1.1 *	58	0
10	Automatic Pilot on Furnaces	100.6	604	0	0	100.6	604	10.5
11	High-Efficiency AC	0	0	17767	1155	60.6	1155	6.3
—	Combined Measures	297.7	1786	29607	1924	398.7	3710	41.6

* Because this measure reduces solar gain year-round, winter heating loads increase. This explains the negative gas savings.

that constitute a major portion of the cooling load. Neither was the case in this building.

Although solar screens typically reduce energy consumption significantly, half of the windows in this apartment building face an inner courtyard and have a 4-ft overhang; solar screens would have very little impact on this situation and were therefore not modeled. The savings in cooling for the other east- and west-facing windows were offset by the increase in heating energy resulting from reductions in winter solar gain.

The combined set of eleven measures yields expected savings of $3,710/yr, a 41.6% site energy savings.

BOSTON APARTMENTS

Using the preretrofit model as a reference, the 7 retrofit measures described in Table 3 were simulated using WYEC weather data for Boston. Results of the retrofit simulations are shown in Table 4, expressed as total (gas and electric) energy savings and as a percentage of the preretrofit total energy use. Cost savings are calculated at utility rates of $6.00/10^6 Btu and $0.065/kWh.

All measures that serve to tighten up the very leaky, poorly insulated envelope of these apartments show significant energy savings. Furthermore, the savings are cumulative because each measure addresses a separate component of heat loss (conduction through windows, conduction through walls, infiltration through penetrations, etc.).

The highest savings (27.8%) result from night setback thermostats on resistance heaters. However, because this measure resulted in fuel switching, the expected energy costs increased by

Table 3: Boston Retrofit Measures

MEASURE # 1: ....STORM WINDOWS

Replace existing windows with double-glazed windows with an additional third pane of glass acting as a storm window. Reduces overall U-value from 0.73 to 0.40 and reduces the shading coefficient from 0.88 to 0.65. Design infiltration is also reduced from 1.10 ac/h to 0.75 ac/h.

MEASURE # 2: ....INDIVIDUAL DHW HEATERS

Replace the two 50-gal gas water heaters with 30-gal gas heaters serving each apartment separately. The smaller units have a lower loss factor and a more efficient burner for a net efficiency increase from 75% to 90%.

MEASURE # 3: ....ADD NIGHT SETBACK THERMOSTATS AND REPLACE GAS HEATER WITH ELECTRIC HEATERS

Install thermostats on the new electric baseboard space heaters that will automatically lower the heating setpoint from 67°F to 60°F when the lights are turned off (11:00 PM thru 7:00 AM). Deactivate heating function of range/heater.

MEASURE # 4: ....INSULATE WALLS

Add 3/4" urethane insulating boards and a vapor barrier inside all exterior walls. This will decrease the overall wall U-value from 0.20 to 0.10 (R-5 to R-10) and reduce the air infiltration rate from 1.10 ac/h to 0.85.

MEASURE # 5: ....INSULATE FLOORS & CEILING

Add 10" fiberglass batt insulation to the roof and between intermediate floors. This will reduce the roof overall U-value from 0.24 to 0.03 (R-4.2 to R-36).

MEASURE # 6: ......GAS RANGES W/ELECTRONIC PILOTS

Replace exisiting gas range with new gas ranges having electronic pilots. This will reduce the baseload gas consumption from 2.9 to 2.7 MBtu/month.

MEASURE # 7: ....CAULKING AND WEATHERSTRIPPING

Apply weatherstripping around all doors and windows in all apartments. Apply caulking to seal air leakage areas in the building structural components (sill plates, around joists, wall outlet penetrations). Results in infiltration reduction from 1.10 ac/h to 0.50 ac/h.

COMBINED MEASURES

All of the above measures are combined into a single retrofit package by incorporating all of the above changes into one simulation. One modification was necessary where two measures competed for energy savings: infiltration impacts of measures 1, 4, and 7 were combined by reducing infiltration of 0.11 ac/h (10% of base case: includes combination of storm windows, wall insulation, and caulking/weatherstripping).

$1,834/yr. This is really a double measure because installation of resistance heaters alone eliminates the gas heater losses. That portion of savings attributable to thermostat setback is subject to the uncertainty in the assumed thermostat setpoint (67°F) for the base case. In apartments heated by

Table 4: Predicted Boston Savings

Measure Number	Description	Annual Energy/Cost Savings						
		Gas (MBtu)	Cost ($)	Elec (kWh)	Cost ($)	Total (MBtu)	Cost ($)	% Energy Saving
1	Storm Windows	57.5	$345	0	$ 0	57.5	$345	16.3
2	Individual DHW Heaters	2.1	13	0	0	2.1	13	0.6
3	Add Night Setback Thermostats & Replace Gas Heaters w/ Electric Heaters	284.0	1704	-54500*	-3542*	98.0	-1834	27.8
4	Insulate Walls	94.0	564	0	0	94.0	564	26.6
5	Insulate Floors & Ceiling	42.1	252	0	0	42.1	252	11.9
6	Gas Ranges w/Electronic Pilots	1.2	4	0	0	1.2	4	0.2
7	Caulking & Weatherstripping	69.8	419	0	0	69.8	419	19.8
—	Combined Measures	286.0	1716	-6516**	-423**	263.8	1292	74.8

* Since electric heaters replace gas heaters, the electricity consumption increases, resulting in negative electric energy savings. For the assumed utility rates, fuel switching does not appear to be cost effective.

** Since electric heaters replace gas heaters, the electricity consumption increases, resulting in negative electric energy savings. With all of the other measures in effect, the increase in electric consumption is much smaller.

a room heater, space temperatures may vary significantly from room to room; 67°F was intended to be an average for the entire apartment. While the combined set of seven measures results in expected annual energy cost savings of only $1,292, the annual energy savings is considerable: 75%.

CONCLUSIONS

This study has resulted in the following conclusions.

1. The preretrofit base-case model, which is based on audit data supplemented by field measurement of key parameters that cannot be accurately determined from the audit data (for example, air-conditioner efficiency and infiltration), can be determined with sufficient accuracy by calibration with metered energy use. However, the specific results of this study are transferable to other multifamily buildings only to the extent that their construction, operation, and climate are similar.

2. For the Austin apartment building, the retrofit measures expected to yield the greatest energy cost savings are high-efficiency air-conditioner replacements, installation of electronic pilots on the furnaces in each unit, and automatic daytime thermostat setforward during the cooling season. The measure yielding the least energy cost savings was the addition of solar screens. The combined set of eleven measures is expected to save $3,710/yr for the 18-unit building, and nearly 42% of the annual preretrofit energy use.

3. For the Boston apartment building, the retrofit measures expected to yield the greatest energy cost savings are envelope measures: wall insulation, caulking/weatherstripping, and storm windows. The measures yeilding the least expected energy cost savings are electronic pilots on the gas ranges and conversion to water heaters serving individual apartment units rather than a central distribution system. The combined set of seven measures is expected to save only $1,292/yr, but 75% of the annual preretrofit energy use for the 6-unit building.

4. Field-measured air-conditioner efficiencies in the Austin apartment building show degradation of 20-25% after 16 years of service.

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